Water resource assessment for the Darwin catchments

A report to the Australian Government from the CSIRO Northern Australia Water Resource Assessment, part of the National Water Infrastructure Development Fund: Water Resource Assessments

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The Assessment was guided by three committees:

(i) The Assessment’s Governance Committee: Consolidated Pastoral Company, CSIRO, DAWR, DIIS, DoiRDC, Northern Australia Development Office, Northern Land Council, Office of Northern Australia, Queensland DNRME, Regional Development Australia - Far North Queensland and Torres Strait, Regional Development Australian Northern Alliance, WA DWER

(ii) The Assessment’s Darwin Catchments Steering Committee: CSIRO, Northern Australia Development Office, Northern Land Council, NT DENR, NT DPIR, NT Farmers Association, Power and Water Corporation, Regional Development Australia (NT), NT Cattlemen’s Association

(iii) The Assessment’s Mitchell Catchment Steering Committee: AgForce, Carpentaria Shire, Cook Shire Council, CSIRO, DoiRDC, Kowanyama Shire, Mareeba Shire, Mitchell Watershed Management Group, Northern Gulf Resource Management Group, NPF Industry Pty Ltd, Office of Northern Australia, Queensland DAFF, Queensland DSD, Queensland DEWS, Queensland DNRME, Queensland DES, Regional Development Australia - Far North Queensland and Torres Strait

Note: Following consultation with the Western Australian Government, separate steering committee arrangements were not adopted for the Fitzroy catchment, but operational activities were guided by a wide range of contributors.

This report was reviewed by Ian Prosser (Independent Consultant) and the summary by Peter Stone (Bureau of Meteorology).

For further acknowledgements, see page xxii.

Photo

Finniss River, Northern Territory. Source: CSIRO
Sustainable regional development is a priority for the Australian, Western Australian, Northern Territory and Queensland governments. In 2015 the Australian Government released the ‘Our North, Our Future: White Paper on Developing Northern Australia’ and the Agricultural Competitiveness White Paper, both of which highlighted the opportunity for northern Australia’s land and water resources to enable regional development.

Sustainable regional development requires knowledge of the scale, nature, location and distribution of the likely environmental, social and economic opportunities and risks of any proposed development. Especially where resource use is contested, this knowledge informs the consultation and planning that underpins the resource security required to unlock investment.

The Australian Government commissioned CSIRO to complete the Northern Australia Water Resource Assessment (the Assessment). In collaboration with the governments of Western Australia, Northern Territory and Queensland, they respectively identified three priority areas for investigation: the Fitzroy, Darwin and Mitchell catchments.

In response, CSIRO accessed expertise from across Australia to provide data and insight to support consideration of the use of land and water resources for development in each of these regions. While the Assessment focuses mainly on the potential for agriculture and aquaculture, the detailed information provided on land and water resources, their potential uses and the impacts of those uses are relevant to a wider range of development and other interests.

Chris Chilcott
Project Director
Key findings for the Darwin catchments

Introduction
In the Darwin catchments the Finniss, Adelaide, Mary and Wildman rivers flow through extensive coastal and marine floodplains into the Arafura Sea. Land use in the 30,000 km² that make up the Darwin catchments is dominated by conservation and natural environments (38%), extensive grazing (32%) and dryland and irrigated cropping (7%). About 140,000 people live in the 2% of the landscape comprising urban and peri-urban development.

Indigenous people have continuously occupied and managed the Darwin catchments for tens of thousands of years and retain significant and growing rights and interests in land and water resources, including crucial roles in water and development planning and as co-investors in future development.

Agriculture and aquaculture opportunities
The Darwin catchments have up to 1 million ha of potentially irrigable agricultural soils. Of this land area, 800,000 ha are suitable for trickle-irrigated crops such as mangoes (Figure 1-1), whereas about 90,000 ha are suitable for flood-irrigated crops such as rice. A further 420,000 ha of land is moderately suitable for aquaculture, including species such as prawns and barramundi, grown in lined ponds. For all of these uses the land is considered moderately suitable with considerable limitations and would require careful soil management.

Groundwater is the Darwin catchments’ most important consumptive water resource. Aquifers in the Darwin Rural Water Control District (DRWCD) currently provide an estimated 25 gigalitres (GL) for the purpose of irrigated agriculture, horticulture, public water supplies and local domestic use. New groundwater resources outside of the DRWCD (35 GL) could, if allocated, enable an additional 7800 ha of trickle-irrigated vegetable production, which could add $320 million and 345 jobs to the regional economy.

Significant new instream surface water storage is possible. Potential dams at Mount Bennett on the Finniss River (343 GL capacity) and the upper Adelaide River (298 GL capacity) could release approximately 436 GL for agriculture in 85% of years. This could support 40,000 ha of mangoes or 60,000 ha of trickle-irrigated vegetables, enabling just 2% of the area of the catchment to add $2.3 billion and 2500 jobs to the regional economy.

Offstream water harvesting is possible on the Margaret River in the Adelaide catchment (200 GL) and the McKinley and Mary rivers in the Mary catchment (400 GL). This could provide water sufficient to trickle irrigate 50,000 ha of vegetables, although the proximity of irrigable soils to locations suitable for water storage may be a limitation of this area.

Impacts and risks
Whether based on groundwater, instream dams or offstream storage, irrigated agricultural development has a wide range of potential benefits and risks that differentially intersect diverse stakeholder views on ecology, economy and culture. The detailed reports upon which this
catchment report is based provide information that can be used to quantify the trade-offs required for agreed development plans.

The general impacts of potential new groundwater-based developments may include a reduction in spring flows and an increase in the depth to groundwater beneath groundwater-dependent vegetation. These impacts can be reduced with good planning, such as evidence based water allocations and appropriately siting groundwater bore infrastructure. In some areas with existing groundwater development, there may be opportunity to intentionally recharge water to underlying aquifers, referred to as managed aquifer recharge (MAR), for subsequent recovery or to provide environmental benefit.

Instream storages, such as the potential upper Adelaide River dam, require trade-offs that occur over both time and space. Construction of large instream dams provide water that is generally secure across many years. This requires significant upfront investment ($190 million) that is intended to generate a future income stream that may contribute to the cost of investment. Instream dams significantly disrupt their immediate upstream and downstream environments but, when located high in the catchment, as with the potential upper Adelaide River dam, have negligible to minor impacts on coastal floodplains and their related mosaic of nationally important wetlands. Streams, wetlands and riparian areas remain of critical importance to Indigenous people. They have cultural significance and provide nutritional food.

Pumping water into offstream storages (water harvesting) generally has less impact on freshwater aquatic, riparian and marine ecosystems than major instream dams, in part because water extraction occurs mainly during floods and is restricted during low-flow periods. Offstream storages are readily scaled to match the availability of financial and physical capital. They are not usually capable of securing water for more than 1 year and, as a result, they ‘make good wet seasons better’ rather than reliably ‘making dry seasons wet’.

Figure 1-1 Mango trees in the Darwin catchments
Overview of the Darwin catchments

A HIGHLY SEASONAL CLIMATE

The world’s tropics are united by their geography but divided by their climates. Northern Australia’s tropical climate is unique for the extremely high variability of rainfall between seasons and especially between years. This has major implications for the assessment and management of risks to development, infrastructure and industry.

The Darwin catchments have a hot and humid climate with a more reliable rainfall than other parts of northern Australia.

- The northerly and coastal position of the Darwin catchments ensures that wet-season rainfall is strongly influenced by the monsoon trough during ‘active’ monsoon phases.
- On average, the wet-season rain starts earlier in the Darwin catchments than anywhere else in northern Australia.
- The mean and median annual rainfall – averaged across the Darwin catchments – are 1423 mm and 1392 mm, respectively. However, there is a strong rainfall gradient that runs from the north-west coastal corner (1625 mm annual mean) to the south-east corner of the catchment (1250 mm annual mean).
- Annual rainfall totals in the Darwin catchments are reliable compared with other parts of northern Australia but less reliable than areas of similar total rainfall in southern Australia and comparable parts of the world.
- The intensity of dry periods in the Darwin catchments is similar to those of the Murray–Darling Basin and other parts of eastern Australia.
- The Darwin catchments experience equally long runs of consecutive dry and wet years and there is nothing unusual about the length of the runs of dry years.

The seasonality of rainfall presents challenges for both wet- and dry-season cropping.

- The wet season in the Darwin catchments is considerably more seasonal than in southern Australia, with 95% of the mean annual rainfall occurring in the wet season (November to April). During the wet season, rainfall can be very intense, increasing the risks of flooding, erosion and soil structural decline.
- The benefits to cropping of wet-season soil water are significantly offset by cloud cover that reduces radiation interception and crop growth. In addition, rainfall occurring over long periods can impair farm operations by restricting trafficability and paddock access.
- The dry season affords radiation that favours crop growth but, in the absence of irrigation water, dryland cropping is not likely to be economically viable.
- While annual rainfall is not always reliable and seasonal forecasting poor, farmers have the advantage of a clear view of water availability – soil water and dam storage levels – when they need it most, which is at the end of the wet season when planting decisions are made. This means farmers can manage risk by choosing crops that optimise use of the available water, or by deciding to forfeit cropping.
Large dams store water more efficiently than small dams.

- Potential evaporation (annual mean 1850 mm to 1950 mm) is only slightly higher than rainfall (annual mean 1423 mm) and, as such, net evaporative losses from major dams are lower than in most other parts of Australia.
- However, storing water in farm-scale storages over the dry season remains challenging. Appropriately sited large farm-scale ringtanks lose about 33% of their capacity to evaporation and seepage between April and September, highlighting the need to use irrigation water early in the dry period as part of a ‘use it or lose it’ irrigation regime.

Even though annual rainfall is increasing, plan for water scarcity.

- A trend for increasing rainfall has been observed in the Darwin catchments over the last three to four decades.
- Climate and hydrology data to support short- to medium-term water resource planning should encapsulate the full range of likely/plausible conditions and variability at different time scales, and particularly periods when water is scarce. These are periods that most affect businesses and the environment.
- Detailed scenario modelling and planning should be broader than just comparing a single climate scenario to an alternative future.

Cyclones pose a frequent risk to business and infrastructure.

- On average, the Darwin catchments receive at least one cyclone every two years. From 1970 to 2016, a single cyclone occurred in 36% of years and two cyclones occurred in 11% of years.

Climate change is unlikely to pose significant limitations to irrigated agriculture.

- For the Darwin catchments, 24% of climate models project a drier future, 33% project a wetter future and 43% are within ±5% of the historical mean, indicating ‘little change’. Recent research indicates tropical cyclones will be fewer but more intense in the future, although considerable uncertainties remain.
- Annual variability, particularly in rainfall, is likely to pose the greatest climate challenge for irrigated agriculture.
- Future changes in temperature, vapour pressure deficit, solar radiation, wind and carbon dioxide will result in positive and negative changes to crop water use and yield under irrigation in northern Australia. However, changes to irrigated crop water use and yield under future climates are likely to be modest compared with improvements arising from new crop varieties and other improved technologies over the next 40 years. These changes will be large and are unpredictable.

THE FINNISS, ADELAIDE, MARY AND WILDMAN RIVERS

An unusually high proportion of rainfall enters streams.

- The mean annual discharge from the Darwin catchments is approximately 11,200 GL. About 40% of the runoff is generated on the tidally affected coastal floodplains, below the point at which it can be captured for consumptive use.
• Approximately 82% of runoff in the Darwin catchments occurs during the period between January and March, with the highest monthly totals occurring during March.

• There is a strong positive relationship between streamflow and fishery catches, especially for species of commercial and recreational importance.

**Floods are relatively common, large and persistent.**

• In the Darwin catchments, broad-scale flooding is largely limited to the coastal floodplains; these areas have limited agricultural value and can be inundated for more than 20 consecutive days. Where flooding does occur upstream of the coastal plains it is limited, with areas typically remaining inundated for less than 3 days.

• Relative to other parts of northern Australia, large flood events can occur over a longer part of the year, potentially reducing the window for cropping without flood protection. Of the ten largest flood events over the last 35 years at Dirty Lagoon on the Adelaide River, one event occurred during December, two in January, three in February, three in March and one in April.

• Flooding can potentially affect wet-season cropping. However, the speed of flood peaks in the tidally affected and relatively flat Darwin catchments are slow (~0.5 km/hour) and do not pose a risk to appropriately constructed storage embankments or levees.

• Flooding is ecologically critical because it connects offstream wetlands to the main river channels and connects and flushes out waterholes that sustain biodiversity during the dry season.

**A DIVERSITY OF HABITATS**

The Darwin catchments contain an enormous diversity, with large coastal floodplains that support freshwater, estuarine and marine habitats and species. These ecological assets have conservation, recreational, commercial and cultural values.

The Darwin catchments include both highly modified urban and agricultural landscapes, operational and legacy mines, and large areas of relatively intact landscapes.

• More than half of the population of the NT lives in the Darwin catchments, yet 53% of the total area is retained as conservation lands and other natural environments, much of it relatively undisturbed.

• These landscapes are important for the wide range of ecosystem services they provide: Darwin’s water supply, recreational activities, tourism, cattle grazing on native pastures, and varied conservation and environmental values.

• Even intact landscapes face environmental threats from invasive plant species and from feral animals such as buffalo, feral pigs and cane toads.

**Freshwater coastal floodplains of the Darwin catchments form a mosaic of highly productive and nationally significant wetland habitats.**

• The floodplains and their waterways are home to a number of threatened species such as the northern river shark, marine turtles and other reptiles, several bird species and the northern quoll. The Darwin catchments also support large populations of some of northern Australia’s most iconic wildlife species, such as saltwater crocodiles and barramundi.
• The Adelaide and Mary river coastal floodplain systems in particular are amongst the most important breeding sites for magpie geese in Australia.

• Five of the 33 wetlands of national significance in the NT are found in the Darwin catchments.

**The Darwin catchments support a number of important terrestrial habitats.**

• The groundwater-dependent ecosystems such as monsoon vine forests provide crucial heavily shaded habitat for a range of animals including fruit-eating birds and bats. Birds move between monsoonal forest patches and require many patches over a large area to maintain their populations.

• Riparian vegetation zones adjacent to watercourses are highly diverse and remain largely intact and provide an important link between terrestrial and aquatic communities. Riparian zones are often more fertile and productive than surrounding terrestrial vegetation.

**INDIGENOUS VALUES, RIGHTS AND DEVELOPMENT GOALS**

**Indigenous people make up a significant and growing proportion of the population of the Darwin catchments.**

• As Traditional Owners they have recognised native title and cultural heritage rights, and control significant natural and cultural resources, including land, water and coastline.

• The history of pre-colonial and colonial patterns of land and natural resource use in the Darwin catchments is important to understanding present circumstances. That history also informs Indigenous responses to future development possibilities.

**From an Indigenous perspective, ancestral powers are still present in the landscape and intimately connect people, country and culture.**

• Those powers must be considered in any action that takes place on country.

• Riverine and aquatic areas are known to be strongly correlated with cultural heritage sites.

**Indigenous land use agreements and Aboriginal land rights, native title and sacred sites legislation are important ways in which Indigenous interests in country are recognised and managed. Securing recognition through these pathways remains an important development goal for Indigenous people in the Darwin catchments.**

• Indigenous people have strong expectations for ongoing involvement in water, catchment and development planning.

• Should development of water resources occur, participants in this study generally expressed preference for flood harvesting, which would fill offstream storages. Large instream dams in major rivers were consistently amongst the least-preferred options.

• Indigenous people have business development objectives designed to create opportunities for existing residential populations and to aid the resettlement and return of people currently living elsewhere.

• Indigenous people want to be owners, partners, investors and stakeholders in any future development. This reflects their status as residing in the catchments for the longest, with deep inter-generational ties to the catchments for the foreseeable future.
All the animals that live in the water, that we forage, we eat from the waterways and that’s very important to helping people. It’s one of the major things ... my ancestors have always been hunting and foraging on the river.

Traditional Owner from the Darwin catchments

We have got enough land and resources that if we plan it properly we should be able to coexist with other development. Good water is a part of that.

Traditional Owner from the Darwin catchments

OPPORTUNITIES FOR AGRICULTURE AND AQUACULTURE

The Darwin rural area within the Darwin catchments currently has the largest area of land under irrigation in the NT.

- Approximately 4400 ha of land are currently under irrigation in the Darwin catchments, mostly for mangoes, melons, Asian vegetables and other vegetables and minor crops.
- There is currently very little broadacre cropping in the Darwin catchments.

Dryland cropping in the Darwin catchments is opportunistic and carries considerable risk, with failure likely in many years.

- In wetter-than-average years, the amount of soil water at the end of January combined with the rainfall received in the following 90 days is sufficient to grow a short-season (e.g. mungbean) or medium-season (e.g. sorghum, maize) crop. However, in these seasons, poor trafficability and limited dry days to enable sowing operations will regularly delay sowing until later in the season, with the likelihood of lower yields.
- Unlike other areas of northern Australia, in drier-than-average years the soil water stored at sowing and the rainfall received in the following 90 days may still be sufficient to grow a short-season crop. In such years, trafficability will be less of a constraint, permitting early establishment of a crop. A risk associated with cropping in these years is dry spells of 2 weeks or more, especially during crop establishment.
- It is possible to achieve break-even yields of dryland medium-season crops, such as sorghum, 5 years in 10. The main limitation is insufficient soil water during the mid- to later parts of the growing season (in the dry season).

Irrigation provides not only for higher yields, but also more reliable production compared with dryland crops.

- A wide range of crops are potentially suited to irrigated production in the Darwin catchments. These include cereals, pulses, forages, vegetables and perennial fruit tree crops as well as industrial crops such as sugarcane and cotton.
- Seasonal water use by crops can vary enormously depending on crop type and season of growth; for example, a rice crop planted at the start of the wet season and reliant only on supplementary irrigation in the final stages of growth can use as little as 1 ML/ha, while a rice crop grown during the dry season requires around 8 ML/ha before accounting for conveyance and field application losses.
Up to 1 million ha of the Darwin catchments are classified as moderately suitable with considerable limitations (Class 3) for irrigated agriculture, depending on the crop and irrigation method chosen.

- These Class 3 soils have considerable limitations that lower production potential or require more careful management than more suitable soils (i.e. Class 1 or Class 2). In this respect, they do not differ from many of Australia’s agricultural soils.

The classes (1 to 5) were derived from a set of attributes such as erodibility, slope, soil depth, permeability, rockiness and others.

The area estimates below are derived from assessing soil, landscape and climate factors within the whole catchment, as an upper starting point. The area actually available for irrigation will be less – once considerations relating to land tenure, land use, flooding risk, availability of water for irrigation and other factors are taken into account.

- Just over 1 million ha, or 33%, of the Darwin catchments are considered to be Class 3 for perennial forage, such as Rhodes grass, under spray irrigation. About 350,000 ha are classified similarly for forage sorghum, using spray irrigation in the dry season.

- About 800,000 ha, or 26%, of the Darwin catchments are considered to be Class 3 mangoes under trickle irrigation.

- For cotton, and some cereals, pulses, oilseeds and forages, approximately 650,000 ha or 22% of the Darwin catchments are considered to be Class 3 for irrigated cropping using spray irrigation in the dry season.

- About 460,000 ha are Class 3 for upland rice under spray irrigation in the dry season. For lowland rice under flood irrigation, there are about 90,000 ha which are Class 3 in the dry season and 67,000 ha in the wet season.

- The loamy soils of the elevated coastal plains, the lower slopes of hills and upper catchment plateaus are most suitable for spray irrigation, although they must be managed to limit water erosion.

- The northern and coastal parts of the Darwin catchments and the floodplains of the major rivers are dominated by seasonally or permanently wet soils. These are poorly drained, regularly flooded and susceptible to cyclone storm surges. They have little to no potential for irrigated agriculture.

- Further inland, shallow and/or rocky soils limit agricultural potential to isolated pockets of better soil, limiting agricultural development to small patches.

An excess of water also carries risk.

- High rainfall and possible flooding means that wet-season cropping carries considerable risk due to potential difficulties with access to paddocks, trafficability and waterlogging of immature crops.

- Due to inadequate drainage of the soil profile in heavier soils, the area suitable for furrow irrigation is much lower than under spray or trickle irrigation.

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• Under furrow irrigation, between 35,000 ha and 90,000 ha are Class 3 in the dry season, depending upon crop or forage type.
• Irrigation in the Darwin catchments, and the NT more generally, has predominantly been undertaken on loamy and sandy soils (e.g. Red Kandosols) with water sourced from groundwater. There is limited irrigated cropping experience on heavy clay soils of the NT based on surface water, and it will take time to establish reliable farming systems on these soils.

Establishing irrigated cropping is challenging, with high input costs and high capital requirements for greenfield development.
• Many irrigated crops are capable of consistently generating a positive gross margin. Careful planning, especially of projected cash flows, is required to identify crops and production methods that can generate the profits required to meet the capital costs of development.
• Gross margins of horticultural crops are generally much higher than those of broadacre crops but are highly price sensitive; establishing reliable market niches, such as early or late season supply, is critical to viability.
• Gross margins for the more established crops such as mangoes and melons are consistent with other regions in Australia.
• The availability of family labour is often an important determinant of profitability for labour intensive crops such as Asian vegetables.
• Amongst the broadacre crops, dry-season rice or a grass forage for hay appear most prospective.

More than one crop per year may be required to sustain greenfield irrigation developments.
• The cash generated from a single crop each year is unlikely to enable the capital costs of development to be met.
• There has been relatively little experience in implementing rotational, two-crops-per-year, broadacre cropping systems in the NT.
• In addition to the potential for higher gross margins, rotations can be designed to help manage disease, pests and weeds, minimise soil and nutrient losses and reduce the need for inorganic nitrogen inputs.
• A rotation system of rainfed wet-season soybean followed by dry-season irrigated rice may be capable of producing yields similar to the sum of the individually grown crops, and could be sufficient to meet capital costs of development in the order of $10,000 to $15,000/ha.
• The development of a range of two-crops-per-year rotation alternatives, and the management packages and skills to support them, is a likely prerequisite for economically sustainable irrigated broadacre cropping. The challenges in developing these should not be under-estimated.

Irrigated cropping has the potential to produce off-site environmental impacts, although these can be reduced by good management and new technology.
• The pesticide and fertiliser application rates required to sustain crop growth vary widely amongst crop types. Selecting crops and production systems that minimise the requirement for these can simultaneously reduce costs and environmental impacts.
• Refining application rates of fertiliser to better match crop requirements, using controlled-release fertilisers, and improving irrigation management are all effective ways to minimise nutrient addition to waterways and, therefore, the risk of harmful microalgae blooms.
The use of best management practices including controlled traffic and banded application of pesticides can substantially reduce their efflux to waterways.

Adherence to well-established best management practices can significantly reduce erosion where intense rainfall and slopes would otherwise promote risk.

While cotton is not currently grown in the Darwin catchments, it is a good example of a genetically modified (GM) crop that allows industry to substantially reduce insecticide and herbicide application. In recent years GM cotton has resulted in cotton farmers in Australia using 85% less insecticide, 62% less residual-grass herbicide and 33% less residual-broadleaf weed herbicide. This technology has considerable application to northern Australia.

Pond-based prawn and barramundi aquaculture offer potentially high returns in the marine-and brackish-water environments of the Darwin catchments.

For marine species, there are approximately 420,000 ha of coastal land at least moderately suitable for lined aquaculture ponds.

On the coastal floodplains, flood protection levee banks may be required. Provided embankments are of sufficient height and appropriately constructed, the slow-moving nature of floodwater in the Darwin catchments should pose an operational risk rather than a risk to infrastructure.

Although other aquaculture species are being trialled in northern Australia, prawns and barramundi have established land-based cultural practices and well-established markets for harvested products.

Long transport distances for specially formulated feed and finished products contribute to the high cost of aquaculture production. Even so, skilfully managed prawn and barramundi pond-based aquaculture can be profitable enterprises in the Darwin catchments.

The remote location of the Darwin catchments provides some biosecurity advantages to aquaculture production.

Aquaculture enterprises are likely to encounter fewer regulatory constraints than those in catchments in other parts of Australia, such as those draining into the Great Barrier Reef. For example, while Australian prawn farms have been found to be some of the most environmentally sustainable in the world, approval processes and strict regulation constrain development along the east coast of Australia.

THE ECONOMIC DEVELOPMENT OPPORTUNITIES PRESENTED BY GROUNDWATER ARE WELL-RECOGNISED IN THE DARWIN CATCHMENTS

Groundwater resources in the Darwin catchments offer niche opportunities that are geographically distinct from surface water development opportunities.

The interconnected sand and dolostone aquifers in the Wildman catchment currently offer the greatest opportunity for groundwater resource development in the Darwin catchments. These aquifers coincide with areas of suitable soil and minimal flood risk.

Groundwater is fresh with low salinity (<500 mg/L), has moderately high bore yields (>10 L/second) and the water-bearing formation is at economically viable depths.
Recharge to the interconnected sand and dolostone aquifers occurs as a combination of infiltration through the soil over large areas and preferentially at features such as sink holes. Recharge is estimated to be in the order of about 30 GL/year.

 Appropriately sited groundwater bores could extract in total between 5 and 10 GL of water from the aquifers depending on their proximity to environmental assets.

In other catchments groundwater is largely used for stock and domestic purposes, though total recharge to the Koolpinyah Dolostone Aquifer east of the Adelaide River, the Kulshill Group Sandstone and the Daly River Limestone is estimated to be in the order of about 100 GL/year. It is estimated that an additional 25 GL/year could potentially be extracted from groundwater in the Darwin catchments. Currently little is known about these systems.

New groundwater extraction in the Darwin catchments could potentially enable an additional 7800 ha of Asian vegetables under trickle irrigation at an annual gross value of production of $220 million, assuming markets could support such an increase. This would occur at distinct locations widely spread across the Darwin catchments.

**Groundwater supplies in the Darwin rural area are currently fully allocated.**

- The Koolpinyah Dolostone and other dolostone aquifers in the DRWCD supply an estimated 25 GL/year for irrigated agriculture, horticulture, public water supplies and local domestic use.
- In wet seasons with low rainfall, groundwater levels in the dolostone aquifers in the DRWCD can fall below the depth of some bores resulting in bore failure.

**Groundwater, which is more economically attractive than managed aquifer recharge (MAR), will always be developed first. However, MAR can enhance the quantity of water available for extraction and help mitigate impacts to the environment.**

- Demand management could potentially be used to help manage late dry-season groundwater levels in the Darwin rural area.
- Where additional groundwater storage capacity exists at the end of the wet season, MAR can increase groundwater availability by storing wet-season rainfall as a buffer against late dry-season drought. This would require a source of surface water.
- The compartmentalised nature of the Koolpinyah Dolostone and the seasonal variability in groundwater levels, would require MAR to have multiple injection sites at strategically selected locations to alleviate the effect of low groundwater levels late in the dry season.
- The potential of MAR to enable greenfield mosaic irrigation developments in many locations in the Darwin catchments is limited by the available groundwater storage capacity at the end of the wet season.
- A potentially promising option for MAR in the Koolpinyah Dolostone is a large-scale (~5 GL/year) aquifer storage and recovery scheme in the confined portion of the aquifer, to the north of current groundwater use.
Groundwater discharge supports a diverse range of ecosystems.

- In the Darwin catchments, groundwater discharging to the natural environment supports springs and partially supports small patches of monsoon vine forests. Discharge is also likely to occur as ‘submarine’ groundwater discharge to the ocean.
- Any extraction of groundwater for consumptive purposes will result in a corresponding reduction in ‘natural’ discharge to rivers, springs and vegetation.
- The time lag between groundwater extraction and the corresponding change in the expression of groundwater where it naturally discharges may be many decades in intermediate scale groundwater systems and longer in regional systems. This presents management challenges.

SURFACE WATER STORAGE POTENTIAL

- Although groundwater offers cheaper water at lower risk than surface water storage in the Darwin catchments, surface water storage can enable considerably larger scales of development.

There is no single water storage and supply solution. Maximising the scale and cost-effectiveness of water supply in the Darwin catchments may require adopting different options in different locations and at different times.

- Major dams at Mount Bennett and upper Adelaide River are potentially the most cost-effective ways of capturing and storing water for irrigation on the Finniss and Adelaide rivers, respectively. Together they could release approximately 436 GL of water in 85% of years. Collectively the two dams would cost about $373 million, or $855/ML released at the dam wall in 85% of years.
- The two dams together would have sufficient water to irrigate 60,000 ha (2% of the area of the Darwin catchments) of dry-season Asian vegetables or 40,000 ha of mangoes after conveyance and field application losses. These would generate an annual gross value of production of approximately $1.7 billion for Asian vegetables or $1.6 billion for mangoes, assuming markets could support such an increase.
- The Adelaide River offstream water storage (AROWS) could extract and store more than 50 GL of water per year at greater than 99% reliability. There is no land suitable for irrigated agriculture in the vicinity of the AROWS.
- The Marrakai potential dam site was deemed likely to have very high construction risks; it has poor foundation conditions and it is likely that considerable environmental impacts would be experienced during construction and operation of a dam at this site. Furthermore, the yield of a dam at this site would far exceed any potential future downstream demand.

The majority of streamflow within the Darwin catchments cannot be readily captured or stored offstream. For example, approximately 75% of total streamflow at Dirty Lagoon is discharged in the highest 10% of days, of which only a small proportion could be pumped.

- Water harvesting, where water is pumped from a major river into an offstream storage such as a ringtank, is the most cost-effective option of capturing and storing water from the Margaret River in the Adelaide catchment and the McKinley and Mary rivers in the Mary catchment.
• It is physically possible to extract 200 GL and 400 GL of water in 85% of years along the Margaret River and in the Mary catchment, respectively. After evaporation, conveyance and field application losses this is sufficient water to irrigate about 50,000 ha (1.7% of the Darwin catchments) of Asian vegetables at an annual gross value of production of $1.4 billion.

• The extracted water could potentially be stored in 150 ringtanks (each of capacity 4 GL) at a cost of about $330 million, or $820/ML released from the ringtank, not including the cost of pumping. Storing this much water in ringtanks may occupy nearly 20,000 ha of land and it is likely that land suitable for the construction of impermeable embankments will limit the scale of water-harvesting development.

• There is no land suitable for construction of ringtanks in the Finniss catchment that is also coincident with land suitable for irrigated agriculture.

• Large-scale water harvesting in the Darwin catchments results in small changes to small flood events and has negligible impact on moderate to large-size flood events.

• In the Darwin catchments there are few opportunities for large farm-scale gully dams in close proximity to soils suitable for irrigated agriculture. Hillslope dams, with higher excavation (cost) to storage ratios may enable small-scale irrigation developments upstream of the Arnhem Highway in specific areas.

The upper Adelaide River Dam could safeguard Darwin’s future water supply and support 8500 ha of irrigated agriculture.

• Darwin’s demand for water is projected to outstrip its system yield in the near future. By 2065 Darwin is projected to require an additional 10 to 20 GL of water annually.

• The upper Adelaide River dam site is the most topographically favourable potential dam site in the Darwin catchments and has a catchment area of 616 km², or 8% and 2% of the area of the Adelaide River catchment and Darwin catchments, respectively.

• The optimum construction for the upper Adelaide River dam is a roller-compacted concrete dam. At the nominated full supply level it would cost an estimated $182 million to construct.

• Substantial land in the area is subject to current or future native title claims and there are a number of registered and/or recorded sacred or cultural heritage sites known to exist in the area that would potentially be inundated.

• The dam’s potential reservoir would be able to release an additional 15 GL/year of high-security water (in more than 99% of years) to Darwin via a pipeline and 125 GL in 85% of years for irrigated agriculture. This would be sufficient water to irrigate 8500 ha of dry-season rice adjacent to the Adelaide and Margaret rivers, upstream of their confluence.

• This would triple the area under irrigation in the Darwin catchments and could generate an annual gross value of production of about $35 million.

• An upper Adelaide River dam would markedly change the volume and timing of flow immediately downstream of the dam to a re-regulating structure potentially 30 km downstream.

• The impact of a dam on streamflow reduces with distance downstream. Below the confluence of the Adelaide and Margaret rivers at Dirty Lagoon, the reduction in mean and median annual streamflow would be about 11% and 15%, respectively.
CHANGES IN TIMING AND VOLUME OF FLOW HAVE ECOLOGICAL IMPACTS

- Although irrigated agriculture typically occupies a very small proportion of the landscape, it can potentially result in large changes to the volume and timing of river flow and, hence, ecological function.

The impact of a major instream dam on aquatic, riparian and near-shore marine ecology is strongly related to its position in a catchment and the size of its reservoir relative to the volume of streamflow.

- The high position of the potential upper Adelaide River dam in the catchment means its ecological footprint would be largely localised. Its impact on the movement and migration of fish species would be relatively minor at the scale of the entire catchment, although this would also depend upon the position of any re-regulating structure downstream.

- The large changes in volume and timing of flow in the reach immediately below the dam and upstream of the point of extraction would have a major impact on species and their flow habitats including barramundi, largetooth sawfish and turtles, and a moderate impact on magpie geese, riparian vegetation, waterholes and wetlands.

- Below the junction of the Adelaide and Margaret rivers, species and their flow habitats would experience a minor impact. The upper Adelaide River dam would have a negligible impact on the inundation of the ecologically important coastal floodplain and minimal impacts on estuarine and coastal species.

- Pumping 50 GL/year of water during high flow in the wet season into the potential AROWS would have a negligible impact on the flow habitats of estuarine and coastal species.

At equivalent storage capacities, pumping water into offstream storages (water harvesting) has less impact on freshwater aquatic, riparian and marine ecosystems than major instream dams.

- Water harvesting less than 150 GL/year in the Mary catchment would have a negligible impact on the flow habitat of most migratory fish, barramundi and magpie geese.

- Water harvesting less than 550 GL/year in the Mary catchment would have a minor impact on the flow habitat of estuarine and coastal species, such as crocodiles, sawfish, snub-nosed dolphin and white banana prawns.

Although intensive land management has the potential to improve some ecological outcomes, past experience suggests this is unlikely to occur; there are currently no incentives for irrigation developments to manage beyond their boundaries or for issues that do not impact their production.

- Direct impacts of irrigation on the terrestrial environment are typically small. However, indirect impacts, such as weeds, pests and landscape fragmentation, particularly to riparian zones, may be considerable.

- Generally, irrigated cropping systems have relatively well-developed invasive species management protocols and the economics of such systems is such that they can bear the cost of controlling weeds and pests that are of concern to them.
COMMERCIAL VIABILITY AND OTHER CONSIDERATIONS

Irrigated agriculture currently makes a sizeable contribution to the economy of the Darwin catchments.

- The gross value of agriculture production in the Darwin catchments is about $135 million, of which $120 million is provided by irrigated fruit, particularly mangoes, and vegetables. Horticultural products are exported to southern domestic markets.

- Beef production in the Darwin catchments is mainly from small properties, with beef cattle production contributing around $13 million in gross agricultural production in the Darwin catchments. However, the Darwin catchments are important for holding cattle prior to live export and high-quality forage is in demand.

While the natural environment of northern Australia presents some challenges for agriculture, the most important factors determining the commercial viability of new developments are management, planning and finances.

- Large developments for agriculture are complex and costly. It would be prudent to ensure there are sufficient funds remaining after the construction phase to safeguard the operation of new enterprises in the likely occurrence of ‘failed’ years at the start of their operation.

- There is a strong incentive to start any new irrigation development with well-established and understood crops, farming systems and technologies as this will reduce the likelihood of initial setbacks and failures.

- There is a systematic tendency for proponents of large infrastructure projects to substantially under-estimate development costs and risks and/or over-estimate benefits. This can be in part due to financial return imperatives driving an overly optimistic assessment of the time frame for positive returns, unanticipated difficulties and project delays, and the difficulty of accurately planning and budgeting over many years.

It is prudent to stage developments to limit negative economic impacts during start-up and to allow small-scale testing on new farms.

- The initial challenge of establishing and adapting agriculture in a new location can be mitigated by learning from past experiences in northern Australia. However, even if well-prepared, each new location and development will provide unique challenges.

- Staging and allowing for sufficient learning time can limit losses where small-scale testing proves initial assumptions of costs and benefits to be overly optimistic or reveal unanticipated challenges in adapting farming practices to local conditions.

Synergies through vertical and horizontal integration present opportunities for commercial returns but increase risk.

- Aggregated farm revenue from broadacre agriculture is unlikely to cover the cost of infrastructure for an irrigation scheme under current farming systems. Value adding through processing will increase revenues and will greatly improve the commercial viability of an irrigation scheme.

- Vertically integrated agricultural enterprises require a sufficient scale of development in order to be viable, with supply commitments of raw farm products necessary to justify the investment in processing facilities.
• The more complex a scheme becomes and the more strongly interdependent the components become, the greater the risk that underperformance of one component could undermine the viability of the entire scheme.

**Distance from the farm gate to agricultural processing plants places a significant cost burden on industry in the Darwin catchments.**

• The Darwin catchments have advantages over other parts of northern Australia in that:
  – there are some refrigerated backloading opportunities, which are best suited to crops that are harvested in most months (e.g. bananas) rather than crops with a short harvest season (e.g. mango or melon)
  – they have good access to Darwin Port for export of live cattle and general freight, access to southern markets via the Stuart Highway, and quality rail access.
  – however, transport to major southern markets will add significant costs and make supplying lower-value broadacre crops unviable when competing against southern production. There are established export supply chains for live cattle and some frozen meat, however the exports of horticultural or broadacre crops out of Darwin Port into Asia are not yet at sufficient scale to justify investment in port infrastructure.

• The nearest processing facilities for higher-value broadacre crops, such as peanuts and sugar, are in Queensland, making these crops currently unviable. Local processing would ensure better farm-gate returns.

• Outside the Darwin urban area, the current road network is sparse and minor unsealed roads are prone to flooding, restricting wet-season access, particularly for those roads on black soils.

• The Arnhem Highway Road was closed 85 days over a 7-year period from 2005 to 2012.

**Irrigated agriculture has a greater potential to generate economic and community activity than rainfed (dryland) production.**

• Studies in the southern Murray–Darling Basin have shown that irrigation generates a level of economic and community activity that is three to five times higher than that generated by rainfed (dryland) production.

• In the Darwin catchments, irrigation development could result in an additional $1.06/year of indirect regional economic benefits for every $1.00 spent during the construction phase. The regional economic impact of an annual increase in irrigated agricultural output (mangoes and vegetables) of $100 million/year is estimated to be an additional $46 million of increased economic activity.

• During the construction phase, aquaculture development may result in a regional economic benefit similar to that from irrigated agriculture. Once businesses have been established, the regional economic impact of aquaculture is considerably higher; each $100 million/year of output is estimated to create an additional $182 million of increased economic activity.

• Justification and support for public investment in new water infrastructure will in part depend on the flow-on and indirect benefits beyond the irrigation scheme.

**Community infrastructure in the Darwin catchments could accommodate a large increase in irrigation development without additional investment.**
• The four Darwin catchments are unique in northern Australia in that they have a large urban centre on their doorstep, with a population of 139,000. The availability of community and soft infrastructure make developments in the Darwin catchments attractive to new workers.

• Unlike in many other parts of northern Australia, a development in the Darwin catchments would not likely require significant investments in new community or soft infrastructure, such as schools and hospitals, emergency services and law enforcement.

Sustainable irrigated development requires resolution of diverse stakeholder values and interests.

• Establishing and maintaining a social licence to operate is a precondition for substantial irrigation development.

• The geographic, institutional, social, and economic diversity of stakeholders increases the resources required to develop a social licence and reduces the size of the ‘sweet spot’ in which a social licence can be established.

• Key interests and values that stakeholders seek to address include the purpose and beneficiaries of development, the environmental conditions and environmental services that development may alter, and the degree to which stakeholders are engaged.

• Potential agricultural investors identified institutional certainty, simplicity and bureaucratic speed as key to enabling investment in irrigated agriculture.
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<table>
<thead>
<tr>
<th>Appendices</th>
<th>431</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appendix A</td>
<td>432</td>
</tr>
<tr>
<td>Assessment products</td>
<td>432</td>
</tr>
<tr>
<td>Appendix B</td>
<td>438</td>
</tr>
<tr>
<td>Shortened forms</td>
<td>438</td>
</tr>
<tr>
<td>Units</td>
<td>440</td>
</tr>
<tr>
<td>Data sources and availability</td>
<td>441</td>
</tr>
<tr>
<td>Glossary and terms</td>
<td>443</td>
</tr>
<tr>
<td>Appendix C</td>
<td>446</td>
</tr>
<tr>
<td>List of figures</td>
<td>446</td>
</tr>
<tr>
<td>List of tables</td>
<td>455</td>
</tr>
<tr>
<td>Appendix D</td>
<td>461</td>
</tr>
<tr>
<td>Detailed location map of the Darwin catchments and surrounds</td>
<td>461</td>
</tr>
</tbody>
</table>
Chapter 1 provides background and context for the Assessment.

This chapter provides the context for and critical foundational information about the Assessment with key concepts introduced and explained.
1 Preamble

Authors: Chris Chilcott, Caroline Bruce, Cuan Petheram, Sally Tetreault Campbell and Ian Watson

1.1 Context

Sustainable regional development is a priority for the Australian, Western Australian, Northern Territory and Queensland governments. In 2015, the Australian Government released the ‘Our North, Our Future: White Paper on Developing Northern Australia’ (PMC, 2015), which highlighted the opportunities for regional development based on northern Australia’s water resources. In particular, many rural communities in northern Australia see irrigated agriculture as a means of reversing the long-term human population declines in these areas and as a critical element of broader regional development. This belief is supported by commentators overseas who have observed that no country or region in a tropical or sub-tropical climate has experienced significant economic development without developing their water resources (Biswas, 2012). Furthermore, studies in Australia have shown that irrigation production in the southern Murray–Darling Basin generates a level of economic and community activity that is three to five times higher than would be generated by rainfed (dryland) production (Meyer, 2005). Domestic investors in irrigation in southern Australia are also increasingly looking north for agricultural opportunities due to recent experience of drought, over allocation of water resources, future projections of reduced rainfall in southern Australia and perceptions of an abundance of water in northern Australia. Some foreign companies have already invested heavily in irrigation in northern Australia and this trend is likely to continue.

Development of northern Australia is not a new idea; there is a long history of initiatives to develop cultivated agriculture in the tropical north of Australia. Many of these attempts have not fully realised their goals, for a range of reasons. It has recently been highlighted that although northern Australia’s environment poses challenges for irrigated agriculture, the primary reason that many of the schemes did not fully realise their goals is that they did not have sufficient or patient capital to overcome the failed years that inevitably accompany every new irrigation scheme (Ash et al., 2014). The only large schemes still in operation in northern Australia had substantial government financial support during the construction phase, as well as ongoing support during establishment and learning phases.

Although 95% of Australia’s irrigated land lies south of the Tropic of Capricorn, and 65% of this is located in the Murray–Darling Basin (MDB), northern Australia is now seen as an opportunity to implement ‘the right policies, at the right time’ (PMC, 2015).

Between 2000 and 2050, the world’s population is projected to grow from 6 to 9 billion people (UNESCO, 2009), and increased food and fibre production is needed to meet anticipated increased demand. Most of this growth is projected to occur in the tropics, particularly sub-Saharan Africa and South-East Asia. Two-thirds of the world’s food insecurity is in Asia, and sharp upward price movements in food have the potential to result in political and social unrest in this region. At the same time, it is projected that Asia will become home to the majority of the world’s middle class,
which will result in an increasing demand for high-quality food produce. Irrigated agriculture in northern Australia has the potential to meet some of that demand as well as the increasing demand for beef.

The efficient use of Australia’s natural resources by food producers and processors requires a good understanding of soil, water and energy resources so they can be managed sustainably. Finely tuned strategic planning will be required to ensure that investment and government expenditure on development are soundly targeted and designed. Northern Australia presents a globally unique opportunity (a greenfield development opportunity in a first-world country) to strategically consider and plan development. Northern Australia also contains ecological and cultural assets of high value and decisions about development will need to be made within that context. Good information is critical to these decisions.

Most of northern Australia’s land and water resources have not been mapped in sufficient detail to provide for reliable resource allocation, mitigate investment or environmental risks, or build policy settings that can support decisions. Better data are required to inform decisions on private investment and government expenditure, to account for intersections between existing and potential resource users, and to ensure that net development benefits are maximised.

In 2013, the Australian Government commissioned CSIRO to undertake the Flinders and Gilbert Agricultural Resource Assessment in north Queensland. This assessment developed fundamental soil and water datasets, and provided a comprehensive and integrated evaluation of the feasibility, economic viability and sustainability of agricultural development in two catchments in north Queensland (Petheram et al., 2013a, 2013b). It identified several opportunities for large-scale (greater than 10,000 ha) irrigation development, based on the coincidence of suitable soils and new water storage capacity. The Flinders and Gilbert Agricultural Resource Assessment described the data and analysis required to identify and support development opportunities in north Queensland. The outcome of the assessment was to reduce the uncertainty for investors and regulators, and to give the base information to allow development to occur in a sustainable manner. However, this previous study covered only 155,000 km² (approximately 5%) of northern Australia, and acquiring a similar level of data and insight across northern Australia’s more than 3 million km² would require more time and resources than were available at the time.

Consequently, the 2015 Northern Australia White Paper prioritised about a dozen regions in northern Australia where more detailed water and agriculture resource assessments should be undertaken. It also provided $15 million to initiate the Northern Australia Water Resource Assessment in the Fitzroy catchment (Western Australia), Darwin catchments (Northern Territory) and Mitchell catchment (Queensland) (Figure 1-1).
The Northern Australia Water Resource Assessment has undertaken a comprehensive and integrated evaluation of the feasibility, economic viability and sustainability of water resource development in three priority areas in northern Australia: the Fitzroy catchment, the Darwin catchments and the Mitchell catchment.

The Fitzroy and Mitchell catchments were identified by the Northern Australia White Paper as being suitable candidates for a large-scale assessment of the economics and sustainability of irrigated agriculture because they appear to have large areas of soil suitable for irrigated agriculture and adequate water. The four catchments adjacent to Darwin were chosen because they are relatively close (about one to four hours’ drive) to the third largest population centre in northern Australia, Darwin, the capital of the Northern Territory.

The assessment of each of the three study areas aimed to:

- evaluate the climate, soil and water resources
- identify and evaluate water capture and storage options
- identify and test the commercial viability of irrigated agricultural, forestry and aquaculture opportunities
- assess potential environmental, social and economic impacts and risks of water resource, aquaculture and irrigation development.
The techniques and approaches used in the Assessment were specifically tailored to the three study areas.

It is important to note that although these four key research areas are listed sequentially here, activities in one part of the Assessment often informed (and hence influenced) activities in an earlier part. For example, understanding ecosystem water requirements (the third part of the Assessment, described in Part IV of this report) was particularly important in establishing rules around water extraction and diversion (i.e. how much water can be taken and when it should be taken – the second part of the Assessment, described in Part III of this report). Thus, the procedure of assessing a study area inevitably included iterative steps, rather than a simple linear process.

In covering the key research areas above, the Assessment was designed to:

- explicitly address the needs of and aspirations for local development by providing objective assessment of resource availability, with consideration of environmental and cultural issues
- meet the information needs of governments as they assess sustainable and equitable management of public resources, with due consideration of environmental and cultural issues
- address the due diligence requirements of private investors, by exploring questions of profitability and income reliability of agricultural and other developments.

Drawing on the resources of all three tiers of government, the Assessment built on previous studies, drew on existing stores of local knowledge, and employed world-class scientific expertise, with the quality assured through peer-review processes.

The Northern Australia Water Resource Assessment took two and a half years between 16 December 2015 and 30 June 2018.

1.2.1 SCOPE OF WORK

The Assessment comprised several activities that together were designed to explore the scale of the opportunity for irrigated agricultural development in the Fitzroy, Darwin and Mitchell catchments. The full suite of activities is outlined below (Section 1.2.2), and a series of technical reports was produced as part of the Assessment (listed in Appendix A).

In stating what the Assessment did, it is equally instructive to state what it did not do.

The Assessment did not seek to advocate irrigation development or assess or enable any particular development; rather it identified the resources that could be deployed in support of potential irrigation enterprises, evaluated the feasibility of development (at a catchment scale) and considered the scale of the opportunities that might exist.

In doing so, the Assessment examined the monetary and non-monetary values associated with existing use of those resources, to enable a wide range of stakeholders to assess for themselves the costs and benefits of given courses of action. The Assessment is fundamentally a resource evaluation, the results of which can be used to inform planning decisions by citizens, investors, and the different tiers of government – local council, state and territory, and Australian Government. The Assessment does not replace any planning processes, nor does it seek to; it does not recommend changes to existing plans or planning processes.
The Assessment sought to lower barriers to investment in the Assessment area by addressing many of the questions that potential investors would have about production systems and methods, crop yield expectations and benchmarks, and potential profitability and reliability. This information base was established for the Assessment area as a whole, not for individual paddocks or businesses.

The Assessment identified those areas that are most suited for new agricultural or aquaculture developments and industries, and, by inference, those that are not well suited. It did not assume that particular sections of the three study areas were in or out of scope. For example, the Assessment was ‘blind’ to issues such as land clearing that may exclude land from development now, but might be possible in the future.

The Assessment identified the types and scales of water storage and access arrangements that might be possible, and the likely consequences (both costs and benefits) of pursuing these possibilities. It did not assume particular types or scales of water storage or water access were more preferable than others, nor does it recommend preferred development possibilities.

The Assessment examined resource use unconstrained by legislation or regulations, to allow the results to be applied to the widest range of uses possible, for the longest time frame possible. In doing so, it did not assume a particular future regulatory environment but did consider a range of existing legislation, regulation and policy and the impact of these on development.

It was not the intention – and nor was it possible – for the Assessment to address all topics related to water, irrigation and aquaculture development in northern Australia. Important topics that were not addressed by the Assessment (e.g. impacts of irrigation development on terrestrial ecology) are discussed with reference to, and in the context of, the existing literature.

Functionally, the Assessment adopted an activities-based approach to the work (which is reflected in the content and structure of the outputs and products, as per Section 1.2.2) with the following activity groups: climate, land suitability, surface water hydrology, groundwater hydrology, agriculture and aquaculture viability, water storage, socio-economics, Indigenous water values, rights and development aspirations, and aquatic and marine ecology.

## 1.2.2 ASSESSMENT PRODUCTS

The Assessment produced written and internet-based products. These are summarised below and written products are listed in full in Appendix A. Downloadable reports and other outputs can be found at:


**Written products**

The Assessment produced the following documents:

- Technical reports, which present scientific work in sufficient detail for technical and scientific experts to independently verify the work. There is at least one technical report for each of the activities of the Assessment.
- Catchment reports, one for each of the three study areas, which combine key material from the technical reports, providing well-informed but non-scientific readers with the information
required to make decisions about the general opportunities, costs and benefits associated with water and irrigated agricultural or aquaculture development.

- A development example report, which through case studies in each study area, provides examples of how information produced by the Assessment can be assembled to help readers ‘answer their own questions’. They are illustrative only, designed to help readers understand the type and scale of opportunity in the catchment.
- Summary reports, one for each of the study areas, are provided for a general public audience.
- Three factsheets providing a summary of key findings for the Fitzroy, Darwin and Mitchell catchments for a general public audience.

**Audio-visual products**

The following audio-visual products were produced by the Assessment:

- video vignettes summarising key results
- video vignettes demonstrating how to use the Assessment’s internet-based products.

**Internet-based products**

The following internet-based platforms were used to deliver information generated by the Assessment:

- CSIRO Data Access Portal (DAP) enables the user to download key research datasets generated by the Assessment.
- The NAWRA Explorer - a web-based tool that enables the user to visualise and interrogate key spatial datasets generated by the Assessment.
- Internet-based applications that enable the user to run selected models generated by the Assessment.

1.3 Report objectives and structure

This is the catchment report for the Darwin catchments. It summarises information from the technical reports for each activity and provides tools and information to enable stakeholders to see the opportunities for development and the risks associated with them. Using the establishment of a ‘greenfield’ (not having had any previous development) irrigation development as an example, Figure 1-2 illustrates many of the complex considerations required for such development – key report sections that inform these considerations are also indicated.
The catchment report addresses questions such as the following:

- What soil and water resources are available for irrigated agriculture?
- What are the existing ecological systems, industries, infrastructure, people and values?
- What are the opportunities for water and irrigation development?
- Is irrigated agriculture economically viable?
- How can water resources be developed and agriculture undertaken sustainably?

Separate catchment reports are provided for the Fitzroy catchment (Petheram et al., 2018a) and the Mitchell catchment (Petheram et al., 2018b). The structure of each catchment report is as follows:

- Part I (Chapter 1) provides background, context and a general overview of the Assessment.
- Part II (Chapter 2 and Chapter 3) looks at current resources and conditions within the catchment/s.
- Part III (Chapter 4 and Chapter 5) considers the opportunities for water and agricultural and aquaculture development based on available resources.
• Part IV (Chapter 6 and Chapter 7) provides information on the economics of development and a range of risks to development, as well as those that might accompany development.

1.3.1 PART I – INTRODUCTION

This provides a general overview of the Assessment. Chapter 1 (this chapter) covers the background and context of the Assessment. Key findings can be found in the front materials of this report.

1.3.2 PART II – RESOURCE INFORMATION FOR ASSESSING POTENTIAL DEVELOPMENT OPPORTUNITIES

Chapter 2 is concerned with the physical environment and seeks to address the question of what soil and water resources are present in the Darwin catchments, describing:

• geology: focusing on those aspects of geology that are important for understanding the distribution of soils, groundwater flow systems, suitable water storage locations and rocks of economic significance
• soils: covering the soil types within the catchments, the distribution of key soil attributes and their general suitability for irrigated agriculture
• climate: outlining the general circulatory systems affecting the catchments and providing information on key climate parameters of relevance to irrigation under current and future climate
• hydrology: describing and quantifying the surface water and groundwater hydrology of the catchments.

Chapter 3 is concerned with the living and built environment and provides information about the people, the ecology of the catchment and the institutional context of the Darwin catchments, describing:

• ecology: ecological systems and assets of the Darwin catchments including the key habitats, key biota and their important interactions and connections
• socio-economic profile: current demographics and existing industries and infrastructure of relevance to water resource development in the Darwin catchments
• stakeholders: their values and potential engagement strategies and the perspectives of potential investors in the Darwin catchments
• Indigenous values, rights, interests, and development objectives: generated through direct participation by Darwin catchments Traditional Owners in the Assessment
• the legal, regulatory and policy environment relevant to water-related development.
1.3.3  PART III – OPPORTUNITIES FOR WATER RESOURCE DEVELOPMENT

Chapter 4 presents information about the opportunities for irrigated agriculture and aquaculture in the Darwin catchments, describing:

- land suitability for a range of crop × season × irrigation type combinations and for aquaculture, including key soil-related management considerations
- cropping and other agricultural opportunities, including crop yields and water use
- gross margins at the farm scale
- the prospects for integration of forages and crops into existing beef enterprises
- aquaculture opportunities.

Chapter 5 presents information about the opportunities to extract and/or store water for use in the Darwin catchments, describing:

- water storage opportunities including major dams, large farm-scale dams, natural water bodies and subsurface water storage opportunities in the Darwin catchments
- estimates of the quantity of water that could be regulated (i.e. made available for irrigation)
- water distribution systems (i.e. conveyance of water from a dam and application to the crop).

1.3.4  PART IV – ECONOMICS OF DEVELOPMENT AND ACCOMPANYING RISKS

Chapter 6 covers economic opportunities and constraints for water resource development, describing:

- regional-scale economic impacts and the costs of infrastructure
- scheme-scale financial viability, including capital costs, farm performance and value adding
- risks due to variability in farm performance, especially during the early years
- learning and staged development as a means of managing risk.

Chapter 7 discusses a range of risks to development, as well as those that might accompany development, describing:

- ecological impacts of altered flow regimes on aquatic, riparian and near-shore marine ecology
- biosecurity risks to agricultural or aquaculture enterprises
- potential off-site impacts due to sediment, nutrients and agro-pollutants to receiving waters in the catchments
- irrigation-induced salinity due to rising watertable.

1.3.5  APPENDICES

This report contains four appendices.

Appendix A – list of information products.
Appendix B – shortened forms, units, data sources, glossary and terms.
Appendix C – list of figures and list of tables.
Appendix D – detailed location map of the Darwin catchments and surrounds.

1.4 Key background

1.4.1 THE DARWIN CATCHMENTS

The Darwin catchments spans an area of approximately 30,000 km² and is comprised of four predominantly north-south draining catchments: the Finniss (9490 km²), Adelaide (7460 km²), Mary (8075 km²) and Wildman (4820 km²) catchments, as defined by the Australian Water Resources Council (AWRC) river basin boundaries (Figure 1-3). These rivers originate as incised channels in the southern uplands before broadening into alluvial plains and then extensive coastal and marine floodplains eventually flowing into the Arafura Sea. They lie in a broader area known locally as the ‘Top End’. Elevation ranges from sea level to the highest point of 385 m AHD on the plateau at the south-eastern boundary. Typically, the catchments are below 100 m AHD elevation with the higher areas along the southern boundary.

The Darwin catchments are characterised by a distinctive wet and dry season due to their location in the Australian summer monsoon. Mean annual rainfall over the 125-year historical period (1890 to 2015) over the Darwin catchments was 1423 mm and decreases from northeast to southwest.

The population of the Darwin catchments is about 140,000, of whom 98% live within the Greater Darwin area. The study area contains two very different settings: the ‘urban areas’ including Darwin and the surrounding suburbs (Greater Darwin area population was 136,828 as at the 2016 census), and the remaining ‘rural areas’. Outside the Darwin urban footprint, the Darwin catchments are characterised by a sparse road network of major roads (Figure 3-18) with the Stuart Highway being the main access to Darwin from the south. Distances across the study area are not great; Darwin to Pine Creek (just outside the southern catchment boundary) is 225 km.

The Darwin catchments fit mostly within the Darwin Coastal and Pine Creek bioregions but contain parts of the Daly Basin and Arnhem Plateau bioregions on the southern and eastern flanks respectively. Land use in the study area is dominated by conservation and natural environments (38%), and production from relatively natural environments (32%). Small areas of dryland agriculture, irrigated agriculture and plantations exist. A significant area is set aside for military training.
1.4.2  WET-DRY SEASONAL CYCLE: THE WATER YEAR

Northern Australia experiences a highly seasonal climate, with most rain falling during 4-month period from December to March. Unless specified otherwise, this Assessment defines the wet season as being the 6-month period from 1 November to 30 April, and the dry season as the 6-month period from 1 May to 31 October. These definitions were chosen because they are the wettest and driest 6-month periods respectively for all three study areas. However, it should be noted that the transition from the dry to the wet season typically occurs in October or November and the definition of the northern wet season commonly used by meteorologists is 1 October to 30 April.

All results in the Assessment are reported over the water year, defined as the period 1 September to 31 August, unless specified otherwise. This allows each individual wet season to be counted in a single 12-month period, rather than being split over two calendar years (i.e. counted as two...
separate seasons). This is more realistic for reporting climate statistics from a hydrological and agricultural assessment viewpoint.

1.4.3 SCENARIO DEFINITIONS

The Assessment considered four scenarios, reflecting combinations of different levels of development and historical and future climates, much like those used in the Northern Australia Sustainable Yields project (NASY) (CSIRO, 2009a, 2009b, 2009c) and the Flinders and Gilbert Agricultural Resource Assessment (Petheram et al., 2013a, 2013b):

• Scenario A – historical climate and current development
• Scenario B – historical climate and future development
• Scenario C – future climate and current development
• Scenario D – future climate and future development.

Scenario A

Scenario A is historical climate and current development. The historical climate series is defined as the observed climate (rainfall, temperature and potential evaporation for water years from 1 September 1890 to 31 August 2015). All results presented in this report are calculated over this period unless specified otherwise. The current level of surface water, groundwater and economic development was assumed (as of 31 August 2015). Scenario A was used as the baseline against which assessments of relative change were made. Historical tidal data were used to specify downstream boundary conditions for the flood modelling.

Scenario B

Scenario B is historical climate and future development, as generated in the Assessment. Scenario B used the same historical climate series as Scenario A. River inflow, groundwater recharge and flow, and agricultural productivity were modified to reflect potential future development. All price and cost information was indexed to mid-2017. The impacts of changes in flow due to this future development were assessed, including impacts on:

• instream, riparian and near-shore ecosystems
• Indigenous water values
• economic costs and benefits
• opportunity costs of expanding irrigation
• institutional, economic and social considerations that may impede or enable adoption of irrigated agriculture.

Scenario C

Scenario C is future climate and current development. It was based on a 125-year climate series (as in Scenario A) derived from global climate model (GCM) projections for an approximate 2.2 °C global temperature rise relative to the ~1990 climate statistics, which under the Representative Concentration Pathway (RCP) 8.5 socio-economic narrative (i.e. high emissions scenario) was projected to occur in about 2060. The GCM projections were used to modify the observed
historical daily climate sequences. The current level of surface water, groundwater and economic development were assumed. Carbon dioxide concentrations were perturbed to reflect projected 2060 carbon dioxide concentrations under RCP 8.5.

Scenario D

Scenario D is future climate and future development. It used the same future climate series as Scenario C. River inflow, groundwater recharge and flow, and agricultural productivity were modified to reflect potential future development, as in Scenario B. Therefore, in this report, the climate data for Scenarios A and B are the same (historical observations from 1 September 1890 to 31 August 2015) and the climate data for Scenarios C and D are the same (the above historical data scaled to reflect a plausible range of future climates).

1.4.4 CASE STUDIES

The case studies in the Assessment are used to show how information produced by the Assessment can be assembled to help readers ‘answer their own questions’. They are also used to help readers understand the type and scale of opportunity for irrigated agriculture or aquaculture in selected parts of the Assessment area, and explore some of the nuances associated with greenfield developments in the study area. Case studies are provided for each study area.

The case studies are illustrative only. They are not designed to demonstrate, recommend or promote particular development opportunities that may be being currently proposed, nor are they CSIRO’s recommendations on how development in the Darwin catchments should unfold. However, they are designed to be realistic representations. That is, the case studies will be ‘located’ in specific parts of the Assessment area, and use specific water and land resources, and realistic intensification options.

The case studies are described in full in the companion technical report on case studies (Petheram et al., 2018c).

1.5 References


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Chapters 2 and 3 provide baseline information that readers can use to understand what soils and water resources are present in the Darwin catchments and the current living and built environment of the Darwin catchments. This information covers:

- the physical environment (Chapter 2)
- the people, ecology and institutional context (Chapter 3).
Chapter 2 examines the physical environment of the Darwin catchments and seeks to identify the available soil and water resources. It provides fundamental information about the geology, soil, climate and the river and groundwater systems of the catchments. These resources underpin the natural environment and existing industries, providing physical bounds to the potential scale of irrigation development. Key components and concepts are shown in Figure 2-1.

Figure 2-1 Schematic diagram of key natural components and concepts in the establishment of a greenfield irrigation development
2.1 Summary

This chapter provides a resource assessment of the geology, soil, climate, groundwater and surface water resources of the Darwin catchments. No attempt is made in this chapter to calculate physically plausible areas of land or volumes of water that could potentially be used for agriculture or aquaculture developments. These analysis are reported in Chapters 4 and 5.

2.1.1 KEY FINDINGS

Soils

The dominant soils in the Darwin catchments are seasonally or permanently wet soils (42% of the catchments). In coastal parts of Asia these soils are extensively used for agricultural production (e.g. ponded rice) using manual labour; however, in Australia, they are generally considered unsuitable for agriculture without extensive drainage works due to problems with trafficability and inadequate drainage of the land. These soils occur as narrow alluvium adjacent to the Adelaide and Mary rivers south of the Arnhem Land Highway (about 87,000 ha), however, they are well suited to dry-season rice production. Elsewhere in the Darwin catchments the red loamy soils (14%) and brown, yellow and grey loamy soils (14%) have moderate to high agricultural potential. The remaining soils of the study area are shallow and/or rocky soils (30%) with negligible agricultural potential.

Climate

The Darwin catchments have a hot and humid climate. The catchment has a highly seasonal climate with an extended dry season. It receives, on average, 1423 mm of rain per year, 95% of which falls during the wet season. Mean daily temperatures and potential evaporation are high relative to other parts of Australia. On average, potential evaporation is over 1900 mm/year, however, the annual net evaporative loss (annual evaporation minus rainfall) ranges from about 0 to 700 mm, less than many parts of southern and northern Australia.

Overall, the climate of the Darwin catchments generally suits the growing of a wide range of crops, though in most years rainfall would need to be supplemented with irrigation. The variation in rainfall from one year to the next is low compared to elsewhere in northern Australia yet is high compared to other parts of the world with similar mean annual rainfall. The length of consecutive dry years is not unusual in the Darwin catchments and the intensity of the dry years is similar to many centres in the Murray–Darling Basin and east coast of Australia. Since 1970, the Darwin catchments experienced one tropical cyclone in 36% of cyclone seasons and two tropical cyclones in 11% of seasons.

Approximately a quarter of the global climate models (GCMs) project an increase in mean annual rainfall, a quarter project a decrease in mean annual rainfall and about half indicate ‘little change’.

Hydrology

The timing and event-driven nature of rainfall events and high potential evaporation rates across the Darwin catchments have important consequences for the catchment’s hydrology. Approximately 95% of runoff occurs during the wet season, with 82% of all runoff occurring during the 3-month period from January to March, which is very high compared to southern Australia.
This means that in the absence of groundwater, water storages are essential for dry-season irrigation.

The major aquifers in the Darwin catchments occur within dissolution features in the dolostone rocks. The extensive Koolpinyah Dolostone aquifer near Darwin is the main groundwater resource in the Darwin catchments, and is generally considered to be fully utilised west of the Adelaide River. There may be opportunities for further groundwater development in the Koolpinyah Dolostone east of the Adelaide River, though little is known about this system. Sandstone aquifers in the northern Mary and Wildman catchments offer the greatest future opportunity for sourcing groundwater for irrigation in the Darwin catchments. Elsewhere, old fractured igneous and metamorphic rocks occur over approximately 80% of the Darwin catchments. Small quantities of groundwater contained in the fractures may support stock and domestic use.

The mean annual discharge from the Finniss (1436 GL), Adelaide (2413 GL), Mary (2405 GL) and Wildman (905 GL) catchments into the Arafura and Timor seas is 7159 GL. However, a large proportion of this discharge (>40%) is generated on the large coastal floodplains. Downstream of the Arnhem Highway the coastal floodplains can be inundated for long periods of time (>20 days) due to the low relief and tidal influence.

Most rivers in the catchment are ephemeral, flowing less than 30% of the time, and are reduced to a few scarce and vulnerable waterholes during the dry season. The waterholes are largely replenished by streamflow, rather than groundwater, and act as critical refugia for aquatic biota (see Section 3.2).

### 2.1.2 INTRODUCTION

This chapter seeks to address the question ‘What soil and water resources are available for irrigated agriculture in the Darwin catchments?’

The chapter is structured as follows:

- **Section 2.2**, examines the geology of the Darwin catchments, which is important in understanding the distribution of valuable minerals, coal, groundwater, soil and areas of high and low relief, which influences flooding and the deposition of soil.
- **Section 2.3**, examines the distribution of soils in the Darwin catchments, their attributes and discusses management considerations.
- **Section 2.4**, examines the climate of the Darwin catchments, including historical and future projections of patterns in rainfall.
- **Section 2.5**, examines the groundwater and surface water hydrology of the Darwin catchments, including groundwater recharge, streamflow and flooding.
2.2 Geology of the Darwin catchments

Geological history is closely linked to resources such as valuable minerals, coal, groundwater and soil. Geology also controls topography, which in turn is a key factor in the location of potential dam sites, flooding and deposition of soil. These resources are all important considerations when identifying suitable locations for large water storages and understanding past and present ecological systems and patterns of human settlement.

The geology of the four Darwin catchments (i.e. Finnis, Adelaide, Mary and Wildman catchments) may be divided into two major topographical and geological divisions: The Pine Creek Orogen in the south and central part of the Darwin catchments and the Money Shoal Basin in the north (Figure 2-2).

Figure 2-2 Major geological provinces of the Darwin catchments

The Pine Creek Orogen is a geological province underlain by sedimentary, metamorphic and igneous rocks of Precambrian age (Archean to Neoproterozoic). The area is undulating with isolated ranges of quartzite and other metamorphic and igneous rocks. The rocks in the Pine Creek Orogen have been intruded with granite, folded, faulted and uplifted and subject to long periods
of erosion since they were formed. Most of the rocks of the Pine Creek Orogen have very low primary porosity (<2%), with pores that are very small and not interconnected. Consequently, they do not hold much groundwater and are essentially impermeable. Where the metamorphic and igneous rocks are weathered and fractured, they can contain volumes of water that, while not large, can have local importance. However, the fractured and karstic carbonate rocks of the Woodcutters Supergroup present in the northern part of the Pine Creek Orogen (Proterozoic dolostones) do contain intermediate-scale aquifers with large volumes of good quality groundwater currently used for town water supplies and irrigation near Darwin (Figure 2-3).

The best potential large dam sites in the Darwin catchments are found where rivers have eroded through meta-sedimentary volcanic or igneous rocks of the Finniss River Group in the Pine Creek Orogen, particularly where there is relatively shallow rock in the valley floor (Figure 2-3). Major ore bodies in the Darwin catchments generally sit within, or above the old igneous and metamorphic rocks (i.e. older than Permian, Figure 2-3) of the Pine Creek Orogen. Initially hot fluids were formed by metamorphism, or expelled from cooling granites, precipitating minerals into veins and into the roofs of intrusions. Most mineral occurrences are alluvial gold and tin systems, which were later eroded from quartz reefs and pegmatites (coarse granites), respectively, and uranium associated with Archean granite. In general, most exploration and mining tenements in the Darwin catchments are closely correlated, with the most economically important being gold and uranium. Gold is hosted in quartz-reef deposits near Pine Creek, while uranium occurs around older Archean age granite (Figure 2-3) sitting at the boundary between the Finniss and Adelaide catchments (McCready et al., 2004). Soils over the older rocks in the Darwin catchments are thin in much of the area but there are channel deposits in the rivers and alluvial terraces and colluvium on many of the slopes. Deeper alluvium occurs on the lower reaches of the rivers in the Pine Creek Orogen and the tidal sections of the rivers are also likely to contain soft estuarine sediments in the valley floor.

The Money Shoal Basin extends up to 50 km inland and is overlain by the present day coastal plains. The plains are underlain by up to at least 20 m of alluvium and estuarine sediments, which in turn are underlain by rocks of Jurassic to Cretaceous age (Figure 2-3). Where the rivers are tidal, the presence of soft estuarine sediments has the potential to make dam design more challenging and construction more expensive, which may compromise the feasibility of a dam.

Most of the rocks of the Money Shoal Basin also have very low primary porosity and do not hold much groundwater. Where these rocks are fractured, however, they can contain volumes of water that, while not large, can have local importance.

Unconsolidated sediments are ‘loose’ grains or aggregates and are prominent across the Money Shoal Basin (Figure 2-3). Where they comprise mainly sand or gravel, they often form highly porous, high-yielding aquifers that can be found in the Mary and Wildman rivers area as palaeochannels (an inactive river or stream channel buried by younger sediments). Those comprising mainly clay often have low porosity, low permeability and low aquifer yield. Unconsolidated alluvial sediments (i.e. deposited by rivers) form in the downstream sections of the Finniss, Adelaide, Mary and Wildman rivers in the northern part of the Darwin catchments, but most of these alluvial sediments comprise clay. Alluvial clay areas are predominantly unsuitable for cropping due to waterlogging conditions, but large areas are moderately suitable for aquaculture.
2.3 Soils of the Darwin catchments

2.3.1 INTRODUCTION

Soils in a landscape occur as complex patterns resulting from the interplay of five key factors: parent material, climate, organisms, topography and time (Fitzpatrick, 1986). Consequently, soils can be highly variable across a landscape, with different soils having different attributes that determine their suitability for growing different crops and guide how they need to be managed. The distribution of these soils and their attributes closely reflect the geology and landform of the catchments. Hence data and maps of soil and soil attributes, which provide a spatial representation of how soils vary across a landscape, are fundamental to regional-scale land use planning.

This section briefly describes the spatial distribution of soil groups (Section 2.3.2) and soil attributes (Section 2.3.3) in the Darwin catchments. The management considerations are also
summarised. Maps showing the suitability of different crops under different irrigation types are presented in Chapter 4.

Unless otherwise stated, the material in Section 2.3 is based on findings described in the companion technical reports on digital soil mapping (Thomas et al., 2018a) and land suitability (Thomas et al., 2018b). Soils and their attributes were collected and described adhering to Australian soil survey standards (National Committee on Soil and Terrain, 2009).

### 2.3.2 SOIL CHARACTERISTICS

The soils of the Darwin catchments can be classified into soil generic groups (SGGs) (Table 2-1 and Figure 2-4). These groupings provide a means of aggregating soils with broadly similar properties and management considerations. While all SGGs are found in the Darwin catchments, only four of them occupy more than 1% of the area, noting that 1% is equivalent to 30,000 ha. These four SGGs are seasonally or permanently wet soils (SGG 3, 42%), loamy soils (SGG 4.1, 14% and SGG 4.2, 14%) and shallow and/or rocky soils (SGG 7, 30%). Red soils generally indicate well-drained soils, whereas yellows, greys and even blue-green indicate increasingly persistent wetness, and ultimately, permanent waterlogging. Mottles indicate cycling between wetting and drying soil conditions, indicating the presence of imperfect drainage and seasonal inundation.

**Table 2-1 Soil generic groups (SGG) for the Darwin catchments**

Figure 2-4 shows the location of the soil generic groups within the Darwin catchments.

<table>
<thead>
<tr>
<th>SGG</th>
<th>SGG OVERVIEW AND % OF AREA</th>
<th>GENERAL DESCRIPTION</th>
<th>LANDFORM</th>
<th>MAJOR MANAGEMENT CONSIDERATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Sand or loam over relatively friable red clay subsoils (&lt;1%)</td>
<td>Strong texture contrast between the A and B horizons, A horizons generally not bleached. B horizon not sodic and may be acid or alkaline. Moderately deep to deep well-drained red soils</td>
<td>Undulating plains to hilly areas on a wide variety of parent materials</td>
<td>The non-acid soils are widely used for agriculture; the strongly acid soils are generally used for native and improved pastures</td>
</tr>
<tr>
<td>1.2</td>
<td>Sand or loam over relatively friable brown, yellow and grey clay subsoils (&lt;1%)</td>
<td>As above, but moderately well-drained to imperfectly drained brown, yellow and grey soils</td>
<td>As above</td>
<td>As above, but may be restricted by drainage related issues</td>
</tr>
<tr>
<td>2</td>
<td>Friable non-cracking clay or clay loam soils (&lt;1%)</td>
<td>Moderate to strongly structured, neutral to strongly acid soils with little or only gradual increase in clay content with depth. Grey to red, moderately deep to very deep soils</td>
<td>Plains, plateaus and undulating plains to hilly areas on a wide variety of parent materials</td>
<td>Generally high agricultural potential because of their good structure, and their moderate to high chemical fertility and water-holding capacity. Ferrosols on young basalt and other basic landscapes may be shallow and rocky</td>
</tr>
<tr>
<td>3</td>
<td>Seasonally or permanently wet soils (42%)</td>
<td>A wide variety of soils grouped together because of their seasonal or permanent inundation. No discrimination between saline and fresh water</td>
<td>Coastal areas to inland wetlands, swamps and drainage depressions. Mostly unconsolidated sediments, usually alluvium</td>
<td>Require drainage works before development can proceed. Acid sulfate soils and salinity are associated problems in some areas</td>
</tr>
<tr>
<td>4.1</td>
<td>Red loamy soils (14%)</td>
<td>Well-drained, neutral to acid red soils with little or only gradual increase in clay content at depth. Moderately deep to very deep red</td>
<td>Level to gently undulating plains and plateaus, and some unconsolidated sediments, usually</td>
<td>Moderate to high agricultural potential with spray or trickle irrigation due to their good drainage. Low to moderate water-holding capacity, often hard-</td>
</tr>
<tr>
<td>SGG</td>
<td>SGG OVERVIEW AND % OF AREA</td>
<td>GENERAL DESCRIPTION</td>
<td>LANDFORM</td>
<td>MAJOR MANAGEMENT CONSIDERATIONS</td>
</tr>
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<td>-----</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>soils</td>
<td>alluvium</td>
<td>setting surfaces</td>
</tr>
<tr>
<td>4.2</td>
<td>Brown, yellow and grey loamy soils (14%)</td>
<td>As above, but moderately well-drained to imperfectly drained brown, yellow and grey soils</td>
<td>As above, but more common in lower parts of the landscape</td>
<td>As above, but may be restricted by drainage related issues</td>
</tr>
<tr>
<td>5</td>
<td>Peaty soils (&lt;1%)</td>
<td>Soils high in organic matter</td>
<td>Predominantly swamps</td>
<td>Low agricultural potential due to very poor drainage</td>
</tr>
<tr>
<td>6.1</td>
<td>Red sandy soils (&lt;1%)</td>
<td>Moderately deep to very deep red sands, may be gravelly</td>
<td>Sandplains and dunes; Aeolian, fluvial and siliceous parent material</td>
<td>Low agricultural potential due to excessive drainage and poor water-holding capacity. Potential for irrigated agriculture</td>
</tr>
<tr>
<td>6.2</td>
<td>Brown, yellow and grey sandy soils (&lt;1%)</td>
<td>Moderately deep to very deep brown, yellow and grey sands, may be gravelly</td>
<td>As above, but more common in lower parts of the landscape</td>
<td>Low agricultural potential due to poor water-holding capacity combined with seasonal drainage restrictions. May have potential for irrigated agriculture</td>
</tr>
<tr>
<td>7</td>
<td>Shallow and/or rocky soils (30%)</td>
<td>Very shallow to shallow &lt;0.5 m. Usually sandy or loamy, but may be clayey. Generally weakly developed soils that may contain gravel</td>
<td>Crests and slopes of hilly and dissected plateaus in a wide variety of landscapes</td>
<td>Negligible agricultural potential due to lack of soil depth, poor water-holding capacity and presence of rock</td>
</tr>
<tr>
<td>8</td>
<td>Sand or loam over sodic clay subsoils (&lt;1%)</td>
<td>Strong texture contrast between the A and B horizons; A horizons usually bleached. Usually alkaline but occasionally neutral to acid subsoils. Moderately deep to deep</td>
<td>Lower slopes and plains in a wide variety of landscapes</td>
<td>Generally low to moderate agricultural potential due to restricted drainage, poor root penetration and susceptibility to gully and tunnel erosion. Those with thick to very thick A horizons are favoured</td>
</tr>
<tr>
<td>9</td>
<td>Cracking clay soils (&lt;1%)</td>
<td>Clay soils with shrink-swell properties that cause cracking when dry. Usually alkaline and moderately deep to very deep</td>
<td>Floodplains and other alluvial plains. Level to gently undulating plains and rises (formed on labile sedimentary rock). Minor occurrences in basalt landscapes</td>
<td>Generally moderate to high agricultural potential. The flooding limitation will need to be assessed locally. Many soils are high in salt (particularly those associated with the treeless plains). Gilgai and coarse structured surfaces may occur</td>
</tr>
<tr>
<td>10</td>
<td>Highly calcareous soils (&lt;1%)</td>
<td>Moderately deep to deep soils that are calcareous throughout the profile</td>
<td>Plains to hilly areas</td>
<td>Generally moderate to low agricultural potential depending on soil depth and presence of rock</td>
</tr>
</tbody>
</table>

The red, yellow and grey loamy soils (SGG 4.1 and SGG 4.2) occur extensively on a variety of geologies and landforms across the catchments. The elevated level to gently undulating sediments along the Darwin Coast and some plateaus in the upper parts of the catchments usually have sandy to loamy surfaced well-drained red soils on the plains and upper slopes, while sandy to loamy surfaced moderately well-drained to imperfectly drained brown, yellow and grey soils occur on the plains and lower landscape positions. These soils are also often associated with the narrow levees adjacent to the major rivers and tributaries on the alluvial plains across the catchments. The depth to iron pans and the abundance of iron nodules relate to position in the landscape, the degree of erosion of the original deeply weathered surface and the colluvial deposition on lower slopes. Moderately deep soils with abundant iron nodules and iron pans frequently occur on mid-to-lower slopes. Exposed laterite is common.
The lower slopes of the metamorphic hills and rises in the upper parts of the catchments usually have moderately deep, moderately well-drained to imperfectly drained, sandy to loamy surfaced, yellow and brown massive soils frequently with rock fragments throughout the profile. Moderately deep to deep, well-drained to imperfectly drained, red and mottled yellow, hard-setting loamy surfaced massive soils occur in association with friable clay or clay loam soils (SGG 2) on the gently undulating rises and plains in the Reynolds River subcatchment within the Finniss catchment.

All the loamy soils in the SGG 4 category are typically nutrient deficient because of their age of weathering, hence irrigated cropping requires very high fertiliser inputs (including trace elements) when land is initially developed. After the initial application, fertiliser rates follow recommended crop requirements. Irrigation potential is limited to spray and drip irrigated crops on the moderately deep to deep soils with low to moderate soil water storage and fewer iron nodules. The current Asian vegetable horticultural industry is largely found on these soils, and where the lateritic pan is close to the surface (i.e. the soil is shallow), growers mound the soil.
All river systems of the Darwin Coast alluvial plains have seasonally wet or permanently wet soils (SGG 3) occurring extensively on a range of swamps, drainage lines, lower slopes and low-lying alluvial, coastal and marine plains. Very poorly drained saline coastal marine plains subject to tidal inundation have very deep strongly mottled grey non-cracking and cracking clays. The marine plains and much of the coastal freshwater swamps are also subject to storm surge from cyclones. The coastal marine clays, salt pans and mangroves often have acid sulfate deposits in the profile, which when disturbed and exposed to air form sulfuric acid in the soil with the potential to release noxious contaminant. These soils all have limited potential for agricultural development. Together, these soils make up 42% of the catchments. The inland low-lying seasonally wet alluvial plains of the upper Adelaide and Mary rivers are suited to dry-season irrigated agriculture.

The shallow sandy and stony soils (SGG 7) occur extensively across the upper parts of the catchments and on exposed laterite of the deeply weathered sediments on the coastal plains. Soils are dominated by shallow gravelly soils with abundant rock or laterite outcrop. All shallow and gravelly soils with abundant rock outcrop have very low to low soil water storage, are generally associated with steep slopes subject to erosion and limited potential for agricultural development. These soils are also fragmented in the landscape due to intense drainage patterns, further affecting development viability because of a lack of sufficiently large coherent areas.

The friable clays and clay loam soils (SGG 2) occur to a very limited extent (a little over 2000 ha in total) predominantly as deep hard-setting loamy surfaced soils over friable mottled yellow and brown subsoils. These have developed on limestone, mudstone and siltstone of the Reynolds River subcatchment within the Finniss catchment. The soils are suitable for cropping and horticultural tree crops. Other areas of friable clays and clay loam soils are very minor, including the lower slopes of the metamorphosed hills in the upper parts of the catchments and the levees on the alluvial plains of the major rivers through the catchments.

Deep sandy soils (SGG 6.1 and SGG 6.2) occur to a limited extent (a little over 2000 ha) as very deep sands on the beach ridges along the coast, as moderately deep to deep well-drained to imperfectly drained red and yellow sands on quartz sandstones, and as very deep red, yellow and grey sand on levees and prior streams on alluvial plains. While only very limited areas are mapped they may occur more widely in small pockets in conjunction with SGG 4.1 and SGG 4.2 soils. These highly permeable soils with very low soil water storage have potential for irrigated horticulture, otherwise the agricultural potential is low.

Sand or loam over relatively friable red (SGG 1.1), brown yellow and grey (SGG 1.2) clay subsoils peaty soils (SGG 5), highly calcareous soils (SGG 10), sodic soils (SGG 8) and cracking clays (SGG 9) have been modelled as very small areas but due to the resolution of the mapping the areas may be underestimated.

2.3.3 SOIL ATTRIBUTE MAPPING

Using a combination of field sampling (Figure 2-5) and digital soil mapping techniques, the Assessment mapped 16 attributes affecting the agricultural suitability of soil for the Darwin catchments as described in the companion technical report on digital soil mapping (Thomas et al., 2018a).
Descriptions and maps for six key attributes are presented below:

- surface soil pH
- minimum soil depth
- soil surface texture
- permeability
- plant available water capacity (PAWC) in the upper 100 cm of the soil profile – referred to as PAWC 100
- rockiness.

An important feature of the predicted attributes map is the companion reliability map indicating the relative confidence in the accuracy of the attribute predictions, noting that mapping is only provided here for regional-scale assessment. Areas of high reliability allow users to be more confident in the quality of mapping, whereas areas of low reliability show where users should be cautious.

Figure 2-5 Field soil sampling to 1.5 m depth of DSM chosen sites for modelling and chemical analysis carried out by CSIRO and the NT Department of Environment and Natural Resources
Photo: CSIRO
Surface soil pH

The pH value of a soil reflects the extent to which the soil is alkaline or acidic. This is important because pH affects the extent to which nutrients are available to the plant and, hence, plant growth. For most plants, most soil nutrients are most available in the pH range 5.5 to 6.5. Nutrient imbalances are common for soils with pH greater than 8.5 and less than 5.5. Soils in these catchments are dominated by acid surface pH (i.e. 5.5 to 7.0, measured in the top 10 cm) generally reflecting the high rainfall and high leaching rate environment of the coastal catchments. Even the soils developed on the limestone and dolomitic rocks of the Reynolds River subcatchment within the Finniss catchment have acid surface pH. The coastal marine plains have a neutral to alkaline pH (7.0 to 8.5) due to the influence of sea water. The reliability associated with pH predictions is high with moderate reliability on the coastal floodplains and swamps due to limited access and site data (Figure 2-6). Farm- and paddock-scale planning of agriculture development should rely on local soil testing and use these maps only as a guide to soil pH.

![Figure 2-6 Surface soil pH of the Darwin catchments](image)

(a) Surface soil pH as predicted by digital soil mapping and (b) reliability of the prediction. Surface soil pH is the pH in the top 10 cm.
Minimum soil depth

Soil depth defines the potential root space and the amount of soil from which plants obtain their water and nutrients. Deep to very deep soils occur on the alluvial plains and coastal wetlands, the deeply weathered coastal plains and plateaus, and lower slopes of the hills and rises in the upper parts of the catchments (Figure 2-7). Shallow soils are dominant on the upper slopes of the hills and edges of plateaus in the upper areas, and mid-to-lower slopes of the deeply weathered coastal plains. The reliability associated with mapping of soil depth is generally moderate to high with lower reliability associated with the complex rugged geologies of the upper parts of the catchments where access and site information is limited (Figure 2-7b).

Figure 2-7 Minimum soil depth of the Darwin catchments
(a) Minimum soil depth as predicted by digital soil mapping and (b) reliability of the prediction.
Soil surface texture

Soil texture refers to the proportion of sand, silt and clay sized particles that make up the mineral fraction of a soil. Surface texture influences soil water-holding capacity, soil permeability, soil drainage, water and wind erosion, workability and soil nutrient levels. Light soils are generally those high in sand and heavy soils are dominated by clay. Sandy surface textures dominate the catchment, reflecting the geology dominated by sandstones on coastal plains, the metamorphic sandstone hills, and the granites of the catchment of the Finniss River and areas around Pine Creek (Figure 2-8). Loamy surface textures are mainly associated with the loamy soils (SGG 4.1) on the deeply weathered coastal plains in the west, various shallow soils (SGG 7) on the fine-grained metamorphic geologies, and on the friable clays and clay loam soils (SGG 2) developed on limestone, dolomitic siltstone, mudstone and siltstone in the subcatchment of the Reynolds River within the Finniss catchment. Silty surface textures are mainly associated with the sodic soils (SGG 3 and SGG 8) on the alluvial plains of the major rivers grading to clay textures (SGG 3 and SGG 9) lower in the catchments. Soil surface texture is mapped with most reliability in areas with uniform soils with good access and site information, such as the alluvial plains and coastal plains. Low reliability is mainly associated with the complex rugged geologies of the upper parts of the catchments.

Figure 2-8 Soil surface texture of the Darwin catchments
(a) Surface texture of soils as predicted by digital soil mapping and (b) reliability of the prediction.
Permeability

The permeability of the profile is a measure of how easily water moves through a soil. Flood and furrow irrigation is most successful on soils with low and very low permeability to reduce root zone drainage (i.e. water that passes below the root zone of a plant), rising watertables and nutrient leaching. Spray or drip irrigation is more efficient on soils with moderate to high permeability. The Darwin catchments are dominated by moderately permeable soils (Figure 2-9), the friable clays and clay loam soils (SGG 2) in the Reynolds River subcatchment within the Finniss catchment; particularly the red, yellow and grey loamy soils (SGG 4.1 and 4.2); and most of the shallow and stony soils (SGG 7). The highly permeable soils are restricted to the sands (SGG 6.1 and SGG 6.2) on the beach ridges along the coast; the red, yellow and grey sands developed on the quartz sandstones; and the shallow sandy soils, mainly of granite origin, on the hills in the upper parts of the catchments. The slowly permeable to very slowly permeable soils are associated with the cracking clay soils of the river alluvial plains and floodplains (SGG 3 and SGG 9), the soils with sand or loam over sodic subsoils of the river alluvial plains and floodplains (SGG 3 and SGG 8) and some of the shallow sandy and stony soils (SGG 7) with sodic subsoils. Permeability mapping reliability is highly variable due to the complex interactions in the soil forming factors, particularly the complex geology, landscape position and the age of the various landscapes. In general, the coastal plains and alluvial plains with uniform soil distribution have a higher reliability.

Figure 2-9 Soil permeability of the Darwin catchments
(a) Soil permeability as predicted by digital soil mapping and (b) reliability of the prediction.
Plant availability water capacity to 100 cm

Plant available water capacity (PAWC) is the maximum volume of water the soil can hold for plant use. PAWC 100 is the maximum volume of water that the top 100 cm of soil can hold for plant use. The higher the PAWC 100 value, the greater the capacity of the soil to supply plants with water. For irrigated agriculture, it is one factor that determines irrigation frequency and volume of water required to wet up the soil profile. Low PAWC 100 soils require more frequent watering and lower volumes of water per irrigation. For dryland agriculture, PAWC 100 determines the capacity of crops to grow and prosper during dry spells.

The PAWC 100 is highest on the seasonally wet to wet clay soils (SGG 3 and SGG 9) of the lower floodplains (Figure 2-10a). Most of the sodic texture contrast and gradational soils on the alluvial plains (SGG 8), some of the deep friable clays and loams (SGG 2) and the loamy surfaced loamy soils (SGG 4.1 and SGG 4.2) have moderate PAWC. Minor sands (SGG 6.1 and SGG 6.2) and shallow coarser grained or stony soils (SGG 7), particularly those developed on granite and quartz sandstones, have very low PAWC 100. The remaining soils, particularly the sandy surfaced loamy soils (SGG 4.1 and SGG 4.2) and some of the shallow soils (SGG 7), have moderate (50 to 75 mm) PAWC 100 values. Figure 2-10b indicates a moderate to high reliability in areas with uniform soils with good access and site information, such as the alluvial plains and coastal plains. Low reliability is mainly associated with the complex rugged geologies of the upper parts of the catchments.

Figure 2-10 Plant available water capacity in the Darwin catchments
(a) Plant available water capacity in the upper 100 cm of the soil profile (PAWC 100) as predicted by digital soil mapping and (b) reliability of the prediction.
Rockiness

The rockiness of the soil has both an impact on agricultural management and on the growth of some crops, particularly root crops. Coarse fragments (e.g. pebbles, gravel, cobbles, stones and boulders), hard segregations and rock outcrop in the plough zone can damage and/or interfere with the efficient use of agricultural machinery. Surface gravel, stone and rock are particularly important and can interfere significantly with planting, cultivation and harvesting machinery used for root crops, small crops, annual forage crops and sugarcane.

The distribution of the rocky soils (Figure 2-11) strongly reflects the patterns from the previous attributes. For example, the uplands are dominated by rocky soils associated with the shallow soils of SGG 7. The reliability of the rockiness predictions is variable, with more reliable predictions associated with the deeper soils in the lower parts of the catchments. Low reliability in the central and upper parts of the catchments is associated with the complex rugged geology and restricted site information, due to limited access.

Figure 2-11 Rockiness in soils of the Darwin catchments
(a) Rockiness represented by presence or absence as predicted by digital soil mapping and (b) reliability of the prediction.
2.4 Climate of the Darwin catchments

2.4.1 INTRODUCTION

Weather is the key source of uncertainty affecting crop yield. It influences the rate and vigour of crop growth, while catastrophic weather events can result in extensive crop losses. Key climate parameters controlling plant growth and crop productivity include rainfall, temperature, radiation, humidity and wind speed and direction. These parameters are interrelated so impact synergistically.

Of all the climate parameters affecting hydrology and agriculture in water-limited environments, rainfall is usually the most important. Rainfall is the main determinant of runoff and recharge and is a fundamental requirement for plant growth. For this reason, reporting of climate parameters is heavily biased towards rainfall data. Other climate variables affecting crop yield are discussed in the companion technical reports on climate (Charles et al., 2016) and agricultural viability (Ash et al., 2018).

Unless otherwise stated, the material in Section 2.4 is based on findings described in the companion technical report on climate (Charles et al., 2016).

2.4.2 WEATHER PATTERNS OVER THE DARWIN CATCHMENTS

The Darwin catchments are characterised by a distinctive wet and dry season due to their location in the Australian summer monsoon belt (Figure 2-12). During the build-up months (typically September to December) the Darwin catchments typically experience low-level easterly winds, which can carry pockets of dry or humid air, and can result in short-lived thunderstorm activity under favourable conditions. During the early build-up months (September to October) the bulk of rain falls within about 100 km of the west coast of the ‘Top End’ including the Finniss and Adelaide catchments, while the Mary and Wildman catchments generally receive less rainfall over this period. From November onwards, rainfall distribution is more uniform across the four catchments.

During the wet season low-level westerly winds dominate. ‘Shallow westerly’ regimes are typical of an ‘inactive monsoon’ period (when the monsoon trough temporarily weakens or retreats north of Australia), and favour early morning thunderstorms along the coast, while afternoon thunderstorm activity is more common inland. ‘Deep westerly’ regimes correspond to an ‘active monsoon’ period, where storms typically have low cloud-top heights and showers and thunderstorms can be gusty and cause heavy rainfall due to the large water content of the maritime air mass.

The mean annual rainfall, averaged over the Darwin catchments for the 125-year historical period (1 September 1890 to 31 August 2015), is 1423 mm. Rainfall is highest in the north-western part of the region (i.e. Finniss catchment) and lowest in the south-eastern part of the region (i.e. Mary catchment) (Figure 2-13). This is because the coastal zone receives more wet-season rainfall as a result of active monsoon episodes, which are subject to a north-westerly wind regime. The Darwin catchments are flat, and consequently there is no noticeable topographic influence on climate parameters such as rainfall or temperature.
Approximately 95% of rain falls in the Darwin catchments during the wet-season months (1 November to 30 April). The spatial distribution of rainfall during the wet and dry seasons is shown in Figure 2-13. Median wet-season rainfall exhibits a very similar spatial pattern to median annual rainfall, and while median dry-season rainfall exhibits a west–east gradient, no north–south gradient is evident. The highest monthly rainfall totals typically occur during January, February and March (Figure 2-14).

The lack of rainfall during the dry season is largely due to the predominance of dry continental south-easterlies and the significant dry air aloft that inhibits shower and thunderstorm formation. During the months where the climate is transitioning to the wet season (i.e. typically mid-September to mid-December) strong sea breezes pump moist air inland, fuelling the steady growth of shower and thunderstorm activity over a period of weeks to months. This can result in highly variable rainfall during these months (Figure 2-14).

Tropical cyclones and tropical lows contribute a considerable proportion of total annual rainfall, but the actual amount is highly variable from one year to the next (see companion technical report on climate (Charles et al., 2016)), since tropical cyclones do not affect the Darwin catchments in half of years. For the 47 tropical cyclone seasons from 1969–70 to 2015–16, 53% of seasons experienced no tropical cyclones, 36% experienced one tropical cyclone, and 11% experienced two. When a tropical cyclone or low crosses the catchments, typically 200 to 500 mm of rain falls over a 2- to 5-day period, and daily rainfall totals can exceed 250 mm in coastal areas.
Figure 2-13 Historical rainfall, potential evaporation and rainfall deficit
Median (a) annual, (b) wet-season and (c) dry-season rainfall. Median (d) annual, (e) wet-season and (f) dry-season potential evaporation, and median (g) annual, (h) wet-season and (i) dry-season rainfall deficit in the Darwin catchments. Rainfall deficit is rainfall minus potential evaporation.

2.4.3 POTENTIAL EVAPORATION AND POTENTIAL EVAPOTRANSPIRATION

Evaporation is the process by which water is lost from open water, plants and soils to the atmosphere; it is a ‘drying’ process. It has become common usage to also refer to this as evapotranspiration.
There are three major ways in which evaporation affects the potential for irrigation:

1. losses that reduce runoff and deep drainage and, hence, the ability to fill water storages (Section 2.5)
2. influence on crop water requirements (Section 4.5)
3. losses from water storages (Section 5.3).

Potential evaporation (PE) or potential evapotranspiration (PET) is defined as the amount of evaporation that would occur if an unlimited source of water was available. The Darwin catchments have a mean annual PE of 1917 mm (1965 to 2015) and it is relatively spatially uniform across the study area (Figure 2-13).

Preliminary estimates of mean annual irrigation demand and net evaporation from water storages are sometimes calculated by subtracting the mean annual (seasonal) PE from the mean annual (seasonal) rainfall. This is commonly referred to as the mean annual (seasonal) rainfall deficit (Figure 2-13). The rainfall deficit or mean annual net evaporative water loss from potential open storages at Wildman Station in the Darwin catchments is about 220 mm.

Two common methods for characterising climates are the United Nations Environment Program (UNEP) aridity index and the Köppen-Geiger classification (Köppen, 1936; Peel et al., 2007). The aridity index classifies the Darwin catchments as ‘Humid’ and the Köppen-Geiger classification classifies them as ‘Tropical monsoon’ (see companion technical report on climate (Charles et al., 2016)).

### 2.4.4 Variability and Long-term Trends in Rainfall and Potential Evaporation

Climate variability is a natural phenomenon that can be observed in many ways, for example, warmer than average winters, low and high rainfall wet seasons. Climate variability can also operate over long-term cycles of decades or more. Climate trends represent long-term, consistent directional changes such as warming or increasingly higher average rainfall. Separating climate variability from climate change is very difficult, especially when comparing climate on a year-to-year basis.

In the Darwin catchments 95% of rain falls during the wet season (November to April). The highest monthly rainfall in the Darwin catchments typically occurs during January and February (Figure 2-14). The months with the lowest rainfall are June through to September. In Figure 2-14, the blue shading represents the range under Scenario A (A range). The upper limit of the A range is the value at which rainfall (or PE) is exceeded 1 year in 5 and is known as the 20% exceedance. The lower limit of the A range is the value at which rainfall (or PE) is exceeded 4 years in 5 and is known as the 80% exceedance. The difference between the upper and lower limits of the A range indicates the variation in monthly values from one year to the next.
PE also exhibits a seasonal pattern. During the month of October mean PE is about 200 mm/month (Figure 2-15). It is at its lowest during June (130 mm/month). Months where PE is high correspond to those months where the demand for water by plants is also high. Mean wet-season and dry-season PE in the Darwin catchments are shown in Figure 2-13. Compared to rainfall, the variation in monthly PE from one year to the next is small (Figure 2-15).

Relative to other catchments in southern and northern Australia the Darwin catchments have a low variability in rainfall from one year to the next. Nevertheless, under Scenario A, rainfall for the Darwin catchments still exhibits considerable variation from one year to the next (Figure 2-16). The highest annual rainfall at Wildman station (2244 mm) occurred in the 2010–11 wet season, which was three times the lowest annual rainfall (701 mm in 1905–06) and 60% higher than the median annual rainfall value (i.e. 1393 mm). The 10-year running mean provides an indication of the sequences of wet or dry years (i.e. variability at decadal time scales). For an annual time series, the 10-year running mean is the average of the 5 years of data either side of every annual data point. The 10-year running mean varied from 1202 to 1784 mm. Under Scenario A, PE exhibits much less inter-annual variability than rainfall (not shown, see companion technical report on climate (Charles et al., 2016)).
Figure 2-16 Annual rainfall at Darwin and Wildman station under Scenario A
(a) Monthly rainfall at Darwin and (b) monthly rainfall at Wildman station. Scenario A is the historical climate (1890 to 2015). The blue line represents the 10-year running mean.

The coefficient of variation (CV) provides a measure of the variability of rainfall from one year to the next, where the larger the CV value, the larger the variation in annual rainfall relative to a location’s mean annual rainfall – it is calculated as the standard deviation of mean annual rainfall divided by the mean annual rainfall. In Figure 2-17, the CV of annual rainfall is shown for rainfall stations with a long-term record around Australia. This figure shows that the inter-annual variation in rainfall in the Darwin catchments is among the lowest in northern Australia and is comparable to the least variable stations in southern Australia.

Figure 2-17 (a) Coefficient of variation of annual rainfall and (b) the coefficient of variation of annual rainfall plotted against mean annual rainfall for 96 rainfall stations around Australia
(a) The grey polygons indicate the extent of the Darwin catchments. (b) Rainfall stations in the Darwin catchments are indicated by black symbols. The light blue diamonds indicate rainfall stations from the rest of northern Australia (RoNA) and hollow squares indicate rainfall stations from southern Australia (SA).

Furthermore, Petheram et al. (2008) observed that the inter-annual variability of rainfall in northern Australia is about 30% higher than that observed at rainfall stations from the rest of the world for the same type of climate as northern Australia. Hence, caution should be exercised
before drawing comparisons between the agricultural potential of the Darwin catchments and other parts of the world with a similar climate.

There are several factors driving this high inter-annual variation in Australia’s climate, including the El Niño – Southern Oscillation (ENSO), the Indian Ocean Dipole, the Southern Annular Mode, the Madden–Julian Oscillation and the Inter-decadal Pacific Oscillation.

Of these influences, the ENSO is a phenomenon that is considered to be the primary source of global climate variability over the 2- to 6-year timescale (Rasmusson and Arkin, 1993) and is reported as being a significant cause of climate variability for much of eastern and northern Australia. One of the modes of ENSO, El Niño, has come to be a term synonymous with drought in the western Pacific and eastern and northern Australia. Rainfall stations along eastern and northern Australia have been observed to have a strong correlation (0.5 to 0.6) with the Southern Oscillation Index (SOI), a measure of the strength of ENSO, during spring suggesting that ENSO plays a key role in between-year rainfall variability (McBride and Nicholls, 1983).

Another known impact of ENSO in northern Australia is the tendency for the onset of useful rains after the dry season to be earlier than normal in La Niña years and later than normal in El Niño years. For all years between 1960 and 2009 the mean rainfall onset date (defined as being the accumulation of 50 mm of rain after the dry season) for the Darwin catchments is the first 10 days of October (see companion technical report on climate (Charles et al., 2016)). In SOI neutral, negative (El Niño) and positive (La Niña) years, the mean rainfall onset dates for the Darwin catchments are the start of October, mid-to-late November, and late September/early October, respectively.

**Trends**

An analysis undertaken as part of the Assessment found an increasing trend in rainfall at Darwin Airport and Oenpelli, approximately 200 km west of Darwin (see companion technical report on climate (Charles et al., 2016)). Previously, CSIRO (2009) found that rainfall between 1997 and 2007 was statistically different to that between 1930 and 1997. In other work, Evans et al. (2014) found a strong relationship between monsoon active periods and the Madden–Julian Oscillation, and that the increasing rainfall trend observed at Darwin Airport was related to increased frequency of active monsoon days rather than increased intensity during active periods. They concluded periods of moderate active monsoon have been increasing in frequency at the expense of the weakest periods of the monsoon.

**Runs of wet and dry years**

The rainfall generating systems in northern Australia and their modes of variability combine to produce irregular runs of wet and dry years. In particular, length and magnitude (intensity) of dry spells strongly influence the scale, profitability and risk of water resource related investments. The Darwin catchments are likely to experience dry periods of similar severity to many centres in the Murray–Darling Basin and east coast of Australia.

The Darwin catchments are characterised by irregular periods of consistently low rainfall when successive wet seasons fail, as well as the typical annual dry season. Runs of wet and dry years occur when consecutive years of rainfall occur that are above or below the median, respectively. These are shown in Figure 2-18 at Darwin and Wildman station as annual differences from the
median rainfall. A run of consistently dry years may be associated with drought (though an agreed definition of drought continues to be elusive). Analysis of annual rainfall at stations in the Darwin catchments indicate equally long runs of wet and dry years and nothing unusual about the length of the runs of dry years.

![Graph of wet and dry years at Darwin and Wildman station under Scenario A](image)

**Figure 2-18** Runs of wet and dry years at Darwin and Wildman station under Scenario A

Wet years are shown by the blue columns and dry years by the red columns. Scenario A is the historical climate (1890 to 2015).

**Palaeoclimate records for northern Australia**

The instrument record is very short in a geological sense, particularly in northern Australia, so a brief review of palaeoclimate data was provided. The literature indicates that atmospheric patterns approximating the present climate conditions in northern Australia (e.g. Pacific circulation responsible for ENSO) are thought to have been in place from about 3 to 2.5 million years ago, which would suggest many ecosystems in northern Australia have experienced monsoonal conditions for many millions of years. However, past climates have been both wetter and drier than the instrument record for northern Australia, and the influence of ENSO has varied considerably over recent geological time. Several authors have found that present low levels of tropical cyclone activity (i.e. over the instrumental record) in northern Australia are possibly unprecedented over the past 550 to 1500 years and that the recurrence frequencies of high intensity tropical cyclones (Category 4 to 5 events) may have been an order of magnitude higher than that inferred from the current short instrumental records. See the companion technical report on climate (Charles et al., 2016) for more information.
2.4.5 CHANGES IN RAINFALL AND EVAPORATION UNDER A FUTURE CLIMATE

The effects of projected climate change on rainfall and PE are presented in Figure 2-19, Figure 2-20 and Figure 2-21. This analysis used 21 GCMs to represent a world where the global mean surface air temperatures are 2.2 °C higher relative to approximately 1990 global temperatures. Because the scale of GCM outputs is too coarse for use in catchment and point-scale hydrological and agricultural computer models, they were transformed to catchment-scale variables using a simple scaling technique (PS) and referred to as GCM-PSs. See the companion technical report on climate (Charles et al., 2016) for further details.

In Figure 2-19 the rainfall and PE projections of the 21 GCM-PSs are spatially averaged across the Darwin catchments and the GCM-PSs are ranked in order of increasing mean annual rainfall. This figure shows that about one-quarter of the projections for GCM-PSs indicate an increase in mean annual rainfall, about one-quarter of the projections indicate a decrease in mean annual rainfall and about half of the projections indicate no change in future mean annual rainfall under a 2.2 °C warming scenario. Hence, it can be argued that, based on the selected 21 GCM-PSs, the consensus result is that mean annual rainfall in the Darwin catchments is not likely to change under Scenario C.

The spatial distribution of mean annual rainfall under Scenario C is shown in Figure 2-20. In this figure only the third ‘wettest’ GCM-PS (i.e. Scenario Cwet), the middle or 11th wettest GCM-PS (i.e. Scenario Cmid), and the third ‘driest’ (i.e. Scenario Cdry) GCM-PS are shown.

Figure 2-21a shows mean monthly rainfall under scenarios A and C. The data suggest that under Scenario Cmid, mean monthly rainfall will be similar to the mean monthly rainfall under Scenario A. Under scenarios Cwet, Cmid and Cdry the seasonality of rainfall in northern Australia is similar to that under Scenario A.

Figure 2-19 Percentage change in mean annual rainfall and potential evaporation under Scenario C relative to under Scenario A
Simple scaling of rainfall and potential evaporation have been applied to global climate model output (GCM-PS). GCM-PSs are ranked by increasing rainfall.
Figure 2-20 Spatial distribution of mean annual rainfall across the Darwin catchments under scenarios Cwet, Cmid and Cdry

Figure 2-21 Monthly rainfall and potential evaporation for the Darwin catchments under scenarios A and C
(a) Monthly rainfall and (b) monthly potential evaporation. C range is based on the computation of the 10th and 90th percentile monthly values separately – the lower and upper limits in C range are therefore not the same as scenarios Cdry and Cwet.

Potential evaporation
The mean annual change in GCM-PS PE show projected PE increases of about 3 to 9% (Figure 2-19). Under scenarios Cwet, Cmid and Cdry, PE exhibits a similar seasonality to that under Scenario A (Figure 2-21b). However, different methods of calculating PE give different results. Consequently, there is considerable uncertainty on how PE may change under a warmer climate. See Petheram et al. (2012) and Petheram and Yang (2013) for a more detailed discussion.

Sea-level rise and sea surface temperature projections
Global mean sea levels have risen at a rate of 1.7 ± 0.2 mm/year between 1900 and 2010, a rate in the order of ten times faster than the preceding century. Australian tide gauge trends are similar to the global trends (CSIRO and Bureau of Meteorology, 2015). Sea-level projections for the Darwin catchments are summarised in Table 2-2. This information may be considered in coastal aquaculture developments and flood inundation of coastal areas.
Table 2-2 Projected sea-level rise for the coast of the Darwin catchments
Values are median of Coupled Model Intercomparison Project (CMIP) Phase 5 GCMs. Numbers in parentheses are the 5 to 95% range of same. Projected sea-level rise values are relative to a mean calculated between 1986 and 2005.

<table>
<thead>
<tr>
<th>DATE (UNIT)</th>
<th>RCP 4.5</th>
<th>RCP 8.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>2030 (m)</td>
<td>0.12 (0.08–0.16)</td>
<td>0.12 (0.08–0.17)</td>
</tr>
<tr>
<td>2050 (m)</td>
<td>0.22 (0.14–0.30)</td>
<td>0.25 (0.17–0.33)</td>
</tr>
<tr>
<td>2070 (m)</td>
<td>0.33 (0.21–0.46)</td>
<td>0.41 (0.28–0.56)</td>
</tr>
<tr>
<td>2090 (m)</td>
<td>0.46 (0.28–0.64)</td>
<td>0.62 (0.41–0.85)</td>
</tr>
<tr>
<td>Rate of change at 2100 (mm/y)</td>
<td>6.1 (3.2–9.0)</td>
<td>11.1 (6.9–16.0)</td>
</tr>
</tbody>
</table>

RCP = Representative Concentration Pathway
Source: CoastAdapt (2017)

Sea surface temperature (SST) increases around Australia are projected with very high confidence for all emissions scenarios, with warming of around 0.4 to 1.0 °C in 2030 under Representative Concentration Pathway (RCP) 4.5 and 2 to 4 °C in 2090 under RCP 8.5, relative to a 1986 to 2005 baseline (CSIRO and Bureau of Meteorology, 2015). There will be regional differences in SST warming due to local hydrodynamic responses, however, there is only medium confidence in coastal projections as climate models do not resolve local processes (CSIRO and Bureau of Meteorology, 2015). For Darwin, the corresponding projected SST increases are 0.8 °C (range across climate models is 0.6 to 1.1 °C) for 2030 and 3.0 °C (2.5 to 3.9 °C) for 2090. These changes are relative to a 1986 to 2005 baseline (CSIRO and Bureau of Meteorology, 2015).

2.4.6 ESTABLISHMENT OF AN APPROPRIATE HYDROCLIMATE BASELINE

The allocation of water and the design and planning of water resources infrastructure and systems require great care and consideration and need to take a genuine long-term view. A hydroclimate baseline from 1890 to 2015 (i.e. current) was deemed the most suitable baseline for the Assessment.

A poorly considered design can result in an unsustainable system or preclude the development of a more suitable and possibly larger system, thus adversely impacting existing and future users, industries and the environment. Once water is overallocated it is economically, financially, socially and politically difficult to reduce allocations in the future, unless water allocations are only assigned over short time frames (e.g. <15 years) and then reassessed. However, many water resource investments, particularly agricultural investments, require time frames longer than 30 years as there are often large initial infrastructure costs and a long learning period before full production potential is realised. Consequently, investors require certainty that over their investment time frame (and potentially beyond), their access to water will remain at the level of reliability initially allocated. A key consideration in the development of a water resource plan, or in the assessment of the water resources of a catchment, is the time period over which the water resources will be analysed, also referred to as the hydroclimate ‘baseline’ (e.g. Chiew et al., 2009).

If the hydroclimate baseline is too short it can introduce biases in a water resource assessment, for various reasons. Firstly, the transformation of rainfall to runoff and rainfall to groundwater recharge is non-linear. For example, averaged across the Flinders catchment in northern Australia the mean annual rainfall is only 8% higher than the median annual rainfall, yet the mean annual
runoff is 59% higher than the median annual runoff (Lerat et al., 2013). Similarly, between 1895 and 1945 the median annual rainfall was the same as the median annual rainfall between 1948 and 1987 (less than 0.5% difference), yet there was a 21% difference in the median annual runoff between these two time periods (and a 40% difference in the mean annual runoff) (Lerat et al., 2013). Consequently, great care is required if using rainfall data alone to justify the use of short periods over which to analyse the water resources of a catchment.

In developing a water resource plan the volume of water allocated for consumptive purposes is usually constrained by the drier years (referred to as spells where consecutive dry years occur) in the historical record (see Section 2.4.4). This is because it is usually during dry spells that water extraction most adversely impacts on existing industries and the environment. All other factors being equal (e.g. market demand, interest rates), consecutive dry years are usually also the most limiting time periods for new water resource developments/investments, such as irrigated agriculture enterprises, particularly if the dry spells coincide with the start of an investment cycle. Consequently, it is important to ensure a representative range of dry spells (i.e. of different durations, magnitudes and sequencing) are captured over the assessment time period. For example, it is possible that two time periods may have very similar median annual runoffs, but the duration, magnitude and sequencing of the dry spells may be sufficiently different that they pose different risks to investors and result in different modelled ecological outcomes.

In those instances where there is the potential for a long memory, such as in intermediate- and regional-scale groundwater systems or in river systems with large reservoirs, long periods of record are preferable to minimise the influence of initial starting conditions (e.g. assumptions regarding initial reservoir storage volume), to properly assess the reliability of water supply from large storages and to encapsulate the range of likely conditions (McMahon and Adeloye, 2005). All these arguments favour using as long a time period as practically possible. However, there may be some circumstances in which a shorter period may be preferable on the basis that it is a more conservative option. For example, in south-western Australia, water resource assessments to support water resource planning are typically assessed from 1975 onwards (Chiew et al., 2012; McFarlane et al., 2012). This is because since the mid-1970s there has been a marked reduction in runoff in south-western Australia, and this declining trend in rainfall is consistent with the majority of GCM projections, which project reductions of rainfall into the future (Charles et al., 2010).

Although there were few rainfall stations in the three study areas at the turn of the 20th century relative to 2016 (Charles et al., 2016), an exploratory analysis of rainfall statistics of the early period of instrument record does not appear to be anomalous when compared to the longer term instrument record.

In deciding upon an appropriate time period over which to analyse the water resources of the Darwin catchments, consideration was given to the above arguments, as well as palaeoclimate records, observed trends in the historical instrumental rainfall data and future climate projections. For the Darwin catchments, although there is evidence of an increasing trend in rainfall in the recent instrumental record, 60% of the GCM-PSs project no change in mean annual rainfall for a 2.2 °C warming scenario. Furthermore, palaeoclimate records indicate multiple wetter and drier periods have occurred in the recent geological past (see companion technical report on climate (Charles et al., 2016)). For these reasons the entire instrument record (i.e. 1890 to 2015), available
through the data drill Scientific Information for Land Owners (SILO) database (Jeffery et al., 2001), was adopted as the baseline for the Assessment.

It should be noted, however, that as climate is changing on a variety of time scales, detailed scenario modelling and planning (i.e. the design of major water infrastructure) should be broader than just comparing a single hydroclimate baseline to an alternative future.

2.5 Hydrology of the Darwin catchments

2.5.1 INTRODUCTION

The timing and event-driven nature of rainfall events and high PE rates across the Darwin catchments have important consequences for the catchments’ hydrology. The spatial and temporal patterns of rainfall and PE across the Darwin catchments are discussed in Section 2.4. Rainfall can be broadly broken into evaporated and non-evaporated components (also referred to as ‘excess water’). The non-evaporated component can be broadly broken into overland flow and recharge (Figure 2-22). Recharge replenishes groundwater systems, which in turn discharge into rivers and the ocean. Overland flow and groundwater discharge into rivers combine to become streamflow. Streamflow in the Assessment is defined as a volume per unit of time. Runoff is defined as the millimetre depth equivalent of streamflow. Flooding is a phenomenon that occurs when the flow in a river exceeds the river channel’s capacity to carry the water resulting in water spilling onto the land adjacent to the river.

Section 2.5 covers the remaining terms of the terrestrial water balance (accounting for water inputs and outputs) of the Darwin catchments, with particular reference to those processes and terms that are relevant to irrigation at the catchment scale. Information is firstly provided on groundwater, groundwater recharge and surface water – groundwater connectivity. Runoff, streamflow, flooding and persistent waterholes in the Darwin catchments are then discussed.

Figure 2-22 shows a schematic diagram of the water balance of the Darwin catchments, along with estimates of the mean annual value spatially averaged across the catchment and an estimate of the uncertainty for each term. The ‘water balance’ comprises all the water inflows and outflows to and from a particular catchment over a given time period.
2.5.2 GROUNDWATER

Within the Darwin catchments the distribution, availability and quality of groundwater resources are heavily influenced by the physical characteristics of rocks of the major geological units (see Section 2.2). In general, several aquifer (rocks and sediments in the subsurface that store and transmit groundwater) types exist:

- fractured rock
- sedimentary dolostones, limestones and sandstones
- surficial sediments that predominantly include alluvium, laterite and regolith.

The sedimentary aquifers of the Pine Creek Orogen – in particular, the Woodcutters Supergroup – host intermediate-scale groundwater systems. That is, the distance between the recharge (inflow of water through the soil, past the root zone and into an aquifer) and discharge (outflow of water from an aquifer into a water body or evaporated from the soil or vegetation) areas can be a few kilometres to tens of kilometres, and the time taken for groundwater to discharge following recharge can be in the order of hundreds of years to thousands of years. The fractured rock aquifers of the Pine Creek Orogen and the surficial aquifers of the Money Shoal Basin host local-scale groundwater systems (Figure 2-23). That is, the distance between the recharge and discharge areas is in the order of 1 to 10 km. The surficial aquifer systems in the Darwin catchments are poorly characterised and are not well understood.
Figure 2.23 Spatial extent of six key hydrogeological units in the Darwin catchments
This does not represent outcropping areas of hydrogeological units; the blanket of surficial sediments has been removed to highlight the spatial extent of various units in the subsurface.
Spring and sinkhole data sourced from DENR (2016a).

Hydrogeological units

Hydrogeological units of the Darwin catchments are shown in (Figure 2.23). These rock and sediment formations host aquifers of various sizes. Major aquifer systems in the Darwin catchments are found in the geological Pine Creek Orogen and primarily include the Proterozoic dolostones and to a lesser extent the Daly Basin limestone and the Bonaparte Basin sandstone. For the Assessment, major aquifer systems are considered to be aquifers that contain intermediate-scale groundwater systems, with adequate storage volumes (i.e. gigalitres) that could potentially yield water at a sufficient rate (i.e. >10 L/second) and sufficient water quality (i.e. <1000 mg/L) for irrigated cropping. Minor aquifers are considered to be aquifers that contain local-scale groundwater systems with lower storage (i.e. megalitres), with variable but often low yields (i.e. <5 L/second) and variable but often poor-quality water (i.e. >1000 mg/L). The distribution and characteristics of these rocks is covered in Section 2.2.

Unless otherwise stated, the material in Section 2.5.2 is based on findings described in the companion technical report on hydrogeological characterisation (Turnadge et al., 2018). Only the major aquifers relevant to opportunities for future groundwater resource development are discussed in detail.
Fractured rock aquifers

The Proterozoic rocks including granite (Figure 2-23) occur over approximately 80% of the Darwin catchments and host fractured rock aquifer systems that supply small quantities of groundwater for stock and domestic use. These aquifers are highly variable in composition and host local-scale flow systems, with most groundwater storage and flow resulting from the size and connectivity of secondary porosity features such as joints, fractures or faults. Individual bore (hole in the ground for extracting groundwater) yields are often low (Figure 2-24), ranging from 0.5 to 2 L/second, and water quality is variable but of low salinity (i.e. <1000 mg/L). Recharge occurs as infiltration of rainfall and some streamflow (where rivers traverse these formations) through the soil to vertical fractures and joints. The main discharge mechanisms are from bores extracting groundwater for stock and domestic use and from evaporation (through the soil or plants) from shallow watertables (the start of the saturated zone of an aquifer).

![Groundwater bore yields for different aquifers in the Darwin catchments](image)

*Figure 2-24 Groundwater bore yields for different aquifers in the Darwin catchments*

Bore yield data sourced from DENR (2016a).

Dolostone aquifers

The Proterozoic age dolostones are associated with the oldest rocks overlying parts of the Pine Creek Orogen, the Woodcutters Supergroup (Figure 2-23). These dolostones host the major aquifers of the Darwin catchments and primarily occur in the north of the Adelaide catchment but
also extend slightly west to the north-east of the Finniss catchment and much further to the east into the Mary and Wildman catchments (Figure 2-23). The most significant aquifer is the regionally extensive Koolpinyah Dolostone aquifer that extends from Gunn Point in the north to Humpty Doo in the south. It is also known as the Howard Groundwater System, the main water resource in the Howard Water Allocation Plan Area and the Darwin Rural Water Control District (DRWCD). This aquifer system is complex, comprising three interconnected aquifers: a young surficial laterite aquifer, overlying a claystone to sandy claystone and sandstone Mesozoic age aquifer, overlying the much older Proterozoic dolostone aquifer. The aquifer system is well characterised from drilling, geophysics and groundwater monitoring, as groundwater resources of the intermediate-scale flow systems have been extensively developed for the purpose of:

- use in irrigated agriculture and horticulture
- use as domestic water supplies for households
- use as a supplementary public water supply for Darwin.

Current groundwater use was estimated in 2012 to be 25 GL/year with the purpose for water use split equally between irrigation and domestic water supplies for both rural households and Darwin (Marsden Jacob Associates, 2012a). The Proterozoic dolostone also occurs at Berry Springs where a karstic aquifer similar in characteristics to the Koolpinyah Dolostone but of much smaller extent occurs. Groundwater resources from the aquifer have also been extensively developed for use in irrigated agriculture and horticulture, as well as for domestic water supplies for rural households. Groundwater use from the dolostone aquifer at Berry Springs was estimated in 2012 to be approximately 5 GL/year, with demand for water split mostly for the purpose of irrigated agriculture and horticulture (Marsden Jacob Associates, 2012b). The characteristics of the dolostone aquifer in the east in the Mary and Wildman catchments is currently less well known. For more information on current groundwater use see Section 3.3.

The interconnected Koolpinyah Dolostone aquifer is a complex aquifer system because:

- The aquifer is compartmentalised in places by dolerite dykes associated with faulting (sheets of rock that cut vertically through the dolostone) that impede lateral groundwater flow and therefore reduce the scale of the flow system.
- The variability in karstic features (the formation of holes and caverns from the dissolving of soluble rocks) affects permeabilities (the ability of a porous rock, sediment or soil to transmit water) and bore yields.
- The aquifer is confined (sealed by overlying claystone so that water cannot infiltrate from the land surface into the aquifer) in the north and semi-confined (water can infiltrate from the land surface into the aquifer) in the south, which influences spatial variability in recharge to the aquifer.
- The aquifer discharges (outflow of water from an aquifer into a water body or evaporated from the soil or vegetation) via a combination of discharge to streams, spring discharge, transpiration from spring-fed vegetation, extraction of groundwater and submarine groundwater discharge (outflow of groundwater to the ocean) (Fell-Smith and Sumner, 2011).

Groundwater flow in the aquifer system is complex due to the compartmentalisation of the aquifer, as well as spatial variability in seasonal recharge and groundwater extraction. The productive (high-yielding) part of the dolostone aquifer occurs in the upper (top 10 to 20 m)
weathered, fractured and karstic zone, above the unweathered (solid) dolostone (Figure 2-25). Bore yields are variable given the complex nature of the karstic aquifer, but yields can be up to 60 L/second, with higher yields more prominent in the south (Figure 2-24), and groundwater quality is generally fresh (>500 mg/L) (Figure 2-26). Given the complexities of this high-yielding aquifer, groundwater storage is also highly variable and is reliant on seasonal recharge from intense wet-season rainfall. When poor wet seasons occur (particularly in succession), storage in the aquifer system becomes depleted in places during the dry season (or a prolonged dry season) and bores can run dry (DENR, 2018). For this reason, the aquifer system requires careful management and future opportunities for groundwater resource development may be limited. Furthermore, opportunities for managed aquifer recharge to keep storage in parts of the aquifer at higher levels throughout the dry season have been evaluated as part of the Assessment (Section 5.2).

Figure 2-25 Two-dimensional conceptual schematic of the interconnected aquifer system and its variability
Bore yields vary depending on where a bore is drilled and at what depth.
Adapted from DENR (2016b).

**Limestone and siltstone aquifers**

A small section of the Cambrian age Daly Basin extends into the southern parts of the Finniss and Adelaide catchments just south of the Reynolds River. Two hydrogeological formations, the Tindall Limestone and Jinduckin Formation, are present but their spatial extents are not yet well defined. The Tindall Limestone is predominantly limestone, while the Jinduckin Formation is siltstone with some limestone. Aquifers of both formations are fractured and karstic in nature and host intermediate- to local-scale flow systems, though they are poorly characterised. Groundwater use from the aquifers is currently only for stock purposes, with bore yields ranging up to 25 L/second.
(Figure 2-24), and water quality is fresh (<500 mg/L) (Figure 2-26). These aquifers may offer some potential for future groundwater resource development; however, further investigation is required to understand the scale of opportunity as well as potential constraints.

Figure 2-26 Groundwater salinity for different aquifers in the Darwin catchments
EC = electrical conductivity; TDS = total dissolved solids.
Salinity data sourced from DENR (2016a).

Sandstone aquifers

Sandstone aquifers are mainly located in the north-eastern and north-western parts of the Mary and Wildman catchments, respectively, occurring as Mesozoic to Cenozoic age sandstone (Figure 2-23). A small component of the Bonaparte Basin occurs on the south-western edge of the Finniss catchment and contains Permian age sandstone. Aquifers in the northern Mary and Wildman catchments offer the greatest opportunity for future groundwater resource development in the Darwin catchments. The catchments contain a sand aquifer that is interconnected at depth with an underlying karstic dolostone aquifer (Koolpinyah Dolostone). The sand aquifer ranges in thickness by up to 15 m and occurs as north-east striking palaeochannels (an inactive river or stream channel that has been filled or buried by younger sediment) (Tickell and Zaar, 2017) overlain by mostly younger clayey sediments. The aquifer can be intersected by drilling at depths ranging between 50 and 100 m and the depth to watertable (the start of the saturated zone of an aquifer) ranges between 5 and 10 m below the land surface. Bore yields range up to 60 L/second
and water quality is fresh (<500 mg/L) (Figure 2-26). Recharge to the aquifer system occurs as some infiltration of intense wet-season rainfall through the overlying clay sediments, but mostly as preferential infiltration from rainfall through dolines (funnel-shaped depression caused by dissolving of the dolostone). Groundwater flow is generally towards the coast and discharge is mostly occurring via small springs, stream discharge and shallow watertable evaporation.

A small component of the Bonaparte Basin occurs in a north–south strip on the south-western edge of the Finniss catchment. It contains Permian age sandstone that hosts an aquifer that predominantly consists of fractured and weathered sandstone. The aquifer hosts local- to intermediate-scale flow systems, though they are poorly characterised. Bore yields range up to 10 L/second (Figure 2-24); however, the aquifer is largely untested. Current groundwater use is for stock and domestic purposes, but it was formerly used for local irrigation. The limited spatial extent of the aquifer constrains its potential for future groundwater resource development other than as a localised or conjunctive water resource.

**Surficial aquifers**

Surficial sediments including Tertiary to Quaternary alluvium, laterite and regolith occur predominantly in the northern parts of the Darwin catchments, as well as the western part of the Finniss catchment. Aquifers within these sediments are associated with the numerous rivers, tributaries and their floodplains, as well as laterite sediments. The alluvial aquifers mainly comprise sodic clay, have very low permeability and do not host suitable aquifers for groundwater use. The lateritic aquifers have low storage but high permeability and therefore act as throughflow to recharge underlying aquifers (Fell-Smith and Sumner, 2011). These aquifers offer little potential for future groundwater resource development.

### 2.5.3 GROUNDWATER RECHARGE

Groundwater recharge is an important component of the water balance of an aquifer (i.e. the sum of the inflow and outflow components of an aquifer). It can inform how much an aquifer is replenished on an annual basis and therefore how sustainable a groundwater resource may be in the long term, particularly for aquifers with either low storage or that discharge to rivers, streams, lakes and the ocean, or via transpiration from groundwater-dependent vegetation. Recharge is influenced to varying degrees by many factors including spatial changes in soil type (and their physical properties), the amount of rainfall and evaporation, vegetation type (and transpiration), topography and depth to the watertable. Recharge can also be influenced by changes in land use, such as land clearing and irrigation. Directly measuring recharge can be very difficult as it usually represents only a small component of the water balance, can be highly variable spatially and temporally, and it can vary depending on the type of measurement or estimate technique used (Petheram et al., 2002).

In the Assessment several independent approaches were used to estimate annual recharge for all aquifers in the Darwin catchments. Figure 2-27 provides an example of the recharge estimates.

For more detail on how these estimates were derived, see the companion technical report on hydrogeological characterisation (Turnadge et al., 2018).
Figure 2-27 Annual recharge estimates for the Darwin catchments
Estimates based on up-scaled chloride mass balance (CMB) method for the (a) 50th (b) 5th and (c) 95th percentiles.

Figure 2-28 provides a summary of the range in recharge estimates related to the area of six key hydrogeological units in the Darwin catchments. The range in recharge estimates are based on the 5th and 95th percentiles and range from approximately:

- 80 to 170 mm/year for the Mesozoic to Cenozoic sandstone
- 90 to 190 mm/year for the Cambrian to Ordovician Daly Basin limestone and siltstone
- 140 to 330 mm/year for the Cambrian to Cenozoic Bonaparte Basin sandstone
- 65 to 210 mm/year for the Proterozoic rocks and granite
- 120 to 290 mm/year for the Proterozoic dolostone.

The estimates of groundwater recharge in the Assessment represent the spatial variability in recharge across the land surface and are a good starting point for estimating a water balance.
arithmetically or using a groundwater model. However, none of the methods account for aquifer storage (available space in the aquifer) so it is unclear whether the aquifers can accept these rates of recharge on an annual basis. The methods also do not account for potential preferential recharge from streamflow or overbank flooding, or through karst features, such as dolines and sinkholes that occur across the Darwin catchments. Therefore, the key features of an aquifer must be carefully conceptualised before simply deriving a recharge volume based on the surface area of an aquifer outcrop and an estimated recharge rate.

**Figure 2-28 Summary of recharge statistics to areas of key hydrogeological units**

Error bars represent the standard deviation from the mean. CMB is the chloride mass balance method.

### 2.5.4 SURFACE WATER – GROUNDWATER CONNECTIVITY

As discussed in Section 2.5.2, groundwater discharge to surface water features occurs from a variety of aquifers across the Darwin catchments. In the DRWCD, groundwater discharge occurs as diffuse discharge to some streams, as localised discharge via springs, and as submarine groundwater discharge to the ocean. Diffuse discharge in the north of the DRWCD occurs from a combination of sources including the shallow lateritic aquifer, the intermediate sandstone aquifer and the deeper dolostone aquifer, which are all interconnected. The source of early dry-season discharge is from the shallow to intermediate aquifers, but as groundwater levels recede during the dry-season, it is primarily from the dolostone aquifers. Diffuse discharge provides dry-season baseflow to reaches of the Howard River, Hollands Creek and Melacca Creek (Fell-Smith and Sumner, 2011; SKM, 2012) though these are currently poorly mapped. Discharge to surface water in the south of the DRWCD occurs from the dolostone aquifer at Berry Springs. Here an array of springs including Berry Springs, Parsons Springs and Twin Springs, provide localised discharge to Berry Creek (Williams, 2009). Outside of the DRWCD, diffuse discharge is known to occur from the shallow sandstone and deep dolostone aquifers in the Wildman catchment providing baseflow to tributaries of the Mary River including Opium Creek and Jimmies Creek (Tickell and Zaar, 2017). Spring discharge in both the DRWCD and the Wildman catchment support ecologically significant groundwater dependant ecosystems (GDEs) including spring-fed monsoon Vine Forest (MVF) (Figure 2-29). Key spring-fed MVF patches in the DRWCD include Howards Springs, Bankers Jungle, Black Jungle and Whitewood Swamps (Fell-Smith and Sumner, 2011). In the Wildman catchment, they include patches at Brians Creek Spring, Jimmies Creek Spring and Opium Creek Spring (Tickell and Zaar, 2017). Submarine groundwater discharge is likely to occur from throughflow in the
dolostone aquifer along the northern most boundary at the coast in the DRWCD, though this process is poorly characterised.

Figure 2-29 Spatial distribution of springs and monsoon vine forest patches across the Darwin catchments
Spring data sourced from DENR (2016a).
Monsoon vine forest data sourced from Russell-Smith (1991).

2.5.5 SURFACE WATER

Streamflow
Approximately 60% of Australia’s runoff is generated in northern Australia (Petheram et al., 2010, 2014). Unlike the large internally draining Murray–Darling Basin, however, northern Australia’s runoff is distributed across many hundreds of smaller externally draining catchments (Figure 2-30). Figure 2-30 shows the magnitude of median annual streamflow of major rivers across Australia, prior to water resource development. To place the Darwin catchments in a broader context it is useful to compare their size and the magnitude of their median annual streamflow to other river systems across Australia.
Figure 2-30 Modelled streamflow under natural conditions
Streamflow under natural conditions is indicative of median annual streamflow prior to European settlement (i.e. without any large-scale water resource development/extractions) assuming the historical climate (i.e. 1890 to 2015).
Source: Petheram et al. (2017)

The Darwin catchments comprise four catchments: the Finniss (9488 km²), Adelaide (7462 km²), Mary (8073 km²) and Wildman (4818 km²) (Figure 2-32). Each catchment features extensive flat, tidally affected coastal plains that extend 20 to 60 km inland, typically lie at less than 10 m AHD and are prone to seasonal flooding (Figure 2-31). The Finniss, Adelaide and Mary rivers extend up to 100 km inland with their headwater catchments situated in low bedrock hills, reaching up to 350 m AHD in the south-western part of the Mary catchment. The Wildman catchment is the narrowest of the four catchments; it does not extend as far inland and attains a maximum elevation of about 100 m AHD.

The two major rivers in the study area are the north–south running Adelaide and Mary rivers. Abandoned river courses are common across the coastal plains of both rivers. The tidal limit of the Adelaide River is located at Marrakai Crossing, almost 100 km from the river mouth. In the Mary catchment, barrages were constructed across the river in the 1980s to try and prevent the incursion of saltwater. The current tidal influence extends to the Shady Camp barrage, except during very high tides when seawater can occasionally overtop the barrage.
The mean annual discharge from the Finniss, Adelaide, Mary and Wildman catchments is 4991, 2693, 2575 and 905 GL, respectively. In the Darwin catchments the annual distribution of runoff is more even than other parts of northern Australia; consequently, the difference between the mean and median annual flows is lower. The median annual discharge from the Finniss, Adelaide, Mary and Wildman catchments is 4546, 2354, 2432 and 855 GL, respectively – approximately 90% of their respective mean values. Although the Finniss catchment has the largest median annual discharge of the four Darwin catchments, no large rivers are evident in Figure 2-30 because runoff in the Finniss catchment is distributed across several dozens of small externally draining rivers.

Measuring streamflow in tidally affected streams is challenging. For this reason, the lowermost streamflow gauging stations in the Finniss, Adelaide and Mary rivers are located a considerable distance upstream of their outlets to the ocean (Figure 2-32). Gitchams Crossing (8150180) on the Finniss River is located approximately 73 km inland from the outlet to the ocean, Dirty Lagoon (8170020) on the Adelaide River is approximately 125 km upstream of the river mouth (though flows less than 144 m$^3$/second are still tidally affected at this gauge) and Mount Bundy (Gauge 8180035) on the Mary River is approximately 97 km upstream of the outlet to the ocean. The Wildman River has no current or discontinued streamflow gauging station. Collectively the lowermost streamflow gauging stations in the Finniss, Adelaide and Mary rivers capture about 60% of the area of these rivers or 37% of the entire study area.
Table 2-3 provides a key summary of metrics for all gauging stations in the Darwin catchments. The difference between the mean and median is less pronounced in the Darwin catchments than other parts of northern Australia.

The cease-to-flow column in Table 2-3 indicates the percentage of time that no streamflow was observed at each location of the streamflow gauging stations in the Darwin catchments. Gauges in the upper Mary River have the longest periods of no flow. These gauging stations coincide with the driest part of the Darwin catchments (Figure 2-13a). About 90% of streamflow gauging stations in the Darwin catchments have a baseflow index between 0.15 and 0.25. Smaller baseflow index values are indicative of rivers that rise and fall relatively quickly. In these river reaches the time over which water can be extracted is limited and a large water pumping capacity may be required to maximise the reliability of extracting a full allocation of water. This is discussed in more detail in Section 5.3 and in the companion technical report on river model simulation (Hughes et al., 2018).
Table 2-3 Streamflow metrics at gauging stations in the Darwin catchments under Scenario A

Annual streamflow data are calculated under Scenario A. These data are shown schematically in Figure 2-33 and Figure 2-35. 20th, 50th and 80th refer to the 20%, 50% and 80% exceedance, respectively. Cease-to-flow determined using observed data, where streamflow less than 0.1 ML/day was assumed to be equal to zero. Baseflow index was calculated using observed data and the Lyne and Hollick method (1979) (using alpha value equal to 0.925).

<table>
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<th>STATION ID</th>
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<th>ANNUAL STREAMFLOW (GL)</th>
<th>CEASE-TO-FLOW (%)</th>
<th>BASEFLOW INDEX</th>
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<td>8150010</td>
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<td>8150097</td>
<td>East Finniss River at Railway Crossing</td>
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<td>100 51 35 22 5</td>
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<td>8150200</td>
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</tr>
<tr>
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<tr>
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<td>5 36</td>
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</table>

Figure 2-33 shows how median annual streamflow increases towards the coast in the Darwin catchments. The Adelaide River is shown in Figure 2-34. As an indication of variability Figure 2-35 shows the 20% and 80% exceedance of annual streamflow in the Darwin catchments.
Figure 2-33 Median annual streamflow (50% exceedance) in the Darwin catchments under Scenario A

Figure 2-34 Adelaide River at the potential Marrakai dam site looking upstream during the dry season
Photo: CSIRO
Figure 2-35 20% and 80% exceedance of annual streamflow in the Darwin catchments under Scenario A

Figure 2-36 and Figure 2-37 illustrate the decrease in catchment area and increase in elevation along the Adelaide and Mary rivers, respectively, from their mouths to their sources. The large ‘step’ changes in catchment area are where major tributaries join the rivers. These figures highlight the flatness of the floodplains of the Adelaide and Mary rivers.

Figure 2-36 Catchment area and elevation profile along the Adelaide River from its mouth to its source
Catchment runoff

The simulated mean annual runoff averaged over the Darwin catchments under Scenario A is 416 mm. Figure 2-38 shows the spatial distribution of mean annual rainfall and runoff under Scenario A (1890 to 2015) across the Darwin catchments. Mean annual runoff broadly follows the same spatial patterns as mean annual rainfall; runoff is highest in the north-west of the study area and lowest in the south-east. The certainty of runoff is lowest on the coastal plains below the lowermost gauging stations.

Mean monthly and annual runoff data in the Darwin catchments exhibit less variation from one year to the next compared to other parts of northern Australia. The annual runoff at 20%, 50% (median) and 80% exceedance averaged across the Darwin catchments is 590, 397 and 232 mm, respectively (Figure 2-39). That is, runoff spatially averaged across the Darwin catchments will exceed 590 mm 1 year in 5, 397 mm half the time and 232 mm 4 years in 5. Figure 2-39 shows the spatial distribution of the annual runoff at 20%, 50% and 80% exceedance under Scenario A.

Intra- and inter-annual variability in runoff

Rainfall, runoff and streamflow in the Darwin catchments are variable between years but also within years. Approximately 82% of all runoff in the Darwin catchments occurs in the 3 months from January to March, which is very high compared to rivers in southern Australia (Petheram et al., 2008). Unlike many parts of northern Australia, the major rivers and tributaries in the mid-to-lower reaches of Darwin catchments are perennial (Table 2-3). Figure 2-40b illustrates that during the wet season there is a high variation in monthly runoff from one year to the next. For example, during the month of March, in 20% of years mean runoff exceeded 184 mm and in 20% of years it was less than 47 mm. The largest catchment average annual runoff under Scenario A was 1195 mm in 2010–11 and the smallest catchment average annual runoff under Scenario A was 43 mm in 1905–06 (Figure 2-40a). The CV of annual runoff in the Darwin catchments is 0.5. Based on data from Petheram et al. (2008) the variability in runoff in the Darwin catchments is low compared to the annual variability in runoff of other rivers in northern and southern Australia with a comparable mean annual runoff.
Figure 2-38 Mean annual rainfall and runoff across the Darwin catchments under Scenario A
Pixel scale variation in mean annual runoff figure is due to modelled variation in soil type.

Figure 2-39 Maps showing annual runoff at 20%, 50% and 80% exceedance across the Darwin catchments under Scenario A
Pixel scale variation in mean annual runoff figure is due to modelled variation in soil type.
Flooding

Widespread flooding occurs on the coastal plains of the Darwin catchments, reducing considerably in extent with distance inland (Figure 2-41). Figure 2-33 and Figure 2-35 show a large proportion (40%) of the runoff in the Darwin catchments is generated on the coastal plains and surrounding land.

Flooding can be catastrophic to agricultural production in terms of loss of stock, fodder and topsoil, and damage to crops and infrastructure; it can isolate properties and disrupt vehicle traffic. However, flood events also provide opportunity for offstream wetlands to be connected to the main river channel. The high biodiversity found in many unregulated floodplain systems in northern Australia is thought to largely depend on flood events, which allow for biophysical exchanges to occur between the main river channel and wetlands.

 Unless otherwise stated, the material in this section is based on findings described in the companion technical report on flood mapping and modelling (Karim et al., 2018).

Figure 2-42 indicates the spatial extent and temporal variation of inundation on the coastal floodplains of the Darwin catchments for selected flood events, based on computer model simulations (see Karim et al., 2018). Where introduced pastures are inundated with stagnant water for a period greater than 5 consecutive days, the above-ground biomass may die; this may extend to 2 weeks if the water is aerated. Where the period of inundation is greater than 20 consecutive days, the entire plant may die. This does, however, vary between pasture species.
Further observations of flooding under the historical climate in the Darwin catchments are as follows:

- Average flood peak propagation speeds along the Adelaide River are slow due to the low relief and tidal influence (approximately 0.5 km/hour), with the flood peak taking 5 to 7 days to travel from Adelaide River town to the Arnhem Highway.

- For flood events of AEP 1 in 5, 1 in 10 and 1 in 20 the peak discharge at Dirty Lagoon on the Adelaide River was 1540, 1920 and 2520 m³/second, respectively.

- Between 1981 and 2015 (35 years) events with a discharge greater than or equal to AEP 1 in 1 occurred during all months between December and April, with about 85% of events occurring between January and March. Of the ten events with the largest flood peak, one event occurred during December, two in January, three in February, three in March and one in April.

Figure 2-41 Flood inundation map of the Darwin catchments
Data captured using MODIS satellite imagery. This figure illustrates the maximum percentage of MODIS pixel inundated between 2000 and 2015.
In the Darwin catchments, the maximum area inundated during events of AEP 1 in 3 (2001) and AEP 1 in 14 (2006) was 1145 and 1583 km², respectively. Downstream of the Arnhem Highway, coastal floodplains can be inundated for long periods of time due to the low relief (Figure 2-36 and Figure 2-37) and tidal influence. For an event of AEP 1 in 30 (2014), parts of the coastal floodplains were inundated for more than 20 days. Due to the low flood propagation speeds and
low relief the average connectivity of wetlands to the main river channel was relatively long, about 12 days for an event of AEP 1 in 3 (2001) and 13 days for an event of AEP 1 in 14 (2006). Larger floods had longer periods of connectivity between the main river channel and offstream wetlands. However, variation in local runoff and the shape of the inflow hydrograph (e.g. single or multiple peaks) had a strong influence on the duration of connectivity.

**Relationship between streamflow, inundation area and flood frequency in the Adelaide River floodplain**

A strong relationship is observed between peak flood discharge at gauge 8170020 and maximum inundated area of the Adelaide River floodplain. This relationship enables maximum inundated area to be estimated from streamflow data (Figure 2-43a). Figure 2-43b shows the relationship between peak flood discharge and annual exceedance probability (AEP). These two figures can be used together to estimate the AEP of maximum inundated areas. For example, Figure 2-43a shows the maximum inundated area of 800 km² corresponds to a peak flood discharge of about 1000 m³/second, which in turn corresponds to an AEP of 20% (or 1 in 5 years) (Figure 2-43b). Hence, a maximum inundated area of 800 km² is exceeded in 20% of years.

![Figure 2-43 Relationships between peak flood discharge, maximum inundated area and annual exceedance probability](image)

(a) Peak flood discharge at gauge 8170020 (Dirty Lagoon) and maximum inundation area of Adelaide River floodplain and (b) peak flood discharge and annual exceedance probability at gauge 8170020.

**Instream waterholes during the dry season**

Unlike many parts of northern Australia, the rivers in the Darwin catchments are perennial in their mid-to-lower reaches (Figure 2-44). In ephemeral reaches, such as the Mary River above its confluence with the McKinley River, and its tributaries, once streamflow has ceased the rivers break up into a series of waterholes during the dry season. Waterholes that ‘persist’ from one year to the next are considered to be key aquatic ‘refugia’ and are likely to be sustaining ecosystems in the Darwin catchments (Section 3.2). In some reaches waterholes may be partly or wholly sustained by groundwater discharge (Section 2.5.4). However, in other reaches there is little evidence that ‘persistent’ waterholes receive water from groundwater discharge and are likely to be replenished following wet-season flows.

The ecological importance and functioning of key aquatic refugia are discussed in more detail in the companion technical report on ecology (Pollino et al., 2018).
The formations of waterholes following a cease-to-flow event were captured using satellite imagery for a reach of the Flinders River in northern Australia (Figure 2-44). Figure 2-46 maps 1-km river reaches/segments where water is recorded in greater than 90% of dry-season satellite imagery. It provides an indication of those river reaches containing permanent water.

**Figure 2-44 Instream waterhole evolution**

This figure shows the area of waterholes at a given time after flow ceased and the ability of the water index threshold to track the change in waterhole area and distribution.

Figure 2-45 shows a persistent waterhole in the Darwin catchments.

**Figure 2-45 Persistent waterhole in the Darwin catchments**

Photo: CSIRO
Figure 2-46 Location of river reaches containing permanent water in the Darwin catchments
Persistent river reaches are defined as 1-km river reaches where water was identified in greater than 90% of the dry-season LandSat imagery between 1989 and 2015. Mapping of persistent river reaches is confounded by riparian vegetation in the Darwin catchments.

Streamflow forecasting
The Bureau of Meteorology (BoM) offers seven-day streamflow forecasting and seasonal streamflow forecasting services. The skill of streamflow forecasting largely depends on knowledge of antecedent catchment conditions and skill of forecast rainfall and/or climate indicators.

Seven-day streamflow forecasting is currently offered by the BoM in the Darwin catchments at the Railway Bridge on Adelaide River (8170002). At this location there is a reasonable level of skill at simulating daily streamflow with a one-day lead time, however, the skill reduces considerably thereafter (see companion technical report on climate (Charles et al., 2016)). Seven-day streamflow forecasting skill is likely to be higher over longer lead times at locations lower in the catchment (e.g. Dirty Lagoon) due to the larger catchment area and the slow flood propagation speeds downstream of Adelaide River town.
During December there is a moderate level of skill at forecasting total streamflow volume in the Darwin catchments for the January to March period (Charles et al., 2016).

While annual rainfall is not always reliable and seasonal forecasting moderate, important information about water availability (i.e. soil water and water in dams at the end of the wet season) is often available when it is most important agriculturally – before planting time for most crops.

**Surface water quality**

Interpreting patterns and trends in water quality data from rivers in the Darwin catchments is confounded by variations arising from spatial and temporal patterns in rainfall and streamflow. General observations based on intermittent water quality measurements between the mid-1970s and 2003 are as follows:

- In the Finniss catchment observed water quality downstream of the Rum Jungle uranium mine, which closed in 1971, has been poor. Heavy metal concentrations, in particular, have been measured as exceeding drinking water quality standards (NHMRC, 2011).

- Samples collected in close proximity to the Rum Jungle mine had particularly elevated concentrations of heavy metals. For example, total lead sampled at the Gitchams Crossing streamflow gauge (8150180) often exceeded safe drinking water thresholds during the 1970s and early 1980s. More recent data from this site were not identified. Where catchments are larger and streamflow is higher, surface water quality in the Darwin catchments appears to be better than the levels recommended by drinking water quality standards. This is likely to be due to dilution with better quality water.

- Recent sampling in the Adelaide catchment by Power and Water Corporation focused on sites that have potential for urban and industrial water extraction, or were identified as being sites with potentially high concentrations of metals and sediments (PWC, 2016). Results show no notable water quality issues for irrigated agriculture or potable use in the larger rivers of the Adelaide catchment.

- In the Mary catchment surface water quality at the Mount Bundey streamflow gauge (8180035) is acceptable with respect to drinking water quality standards. Sample concentrations for total nitrogen, phosphorus, lead, arsenic and copper were all within acceptable levels.

- No surface water quality measurements were available for the Wildman catchment.

### 2.6 References


Marsden Jacob Associates (2012a) Socio-economic assessments to inform water resource planning in the Darwin region: Howard East Water Allocation Planning Area (HEWAPA). Report prepared for the Northern Territory Department of Natural Resources, Environment, the Arts and Sport.

Marsden Jacob Associates (2012b) Socio-economic assessments to inform water resource planning in the Darwin region: Berry Springs Water Allocation Planning Area (BSWAPA). Report prepared for the Northern Territory Department of Natural Resources, Environment, the Arts and Sport.


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Chapter 3 discusses a wide range of considerations relating to the living component of the catchment and the environments that support these components, the people who live in the catchment or have strong ties to it, the perspectives of investors, the existing transport, power and water infrastructure and the legal, policy and regulatory environment relating to the development of land and water.

The key components and concepts of Chapter 3 are shown in Figure 3-1.

Figure 3-1 Schematic diagram of key components of the living and built environment to be considered in the establishment of a greenfield irrigation development
3.1 Summary

This chapter provides information on the living and built environment including information about the people, the ecology, the infrastructure and the institutional context of the Darwin catchments. It also examines the values, rights, interests, and development objectives of Indigenous people.

3.1.1 Key Findings

Ecology

The Darwin catchments support a diverse range of flora and fauna that are fundamentally adapted to the seasonal wet-dry climate (Warfe et al., 2011). Seasonal flows of the Darwin catchments underpin river-floodplain productivity and provide critical habitats for species (Warfe et al., 2013). These flows also support a range of fish species, including the freshwater sawfish (*Pristis pristis*) (listed as vulnerable under the *Environment, Protection and Biodiversity Conservation Act 1999* (Cth) EPBC Act) and a commercial and recreational barramundi (*Lates calcarifer*) fishery.

The intact landscapes of the Darwin catchments provide ecosystem services that support the water supply of Darwin, recreational activities, tourism, and some areas of agricultural production. The study area also supports some of northern Australia’s most iconic wildlife species, such as saltwater crocodiles (*Crocodylus porosus*), magpie geese (*Anseranas semipalmata*) and barramundi, as well as many lesser-known plants and animals that are also of great conservation significance. Five of the 33 wetlands in the NT listed on the Directory of Important Wetlands in Australia are found in the Darwin catchments (Environment Australia, 2001).

The richness of biodiversity in the study area is attributed to the integrity, extent and heterogeneity of its wetland habitats (Department of Land Resource Management, 2015; Environment Australia, 2001). This includes a high fish biodiversity, with the Finniss River having had 46 fish species recorded, the Adelaide River 44, the Mary River 34 and the Wildman River 22. There is also high fish endemism, and there are a number of rare species in the study area.

In the dry season, waterholes provide crucial refugia in an otherwise dry landscape and allow plants and animals to colonise areas in the wet season. In the wet season, flows also lead to a boost of productivity with the addition of carbon and nutrients draining from the landscape. Changes in land and water resources can have serious consequences for the ecology of rivers (Bunn and Arthington, 2002). Flow change can also facilitate or exacerbate impacts, including the spread of invasive species and changes to water quality, particularly in the availability and distribution of nutrients (Olden et al., 2008).

Demographics, industries and infrastructure

The population of the Darwin catchments is about 140,000, of whom 98% live within the Greater Darwin area. Unemployment (4.7%) is below the national mean (6.9%) and socio-economic advantage is similar to the rest of the country. The main land uses are for conservation (53%) and grazing (37%, including modified pastures). The gross value of agricultural production (GVAP) in the Darwin area is approximately $136 million (ABS, 2017; NT Farmers Association, 2016). Cropping accounts for about 90% of the GVAP ($123 million), mostly from fruit, vegetables and hay (NT Farmers Association, 2016). Beef cattle contribute around $13 million to GVAP (ABS, 2017).
Outside the Darwin urban footprint, the study area is characterised by a sparse network of major roads, with the Stuart Highway being the main access to Darwin from the south. Except for urban roads in Darwin and other towns, all roads within the Darwin catchments permit Type 2 road trains, which are vehicles up to 53 m in length. Darwin Port is also accessible by these road trains. The Darwin catchments have a good quality standard gauge rail line, providing freight access to the port. From 2000 to 2004 the line was extended from Alice Springs to Darwin Port (East Arm), providing rail access to the southern states. The rail line is primarily used for bulk commodity transport (mostly minerals) to Darwin Port. Electricity in the Darwin catchments is supplied by four main power stations and delivered via the Darwin-Katherine Interconnected System (DKIS). Darwin River Dam currently supplies 85% of the urban water demand and the McMinns and Howard East Borefields in the Darwin Rural Water Control District (DRWCD) area currently supply on average 15% of urban water demand (Power and Water Corporation, 2015a).

**Social and investor values**

The diverse stakeholders in the Darwin catchments sometimes have conflicting interests and values relating to the use of water resources and irrigated agricultural development. This has implications for the ability of developers to gain and maintain social licence to operate through the development process. Stakeholder values relate to the purpose of development, the environmental conditions and ecosystem services that development may alter, how stakeholders are engaged, and to whom benefits accrue. Systematic social impact analysis that investigates stakeholders and their interests will be needed for development at scale. A survey of potential agricultural investors identified that they perceived institutional certainty, simplicity and bureaucratic speed as the key enablers of investment in irrigated agriculture. There was less consistency between investors regarding other enablers of irrigated development.

**Indigenous values and development objectives**

Indigenous people have recognised native title and cultural heritage rights, and control significant natural and cultural resource assets, including land, water, and coastline. Understanding key aspects of pre-colonial and post-colonial patterns of land and natural resource use in the Darwin catchments is important to understanding both present circumstances and Indigenous responses to future possibilities. Indigenous people have strong expectations for involvement in water, catchment, and development planning. Indigenous people have a range of existing business development plans and objectives that may be impacted by development proposals. They wish to be crucial owners, partners, investors, and stakeholders in future development.

**Legal, policy and regulatory environment**

Government powers and responsibilities concerning the management of land and water resources in the Darwin catchments are shared. The Australian Government oversees native title and the implementation of international law obligations. The Northern Territory Government manages land and water assets. Land in the Darwin catchments is primarily held as Crown leasehold land or reserves, national parks, and freehold land, with much of the catchment also subject to native title, a unique form of property interest that consists of a bundle of rights defined by the laws and customs of the relevant Indigenous community. The rights to the use, flow and control of all water in the NT are vested in the Northern Territory Government, who controls the processes for water planning, the regulation of taking and interference with water, and the construction and operation
of water infrastructure (e.g. dams, bores, levies and pipes). Land owners' rights to use and develop land are limited by government regulations. The most relevant government regulations are those imposed under federal and state planning, environment and heritage statutes. Analysis of 36 recent development proposals (only three that were for agriculture or aquaculture), showed that the median length of the total assessment time under the *Environmental Assessment Act* (NT) was 517 days, with an average of 784 days. A similar analysis of eight proposals in the Northern Territory under the *EPBC Act* found that the median time of the assessment and approval process was 511 days.

3.1.2 INTRODUCTION

This chapter seeks to address the question ‘What are the existing: ecological systems; the demographic and economic profile; the land use, industries and infrastructure, stakeholder values and investor perspectives; the values, rights, interests and development objectives of Indigenous people; and the legal, policy and regulatory environment in which development would occur in the Darwin catchments?’

The chapter is structured as follows:

- Section 3.2 examines the ecological systems and assets of the Darwin catchments including the key habitats and key biota, and their important interactions and connections.
- Section 3.3 examines the socio-economic profile of the Darwin catchments including the current demographics and existing industries, and infrastructure of relevance to water resource development.
- Section 3.4 examines the stakeholders, their values and potential engagement strategies and the perspectives of potential investors in the Darwin catchments.
- Section 3.5 examines the Indigenous values, rights, interests, and development objectives of Traditional Owners from the Darwin catchments, generated through direct participation in the Assessment.
- Section 3.6 examines the legal, regulatory and policy environment relevant to water-related development.

3.2 Ecology of the Darwin catchments

3.2.1 INTRODUCTION

The catchments of the north-western portion of the NT encompass a variety of landscapes and ecosystems including the Arnhem Land plateau, undulating hills, coastal plains and coastal saline environments such as mangroves. These are some of northern Australia’s most iconic landscapes and their ecosystems support a great diversity of species and communities. A large part of the Darwin catchments consists of intact, more or less functioning natural landscapes and ecosystems. These intact landscapes are important for the ecosystem services they provide, including the water supply of Darwin, recreational activities, tourism, and some areas of agricultural production, notably cattle grazing on native pastures. In addition, they hold important ecological and environmental values (Figure 3-2). The study area supports large populations of some of northern
Australia’s most iconic wildlife species, such as saltwater crocodiles, magpie geese and barramundi, as well as many lesser-known plants and animals that are also of great conservation significance. Five of the 33 wetlands of national significance in the NT are found in the Darwin catchments (Environment Australia, 2001). The richness of biodiversity in the study area is attributed to the integrity, extent and heterogeneity of its wetland habitats (Department of Land Resource Management, 2015; Environment Australia, 2001).

The Finniss catchment features a number of areas and wetlands of conservation significance, including:

- Finniss River Coastal floodplain, which supports breeding for waterbirds, magpie geese and saltwater crocodiles and is a habitat for threatened species such as the great knot (\textit{Calidris tenuirostris}), eastern curlew (\textit{Numenius madagascariensis}) and marine turtles (members of the super family Chelonioidae) (Northern Territory Government, 2009).
- Fog Bay, which supports migratory shorebirds and marine turtles, many of which are threatened (Northern Territory Government, 2009).
- Darwin Harbour, which has extensive and diverse mangrove areas, supporting specialised bird species. There are also extensive mudflat areas and the harbour supports a diverse range of marine species including dugongs (\textit{Dugong dugon}), dolphins (members of the family Delphinidae), marine turtles (members of the super family Chelonioidae) and a large variety of fish. The harbour is habitat for threatened species such as the curlew sandpiper (\textit{Calidris ferruginea}), red goshawk (\textit{Erythrotriorchis radiates}), flatback turtle (\textit{Natator depressus}) and floodplain monitor (\textit{Varanus panoptes}) (Northern Territory Government, 2009).
- The upper Finniss catchment also has a legacy mining site, the Rum Jungle mine.

The Adelaide catchment features the coastal floodplain of the Adelaide River, which is a large seasonally-inundated freshwater floodplain, and features a mix of wetland, grass and sedge, and open woodland communities, with pockets of monsoon forest. This floodplain provides breeding habitat for waterbirds, including magpie geese. Mangroves are found in the lower reaches of the Adelaide River as are migratory shorebirds utilising wetlands and mudflats. The floodplain is habitat for threatened species, including the northern quoll (\textit{Dasyurus hallucatus}), plain death adder (\textit{Acanthophis hawkei}) and Gouldian finch (\textit{Erythrura gouldiae}) (Northern Territory Government, 2009).

The Mary catchment features the coastal floodplain of the Mary River, which is a mix of dry and wet habitats that support waterbirds, magpie geese and is a breeding area for barramundi. This floodplain is habitat for threatened species, including the brush-tailed rabbit-rat (\textit{Conilurus penicillatus}) and the bar-tailed godwit (\textit{Limosa lapponica}). There are barrages in place to prevent saltwater intrusion into the freshwater wetland systems (Northern Territory Government, 2009).

The Wildman catchment neighbours and incorporates part of Kakadu National Park, which contains a diversity of wetlands, habitats and species. It is a Ramsar-listed wetland and provides habitat for more than 75 threatened species.
The Adelaide and Mary River coastal floodplain systems are recognised as an important breeding area for waterbirds and crocodiles, and are among the most important breeding sites for magpie geese in Australia (SKM, 2009). About 27% of the Darwin catchments is protected within national parks and reserve systems (Department of Land Resource Management, 2015). Protected areas include Litchfield National Park (Finniss River), Djukbinj National Park (Adelaide River) and Mary River National Park (Mary River). In total, 53% of the catchments are conservation lands or other natural environments.

The Darwin catchments include both highly modified urban and agricultural landscapes and large areas of intact landscapes with a distinctive wet-dry tropical climate, as well as the downstream marine environment to which they are connected. The Darwin catchments discharge into the Arafura and Timor Seas and so their condition influences the ecological and economic values of these marine environments.

Coastal floodplains, mangroves and mudflats are characteristic habitats at the end of the Darwin catchments (Territory Natural Resource Management, 2016). Within the NT, mangroves are
considered to be unusually diverse and extensive (Woinarski, 2004). Important inland habitats throughout the catchments include extensive floodplains, wetlands and inchannel waterholes, riparian zones and groundwater-dependent monsoon forests (Warfe et al., 2010). The extensive floodplain wetlands support aquatic fauna, including waterbirds, fish invertebrates, crocodiles, frogs and turtles (Figure 3-1). Seasonal flooding of the Darwin catchments sustains off-river wetlands and leads to a boom in productivity, while the groundwater baseflow maintains permanent waterholes as important refuge habitat (Warfe et al., 2011). Many permanent waterholes through the river systems are also in part replenished by groundwater, with the waterholes creating refugia in the dry season. Floodplains provide an important source of nutrients for a sub-set of fish species, including those feeding on benthic algae (Douglas et al., 2005). Fish, crayfish, prawns and shrimps access carbon from the floodplain as a source of energy. In turn, these animals are an important food source for large predators, particularly in waterholes during the dry season (Douglas et al., 2005).

The NT has a relatively simple patterning of vegetation over large areas, but with localised variation (Woinarski et al., 2005). Examples of this variation are the highly diverse monsoon forest patches, comprising only a small area (Woinarski et al., 2005). Spring-fed monsoon forests are of high conservation value in the Wildman catchment and are vulnerable to increased use of groundwater resources. Riparian zones are another vegetation variant and are represented as only narrow strips that have high biodiversity and productivity. Riparian zones are rich in birdlife (Woinarski et al., 2000) and are sensitive to changes in both surface water and groundwater regimes (Pusey and Kennard, 2009). Melaleuca forests and woodlands occur in seasonally-inundated areas, especially on the floodplains of the lower reaches of major river systems (Woinarski, 2004).

The Darwin catchments also have a high fish biodiversity. The Finniss River has had 46 fish species recorded, the Adelaide River 44, the Mary River 34 and the Wildman River 22 (Burrows, 2008). With further survey effort, it is anticipated that further species would be found (Burrows, 2008). The Darwin catchments have high fish endemism within northern Australia (Hermoso et al., 2011). There are a number of rare species in the study area including some with disjointed distributions on the tip of Cape York and the Fly River in Papua New Guinea.

Of the rarer Australian species a tongue sole (*Cynglossus heterolepis*) and an eel-tailed tandan (*Porochilus obbesi*) have been found in the Adelaide River; a halfbeak (*Zenarchopterus spp.*) and a circumspect goby (*Glossogobius circumspectus*) have been recorded from the Finniss River catchment; while a rare rainbowfish (*Melanotaenia exquisita*) is present in the region and is most abundant in the Mary River catchment (Pusey et al., 2017). The Darwin catchments also have the highest Australian records of the nursery fish (*Kurtis gulliveri*), a peculiar animal which has a hook on its head upon which the embryos sit prior to hatching. Lorentz grunter (*Pingalla lorentzi*) is a narrowly distributed freshwater fish in Australia, being found in the Finniss catchment, though it is extremely rare there relative to its populations on Cape York (Pusey et al., 2017). Elasmobranch fauna has not been closely investigated in the Darwin catchments, nevertheless, there are records of freshwater sawfish, freshwater whipray (*Urogymnus dalyensis*) and bull sharks (*Carcharhinus leucas*) (Allen et al., 2002; Last and Stevens, 2009). The Adelaide River is also habitat for the speartooth shark (*Glyphis glyphis*) and the northern river shark (*Glyphis garricki*), which are listed as critically endangered and endangered respectively under the EPBC Act (Burrows, 2008).
Freshwater fishes perform central ecological functions and structure ecological communities within floodplain river ecosystems (Jardine et al., 2012). In the Darwin catchments there are several species of large-bodied diadromous species (species that migrate between freshwater and seawater) that provide the basis for recreational and subsistence fisheries, and are of cultural significance (Bayliss et al., 2014; Close et al., 2014; Ebner et al., 2016). In the absence of definitive local studies of fish ecology in the study area, the movement and migration ecology of the fish fauna is perhaps best inferred from research in the Alligator Rivers region. This research revealed considerable seasonal migration between lowland floodplain and main channel habitats (Bishop et al., 1990). As with fish assemblage studies in all northern Australian river systems since, wet-season related connectivity of aquatic habitats is an important driver of fish assemblage dynamics.

Species such as barramundi, threadfin salmon (*Polydactylus sheridani*) and mudcrab (*Scylla serrata*) are particularly important to commercial and cultural fisheries, and they also support recreational fishing (Bayliss et al., 2014). Other significant fauna in the Darwin catchments include saltwater and freshwater crocodiles, Australian snubfin dolphins (*Orcaella heinsohni*) and the pig-nosed turtle (*Carettochelys insculpta*). The ecology of many of these species is highly dependent on the quality and quantity of water resources, and maintenance of habitat complexity.

The NT has the world’s largest intact savanna ( Territory Natural Resource Management, 2016) and about 20% of Australia’s eucalypt forests and woodlands, with low clearing rates (Woinarski, 2004), although there are some areas of clearing in the Darwin catchments (Ziembicki et al., 2014). Dry-season fires are a feature of tropical savannas of northern Australia, with the northern half of the NT being burnt annually or biennially (Williams et al., 1999). Low-frequency, high-intensity fires cause high mortality of trees, unlike low-intensity, high-frequency fires (Williams et al., 1999). The riparian zone is particularly sensitive to fire, far more so than the surrounding savanna (Douglas et al., 2015).

To describe the ecology of the Darwin catchments and discuss the likely impacts of future water resource development on this system, ecological assets have been selected. This chapter considers a key sub-set of assets, as shown in Table 3-1. More information on catchment assets and their distribution is available in the companion technical reports on ecology (Pollino et al., 2018a, 2018b). In Chapter 7, models are used to explore the potential of change to these assets, as a consequence of changes in flow. Please refer to Figure 3-1 for the spatial distribution of important areas for conservation (protected areas and important wetlands).
Table 3-1 Asset types and asset names in the Darwin catchments
All assets listed in this table are detailed in the companion technical reports on ecology (Pollino et al., 2018a, 2018b). Assets are water dependent on either surface water flows or groundwater, resulting in either periodic or sustained inundation. Assets consist of species of significance, functional groups, important habitats or ecosystem processes. An asterisk (*) represents assets included in analysis (see Chapter 7.5). Barramundi and sawfish are considered freshwater assets as the asset analysis only considers the freshwater stage of their life cycle.

<table>
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<tr>
<th>CATEGORY</th>
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<td>Riparian vegetation *</td>
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<td>Stable flow spawners *</td>
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<td>Turtles / Long-necked turtles</td>
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<td>Barramundi*</td>
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<td>Freshwater whipray</td>
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<td>Banana prawns *</td>
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<td>King threadfin*</td>
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<td>Saltwater crocodile</td>
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3.2.2 CURRENT CONDITION OF THE DARWIN CATCHMENTS

The Darwin catchments reflect enormous diversity, in terms of their landscapes, the ecological and environmental assets that they encompass, the economic enterprises that they support and the nature and extent to which they have been modified by human activity.

The study area includes Darwin, the NT’s largest urban area. Other parts of the catchments have also been modified for agricultural development. While a very large proportion of the Darwin catchments are under conservation reserves in very good environmental condition, the region does face significant environmental threats.
One of the most significant threats to the environment and ecosystems of the Darwin catchments comes from invasive plant species. The northern section of the NT has been subject to invasion by several Weeds of National Significance as well as numerous other recognised weeds. Particularly noteworthy are the invasions of wetlands by olive hymenachne (*Hymenachne amplexicaulis*) and mimosa (*Mimosa pigra*). These, along with para grass (*Urochloa mutica*) and Aleman grass (*Echinochloa polystachya*), have radically altered the composition, structure and function of floodplain environments, especially on the Adelaide River floodplain. Terrestrial environments have also been subject to plant invasions with perhaps the most important being that by gamba grass (*Andropogon gayanus*). This species is continuing to invade woodland environments and radically alter the composition of both the ground and tree layers of the vegetation through sequestration of resources and increasing the intensity of fires.

Feral animals have also had major impacts on the ecosystems of the Darwin catchments. Large numbers of water buffalo (*Bubalus bubalis*) and feral pigs (*Sus scrofa*) have increased levels of physical disturbance in wetlands and monsoon vine forests and, especially in wetlands, the activities have led to changes in the composition, structure and function of the vegetation. Cane toads reached the Darwin region as recently as 2005 with significant negative consequences for native wildlife, particularly native carnivores such as the northern quoll.

Most river systems of the Darwin catchments are largely unregulated. Water supply infrastructure for Darwin includes two dams, the Darwin River Dam on the Darwin River, and Manton Dam, on a tributary of the Adelaide River. Otherwise the region’s water supply comes from groundwater sources and the drawdown from these sources can affect natural springs and waterholes in creeks and rivers. Historical mining activity has resulted in some contamination of water sources, notably in the east branch of the Finniss River as a result of uranium and copper mining at Rum Jungle up until 1971. Saltwater intrusion into formerly freshwater wetlands of the lower Mary River floodplain has been reported since the 1940s, a change attributed to several factors, including overgrazing and other activity by feral water buffalo (Applegate, 1999).

Since the 1970s numerous land resource surveys (e.g. Fogarty, 1980; Fogarty et al., 1979; Lynch and Manning, 1998; Mangion and Parkinson, 2012; Napier and Steen, 2002; Olsen, 1985) covering approximately 70% of the Darwin catchments and undertaken in urban, agricultural, pastoral and conservation lands, have consistently reported concerns over the potential for, and management of, soil erosion. Key concerns include granitic soils in drainage depressions within the lower Finniss catchment, particularly where these soils have been cleared (Hill et al., 2002), yellow earths within the upper Adelaide catchment (Forster and Fogarty, 1975), and coarse granitic sands, fine siltstone ‘bulldust’ earths and sodic soils of the upper Mary River catchment (Napier and Steen, 2002).

### 3.2.3 KEY HABITATS

Northern Australia contains rivers with highly seasonal flow regimes that support a diversity of habitats. These habitats require flows across the flow regime and are key for breeding, supporting juvenile aquatic animals, foraging and refuge. Habitats of significance in the Darwin catchments that can potentially be impacted by agricultural and water resource development are described below.
Waterholes and wetlands

During the dry season, many ephemeral rivers of northern Australia cease to flow but retain water in a series of disconnected instream waterholes (McJannet et al., 2014; Waltham et al., 2013). The waterholes that remain during the dry season are an important cultural resource and provide a range of ecosystem functions (Centre of Excellence in Natural Resource Management, 2010; McJannet et al., 2014). For example, at the landscape scale, the number of waterholes and their connectivity allows for movement of biota across the landscape (Department of Environment and Resource Management, 2010). While at the local scale, the size of waterholes confers water-dependent species a refuge in periods without surface flows (Department of Environment and Resource Management, 2010). Permanent waterholes retain water during the dry season, with some being maintained or supported by groundwater inputs. See Section 2.5 (Figure 2-46) for the distribution of permanent waterholes in the Darwin catchments.

During dry-season low-flow or cease-to-flow periods, the size, quality and connectivity of waterholes remaining within the landscape decreases (Department of Environment and Resource Management, 2010; McJannet et al., 2014). Waterholes are typically surrounded by riparian vegetation, which offer shade and structural diversity, and act as an interface between aquatic and terrestrial ecosystems, supporting high biodiversity. Changes in the flow regime associated with water resource development, surface and groundwater extraction and climate change have the potential to alter the natural filling and drying cycles of waterholes as well as water quality, including turbidity (McJannet et al., 2014; Waltham et al., 2013). Changes in waterhole permanence could have impacts on the plants and animals at a local scale and on habitats across regional landscapes.

The extensive wetlands of northern Australia are highly productive. Aquatic production in tropical rivers is primarily driven by hydrology and the annual flooding that occurs (Pettit et al., 2017) and this cycle influences the availability of nutrients within rivers and the coastal zone (Junk et al., 1989), providing a boost to the overall annual energy budget. In rivers, this supports huge biomasses of fish and invertebrates, and large bird breeding events. Prolonged inundation of wetlands promotes the productivity and biomass of aquatic vegetation (Finlayson, 1991; Pettit et al., 2011; Warfe et al., 2011), which provides important habitat for aquatic fauna.

The floodplains of the Darwin catchments are extensive, with a high density of wetlands (Figure 3-1) including those of national significance in the coastal lower catchments. The NT has some of Australia’s largest and relatively unmodified wetlands (Whitehead et al., 1990). Floodplain wetlands provide extensive habitat for a wide range of aquatic biota during the wet season and refugia habitats for aquatic biota and waterbirds during the dry season (Warfe et al., 2010). They provide habitats for large congregations of birds, including magpie geese (Territory Natural Resource Management, 2016). In a study of the Mary River coastal floodplain wetlands, plant communities were simple, with low species richness, however diversity of wildlife habitats were high (Whitehead et al., 1990). The distribution of plant species across catchments in the NT was similar, but there were some regional variations (Whitehead et al., 1990). Despite being in relatively pristine condition, they are threatened by feral animals and invasive plants.
Mangroves and salt flats

Mangrove communities are assemblages of trees and shrubs that are found fringing most of the coastline of mainland Australia, with the most extensive and diverse communities found along the northern coastline. Mangroves occur extensively across the NT (Woodroffe, 1995), including the coastal floodplains of the Darwin catchments (Figure 3-3). Mangroves support diverse and complex food webs, including crustaceans such as prawns, and a diversity of fish species. While associated with the marine system, mangroves require freshwater input, with many of them living close to their salinity tolerance levels. Changes in flow regimes can potentially affect mangroves.

![Figure 3-3 Distribution of mangroves and salt flats in the coastal area of the Darwin catchments](image)

Hydrology of mangroves is complex: tidal inundation, rainfall, groundwater seepage and evaporation all influence soil salinity and have a profound effect on mangrove growth and distribution. Freshwater flows into mangroves reduces salinity, creating favourable conditions. Extraction of water from rivers and subsequent changes to flow regimes can negatively impact the productivity and extent of mangroves (Röderstein et al., 2014). A reduction in the volume of wet-season flow is likely to reduce the productivity (growth) and composition of mangroves, their extent and their connectivity, particularly in the upper reaches of estuaries and in the high
intertidal zone. Minor reductions in flow regimes have led to massive mortality of mangroves (Blasco et al., 1996). There is a high species richness, with 22 species of mangroves found in a study of the tidal areas of the Adelaide River (Ball, 1998). Darwin Harbour, which represents a broad open embayment, contains the largest single stand of mangroves in the NT (Woodroffe, 1995).

Coastal salt flats or claypans are shallow coastal basins which are only infrequently tidally inundated. They are often found adjacent to coastal mangrove forests. Tropical northern Australia has extensive areas of these salt flats which remain relatively pristine. These low-lying systems are mostly vegetation free, and are coated in a thick salt crust for most of the year. During large rainfall events when overbank flow occurs, or during sustained local rainfall, they may be flooded for extensive periods. Wetting of salt flats results in the release of high concentrations of nutrients and benthic algae, which become a food source for animals, including prawns.

Salt flats contribute significantly to primary production in coastal areas (Burford et al., 2016). Reduced flows can impact salt flats through reduced inundation, affecting the growth of primary producers that form the base of the food web, with impacts potentially extending into coastal areas (Burford et al., 2016).

**Riparian vegetation**

The interface between land and rivers is the riparian zone, which provides an important link between aquatic and terrestrial communities. Riparian zones are regarded as highly diverse, dynamic and complex habitats (Naiman and Decamps, 1997) that act as a thermal buffer to streams. They also influence a number of environmental processes such as instream primary production; nutrient interception, storage and release; enhancement of bank stability; the provision of coarse woody material as habitat and substrate for fish, invertebrates and microalgae; channel morphology and habitat diversity (Pusey and Arthington, 2003). Riparian vegetation is important for providing bank stability, terrestrial and instream habitat and food resources, as well as acting as corridors for wildlife movement and the movement of sediment, carbon and nutrients into rivers. Riparian zones are often more fertile and productive than surrounding terrestrial vegetation. The timing and quantity of water available to the riparian zone is critical for determining its structure, function and resilience, such that all aspects of the flow regime (i.e. precipitation, runoff and evapotranspiration) exert some control over how riparian vegetation access water (Tabacchi et al., 1998). Change to the flooding regime or reduced access to groundwater as a consequence of water resource development can lead to deterioration of the condition of the vegetation of riparian zone, and over longer timespans, affect the extent and diversity of riparian zones. There have only been a few systematic studies of riparian vegetation in the NT (Woinarski, 2004). Within the riparian zone of the nearby Daly catchment, 40 tree species were identified, of which many were highly groundwater dependent (O’Grady et al., 2006).

The ecological integrity of riparian zones across northern Australia is threatened by a range of existing processes, including land clearing, weed invasions and disturbance by livestock (Woinarski et al., 2000). Unlike other parts of Australia, NT riparian zones are largely unmodified (Woinarski, 2004). They provide important habitat for birds including waterfowl, especially in the dry season (Woinarski et al., 2000), likewise for flying foxes, invertebrates and frogs (Woinarski, 2004).
Monsoon vine forest

The monsoon rainforest patches of northern Australia (also known as monsoon vine forests) are an example of groundwater-dependent forests that rely on year-round availability of water. They are associated with areas in the landscape where the water is trapped or the watertable is close to the surface and so occur around the coastline, springs, watercourses and deep rocky gullies, or areas that are naturally fire protected by topographic features such as steeper, rockier terrain (dry monsoon vine forests comprising deciduous species) and especially sheltered gorges or areas with moist substrate (Bowman, 2000). The monsoon vine forests stand out from the sparsely wooded eucalypt savanna that covers much of northern Australia, and are most common in the Darwin catchments (Figure 3-4) (Russell-Smith, 2001).

![Figure 3-4 Distribution of monsoon vine forest in the Darwin catchments](image)

Although there is about 2700 km² of this habitat in the NT, it only accounts for 0.2% of the total land area. The monsoon vine forests in the NT are made up of 15,000 patches ranging from 1 to 4000 ha with a median size of 3.6 ha (Northern Territory Department of Land Resource Management, 2010; Price et al., 1999). They contain very small populations of mostly less than 50 plants (Russell-Smith and Lee, 1992). Access to water is critical to the type and functioning of
tropical tree stands. Even with the monsoonal wet season, many trees must survive primarily on
soil water (1 to 2 m of soil (Liedloff and Cook, 2007)). As plant roots can access groundwater
throughout an otherwise long, rain-free dry season, these forests support dense stands of tall
trees, palms and vine thickets.

Bowman and Panton (1993) found that the monsoon rainforest patches of the Darwin area are
susceptible to development, fire, weed invasion and cyclones, with a 60% reduction in cover of
pre-1945 monsoon rainforest extent; while Russell-Smith and Bowman (1992) also found impacts
from introduced cattle and buffalo, pigs and flood damage on the rainforest patches. These moist,
heavily shaded habitats and their concentration of fleshy, fruit-bearing plant species support a
variety of animals dependent upon these forests, especially the fruit-eating birds (Price et al.,
1999) and bats. Birds move between monsoonal vine forest patches and require many patches
over a large area to maintain their populations (Price et al., 1999).

3.2.4 KEY BIOTA

Native fish
Freshwater fish are an important component of the aquatic biodiversity in northern Australia
(Pusey et al., 2017). Fishes comprise the dominant aquatic-vertebrate group in terms of species
richness in tropical freshwater catchments of northern Australia. In a recent synthesis of a range of
information sources from northern Australia, Pusey et al. (2017) mapped the distribution of
111 freshwater and 42 estuarine fishes, not including those that are elasmobranchs (sharks, rays
and skates). An earlier publication documented 176 species of bony fish and six species of
elasmobranch recorded in northern Australia (Pusey, 2011). A total of 86 of these species reside
exclusively in freshwaters and 90 out of 176 require access to marine or estuarine waters for part
of their life cycle (Pusey, 2011).

Many northern Australian freshwater fish reproduce during the wet season, when initial flooding
increases the area and diversity of available aquatic habitats, as well as increasing plankton and
other foods (Bishop et al., 1990). In a synthesis of information on fish in the Alligator Rivers of the
NT, it was found that the lowland backflow billabongs were important spawning habitat (Bishop
et al., 1990). In a study of the intermittent (seasonal) Fergusson River in the NT, it was concluded
that the persistence of refuge waterholes of sufficient size were essential for maintaining
freshwater biodiversity, particularly fish, as these waterholes provided suitable habitat (Pusey
et al., 2018). The size of the waterholes was determined by the hydrology of the previous year.
Each of the rivers within the Darwin catchments have extensive floodplain areas, particularly in
their lower reaches. For example, the Mary River dissipates into a distributed floodplain, with
extensive floodplains above the estuary, making it an ideal nursery for fish (Erskine et al., 2005).
There are few local studies of fish ecology in the Darwin catchments.

A fish group vulnerable to inchannel barriers and changes to flows are freshwater migratory fishes.
Migratory fish are distributed throughout the Darwin catchments (Figure 3-5) and include species
with populations or subpopulations which undertake large-scale movement during their life cycle.
While there are many species in this group, a range of species are distributed through freshwater
habitats including inchannel and offchannel environments, as well as upper and lower catchment
areas, such as barramundi, freshwater sawfish, bull shark, black catfish (Neosilurus ater) and
Hyrtl’s tandan (Neosilurus hyrtlii), sooty grunter (Hephaestus fugilinosus and H. jenkinsi),
freshwater longtom (*Strongylura kreffti*) and spangled perch (*Leiopotherapon uniclor*). These migrations may be required for reproductive purposes or exploiting available habitat and food resources. Movement and migration of fishes in the Darwin catchments is critical. Species can move over the floodplain for weeks to months during the wet season but be confined to the main channel and distributary refugia during the dry season. The distributary refugia are in streams branching off and flowing away from the main stream channel. In the dry season, inundated habitats play a critical role in providing resilience for fish.

**Figure 3-5 Distribution of focal migratory freshwater fishes in the Darwin catchments**

Another important group of fish are the stable flow spawners. While they are distributed throughout the Darwin catchments, this group is more prominent in the upper parts of the catchments (Figure 3-6).
This group includes a large number of species, including the freshwater longtom, mouth almighty (*Glossamia aprion*), bony bream (*Nematalosa erebi*), barred grunter (*Amniataba percoides*), flyspecked (*Craterocephalus stercusmuscarum*) and freckled hardyhead (*Craterocephalus lentiginosus*) and the eastern (*Melanotaenia splendida splendida*), chequered (*Melanotaenia splendida inornata*) and western (*Melanotaenia australis*) rainbowfish.

### Threatened and endangered fish species

**Freshwater sawfish**

The threatened freshwater sawfish currently occupies the Darwin catchments (Figure 3-7) (Morgan et al., 2004). It is listed as vulnerable under the EPBC Act and as critically endangered by the International Union for Conservation of Nature (IUCN). Given the EPBC Act listing, any proposed action that is likely to have a significant impact on their populations or on their habitat may need an environmental impact assessment. The freshwater sawfish is distributed throughout the Darwin catchments (Figure 3-7; Figure 3-8), although there are limited records, reflecting the
limited fish studies in this area. Historically this species has been distributed across the west coast of Australia, in the NT and in Queensland.

The prospect of inchannel barriers along migration routes and in the lowlands of the Darwin catchments poses a threat to the passage of migratory fishes, including the freshwater sawfish. The freshwater sawfish has a marine adult phase while the juvenile phase is in freshwater or saline environments (Morgan et al., 2016; Peverell, 2005). Pupping occurs in estuaries and river mouths (Last and Stevens, 1994), and juveniles and adults occupy large pools and waterholes mostly in the main channel of larger rivers (Morgan et al., 2004; Peverell, 2005). Occasionally they are also found in larger offchannel habitat. Juveniles enter the river in the wet season (January to April) with higher survival or recruitment correlating with years with high, late wet-season flows (Centre of Excellence in Natural Resource Management, 2010).

![Image of freshwater sawfish](image_url)

*Figure 3-7 The freshwater sawfish (Pristis pristis)*

Species of sawfish can attain very large sizes (5–7 m total length) and live in tropical and subtropical coastal marine waters as adults (Last and Stevens, 1994). A key feature of the group is the tooth-lined rostrum (or saw) which is a flattened extension of the snout. The saw is important in the specialist, stealth feeding strategies of these species, being used to sense and in some cases strike and impale prey, including prawns and fish (Morgan et al., 2016). The freshwater sawfish is a top predator that feeds on fishes and crustaceans (Thorburn et al., 2014).
Barramundi is a large fish that occurs throughout northern Australia in rivers, lagoons, swamps and estuaries. It is a voracious predator and arguably the most important fish species to cultural, recreational and commercial fisheries throughout wet-dry tropical Australia. The species makes up a substantial component of the total commercial fish catch in northern Australia (Savage and Hobsbawn, 2015). In 2015 the commercial barramundi catch in the NT alone was 344.2 tonnes. Barramundi is also a fish of cultural significance, as well as being an important food source for Indigenous populations (Jackson et al., 2012; Toussaint et al., 2005). Barramundi is found extensively throughout the Darwin catchments (Figure 3-9).
The barramundi is impacted by changes in the flow regimes of rivers and via infrastructure impacting movement of fish. Spawning occurs in the estuary at the beginning of the wet season and young male fish move into floodplain and freshwater habitats when suitable flows provide access (Russell and Garrett, 1985). Recent work has proposed three primary life cycle strategies employed by barramundi (Crook et al., 2017), whereby some male adults return to the estuary to spawn after spending up to several years in freshwater habitats, while some may delay downstream spawning migrations for several years until they have undergone the transition to females in freshwater habitats. Migrations are thought to be triggered by variation in the flow regime (Crook et al., 2017), making the species particularly vulnerable to water resource development. Barramundi can be caught throughout all four fishing seasons, but higher catch rates occur during the build-up and wet season, as barramundi becomes more active with warmer temperatures.

White banana prawn

The white banana prawn (*Fenneropenaeus merguiensis*), is a short-lived, fast-growing crustacean species that is an important major commercial fishery resource across tropical Australia (see...
Section 3.3.3). White banana prawns complete their life cycle within a year and can be wild-harvested annually. Their stock is tied to key environmental drivers, particularly annual flood flow (Staples and Vance, 1986; Vance et al., 1985). Each year’s catch of banana prawns is highly variable, being dependent on temporal cycles of monsoonal rainfall and river flows. In addition to forming a major constituent of a high value fishery, white banana prawns are an important ecological species and a key component of marine and estuarine food webs. They provide a significant food source for a myriad of commercially and recreationally valuable fish species in the coastal ecosystem.

A significant body of research has investigated the life cycle, growth, behaviour, and habitat use of the white banana prawn across multiple life stages to help inform the management of the Northern Prawn Fishery (NPF) (Vance et al., 1996; Wang and Haywood, 1999). The NPF is a very well-managed fishery of high economic value. Larger flow events increase prawn catch through greater juvenile emigration from estuaries to offshore habitats where growth is enhanced and mortality is lower for the sub-adult and adult phases (Robins et al., 2005). Recent studies suggest that nutrients exported during the flood flows support enhanced growth and survival and enhanced food availability through primary and secondary production in near-shore habitats (Burford et al., 2010). Assessing the potential impact of water resource development on the NPF is a critical issue, especially for white banana prawns, whose life cycles are intrinsically linked to natural flow regimes.

**Species of significance**

**Magpie goose**

The magpie goose is an iconic waterfowl and wildlife species with significant socio-economic value. Magpie geese are harvested annually and important to cultural practice (Pusey and Kennard, 2009). They are widespread and abundant across the coastal floodplains of northern Australia, with an estimated population size of 3.5 million in the NT alone (Figure 3-10) (Traill et al., 2009). The magpie goose occurs within sub-coastal wetlands across tropical northern Australia. During the wet season, magpie geese make nests from vegetation including sedges and grasses (Colley, 1999). During the dry season magpie geese gather on floodplains in large numbers and feed on the tubers of the sedge *Eleocharis dulcis* (Traill and Brook, 2011). These birds move between river systems in response to seasonal rainfall to find breeding and foraging sites (Traill et al., 2010; Wilson, 1997). The timing of rainfall and monsoonal flooding provide cues for nesting and hatching in magpie geese (Warfe et al., 2011). Flooding triggers dramatic changes in the composition and biomass of floodplain vegetation and, hence, the availability of magpie goose nesting habitat and food (Pusey and Kennard, 2009).
Once prevalent throughout south-east Australia, the distribution of the magpie goose has largely contracted to northern Australia in association with threatening processes including habitat loss, invasive species (e.g. mimosa, para grass, olive hymenachne and pigs) and drought (Traill and Brook, 2011). Recent information suggests that the numbers of magpie geese are on a downward trend, with successive poor wet seasons affecting breeding in the NT (Burton, 2017). Changes to the flooding regime or wetland persistence is likely to impact magpie geese (Pusey and Kennard, 2009).

3.2.5 TERRESTRIAL SYSTEMS

The northern section of the NT has the world’s largest intact savanna and is one of the few remaining natural areas of its kind on Earth (Kutt et al., 2009; Territory Natural Resource Management, 2016). The monsoonal climate controls the ecology of terrestrial, freshwater and coastal systems of northern Australia’s plant and animal species (Figure 3-11). Annual fluctuations in resources dictating migration, dispersal patterns, and fruiting, seeding and flowering are synchronised with this highly seasonal pattern of rainfall (Woinarski et al., 2005).
Intensive agricultural development can cause habitat fragmentation as a consequence of land clearing but the extent of this is dependent on the scale and type of development and the extent to which it is contiguous or in a mosaic. Habitat fragmentation is a critical issue for biodiversity conservation. Fragment size, isolation and the impact of livestock, feral predators and weeds all affect conservation outcomes (Hobbs, 2001). In developing agricultural landscapes in northern Australia, lessons from fragmentation studies are critical. For savanna species, subtle landscape variations provide critical resources for wildlife, and the loss of this variation can lead to local extinctions (Woinarski et al., 2005). For example, for fruit-eating birds, the loss of some of the rainforest or monsoon forest patches within a region is likely to lead to the extinction of many species (Price et al., 1999).

Fragmented habitats in northern Australia are likely to be under extreme pressure from introduced weeds, altered fire regimes and altered hydrology. Taking those issues into account along with the subtle, complex and largely unknown spatial and temporal fluctuations in critical resources required for many vertebrates presents a considerable challenge.

### 3.2.6 ENVIRONMENTAL PROTECTION

There are a number of both aquatic and terrestrial species in the Darwin catchments currently listed as critically endangered, endangered and vulnerable under the EPBC Act and by the Northern Territory Government’s wildlife classification system, which is based on the IUCN Red List categories and criteria (Figure 3-12).
If a proposed development is predicted to have a significant impact on a matter of national environmental significance (e.g. the populations of a nationally listed species, communities, migratory species or wetlands of importance) it would require approval to proceed under the EPBC Act (Table 3-2). This approval is required irrespective of local government policies. The Northern Territory Government lists 18 species, most of them as vulnerable, but one as critically endangered.
Table 3-2 Definition of threatened categories under the EPBC Act (Cth) and the Northern Territory wildlife classification system

<table>
<thead>
<tr>
<th>ACT</th>
<th>CATEGORY</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPBC Act (Cth)</td>
<td>Matters of National Environmental Significance</td>
<td>World heritage properties, National Heritage places, wetlands of international importance (listed under the Ramsar Convention), listed threatened species and ecological communities, migratory species protected under international agreements, Commonwealth marine areas, the Great Barrier Reef Marine Park, nuclear actions (including uranium mines), and water resources, in relation to coal seam gas development and large coal mining development</td>
</tr>
<tr>
<td></td>
<td>Critically endangered species</td>
<td>It has undergone, is suspected to, or is likely to undergo very severe reduction in numbers in the immediate future; its geographic distribution is precarious for the survival of the species and is very restricted. The estimated total number of mature individuals is very low and evidence suggests that the number will continue to decline at a very high rate and the probability of its extinction in the wild is at least 50% in the immediate future</td>
</tr>
<tr>
<td></td>
<td>Endangered species</td>
<td>It has undergone, is suspected to, or is likely to undergo severe reduction in numbers in the immediate future; its geographic distribution is precarious for the survival of the species and is restricted. The estimated total number of mature individuals is low and evidence suggests that the number will continue to decline at a high rate and the probability of its extinction in the wild is at least 20% in the near future.</td>
</tr>
<tr>
<td></td>
<td>Vulnerable species</td>
<td>It has undergone, is suspected to, or is likely to undergo substantial reduction in numbers in the immediate future; its geographic distribution is precarious for the survival of the species and is limited. The estimated total number of mature individuals is limited and either evidence suggests that the number will continue to decline at a substantial rate and the probability of its extinction in the wild is at least 10% in the medium-term future.</td>
</tr>
<tr>
<td></td>
<td>Critically endangered communities</td>
<td>Extremely high risk of extinction in the next 10 years or three generations of key species</td>
</tr>
<tr>
<td></td>
<td>Endangered communities</td>
<td>Extremely high risk of extinction in the next 20 years or five generations of key species</td>
</tr>
<tr>
<td></td>
<td>Vulnerable communities</td>
<td>Extremely high risk of extinction in the next 50 years or ten generations of key species</td>
</tr>
<tr>
<td>NT wildlife classification†</td>
<td>Critically endangered</td>
<td>A: Reduction in population size of ≥80% over three generations or ten years (whichever is longer)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B: Geographic range of extent of occurrence &lt;100 km²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C: Small population size and decline (less than 250 mature individuals)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D: Very small or restricted populations (less than 50 mature individuals)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E: At least 50% chance of going extinct in the wild over three generations or ten years (whichever is longer).</td>
</tr>
<tr>
<td></td>
<td>Endangered</td>
<td>A: Reduction in population size of ≥50% over three generations or ten years (whichever is longer)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B: Geographic range of extent of occurrence &lt;5,000 km²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C: Small population size and decline (less than 2500 mature individuals)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D: Very small or restricted populations (less than 250 mature individuals)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E: At least 20% chance of going extinct in the wild over five generations or 20 years (whichever is longer).</td>
</tr>
<tr>
<td></td>
<td>Vulnerable</td>
<td>A: Reduction in population size of ≥30% over three generations or ten years (whichever is longer)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B: Geographic range of extent of occurrence &lt;20,000 km²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C: Small population size and decline (less than 10,000 mature individuals)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D: Very small or restricted populations (less than 1,000 mature individuals)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E: At least 10% chance of going extinct in the wild over five generations or 100 years (whichever is longer).</td>
</tr>
</tbody>
</table>

†The Northern Territory wildlife classification categories are based on the International Union for the Conservation of Nature Red List categories and criteria. An extract of each category is presented here. For the full definition see https://nt.gov.au/__data/assets/pdf_file/0010/192538/red-list-guidelines.pdf
3.3 Demographic and economic profile

3.3.1 INTRODUCTION

This section describes the current social and economic characteristics of the Darwin catchments including the demographics of local communities (Section 3.3.1), current industries and land use (Section 3.3.2), and the existing infrastructure (transport, supply chains, utilities and community infrastructure) on which any new development would build (Section 3.3.3). Unless stated otherwise material for this section was sourced from the companion technical report on socio-economics (Stokes et al., 2017).

3.3.2 DEMOGRAPHICS

The Darwin catchments encompass all or part of a number of different local government areas, including the municipalities of Darwin, Darwin Waterfront Precinct, Palmerston and Litchfield, the shires of Wagait, Belyuen and Coomalie, and the most western edge of West Arnhem Regional Council. The Darwin catchments also encompass unincorporated areas, which do not form part of any local council. At the territory level, the Darwin catchments include part or all of a number of electoral divisions, including all of Cuarina, Wanguri, Nightcliff, Johnston, Sanderson, Karama, Fannie Bay, Fong Lim, Port Darwin, Spillett, Drysdale, Brennan, Blain, Nelson and Goyder, and part of Daly and Arnhem. At the federal level, the Darwin catchments encompass all of the electoral division of Solomon (the region around Darwin) plus a part of the division of Lingiari (which encompasses the remainder of the NT).

The population of the Darwin catchments is concentrated in the Greater Darwin area (ABS ‘Darwin’ SA4 area, population 136,828), comprising Darwin City (population 6464), Howard Springs (population 5132), several smaller population centres (Palmerston, Howard Springs, and McMinns Lagoon), and surrounding suburbs and rural areas. Population centres outside Greater Darwin, such as Belyuen, Batchelor and Adelaide River, all have populations of less than 1000 according to the 2016 Australian Bureau of Statistics (ABS) census (ABS, 2016a). Other towns within the Darwin catchments include Palmerston, Howard Springs, Belyuen, McMinns Lagoon, Batchelor and Adelaide River. With the exception of Howard Springs (population 5132), all of these towns have populations of less than 1000 according to the 2016 census.

The demographic profile of the Darwin catchments, based on data from the 2016 and 2011 censuses, is shown in Table 3-3. The Darwin catchments contain two very different areas: the urban areas including Darwin and the surrounding suburbs, and the remaining rural areas. The population of the urban areas is predominantly younger, with a larger proportion of Indigenous people than is typical compared to the country as a whole. However, the trends suggest these characteristics are moving towards the national average. The population of the rural areas is older and the proportion of males and of Indigenous people are significantly above the national average. Furthermore the trend over time demonstrates these characteristics of the rural areas are strengthening. The median weekly gross household income for both the urban ($2160) and rural ($1965) areas was above the average for Australia in 2016.
### Table 3-3 Major demographic indicators for the Darwin catchments

The Darwin catchments are separated into urban and rural areas because the demographics of the two are so different. The overall demographics for the Darwin catchments are given in the ‘combined’ column.

<table>
<thead>
<tr>
<th>INDICATOR</th>
<th>UNIT</th>
<th>URBAN AREAS</th>
<th>RURAL AREAS</th>
<th>COMBINED (URBAN + RURAL)</th>
<th>NT</th>
<th>AUSTRALIA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total population, 2016†</td>
<td>number</td>
<td>112,134</td>
<td>26,918</td>
<td>139,052</td>
<td>228,833</td>
<td>23,401,892</td>
</tr>
<tr>
<td>Total population, 2011‡</td>
<td>number</td>
<td>101,136</td>
<td>21,598</td>
<td>122,734</td>
<td>211,943</td>
<td>21,507,719</td>
</tr>
<tr>
<td>% change in population</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indigenous population, 2016, as % of total§</td>
<td>%</td>
<td>10.9</td>
<td>24.6</td>
<td>13.3</td>
<td>8.0</td>
<td>8.8</td>
</tr>
<tr>
<td>Indigenous population, 2011, as % of total*</td>
<td>%</td>
<td>9.6</td>
<td>9.3</td>
<td>9.6</td>
<td>26.8</td>
<td>2.5</td>
</tr>
<tr>
<td>Male population, 2016, as % of total†</td>
<td>%</td>
<td>51.0</td>
<td>59.0</td>
<td>52.5</td>
<td>51.8</td>
<td>49.3</td>
</tr>
<tr>
<td>Male population, 2011, as % of total‡</td>
<td>%</td>
<td>51.7</td>
<td>54.4</td>
<td>52.2</td>
<td>51.7</td>
<td>49.4</td>
</tr>
<tr>
<td>Population density, 2016†</td>
<td>people/km²</td>
<td>497.2</td>
<td>0.9</td>
<td>4.5</td>
<td>0.2</td>
<td>3.0</td>
</tr>
<tr>
<td>Median age, 2016†</td>
<td>years</td>
<td>33</td>
<td>38</td>
<td>34</td>
<td>32</td>
<td>38</td>
</tr>
<tr>
<td>Change in median age, from 2011 to 2016†‡</td>
<td>years</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Median weekly gross household income, 2016‡‡</td>
<td>$</td>
<td>2,160</td>
<td>1,965</td>
<td>2,130</td>
<td>1,983</td>
<td>1,438</td>
</tr>
<tr>
<td>Change in median household income, from 2011 to 2016‡‡</td>
<td>%</td>
<td>20.6</td>
<td>37.3</td>
<td>23.0</td>
<td>18.5</td>
<td>16.5</td>
</tr>
<tr>
<td>Average people per household, 2016†</td>
<td>number</td>
<td>2.5</td>
<td>3.2</td>
<td>2.6</td>
<td>2.9</td>
<td>2.6</td>
</tr>
<tr>
<td>Change in average people per household, from 2011 to 2016‡‡</td>
<td>number</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>No change</td>
<td>No change</td>
</tr>
</tbody>
</table>

†Data sourced from ABS (2016c).
‡Data sourced from ABS (2011c).
§Data sourced from ABS (2016a).
*Data sourced from ABS (2011a).
†† Data sourced from ABS (2016b).
‡‡ Data sourced from ABS (2011b).

Socio-Economic Indexes for Areas (SEIFA) scores, which provide measures of socio-economic advantage and disadvantage, indicate that the combined Darwin catchments study area is around the middle or a little higher than the rest of the country (Table 3-4) but with differences between rural and urban areas.

### Table 3-4 SEIFA scores of relative socio-economic advantage for the Darwin catchments

Scores are relativised to a national mean of 1000, with higher scores (smaller deciles) indicating greater advantage. The Darwin catchments are separated into urban and rural areas because the demographics of the two are so different. The overall demographics for the Darwin catchments are given in the ‘combined’ column.

<table>
<thead>
<tr>
<th>INDICATOR</th>
<th>URBAN AREAS</th>
<th>RURAL AREAS</th>
<th>COMBINED (URBAN + RURAL)</th>
<th>NT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Index of Relative Socio-economic Advantage and Disadvantage†</td>
<td>1028 (6)</td>
<td>977 (4)</td>
<td>1019 (6)</td>
<td>922 (3)</td>
</tr>
<tr>
<td>Index of Relative Socio-economic Disadvantage‡</td>
<td>1021 (6)</td>
<td>973 (4)</td>
<td>1011 (5)</td>
<td>899 (2)</td>
</tr>
<tr>
<td>Index of Economic Resources</td>
<td>999 (5)</td>
<td>1004 (5)</td>
<td>1000 (5)</td>
<td>896 (2)</td>
</tr>
<tr>
<td>Index of Education and Occupation</td>
<td>1025 (7)</td>
<td>965 (4)</td>
<td>1013 (6)</td>
<td>976 (5)</td>
</tr>
</tbody>
</table>
3.3.3 CURRENT INDUSTRIES AND LAND USE

New agricultural development could affect current land users and other industries that rely on natural resources. This section describes current agriculture and fisheries industries in the Darwin catchments, and the other land uses and industries that might be impacted by new development projects.

Employment

Within both the urban and rural areas of the Darwin catchments, the overall unemployment rate is close to full employment at less than 5% which is noticeably lower than that seen across the NT and the country as a whole (Table 3-5). The low level of unemployment suggests that industries within the study area may struggle to find enough workers to meet their growth needs, which could place upward pressures on wage rates in the study area.

There are noticeable differences in the industries providing the most jobs, both across the Darwin catchments and compared to Australia as a whole. In terms of the ABS-defined major industry categories, ‘Public administration and safety’ is by far the most significant employer in the urban part of the Darwin catchments and the NT, providing around one in five jobs, but does not feature as one of the top five employers in the country as a whole. Within the rural areas of the Darwin catchments, ‘Construction’ is by far the largest employer. These differences may significantly impact the regional economic benefits that could result from development projects initiated within the Darwin catchments (see Section 6.5).

Table 3-5 Key employment data in the Darwin catchments in relation to state and national means

The Darwin catchments are separated into urban and rural areas because the demographics of the two are so different. Employment within ‘Agriculture, forestry and fishing’ was 0.5% in urban areas, 4.6% in rural areas and 1.2% in the combined Darwin catchments study area. Only the top five industries are provided for each location.

<table>
<thead>
<tr>
<th>EMPLOYMENT STATISTIC</th>
<th>URBAN AREAS</th>
<th>RURAL AREAS</th>
<th>COMBINED (RURAL + URBAN)</th>
<th>NT</th>
<th>AUSTRALIA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unemployment rate (%), 2016*</td>
<td>4.8</td>
<td>4.6</td>
<td>4.7</td>
<td>7.0</td>
<td>6.9</td>
</tr>
<tr>
<td>Unemployment rate (%), 2011\†</td>
<td>3.7</td>
<td>3.8</td>
<td>3.7</td>
<td>5.3</td>
<td>5.6</td>
</tr>
<tr>
<td>Major industries of employment – top five industries % of employment for each location\‖</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Public administration and safety</td>
<td>19.9</td>
<td>17.1</td>
<td>19.4</td>
<td>19.0</td>
<td>na</td>
</tr>
<tr>
<td>Construction</td>
<td>11.1</td>
<td>19.3</td>
<td>12.5</td>
<td>10.6</td>
<td>8.9</td>
</tr>
<tr>
<td>Health care and social assistance</td>
<td>10.8</td>
<td>na</td>
<td>9.9</td>
<td>11.6</td>
<td>13.2</td>
</tr>
<tr>
<td>Education and training</td>
<td>8.7</td>
<td>8.2</td>
<td>8.6</td>
<td>9.7</td>
<td>9.1</td>
</tr>
<tr>
<td>Retail trade</td>
<td>8.0</td>
<td>6.3</td>
<td>7.7</td>
<td>7.6</td>
<td>10.3</td>
</tr>
<tr>
<td>Professional, scientific and technical services</td>
<td>na</td>
<td>7.0</td>
<td>na</td>
<td>na</td>
<td>7.6</td>
</tr>
</tbody>
</table>

na = not applicable.
*Data sourced from ABS (2016b).
†Data sourced from ABS (2011b).
Land use

Land use in the Darwin catchments is dominated by conservation and protected land (53%), including 7280 km² of national parks and 1163 km² under traditional Indigenous uses (Figure 3-13). A further 7.2% is classified as water and wetlands, most of which is in several large areas on the western and northern boundaries of the Darwin catchments. Most of the remaining area (36.5%) is used for grazing and livestock production. This includes about 15,000 ha of intensive agriculture and 16,000 ha of dryland cropping. Urban areas (2%) make up most of the remainder of the Darwin catchments, and mining has a concentrated footprint (0.3%).

Agriculture and fisheries

Agriculture is a significant contributor to the economy of the Darwin region, with the gross value of agricultural production (GVAP) in the Darwin area approximately $136 million (ABS, 2017; NT Farmers Association, 2016). Cropping accounts for about 90% of the GVAP ($123 million), mostly from fruit, vegetables and hay (NT Farmers Association, 2016). Beef cattle contribute around $13 million to GVAP (ABS, 2017). This is mostly from smallholder beef production as there

Figure 3-13 Land use classification for the Darwin catchments
are very few pastoral stations of any significant size in the Darwin catchments. Agriculture is not a major source of employment in the Darwin catchments (Table 3-5).

**Grazing industry in the Darwin catchments**

The pastoral industry developed mostly in the regions to the south of Darwin, where larger areas of grassy savanna are well-suited to pastoral production. As the live export trade has developed, the Darwin region has become extremely important as an export hub via Darwin Port. Associated with that, in the Darwin region there are properties for holding cattle prior to export and areas of forage production.

**Past and existing irrigation in the Darwin catchments**

Early agricultural interest in the Darwin catchments was in plantation agriculture. During the 1870s and 1880s around 60,000 ha of land was granted to a number of companies for sugarcane production (Hillock, 2005). A modest sugar mill was established at Delissaville (now known as Belyuen). However, much of this early investment in plantation agriculture was speculative and by 1890 all plantations had been abandoned. There were also efforts by Chinese farmers from 1884 onwards to grow rice on the sub-coastal plains of the Adelaide River (Forster, 1961). However, rice as an industry didn’t receive significant investment until after World War II. Territory Rice Limited was established in 1954 and 300,000 ha was to be made available on the sub-coastal plains. However, only a small area of rice (around 1000 ha) was grown before the operation folded in the early 1960s.

These early attempts at large-scale agriculture in the Darwin region relied on rainfall, exploiting the reliable wet seasons. However, the rainy season is short and it proved difficult to grow grain crops, such as rice. Vegetables and fruit were grown locally from an early stage of development, with early production focusing on providing fresh fruit and vegetables to local residents. Pests and diseases during the wet season proved a challenge for larger scale commercial production, as well as the ability to transport products to markets outside of the NT. Over more recent decades transport links and the ability to control pests have improved and the horticultural industry has developed, with a focus on supplying mangoes and Asian vegetables to the Australian market. There is about 4,400 ha of irrigated land in the Darwin catchments.

**Northern Prawn Fishery**

The Northern Prawn Fishery (NPF) spans the northern Australian coast between Cape Londonderry in WA to Cape York in Queensland (Figure 3-14). It is one of the most valuable fisheries in the country and is managed by the Australian Government (via the Australian Fisheries Management Authority) through input controls such as gear restrictions (number of boats and nets, length of nets) and restricted entry. The Darwin catchments flow into the three western NPF regions: the Joseph-Bonaparte Gulf, Fog Bay and Cobourg-Melville (Figure 3-14). Together, these three NPF regions account for about one-fifth of the total annual NPF prawn catch. Like many tropical fisheries, the target species exhibit an inshore-offshore larval life cycle and are dependent on inshore habitats, including estuaries, during the postlarval and juvenile phase (Vance et al., 1998). Monsoon-driven freshwater flood flows cue juvenile prawns to emigrate from estuaries to the fishing grounds and flood magnitude explains 30% to 70% of annual catch variation, depending on catchment region (Buckworth et al., 2014; Vance et al., 2003).
Initially comprising over 200 vessels in the late 1960s, the number of vessels in the NPF has reduced to just 52 trawlers and 19 licensed operators after management initiatives including effort reductions and vessel buy-back programs (Dichmont et al., 2008). Fishing activity for banana and tiger prawns, which constitute 80% of the catch, is also limited to two seasons: a shorter banana prawn season from April to June, and a longer tiger prawn season from August to November. The specific dates of each season are adjusted depending on catch rates. Banana prawns generally form the majority of the annual prawn catch by volume.

The catch is often frozen on-board and sold in domestic and export markets. The catch from the NPF was valued at $106.8 million in 2015 by the Australian Fisheries Management Authority (AFMA). Given recent efforts to alleviate fishing pressure in the NPF, there is little opportunity for further expansion of the industry.

**Land-based aquaculture in the Darwin catchments**

There is minimal land-based aquaculture in the Darwin catchments (see companion technical report on aquaculture (Irvin et al., 2018)). A farm near Humpty Doo produces more than 1000 tonnes of barramundi per year. The fish are farmed in ponds, with marine water pumped from the
Adelaide River. The Aquaculture Research Centre in Darwin is conducting research on marine species (black-lipped oysters, giant clams and sea cucumbers) with the engagement of Indigenous communities as a key component. Barramundi and tiger prawns were identified as established species suitable for culture in the Darwin catchments. Potential opportunities for land-based aquaculture in the Darwin catchments are discussed in Chapter 4.

**Tourism**

Tourism contributed $52.9 billion (3.2% of GDP) to the Australian economy in 2015–16 (ABS Tourism satellite accounts, 2015–16). International visitors account for 29% of this total contribution to GDP, with the remainder generated by domestic day and overnight stay visitors. The countries providing the largest numbers of international visitors are New Zealand (NZ), China, the United Kingdom (UK) and United States of America (USA).

Of the 76 regions for which Tourism Research Australia collects data, the ‘Darwin’ and ‘Kakadu Arnhem’ tourism regions are most relevant to the Darwin catchments (Figure 3-15). Some of the data regions can be further broken down into smaller ABS SA2 regions. The relevant region for the Darwin catchments is ‘Alligator’, which lies within the larger Kakadu Arnhem tourism region. The boundaries of the Darwin catchments, tourism regions, and the smaller ABS region of Alligator, are shown in Figure 3-16.

*Figure 3-15 Tourism is a major contributor to the economy of the Darwin catchments*

*Photo: CSIRO*
Figure 3-16 Tourism Research Australia and Australian Bureau of Statistics (ABS) statistical regions relevant to the Darwin catchments
The smaller ABS Alligator region lies within the Kakadu Arnhem tourism region.

More than 1.1 million ‘visitors’ (see Table 3-6 footnote, §§, for definition of a ‘visitor’), both international and domestic) visit the Darwin tourism region annually, and over 0.7 million visit the Kakadu Arnhem tourism region (Table 3-6). However, adding the data together risks double counting because the two regions likely receive many of the same visitors. A larger proportion of international visitors (mostly from the UK and Germany) travel to Darwin compared to the national average, but a smaller proportion visit Kakadu Arnhem. For Darwin, day visitors are less frequent than the national average, probably due to the tourism region’s considerable distance from the major population centres. Accordingly, the average length of stay is longer than that for the whole country, and the average spend per visitor is also higher. In contrast, day visitors are more common in the Kakadu Arnhem tourism region than in the rest of Australia, and overnight visitors stay fewer nights and visitors spend less overall.
Table 3-6 Key 2015 tourism data relevant to the Darwin catchments
The extent of the Darwin and Kakadu Arnhem tourism regions are shown in Figure 3-13.

<table>
<thead>
<tr>
<th>TOURISM STATISTIC</th>
<th>DARWIN</th>
<th>KAKADU ARNHEM</th>
<th>NT</th>
<th>AUSTRALIA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visitors (thousands)†,‡, §§</td>
<td>1,147</td>
<td>743</td>
<td>2,480</td>
<td>266,874</td>
</tr>
<tr>
<td>International visitors (% visitors)†,‡, §§</td>
<td>11</td>
<td>4</td>
<td>11</td>
<td>3</td>
</tr>
<tr>
<td>Domestic day visitors (% visitors)†,‡, §§</td>
<td>39</td>
<td>58</td>
<td>40</td>
<td>66</td>
</tr>
<tr>
<td>Visitor nights (thousands)†</td>
<td>6,378</td>
<td>1,358</td>
<td>12,400</td>
<td>560,116</td>
</tr>
<tr>
<td>International visitors (% visitor nights)†,‡</td>
<td>40</td>
<td>11</td>
<td>35</td>
<td>43</td>
</tr>
<tr>
<td>Average stay per overnight visitor (number of nights)‡</td>
<td>9</td>
<td>4</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Spend ($ million)†,‡</td>
<td>$972</td>
<td>$231</td>
<td>$2,032</td>
<td>$99,086</td>
</tr>
<tr>
<td>Average spend per visitor ($)†,‡</td>
<td>$847</td>
<td>$311</td>
<td>$820</td>
<td>$371</td>
</tr>
<tr>
<td>International visitors (% spend)†,‡</td>
<td>16</td>
<td>9</td>
<td>21</td>
<td>23</td>
</tr>
<tr>
<td>Room occupancy rate 2015–16 for hotels, resorts, motels, guest houses and serviced apartments§,‡‡</td>
<td>61.6%</td>
<td>42.6%</td>
<td>60.6%</td>
<td>66.0%</td>
</tr>
<tr>
<td>Top three/four countries of origin for international visitors†,∗</td>
<td>UK, Germany, USA</td>
<td>UK, Germany, France</td>
<td>NA</td>
<td>NZ, China, UK, USA</td>
</tr>
<tr>
<td>Number of tourism businesses in region†,††</td>
<td>1,288</td>
<td>95</td>
<td>2,066</td>
<td>273,512</td>
</tr>
</tbody>
</table>

NA = no available data.
§§Domestic ‘visitors’ represent the number of trips recorded in the National Visitor Survey†,‡ where trip types include (domestic) overnight trips, (domestic) day trips and outbound (international) trips. Some routine trips, such as same-day journeys to work, are excluded. International ‘visitors’ represents the number of short term travellers to Australia from overseas†,‡,∗.

Low room occupancy rates (even during the peak tourism season from July to September) suggest that there is capacity to accommodate additional visitors to the tourism regions, particularly within Kakadu Arnhem. Visitors are drawn to these tourism regions to pursue both city- and nature-based activities (Stokes et al., 2017). In particular, visitors are drawn to the many protected areas close to the Darwin catchments including the Charles Darwin River, Djuibinj, Litchfield, Mary River, Nitmiluk (Katherine Gorge) and Kakadu National Park, which was listed as a World Heritage Site in 1981 for its outstanding cultural and natural values.

Mining

The NT contributes a small proportion to Australian mining industry jobs and revenue, but within the NT, the contribution made by the Darwin catchments is significant. Based on employment by industry sector in the 2011 census data, the Darwin catchments supplied more than 60% of the workers for the NT mining sector (Table 3-7). Based on 2011 census data, mining was the thirteenth most important industry in the Darwin catchments out of 19 industries.
Table 3-7: Key statistics relating to the mining industry in the Darwin catchments

<table>
<thead>
<tr>
<th>EMPLOYMENT STATISTIC</th>
<th>URBAN AREAS</th>
<th>RURAL AREAS</th>
<th>COMBINED (URBAN + RURAL)</th>
<th>NT</th>
<th>AUSTRALIA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numbers employed in mining, Census 2016†</td>
<td>1,081</td>
<td>422</td>
<td>1,503</td>
<td>2,522</td>
<td>177,640</td>
</tr>
<tr>
<td>Numbers employed in mining, Census 2011‡</td>
<td>1,076</td>
<td>563</td>
<td>1,639</td>
<td>2,694</td>
<td>176,560</td>
</tr>
<tr>
<td>Sales and service income of mining sector*, 2014–15 ($ million)§</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>$4,395</td>
<td>$195,519</td>
</tr>
</tbody>
</table>

% Employment within mining sector:

| Census 2016† | 1.9 | 3.5 | 2.2 | 2.6 | 1.7 |
| Census 2011‡ | 2.0 | 5.1 | 2.6 | 2.8 | 1.8 |

*Mining sector is defined as coal mining, oil and gas extraction, metal ore mining, non-metallic mineral mining and quarrying. It does not include exploration and other mining support services.
NA = no available data
†Data sourced from ABS (2016b).
‡Data sourced from ABS (2011b).
§Data sourced from ABS (2015).

The mining industry currently has a footprint covering less than 3.5% of the land within the Darwin catchments. However, there are a number of mining exploration licenses in place, covering just over 43% of the land area, indicating the significant potential for further mining operations in the future (Figure 3-17).

Exploration and mining tenements in the Darwin catchments are closely correlated with the Pine Creek Orogen (Figure 2-2), which underlies much of the study area. The Pine Creek Orogen hosts over a thousand mineral occurrences and is among the most prospective geological regions of Australia. It contains approximately 20% of the world’s total uranium resource and approximately nine million mega ounces of gold have been identified. Considerable resources of other commodities exist, including copper, nickel, cobalt, lead, zinc, silver, platinum, palladium, tin, tantalum, tungsten, iron, magnesite and phosphate (Ahmad and Hollis, 2013).

The most economically important gold is hosted in quartz-reef near Pine Creek (the Spring Hill and Mount Porter gold mines). Alluvial gold was originally discovered at Pine Creek in 1871 by workers digging holes for the telegraph line, triggering a gold rush at the time. However, in recent years the main exploration focus has been on hard rock gold, which uses far less water than that required for processing alluvial gold. Gold mineralisation similar to that at Pine Creek also occurs at Tom’s Gully 115 km to the north-north-west, and exploration for areas of similar mineralisation is taking place regionally.

Alluvial tin was mostly mined in the late 1800s with the majority of historic workings located within a north to south corridor extending south of Darwin and in a broad zone north of Pine Creek. Although there are currently no major tin projects operating in the Darwin catchments, recent exploration has refocussed on the potential for sourcing lithium for battery production from Tin-Tantalum-rich pegmatites in the Finniss area south of Darwin.
Large quantities of uranium (including the Jabiluka and Ranger Mines) occur to the east of the Darwin catchments in west Arnhem Land (Lambert et al., 2005). Significant uranium deposits also halo an Archean–aged granite dome (McCready et al., 2004), sitting at the boundary between the Finniss and Adelaide catchments in the vicinity of the Rum Jungle Uranium mine. While Rum Jungle is no longer operational, the nearby Browns base metal project is a major resource. Base metals and uranium should be considered largely restricted to a halo around the Archean embayment.

Onshore and offshore basins to the north and west of the Darwin catchments have been covered by oil and gas tenements in the past and are currently under application for exploration rights. However, the prime areas of interest lie predominantly outside of the study area.
3.3.4 CURRENT INFRASTRUCTURE

Existing infrastructure in the Darwin catchments provides a base from which any future development could build. Current infrastructure is described below in terms of transport, supply chains and processing facilities, energy and water services, and community facilities. Costs of new infrastructure are discussed in Chapter 6.

Transport

Outside the Darwin urban footprint, the study area is characterised by a sparse network of major roads (Figure 3-18) with the Stuart Highway being the main access to Darwin from the south.

![Figure 3-18 Road rankings and conditions for the Darwin catchments](image)

*Figure 3-18 Road rankings and conditions for the Darwin catchments*

Rank 1 = well-maintained highways or other major roads, usually sealed; Rank 2 = secondary ‘state’ roads; Rank 3 = minor routes, usually unsealed local roads.

Other major sealed roads include the Cox Peninsula Road and the 230 km Arnhem Highway that links parts of Kakadu National Park with the Stuart Highway. Despite the proximity to Darwin, there are a large number of unsealed minor roads connecting communities and cattle properties.
in the Darwin catchments. These roads involve several creek crossings with limited or no causeway or bridge infrastructure, and are often inaccessible during the wet season.

Figure 3-19 shows the heavy vehicle access restrictions for roads within the Darwin catchments, as per the National Heavy Vehicle Regulator. Except for urban roads in Darwin and other towns, all roads within the Darwin catchments permit Type 2 road trains, which are vehicles up to 53 m in length (typically a prime mover pulling three 40-foot trailers, Figure 3-20). Darwin Port is also accessible by these road trains. Despite the poor condition of many of the local roads, these large road trains are permitted due to minimal safety issues from low traffic volumes and minimal road infrastructure restrictions (e.g. bridge limits, intersection turning safety). However, drivers would regularly use smaller vehicle configurations on the minor roads due to the difficult terrain, single lane access and during wet conditions.

Figure 3-19 Vehicle access restrictions for the Darwin catchments
Truck classes listed from shortest to longest in legend, as shown in Figure 3-17.
Figure 3-21 shows the speed limits for the road network within the Darwin catchments. These speed limits are usually higher than the average speed achieved for freight vehicles, particularly on unsealed Rank 2 and 3 roads. Heavy vehicles using such unsealed roads would usually achieve average speeds of no more than 60 km/hour, often as low as 20 km/hour when transporting livestock.
The Stuart Highway is the main route to Darwin Port and to markets in the south. From 2002 to 2013 the highway has been closed a total of 41 days due to impassable flooding and high-clearance only restrictions (NT road closure data). For access to Darwin, road closures are minimal. The Darwin catchments have a good quality standard gauge rail line, providing freight access to the port. From 2000 to 2004 the line was extended from Alice Springs to Darwin Port (East Arm), providing rail access to the southern states. The rail line is primarily used for bulk commodity transport (mostly minerals) to Darwin Port. There are no branch lines in the Darwin catchments, and use of the railway within or near the study area requires road transport to loading points (e.g. Adelaide River).

Supply chains and processing

A large proportion of cattle stations in the Darwin catchments (Figure 3-22) can only be accessed via unsealed Rank 3 local roads. Agricultural production is currently dominated by beef and horticulture, particularly live cattle export.

Figure 3-22 Agricultural enterprises in the Darwin catchments

Roads are colour-coded to show the number of trailers per year of agricultural produce transported along them.
The road network has high volumes of annual truck movements along the Stuart Highway, mostly to Darwin Port (487,000 head of cattle in 2015) via the cattle export depots. There are also up to 400 head per day transported to the AACo (Australian Agricultural Company) abattoir at Livingstone although AACo announced in May 2018 that this abattoir was to be closed.

Table 3-8 provides volumes of agricultural commodities transported into and out of the Darwin catchments. Live export of cattle is by far the biggest industry in terms of volume (2014 values). Some export depots are located outside of the Darwin catchments, which is why there is significant live export temporarily transported outside the study area en route to the port.

Table 3-8 Overview of agriculture commodities transported into and out of the Darwin catchments

Prices for horticultural produce can vary substantially over time, which in turn can affect what farmers choose to grow.

<table>
<thead>
<tr>
<th>COMMODITY</th>
<th>DESTINATION</th>
<th>INBOUND</th>
<th>OUTBOUND</th>
<th>INDICATIVE PRICES ($/KG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beef (head)</td>
<td>Live export</td>
<td>305,280</td>
<td>215,760</td>
<td>3.00</td>
</tr>
<tr>
<td></td>
<td>Abattoirs</td>
<td>90,240</td>
<td>16,560</td>
<td>2.68</td>
</tr>
<tr>
<td></td>
<td>Property</td>
<td>43,440</td>
<td>23,530</td>
<td>2.15</td>
</tr>
<tr>
<td></td>
<td>Feedlots</td>
<td>0</td>
<td>2,400</td>
<td>2.60</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>0</td>
<td>5,040</td>
<td>NA</td>
</tr>
<tr>
<td>Boxed beef (t)</td>
<td></td>
<td>630</td>
<td>29,884</td>
<td>5.48</td>
</tr>
<tr>
<td>Boxed chicken (t)</td>
<td></td>
<td>330</td>
<td>0</td>
<td>NA</td>
</tr>
<tr>
<td>Mixed (t)†</td>
<td></td>
<td>19,723</td>
<td>381</td>
<td>NA</td>
</tr>
<tr>
<td>All horticulture (t)</td>
<td></td>
<td>21,573</td>
<td>0</td>
<td>NA</td>
</tr>
<tr>
<td>Bananas (t)</td>
<td></td>
<td>0</td>
<td>3,206</td>
<td>1.92</td>
</tr>
<tr>
<td>Mango (t)</td>
<td></td>
<td>0</td>
<td>16,455</td>
<td>3.14</td>
</tr>
<tr>
<td>Melons (t)</td>
<td></td>
<td>0</td>
<td>7,776</td>
<td>1.07</td>
</tr>
<tr>
<td>Pumpkins (t)</td>
<td></td>
<td>0</td>
<td>559</td>
<td>0.75</td>
</tr>
<tr>
<td>Onions (t)</td>
<td></td>
<td>0</td>
<td>5</td>
<td>0.45</td>
</tr>
<tr>
<td>Asian vegetables (t)‡</td>
<td></td>
<td>0</td>
<td>8,800</td>
<td>NA</td>
</tr>
</tbody>
</table>

NA = not available.
†Mixed – mixture of horticulture and cold meat, usually from distribution centres.
‡Source: NT Farmers (2015).

Horticulture, particularly mangoes, melons and Asian vegetables, also has a significance presence in the Darwin catchments. Inbound horticulture and mixed agriculture represents food transported to supermarkets in Darwin.

Energy

Electricity in the Darwin catchments is supplied by four main power stations and delivered via the Darwin-Katherine Interconnected System (DKIS), the largest energy grid system in the NT. The DKIS is isolated from other Australian grids such as the east coast National Electricity Market (NEM) grid (EPRI, 2015). Combined generation capacity is 511.3 MW and annual electricity production is in the order of 1547 GWh (Power and Water Corporation, 2015a; Territory Generation, 2017) (Table 3-9). Generation and network infrastructure in the vicinity of Darwin are
centrally managed by the Northern Territory Government-owned entities Territory Generation and the Power and Water Corporation respectively. The largest generation facility is the 310 MW Channel Island Power Station (CIPS), located on the island of the same name across the Darwin Harbour to the south of the central business district (CBD) and connected by road to the mainland. CIPS is the main source of electricity for the Darwin-Katherine grid, and is powered by natural gas with diesel fuel back-up capability. Two smaller power stations are located at Pine Creek (26.6 MW, privately owned by a mining company) and Katherine (34.7 MW, also managed by Territory Generation), and provide supplementary energy to the grid and run on gas with diesel fuel back-up capability. The Power and Water Corporation are also investigating the use of an estimated 30 MW of standby generation from commercial customers in the DKIS, additional generation that may be made available under constrained network conditions (Power and Water Corporation, 2015a).

Table 3-9 Energy generation facilities in the Darwin catchments

<table>
<thead>
<tr>
<th>POWER STATION FACILITY NAME</th>
<th>CAPACITY (MW)</th>
<th>ANNUAL ELECTRICITY PRODUCTION (MWh)</th>
<th>GRID</th>
<th>PRIMARY FUEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Island Power Station</td>
<td>310</td>
<td>1,068,439</td>
<td>DKIS</td>
<td>Natural gas (diesel back-up)</td>
</tr>
<tr>
<td>Weddell Power Station</td>
<td>129</td>
<td>430,558</td>
<td>DKIS</td>
<td>Natural gas</td>
</tr>
<tr>
<td>Pine Creek Power Station</td>
<td>26.6</td>
<td>191,081</td>
<td>DKIS</td>
<td>Natural gas</td>
</tr>
<tr>
<td>Katherine Power Station</td>
<td>34.7</td>
<td>11,247</td>
<td>DKIS</td>
<td>Natural gas (diesel back-up)</td>
</tr>
<tr>
<td>Berrimah Power Station</td>
<td>10</td>
<td>Back-up/standby</td>
<td>DKIS</td>
<td>Natural gas</td>
</tr>
<tr>
<td>Shoal Bay Landfill Gas Facility</td>
<td>1.0</td>
<td>7,688</td>
<td>DKIS</td>
<td>Landfill methane gas</td>
</tr>
<tr>
<td>Total</td>
<td>511.3</td>
<td>1,709,013</td>
<td>na</td>
<td>na</td>
</tr>
</tbody>
</table>

na = not applicable.
DKIS = Darwin-Katherine Interconnected System.

While there is significant potential for renewable energy generation, there currently exists only one renewable energy power station in the Darwin catchments. The 1 MW Shoal Bay Landfill Gas facility is a methane generation plant owned by Darwin City Council. Electricity generated is sold back into the grid through a power purchase agreement with Territory Generation (Territory Generation, 2016). There is also an increasing array of large-scale rooftop solar installations such as those at Darwin Airport and Casuarina Shopping Centre. The NT Government has signalled its intent to increase renewable energy generation to 50% by 2030, and as such the renewable generation component is anticipated to increase (Northern Territory Government, 2016).

The DKIS services Darwin city, Palmerston, suburbs and surrounding rural areas of Darwin, terminating some 300 km south at the township of Katherine and its surrounding rural areas (Figure 3-23). The network operations for the DKIS are managed by the Northern Territory Government-owned Power and Water Corporation and regulated by the Utilities Commission of the NT. The Utilities Commission regulates licences and applies a Guaranteed Service Level Scheme to customers consuming below 160 MWh (Power and Water Corporation, 2015a). The DKIS electrical network operates at transmission voltages of 132 and 66 kV and distribution reticulation at 22 kV and 11 kV.

The Darwin-Katherine Transmission Line (132kV) extends from CIPS to a 132/22 kV substation adjacent to the Katherine Power Station, with a 132/22 kV substation at Manton Dam and a
132/66 kV substation at Pine Creek. South of Darwin, a single 66 kV 15 MVA overhead line extends south-eastward from the Stuart Highway near Humpty Doo and along the Arnhem Highway to the Mary River (Power and Water Corporation, 2015a). This small rural system is not cyclone coded and is being upgraded to provide an alternative supply from the Humpty Doo Zone Substation (Power and Water Corporation, 2015a).

![Diagram of the electricity network serving the Darwin catchments](source)

Figure 3-23 Extent of the electricity network serving the Darwin catchments, illustrating transmission and distribution networks and generation facilities

Source: Power and Water Corporation (2017b).

The Northern Territory Government-owned Jacana Energy is the dominant electricity retailer for the majority of residential and light commercial customers in the DKIS. There is competition in the market for major commercial and industrial customers and these customers have a number of retailers (Utilities Commission, 2016).

**Water**

Darwin River Dam currently supplies 85% of the urban water demand and the McMinns and Howard East Borefields in the DRWCD currently supply on average 15% of urban water demand (Power and Water Corporation, 2015a). Storage capacity of the Darwin River Dam is approximately...
265,000 ML, and the borefields can supply a maximum capacity of approximately 23 ML/day under best operating conditions (Power and Water Corporation, 2015b). The utilisation rate for the source water asset is between 71% (based on water licences) and 100% (based on available extraction) and heavily dependent on seasonal water yields (Power and Water Corporation, 2015b). There is no conventional water treatment plant for the Darwin water supply; the water is simply disinfected and fluoridated before provision to customers (Power and Water Corporation, 2015b). The Darwin area requires a new water source to be identified and developed to meet the needs of the projected demand over the next five years (Power and Water Corporation, 2015b). Possible future water supply sites short-listed by Power and Water for future consideration include Adelaide River offstream water storage (AROWS), Upper Adelaide River Dam, Mount Bennett Dam and the Marrakai Dam (DLPE, 2015).

The extent of reticulated water supply in the Greater Darwin area extends from the Darwin CBD in the north, to some 75 km south along the Stuart Highway to the intersection of Manton Dam (Figure 3-24). The easternmost point of the reticulated network extends about 13 km east from the Stuart Highway at Coolalinga to Herbert (Power and Water Corporation, 2017a).

Beyond Manton Dam in the south-west, bulk supply pipeline infrastructure connects the Darwin River Dam (DLPE, 2015). Manton Dam is not currently in service, and will require major infrastructure investment (about $100 million) to return to service (Power and Water Corporation, 2015b).

Outside of the Darwin urban water network, private water supplies rely on groundwater as the dominant form of water supply. Some isolated settlements are also provided with off-grid reticulated water within small residential zones. The satellite residential area of Mandorah, located across the Darwin Harbour from the Darwin CBD, has a local borefield and 12 km of water reticulation network for approximately 200 residential lots (Power and Water Corporation, 2015b, 2017a).

A second isolated water network at Murrumujuk, to the north north-east of the Darwin water grid, consists of 16 km of water reticulation and is 20 km from the nearest link to the Darwin water grid (DLPE, 2015; Power and Water Corporation, 2017a). Two Indigenous communities, Belyuen and Acacia-Larrakia (both with populations under 200) are supplied with isolated public (ground) water and sewerage services with local reticulation by Power and Water Corporation under a community service obligation to the Northern Territory Government (IES, 2016).
Before investigating the potential for new dams in the Darwin catchments it is prudent to first examine existing dams and the extent of regulation and quantities of general and strategic reserves in river systems. Table 3-10 lists existing large dams (>10 GL capacity and >10m wall height) in the Darwin catchments.

Two large dams have been constructed in the Darwin catchments, Darwin River Dam and Manton Dam. Further detail on these existing dams is provided in the companion technical report on surface water storage (Petheram et al., 2017).
Table 3-10 Constructed large dams in the Darwin catchments
Locations in parentheses indicate Australian Water Resource Council catchment.

<table>
<thead>
<tr>
<th>NAME OF DAM</th>
<th>NEAREST TOWN</th>
<th>ORIGINAL OWNER</th>
<th>YEAR CONSTRUCTED</th>
<th>HEIGHT ABOVE BED LEVEL (M)</th>
<th>STORAGE CAPACITY AT FSL (GL)</th>
<th>PRIMARY INTENDED PURPOSE</th>
<th>TYPE OF DAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Darwin River Dam (Darwin)</td>
<td>Darwin</td>
<td>NT PWC</td>
<td>1972</td>
<td>27</td>
<td>265</td>
<td>Water supply</td>
<td>Concrete gravity</td>
</tr>
<tr>
<td>Manton Dam (Adelaide)</td>
<td>Darwin</td>
<td>NT PWC</td>
<td>1942</td>
<td>24</td>
<td>13</td>
<td>Recreation</td>
<td>Concrete gravity</td>
</tr>
</tbody>
</table>

Source: ANCOLD Register of Large Dams (https://www.ancold.org.au/).

**Darwin River Dam**

The Darwin River Dam, owned and operated by the Northern Territory Power and Water Corporation, currently provides 85% of Darwin’s water supply (Figure 3-25). The dam was completed in 1972 with a 35 m wide uncontrolled spillway on the left abutment. The spillway was widened in 2002 to 265 m to improve spillway capacity and in 2010, the embankment was upgraded and the spillway crest raised 1.3 m, increasing storage capacity and water yield. There is limited capacity to further increase the storage capacity of the Darwin River Dam.

![Figure 3-25 Darwin River Dam looking upstream](Photo: CSIRO)

Releases from the dam are made via a pipeline to a pump station downstream of the dam and then via pipeline to a reservoir and transfer station where the supply is blended with the bore
water supply. Environmental flow releases are also made to the river. Power and Water is licensed to extract 49.1 GL from the dam.

**Manton Dam**

Manton Dam was Darwin’s first source of surface water supply (Figure 3-26). Construction was completed in 1942. Supply was conveyed to Darwin via a pump station downstream of the dam and two transmission pipelines (300 mm and 375 mm diameter). Since the completion of the Darwin River Dam in 1972, Manton Dam has not been used as part of the Darwin supply. Releases from the dam can be made to the river through a micro hydro-electric power plant. The dam, which is also managed by the Northern Territory Power and Water Corporation, has in recent years become a popular recreation facility for boating, water sports and fishing.

The Power and Water Corporation intend to return the dam to its water supply service function by about 2025 as a short-term measure to provide additional water supply to Darwin. Consideration has been given to developing larger storage at the site by constructing a higher dam downstream of the existing structure or, alternatively, a higher dam further upstream in the catchment, maintaining the storage level in the existing dam. Consideration has also been given to a raising of the existing dam structure. These options would have major impacts on the existing recreation facilities and only provide a modest increase in the available supply.

![Manton Dam looking upstream](Image)

*Photo: CSIRO*

The return to service of Manton Dam would involve a new intake arrangement, new suction main, pump station and 21 km long 1050 mm diameter delivery main to a proposed new storage and treatment facility at Strauss, south of Darwin city.
Current surface water use and allocation

Surface water allocations have been granted for urban and agricultural use in the Darwin area from various streams. The largest allocation is for public water supply at 56 GL/year, extracting water mainly from Darwin River. Agriculture is the next largest user of fresh surface water with allocations totalling 3.8 GL/year most of which is located in the Adelaide River catchment.

Current groundwater use and allocation

Groundwater allocations are prominent in parts of the Darwin catchments, particularly in the DRWCD in the northern Finniss and Adelaide catchments (Figure 3-27).

![Figure 3-27 Current groundwater allocations for the Darwin catchments](source)

Most of the groundwater allocated comes from the Proterozoic dolostone (Koolpinyah Dolostone, Coomalie Dolostone and the Berry Springs Dolostone) aquifers. The purpose of the allocations from these aquifers is mostly for irrigated agriculture (6.6 GL/year) and to supplement Darwin’s public water supply (8.4 GL/year). An almost equivalent amount of groundwater is also allocated for the purpose of irrigated horticulture and domestic supplies, but the use is unmetered due to the ‘15 litre per second exemption’. This exemption, which excludes bores that pump less than 15 litres per second from having a licensed allocation, has been in place since the commencement of the Water Act in 1992, but has recently been revoked (DENR, 2017). Marsden Jacob Associates
(2012) estimated that in 2012 approximately 10 GL/year of unmetered groundwater use was occurring in the DRWCD from bores using groundwater for irrigated horticulture and domestic purposes under the ‘15 litre per second exemption’. Other major allocations of groundwater are associated with the Coomalie Dolomite aquifer, where approximately 2 GL/year is allocated for the water supply for the town of Batchelor. The only other significant groundwater allocation is for the Koolpinyah Dolostone aquifer in the Wildman catchment. This allocation is approximately 8 GL/year and was for irrigated agriculture which has now ceased and the allocation is now not fully utilised.

**Projected urban and industrial water demand**

Current annual demand for water in the Greater Darwin region (i.e. between about 40 to 45 GL) is approaching the current water supply system yield. The Power and Water Corporation is currently investigating short and medium-term supply augmentation options. The Darwin River Dam storage level was raised in 2010 as a short-term option at the time. The return to service of Manton Dam to provide additional water supply to Darwin is an additional short-term option. Medium to long-term options include the construction of a new reservoir. At the moment the preferred option of the Power and Water Corporation is the Adelaide River offstream water storage (AROWS).

Darwin’s future annual water demand to 2065 is projected to be between about 50 and 60 GL depending upon assumptions regarding population growth and the success of demand management programs (e.g. Living Water Smart).

**Community infrastructure**

The availability of community services and facilities can play an important role in attracting or deterring people from living in newly-developed areas in the Darwin catchments. The rural parts of the Darwin catchments are served by 16 schools and total student numbers have risen slightly from 2991 in 2012 to 3308 in 2016. A further 59 schools service the urban parts of the Darwin catchments (Stokes et al., 2017).

Within the Darwin catchments there is one public and one private hospital, both located in Darwin (Table 3-11). A new public hospital in Palmerston is scheduled to come into service in 2018. Each 1000 people in Australia require 4.0 hospital beds served by 28 fulltime equivalent hospital staff and $4.0 million/year funding to maintain current mean national levels of hospital service (AIHW, 2017a).

Recent census data showed that approximately 10% of private dwellings in the Darwin catchments were unoccupied. This is a smaller proportion than the NT and national average (Table 3-12) and suggests that the current pool of housing may have limited capacity to absorb any future increases in population.
3.4 Social and investor values

3.4.1 INTRODUCTION

There are a diverse set of stakeholders with different and sometimes conflicting interests and values relating to the use of water resources and irrigated agricultural development across the Darwin catchments. If greenfield developments were to proceed, the diversity of stakeholder perspectives has implications for the ability of developers to gain and maintain social licence to operate throughout the development process.

3.4.2 STAKEHOLDERS, THEIR VALUES AND POTENTIAL ENGAGEMENT STRATEGIES

Stakeholder analysis and a literature review suggests that northern Australia is highly valued, with the extent and nature of these values shifting through time and between stakeholder groups. For example, from about the late 20th century northern Australia has become increasingly valued for the environmental, aesthetic, cultural and recreational services it provides, rather than its ability to produce agricultural commodities. The rainbow diagram in Figure 3-28 illustrates the diversity of local and national stakeholders in the Darwin catchments, and their likely support for greenfield development of irrigated agriculture. It is important to note that many context-specific factors are missed in this top-down process, and that factors such as the scale of the benefits and to whom benefits may flow may impact support.
Underpinning the likely support, or lack thereof, of stakeholder or interest groups for the potential development of greenfield irrigated agriculture in northern Australia are a set of social values, beliefs, attitudes and norms that are often shared within each group. In general, demographers and commentators note a shift from productivist values (Irving, 2014) centred around the belief that economic productivity and growth are desirable outcomes, towards consumptive (for amenity) and protectionist values in northern Australia (Holmes, 2012). Table 3-13 summarises key stakeholder values that may impact the social licence to operate of development initiatives such as greenfield agriculture. Indigenous-specific values are summarised in Section 3.5.
### Table 3-13 Summary of published stakeholder and interest group values relevant to the development of greenfield irrigated agriculture in northern Australia

Ordered least likely to support development through to most likely to support development (as per Figure 3-25). Stakeholder groups who broadly share values related to potential development are combined.

<table>
<thead>
<tr>
<th>STAKEHOLDER</th>
<th>VALUES, ATTITUDES, BELIEFS AND NORMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Inter)national environmental organisations</td>
<td>Want natural environment protected, Indigenous culture valued, sustainability maintained. The ‘real Australia’, utopia, setting for psychological challenges, a ‘proving ground’. Current human geography valued (e.g. few people, poor roads/lack of 2WD access). Valued for nature-based activities, large fish populations, scenic areas and secluded locations. Concern about land clearing, threats to Indigenous values, river diversion, irrigated agriculture, water as a public asset, rivers not dammed, no inter-basin transfer of water or groundwater extraction.</td>
</tr>
<tr>
<td>Four-wheel drivers, retired domestic tourists, international tourists, bushwalkers, safari hunters</td>
<td>High value placed upon condition of floodplains, quality of recreational fishing, condition of waterholes. High willingness to pay for rivers to be managed for recreation, cultural and environmental services. Small proportion considers irrigated agriculture important, or wishes it to increase significantly.</td>
</tr>
<tr>
<td>Southern Australians</td>
<td>Passion for rivers, camping, fishing, strong place attachment to rivers and related recreation.</td>
</tr>
<tr>
<td>Residents</td>
<td>Strongly value perceived easy lifestyle (current human geography). Environment and recreation more important than new commercial/retail business and primary industries. Low value placed on income from irrigation agriculture, high value on environmental and cultural assets. Less willing to pay for management of cultural services than southern Australians. Lack of trust in government-driven planning.</td>
</tr>
<tr>
<td>Amateur fishers and their representatives</td>
<td>Vision: highly productive, innovative, resilient, commercially exciting economy, culturally diverse, dynamic, inclusive communities, relaxed. Value developments that leverage and consider social, economic and environmental assets, impacts. Interest in carbon trading, arts and culture sector, nature and culture-based tourism. Infrastructure, institutions and social capital cited as higher concerns to development than lack of water.</td>
</tr>
<tr>
<td>Local shires</td>
<td>Occupation as a lifestyle choice and for identity. Environmental stewardship goals and lifestyle goals more important than economic goals Low ability to adapt to change. Free trade, open markets, property rights and private enterprise. Want institutions and infrastructure (largely road networks, but also soft infrastructure) for development.</td>
</tr>
<tr>
<td>Pastoralists</td>
<td>Self-identify as innovators, high adaptive capacity, strong motivations towards profitability. Express concern about the environment (including water quality) but not the rhetoric of wilderness.</td>
</tr>
</tbody>
</table>

Stakeholders are also differentiated in terms of their level of interest in, and influence over, an action or change. These differences can help guide engagement strategies, especially when combined with an understanding of stakeholder values like those highlighted in Table 3-13. Interest/influence matrices generated by the Assessment’s stakeholder analysis and literature
review mapped stakeholders into four broad types of appropriate engagement: (i) partner, (ii) involve/engage, (iii) consult, and (iv) inform (Table 3-14). It is important to note that this approach is indicative: a bottom-up stakeholder identification process is a more intensive, rigorous and best-practice approach (Reed et al., 2009) for understanding stakeholders. The approach used by Nolan (2010) for the Howard East Aquifer provides a good example.

Table 3-14 Stakeholder engagement typology for the Darwin catchments, as determined via influence/interest matrices related to the development of irrigated agriculture in a greenfield site.
Partner = High interest, high influence. Involve/engage = Low or moderate interest, high influence. Consult = High interest, low or moderate influence. Inform = Low interest, low influence.

<table>
<thead>
<tr>
<th>SCALE</th>
<th>PARTNER</th>
<th>INVOLVE/ENGAGE</th>
<th>CONSULT</th>
<th>INFORM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local</td>
<td></td>
<td>Amateur fishers</td>
<td>Horticulturalists</td>
<td>Australian Government</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Irrigated foresters</td>
<td>– environment</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mining interests</td>
<td>– defence</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Natural resource management organisations</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pastoralists</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Residents</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Traditional Owners</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Traditional Owner corporations</td>
<td></td>
</tr>
<tr>
<td>Regional</td>
<td>Australian Government</td>
<td>Office of Northern Australia</td>
<td>Agricultural representatives (Northern Territory)</td>
<td>Agricultural representatives</td>
</tr>
<tr>
<td></td>
<td>– primary industries</td>
<td>Southern Australians</td>
<td>Environmental organisations (international and national)</td>
<td>Bushwalkers</td>
</tr>
<tr>
<td></td>
<td>– water</td>
<td></td>
<td>Indigenous business representatives</td>
<td>Creative industry</td>
</tr>
<tr>
<td></td>
<td>Northern Australia</td>
<td></td>
<td>Indigenous heritage protection agencies</td>
<td>Australian Government</td>
</tr>
<tr>
<td></td>
<td>Development Office</td>
<td></td>
<td>Indigenous Land Councils</td>
<td>– environment</td>
</tr>
<tr>
<td></td>
<td>NT Government</td>
<td></td>
<td>Indigenous natural resource management organisations</td>
<td>Four-wheel drivers</td>
</tr>
<tr>
<td></td>
<td>– environment</td>
<td></td>
<td>Regional economic development representatives (regional and national)</td>
<td>Mining interests</td>
</tr>
<tr>
<td></td>
<td>– infrastructure,</td>
<td></td>
<td></td>
<td>Natural resource management organisations</td>
</tr>
<tr>
<td></td>
<td>planning, logistics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>– primary industries</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Utilities provider(s)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Stakeholders in the ‘partner’ section are likely to have a high level of interest and influence related to potential developments in the Darwin catchments. Early, intensive, iterative engagement with these groups, resulting in the co-design of development initiatives, may be most appropriate for these groups. Regular discussions are likely to be appropriate with involve/engage/consult stakeholders. Stakeholders in the ‘inform’ section may accept occasional one-way communication about development in the Darwin catchments.

The results of this analysis suggest that careful thought is needed as to the purpose of development, which ecosystem services may change through the development, how stakeholders are engaged and to whom benefits are intended, as key stakeholder values relate to all of these factors. At scale, development planning and implementation is likely to require a systematic and robust social impact analysis, including an investigation of, and ongoing engagement with, stakeholders and their interests.
3.4.3 POTENTIAL INVESTORS IN IRRIGATED AGRICULTURE

Very little is known about pre-existing or potential investors. To help address this gap, this section provides an initial exploration of potential investors in irrigated agriculture in northern Australia. An initial typology of potential investors across northern Australia highlighted the variety of potential groups and their disparate investor potential, indicated by access to natural and human/financial/social capital. For example, Indigenous landholding/leaseholding corporations have potential access to a significant level of natural capital for development, whereas family trusts may have high levels of human/financial/social capital but little access to natural capital. From this typology, six groups were interviewed (see Section 3.5 for the results of interviews with Indigenous Traditional Owners). Investors or potential investors from international agribusinesses, large companies with agricultural interests and small-scale owner-operator horticulturalist types were also interviewed across northern Australia, with five from the Darwin catchments. These investors perceived similar investment constraints as investors across northern Australia, and there was no difference between investor perspectives and investor type. In order of importance, these perceived constraints were: i) institutional uncertainty, ii) institutional complexity, iii) economy of scale issues, iv) poor infrastructure, and v) training and retaining a skilled workforce. Institutional certainty, simplicity and bureaucratic speed were the key perceived potential enablers of investment in irrigated agriculture. There was less consistency between investors regarding other enablers of irrigated development. Regardless, government support was the most consistently cited enabler of further investment.

The data represents a preliminary sample that acts as a marker of the additional information required to secure investor potential. This is particularly so for small- to medium-scale investors (including local landowners and leaseholders) whose views may not be so effectively represented at higher levels of decision making.

3.5 Indigenous values, rights, interests and development objectives

3.5.1 INTRODUCTION AND RESEARCH SCOPE

Indigenous people represent a substantial and growing proportion of the population across northern Australia, and control significant natural and cultural resource assets, including land, water, and coastlines. They will be crucial owners, partners, investors, and stakeholders in future development. Understanding the past is important to understanding present circumstances and future possibilities. Section 3.5 provides some key background information about the Indigenous Australians of the Darwin catchments and their specific values, rights and objectives in relation to water and irrigated agricultural development. Section 3.5.2 describes the past habitation by Indigenous people, the significance of water in habitation patterns, and the impact of exploration and colonisation processes. Section 3.5.3 reviews the contemporary situation with respect to Indigenous residence, land ownership and access. Section 3.5.4 outlines Indigenous water values and responses to development, and Section 3.5.5 describes Indigenous-generated development objectives.

The material provided here represents a short summary of the research undertaken, and further details regarding this component of the Assessment are contained in the companion technical
Engagement with Indigenous people is a strong aspiration across governments and key industries, but models of engagement can vary considerably and competing understandings of what ‘engagement’ means (consultation, involvement, partnership, etc.) can substantially affect successful outcomes. Standard stakeholder models can also marginalise Indigenous interests, reducing what Indigenous people understand as prior and inalienable ownership rights to a single ‘stake’ equivalent to all others at the table.

Guided by advice from the Northern Land Council (NLC) and from senior Traditional Owners in the study area, the Assessment engaged nominated senior Indigenous decision makers from within the Darwin catchments in one-on-one and small group interviews and in regional NLC meetings to establish a representative range of views regarding water and agricultural development. The companion technical report (Barber, 2018) provides details of this data and is a crucial supporting document for the summary provided here. A small number of comments are replicated in the following sections to show the type of data obtained, complemented by key themes analysed in the data. The Assessment does not provide formal Indigenous group positions about any of the issues raised and does not substitute for formal processes required by cultural heritage, environmental impact assessment, water planning, or other government legislation. Nevertheless, the research undertaken for this component of the Assessment identifies key principles, important issues and potential pathways to provide effective guidance for future planning and for formal negotiations with Indigenous groups.

3.5.2 PRE-COLONIAL AND COLONIAL HISTORY

Pre-colonial Indigenous society

Pre-colonial Indigenous society is distinguished by four primary characteristics: long residence times; detailed knowledge of ecology and food gathering techniques; complex systems of kinship and territorial organisation; and a sophisticated set of religious beliefs, often known as Dreamings. These Indigenous religious cosmologies provided a source of spiritual and emotional connection as well as guidance on identity, language, law, territorial boundaries, and economic relationships (Rose, 2002; Strang, 1997; Williams, 1986). From an Indigenous perspective, ancestral powers are present in the landscape in an ongoing way, intimately connected to people, country, and culture. Those powers must be considered in any action that takes place on the country. Northern Australia contains archaeological evidence of Indigenous habitation stretching back many thousands of years (Clarkson et al., 2017), but there remain gaps in the published archaeological record. Resource-rich riverine habitats were central to Indigenous economies based on seasonally-organised hunting, gathering and fishing. Rivers were also major corridors for social interaction, containing many sites of cultural importance (McIntyre-Tamwoy et al., 2013).
Colonisation

European colonisation resulted in very significant levels of violence towards Indigenous Australians, with consequent negative effects on the structure and function of existing Indigenous societies across the continent. Avoidance, armed defensiveness, and overt violence were all evident in colonial relationships as hostilities occurred as a result of competition for food and water resources, colonial attitudes and cultural misunderstandings. The establishment of pastoralism was a focus for conflict as pastoral homesteads and outstations were sited close to permanent water and the animals grazed fertile plains and river valleys used by Indigenous people for food and other resources (McGrath, 1987). As a consequence, Indigenous attacks on colonial pastoral operations were made both in retaliation for past attacks by colonists and as a response to shortages of food and other resources.

The Darwin area was first colonised in the 1860s and grew quickly following the discovery of gold at Pine Creek soon after. When the Northern Territory Aboriginals Act 1910 (SA) was passed, it made the Chief Protector of Aborigines in the NT the guardian of all children designated as either Aboriginal or half-caste (Aboriginal people of mixed descent) until they were 18 years old. Movements became restricted and children were forcibly removed. Children continued to be removed under this policy for decades, and some of the participants in the Assessment were people who were removed in this way.

Through the first half of the 20th century, Indigenous people became increasingly employed in the pastoral industry and took positions as stockmen and domestic workers. Extended families resided with their employed kin on the stations and received rations from the station owners, increasing the importance of the stations to Indigenous lives. Stock work also meant that some people were able to access their traditional lands, albeit in a modified way. In the second half of the 20th century, the closure of missions and government reserves, followed by the implementation of the Federal Pastoral Industry Award in 1968 resulted in considerable further social dislocation. Indigenous stockworkers and their families either left, or were evicted from stations and reserves, and the subsequent technological development in pastoralism (helicopters, motorcycles) further reduced the demand for Indigenous labour. Indigenous people from the Darwin catchments retained strong ties to one another and to local cultural landscapes, but were obliged to move into Darwin and into regional towns such as Adelaide River and Batchelor as well as to smaller settlements and encampments.

3.5.3 CONTEMPORARY INDIGENOUS OWNERSHIP, MANAGEMENT, RESIDENCE AND REPRESENTATION

Despite the pressures entailed by colonisation, country remained crucial to Indigenous peoples’ lives, sustaining a distinct individual and group identity as well as connections to past ancestors and future descendants. People are connected to places through a combination of genealogical, traditional and residential ties. Only some of these connections are formally recognised by the Australian state.

Indigenous ownership

The Indigenous owners of the Darwin catchments include the Makmak Marranungu, Kungarakan, Warai, Limilngan-Wulna, Minitja, and Larrakia peoples. There are also a range of related groups.
and subgroups within these regional ownership descriptors. The Assessment focused on the upstream rural and regional areas of the Darwin catchments and so did not engage the Larrakia people of Darwin itself, but focused on the other named groups. Ownership patterns tend to follow natural landscape features such as rivers and hills, and in some cases formal boundaries between ownership groups have been negotiated. However, in other places the edges of group territory are less distinct and/or there are overlapping claims. Information regarding the identification of potential owners and interest holders is provided by registered organisations such as the NLC and the Aboriginal Areas Protection Authority (AAPA).

In the NT jurisdiction there is specific land rights legislation that covers a wide area of the NT, namely the *Aboriginal Land Rights (Northern Territory) Act 1976* (Cth) (ALRA). This provides a form of collective freehold ownership, and two significant areas of the Finniss catchment are held through this form of ownership (Figure 3-29).

Figure 3-29 Indigenous freehold (Aboriginal Land) in the Darwin catchments as at July 2017
Data source: Northern Land Council (NLC)

Across the whole of Australia, the primary form of recognition for Indigenous interests is native title and associated Indigenous Land Use Agreements (ILUAs). Native title provides a series of
Indigenous native title claims and determinations

Native title determined not to exist
Registered applications for native title
Schedule of native title determination applications
ILUA registered

Figure 3-30 Indigenous native title claims and determinations in the Darwin catchments as at July 2017
Data sources: National Native Title Tribunal and Northern Land Council

Indigenous population and residence

Indigenous people comprise 9% of the total population in the Darwin catchments (Table 3-3). This includes Indigenous people who are part of the recognised local ownership groups identified above, as well as residents who identify as Indigenous but have their origins elsewhere. For many Traditional Owners, primary residential locations may be outside of the traditional lands to which they have formal ties. These patterns of residence and dispersal reflect a combination of historical involuntary relocation, voluntary movement to seek jobs and other opportunities, and kinship and family links. Indigenous communities in the Darwin catchments face a range of social and
demographic challenges, including significant unemployment, poor health and housing, structural impediments to economic participation, and social and family units under high levels of stress. Assessment participants sought economic and social conditions that would enable more of their people to reside on their own traditional lands as one response to these circumstances.

**Indigenous governance and representation**

Indigenous organisational and political structure within the Darwin catchments is quite diverse. The NLC is the major regional Indigenous representative organisation for the Darwin catchments, representing and acting for Traditional Owners with respect to Indigenous access, participation, partnership and ownership. Local groups in the area are represented through a range of Indigenous corporations and entities. Amongst the Indigenous groups consulted for this study, there were significant variations in existing capacity, resourcing, and ability to participate in natural resource management decision making.

3.5.4 **INDIGENOUS WATER VALUES AND RESPONSES TO DEVELOPMENT**

**Introduction: attachment, ownership, protection**

Indigenous values in relation to their country in the Darwin catchments encompass principles of attachment, ownership, and the responsibility to protect it. These are manifested in practical terms through:

- The assumption of Indigenous ownership of land and water resources.
- The need for formal external recognition of that ownership.
- The role of local histories in establishing local Indigenous connections and authority.
- The ongoing role of religious and spiritual beliefs.
- The existence of ongoing knowledge of group and language boundaries and identities.
- The importance of hunting and fishing activity to Indigenous cultures.
- Inter-generational obligations to both ancestors and descendants to care for the country.
- Regional responsibilities to near neighbours and downstream groups to maintain the integrity of the country.

These principles also apply to Indigenous attitudes to non-Indigenous activities on Indigenous lands. Four frequently highlighted principles include:

- consultation with the relevant owners
- consent for development
- compliance with the terms of policies and agreements, including Traditional Owner employment
- compensation for the access and use of resources.

These principles have clear implications for native title, cultural heritage and environmental impact assessment, as well as for broader issues of sustainable development.

**Cultural heritage**

Indigenous cultural heritage is a crucial manifestation of the principles of attachment, ownership, and protection. Cultural heritage itself has a number of components: archaeological sites; places
associated with traditional stories or traditional knowledge; and places of historical or contemporary importance. Cultural heritage is strongly correlated with permanent water, meaning that riverine and aquatic areas that are the focus of development interest are also likely to contain significant cultural heritage. Figure 3-31 shows the general concentration of Indigenous cultural heritage in the Darwin catchments listed in the Northern Territory Government record. This record is incomplete; the map demonstrates the presence of a layer, not its full extent. Consultations between development proponents and Traditional Owners will be significantly aided by early stage field scoping of cultural heritage issues and requirements.

Figure 3-31 General location of registered Indigenous cultural heritage sites in the Darwin catchments as at July 2017
Source: Aboriginal Areas Protection Authority (AAPA)

Contemporary Indigenous water values
In general terms, Indigenous water values emphasise securing sufficient water to maintain healthy landscapes and to support Indigenous needs. Those needs can be defined in multiple ways, and from an economic perspective encompass such activities as art and cultural production, hunting and gathering, and traditional medicine supply, as well as pastoralism, ecotourism, agriculture and
aquaculture. All of these needs depend on natural resources, highlighting the importance of securing and maintaining water supplies. Data from the Assessment clearly demonstrates the overall importance of water for practical hygiene, religious symbolism, and ancestral connection:

*Water is part of everything, you use it for drinking, washing. Following our tradition it is associated in Dreamtimes when water was created. We have that strong belief in the rainbow serpent it is the creator that makes billabongs and waterways. There is places that you go where the serpent lives under water. All those stories were passed on from one generation to the other, the elders. That is why water is important.*

*Traditional Owner from the Darwin catchments*

Statements about the importance of water from participants in the Assessment are consistent with broader statements that outline significant Indigenous water rights, values and interests, both in Australia (NAILSMA, 2009) and internationally (World Water Council, 2003).

**Responses to water and irrigation development**

In the Darwin catchments, Indigenous responses to water and irrigation development are interpreted through perceptions of past development, and through observations of ongoing environmental and climate change. Indigenous responses to water development and extraction included considerations of impacts on water quality, on streamflow, and on water-dependent ecosystems and human cultural practices. Large instream dams were not a favoured form of development, and in general, larger scale water and agricultural development was seen as incompatible with contemporary Indigenous values and lifeways. Indigenous concerns about water development also encompassed concerns about the cumulative impacts from other industries, particularly mining.

Awareness of their position as long-term custodians and their marginalised socio-economic and educational status affected Indigenous assessments of the relative risks and benefits associated with development proposals. Noting the above cautions, Indigenous participants also recognised that power imbalances may see large-scale development proceed. In this context, some data on preferences for particular kinds of water development were gathered, and the general trend from most to least favourable was:

1. flood harvesting to supply smaller, offstream storages
2. bore and groundwater extraction
3. smaller instream dams constructed in side tributaries or branches which do not restrict all of the flow
4. large instream dams in major river channels.

Proposals for specific sites may not accord with this general trend, and new information may alter the above order at both local and regional scales. With respect to major water and irrigation development, key Indigenous criteria for evaluation include:

- early and further formal group consultations about options, impacts and preferences
- development that specifically address Indigenous needs (for example, access, education, amenity, and recreational opportunities)
- appropriate cultural heritage surveys of likely areas of impact
• agreements that support Indigenous employment and other benefits during development
  construction and operation
• the need for ongoing monitoring of impacts that employs Traditional Owners
• support for Indigenous roles in development projects that connect water development with
  both water planning, wider catchment management and enterprise development.

**Indigenous interests in water planning**

Water planning is understood as one way of managing water development risk, but water
planning also has particular challenges. In Australia, the National Water Initiative set the goal that
jurisdictionally-based water plans need to recognise Indigenous needs in terms of access and
management (Department of Agriculture and Water Resources, 2017). This encompasses
Indigenous representation, incorporation of Indigenous social, spiritual and customary objectives,
and recognition of native title needs and uses. However, progress in implementing that
recognition has been slow due to a lack of knowledge about those interests, competing water
demands and the challenges of accommodating Indigenous perspectives in conventional planning
frameworks. However, a new water planning initiative has been publicised for Indigenous
landowners in the NT. Known as the Strategic Aboriginal Water Reserve (Northern Territory
Government, 2017), this initiative provides scope for further Indigenous recognition by creating
reserved water allocations for Indigenous people for development purposes.

Based on the data generated during the Assessment, formalising and refining Indigenous water
values and water planning issues in the Darwin catchments may require:

• Formal scoping discussions at local and catchment-scales about how best to support Indigenous
  involvement in water planning.
• Refinement of Indigenous governance rights, roles and responsibilities in water planning.
• Resourcing of Indigenous involvement in water planning, including formal training.
• The reservation of Indigenous-specific water allocations for development purposes.
• Further specification of the impacts on current and potential future native title rights and on
  cultural heritage.
• Articulating water planning processes with land and development planning.
• Addressing continuing Indigenous water research needs and information priorities.

These principles can also be applied to broader processes of catchment management and
associated development planning.

3.5.5 **INDIGENOUS DEVELOPMENT OBJECTIVES**

Indigenous people have a strong desire to be understood as development partners and investors
in their own right, and have generated their own development objectives. This stance informs
responses to development proposals outlined by others. As a group, Indigenous people are socially
and economically disadvantaged, but also custodians of ancient landscapes. They therefore seek
to balance short- to medium-term social and economic needs with long-term cultural, historical
and religious responsibilities to ancestral lands. Past forums have outlined Indigenous
development agendas that are consistent with Indigenous perspectives in the Darwin catchments (NAILSMA, 2012, 2013). These agendas are informed by two primary goals:

- greater ownership of and/or management control over traditional land and waters
- the sustainable retention and/or resettlement of Indigenous people on their country.

These goals are interrelated, because retention and/or resettlement relies on employment and income generation, and the majority of business opportunities identified by Indigenous people are land- and natural-resource dependent: pastoralism, conservation services, wild and cultivated bush foods and bush products, ecotourism, agriculture, horticulture, and aquaculture. Each group in the Darwin catchments has multiple responsibilities and management roles but, based on geography, residence, assets, governance and/or skills, some may more easily be able to sustain multiple business activities, while others may achieve greater success focusing on a single activity.

**Partnerships and planning**

Indigenous people in the Darwin catchments possess valuable natural and cultural assets and represent a significant potential labour force, but collectively lack business development skills and expertise. Partnerships can address this gap, but there is a need to improve the opportunities for business to understand and invest in Indigenous people and lands in the Darwin catchments. The development of a full business analysis may include the following actions:

- The investigation of the full range of potential business activities and options.
- The production of group and/or catchment plans and prospectuses to coordinate and define collective Indigenous assets and opportunities and to aid communication with potential investors.
- Further information and training for Indigenous people about the opportunities and constraints of partnerships with private industry, including effective use of Indigenous resource rights (land ownership and leaseholding native title, future water allocations, etc.).
- Targeted non-Indigenous community training regarding partnerships with Indigenous people, including models for shared benefit agreements and partnership arrangements, employment and training opportunities, etc.
- Creating incentives for Indigenous involvement in new development initiatives, including relocation and resettlement allowances, pathways from training to jobs, employer incentives to hire and retain Indigenous staff, etc.
- Training for younger Indigenous people about career planning as well as formal job skills.

Indigenous development objectives, and Indigenous development partnerships, are best progressed through locally specific, group and community-based planning and prioritisation processes that are nested in a system of regional coordination. Such planning and coordination can greatly increase the success of business development and of the opportunities for Indigenous employment, retention and resettlement that arise from them. Significant returns on investment may be achievable through well-targeted resourcing to local Indigenous entities, particularly PBCs, to build understanding of business priorities and development objectives, as well as regional coordination processes such as water planning and catchment management.
3.6 Legal and policy environment

3.6.1 INTRODUCTION

This section provides an overview of the legal and policy institutions relevant to water-related development in the Darwin catchments. The term ‘institutions’ is used here to refer to the rules and norms that govern water-related development that stem from international and domestic law and policy. The analysis sheds light on the nature of the rights and interests that are necessary to undertake, and could be affected by, water-related development. Four themes are used to structure the analysis: legal and policy context, interests in land, interests in water, and government approvals.

3.6.2 LEGAL AND POLICY CONTEXT

Government powers and responsibilities concerning the management of land and water resources in the Darwin catchments are shared between the Australian and Northern Territory Governments. While there is a degree of overlap between the powers and responsibilities of these two governments, each perform discrete functions.

Australian Government

The Australian Government performs three key functions in the Darwin catchments: oversight of native title, oversight of Aboriginal freehold land, and the implementation of Australia’s obligations under international law. Unlike other types of interests in land, native title and Aboriginal freehold land in the NT are federal responsibilities. Native title is managed under the Native Title Act 1993 (Cth), while Aboriginal freehold land is managed under the Aboriginal Land Rights (Northern Territory) Act 1976 (Cth). Similarly, in relation to international law, the Australian Government is responsible for ensuring Australia meets its international obligations. Under Australian law, international legal obligations have no direct effect on domestic law until and unless they are incorporated into it by an act of parliament. The most relevant federal statutes that give effect to international obligations and responsibilities are the Racial Discrimination Act 1975 (Cth) and Australian Human Rights Commission Act 1986 (Cth), which prohibit discriminatory behaviour, and the EPBC Act, which regulates activities that adversely affect ‘Matters of National Environmental Significance’.

Northern Territory Government

The Northern Territory Government is primarily responsible for the management of the land and water resources within the Darwin catchments. It is the ultimate ‘owner’ of most of the land in the NT, is responsible for the NT system of land title, manages Crown lands and reserves, regulates access to and the use of surface and groundwater, and manages the positive and negative externalities associated with development through planning, environmental and heritage regulations.
3.6.3 INTERESTS IN LAND

Proponents of water-related developments will require legal entitlements to access and use the subject land. This could involve the grant or acquisition of a freehold or leasehold interest in the land or the issuance of a licence for a period of time. Freehold and leasehold interests give the holder a legal interest in the land. In contrast, the holder of a licence obtains no property rights in relation to the land. Depending on the nature of the licence, the licensee will either have personal rights of access that are enforceable under contract or the licence will simply make an act lawful that would otherwise be unlawful. For proponents of water-related developments, licences will typically be used for initial exploratory purposes only. To undertake any material development, proponents will usually need to acquire a freehold or leasehold interest in the land from the current landholder, or have a freehold or leasehold interest granted by the state or territory government. Freehold and leasehold interests provide greater security and control than licences, and enable the holder to exclude most third parties from the land and the benefits that stem from its development and use.

Most of the land in the Darwin catchments is held as Crown leasehold land, Crown reserves, unallocated Crown land, freehold land and Aboriginal freehold land.

Crown leasehold land

Crown leasehold land is government owned land held under a lease, typically by a private party. The management of, and issuance of leasehold interests in, Crown land in the NT is governed by the *Crown Lands Act* (NT), *Pastoral Land Act* (NT) and *Special Purposes Leases Act* (NT). There are four main types of Crown leasehold interests that can be issued under these statutes: fixed term leases; perpetual leases; pastoral leases; and special purpose leases. These leases can be subject to restrictions on the use, development and transfer of land. For example, pastoral leasehold land can only be used for pastoral purposes unless a permit authorising a non-pastoral use has been issued by the Pastoral Land Board.

Crown reserves

Crown reserves are government owned land that have been reserved for specific purposes such as nature conservation, travelling stock and Indigenous people. These reserves are usually required to be managed in a manner consistent with the purposes for which they were declared. Generally, people wanting to use a reserve must obtain a licence to do so and there are restrictions on the circumstances in which licences can be issued.

Vacant Crown land

Vacant Crown land is government owned land that has not been reserved for any purpose and in which no interest has been granted. While unallocated, the land is not freely available for the public to use. To occupy or use vacant Crown land, it is necessary to obtain a licence under the *Crown Lands Act*, which will merely make the relevant activity lawful (rather than conferring a legal interest in the land). Freehold and leasehold estates can also be issued in relation to unallocated Crown land.
Freehold land

Freehold land is land in which a freehold estate has been granted. Freehold estates are the most complete legal interest in land under Australian law. While close to absolute ownership, freehold estates do not give the landholder the right to use the land as they please. The estates are almost always subject to reservations and the use and development of the land is regulated under planning, environment and other similar statutes.

Aboriginal freehold land

Aboriginal freehold land is freehold land held on trust for Indigenous Traditional Owners under the Aboriginal Land Rights (Northern Territory) Act 1976. Under this Act, Aboriginal Land Councils were established to represent and protect the interests of Traditional Owners, with Aboriginal Land Trusts created as the formal legal bodies that hold the freehold estates. There are four Land Councils in the NT: Northern, Central, Tiwi and Anindilyakwa. The Northern Land Council (NLC) covers the Darwin catchments. Like the other Land Councils, the NLC oversees dealings with the land held by the land trusts in its region. There are restrictions on dealings with Aboriginal freehold land under the Aboriginal Land Act (NT), including a prohibition on sale and transfer. The Aboriginal Land Act also makes it an offence for a person to enter onto or remain on Aboriginal land, unless they hold a permit from the Land Council or are an Aboriginal person who is entitled to do so in accordance with Aboriginal tradition.

In addition to the need for a freehold or leasehold interest, or a licence, any water-related development must be consistent with the native title arrangements that apply to the land. A significant proportion of the Darwin catchments to the south and east of the Adelaide River is subject to registered native title claims. Native title is a unique form of property interest under Australian law consisting of a bundle of rights defined by the laws and customs of the relevant Indigenous community. Reflecting its unique status, native title has its own system of determination (through the Federal Court of Australia), registration (at the National Native Title Registry, maintained by the National Native Title Tribunal) and protection (under the Native Title Act).

Where a native title claim or determined native title exists over an area of land, proponents will be required to engage with relevant Traditional Owners and the federal native title process. Importantly, water-related development in the Darwin catchments could involve ‘future acts’ that could be rendered invalid by the operation of the Native Title Act 1993, or trigger a right to compensation. In this context, relevant ‘future acts’ could consist of special legislation (or legislative amendments) made to facilitate the development, the issuance of property interests and approvals to support or authorise the development, and the conduct of related public works. There are a number of ways of avoiding invalidity of future acts, one of the most notable being entry into ILUAs with Traditional Owners. ILUAs are agreements between native title parties and others about the use of land and waters subject to native title, or over which native title is claimed. Where a determination is made that native title exists, ILUAs can be used to settle arrangements concerning the area and the treatment of native title. Even when native title has not been determined, ILUAs can be used to proactively settle arrangements concerning native title and the use and development of an area with Traditional Owners.
3.6.4 INTERESTS IN WATER

The ‘rights’ to the use, flow and control of all water in the NT are vested in the Northern Territory Government under the Water Act (NT). This legislation contains processes for water planning, the regulation of taking water (with and without government authorisation), and statutory requirements to obtain government approval for works related to water infrastructure (e.g. dams, bores, levies and pipes).

Water planning

The Water Act contains two main legislative mechanisms to support water management and planning: water control district declarations; and water allocation plans. Water control districts are typically in areas where there is a demand for water such that additional controls are required. For declared water control districts, the priority water uses (referred to as ‘beneficial uses’ under the Water Act) are identified and sustaining the beneficial uses forms the basis for the preparation of water allocation plans. Water allocation plans typically describe the total available water resources for an area, current and projected demand and the sustainable water yield and allocation of water to beneficial uses, and strategies for achieving its stated objectives. They also include rules for managing licences and permits, including water trading rules if applicable. The Darwin Rural Water Control District (DRWCD) lies within the Darwin catchments, and there are two relevant water allocation plans within this area: the Berry Springs water allocation plan; and the Howard water allocation plan (which is currently being developed).

Approvals for taking water

Under the Water Act, activities involving taking water are divided into two broad categories: those that can occur without a water licence; and those that can only occur with a water licence. Most water-related developments will require a licence. Licences are typically granted on a ‘first-in-first-serve’ basis, and for a period of up to 10 years. They are not attached to land but specify the land on which the water is to be taken and used. Importantly, the amount of water taken under a licence in any particular year can be limited by an Annual Announced Allocation. Annual Announced Allocations, announced in May each year by the Water Controller, are guided by water allocation plans or default allocation rules.

Water-related works approvals

Permits or licences are generally required under the Water Act to undertake water-related works involving waterways and groundwater. Specifically: (i) a permit is required to construct or alter a dam, water storage or other water control structure in a waterway, or in such a way as to affect the flow or likely flow of water in a waterway; (ii) a permit is required to construct works to take water from groundwater (including the drilling, construction, alternation, lugging, backfilling or sealing of a bore); and (iii) a licence is required to recharge groundwater. Landholders are able to drain their land and capture overland flows by constructing farm dams and other water storages without approval but only if: (a) the works are not in a waterway; and (b) the works do not sensibly diminish or increase the flow or likely flow of water in, or into, a waterway.
3.6.5 GOVERNMENT APPROVALS

In addition to holding the requisite rights and interests to access the land, and to take water, proponents of water-related development must have the necessary privileges to undertake the development. Some of these privileges will come with proponents’ interests in land. However, ownership of an interest in land does not provide the holder with the legal ability to use and develop the land as they please. Government regulations can control the use and development of land and water resources. The most relevant government regulations are those imposed under federal and territory planning, environment and heritage statutes.

Australian Government regulations

The Australian Government does not have planning legislation that applies to the Darwin catchments. However, it does have both environmental and heritage regulations that could apply to water-related development in the region. The principal federal environmental statute is the EPBC Act, which regulates actions that have significant impacts on ‘Matters of National Environmental Significance’, the environment on Commonwealth land, and the environment generally where the relevant action is carried out by a Commonwealth agency or on Commonwealth land. There are nine Matters of National Environmental Significance, the most relevant of which are World Heritage areas and National Heritage places (e.g. Kakadu National Park, located in the east of the Darwin catchments), Ramsar wetlands (Kakadu National Park), listed threatened species and ecological communities, and listed migratory species. Water-related development that could have significant adverse impacts on these matters must be referred under the EPBC Act for assessment and approval. Guidelines have been published by the federal environment department to help proponents determine when projects are likely to have significant impacts on matters protected under the Act. Due to the ambiguity associated with determining the significance of potential impacts, proponents should consult with the federal environment department about the need for referrals before undertaking water-related developments. In addition to the regulatory requirements under the EPBC Act, stakeholders interested in water-related development should be aware of the Aboriginal and Torres Strait Islander Heritage Protection Act 1984 (Cth) (ATSIHP Act). Declarations can be issued under the ATSIHP Act to protect significant Aboriginal areas and objects from injury or desecration. These declarations are rarely made but they can be powerful, forcing the cessation of projects affecting the relevant area or object. There are a number of other federal regulatory regimes that could apply to proponents involved in water-related development. Foreign investors should take particular note of the federal regulation of foreign investment under the Foreign Acquisitions and Takeovers Act 1975 (Cth) and Foreign Acquisitions and Takeovers Fees Imposition Act 2015 (Cth). Under this regulatory regime, the federal Treasurer can impose conditions and even block foreign investment proposals in Australia. Foreign interests in agricultural land are also required to be registered with the Australian Taxation Office under the Register of Foreign Ownership of Agricultural Land Act 2015 (Cth).
Northern Territory regulations

Planning

Land use planning in the NT is governed by the *Planning Act* (NT). Whether a development permit will be required for water-related development will depend on the zoning that applies to the land under the Northern Territory Planning Scheme. The Northern Territory Planning Scheme applies across the jurisdiction, except where an area is subject to a specific planning scheme (there is currently only one specific scheme, the Jabiru Town Plan). Not all land is zoned in the NT. Where land is unzoned, planning restrictions can still apply to the site. For example, planning restrictions apply to the clearing of native vegetation on unzoned land. For most water-related developments in the Darwin catchments, the consent authority will be the NT planning minister. The Northern Territory Planning Commission may be required to prepare a significant development report if the development is deemed to be a ‘significant development proposal’.

Environment

The main environment protection statute in the NT is the *Environmental Assessment Act* (NT). Projects that could have significant environmental impacts will usually require assessment by the Environmental Protection Authority (EPA) under the Act. The EPA and the NT environment minister are not responsible for approving projects; their role is advisory. The environment minister provides the EPA’s assessment report to the ‘responsible minister’ for decision, with additional comments if they consider they are necessary. In this context, the responsible minister is another minister with statutory decision-making responsibilities in relation to the project (e.g. the planning minister). In addition to the requirements under the Environmental Assessment Act, the *Waste Management and Pollution Control Act* (NT) regulates polluting and waste generating activities. Certain types of water-related developments could require approval under this Act.

Heritage

The two main NT heritage statutes are the *Heritage Act* (NT) and the *Northern Territory Aboriginal Sacred Sites Act* (NT). The *Heritage Act* protects three classes of places and objects: Aboriginal and Macassan archaeological places and objects; places and objects declared to be heritage places and objects under Part 2.2 of the Act; and places and objects declared to be protected classes of places and objects of heritage significance under Part 2.3. Under the Act, it is an offence to knowingly damage a heritage place, to remove something from a heritage place or damage or remove a heritage object, unless one of the exemptions applies. Most relevantly, these exemptions include when the activity is carried out under a work approval issued, or heritage agreement made, under the Act. The Northern Territory Aboriginal Sacred Sites Act protects sites that are sacred to Indigenous people or of significance according to Indigenous tradition. The Act prohibits entry onto sacred sites, the carrying out of work on or use of sacred sites and the desecration of sacred sites, other than in accordance with certificates issued under the Act by the Aboriginal Areas Protection Authority or responsible minister. It is a defence to prosecution if the defendant can prove there were no reasonable grounds for suspecting the site was a sacred site. On Aboriginal land, this defence can only be used if the defendant can also prove they had authority to be on the land and had taken reasonable steps to ascertain the location and extent of sacred sites on the land.
Major projects
The Northern Territory Government has a policy, the Major Project Status Policy Framework, that is intended to help major project proponents navigate government approval requirements. Under the policy, major project status is awarded to developments by the Northern Territory Government having regard to six main criteria: project significance (e.g. capital expenditure, employment); strategic impact (e.g. flow on benefits to other industries); complexity (government approval requirements and environmental, economic and social impacts beyond the project footprint); project feasibility; proponent’s capacity to deliver the project; and ancillary (covering the need for government support and local industry participation, local workforce development and social impacts on the community). While these criteria are used as a guide, ultimately, decisions on major project status are made at the discretion of the Northern Territory Government. If major project status is awarded, the proponent receives assistance with the identification of relevant government approval processes, whole of government coordination and facilitation of the project and project-related government approvals, and a dedicated government project case manager who works as a single point of contact on the project.

3.6.6 DURATION OF GOVERNMENT ASSESSMENT AND APPROVAL TIMES
Proponents of water-related developments should be aware that government assessment and approval processes can be resource intensive and time consuming. To illustrate this, an analysis was undertaken of the length of environmental assessments under the Environmental Assessment Act (NT) and the EPBC Act. The NT analysis covered all completed assessments under the Environmental Assessment Act since June 2006, while the EPBC Act analysis covered all projects located in the NT that were approved over the period 2010 to 2018.

Figure 3-32 shows the median length of each stage of the environmental assessment process for the sampled projects under the Environmental Assessment Act. The results are presented by industry and for the entire sample of 36 projects. There are four main stages in the process (not all of which are mandatory for all projects): i) screening (where the EPA determines whether the project requires formal assessment), ii) scoping (where the EPA determines the scope of, or Terms of Reference for, the environmental assessment), iii) assessment documentation (where the proponent prepares the assessment documentation), and iv) EPA report (where the EPA prepares its advice on the project).

The aggregate of the median length of each stage was 494 days, with the longest part of the process being the preparation of the assessment documentation (328 days). The median total assessment time was 517 days, with an average of 784 days. While these results are noteworthy, the length of the process varied considerably between projects and project types. For example, 22% of assessments took under 365 days, while 36% took longer than 730 days. The variability in assessment times reflects the flexibility of the process and the factors that influence its length, including the size and complexity of the proposals, the nature, magnitude and likelihood of relevant economic, social and environmental impacts, resource constraints within the EPA, and the speed with which proponents are able to produce relevant assessment information.
Figure 3-32 Median length of each stage of the assessment process under the Environmental Assessment Act (NT), 2006–2018

Industry codes: AG = agriculture; AQ = aquaculture; MAN = manufacturing; MNC = mining (non-coal); OG = oil and gas; RC = residential and commercial; TR = transport; WD = water resource development; Oth = other. The number of projects in each industry code is provided in parentheses.
Source: Northern Territory EPA

The federal EPBC Act assessment and approval process often runs in parallel with state and territory processes, meaning it does not necessarily add to project delays. Further, under the EPBC Act, assessments are frequently undertaken through relevant state and territory processes. For example, where a project requires Northern Territory Government approval under the Planning Act and Australian Government approval under the EPBC Act, the assessment carried out under the Environmental Assessment Act that guides and informs the Planning Act approval will often also cover, and be used for, the federal approval process. While the EPBC Act process has been designed to minimise duplication and delays, it can still be time consuming, particularly where state and federal approvals are sought sequentially.

Figure 3-33 shows the median length of the three main stages of the EPBC Act assessment and approval process (screening, assessment and approval) for the eight Northern Territory projects approved over the period 2010 to 2018. Again, the results are presented by industry and for the entire sample.

Figure 3-33 Median length of each stage of the assessment and approval process under the EPBC Act, all projects in the Northern Territory over the period 2010-2018
Source: Department of the Environment and Energy

The aggregate of the median length of each stage was 511 days. The assessment phase accounted for almost 80% of that time, highlighting the importance of proponents ensuring assessment
information is provided in a timely manner. Similar to the results from the *Environmental Assessment Act* analysis, the length of the EPBC Act assessment and approval process was variable, ranging from 340 to 826 days (Figure 3-34).

![Figure 3-34 Total length of EPBC Act assessment and approval process, Northern Territory projects from 2010-2018, by industry and length of process](image)

*Source: Department of the Environment and Energy*

The potential for government assessment and approval processes to cause delays, and the measures available to reduce regulatory timelines and uncertainty, are illustrated by the two aquaculture projects assessed under the *Environmental Assessment Act* over the period 2006 to March 2018. Both of these projects concerned Project Sea Dragon, a proposed large-scale, integrated prawn aquaculture project involving six major components located across the NT and WA.

The first major component of the project is a Stage 1 Grow-out Facility on Legune Station in the NT. The Stage 1 Facility consists of three farms and associated infrastructure, with each farm comprising 36-40 production ponds, for a total of 1120 ha of grow-out ponds. The project will impact on a further area of approximately 7,500 ha for associated infrastructure including water storage, recirculation ponds, water access channels, an intake channel, an environmental protection zone, and roads. The site is located on the Legune Coastal Floodplain; an area of conservation significance. The project will involve broad-scale vegetation clearing, and may impact on the habitat of threatened and migratory species. There are also a number of Aboriginal sacred sites located on the station.

Because of the regional economic significance of the project, and its potential environmental and heritage impacts, the project was given ‘Major Project Status’ under the Northern Territory Major Project Status Policy Framework. This enabled the proponent to receive assistance from the Northern Territory Department of the Chief Minister to navigate NT approval processes, and to engage with the Australian Government. The project was also granted ‘Major Project Facilitation’ status through the Australian Government Department of Infrastructure and Regional Development, which provided it with a single entry point for all necessary federal approvals.

A notice of intent concerning the Stage 1 Facility was submitted to the EPA in July 2015. Simultaneously, the proponent also referred the project under the EPBC Act. In late August 2015, the federal environment minister determined that the project was a controlled action due to its potential impacts on Matters of National Environmental Significance (listed threatened species and ecological communities, and listed migratory species), meaning it would require formal
assessment and approval under the Act. Soon after, on 14 September, the NT EPA determined the
project would be assessed under the Environmental Assessment Act by way of an environmental
impact statement (EIS).

To reduce duplication, the EPBC Act assessment was done under the terms of the bilateral
assessment agreement between the Australian and Northern Territory Governments. This meant
the EIS prepared under the Environmental Assessment Act served the purposes of the EPBC Act
and the NT approval processes.

The EPA assessment took a total of 609 days, with the final EPA assessment report issued in March
2017. At the NT level, the EPA assessment report does not constitute an approval in its own right.
The EIS and EPA assessment report are used to inform decisions on the grant of required Northern
Territory Government approvals, including an aquaculture licence under the Fisheries Act (NT), a
native vegetation clearing permit under the Pastoral Land Act (NT), and an environmental
protection approval and environmental protection licence under the Waste Management and
Pollution Control Act (NT).

At the federal level, the EIS was used to inform the grant of the EPBC Act approval, which was
provided in May 2017. While the EPBC Act assessment and approval process took 659 days, much
of that time overlapped with the Environmental Assessment Act assessment, meaning the
additional delays associated with the EPBC Act were negligible. This demonstrates how regulatory
delays and costs can be reduced by ensuring federal, state and territory approvals are sought in
parallel and allowing assessments to serve dual purposes.

The second major component of Project Sea Dragon is a core breeding centre and broodstock
maturation centre proposed to be located at Point Ceylon, on the southern side of Bynoe Harbour.
At the core breeding centre, high performing prawn stock will be developed and produced, and
the best performing individuals will then be transferred to the broodstock maturation centre. In
the broodstock maturation centre, the selected prawns are grown and bred to produce
commercial numbers of broodstock for use in a hatchery. The combined site area of the two
centres at completion is 152 ha.

A notice of intent for the project was sent to the EPA in February 2016. Due to the potential
impacts of the discharge of prawn farm effluent into a local waterway (Wheatley Creek), the
management requirements concerning solid and liquid wastes, the risks associated with securing
fresh water for the project and the high level of public interest in the project, the EPA decided to
assess it by way of another EIS. However, this decision was not made until August, six months after
the submission of the notice of intent. Part of the reason for the delay was the EPA required
further information from the proponent to inform its approach. In total, the assessment took 402
days, with the final EPA assessment report issued in late March 2017.

In contrast to the assessment of the project under the Environmental Assessment Act, the EPBC
Act process was short. The project was referred on 10 June 2016 and, in mid-September, it was
declared not to be a controlled action, meaning it was allowed to proceed without further
assessment and approval under the EPBC Act.

The Environmental Assessment Act and EPBC Act will not apply to all water-related developments
in the Darwin catchments. Proponents should seek advice on the government approvals required
for their projects well in advance of commencement, including on the likely cost and duration of
the processes.

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Part III  Opportunities for water resource development

Chapters 4 and 5 provide information on opportunities for agriculture and aquaculture in the Darwin catchments. This information covers:

- opportunities for irrigated agriculture and aquaculture (Chapter 4)
- opportunities to extract and/or store water for use (Chapter 5).
4 Opportunities for agriculture and aquaculture

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Chapter 4 presents information about the opportunities for irrigated agriculture and aquaculture in the Darwin catchments, describing:

- land suitability for a range of crop $\times$ season $\times$ irrigation type combinations and for aquaculture, including key soil-related management considerations
- cropping and other agricultural opportunities, including crop yields and water use
- gross margins at the farm scale
- the prospects for integration of forages and crops into existing beef enterprises
- aquaculture opportunities.

The key components and concepts of Chapter 4 are shown in Figure 4-1.

Figure 4-1 Schematic diagram of agriculture and aquaculture enterprises as well as crop and/or forage integration with existing beef enterprises to be considered in the establishment of a greenfield irrigation development.
4.1 Summary

This chapter provides information on land suitability and the potential for agriculture and aquaculture in the Darwin catchments. The approach used to generate the results presented in this chapter involves a mixture of field surveys and desktop analysis. For example, the land suitability results draw on extensive field visits to describe, collect and analyse soils that are integrated with state of the art digital soil mapping. Many of the results are expressed in terms of potential. For example, the area of land suitable for cropping or aquaculture is estimated by considering the set of relevant soil and landscape biophysical attributes at each location and determining the most limiting attribute among them. It does not include water availability, cyclone or flood risk, legislative, regulatory, ecological, social or economic drivers that will inevitably constrain the actual area of land that is developed. Crops, forages and cropping systems results are based on data analysis and simulation models and assume good agronomic practices producing optimum yields given the soil and climate attributes in the catchment. Likewise, aquaculture is assessed in terms of potential using a combination of land suitability and productive capacity of a range of aquaculture species. Information is presented in a manner to enable the comparison of a variety of agriculture and aquaculture options.

The results from individual components (land suitability, agriculture, aquaculture) are integrated to provide a sense of what is potentially viable in the catchment. This includes providing economic analyses such as gross margins (crops); how with the advantage of irrigation more intensive rotational cropping systems might be feasible; specific information on a wide range of crop types for agronomy, water use and land suitability for different irrigation types; and integrating agriculture and aquaculture to provide value-add within the catchment.

4.1.1 KEY FINDINGS

Land suitability

A major question for any agricultural resource assessment is how much soil is suitable for a particular land use and the location of that soil. Based on a sample of 14 crop × season of use × irrigation type combinations, the amount of land classified as ‘moderately suitable with considerable limitations’, or better, ranges from less than 100,000 ha to 1 million ha before constraints such as water availability, environmental and other legislation and regulations, and a range of biophysical risks are considered. There are more than 200,000 ha of land classed as ‘suitable with minor limitations’ for Rhodes grass under spray irrigation and fewer than 50,000 ha for some other crops under spray or trickle irrigation.

Dryland cropping

Analysis of cropping opportunities indicates some potential for dryland cropping. Moderate yields of grain sorghum, mungbean, maize and peanut can be achieved in most years given the relatively reliable wet-season rainfall. This translates into gross margins that are for the most part positive but only modestly so. However, these results are predicated on being able to access the country in January and on being able to sow at the climatically optimum time. In many years the soils would not be trafficable in January or February, especially the heavy clay Vertosols, so realising viable crop yields would be challenging. Delaying sowing until March, after the main part of the wet
season, would dramatically reduce crop yields because there would not be enough stored soil water to grow a crop to a successful harvest. It is not feasible to grow most horticultural crops solely on rainfall, although some short-season crops such as snake bean can be successfully grown during the wet season.

**Irrigated cropping**

Irrigation provides the opportunity to achieve high yields of broadacre crops, with year to year variation in yield greatly reduced compared with dryland cropping. Water required by crops varies enormously depending on crop type and season of growth; a rice crop planted at the start of the wet season and reliant only on supplementary irrigation in the final stages of growth can use as little as 1 ML/ha, while a rice crop grown during the dry season requires around 8 ML/ha. Broadacre crops that are planted towards the end of the wet season generally require less than 4 ML/ha because they can utilise the rainfall at the end of the wet season and stored soil water. Horticultural crops similarly vary widely in their crop water requirements, with snake beans grown almost completely during the wet season requiring almost no additional water. In contrast bananas, which are grown year-round, can require over 9 ML/ha.

The high costs of irrigation, fertiliser and transport means that gross margins for broadacre crops, while positive, may not be sufficient to provide net returns capable of meeting the investment returns required to service the high capital costs of development. Exceptions to this might be dry-season rice or a grass forage hay, which appear to be capable of producing higher gross margins. The gross margin analyses for broadacre crops assumed products had to be transported to southern markets, which can represent more than 40% of the gross value of production and greatly reduce net returns.

Compared with broadacre crops, gross margins of horticultural crops are generally much higher. Asian vegetables in particular could produce very high gross margins, assuming family labour is used. If labour costs associated with planting, maintenance and harvesting are included then gross margins can be negative. Gross margins for the more established crops such as mangoes and melons are consistent with other regions in Australia. The higher returns for horticulture are to be expected because areas used for horticulture are considerably smaller than for broadacre cropping and the costs of development are usually much higher. Further, risk tends to be higher with horticulture because returns are highly sensitive to prices received. Prices are volatile on short timescales for most horticultural crops because of the relatively small size of the Australian domestic market. Additional risks in horticulture include extreme events (cyclones, disease outbreaks) which can cause a loss of the entire crop.

It may be possible to utilise rotational cropping systems, where more than one crop is grown in a year, in the Darwin catchments to try to generate higher net returns per year. Given that irrigated broadacre cropping is still not widely practised in the NT, there has been relatively little experience in implementing rotational cropping systems. The analysis of cropping systems shows that, for example, a rotation system of wet-season soybean followed by dry-season rice may be capable of producing yields similar to individually grown crops and consequently the gross margin for this rotation increased annual returns. However, the management skills required to successfully implement intensive cropping rotations in tropical environments should not be underestimated.
Aquaculture

There are considerable opportunities for aquaculture development in northern Australia based on the natural advantages that northern Australia possesses in terms of political stability, proximity to large global markets, and a climate suited to farming of valuable tropical species, and through the large areas identified by the Assessment as suitable for aquaculture in the Darwin catchments. While challenges to the development and operation of aquaculture enterprises do present in terms of regulatory barriers, global cost competitiveness, and the remoteness of much of the available land area, the potential to exploit the natural advantages of northern Australia and develop modern and sustainable aquaculture industries appears a compelling opportunity.

Candidate species include black tiger prawns, barramundi and red claw. Black tiger prawns require marine water, red claw are a freshwater species and barramundi can be farmed in water ranging from fresh to marine. Marine water temperatures and salinity are suitable for a range of tropical aquaculture species. Pond water temperatures are optimal for most tropical aquaculture species between September and April.

A land suitability analysis was applied to marine ponds, earthen and lined, and to freshwater ponds, earthen and lined. For those species requiring marine water, distance to a marine water source is a key limitation and limits the area of available land to coastal areas. Areas of shallow rocky soils, landscapes where slopes exceed 5% and those areas with high acid sulfate soil potential are generally precluded from aquaculture development. Earthen ponds are restricted to areas of deeper clay (>0.5 m depth) and heavier loam soils where soil compaction and stability properties are suitable for pond construction. Areas with moderate to rapid soil permeability, such as deep sands, are not suitable because loss of pond water and potential contamination of groundwater are major constraints.

There are opportunities for integrating aquaculture production with agriculture but these are not widely practised in northern Australia. Emerging technologies and more locally based feed mills may provide opportunities for agricultural products to be used in manufacturing aquaculture feedstuffs.

4.1.2 INTRODUCTION

This chapter seeks to address these questions for the Fitzroy catchment: ‘How much land is suitable for cropping and in which suitability class?’, ‘Is dryland and/or irrigated cropping economically viable?’, ‘Can crops and forages be economically integrated with beef enterprises?’ and ‘What aquaculture production systems might be possible?’.

The chapter is structured as follows:

- Section 4.2 briefly discusses the history of irrigated agriculture development in the catchment and its challenges, existing cropping, recent initiatives and the approach taken in the Assessment to assess derived yields.
- Section 4.3 describes how the land suitability classes are derived from the attributes provided in Chapter 2, with results given for a set of 14 combinations of crop × season × irrigation type. Versatile agricultural land is described and a qualitative evaluation of cropping provided for a set of specific locations within the catchment.
Section 4.4 provides detailed information on crop and forage opportunities, including dryland and irrigated yields, gross margins and water use. A cropping calendar is provided and information given about the impact of sowing time on production. Four rotational cropping systems are modelled in which two crops per year are planted, as a means of increasing returns in an attempt to meet capital development costs.

Section 4.5 provides synopses for 11 crop and forage groups, including a focus on specific example species.

Section 4.6 discusses the candidate species and likely production systems for aquaculture enterprises, including the prospects for integrating aquaculture with agriculture.

4.2 The opportunity for more intensive agriculture in the Darwin catchments

4.2.1 INTRODUCTION

Aspirations to expand agricultural development in the Darwin catchments are not new and across northern Australia there have been a number of initiatives to put in place large-scale agricultural developments since World War II. Ash (2014) assessed 13 such agricultural developments, which included both irrigated and dryland developments, to determine factors that affected success and failure.

Key points to emerge from this analysis include the following:

- The natural environment (climate, soils, pests and diseases) makes agriculture in northern Australia challenging, but these inherent environmental factors are not generally the primary reason for a lack of success.

- Management, planning and finances are the most important factors in determining the ongoing viability of agricultural developments.

- Unrealistic expectations of achieving a reasonable return on investment in the first few years brought a number of developments to a premature end. Two factors are key in contributing to the overestimated returns: overly optimistic expectations of the ability to scale up rapidly in area of land developed, and not coming to grips with the operating environment and being able to take time to build experience at smaller scales.

- Supply chains and markets were also important factors in determining the success of developments. For broadacre commodities that require processing facilities, these facilities need to be within a reasonable distance of production sites and at a scale to make them viable in the long term. In more remote regions, higher value products such as fruit, vegetables and niche crops proved more successful, although high supply chain costs to both domestic and export markets remain as impediments to expansion.

The analysis of Ash (2014) shows that for developments to be successful, all factors relating to climate, soils, agronomy, pests, farm operations, management, planning, supply chains and markets need to be thought through in a comprehensive systems design. Particular attention needs to be paid to scaling up at a considered pace and being prepared for reasonable lags before positive returns on investment are achieved.
4.2.2 QUANTIFYING OPPORTUNITIES FOR FURTHER AGRICULTURAL DEVELOPMENT IN THE DARWIN CATCHMENTS

The Darwin catchments offer a challenging environment for the development of irrigated agriculture. A brief overview is provided in Chapter 2, with detailed data and analyses available in the companion technical reports on climate (Charles et al., 2016), digital soil mapping (Thomas et al., 2018a), land suitability (Thomas et al., 2018b), river model calibration (Hughes et al., 2018), flood mapping and modelling (Karim et al., 2018) and hydrogeological characterisation (Turnadge et al., 2018).

Existing cropping activities in the Darwin catchments provide good insights into crop growing seasons, agronomic management, yields, and pests and diseases, particularly for fruit crops and Asian vegetables. Potential new areas for cropping are likely to be further south and to the west in the Darwin catchments, on different soils and with a different local climate. Assessing potential crop suitability and production aspects in these new areas can draw on knowledge from existing crop production, complemented by using crop and forage models, which have the capability to predict yields of broadacre crops and forages using local soils, climate and management.

In the Assessment, crop and forage models are used to predict broadacre crop and forage yields, as described in the companion technical report on agricultural viability (Ash et al., 2018a). It is important to note that the analysis used in the Assessment estimates potential rather than actual yields. Potential yields are often, but not always, higher than actual yields. It is important to recognise that actual yields are highly dependent on a range of factors associated with management, which means that achieving potential yields can be challenging. For horticulture crops, yield estimates are based on available production data, sourced from production areas in neighbouring regions or from literature sources.

Cropping assessments are provided for two climate locations (Adelaide River and Wildman area) within the Darwin catchments. These locations are shown in Figure 1-3.

4.3 Land suitability assessment

4.3.1 INTRODUCTION

A major question for any agricultural resource assessment is how much soil is suitable for a particular land use and the location of that soil. The overall suitability for a particular land use is determined by a number of attributes. These include climate at a given location, slope, drainage, permeability, plant available water capacity, pH, soil depth, surface condition and texture as well as a number of other attributes. Some of these attributes are provided in Section 2.3. From these attributes a set of limitations are derived, which are then considered against each potential land use.

Note that the use of the term suitability in the Assessment refers to the potential of the land for a specific land use such as furrow irrigated cotton, while the term capability (not used in the Assessment) refers to the potential of the land for broadly defined land uses, such as cropping or pastoral (DSITI and DNRM, 2015).
4.3.2 LAND SUITABILITY CLASSES

The overall suitability for a particular land use is calculated by considering the set of relevant attributes at each location and determining the most limiting attribute among them. This most limiting attribute then determines the overall land suitability classification. The classification is on a scale of 1 to 5 from ‘Suitable with negligible limitations’ (Class 1) to ‘Unsuitable with extreme limitations’ (Class 5) as shown in Table 4-1. The companion technical report on land suitability (Thomas et al., 2018b) provides a complete description of the land suitability assessment method and the material presented below is taken from that report. Note that for the land suitability maps and figures presented in this section there is no consideration of flooding, risk of secondary salinisation or availability of water as discussed by Thomas et al. (2018b). Consideration of these risks and others, along with further detailed soil physical, chemical and nutrient analyses would be required to plan development at scheme, enterprise or property scale. Caution should therefore be employed when using these data and maps at fine scales.

Table 4-1 Land suitability classification used in the Assessment

<table>
<thead>
<tr>
<th>CLASS</th>
<th>SUITABILITY</th>
<th>LIMITATIONS</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Highly suitable land</td>
<td>Negligible</td>
<td>Highly productive land requiring only simple management practices to maintain economic production.</td>
</tr>
<tr>
<td>2</td>
<td>Suitable land</td>
<td>Minor</td>
<td>Land with limitations that either constrain production or require more than the simple management practices of Class 1 land to maintain economic production and minimise land degradation.</td>
</tr>
<tr>
<td>3</td>
<td>Moderately suitable land</td>
<td>Considerable</td>
<td>Land with limitations that either further constrain production or require more than those management practices of Class 2 land to maintain economic production and minimise land degradation.</td>
</tr>
<tr>
<td>4</td>
<td>Currently unsuitable land</td>
<td>Severe</td>
<td>Currently considered unsuitable land due to severe limitations that preclude successful sustained use of the land for the specified land use. In some circumstances, the limitations may be surmountable with changes to knowledge, economics or technology.</td>
</tr>
<tr>
<td>5</td>
<td>Unsuitable land</td>
<td>Extreme</td>
<td>The limitations are so extreme that the specified land use is precluded. The benefits would not justify the inputs required to maintain production and prevent land degradation in the long term.</td>
</tr>
</tbody>
</table>

4.3.3 LAND SUITABILITY FOR CROPS, VERSATILE AGRICULTURAL LAND AND EVALUATION OF SPECIFIC AREAS

Land suitability has been determined for 126 combinations of crop × season × irrigation type within the Assessment (Thomas et al., 2018b). A sample of 14 of these land use combinations is shown in Figure 4-2. Depending on land use, the amount of land classified as Class 3 or better for these sample land uses ranges from less than 100,000 ha (furrow irrigation) to closer to 1 million ha (spray or trickle irrigation). Almost all of this land is rated as Class 3, and so has considerable limitations, although there is more than 200,000 ha of Class 2 land available for Rhodes grass under spray irrigation and fewer than 50,000 ha of Class 2 for some other crops under spray or trickle irrigation.
Figure 4-2 Area (ha) associated with each land suitability class in the Darwin catchments for 14 potential crop land uses

A description of the five classes is provided in Table 4-1.

In order to provide an aggregated summary of the land suitability products, an index of agricultural versatility was derived for the Darwin catchments (Figure 4-3). Versatile agricultural land was calculated by identifying where the highest number of the 14 selected land use options presented in Figure 4-2 were mapped as being suitable (i.e. suitability classes 1 to 3).
Figure 4-3 Agricultural versatility index map for the Darwin catchments

High index values denote land that is likely to be suitable for more of the 14 selected land use options. The map also shows areas of interest from a land suitability perspective, discussed in the table below. Note that this map does not take into consideration flooding, risk of secondary salinisation or availability of water.

Qualitative observations on each of the areas mapped as ‘A’ to ‘G’ in Figure 4-3 are provided in Table 4-2.
Table 4-2 Qualitative land evaluation observations for locations in the Darwin catchments shown in Figure 4-3

Further information on each soil generic group (SGG) and a map showing spatial distribution can be found in Section 2.3.

<table>
<thead>
<tr>
<th>AREA</th>
<th>LOCATION NAME</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Darwin elevated coastal plains</td>
<td>Shallow to deep red loamy soils (SGG 4.1) on elevated plains, low plateaus and undulating rises developed on remnant Tertiary sediments suitable for a range of spray- or trickle-irrigated sugarcane, grain crops and horticultural crops. Soils vary greatly in depth and abundance of iron nodules in the soil profile affecting soil water holding capacity and therefore irrigation management requirements. Deeper soils with fewer nodules occur on level plains, and shallower soils with an increase in the number of nodules generally occur on the edge of the plateaus and rises. Seasonal wetness (SGG 3) also increases on lower slopes, essentially restricting cropping to the dry season. Crop, irrigation and land management is required on sloping lands to control water erosion, particularly during the very high rainfall intensity wet season when soil cultivation and bare loose soil surfaces should be avoided.</td>
</tr>
<tr>
<td>B</td>
<td>Reynolds River catchment</td>
<td>Very deep yellow, brown and red friable loams and loamy soils (SGG 4.1 and 4.2) on level to gently undulating plains and rises. Soils on level and gentle slopes are moderately suitable for a variety of grain and horticultural crops. Appropriate crop, irrigation and land management practices are required on sloping lands to control water erosion, particularly during the very high rainfall intensity wet season when soil cultivation and bare loose soil surfaces should be avoided.</td>
</tr>
<tr>
<td>C</td>
<td>Upper river alluvium</td>
<td>Some seasonally or permanently wet soils (SGG 3) and cracking clay soils (SGG 9) and soils with loam over sodic clay subsoils (SGG 8) in the upper alluvial plains, such as the upper Adelaide and Mary rivers, are moderately suitable for dry-season irrigated cropping, particularly crops tolerant of wetness such as rice, sugarcane and forage crops. The narrow plains may restrict paddock size and infrastructure layout. These seasonally wet soils require drainage works and surface levelling to improve surface and subsurface drainage.</td>
</tr>
<tr>
<td>D</td>
<td>Lower slopes of hills throughout the catchments</td>
<td>The lower slopes of the hills and gently undulating rises throughout the catchments (particularly the catchments of the Adelaide and Mary rivers) are dominated by yellow and brown loamy soils (SGG 4.2) and are moderately suitable for a range of crops. However, the short slopes and large number of drainage lines may restrict the size of usable areas and infrastructure layout. Appropriate crop, irrigation and land management practices are also required on sloping lands to control water erosion, particularly during the very high rainfall intensity wet season when soil cultivation and bare loose soil surfaces should be avoided.</td>
</tr>
<tr>
<td>E</td>
<td>Upper catchment plateaus</td>
<td>Deep, permeable, mainly red loamy soils (SGG 4.1) on plateaus in Litchfield National Park and in the upper catchment east of Pine Creek. Abundant rock outcrop occurs on the edges of the plateaus. These loamy soils are suitable for irrigated horticulture and a range of spray-irrigated grain crops.</td>
</tr>
<tr>
<td>F</td>
<td>Uplands</td>
<td>Shallow rocky soils (SGG 7) dominate the uplands. Irrigation potential is generally limited to small areas (&lt;100 ha each) of deeper, gently sloping, well-drained, rock-free soils. The small and/or narrow areas limit paddock size and irrigation infrastructure layout. Erosion management is required.</td>
</tr>
<tr>
<td>G</td>
<td>Lower river alluvium and coastal plains</td>
<td>Poorly drained to very poorly drained swamps and coastal marine plains with seasonally or permanently wet soils (SGG 3). Acid sulfate soils, regular flooding and storm surge from cyclones require considerable management. Negligible potential for irrigated agriculture but some suitable areas for aquaculture.</td>
</tr>
</tbody>
</table>

Land suitability and its implications for crop management are discussed in more detail for a selection of crops in Section 4.6. There, land use suitability of a given crop and irrigation combination are mapped, along with information critical to the consideration of the crop in an irrigated farm enterprise. Land suitability maps for all 126 land use combinations are presented in the companion technical report on land suitability (Thomas et al., 2018b).
4.4 Crop and forage opportunities in the Darwin catchments

4.4.1 INTRODUCTION

Dryland, or rainfed, cropping (farming without irrigation) is not widely practised in the Darwin catchments with most cropping relying on irrigation, mainly from groundwater aquifers. Dryland cropping is wholly dependent on water stored in the soil and rainfall occurring during crop growth. The relatively short wet season combined with high cloud cover during the monsoonal wet season means that continuous year-on-year dryland cropping is not well-suited to the Darwin catchments, although dryland forages are grown on the Tortilla Flats on the upper Adelaide River alluvial soils. A little further to the south of the Darwin catchments, in the Douglas–Daly region, dryland forage production is also widely practised.

When crops are fully irrigated they can produce up to twice as much yield as dryland crops, as demonstrated in Table 4-3, which shows dryland and irrigated yields for grain sorghum, mungbean and peanut. The use of 125 seasons of data provides for robust assessments of both median yield and the variability that can be expected about the average due to variations in climate. The 20th percentile exceedance values represent the yield that is exceeded in 20% of all years (i.e. in 20% of years the yield will be higher than this value). The 50th percentile represents the median yield. Similarly, the 80th percentile exceedance values represent the yield that is exceeded in 80% of years (i.e. in 80% of years the yield will be higher than this value). The irrigated yield is highly dependent on the volume of water applied. In essence, more irrigation equals more yield up to the point that the full water needs of the crop are satisfied. The yield response curves can provide insights into the relative response of crops to irrigation and could be used to help guide decisions about which crops and which areas of crop could preferentially receive irrigation water in the event that it is limiting.

Table 4-3 Yields (20th, 50th (median), 80th percentile) of three crops at Wildman River under dryland and irrigated conditions

<table>
<thead>
<tr>
<th>CROP</th>
<th>DRYLAND YIELD</th>
<th>IRRIGATED YIELD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20th</td>
<td>50th</td>
</tr>
<tr>
<td>Sorghum (t/ha)</td>
<td>5.0</td>
<td>4.2</td>
</tr>
<tr>
<td>Mungbean (t/ha)</td>
<td>1.5</td>
<td>1.3</td>
</tr>
<tr>
<td>Peanut (t/ha)</td>
<td>3.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Whether or not water is limiting in a particular situation will depend on rainfall, the availability and reliability of irrigation water, the area and time for which irrigation water is required and the characteristics of the soil.

Water storage options are discussed in detail in Chapter 5 but, suffice to say, because there is more moderately suitable soil in the Darwin catchments than there is water to irrigate it, decisions will need to be made on whether irrigation is economically feasible, and if so, the most efficient and cost-effective use of limited irrigation water. This will require consideration at regional, farm and...
paddock scales. At the farm and paddock scales, these decisions may need to be made each cropping season.

Eleven crop and forage land use categories were developed by the Assessment and used as a basis for the land suitability analysis. These were based on knowledge of existing or historical cropping in the catchment, knowledge of the crops that have grown well in similar tropical regions, and an understanding of the commercial aspirations of local landholders in the Assessment area. The 11 categories, and a range of the crops that comprise them, are shown in Table 4-4.

The 41 crop examples listed in Table 4-4 were subsequently analysed in more detail to identify critical environmental requirements and management considerations. Critical among these is season of growth and sowing time, which determines the conditions in which the crop grows and, consequently, critical factors such as water requirements and yield potential.

### Table 4-4 Crop types and crops explored in the Assessment

<table>
<thead>
<tr>
<th>CROP TYPE</th>
<th>CROP EXAMPLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cereals and pseudo-cereals</td>
<td>Chia, maize (grain), millet, quinoa, rice (lowland and upland), sorghum (grain)</td>
</tr>
<tr>
<td>Food legumes (pulses)</td>
<td>Chickpea, lentil, mungbean, navy bean</td>
</tr>
<tr>
<td>Forage grazing, hay, silage</td>
<td>Rhodes grass, maize (silage), sorghum (forage)</td>
</tr>
<tr>
<td>Forage legume</td>
<td>Lablab</td>
</tr>
<tr>
<td>Industrial crops</td>
<td>Cotton, sugarcane</td>
</tr>
<tr>
<td>Intensive horticulture (vegetables)</td>
<td>Asian vegetables, asparagus, capsicum/chilli, cucurbits (melons), snake bean, sweet corn, tomato</td>
</tr>
<tr>
<td>Oilseeds</td>
<td>Poppy, sesame, soybean, sunflower</td>
</tr>
<tr>
<td>Root crops</td>
<td>Cassava, peanut, sweet potato</td>
</tr>
<tr>
<td>Silviculture (plantation)</td>
<td>African mahogany, Indian sandalwood, teak</td>
</tr>
<tr>
<td>Tree crops/horticulture (fruit)</td>
<td>Avocado, banana, citrus (generic), coffee, lychee, mango, papaya</td>
</tr>
<tr>
<td>Tree crop (nuts)</td>
<td>Almond, cashew, macadamia</td>
</tr>
</tbody>
</table>

By integrating the information on climate, suitable soils, and general agronomic principles for dryland and irrigated crop and forage production it is now possible to undertake a more detailed analysis of the crop and forage opportunities in the Darwin catchments. This analysis commences with an understanding of optimal times for sowing different crops and forages through the development of cropping calendars. It then examines potential crop yields, crop management and gross margins of crops. Given the costly nature of developing land for agriculture and providing irrigation, it is important to examine the potential for cropping systems that involve crop rotations and double cropping that can increase annual revenues. Such cropping systems provide opportunities but also challenges for management; these are addressed in this section.

In Section 4.5 a more detailed description of crop types, their suitability to the Darwin catchments, management and irrigation requirements, and indicative market opportunities is provided.
4.4.2 CROPPING CALENDAR

Cropping calendars identify optimum sowing times and the growing season for different crops. They are an essential crop management tool. Prior to the Assessment no cropping calendar existed for the Darwin catchments.

The time during which a crop can be reliably and profitably sown is called the sowing window. Sowing windows vary in both timing and length among crops and regions. Figure 4-5 provides a cropping calendar for 32 agricultural crops, most of which are likely to be broadly adapted to the Darwin catchments. Perennial crops are grown throughout the year, and consequently have a less well-defined growing season or planting window. Generally, perennial tree crops are transplanted as small plants (not seeds), and in the tropical north this is usually timed towards the beginning of the wet season to take advantage of wet-season rainfall.

The cropping calendar in Figure 4-5 is based on knowledge of these crops derived from elsewhere in the tropics combined with an understanding of plant physiology, which enables crop response to differences in local climate to be anticipated. The optimum planting window and growing season have been further refined through local experience and through use of the Agricultural Production Systems sIMulator (APSIM) crop model (see companion technical report on agricultural viability (Ash et al., 2018a)).

The sowing windows identified in Figure 4-5 correspond with the times of sowing that are likely to maximise potential crop yield in the Darwin catchments. Sometimes crops can be successfully sown outside of the identified sowing windows and only a small yield penalty would apply. In this analysis, sowing dates between September and November have been avoided because high evaporative demand (see Section 2.4) and low water availability are not conducive to seedling establishment; however, it is possible to sow at this time for many crops. It should be noted that sowing to achieve maximum potential crop yield may not always be possible. However, wet-season difficulties in access and trafficability may prevent sowing at optimum times.

Figure 4-4 A mungbean crop ready to be harvested
Photo: CSIRO
### YIELDS AND CROP MANAGEMENT

#### Dryland cropping

The annual cropping calendar in Figure 4-5 shows that, for many crops, the sowing window includes the month of January. For relatively short-season crops such as sorghum and mungbean, this coincides with both the sowing time that provides close to maximum yield and the time at which the season’s rainfall can be most reliably assessed. In January the prospects of near-future rainfall can be assessed with a high degree of confidence. On average significant rainfall is expected in January and February (median of 321 and 321 mm, respectively, for Adelaide River).
Table 4-5 shows how soil water content at sowing and rainfall received in the 90 days after sowing varies for three different sowing dates. As sowing is delayed from January to March the amount of stored soil water remains relatively constant. However, as sowing is delayed the amount of rainfall received from time of sowing onwards decreases significantly. Combining the mean soil water content at sowing and the mean rainfall received in the 90 days following sowing provides totals of 826, 526 and 218 mm for the January, February and March sowing dates, respectively. In ‘wetter than average years’ (i.e. the years that exceed the 20th rainfall percentile) the amount of soil water at the end of January combined with the rainfall received in the following 90 days is 980 mm. In these seasons, poor trafficability and limited dry days to enable sowing operations will regularly delay sowing a crop until later in the season. For ‘drier than average years’ (i.e. the years that exceed the 80th rainfall percentile), the soil water stored at sowing and the rainfall received in the following 90 days is 644 mm and may be sufficient to grow a short-season crop. These drier seasons may provide more opportunities for early establishment of a dryland crop on the more free-draining soils in the catchments.

Table 4-5 Soil water content at sowing and rainfall for the 90-day period following sowing for three sowing dates (Wildman River), based on a Red Kandosol soil type
The 20th percentile, 50th percentile (median) and 80th percentile exceedance values are reported, for the 125 years between 1890 and 2015.

<table>
<thead>
<tr>
<th>SOWING DATE</th>
<th>SOIL WATER CONTENT AT SOWING DATE (mm)</th>
<th>RAINFALL IN 90 DAYS FOLLOWING SOWING DATE (mm)</th>
<th>TOTAL STORED SOIL WATER + RAINFALL IN SUBSEQUENT 90 DAYS (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>31 January</td>
<td>164 157 154</td>
<td>823 656 493</td>
<td>980 826 644</td>
</tr>
<tr>
<td>28 February</td>
<td>154 151 149</td>
<td>512 375 246</td>
<td>664 526 397</td>
</tr>
<tr>
<td>31 March</td>
<td>150 148 146</td>
<td>149 68 28</td>
<td>297 218 176</td>
</tr>
</tbody>
</table>

When planted at an appropriate time, good yields were simulated for the dryland crops of sorghum, mungbean, soybean and peanut, especially in the best 20% of years (Table 4-6). Given the relatively high rainfall in the wet season in the Darwin catchments, there is an opportunity for rainfed crops to be grown that produce positive returns. Rice on the Vertisol and mungbean and soybean on the Red Kandosol produced median gross margins (see Section 4.5.3 for description) ranging from $365 to $540/ha. Peanut produced a gross margin of nearly $1200/ha but this assumed a local processing plant (drying and shelling) existed. All of these crops are legumes and are susceptible to disease over the humid wet season and the yields and gross margins assumed pests and disease were well managed. The actual seasons in which growers will find cropping most or least profitable will vary among farms, which vary in physical attributes, management style and cost structures.
Table 4-6 Sowing date, crop yield, price, variable cost, gross margin and break-even crop yield for dryland crops in the Darwin catchments, with data shown for a Vertosol at Adelaide River and a Red Kandosol at Wildman River. The 20th percentile, 50th percentile (median) and 80th percentile exceedance values are reported for the 125 years from 1890 to 2015. Gross margins for the 20th, 50th and 80th percentiles are calculated using variable cost in the table, and the 20th, 50th and 80th percent yields, respectively. Gross margins for peanut assumes delivery to a (currently non-existent) processing plant.

<table>
<thead>
<tr>
<th>CROP</th>
<th>SOWING DATE</th>
<th>CROP YIELD (t/ha)</th>
<th>PRICE ($/unit)</th>
<th>VARIABLE COST ($/ha)</th>
<th>GROSS MARGIN ($/ha)</th>
<th>BREAK-EVEN CROP YIELD (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20th</td>
<td>50th</td>
<td>80th</td>
<td>20th</td>
<td>50th</td>
<td>80th</td>
</tr>
<tr>
<td>Vertosol</td>
<td>Rice</td>
<td>1 Dec–30 Jan</td>
<td>4.4</td>
<td>3.5</td>
<td>2.5</td>
<td>420/t</td>
</tr>
<tr>
<td>Kandosol</td>
<td>Sorghum</td>
<td>20 Jan–20 Mar</td>
<td>5.0</td>
<td>4.2</td>
<td>3.2</td>
<td>240/t</td>
</tr>
<tr>
<td></td>
<td>Mungbean</td>
<td>1 Feb–15 Mar</td>
<td>1.5</td>
<td>1.3</td>
<td>1.0</td>
<td>1100/t</td>
</tr>
<tr>
<td></td>
<td>Soybean</td>
<td>15 Dec–31 Jan</td>
<td>3.1</td>
<td>2.8</td>
<td>2.2</td>
<td>475/t</td>
</tr>
<tr>
<td></td>
<td>Peanut</td>
<td>1 Jan–15 Feb</td>
<td>3.5</td>
<td>3.0</td>
<td>2.5</td>
<td>1000/t</td>
</tr>
</tbody>
</table>

Figure 4-6 illustrates the problems that are likely to be encountered sowing a dryland crop at the end of March, where the majority of crop water will come from stored soil water as there is little prospect of useful rain in the dry season. Median yields of grain sorghum decline from about 6 t/ha if they are able to be planted in mid-January to around 2.5 t/ha when planted at the beginning of April. However, the ability to access the land for machinery operations in January when there are many rain days would be challenging, even on Red Kandosols. The Vertosols at Adelaide River would not be accessible in January or February in nearly all years. Without the certainty provided by irrigation, dryland cropping is opportunistic in nature, relying on favourable conditions in which to establish, grow and harvest a crop.

Figure 4-6 Probability of exceedance graph of simulated dryland sorghum yields (t/ha) for fortnightly sowing dates from January to April on a Red Kandosol at Wildman River.
**Irrigated cropping**

Table 4-7 shows potential irrigated crop yields at the 20th, 50th and 80th percentile exceedance averaged over all years (1890 to 2015) in simulation models. In comparison, Table 4-8 shows crop yield and water requirement data for horticultural crops based on expert observed data from production, experimental trials and expert opinion.

The modelled yield of irrigated crops is much less variable than that of dryland crops. Consequently, irrigation provides not only for higher, but also more reliable production compared with dryland crops. The irrigation water required to fully irrigate a crop varies significantly from year to year, especially for those crops that are grown partly or fully over the wet season. Analysis of the ‘applied irrigation water’ exceedance values in Table 4-7 shows that the difference in the volume of water required to irrigate a crop can vary as much as three times between 20th percentile years versus 80th percentile years for crops grown in the wet season. Water requirements are less in the years of low crop yields as these are typically wet years where radiation limits crop production. Higher yields and higher applied irrigation water occur in years with lower rainfall since radiation is higher. For crops grown over the dry season, there is much less variation in crop water use and yield.

In the Darwin catchments, fully irrigated crops of mungbean and grain sorghum significantly outperform those of dryland crops (Figure 4-7; Figure 4-8) and the between-year yields under irrigation are much less variable than under dryland cropping.

In 50% of years dryland mungbean crops (Figure 4-7) would be expected to yield more than 1.2 t/ha on a Red Kandosol at Wildman River and potential crop yields of about 1.5 t/ha could be achieved in 20% of years. The break-even crop for dryland mungbean grown at Wildman River is estimated to be approximately 0.9 t/ha (Table 4-6). This could be expected to be achieved in approximately 89% of years. Under fully irrigated conditions a yield of 2.1 t/ha could be expected in 50% of years.

For grain sorghum (Figure 4-8) a yield of 4.2 t/ha could be expected in 50% of years under dryland and 7.2 t/ha under full irrigation on a Red Kandosol at Wildman River. Potential crop yields of about 5.0 t/ha and 7.5 t/ha could be expected in approximately 20% of years under dryland and irrigated respectively. The break-even crop for dryland sorghum grown at Wildman River is
estimated to be approximately 4.0 t/ha (Table 4-6). This could be expected to be achieved in approximately 58% of years.

Figure 4-8 Probability of yield potential for dryland and fully irrigated grain sorghum sown in Wildman River climate on a Red Kandosol in January to March (dryland) and March (irrigated)

Yields typically increase with increasing irrigation until a point at which the full water needs of the crop are met (Figure 4-9; Figure 4-10).

Figure 4-9 Crop yield plotted against applied irrigation water in Wildman River climate for peanut planted in April
Modelled confidence limits (20th to 80th percentile) and mean crop yield for peanut. Representative of the production potential (i.e. assumes no nutrient limitations or pest damage). Assumes perfect timing of irrigation (i.e. no losses).

In Figure 4-9 and Figure 4-10 the slope of the rising part of the curve provides an insight into the relative response of crops to irrigation and could be used to help guide decisions about which crops and which areas of crops should preferentially receive irrigation water in the event that it is limiting.
Yields are highest for crops grown over the dry season when radiation tends to be less limiting. Yields of all crops are consistent with other areas in northern Australia, with the exception of peanut. Simulated yields indicate production of around only 3.5 t/ha, which is lower than yields simulated for the Mitchell catchment in Queensland (Ash et al., 2018b) or for trial yields in the Katherine region (4 to 6 t/ha). The simulations suggest a climate–soil interaction in the Wildman region that is not conducive to high yields compared with other areas. Rice grown over the wet season with supplementary irrigation also produced quite low yields, but this is due to low radiation levels during the monsoon period.

A wide range of horticultural crops can be grown in the Darwin catchments and production data for a number of these crops is shown in Table 4-8. This is one of the first attempts to try to quantify production and returns for Asian vegetables in the Darwin catchments.

Climate change poses a potential risk to agricultural production and viability in future decades (see Section 2.4). To assess the potential impacts of climate change on crop yields, climate change scenarios (rainfall, temperature, evaporation) for 2060 were incorporated into crop modelling analyses. In addition to climate variables, increased concentrations of carbon dioxide in the atmosphere affect plant growth and crop yields by increasing photosynthetic and water use efficiencies, which can increase plant growth and may offset negative impacts of decreased rainfall and higher temperatures. Given the importance of carbon dioxide on plant growth this was also assessed in the crop analysis.

Assuming irrigation supplies are not compromised, in simulations of future climate scenarios, broadacre crops such as rice, forage sorghum, grain sorghum and mungbean were projected to maintain or even increase yields despite higher temperatures and evaporative demand because of the positive effects of increased carbon dioxide concentrations. However, under dryland conditions (no irrigation), the yield of sorghum was significantly reduced under a drier future climate scenario.
Table 4-7 Cropping season, applied irrigation water, crop yield, price, variable cost, gross margin and break-even yield for crops in the Darwin catchments, with data shown for a Vertosol soil type at Adelaide River and a Red Kandosol soil type at Wildman River.

20th percentile, 50th percentile (median) and 80th percentile exceedance values are reported for the 125 years from 1890 to 2015. Gross margins for the 20th, 50th and 80th percentiles are calculated using variable cost in the table, and the 20th, 50th and 80th percent yields, respectively. Gross margins for peanut assumes delivery to a (currently non-existent) processing plant.

<table>
<thead>
<tr>
<th>CROP</th>
<th>SEASON</th>
<th>APPLIED IRRIGATION WATER (ML/ha)</th>
<th>CROP YIELD (t/ha)</th>
<th>PRICE ($/t)</th>
<th>VARIABLE COST ($/ha)</th>
<th>GROSS MARGIN ($/ha)</th>
<th>BREAK-EVEN CROP YIELD (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>20th</td>
<td>50th</td>
<td>80th</td>
<td>20th</td>
<td>50th</td>
<td>80th</td>
</tr>
<tr>
<td>Adelaide River (Vertosol)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rice</td>
<td>DS†</td>
<td>8.5</td>
<td>8.1</td>
<td>7.5</td>
<td>9.9</td>
<td>9.7</td>
<td>9.3</td>
</tr>
<tr>
<td>Rice</td>
<td>WS‡</td>
<td>1.6</td>
<td>1.0</td>
<td>0.7</td>
<td>5.0</td>
<td>4.3</td>
<td>3.5</td>
</tr>
<tr>
<td>Rice (aromatic)</td>
<td>DS</td>
<td>NA§</td>
<td>NA</td>
<td>NA</td>
<td>6.0</td>
<td>NA</td>
<td>620</td>
</tr>
<tr>
<td>Soybean</td>
<td>WS</td>
<td>3.1</td>
<td>2.3</td>
<td>1.5</td>
<td>3.9</td>
<td>3.6</td>
<td>3.4</td>
</tr>
<tr>
<td>Forage sorghum</td>
<td>WS+DS</td>
<td>2.9</td>
<td>2.4</td>
<td>1.9</td>
<td>19.6</td>
<td>17.6</td>
<td>16.0</td>
</tr>
<tr>
<td>Cavalcade</td>
<td>DS</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>8.0</td>
<td>NA</td>
<td>1066</td>
</tr>
<tr>
<td>Wildman (Red Kandosol)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sorghum</td>
<td>WS + DS</td>
<td>3.1</td>
<td>2.8</td>
<td>2.5</td>
<td>7.5</td>
<td>7.2</td>
<td>6.9</td>
</tr>
<tr>
<td>Mungbean</td>
<td>DS</td>
<td>1.9</td>
<td>1.7</td>
<td>1.3</td>
<td>2.3</td>
<td>2.1</td>
<td>1.9</td>
</tr>
<tr>
<td>Soybean</td>
<td>WS</td>
<td>1.1</td>
<td>0.7</td>
<td>0.3</td>
<td>3.3</td>
<td>3.1</td>
<td>2.9</td>
</tr>
<tr>
<td>Peanut</td>
<td>DS</td>
<td>4.2</td>
<td>4.0</td>
<td>3.6</td>
<td>3.7</td>
<td>3.5</td>
<td>3.4</td>
</tr>
<tr>
<td>Chia</td>
<td>DS</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0.9</td>
<td>3000</td>
</tr>
<tr>
<td>Forage sorghum</td>
<td>WS + DS</td>
<td>4.7</td>
<td>3.9</td>
<td>3.4</td>
<td>24.6</td>
<td>22.5</td>
<td>19.5</td>
</tr>
<tr>
<td>Lablab</td>
<td>DS</td>
<td>3.7</td>
<td>3.4</td>
<td>3.1</td>
<td>9.1</td>
<td>9.0</td>
<td>8.9</td>
</tr>
</tbody>
</table>

†DS = dry season
‡WS = wet season
§NA = not available
Table 4-8 Cropping season, irrigation water requirement, crop yield, price, variable cost, gross margin and break-even crop yield for horticultural and tree crops in the Darwin catchments, assuming a Red Kandosol soil type

Gross margins (+25%, Average, –25%) reflect price variability. For okra, snake bean, bitter melon, luffa and cucumbers, family labour is assumed in the gross margin analysis. For mangoes, KP is Kensington Pride and PVR refers to plant variety rights mangoes, of which Calypso is an example. Gross margin for sandalwood is over 15 years as it takes that long for a crop to reach harvest.

<table>
<thead>
<tr>
<th>CROP</th>
<th>SEASON</th>
<th>APPLIED IRRIGATION WATER (ML/ha)</th>
<th>CROP YIELD (unit/ha)</th>
<th>UNIT</th>
<th>PRICE ($/unit)</th>
<th>VARIABLE COST ($/ha)</th>
<th>GROSS MARGIN ($/ha)</th>
<th>BREAK-EVEN CROP YIELD (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20th</td>
<td>50th</td>
<td>80th</td>
<td>Average</td>
<td>+25%</td>
<td>Average</td>
<td>–25%</td>
<td></td>
</tr>
<tr>
<td>Okra</td>
<td>DS†</td>
<td>3.9</td>
<td>3.5</td>
<td>3.3</td>
<td>1,697</td>
<td>12-kg carton</td>
<td>68</td>
<td>26,769</td>
</tr>
<tr>
<td>Snake bean</td>
<td>DS</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
<td>2,310</td>
<td>12-kg carton</td>
<td>70</td>
<td>36,628</td>
</tr>
<tr>
<td>Bitter melon</td>
<td>DS</td>
<td>3.9</td>
<td>3.5</td>
<td>3.3</td>
<td>1,219</td>
<td>12-kg carton</td>
<td>24</td>
<td>23,852</td>
</tr>
<tr>
<td>Luffa</td>
<td>DS</td>
<td>6.8</td>
<td>6.2</td>
<td>5.4</td>
<td>1,108</td>
<td>12-kg carton</td>
<td>30</td>
<td>22,198</td>
</tr>
<tr>
<td>Cucumbers</td>
<td>DS</td>
<td>3.6</td>
<td>3.5</td>
<td>3.3</td>
<td>3,167</td>
<td>12-kg carton</td>
<td>25</td>
<td>49,886</td>
</tr>
<tr>
<td>Sweet corn</td>
<td>DS</td>
<td>3.0</td>
<td>2.8</td>
<td>1.7</td>
<td>1,086</td>
<td>18-kg carton</td>
<td>15</td>
<td>11,636</td>
</tr>
<tr>
<td>Dragon fruit</td>
<td>P‡</td>
<td>5.0</td>
<td>4.5</td>
<td>3.8</td>
<td>2,944</td>
<td>3-kg carton</td>
<td>40</td>
<td>37,988</td>
</tr>
<tr>
<td>Banana</td>
<td>P</td>
<td>10.4</td>
<td>9.5</td>
<td>8.4</td>
<td>3,400</td>
<td>13-kg carton</td>
<td>18</td>
<td>42,752</td>
</tr>
<tr>
<td>Mango (KP)</td>
<td>P</td>
<td>6.3</td>
<td>5.7</td>
<td>4.8</td>
<td>1,000</td>
<td>7-kg tray</td>
<td>24</td>
<td>12,285</td>
</tr>
<tr>
<td>Mango (PVR)</td>
<td>P</td>
<td>6.3</td>
<td>5.7</td>
<td>4.8</td>
<td>2,700</td>
<td>7-kg tray</td>
<td>21</td>
<td>29,402</td>
</tr>
<tr>
<td>Rockmelon</td>
<td>DS</td>
<td>3.9</td>
<td>3.4</td>
<td>2.7</td>
<td>1,808</td>
<td>13-kg carton</td>
<td>18</td>
<td>23,051</td>
</tr>
<tr>
<td>Watermelon</td>
<td>DS</td>
<td>4.4</td>
<td>3.9</td>
<td>3.1</td>
<td>47.5</td>
<td>tonne</td>
<td>900</td>
<td>25,456</td>
</tr>
<tr>
<td>Sandalwood</td>
<td>P</td>
<td>3.9</td>
<td>3.4</td>
<td>2.9</td>
<td>380</td>
<td>kg oil</td>
<td>4,000</td>
<td>63,246</td>
</tr>
</tbody>
</table>

†DS = dry season  
‡P = perennial
4.4.4 CROP GROSS MARGINS

A key component of determining potential financial viability is gross margin analysis. Gross margins are defined as total sales revenue less the costs of direct production, marketing and transport costs. Gross margin estimates are calculated on a dollar per hectare basis. No specific farm area is used but it is assumed that it is operationally of a commercial size.

Indicative crop gross margins are provided in Table 4-7 and Table 4-8; for several reasons, great care needs to be taken with their use. Gross margins are sensitive to variation in yield and price of outputs, and levels and costs of inputs. These vary from farm to farm, paddock to paddock and year to year.

Perhaps more importantly, gross margins provide no insight into the cost of establishing new enterprises. This requires the use of whole or partial farm budgets which, because of their enterprise specificity, are explored in Chapter 6.

The gross margins are provided merely as an indication of the cash flow that might be generated by established irrigated cropping enterprises in the Darwin catchments. Gross incomes are based on crop yield values and the yields are also used to calculate tonnage-related variable costs (e.g. cartage, levies, harvesting), which are converted to a dollar per hectare cost and added to other variable costs of production. Pumping costs are calculated using the modelled median applied irrigation water (ML/ha). Costs and prices are obtained from a range of sources and full details are provided in the companion technical report on agricultural viability (Ash et al., 2018a).

Gross margins are highly variable between broadacre crops, with dry-season rice (medium grain and aromatic) returning the highest gross margin of nearly $1800/ha and forage sorghum up to $1300/ha, depending on location. No other broadacre crops provide gross margins greater than $1000/ha, except in the best 20% of years. Compared with other catchments, peanut produces only modest gross margins because of moderate yields. Gross margins of broadacre crops are highly sensitive to yield and if peanut yields are increased from 3.5 to 5 t/ha the gross margin increases from $555 to over $1700/ha. The relatively high cost of freighting high-volume, low-value grains to southern markets reduces their ability to generate high returns.

Gross margins are also highly variable between the different horticultural crops. High gross margins can be achieved for the Asian vegetable crops of okra, snake bean, luffa and cucumber. Most of these vegetables are grown on a small scale utilising family labour. As such, the gross margins for Asian vegetables in this analysis do not include labour costs for planting, weeding, harvesting or packing. If full labour costs at $30.00 per hour are included, all of the Asian vegetable crops show negative gross margins. Freight costs are high for Asian vegetables because they are not shipped in bulk and require consolidation through a local transport company. This doubles freight costs compared with bulk transport. The niche crop dragon fruit produces a very high gross margin. Some considerable caution needs to be used with this result as dragon fruit has a small market in Australia and oversupply can rapidly reduce prices received (i.e. its returns are highly volatile). Imports of dragon fruit have recently been approved and this is likely to affect the returns that local producers can achieve.

For the more established horticultural crops (mango, banana, melons) gross margins are highly variable ranging from $3,000/ha for honeydew to over $17,000/ha for Calypso mangoes. These
results are consistent with other regions in northern Australia (e.g. Katherine, WA, north Queensland). Gross margins of horticultural crops are highly sensitive to price variation, with negative returns common when prices 25% lower than the assumed mean were used.

Sandalwood is being commercially grown in northern Australia, with a strong presence in the Ord valley. Financial information is difficult to source as most information is commercial in confidence. In addition, unlike all the other crops in the Assessment, which are harvested at least annually, sandalwood is a tree crop that is harvested every 15 years. Based on information obtained from commercially available reports and experts working in the sandalwood industry, the NPV gross margin analysis shows an NPV gross margin per ha of nearly $700,000. If this is annualised this represents a gross margin of around $47,000/ha/year.

The inability of most broadacre crops to generate high gross returns as a single annual crop raises the challenge of how might gross margins be improved to better align with required returns for investment. Gross margins can be improved by either reducing costs or increasing returns. In terms of reducing costs, achieving efficiencies in input costs (water, fertiliser, herbicides and pesticides) is usually an ongoing priority for management.

Freight costs can represent up to 40% of gross returns for broadacre grain costs and are very sensitive to the distance to market given the relatively low prices received per tonne of product. In contrast, freight costs represent about 10% of gross returns for pulse crops (mungbean, chickpea) even though they need to be transported to Adelaide for processing. A combination of high prices per tonne and relatively low yields means total tonnage of pulses transported is low compared with coarse grains.

Where local processing facilities are available (peanut drying and shelling facilities) freight costs as a percentage of gross returns is generally less than 10%.

High-volume horticulture crops (melons, bananas) have relatively high transport costs (18 to 30% of gross returns) compared with higher value crops such as mangoes. Asian vegetables have significant costs tied up in freight because volumes from individual growers are small, which requires use of local freight consolidators. Ash et al. (2017) identified supply chain costs as a significant challenge for agricultural development in northern Australia. Options for reducing freight costs to market include local processing facilities or for horticultural products, establishing lower cost export options through the port of Darwin. Achieving a long-term profitable cropping enterprise will be difficult without a pathway for reducing freight costs as a percentage of the value of product.

Options for increasing gross returns are either through increasing yields or employing more intensive rotational cropping systems (particularly for broadacre crops) that provide more than one crop per year. Significant increases in yield of most crops have been achieved over the last few decades but these increases are over the longer term through improved genetics and farming system technologies. More intensive cropping systems potentially offer more immediate gains in financial returns. However, implementing more intensive rotational systems, including double cropping (two crops per year), is dependent on the interaction between soils, climate and water availability. These issues are explored in the next section on cropping systems.
4.4.5 CROPPING SYSTEMS

As indicated above, new agricultural developments that focus on field cropping may require more than a single crop in a year to generate significant enough revenues to meet development, fixed and variable costs. The number of different possibilities for cropping systems is very large, given the range of field crops, horticultural crops, forages and rotations that can be grown in northern Australia. The approach adopted in the Assessment focused on examining possible cropping system combinations that could be practically integrated into the climate and environment of the Darwin catchments. For example, does the pattern of rainfall and soil trafficability permit two crops per year when combined with management resources and capacity to rapidly finish one crop and move into another crop with tightly constrained planting windows?

Two scenarios were explored:

1. Rice grown over the wet season followed by mungbean in the dry season.
2. Soybean grown over the wet season followed by rice during the dry season.

Rice grown over the wet season achieves lower yields (4.4 t/ha) compared with dry-season yields (10.5 t/ha) due to lower solar radiation associated with increased cloud cover, as discussed earlier in this chapter. Mungbean sown over the dry season following the wet-season rice crop averages 2 t/ha, which is a good yield for mungbean. Soybean yields of 3.5 t/ha are achievable during the wet season under rainfed conditions with some supplementary irrigation, if needed.

The two examples outlined above highlight how cropping systems and rotations need to be considered carefully to fit with the soil, climate and agronomic environment. Growing wet-season rice followed by mungbean in an annual double crop produced total gross margin returns of less than $800/ha because of the low yields and returns from growing rice over the wet season. Growing rice in the dry season after a wet-season soybean crop produces higher yields and returns than from a single annual rice crop, with total gross margins in the order of $1900/ha. This return could be sufficient to meet capital costs of development in the order of $10,000 to $15,000/ha.

More broadly, the design of, and the management skills required to successfully implement either best-practice management for individual crops or intensive cropping rotations in tropical environments should not be underestimated. Throughout this assessment of agriculture in the Darwin catchments, there is an assumption of good agronomic practice, which provides an optimistic view of potential yield and returns.

4.5 Crop synopses

4.5.1 INTRODUCTION

Note that the estimates for land suitability in these synopses represent the total areas of the catchment unconstrained by factors such as water availability; land tenure; environmental and other legislation and regulations; and a range of biophysical risks such as cyclones, flooding and secondary salinisation. These are addressed elsewhere by the Assessment. The land suitability maps are designed to be used predominantly at the regional scale. Farm-scale planning would require finer scale, more localised assessment.
4.5.1 CEREAL CROPS

Cereal production is well-established in Australia. Around 20 million ha of land is devoted to grain (wheat, barley, grain, sorghum, oats, triticale, maize, etc.) production each year, yielding over 50 Mt/year with a value in 2016–17 of $26.1 billion (ABARES, 2018). Domestic markets demand all cereals. Significant export markets exist for wheat, barley and sorghum (grain) and there are niche export markets for grains such as maize and oats.

Among the cereals, the ‘summer crops’ such as sorghum (grain) and maize are the most promising for the Darwin catchments. These could be grown opportunistically using dryland production, although the years in which this could be successfully done will be limited. Cereal crops could be grown more consistently during the dry season using irrigation.

Assuming unconstrained development, approximately 710,000 ha of the Darwin catchments are considered to be moderately suitable with considerable limitations (Class 3; Table 4-1) or better (Class 2) for irrigated cereal cropping using spray irrigation in the dry season. About 88,000 ha are moderately suitable with considerable limitations (Class 3) for dry-season furrow irrigation of rice (Figure 4-11). The other dry-season furrow irrigated cereals are moderately suitable with considerable limitations (Class 3) to a lesser extent, approximately 50,000 ha, due to inadequate soil drainage. There is potential for dryland cereal production in the wet season in areas ranging from about 10,000 ha for sorghum (grain), 15,000 ha for maize and 85,000 ha for millet.

The ‘winter cereals’ such as wheat and barley are not well-adapted to the climate of the Darwin catchments. If grown during winter, they would require full irrigation.

To grow cereal crops, farmers will require access to tillage, fertilising, planting, spraying and harvesting equipment. Harvesting is often a contract operation, and in larger growing regions other activities can also be performed under contract.

Table 4-9 provides summary information relevant to the cultivation of cereals, using sorghum (grain) as an example. The companion technical report on agricultural viability (Ash et al., 2018a) provides greater detail for a wider range of crops.
Figure 4-11 Modelled land suitability for (a) dry-season rice using furrow irrigation and (b) wet-season grain sorghum using furrow irrigation

Note that this land suitability map does not take into consideration flooding, risk of secondary salinisation or availability of water. The methods used to derive the reliability data in the inset map are outlined in Thomas et al. (2018b).

Figure 4-12 Sorghum (grain)
Photo: CSIRO
Table 4-9 Sorghum (grain) (*Sorghum bicolor*)

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Summary</strong></td>
<td>Major summer rainfed (dryland) grain crop grown mainly for stock feed. Currently grown extensively in southern and central Queensland (600,000 to 700,000 ha). Sorghum has been a major grain crop in the NT, grown in rotation with pasture legumes such as Cavalcade. It potentially can supply an intensification of the northern Australian cattle industry.</td>
</tr>
<tr>
<td><strong>Growing season</strong></td>
<td>Planting window December to July. 120- to 180-day duration of growth. Ranges of sorghum cultivars are available to suit different sowing times and geographic locations.</td>
</tr>
<tr>
<td><strong>Land suitability assessment</strong></td>
<td>Land suitability is highly dependent on season of planting and type of irrigation. While 24% of the catchments are suitable (Class 3) or better for sorghum under spray irrigation in the dry season, this drops to 2% for furrow irrigation. Wet-season spray irrigation is limited to only 7% of the catchments and wet-season furrow to 1%. Less than 1% is Class 3 for rainfed (dryland) although opportunistic use after good wet seasons may allow a greater area in some years. The coastal lowlands are limited by potential acid sulfate soils with other low-lying parts of the catchments seasonally or permanently wet. The extensive uplands are dominated by excessive slope, rockiness and low soil water storage due to shallow and/or stony soils. Wet-season cropping is limited by inadequate drainage of the soil profile on heavier soils with the clay soils in the upper Adelaide and Mary catchments most suitable for furrow irrigation.</td>
</tr>
<tr>
<td><strong>Irrigation system requirements</strong></td>
<td>Spray, surface, micro</td>
</tr>
<tr>
<td><strong>Applied irrigation water (median)</strong></td>
<td>2.8 ML/ha (Sowing late wet season). Assumes perfect timing of irrigation (i.e. no losses).</td>
</tr>
<tr>
<td><strong>Crop yield (median)</strong></td>
<td>Dryland: 4.2 t/ha</td>
</tr>
<tr>
<td></td>
<td>Irrigated: 7.2 t/ha</td>
</tr>
<tr>
<td><strong>Salinity tolerance</strong></td>
<td>Moderately tolerant – EC&lt;sub&gt;e&lt;/sub&gt; threshold for yield decline 6.8 dS/m</td>
</tr>
<tr>
<td><strong>Downstream processing</strong></td>
<td>Available for direct delivery to end user.</td>
</tr>
<tr>
<td><strong>By-products</strong></td>
<td>Biomass for stock feed, bio-processing?</td>
</tr>
<tr>
<td><strong>Production risks</strong></td>
<td>Frost, heat stress at flower, minimum soil temperature for germination</td>
</tr>
<tr>
<td><strong>Rotations</strong></td>
<td>High potential for annual rotation.</td>
</tr>
<tr>
<td><strong>Management considerations</strong></td>
<td>Header, row crop planter, spray rig (pest control), fertiliser</td>
</tr>
<tr>
<td><strong>Complexity of management practices</strong></td>
<td>Medium</td>
</tr>
<tr>
<td><strong>Markets and emerging markets</strong></td>
<td>In Australia sorghum grain is used mostly for stock feed in the cattle, pig and poultry industries. A large amount of grain is exported. Potential emerging market for feedlots supplying local abattoir.</td>
</tr>
<tr>
<td><strong>Prices</strong></td>
<td>Generally $150/t to $300/t</td>
</tr>
<tr>
<td><strong>Opportunities and risks under a changing climate</strong></td>
<td>More tolerant of drought and temperature stress than maize.</td>
</tr>
<tr>
<td><strong>Further reading</strong></td>
<td>DAFF (2011a)</td>
</tr>
</tbody>
</table>
4.5.2 FOOD LEGUME (PULSE CROPS)

Pulse production is well-established in Australia. Over 2 million hectares of pulse crops are grown annually, producing around 5 million tonnes of mainly chickpea, lupin and field pea with a value greater than $3.2 billion in 2016–17 (ABARES, 2018). Pulses produced in the Darwin catchments would most likely be exported although there is presently no cleaning or bulk handling facility.

The pulses, many of which have a short growing season, are often well-suited to opportunistic dryland production or more continuous irrigated production, probably in rotation with cereals or other non-legume crops.

Not all pulse crops are likely to be suited to the Darwin catchments. Those that are ‘tender’ such as field peas and beans may not be well-suited to the highly desiccating environment and periodically high temperatures. Direct field experimentation in the catchments is required to confirm this, for these and other species.

Assuming unconstrained development, approximately 750,000 ha of the Darwin catchments are considered to be moderately suitable with considerable limitations (Class 3; Table 4-1) for irrigated cropping of pulses using spray irrigation in the dry season (Figure 4-13). Navy bean is suitable to a lesser extent, limited by soil water holding capacity. About 70,000 ha are moderately suitable with considerable limitations (Class 3) for dry-season furrow irrigation, with mungbean and navy bean suitable to a smaller extent. Only 13,000 ha are Class 3 suitable for dryland cropping.

Pulses are often advantageous in rotation with other crops because they provide a disease break and, being legumes, often provide nitrogen for subsequent crops. Even where this is not the case, their ability to meet their own nitrogen needs can be beneficial. This may be a distinct advantage in areas such as the Darwin catchments where freight costs (for fertiliser, etc.) pose a considerable cost burden on potential growers. Mungbeans are also high value (> $1000/t) and so the freight costs as a percentage of the value of the crop are low compared with cereal grains.

To grow pulse crops, farmers will require access to tillage, fertilising, planting, spraying and harvesting equipment. Harvesting is generally a contract operation, and in larger growing regions other activities can also be performed under contract. The equipment required for pulse crops is the same as is required for cereal crops, so farmers intending on a pulse and cereal rotation would not need to purchase extra ‘pulse-specific’ equipment.

Table 4-10 provides summary information relevant to the cultivation of many pulses, using mungbean as an example. The companion technical report on agricultural viability (Ash et al., 2018a) provides greater detail for a wider range of crops.
Figure 4-13 Modelled land suitability for mungbean in the dry season using (a) furrow irrigation and (b) spray irrigation
Note that this land suitability map does not take into consideration flooding, risk of secondary salinisation or availability of water. The methods used to derive the reliability data in the inset map are outlined in Thomas et al. (2018b).

Figure 4-14 Mungbean
Photo: CSIRO
Table 4-10 Mungbean (*Vigna radiata*)

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Summary</strong></td>
<td>Mungbean is a relatively quickly maturing (90 days) grain legume that can be sown in early spring or late summer as part of a planned rotation or as an opportunity crop. Mainly used for human consumption (sprouting and processing) but can be used as green manure and livestock forage. In the northern grains region of Queensland and NSW, 66,000 ha were grown in 2011. Generally reliable production for spring and summer plantings for both rainfed (dryland) and irrigation. Market-driven demand for high-quality product for sprouting.</td>
</tr>
<tr>
<td><strong>Growing season</strong></td>
<td>Planting window February to May</td>
</tr>
<tr>
<td><strong>Land suitability assessment</strong></td>
<td>Dry-season irrigated cropping is more suited to mungbean with &lt;1% of the catchments suitable for rainfed (dryland) in the wet season. While 23% of the catchments are Class 3 for spray irrigation, this drops to 1% under furrow irrigation. Opportunistic planting after good wet seasons may allow a greater area for rainfed in some years. The coastal lowlands are limited by potential acid sulfate soils with other low-lying parts of the catchments seasonally or permanently wet. The extensive uplands are dominated by excessive slope, rockiness and low soil water storage due to shallow and/or stony soils. Wet-season cropping is limited by inadequate drainage of the soil profile on heavier soils with the clay soils in the upper Adelaide and Mary catchments most suitable for furrow irrigation.</td>
</tr>
<tr>
<td><strong>Irrigation system requirements</strong></td>
<td>Spray, surface, micro</td>
</tr>
<tr>
<td><strong>Applied irrigation water (median)</strong></td>
<td>1.7 ML/ha (March sowing). Assumes perfect timing of irrigation (i.e. no losses).</td>
</tr>
</tbody>
</table>
| **Crop yield (median)**        | Dryland: 1.3 t/ha  
Irrigated: 2.1 t/ha                                                                                                                                                                    |
| **Salinity tolerance**         | Sensitive – ECe Threshold for yield decline 1.8 dS/m                                                                                                                                               |
| **Downstream processing**      | Available for direct delivery to end user.                                                                                                                                                           |
| **By-products**                | Biomass for stock feed                                                                                                                                                                               |
| **Production risks**           | Rain periods during late grain fill for spring-sown mungbean. Insect damage resulting in quality downgrades                                                                                         |
| **Rotations**                  | Opportunity crop, annual rotation                                                                                                                                                                   |
| **Management considerations**  | Header, row crop planter, spray rig (pest control)                                                                                                                                                  |
| **Complexity of management practices** | Medium                                                                                                                                                                                            |
| **Markets and emerging markets** | Increasing demand for high-quality grain to supply the domestic market. Nearly all (95%) of the Australian mungbean crop is exported (DEEDI, 2010). |
| **Prices**                     | World mungbean prices are largely determined by both the volume and quality of the crops in China and Burma. Price trends usually become obvious in December when the harvest of the Chinese crop nears completion and both the volume and quality of production become apparent. Mungbeans are classified into five grades and price varies accordingly. |
| **Opportunities and risks under a changing climate** | Short-season opportunity crop, lower fertiliser requirements, potential for increased insect pest pressure as a result of increased temperatures |
| **Further reading**            | DEEDI (2010), DAFF (2012c)                                                                                                                                                                          |
4.5.3 OILSEED CROPS

Soybean, canola and sunflowers are oilseed crops used to produce vegetable oils, biodiesel and for supplementary use as high protein meals for intensive animal production (cottonseed is also classified as an oilseed that is used for animal production). Soybean is also used in processed foods such as tofu; it can provide both green manure and soil benefits in crop rotations, with symbiotic nitrogen fixation adding to soil fertility and sustainability in an overall cropping system. Soybean is used commonly as a rotation crop with sugarcane in northern Queensland. Summer oilseed crops such as soybean and sunflower are more suited to tropical environments than winter-grown oilseed crops such as canola.

Soybean is sensitive to photoperiod (day length) and requires careful consideration in selection of the appropriate variety for a particular sowing window. Unlike soybean, sunflower cannot be baled or used for forage and because it is susceptible to many of the same diseases as legumes it should not be used in rotation with legumes.

Australia produces around 5 to 6 million tonnes of oilseed crop annually, about 80% of which is from canola and the remainder primarily from cottonseed (ABARES, 2018), with soybean and sunflowers contributing 3% and 4%, respectively.

Assuming unconstrained development, approximately 700,000 ha of the Darwin catchments are considered to be moderately suitable with considerable limitations (Class 3; Table 4-1) or better (Class 2) for irrigated oilseed cropping using spray irrigation in the dry season (Figure 4-15). About 40,000 ha are moderately suitable with considerable limitations (Class 3) for dry-season furrow irrigation. Inadequate soil drainage restricts wet-season furrow irrigation, although approximately 180,000 ha are suitable Class 3 or better for wet-season spray irrigation occurring on the elevated lighter textured soils. There is potential for dryland oilseed production in the wet season of suitable Class 3 or better in areas ranging from about 10,000 ha for soybean and 30,000 ha for sesame.

To grow oilseed crops, farmers will require access to tillage, fertilising, planting, spraying and harvesting equipment. Harvesting is generally a contract operation, and in larger growing regions other activities can also be performed under contract. The equipment required for pulse crops is the same as is required for cereal crops, so farmers intending on a pulse and cereal rotation would not need to purchase extra ‘pulse-specific’ equipment.

Table 4-11 provides summary information relevant to the cultivation of oilseed crops, using soybean as an example. The companion technical report on agricultural viability (Ash et al., 2018a) provides greater detail for a wider range of crops.
Figure 4-15 Modelled land suitability for soybean in the dry season using (a) spray irrigation and (b) furrow irrigation

Note that this land suitability map does not take into consideration flooding, risk of secondary salinisation or availability of water. The methods used to derive the reliability data in the inset map are outlined in Thomas et al. (2018b).

Figure 4-16 Soybean
Photo: CSIRO
Table 4-11 Soybean (*Glycine max*)

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Summary</strong></td>
<td>Soybean (<em>Glycine max</em>) is a legume with a compact growth habit less than 1 m high. Soybean is the most widely grown oilseed crop, with many varieties available to match a wide range of Australian environments – primarily differentiated by the time taken to maturity. Soybeans flower as day length becomes shorter, so varieties are matched to a combination of latitude and planting time. Longer varieties are planted earlier (November) and shorter maturing varieties can be planted later (January). Soybean is suited to a range of soil types and can be successfully grown without irrigation, relying on wet-season rain, but will yield better with irrigation. It is able to tolerate moderate levels of flooding and soil salinity. It is being increasingly used as an irrigated forage in northern Australia because of its high productivity and ease of establishment.</td>
</tr>
<tr>
<td><strong>Growing season</strong></td>
<td>Under irrigation planting from late spring (November) through to January. Sowing time is matched to variety.</td>
</tr>
<tr>
<td><strong>Land suitability assessment</strong></td>
<td>Extensive areas of a range of soils, 23% of the catchments, are Class 3 or better for soybean under spray irrigation in the dry season, this drops to 1% under furrow irrigation on the heavier textured soils. The coastal lowlands are limited by potential acid sulfate soils with other low-lying parts of the catchments seasonally or permanently wet. The extensive uplands are dominated by excessive slope, rockiness and low soil water storage due to shallow and/or stony soils. Wet-season cropping is limited by inadequate drainage of the soil profile on heavier soils with the clay soils in the upper Adelaide and Mary catchments most suitable for furrow irrigation.</td>
</tr>
<tr>
<td><strong>Irrigation system requirements</strong></td>
<td>Spray, surface</td>
</tr>
<tr>
<td><strong>Applied irrigation water (median)</strong></td>
<td>1 to 4 ML/ha (low applied irrigation water if grown over the wet season). Assumes perfect timing of irrigation (i.e. no losses).</td>
</tr>
<tr>
<td><strong>Crop yield (median)</strong></td>
<td>Dryland: 2.8 t/ha</td>
</tr>
<tr>
<td></td>
<td>Irrigated: 3.1 to 3.6 t/ha</td>
</tr>
<tr>
<td><strong>Salinity tolerance</strong></td>
<td>Moderately tolerant</td>
</tr>
<tr>
<td><strong>Downstream processing</strong></td>
<td>Either sourced for edible trade (which attracts a premium) or delivered for crushing and oil extraction.</td>
</tr>
<tr>
<td><strong>By-products</strong></td>
<td>Crushed by-product is used for stock feed. Oil has potential use in biofuels.</td>
</tr>
<tr>
<td><strong>Production risks</strong></td>
<td>Wet conditions at harvest can be detrimental to grain quality. Wet growing conditions can also increase pest and disease pressure, requiring more control.</td>
</tr>
<tr>
<td><strong>Rotations</strong></td>
<td>Soybean is commonly used in rotations including sugarcane, cotton, rice and other crops. Soybean is a legume and therefore able to ‘fix’ atmospheric nitrogen, providing a benefit to the following crop.</td>
</tr>
<tr>
<td><strong>Management considerations</strong></td>
<td>Ability to effectively use inoculants and desiccants. Direct seeders and headers. Ability to identify pests and diseases and apply effective control measures appropriately.</td>
</tr>
<tr>
<td><strong>Complexity of management practices</strong></td>
<td>Medium</td>
</tr>
<tr>
<td><strong>Markets and emerging markets</strong></td>
<td>Primarily domestic market</td>
</tr>
<tr>
<td><strong>Prices</strong></td>
<td>$450 to $750 per tonne</td>
</tr>
<tr>
<td><strong>Opportunities and risks under a changing climate</strong></td>
<td>Under water constraints varieties with shorter times to maturity can be planted to conserve water.</td>
</tr>
</tbody>
</table>
4.5.4 ROOT CROPS, INCLUDING PEANUT

Root crops are those vegetables where the harvested material grows under the ground. The harvesting of root crops involves ‘pulling’ the material from the ground, prior to either direct harvest or drying prior to harvest. While peanut is technically an oilseed crop, it has been included in the root crop category due to its similar agronomic requirements (i.e. the need for it to be ‘pulled’ from the ground as part of the harvest operation).

When peanut is included in the root crop category, peanut is by far the most likely root crop that would be grown in the Darwin catchments. Other potential crops such as sweet potatoes and cassava are higher value, and therefore more likely to be grown in smaller areas. The Australian peanut industry currently produces approximately 20,000 to 25,000 t/year from around 8000 ha, with an on-farm annual value of production of $15 to $20 million. The Australian industry is focused in Queensland, with a major production area just to the south of the Mitchell catchment in Tolga.

Root crops are potentially well-suited to the lighter soil types in the Darwin catchments. Root crops are not suited to growing on heavier clay soils because they need to be pulled from the ground for harvest, and the heavy clay soils, such as cracking clays, are not conducive to easy crop pulling.

Assuming unconstrained development, approximately 570,000 ha of the Darwin catchments are considered to be moderately suitable with considerable limitations (Class 3; Table 4-1) or better (Class 2) for irrigated cropping of root crops using spray irrigation in the dry season (Figure 4-17). In the wet season this area is reduced to around 105,000 ha by the erosion limitation and about 95,000 ha are Class 3 or better for dryland cropping in the wet season. Furrow irrigation is not suited to either season with wetness on the heavier textured soils being the limitation and the lighter textured soils being too permeable. Given root crops are not suited to heavy soils and these heavier textured soils are most suited to furrow irrigation, the root crops are largely suited to spray irrigation.

To grow root crops, farmers will require access to tillage, fertilising, planting, spraying and harvesting equipment. The harvesting operation requires specialised equipment to ‘pull’ the crop from the ground, and then to pick it up either immediately or after a drying period.

Table 4-12 provides summary information relevant to the cultivation of root crops, using peanut as an example. The companion technical report on agricultural viability (Ash et al., 2018a) provides greater detail for a wider range of crops.
Figure 4-17 Modelled land suitability for (a) dry-season peanut using spray irrigation and (b) dry-season sweet potato using spray irrigation

Note that this land suitability map does not take into consideration flooding, risk of secondary salinisation or availability of water. The methods used to derive the reliability data in the inset map are outlined in Thomas et al. (2018b).

Figure 4-18 Peanuts
Photo: Shutterstock
Table 4-12 Peanut (*Arachis hypogaea*)

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Summary</strong></td>
<td>Peanut (<em>Arachis hypogaea</em>) is a legume with a compact growth habit less than 0.6 m high. Most peanuts grown in Australia are grown in Queensland, primarily around Kingaroy, Bundaberg/Childers, Emerald and the Atherton Tablelands. While technically an oilseed crop, the agronomic requirements of peanut are close to those of root crops. Peanut can be grown under irrigation or dryland where rainfall is suitable. Peanut varieties are either Virginia, runner or Spanish type. Virginia is used in the snack food industry, with runner and Spanish used in the manufacturing industries. Harvesting of peanut is specialised, occurring in two distinct operations requiring specialised equipment. First the crop roots are cut below the pods and the bush is ‘pulled’ from the ground. In the second stage the pods are removed from the rest of the bush in a process called ‘threshing’. Most peanut pods will then need drying prior to being safe for storage.</td>
</tr>
<tr>
<td><strong>Growing season</strong></td>
<td>Under irrigation peanut can be grown in the wet season or dry season. Planting for wet-season production is from December to February and planting for dry-season production is from late March to early June.</td>
</tr>
<tr>
<td><strong>Land suitability assessment</strong></td>
<td>Land suitability for root crops are highly dependent on soils, preferring lighter textured soils. Approximately 20% of the catchments are Class 3 or better for peanuts under spray irrigation in the dry season, reflecting these lighter textured soils. The coastal lowlands are limited by potential acid sulfate soils with other low-lying parts of the catchments seasonally or permanently wet. The extensive uplands are dominated by excessive slope, rockiness and low soil water storage due to shallow and/or stony soils.</td>
</tr>
<tr>
<td><strong>Irrigation system requirements</strong></td>
<td>Spray. Peanut is not suited to the heavy soils suited to surface irrigation.</td>
</tr>
<tr>
<td><strong>Applied irrigation water</strong></td>
<td>4.0 ML/ha. Assumes perfect timing of irrigation (i.e. no losses).</td>
</tr>
<tr>
<td><strong>Crop yield</strong></td>
<td>Irrigated: 3.5 t/ha</td>
</tr>
<tr>
<td><strong>Salinity tolerance</strong></td>
<td>Moderately sensitive</td>
</tr>
<tr>
<td><strong>Downstream processing</strong></td>
<td>Peanuts must be dried prior to storage, which is commonly done in dryers, but under favourable conditions can be done in the field prior to threshing. Peanuts are then transferred to a processing facility (e.g. Kingaroy) where they are shelled and graded, prior to being sent to market either raw or blanched, crushed for oil extraction and used in manufacturing peanut-based products for human consumption.</td>
</tr>
<tr>
<td><strong>By-products</strong></td>
<td>Peanut shell is used for mulch or animal feed. Crushed by-product used in stock feed mixes.</td>
</tr>
<tr>
<td><strong>Production risks</strong></td>
<td>Dry soil at harvest can damage crop during ‘pulling’. Wet conditions after pulling can degrade crop quality. Hot dry conditions reduce yield. High temperatures and high moisture content after harvest increases aflatoxin risk.</td>
</tr>
<tr>
<td><strong>Rotations</strong></td>
<td>Peanut is well-suited to crop rotations with cereals such as maize or rice, and can be planted in a sugarcane fallow. Peanut can be wet- or dry-season grown in the Darwin catchments. Peanut is a legume and therefore able to ‘fix’ atmospheric nitrogen, providing a benefit to the following crop.</td>
</tr>
<tr>
<td><strong>Management considerations</strong></td>
<td>Ability to effectively use inoculants and desiccants. Harvesting and threshing equipment, access to dryers</td>
</tr>
<tr>
<td><strong>Complexity of management practices</strong></td>
<td>Medium</td>
</tr>
<tr>
<td><strong>Markets and emerging markets</strong></td>
<td>Primarily domestic market</td>
</tr>
<tr>
<td><strong>Prices</strong></td>
<td>$1000 per tonne</td>
</tr>
<tr>
<td><strong>Opportunities and risks under a changing climate</strong></td>
<td>Hotter and drier dry seasons could limit areas suitable to peanuts.</td>
</tr>
<tr>
<td><strong>Further reading</strong></td>
<td>DAFF (2011b)</td>
</tr>
</tbody>
</table>
4.5.5 FORAGES

Forage, hay and silage are crops that are grown for consumption by animals. Forage is consumed in the paddock in which it is grown, which is often referred to as ‘stand and graze’. Hay is cut, dried, baled and stored before being fed to animals at a time when natural pasture production is low (generally towards the end of the dry season). Silage use resembles that for hay, but crops are stored wet, in anaerobic conditions where fermentation occurs to preserve the feed’s nutritional value.

Dryland and irrigated production of fodder is well-established throughout Australia, with over 20,000 producers, most of whom are not specialist producers. Fodder is grown on approximately 30% of all commercial Australian farms each year, and 70% of fodder is consumed on the farms on which it was produced. Approximately 85% of production is consumed domestically. The largest consumers are the horse, dairy and beef feedlot industries. Fodder is also widely used in horticulture for mulches and for erosion control. There is a significant fodder trade in support of the northern beef industry, though there is room for expansion as fodder costs currently comprise less than 5% of beef production costs (Gleeson et al., 2012).

Non-leguminous forage, hay and silage

The Darwin catchments are suited to dryland or irrigated production of non-leguminous forage, hay and silage. A significant amount of dryland hay production occurs in the Douglas–Daly region, to the south of Darwin. Most of that hay is either used in the Darwin catchments for feeding cattle destined for live export or used as part of a feed pellet used on boats carrying live export cattle.

Forage crops include grasses, both annual and perennial, such as sorghum, Rhodes grass, maize, and Jarrah grass, with particular cultivars specific for forage. These grass forages require considerable amounts of water and nitrogen as they can be high yielding (20 to 40 t dry matter/ha). Given their rapid growth, crude protein levels can drop very quickly, reducing their value as a feed for livestock. To maintain high nutritive value, high levels of nitrogen need to be applied and in the case of hay, the crop needs to be cut every 45 to 60 days. The rapid growth of forage during the late spring and summer months can make it challenging to match animals to forage growth so that it is kept leafy and nutritious and does not become rank and of low quality. Dryland hay production from perennials gives producers the option of irrigation when required or, if water becomes limiting, allowing the pasture to remain dormant before water again becomes available. Silage can be made from a number of crops, such as grasses, maize and sorghum.

The three crop examples for the hay, forage or silage production (Rhodes grass, sorghum and maize) have different tolerances to limitations, especially soil wetness conditions and available soil water storage reflected in the wide range of areas suited to these crops. Assuming unconstrained development, for Rhodes grass, just over 1 million ha of the Darwin catchments (Figure 4-19) are considered to be moderately suitable with considerable limitations (Class 3; Table 4-1) or better (Class 2) for irrigated cropping using spray irrigation in the dry season, whereas maize is approximately 700,000 ha and forage sorghum 380,000 ha. About 45,000 ha are moderately suitable with considerable limitations (Class 3) for dry-season furrow irrigation of maize and 25,000 ha for sorghum because it is less tolerant of soil wetness conditions in the clay soils. These soil wetness conditions reduce the Class 3 area for sorghum and maize furrow irrigation in the wet season to around 1,000 ha. Approximately 180,000 ha are considered to be moderately suitable.
with considerable limitations (Class 3) or better (Class 2) for irrigated sorghum and maize using spray irrigation in the wet season, which is reduced to around 15,000 ha for rainfed cropping.

Apart from irrigation infrastructure, the equipment needed for forage production is machinery for planting and fertilising. Spraying equipment is also desirable but not necessary. Cutting crops for hay or silage requires more specialised harvesting, cutting, baling and storage equipment.

Table 4-13 describes Rhodes grass production for hay over a 1-year cycle. Information similar to that in Table 4-13 for grazed forage crops is presented in the companion technical report on agricultural viability (Ash et al., 2018a).
Figure 4-19 Modelled land suitability for (a) Rhodes grass and (b) forage sorghum, both grown using spray irrigation. Note that this land suitability map does not take into consideration flooding, risk of secondary salinisation or availability of water. The methods used to derive the reliability data in the inset map are outlined in Thomas et al. (2018b).

Figure 4-20 Rhodes grass
Photo: CSIRO
**Table 4-13 Rhodes grass (Chloris gayana)**

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Summary</strong></td>
<td>Rhodes grass (Chloris gayana) is a drought tolerant perennial grass with a growth habit of 0.75 to 1.5 m in height. In dryland environments it prefers an annual rainfall of at least 650 mm and it is well-suited to a wide range of soils from light loams to heavy clays. Rhodes grass has a high leaf to stem ratio for a tropical grass but it can quickly go to seed if not cut or grazed regularly. It is able to tolerate moderate levels of flooding and soil salinity. It is being increasingly used as an irrigated forage in northern Australia because of its high productivity and ease of establishment.</td>
</tr>
<tr>
<td><strong>Growing season</strong></td>
<td>Under irrigation planting from early spring (September) through to autumn, though growth continues, albeit more slowly, through the cooler dry-season months.</td>
</tr>
<tr>
<td><strong>Land suitability assessment</strong></td>
<td>Large areas, ~42% of the catchments, are Class 3 or better for perennial Rhodes grass under spray irrigation, this drops to 3% under furrow irrigation, indicating the high permeability of sandier soils and wetness restrictions of clay soils. The coastal lowlands are limited by potential acid sulfate soils with other low-lying parts of the catchments seasonally or permanently wet. The extensive uplands are dominated by excessive slope, rockiness and low soil water storage due to shallow and/or stony soils. Wet-season cropping is limited by inadequate drainage of the soil profile on heavier soils, with the clay soils in the upper Adelaide and Mary catchments most suitable for furrow irrigation.</td>
</tr>
<tr>
<td><strong>Irrigation system requirements</strong></td>
<td>Spray, surface, micro</td>
</tr>
<tr>
<td><strong>Applied irrigation water (median)</strong></td>
<td>15.0 ML/ha. Assumes perfect timing of irrigation (i.e. no losses).</td>
</tr>
<tr>
<td><strong>Crop yield (median)</strong></td>
<td>Irrigated: 30 to 35 t/ha</td>
</tr>
<tr>
<td><strong>Salinity tolerance</strong></td>
<td>Moderately tolerant</td>
</tr>
<tr>
<td><strong>Downstream processing</strong></td>
<td>Available for direct delivery to end user.</td>
</tr>
<tr>
<td><strong>By-products</strong></td>
<td>Potential use in biofuels.</td>
</tr>
<tr>
<td><strong>Production risks</strong></td>
<td>Slow to establish without adequate water post sowing. Low frost tolerance.</td>
</tr>
<tr>
<td><strong>Rotations</strong></td>
<td>Perennial pasture. Potentially a component of a ley farming system, where crops are grown in rotation with grass pastures or legumes to disrupt carry-over pest and disease and improve soil fertility and structure.</td>
</tr>
<tr>
<td><strong>Management considerations</strong></td>
<td>Baler, forage cutter. Nitrogen fertiliser may be required to maintain productivity if not sown with legumes. No significant pests or diseases.</td>
</tr>
<tr>
<td><strong>Complexity of management practices</strong></td>
<td>Low</td>
</tr>
<tr>
<td><strong>Markets and emerging markets</strong></td>
<td>Growing demand from northern Australian livestock industry for good-quality forages.</td>
</tr>
<tr>
<td><strong>Prices</strong></td>
<td>Primarily for use on-farm. Price received will depend on drought conditions, with higher prices during dry periods.</td>
</tr>
<tr>
<td><strong>Opportunities and risks under a changing climate</strong></td>
<td>Drought tolerant, with some tolerance of moderate soil salinity (when established).</td>
</tr>
<tr>
<td><strong>Further reading</strong></td>
<td>DAFF (2013a)</td>
</tr>
</tbody>
</table>
**Forage legume**

The use of forage legumes is similar to that of forage grasses. They are generally grazed by animals but can also be cut for silage or hay. Some forage legumes are well-suited to the Darwin catchments, and would be considered among the more promising opportunities for irrigated agriculture (Figure 4-21).

Forage legumes are desirable because of their high protein content and their ability to fix atmospheric nitrogen. The nitrogen fixed during a forage legume phase is often in excess of that crop’s requirements, which leaves the soil with additional nitrogen. Forage legumes are being used by the northern cattle industry, and farmers primarily engaged in extensive cattle production could use irrigated forage legumes to increase the capacity of their enterprise, turning out more cattle from the same area. Cavalcade and lablab are currently grown in northern Australia and would be well-suited to the Darwin catchments. Cavalcade is already grown in the catchments and used for grazing and for hay. Hay crops are commonly used as a component of forage pellets that are used to feed live export cattle in holding yards and on boats during transport.

Assuming unconstrained development, approximately 740,000 ha of the Darwin catchments are considered to be moderately suitable with considerable limitations (Class 3; Table 4-1) or better (Class 2) for irrigated forage legumes using spray irrigation in the dry season (Figure 4-21) and about 170,000 ha for spray irrigation in the wet season on the lighter textured soils. About 50,000 ha are moderately suitable with considerable limitations (Class 3) for dry-season furrow irrigation occurring on the inland clay soils with negligible areas suitable in the wet season. Only 17,000 ha are moderately suitable with considerable limitations (Class 3) or better (Class 2) for rainfed cropping due to soil wetness conditions.

The equipment needed for grazed forage legume production is similar to that for forage grasses, that is, a planting method, with fertilising and spraying equipment being desirable but not essential. Cutting crops for hay or silage requires more specialised harvesting, cutting, baling and storage equipment.

Table 4-14 describes Cavalcade production over a 1-year cycle. The comments could be applied equally to lablab production.
Figure 4-21 Modelled land suitability for lablab using spray irrigation in (a) the dry season and (b) the wet season. Note that this land suitability map does not take into consideration flooding, risk of secondary salinisation or availability of water. The methods used to derive the reliability data in the inset map are outlined in Thomas et al. (2018b).

Figure 4-22 Lablab
Photo: CSIRO
Table 4-14 Cavalcade (Centrosema pascuorum ‘Cavalcade’)

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summary</td>
<td>Cavalcade is an annual or short-lived perennial, twining legume, which is widely adapted to grazing, hay production and green manure. It is used in mixed cropping and livestock systems and sometimes as a legume ley in cropping systems to address soil fertility. It is adapted to a wide range of soils and is able to survive prolonged waterlogging and partial submersion on the seasonally flooded coastal plains of the Top End of the NT. It can also tolerate high internal moisture deficits during droughts.</td>
</tr>
<tr>
<td>Growing season</td>
<td>Under irrigation, planting from March/April and grown until October/November or for a few years as a short-lived perennial. If grown perennially it requires periodic renovation.</td>
</tr>
<tr>
<td>Land suitability assessment</td>
<td>In Figure 4-21 the suitability for lablab is shown at around 25% of the catchments for spray irrigation in the dry season, a similar area to what is expected of Cavalcade. Wet-season spray irrigation of lablab with Class 3 or better is limited to only 6% but with Cavalcade more tolerant of prolonged waterlogging, larger areas of the catchments are expected to be suitable. The coastal lowlands are limited by potential acid sulfate soils with other low-lying parts of the catchments seasonally or permanently wet. The extensive uplands are dominated by excessive slope, rockiness and low soil water storage due to shallow and/or stony soils. Wet-season cropping is limited by inadequate drainage of the soil profile on heavier soils with the clay soils in the upper Adelaide and Mary catchments most suitable for furrow irrigation.</td>
</tr>
<tr>
<td>Irrigation system requirements</td>
<td>Spray, surface, micro</td>
</tr>
<tr>
<td>Applied irrigation water (median)</td>
<td>Approximately 5 ML/ha</td>
</tr>
<tr>
<td>Crop yield (median)</td>
<td>Dryland: 4 t/ha</td>
</tr>
<tr>
<td></td>
<td>Irrigated: 8 t/ha (estimate)</td>
</tr>
<tr>
<td>Salinity tolerance</td>
<td>Moderately sensitive</td>
</tr>
<tr>
<td>Downstream processing</td>
<td>Available for direct delivery to end user.</td>
</tr>
<tr>
<td>By-products</td>
<td>Biomass for stock feed, potential use in biofuels.</td>
</tr>
<tr>
<td>Production risks</td>
<td>Timing of crop establishment to avoid high temperature stress at flowering and to maximise harvesting outside of major rainfall periods. Does not tolerate heavy grazing.</td>
</tr>
<tr>
<td>Rotations</td>
<td>Annual rotation, break crop in cotton or sugar rotation</td>
</tr>
<tr>
<td>Management considerations</td>
<td>Baler, forage cutter</td>
</tr>
<tr>
<td>Complexity of management practices</td>
<td>Low</td>
</tr>
<tr>
<td>Markets and emerging markets</td>
<td>Growing demand from northern Australian livestock industry for good-quality forages.</td>
</tr>
<tr>
<td>Prices</td>
<td>Primarily used on-farm.</td>
</tr>
<tr>
<td>Opportunities and risks under a changing climate</td>
<td>Drought tolerant (when established). Provides additional soil nitrogen in crop rotation.</td>
</tr>
<tr>
<td>Further reading</td>
<td>Clements (1990)</td>
</tr>
</tbody>
</table>
Dryland and irrigated cotton production are well-established in Australia. The area of land devoted to cotton production varies widely from year to year, largely in response to availability of water. Assuming unconstrained development, on average 320,000 ha is planted each year, though this has varied from about 70,000 to almost 600,000 ha over the last 20 years. Gross value of production varies greatly; it was $2.5 billion in 2016–17 and $2.95 billion in 2011–12 as a consequence of favourable La Niña crop growing conditions and abundant irrigation supplies (ABARES, 2018). Genetically modified (GM) cotton varieties were introduced in 1996 and account for 98% of cotton produced in 2016. Australia was the fourth largest exporter of cotton in 2015. Cottonseed is a by-product of cotton processing and is a valuable cattle feed. Mean lint production in 2015–16 was 2.25 t/ha (ABARES, 2018).

Commercial cotton has had a long but discontinuous history of production in northern Australia, including in Broome, the Fitzroy River and the Ord River Irrigation Area in WA; in Katherine and Douglas–Daly in the NT; and near Richmond and Bowen in northern Queensland. An extensive study undertaken by the Australian Cotton Cooperative Research Centre in 2001 (Yeates, 2001) noted that past ventures suffered from:

- a lack of capital investment
- too rapid movement to commercial production
- a failure to adopt a systems approach to development
- climate variability.

Mistakes in pest control were also a major issue in early projects. Since the introduction of GM cotton in 1996, yields and incomes from cotton crops have increased in most regions of Australia. The key benefits of GM cotton (compared to conventional cotton) are savings in insecticide and herbicide use, and improved tillage management. In addition, farmers are now able to forward-sell their crop as part of a risk management strategy.

Research and commercial test farming have demonstrated that the biophysical challenges are manageable if the growing of cotton is tailored to the climate and biotic conditions of northern Australia (Yeates et al., 2013). In recent years irrigated cotton crops achieving 10 bales/ha have been grown successfully in the Burdekin irrigation region and experimentally in the Gilbert catchment of north Queensland. New GM cotton using CSIRO varieties that are both pest and herbicide resistant are an important component of these northern cotton production systems.

Climatic constraints will continue to limit production potential of northern cotton crops when compared to cotton grown in more favourable climatic regions of NSW and Queensland. On the other hand, the low risk of rainfall occurring during late crop development favours production in northern Australia, as it minimises the likelihood of late season rainfall that can downgrade fibre quality and price. Demand for Australian cotton exhibiting long and fine attributes is expected to increase by 10 to 20% of the market during the next decade and presents local producers with an opportunity in targeting production of high-quality fibre.

Assuming unconstrained development, approximately 705,000 ha of the Darwin catchments are considered to be moderately suitable with considerable limitations (Class 3; Table 4-1) or better (Class 2) for irrigated cotton cropping using spray irrigation in the dry season and about
180,000 ha for spray irrigation in the wet season (Figure 4-23). About 45,000 ha are moderately suitable with considerable limitations (Class 3) for dry-season furrow irrigation occurring on the inland clay soils, and a much lesser extent for wet-season furrow irrigation at approximately 1,000 ha due to inadequate soil drainage. There is potential for dryland cotton production in the wet season on about 17,000 ha although not in large contiguous areas.

In addition to a normal row planter and spray rig equipment used in cereal production, cotton requires access to suitable picking and module or baling equipment as well as transport to processing facilities. Initial development costs and scale of establishing cotton production in the catchments would need to consider sourcing of external contractors and could provide an opportunity to develop local contract services to support a growing industry.

Cotton production is also highly dependent on access to processing plants (cotton gins). There are no processing facilities in the NT, and the nearest gin is in Emerald, approximately 2600 km by road, which would make cotton production uneconomic. There may be opportunities to export raw cotton via ship to Asia if highly competitive transport costs could be negotiated.

The high oil and protein content of cottonseed, a co-product of the ginning process, is a profitable source of oil for domestic and export markets and local stock feed. Cottonseed contains about 20% crude protein and is a major component in drought feeding when mixed with molasses or grain. Regional processing of cotton could supply local cattle producers with a cost-effective high-quality feed supplement.

Other industrial crops such as tea and coffee are unlikely to yield well in the Darwin catchments. Niche industrial crops, such as guar and chia, may be feasible for the Darwin catchments, but there is only limited verified agronomic and market data on these crops. Past research on guar has been conducted in the NT and current trials are underway. These could prove feasible in the future. The companion technical report on agricultural viability (Ash et al., 2018a) provides greater detail for a wider range of industrial crops.

Table 4-15 describes some key considerations relating to cotton production.
Figure 4-23 Modelled land suitability for cotton grown in the wet season using (a) spray irrigation and (b) furrow irrigation

Note that this land suitability map does not take into consideration flooding, risk of secondary salinisation or availability of water. The methods used to derive the reliability data in the inset map are outlined in Thomas et al. (2018b).

Figure 4-24 Cotton
Photo: CSIRO
Cotton is a shrub native to some tropical and sub-tropical regions, producing 32% (in 2009) of the world’s fibre production. Australian cotton production is small compared with production in the USA and Israel. However, due to a favourable climate during the growing season, Australia is recognised (along with Egypt) as currently producing the world’s best cotton. A high proportion of Australian cotton (84% in 2005–06) is produced under irrigation with rainfed (dryland) crops sown into stored soil water resulting from traditional fallowing processes. Cotton is marketed on qualities of grade, colour and fibre length.

Cotton can be grown on the majority of deep arable soils with adequate rainfall or supplementary irrigation. CSIRO GM cotton has been successfully grown in the catchment of the Gilbert River and is currently grown in the catchment of the Burdekin River.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summary</td>
<td>Cotton is a shrub native to some tropical and sub-tropical regions, producing 32% (in 2009) of the world’s fibre production. Australian cotton production is small compared with production in the USA and Israel. However, due to a favourable climate during the growing season, Australia is recognised (along with Egypt) as currently producing the world’s best cotton. A high proportion of Australian cotton (84% in 2005–06) is produced under irrigation with rainfed (dryland) crops sown into stored soil water resulting from traditional fallowing processes. Cotton is marketed on qualities of grade, colour and fibre length. Cotton can be grown on the majority of deep arable soils with adequate rainfall or supplementary irrigation. CSIRO GM cotton has been successfully grown in the catchment of the Gilbert River and is currently grown in the catchment of the Burdekin River.</td>
</tr>
<tr>
<td>Growing season</td>
<td>Planting window December to February, maturity May to July</td>
</tr>
<tr>
<td>Land suitability assessment</td>
<td>Land suitability for cotton is highly dependent on season of planting and type of irrigation. While 24% of the catchments are Class 3 or better for spray irrigation in the dry season, this drops to 1.5% under furrow irrigation. Wet-season spray irrigation is limited to only 6% of the catchments and there are no areas potentially suitable for wet-season furrow. Less than 1% is Class 3 for rainfed (dryland) although opportunistic use after good wet seasons may allow a greater area in some years. The coastal lowlands are limited by potential acid sulfate soils with other low-lying parts of the catchments seasonally or permanently wet. The extensive uplands are dominated by excessive slope, rockiness and low soil water storage due to shallow and/or stony soils. Wet-season cropping is limited by inadequate drainage of the soil profile on heavier soils with the clay soils in the upper Adelaide and Mary catchments most suitable for furrow irrigation.</td>
</tr>
<tr>
<td>Irrigation system requirements</td>
<td>Spray, surface, micro</td>
</tr>
<tr>
<td>Applied irrigation water (median)</td>
<td>4.0 ML/ha (wet-season crop); 5.3 ML/ha (dry-season crop). Assumes perfect timing of irrigation (i.e. no losses). The water balance component of the APSIM cotton model has not been validated for northern Australia and the model outputs are likely to be underestimated. For this reason, the applied irrigation water values for cotton have been based on similar summer-grown crops (sorghum (grain)). More work is required for validating the cotton model in the tropics.</td>
</tr>
<tr>
<td>Crop yield (median)</td>
<td>Dryland: 3.5 bales/ha</td>
</tr>
<tr>
<td></td>
<td>Irrigated: 9.8 bales/ha (wet-season crop); 10.2 bales/ha (dry-season crop)</td>
</tr>
<tr>
<td>Salinity tolerance</td>
<td>Tolerant – ECe Threshold for yield decline 7.7 dS/m</td>
</tr>
<tr>
<td>Downstream processing</td>
<td>Cotton gin</td>
</tr>
<tr>
<td>By-products</td>
<td>Cottonseed for stock feed</td>
</tr>
<tr>
<td>Production risks</td>
<td>Early frost, prolonged water logging, reduced radiation due to cloud cover</td>
</tr>
<tr>
<td>Rotations</td>
<td>High potential for annual rotation</td>
</tr>
<tr>
<td>Management considerations</td>
<td>Picker, row crop planter, spray rig (pest control), fertiliser</td>
</tr>
<tr>
<td>Complexity of management practices</td>
<td>High</td>
</tr>
<tr>
<td>Markets and emerging markets</td>
<td>Price is influenced by international commodity markets. Australia is one of the world’s largest exporters of raw cotton, with more than 90% of production exported, mainly to Asian spinning mill customers. China, Indonesia, Thailand, South Korea, Japan, Taiwan, Pakistan and Italy are the main buyers. Cotton growers have the option of delivering their cotton directly to a processor or having it marketed by an independent merchant. There are several pricing options available, including forward contracts.</td>
</tr>
<tr>
<td>Prices</td>
<td>Currently approx. $450/bale</td>
</tr>
<tr>
<td>Opportunities and risks under a changing climate</td>
<td>Seasonal climate variability, water availability for irrigation</td>
</tr>
</tbody>
</table>

Further reading: DAFF (2012a)
4.5.7 INDUSTRIAL (SUGARCANE)

Sugar production is well-established in Queensland, which produces approximately 95% of the Australian crop. Sugarcane was grown around Darwin in the late 1800s but was never established as a successful industrial crop. It was grown in the Ord River Irrigation Area until 2007. There is approximately 370,000 ha of cane grown annually in Australia, supplying 24 mills that produce approximately 4.4 Mt of sugar. The gross value of production is approximately $1.8 billion.

Sugarcane is classified as an industrial crop in the Assessment because it requires a local processing facility. It is estimated that at least 30,000 ha are required for a sugar mill to be economically viable. As a consequence, sugarcane is considered to be a promising crop only where large areas of suitable irrigable land are available. Given the high costs of transport of harvested cane per unit of sugar produced, it can only be economically transported relatively short distances. If a production area was to be established around Darwin, then local processing facilities would be required.

Assuming unconstrained development, approximately 940,000 ha of the Darwin catchments are considered to be moderately suitable with considerable limitations (Class 3; Table 4-1) or better (Class 2) for irrigated sugarcane cropping using spray irrigation in the dry season. About 85,000 ha are moderately suitable with considerable limitations (Class 3) for dry-season furrow irrigation (Figure 4-25) on the inland clay soils.

It may be useful to explore the theoretical upper limits of sugarcane production in the Darwin catchments. Dryland sugarcane production is not feasible. Economic production would require continual irrigation throughout the dry season.

Equipment required for growing sugarcane is mostly industry-specific, with only tillage, spraying and some fertiliser equipment, such as used on other crops. Specialised planting, row formation, and harvesting equipment is required, but most farmers use contract harvesting, and many also use contract planters. At least 10 to 12 contract harvesters would be needed to service the minimum 30,000 to 40,000 ha of sugarcane required to support a viable sugar mill.

Table 4-16 describes some key considerations relating to sugarcane production.
Figure 4-25 Modelled land suitability for sugarcane grown using (a) spray irrigation and (b) furrow irrigation
Note that this land suitability map does not take into consideration flooding, risk of secondary salinisation or availability of water. The methods used to derive the reliability data in the inset map are outlined in Thomas et al. (2018b).

Figure 4-26 Sugarcane
Photo: CSIRO
### Table 4-16 Sugarcane (*Saccharum*)

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Summary</strong></td>
<td>Sugarcane is a tall tropical and sub-tropical perennial grass supplying 80% of the world’s sugar production. Australia is the 3rd largest raw sugar producer, milling about 4 to 4.5 Mt raw sugar annually. Depending on the local conditions, sugar is usually harvested between July and November and allowed to regrow (ratoon) for a further 3 to 4 years. Sugarcane can be grown on the majority of well-structured arable soils, with a preference for free-draining soils. Acid sulfate soils can present management problems.</td>
</tr>
<tr>
<td><strong>Growing season</strong></td>
<td>Sugarcane is grown from 12 to 16 months before harvesting. A plant crop of 15 to 16 months is followed by four ratoon crops of 12 months. Harvesting occurs between June and December.</td>
</tr>
<tr>
<td><strong>Land suitability assessment</strong></td>
<td>While 32% of the catchments are Class 3 or better for spray irrigation in the dry season, this drops to 3% under furrow irrigation occurring on the inland clay soils. The coastal lowlands are limited by potential acid sulfate soils with other low-lying parts of the catchments seasonally or permanently wet. The extensive uplands are dominated by excessive slope, rockiness and low soil water storage due to shallow and/or stony soils. Wet-season cropping is limited by inadequate drainage of the soil profile on heavier soils with the clay soils in the upper Adelaide and Mary catchments most suitable for furrow irrigation.</td>
</tr>
<tr>
<td><strong>Irrigation system requirements</strong></td>
<td>Spray, surface, micro</td>
</tr>
<tr>
<td><strong>Applied irrigation water (median)</strong></td>
<td>9.3 ML/ha (May sowing, September harvest). Assumes perfect timing of irrigation (i.e. no losses).</td>
</tr>
<tr>
<td><strong>Crop yield (median)</strong></td>
<td>Irrigated: 109 t/ha (May planting, September harvest). Break-even crop yield 32 t/ha, assuming local processing.</td>
</tr>
<tr>
<td><strong>Salinity tolerance</strong></td>
<td>Moderately sensitive – EC$_e$ threshold for yield decline 1.7 dS/m</td>
</tr>
<tr>
<td><strong>Downstream processing</strong></td>
<td>Requires local processing soon after harvest.</td>
</tr>
<tr>
<td><strong>By-products</strong></td>
<td>Molasses, bagasse, ethanol. Ash and filter mud as a source of fertiliser</td>
</tr>
<tr>
<td><strong>Production risks</strong></td>
<td>Significant production losses occur if sugarcane is flooded for prolonged periods when less than 1 m tall. Productivity can be affected by rats, pigs, cane grubs and insects. Exotic pests and diseases present a significant threat to the sugarcane industry.</td>
</tr>
<tr>
<td><strong>Rotations</strong></td>
<td>5-year rotation (one plant and four ratoon crops). Can be sown in rotation with a legume crop, such as soybean.</td>
</tr>
<tr>
<td><strong>Management considerations</strong></td>
<td>Header, row crop planter, spray rig (pest control). Permits may be required for burning.</td>
</tr>
<tr>
<td><strong>Complexity of management practices</strong></td>
<td>Medium</td>
</tr>
<tr>
<td><strong>Markets and emerging markets</strong></td>
<td>Sugarcane is one of Australia’s most important industries, worth $1.7 to $2.0 billion. Increasing demand from developing nations in South-East and southern Asia. More than 80% of all sugar produced in Australia is exported as bulk raw sugar, with key export markets including South Korea, Indonesia, Japan and Malaysia. Returns to producers are determined primarily by the world futures price for sugar but are also influenced by the level of the Australian dollar, regional sugar premiums, and the costs for marketing and transporting the product.</td>
</tr>
<tr>
<td><strong>Prices</strong></td>
<td>Currently approximately $400/t of sugar, which converts to a price of around $35/t of sugarcane</td>
</tr>
<tr>
<td><strong>Opportunities and risks under a changing climate</strong></td>
<td>Reduced water availability in a drier climate will reduce yields.</td>
</tr>
<tr>
<td><strong>Further reading</strong></td>
<td>Canegrowers (2017), DAFF (2012b)</td>
</tr>
</tbody>
</table>
4.5.8 INTENSIVE HORTICULTURE

Intensive horticulture is an important and widespread Australian industry, occurring in every state, particularly close to capital city markets. It is something of a ‘sleeping giant’ of Australian agriculture, employing approximately one-third of all people employed in agriculture, and having a farm gate value of approximately $10 billion (out of a total of about $28 billion for all Australian crops in 2015–16) (ABARES, 2018).

Production is highly seasonal and often involves the growth on a particular farm of a wide range of crops. The importance of freshness in many horticultural products means seasonality of supply is important in the market. The Darwin catchments have advantages in that that they can supply southern markets ‘out of season’. This requires a heightened understanding of risks, markets, transport and supply chain issues. Intensive horticulture is already widely practised in the Darwin catchments, with an emphasis on Asian vegetable and melon production, with $39 million in production in 2015 (NT Farmers Association, 2016).

Most Asian vegetable production goes to Asian wholesalers in Sydney and Melbourne. Local farmers have expanded into traditional vegetables like Lebanese cucumber and tomato and into intensive protected crop systems under shadecloth and hydroponics. Production is from smallholders, with around 100 small farms, some less than 10 ha. Almost all is shipped through two freight consolidators set up to handle small shipments. Melon production involves larger producers who freight product directly from the farm to southern markets.

The Assessment provides details on a subset of the horticultural crops possible in the catchments. Large areas of the Darwin catchments are suitable for dry-season trickle- and spray-irrigated intensive horticulture including Asian vegetables, asparagus, capsicum, chilli and cucurbits. Assuming unconstrained development, approximately 960,000 ha are considered to be moderately suitable with considerable limitations (Class 3; Table 4-1) for trickle irrigation in the dry season (Figure 4-27) and a slightly lower area of 910,000 ha suitable for spray irrigation, reflecting trickle irrigation to be more efficient on sandier soils. Cucurbits, snake beans and sweet corn considered in the wet season are moderately suitable with considerable limitations (Class 3) or better (Class 2) for 175,000 ha with trickle irrigation and 170,000 ha using spray irrigation. There is potential for wet-season rainfed (dryland) cropping on an opportunistic basis.

Horticulture typically requires specialised equipment and a large labour force. Therefore, a system for attracting, managing and retaining sufficient staff is also required. Harvesting is often by hand, but packing equipment is highly specialised. Irrigation is with micro equipment, but overhead spray is also feasible. Leaf fungal diseases need to be more carefully managed with spray irrigation. Micro spray equipment has the advantage of also being a nutrient delivery (fertigation) mechanism, as fertiliser can be delivered via the irrigation water.

Table 4-17 describes some key considerations relating to Asian vegetable production, as an exemplar of those relating to horticultural production more broadly.
Figure 4-27 Modelled land suitability for (a) cucurbits (e.g. rockmelon) in the wet season using trickle irrigation and (b) Asian vegetables in the dry season using trickle irrigation
Note that this land suitability map does not take into consideration flooding, risk of secondary salinisation or availability of water. The methods used to derive the reliability data in the inset map are outlined in Thomas et al. (2018b).

Figure 4-28 Asian vegetables in the Darwin catchments
Photo: CSIRO
### Table 4-17 Asian vegetables

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Summary</strong></td>
<td>Asian vegetables include Lebanese cucumber, bitter melon, hairy melon, long melon, okra and snake beans. Production is mostly over the dry season from April to November. While yields are often modest, prices received are high.</td>
</tr>
<tr>
<td><strong>Growing season</strong></td>
<td>Mostly over the dry season from April to November.</td>
</tr>
<tr>
<td><strong>Land suitability assessment</strong></td>
<td>A selection of horticultural crops and irrigation types have been provided in the Assessment and suitability varies across crop, season of planting and type of irrigation. While 33% of the catchments are Class 3 or better for Asian vegetables under trickle irrigation in the dry season, due to the erosion limitation this drops to 6% during the wet season using cucurbit as an example in Figure 4-27. The coastal lowlands are limited by potential acid sulfate soils with other low-lying parts of the catchments seasonally or permanently wet. The extensive uplands are dominated by excessive slope, rockiness and low soil water storage due to shallow and/or stony soils. Wet-season cropping is limited by inadequate drainage of the soil profile on heavier soils with the clay soils in the upper Adelaide and Mary catchments most suitable for furrow irrigation.</td>
</tr>
<tr>
<td><strong>Irrigation system requirements</strong></td>
<td>Micro, spray</td>
</tr>
<tr>
<td><strong>Salinity tolerance</strong></td>
<td>Range from moderately sensitive to tolerant – ECe threshold for yield decline 1.7 dS/m</td>
</tr>
<tr>
<td><strong>Downstream processing</strong></td>
<td>Requires local processing soon after harvest. Rapid transport and cooling of fresh market crops is important to maintain quality.</td>
</tr>
<tr>
<td><strong>By-products</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Production risks</strong></td>
<td>Pests and diseases</td>
</tr>
<tr>
<td><strong>Rotations</strong></td>
<td>As Asian vegetables are grown mostly in the dry season, a wet-season manure crop is recommended.</td>
</tr>
<tr>
<td><strong>Management considerations</strong></td>
<td>Cultivation equipment, spray rig, fertiliser, insect pest control (chemical resistance). There is a high labour requirement for weeding, harvesting, grading and packing.</td>
</tr>
<tr>
<td><strong>Complexity of management practices</strong></td>
<td>Medium</td>
</tr>
<tr>
<td><strong>Markets and emerging markets</strong></td>
<td>Most production goes to Asian wholesalers in Sydney and Melbourne. Some farmers have recently expanded into traditional vegetables like Lebanese cucumber and tomato, as well as intensive protected crop systems under shadecloth and hydroponics. Almost all is shipped through two freight consolidators set up to handle small shipments. Some of these products have very exacting temperature requirements for the 4-day freight to market and losses in sensitive products can be high.</td>
</tr>
<tr>
<td><strong>Prices</strong></td>
<td>Prices vary greatly depending on current supply and demand.</td>
</tr>
<tr>
<td><strong>Opportunities and risks under a changing climate</strong></td>
<td>A drier climate may allow a longer growing period but there will be trade-offs with higher temperatures.</td>
</tr>
<tr>
<td><strong>Further reading</strong></td>
<td>NT Farmers Association (2016)</td>
</tr>
</tbody>
</table>
4.5.9 PLANTATION TREE CROPS

Of all the potential plantation tree species available to be grown in the Darwin catchments, African mahogany and Indian sandalwood are the only two that would be considered economically feasible. Many other plantation species could be grown; however, returns are much lower than for these two crops. African mahogany is well-established in plantations near Katherine and Indian sandalwood is being grown in the Ord valley, around Katherine and in north Queensland. The first commercial crops of Indian sandalwood are being harvested and over that 16-year period, many agronomic challenges have been solved.

Plantation timber species require over 15 years to grow, but once established can tolerate prolonged dry periods. Irrigation water is critical in the establishment and first 2 years of a plantation. In the case of Indian sandalwood, the provision of water is not just for the trees themselves but the leguminous host plant associated with Indian sandalwood, as it is a semi-parasite.

Depending on the specific tree species being planted and their tolerance to poorly drained soils and waterlogging, the suitable areas vary considerably. Assuming unconstrained development, approximately 1 million ha of the Darwin catchments are considered to be moderately suitable with considerable limitations (Class 3; Table 4-1) or better (Class 2) for trickle irrigation with Indian sandalwood about 800,000 ha and teak 600,000 ha (Figure 4-29). Negligible areas are suitable for furrow irrigation.

Cyclones are a significant risk to long cycle tree crops and there is a reasonably high risk of cyclones in the Darwin catchments.

Areas of the Darwin catchments that are considered suitable (Class 2 and 3) for Indian sandalwood are shown in Figure 4-29. Table 4-18 describes Indian sandalwood production.
Figure 4-29 Modelled land suitability for Indian sandalwood grown using (a) mini spray or (b) furrow irrigation.
Note that this land suitability map does not take into consideration flooding, risk of secondary salinisation or availability of water. The methods used to derive the reliability data in the inset map are outlined in Thomas et al. (2018b).

Figure 4-30 Indian sandalwood and host plant
Photo: CSIRO
<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Summary</strong></td>
<td>Sandalwood is a medium-sized, hemiparasitic tree grown for its aromatic wood and essential oils. The key product of value from sandalwood trees is the heartwood, which contains most of the oil and scented wood. Heartwood starts to develop when the tree is about 10 years old, with the proportion of heartwood (and value of the plantation) increasing with age after that time. Commercially viable sandalwood can take at least 15 years to reach harvestable maturity, but many plantations are not harvested for 20 to 35 years. Large areas of Indian sandalwood have been planted in the Ord River Irrigation Area, with some plantations reaching maturity in 2013. Production risks are mostly associated with the long period of time from planting to harvest, and uncertainty about the market for sandalwood in 20 years.</td>
</tr>
<tr>
<td><strong>Land suitability assessment</strong></td>
<td>While 28% of the catchments are suitable (Class 3) or better for Indian sandalwood under mini-spray irrigation, this drops to less than 1% for furrow irrigation as Indian sandalwood is susceptible to poorly drained soils and waterlogging and the lighter textured soils are too permeable. The coastal lowlands are limited by potential acid sulfate soils with other low-lying parts of the catchments seasonally or permanently wet. The extensive uplands are dominated by excessive slope, rockiness and low soil water storage due to shallow and/or stony soils. Cyclones are also a risk to tree crops closer to the coast.</td>
</tr>
<tr>
<td><strong>Irrigation system requirements</strong></td>
<td>Surface, micro</td>
</tr>
<tr>
<td><strong>Irrigation demand</strong></td>
<td>6 ML/ha</td>
</tr>
<tr>
<td><strong>Crop yield (median)</strong></td>
<td>Heartwood 8 to 10 t/ha at 15 years, with oil 2 to 7% of heartwood</td>
</tr>
<tr>
<td><strong>Salinity tolerance</strong></td>
<td>Unknown</td>
</tr>
<tr>
<td><strong>Downstream processing</strong></td>
<td>Sandalwood can be processed in Australia or exported overseas for oil extraction.</td>
</tr>
<tr>
<td><strong>By-products</strong></td>
<td>Spent pulp after oil extraction is available for production of incense. Sandalwood nuts are edible, but there may also be potential markets in the cosmetics industry. The host plants may be harvested for timber or biofuels.</td>
</tr>
<tr>
<td><strong>Production risks</strong></td>
<td>Long length of time between planting and harvest. Termites can significantly reduce the yields of plantations. Synthetic and biosynthetic sandalwood oil is the greatest threat to the Australian sandalwood industry.</td>
</tr>
<tr>
<td><strong>Rotations</strong></td>
<td>Perennial tree crop not suited for rotation with other species. Sandalwood requires a host plant to supply water and nutrients.</td>
</tr>
<tr>
<td><strong>Management considerations</strong></td>
<td>Harvesting is usually done by contractors. May require several hosts during the lifespan of the tree. The first host is usually a herbaceous plant (e.g. Alternanthera) introduced to the container-grown sandalwood 1 month prior to planting. The second short-term host aims to produce rapid sandalwood growth and will die 2 to 4 years after establishment (e.g. Sesbania formosa). A long-term host (e.g. Cathormion umbellatum) supports the sandalwood over its production life. These hosts are planted at the same time as the sandalwood. Host species also need to be suited to local soil type and climate. Two to three host trees are required per sandalwood tree. Using several species of host plants will minimise risks from pests and diseases. Weed control is important and must use methods that do not negatively impact the sandalwood or host plant.</td>
</tr>
<tr>
<td><strong>Complexity of management practices</strong></td>
<td>Medium</td>
</tr>
<tr>
<td><strong>Markets and emerging markets</strong></td>
<td>Globally, sandalwood is highly valued due to the presence of unique aromatic substances in the heartwood, and it is important to certain cultures and religions. The incense industry is the largest consumer of sandalwood material. High prices are paid for good-quality timber suitable for carving, but the proportion of such material is low. The next most valuable product is the oil, which is the main driver of international trade and is sought after for high-value end uses such as perfumery.</td>
</tr>
<tr>
<td>PARAMETER</td>
<td>DESCRIPTION</td>
</tr>
<tr>
<td>-------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>The traditional markets of Taiwan, Hong</td>
<td>The traditional markets of Taiwan, Hong Kong and China are the biggest consumers of sandalwood.</td>
</tr>
<tr>
<td>Kong and China are the biggest consumers</td>
<td>Prices</td>
</tr>
<tr>
<td>of sandalwood.</td>
<td>Prices have increased over the past decade in response to a steady decline in worldwide supply.</td>
</tr>
<tr>
<td>Opportunities and risks under a changing</td>
<td>Can take advantage of soil water at any time of year.</td>
</tr>
<tr>
<td>climate</td>
<td>Planting several species of sandalwood and host plants together makes the plantation more resilient to climate change.</td>
</tr>
<tr>
<td></td>
<td>Sandalwood trees are not fire tolerant.</td>
</tr>
<tr>
<td>Further reading</td>
<td>Forest Products Commission Western Australia (2008), Clarke (2006), Brand et al. (2012)</td>
</tr>
</tbody>
</table>
4.5.10 TREE CROPS (FRUIT)

Some fruit and tree crops – such as mangoes, bananas and cashews – are well-suited to the climate of the Darwin catchments and are already grown within the catchments. Other species such as avocado and lychee are not likely to be as well-adapted to the climate and soils. Tree crops are generally not well-suited to cracking clays, which make up some of the suitable soils for irrigated agriculture in the Darwin catchments.

Fruit production shares many of the marketing and risk features of intensive horticulture such as a short season of supply and highly volatile prices as a result of highly inelastic supply and demand. Managing these issues requires a heightened understanding of risks, markets, transport and supply chain issues. However, fruit and nut tree production has been growing rapidly in Australia and in 2015–16, gross value of production was $4.74 billion out of a total value of $11.3 billion for horticulture in Australia (Horticulture Innovation Australia, 2017).

The perennial nature of tree crops makes a reliable year-round supply of water essential. However, some species, such as mango and cashew, can survive well under mild water stress until flowering (generally August to October for most fruit trees). It is critical for optimum fruit and nut production that trees are not water stressed from flowering through to harvest. This is the period approximately from August up to November through to February, depending on the species. This is a period in the Darwin catchments when very little rain falls, and farmers would need to have a system in place to access irrigation water during this time.

Depending on the specific fruit tree crops being planted, somewhere between 500,000 ha and 800,000 ha of the Darwin catchments are considered to be moderately suitable with considerable limitations (Class 3; Table 4-1) or better (Class 2), assuming unconstrained development. Trickle and mini spray irrigation (Figure 4-31) are more efficient on the sandier soils, showing larger areas of suitable land than the spray-irrigated tree crops. Avocado, approximately 140,000 ha, and papaya, 500,000 ha, are suited to a lesser extent because they are susceptible to inadequate soil drainage.

Specialised equipment for fruit and nut tree production is required. The requirement for a timely and significant labour force necessitates a system for attracting, managing and retaining sufficient staff. Tree pruning and packing equipment is highly specialised for the fruit industry. Optimum irrigation is usually via micro spray. This equipment is also able to deliver fertiliser directly to the trees through fertigation.

Table 4-19 describes some key considerations relating to mango production in the Darwin catchments, as an exemplar of those relating to tree crop production more broadly. Similar information for other fruit tree crops is described in the companion technical report on agricultural viability (Ash et al., 2018a).
Figure 4-31 Modelled land suitability for (a) mango and (b) banana, both grown using trickle irrigation

Note that this land suitability map does not take into consideration flooding, risk of secondary salinisation or availability of water. The methods used to derive the reliability data in the inset map are outlined in Thomas et al. (2018b).

Figure 4-32 Mangoes

Photo: Shutterstock
Table 4-19 Mango (*Mangifera indica*)

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Summary</strong></td>
<td>Mangoes are one of the major horticultural crops grown in Australia and around 6000 ha are currently grown in the NT. The main production areas are around Darwin and Katherine.</td>
</tr>
<tr>
<td><strong>Growing season</strong></td>
<td>Mango harvests start in September in the Darwin catchments and extends to the end of November – depending on variety.</td>
</tr>
<tr>
<td><strong>Suitable soils</strong></td>
<td>Trickle and mini spray irrigation of mangoes is suitable (Class 3) or better for 26% of the catchments occurring on a range of soil types, predominantly lighter clay to sandy soils. The coastal lowlands are limited by potential acid sulfate soils with other low-lying parts of the catchments seasonally or permanently wet. The extensive uplands are dominated by excessive slope, rockiness and low soil water storage due to shallow and/or stony soils. Wet-season cropping is limited by inadequate drainage of the soil profile on heavier soils with the clay soils in the upper Adelaide and Mary catchments most suitable for furrow irrigation. Cyclones are also a risk to tree crops closer to the coast.</td>
</tr>
<tr>
<td><strong>Irrigation system requirements</strong></td>
<td>Micro, need capacity to apply up to 0.3 ML/ha per week in peak demand</td>
</tr>
<tr>
<td><strong>Applied irrigation water (median)</strong></td>
<td>5 to 7 ML/ha</td>
</tr>
<tr>
<td><strong>Crop yield (median)</strong></td>
<td>Irrigated: 7 t/ha Kensington Pride, 15 to 20 t/ha PVR (e.g. Calypso)</td>
</tr>
<tr>
<td><strong>Salinity tolerance</strong></td>
<td>Sensitive</td>
</tr>
<tr>
<td><strong>Downstream processing</strong></td>
<td>Requires local processing soon after harvest. Unripe fruits are used in pickles, chutneys and salads. Ripe fruits can be eaten fresh or frozen, or can be dehydrated, canned or made into products such as jams and juices.</td>
</tr>
<tr>
<td><strong>By-products</strong></td>
<td>None</td>
</tr>
<tr>
<td><strong>Production risks</strong></td>
<td>Susceptible to cold and frost. Many varieties have irregular yields, with a heavy crop one year followed by several lighter crops.</td>
</tr>
<tr>
<td><strong>Rotations</strong></td>
<td>Perennial tree crop not suited for rotation. Could be planted for alley cropping.</td>
</tr>
<tr>
<td><strong>Management considerations</strong></td>
<td>Packing equipment, harvest aids. A wide range of climate zones in northern Australia provides opportunities to maintain a sustained period for supplying the domestic market. The two most common varieties grown in the NT are Kensington Pride and Calypso, while other varieties are grown on a limited scale to extend seasonal availability or supply niche markets.</td>
</tr>
<tr>
<td><strong>Complexity of management practices</strong></td>
<td>Medium</td>
</tr>
<tr>
<td><strong>Markets and emerging markets</strong></td>
<td>The majority of fruit are sold on the domestic market with only a small amount exported.</td>
</tr>
<tr>
<td><strong>Prices</strong></td>
<td>Highly variable depending on timing.</td>
</tr>
<tr>
<td><strong>Opportunities and risks under a changing climate</strong></td>
<td>Increasing opportunity to supply processed market for canned mango, juice and flavoured products.</td>
</tr>
<tr>
<td><strong>Further reading</strong></td>
<td>Johnson and Parr (2000), DAFF (2013b)</td>
</tr>
</tbody>
</table>
4.6 The opportunity for more intensive aquaculture in northern Australia

4.6.1 INTRODUCTION

Based on the natural advantages that northern Australia possesses in terms of political stability, proximity to large global markets, and a climate suited to farming of valuable tropical species, and through the large areas identified as suitable for aquaculture in the three study areas (as shown below), there appears considerable opportunity for aquaculture development in northern Australia (see the companion technical report on aquaculture viability (Irvin et al., 2018)).

While challenges to the development and operation of aquaculture enterprises do present in terms of regulatory barriers, global cost competitiveness, and the remoteness of much of the available land area, the potential to exploit the natural advantages of northern Australia and develop modern and sustainable aquaculture industries appears a compelling opportunity.

The text below considers the most likely candidate species, an overview of production systems and the prospects for integrating aquaculture with agriculture. Information on biodiversity is provided in Chapter 7. Farm scale and scheme scale economics for an intensive and extensive prawn farm and for a barramundi farm are found in Chapter 6 and in the Development Examples Report (Petheram et al., 2018).

4.6.2 CANDIDATE SPECIES

There are a number of candidate species for aquaculture in northern Australia including black tiger prawns (*Penaeus monodon*), banana prawns (*Fenneropenaeus merguiensis*), barramundi (*Lates calcarifer*), red claw (*Cherax quadricarinus*), marron (*Cherax tenuimanus*), cobia (*Rachycentron canadum*), silver perch (*Bidyanus bidyanus*), Murray cod (*Maccullochella peelii peelii*), jade perch (*Scortum barcoo*) and oysters.

However, for a range of reasons, the most appropriate species for considering aquaculture potential in the Darwin catchments are black tiger prawns (Figure 4-33), barramundi (Figure 4-34) and red claw. The first two species are suited to many marine and brackish water environments of northern Australia and have established land-based culture practices and well-established markets for harvested products. Prawns could potentially be cultured in either extensive (low density, low input) or intensive (higher density, higher inputs) pond-based systems in northern Australia, whereas land-based culture of barramundi would likely be intensive. The red claw crayfish is another potential candidate, for fresh water, that is currently cultured by a much smaller industry than the previous two species.

Black tiger prawns are found naturally at low abundances across the waters of the Western Indo-Pacific region, with wild Australian populations making up the southernmost extent of the species. Within Australia, the species is most common in the tropical north, but does occur at lower latitudes.
Barramundi are one of Australia’s most recognisable and highly prized sporting and eating fish. Its iconic status coupled with excellent palatability has created significant recreational and commercial fishing industries in northern Australia as well as making it the most highly produced and valuable tropical fish species in Australian aquaculture. Barramundi inhabit the tropical north of Australia from the Exmouth Gulf in WA through to the Noosa River on Queensland’s east coast. While the term ‘barramundi’ or ‘barra’ is used to describe the species in Australian waters, it is also commonly known as the ‘Asian sea bass’ or ‘giant sea perch’ throughout its natural areas of distribution in the Persian Gulf, the Western Indo-Pacific region and Southern China (Schipp et al., 2007).

Barramundi have many attributes that make them an excellent aquaculture candidate: fast growth (1 kg or more in 12 months); year-round fingerling availability; well-established production methods; and hardiness (i.e. they have a tolerance to low oxygen levels, high stocking densities and handling as well as a wide range of temperatures) (Schipp et al., 2007). Possibly the most attractive attribute is that barramundi are euryhaline, and so able to thrive and be cultured in fresh and marine water, although freshwater barramundi can have an earthy flavour that is not favoured by Australian consumers. Proper final preparation such as purging (holding in clean saltwater without feed) prior to final harvest can assist in removing these flavours.
There are over 100 species of freshwater crayfish in Australia. The main species of commercial interest in northern Australia is red claw. The name ‘red claw’ is derived from the distinctive red markings present on the claws of the male crayfish. Red claw is a warm water species, which inhabits still or slow-moving water bodies. The natural distribution of red claw ranges from the tropical catchments of Queensland and the NT to southern New Guinea.

Red claw have many traits that make them attractive for aquaculture production. A simple life cycle is beneficial, in that complex hatchery technology is not required (Jones et al., 1998). The crayfish can survive in high temperature and oxygen depleted water (<2 mg/L) and remain out of the water for extended periods. Low oxygen is a major stressor to most aquatic species. The ability of red claw to tolerate low oxygen levels is beneficial in terms of handling, grading and transport (Masser and Rouse, 1997). Red claw have a broad thermal tolerance, with optimal growth achievable between 23 and 31 °C.

4.6.3 GENERAL PRODUCTION SYSTEMS

Overview

Aquaculture production systems can be broadly classified into extensive, semi-intensive and intensive systems. Intensive systems require high inputs, with expected high outputs. They require high capital outlay; high running costs; specially formulated feed; specialised breeding, water quality and biosecurity processes; and high production per hectare (in the order of 5,000 to 20,000 kg/ha per crop). Recirculating aquaculture systems using indoor tanks are an example of intensive systems but were not considered for the study area. Semi-intensive systems involve
stocking seed from a hatchery, routine provision of a feed, and monitoring and management of water quality. Production is typically 1000 to 5000 kg/ha per crop. Extensive systems are characterised by low inputs and low outputs. They require less sophisticated management and often require no supplementary feed because the farmed species live on naturally produced feed in open air ponds. Extensive systems produce about half the volume of global aquaculture production. There are few examples of commercial extensive systems in Australia although there are many non-commercial examples, such as farm dams stocked with yabbies.

Water salinity and temperature are the key parameters that determine species selection and production potential for any given location. Most species can survive a broad range of temperatures. However, optimal production only occurs within a much narrower temperature range, and farming profitability is driven by the optimality of water temperature. Suboptimal water temperature (even within tolerable limits) will prolong the production season (slow growth) and increase the risk of disease.

**Pond types**

The primary culture unit for land-based farming is purpose-built ponds. Pond structures typically include an intake channel, production pond, discharge channel and a bioremediation pond (Figure 4-35). In most cases the ponds and channels are earthen based but may be partly or fully plastic-lined. The objective of the pond is to be a containment structure, an impermeable layer between the pond water and the local surface and groundwater.

![Figure 4-35 Schematic of marine aquaculture farm](image)

Soils for earthen ponds should have low permeability and high structural stability. During production the environment in an established earthen pond is relatively stable, with the organic material from production being well mixed with the organic material that pre-existed in the soil. The production process results in the accumulation of organic materials on the pond base, which may require seasonal removal. The majority of production ponds in Australia are earthen.
Ponds should be lined if the soils are permeable and haulage of suitable soils is not an economical option. Synthetic liners have a higher capital cost but provide an impermeable layer between the pond and the local surface and groundwater. They are often used in high intensity operations, which require high levels of aeration conditions that would lead to significant erosion in earthen ponds.

**Farm design and pond operation**

Optimal sites for farms are flat and have sufficient elevation to enable ponds to be completely drained between seasons. The elevation of the land on which the ponds and channels are constructed has a large bearing on production efficiency. It is critical that all ponds and channels can be fully drained during the off (dry-out) season to enable machinery access to sterilise and undertake pond maintenance. Optimal land for ponds is flat and has an elevation of 5 to 10 m above the Australian Height Datum (AHD) due to the impact of floods and cyclone surges.

Farms use aerators (typically electric paddlewheels and aspirators) to help maintain optimal water quality in the pond. The aerators provide oxygen and create a current that concentrates waste material in the centre of the pond. A medium-sized 50-ha prawn farm in Australia uses around 4 GWh annually (Paterson and Miller, 2013). The majority of the power requirement is to run pond aeration. Back-up power, usually via a diesel generator, is required to run all the aerators on the farm during power failure. Large farms may require multiple generators.

**4.6.4 PRODUCTION SYSTEMS FOR CANDIDATE SYSTEMS**

**Black tiger prawns**

For black tiger prawns, a typical pond in the Australian industry would be rectangular in shape, about 1 ha in area and about 1.5 metre in depth, although there are considerable variations between and within farms. The ponds are either wholly earthen, lined on the banks with black plastic and earthen bottoms, or fully lined, although this is not common in the Australian industry. In Australia, pond grow-out of black tiger prawns typically operates at stocking densities considered as ‘semi-intensive’ or ‘intensive’ (‘intensive’ is used for the remainder of this report), which typically means that ponds are stocked with between 25 to 50 individuals per square metre. These pond systems are fitted with multiple aeration units, such as paddlewheels and aspirators that serve to both aerate and circulate the water, the former for purposes of consolidating the waste into a central sludge pile, which allows a greater area of the pond bottom to be optimal for the prawns while also making the sludge easier to remove at the end of the crop. As an example, for intensive farming, ponds may be fitted with about eight aeration units early in the crop, which might consist of six paddlewheels and two aspirators set up in an optimised configuration to achieve good water circulation, whereas the number required might double by the end of the crop when prawn biomass is greatest (Mann, 2012).

At the start of each prawn crop, prior to stocking with postlarvae, the ponds need to be prepared and filled with water. Between harvests, the pond bottoms are dried and unwanted sludge from the previous crops is removed, and if needed, additional substrate is added. Prior to filling the ponds lime is often added to buffer pH, particularly in areas where there are acid sulfate soils. The ponds are then filled with filtered seawater and left for about 1 week prior to postlarval stocking. Algal blooms in the water are encouraged through addition of organic fertiliser. These blooms are
essential for both shading of the prawns and to discourage benthic algal growth, but also for the nutritional value they provide for the planktonic community within the ponds (QDPIF, 2006).

Postlarvae are produced at hatcheries and when transported great distances from the hatcheries to the ponds are typically packed into polystyrene boxes with highly oxygenated seawater, or stocked into specialist transporters fitted with aeration/oxygenation systems appropriate for holding postlarvae for many hours during transit (QDPIF, 2006).

In the first month after stocking, the postlarvae grow rapidly into small prawns, primarily relying on the natural productivity (zooplankton, copepods, and algae) supported by the algal bloom for their nutrition. Very small quantities of commercial feed are also added multiple times daily to assist with the weaning process and provide an energy source for the pond bloom. During this period no water exchange is required.

Approximately 1 month after the prawns are stocked, pellet feed becomes the primary nutrition source; this occurring when the daily feed requirement of the prawn population exceeds what is available from the natural productivity provided by the pond bloom. The major component of pelleted feeds are meals of terrestrial plant origin, and meals of captured marine fish and crustaceans (e.g. krill) origin, the latter typically the more expensive and valued of the basal components. Feed is a major cost of prawn production; around 1.5 kg of feed is required to produce 1 kg of prawns. Prawns typically reach optimal marketable size within 6 months of pond culture, with a common target prawn harvest size of 30 g. After harvest, prawns are typically processed immediately, with larger farms having their own production facilities that enable grading, cooking, packaging and freezing activities.

Effective prawn farm management involves maintaining water quality conditions within ranges optimal for prawn growth and survival, and this becomes progressively complex as prawn biomass and the quantity of feed added to the system increases. As the crop proceeds, both the prawn biomass increases, as does the biological oxygen demand required by the microbial population within the pond in breaking down organic materials. With these increasing demands, the requirement for water exchange and mechanical oxygen addition from paddlewheels increases. Towards the end of the production season the prawn biomass peaks and increasing numbers of aeration units are required in each pond to maintain optimal oxygen. Water exchange involves either the introduction of new water or recycling of existing water from the bioremediation pond back to the production pond. Fresh water, if available, can be added to manage high water salinity from evaporative losses. In most cases water salinity is not managed, except through seawater exchange, and will increase naturally with evaporation and decrease with rainfall and flooding. Strict regulation of the quality and volume of water that can be discharged means efficient use of water is standard industry practice.

Effluent water released to the environment from a prawn pond will often contain nutrients, algae and sediment particles at higher levels than occur naturally in ocean waters. To mitigate these impacts on the environment, most Australian prawn farms allocate up to 30% of their productive land for water treatment by pre-release containment in settlement systems. Such treatment reduces suspended solids and dissolved nutrients in the effluent before release to the environment (QDPIF, 2006). Many Australian farms also recirculate water, which minimises fluctuations in water quality and reduces the risk of introducing pathogens from the natural environment.
**Barramundi**

In commercial production systems, the conditioning and spawning of broodstock and the rearing of larval fish through to fingerlings takes place in land-based hatcheries. Barramundi are a highly fecund species, with females able to produce millions of eggs per spawning (Davis, 1984). However, subsequent mortality rates during the earliest larval and rearing phases can be very high. In the hatchery, at around 20 to 25 mm in length, the fingerlings are weaned off a live diet (rotifers and *Artemia*) to a commercial pellet. Due to the cost and infrastructure required many producers elect to purchase fingerlings from independent hatcheries, moving fish straight into their nursery cycle. Regular size grading is essential during the nursery stage due to aggressive and cannibalistic behaviour. Size grading helps to prevent mortalities and damage due to predation on smaller fish, and assists with consistent growth.

The main factors that determine productivity are the provision of optimal water temperature, dissolved oxygen, effective waste removal, expertise of farm staff and the overall health of the stock.

A pellet feed is produced by the two largest Australian aquafeed manufacturers (located in Brisbane and Hobart), providing a specific diet promoting efficient growth and feed conversion. The industry is heavily reliant on these mills to provide a regular supply of high-quality feed. Cost of feed transport would be a major cost to barramundi production in the study area. As a carnivorous species, high dietary protein levels, with fishmeal as a primary ingredient, is required for optimal growth. Barramundi typically require between 1.2 and 1.5 kg of pelleted feed for each kilogram of body weight produced.

In terms of stocking rates, typical pond biomass will be around 3 kg per 1000 L. Under optimal conditions barramundi can grow to over 1 kg in 12 months and to 3 kg within 2 years (Schipp et al., 2007). Warm water temperatures in northern Australia enable fish to be stocked in ponds year-round. Depending on the intended market, harvested product is processed whole or as fillets and delivered fresh (refrigerated, ice slurry) or frozen. Smaller niche markets for live barramundi are available for Asian restaurants in some capital cities.

Barramundi are susceptible to a variety of bacterial, fungal and parasitic organisms, and are at highest risk of disease when exposed to suboptimal water quality conditions (e.g. low oxygen, temperature extremes).

**Red claw**

The red claw life cycle is simple. In tropical regions, mature females can be egg bearing year-round. A 10-week incubation follows mating, after which the eggs hatch to produce small crayfish. After 3 months, the juveniles weigh around 15 g and around 100 g after 12 months. Red claw can live for up to 5 years and reach a maximum size of 600 g (Jones, 1990). Red claw breed freely in production ponds. A common industry practice is to manage mixed generations of red claw in the one pond. The crayfish are harvested at regular intervals, with re-stocking occurring from natural reproduction.

Water temperature and feed availability are the variables that most affect crayfish growth. Red claw are a robust species but are most susceptible to disease (including viruses, fungi, protozoa, bacteria) when conditions in the production pond are suboptimal (Jones, 1995).
Production ponds are earthen lined, rectangular in design and average 1 ha, and are sloping in depth from 1.2 m to 1.8 m. Sheeting is used on the pond edge to keep the red claw in the pond (migration tendency) and netting surrounds the pond to protect stock from predators (Jones et al., 2000).

At the start of each crop, prior to stocking with red claw, the ponds need to be prepared and filled with water. Between harvests, the pond bottoms are dried and unwanted sludge from the previous crops is removed, and if needed, additional substrate and shelters are added. Lime is often added prior to filling the ponds to buffer pH, particularly in areas where there are acid sulfate soils. The ponds are then filled with fresh water and left for about 2 weeks prior to stocking. Algal blooms in the water are encouraged through addition of organic fertiliser. These blooms are essential for both shading of the red claw and to discourage benthic algal growth, but also for the nutritional value they provide for the planktonic community within the ponds.

A prepared pond is stocked with around 250 females and 100 males that have reached sexual maturity. Natural mating results in the production of around 20,000 advanced juveniles. Red claw are omnivorous, foraging on natural productivity such as microbial biomass associated with decaying plant and animals. Early stage crayfish almost solely rely on natural pond productivity (phytoplankton and zooplankton) for nutrition. As the crayfish progress through the juvenile stages, the greater part of the diet changes from planktonic to organic particulates (detritus) found on the pond bottom. Very small quantities of a commercial feed are also added on a daily basis to assist with the weaning process and provide an energy source for the pond bloom. During this period no or minimal water exchange is required. The provision of adequate shelters (net bundles) is essential at this stage to improve survival (Jones, 2007). Approximately 4 months after stocking, the juveniles are harvested and graded by size and sex for stocking in production ponds.

Juveniles are stocked in production ponds from 5 to 10 per square metre. Shelters are important during the grow-out stage, with 250/ha recommended. During the grow-out phase pellet feed becomes an important nutrition source, along with the natural productivity provided by the pond. The major components of pelleted feeds are meals of terrestrial plant origin. The quality of pelleted red claw diets is often broadly ascribed to protein content, with most Australian farmers using diets consisting of 25 to 30% protein.

Effective farm management involves maintaining water quality conditions within ranges optimal for crayfish growth and survival, and this becomes progressively complex as crayfish biomass and the quantity of feed added to the system increase. As the crop proceeds, the crayfish biomass increases, as does the biological oxygen demand required by the microbial population within the pond in breaking down organic materials. With these increasing demands, the requirement for water exchange and mechanical oxygen addition from paddlewheels increases. Towards the end of the production season the crayfish biomass peaks and increasing numbers of aeration units may be required in each pond to maintain optimal oxygen levels in the pond. Water exchange involves either the introduction of new water or recycling of existing water from the bioremediation pond back to the production pond. Strict regulation on the quality and volume of water that can be discharged means efficient use of water is standard industry practice.

Red claw are harvested within 6 months of stocking to avoid reproduction in the production pond. At this stage the crayfish will range between 30 g to 80 g. Stock are graded by size and sex into groups for market, breeding or further grow-out (Jones, 2007). After harvest, red claw are
transported to a processing shed where they are stocked in tanks until being packed live for market. There is high global demand for freshwater crayfish.

Current commercial feeds are low cost and provide a nutrition source for natural pond productivity as much as the crayfish. The small size of the industry means that feed is produced in a terrestrial animal (e.g. poultry) mill, rather than a dedicated aquaculture mill. This use of terrestrial animal mills has resulted in the production of feed with low water stability and limited ability to manipulate pellet size.

Red claw breed freely in production ponds. This is beneficial in that complex hatchery technology is not required. However, low fecundity, and the associated inability to source high numbers of quality seed, is also an impediment to intensive expansion of the industry. Fecundity of red claw compared to marine prawns is low, 1,000 to 200,000 eggs respectively. Unlike the prawn industry, where there is clear demarcation between the hatchery and grow-out operation, there is no dedicated hatchery operation to allow focused improvements in fecundity and seedstock production.

Predicted water use for candidate species production

A broad-scale assessment of the volumes of water used during the culture of the three candidate species in ponds under typical farming scenarios was provided as context for the overall water requirements of aquaculture. An average crop of prawns farmed in intensive pond systems (8 t/ha over 150 days) is estimated to require 127 ML of marine water, which equates to 15.9 ML of marine water for each tonne of harvested product. For pond culture of barramundi (30 t/ha over two years), 562 ML of marine water, or fresh water, is required per crop, equating to 18.7 ML of water for each tonne of harvested fish. For extensive red claw culture (3 t/ha over 300 days) 240 ML of fresh water is required per pond crop, equating to 16 ML of water for each harvested tonne of crayfish.

4.6.5 INTEGRATING AQUACULTURE WITH AGRICULTURE

While the practice of combining the production of fish and crops in a single system is commonly used by small-scale freshwater aquaculture enterprises in South-East Asia and developing countries, it is not widely practised in Australia. However, there are theoretically potential opportunities in northern Australia to optimise the integration between agriculture and aquaculture.

Fresh and marine pond-based operations provide up to 15 ML/ha/year of nutrient-rich waste water for potential diversion to irrigation. For obvious reasons, only waste water from freshwater aquaculture operations is suitable for irrigation of agricultural crops. The main nutrients of value in the discharge water are nitrogen and phosphorus.

In recent years a technology has been developed that utilises the discharge water from prawn farms for the production of high-value seaweed (MBD, 2017). The seaweed is efficient at stripping nitrogen, which enables the treated waste water to be recycled to the prawn ponds or discharged within allowable nutrient limits.

An integrated aquaculture–agriculture model for water use has been proposed for irrigated farming systems in Australia (Gooley et al., 2000). The concept involves stocking of fish in cages in
water storage dams, which provide final irrigation to an agricultural crop. This is seen as an efficient use of water, as in this model the aquaculture component is a non-consumptive user of the water, which enhances the nutrient load of the water, possibly off-setting some of the farm fertiliser costs. Red claw is a good candidate because the crayfish readily consume raw agricultural plants and are suitable for production in irrigation storage water, providing the pond or tanks are not completely emptied (Saoud et al., 2013).

There is wide scope for the use of raw agricultural plant products in the production of red claw. Red claw farmers commonly feed raw agricultural plant meals as a nutrition supplement to a pellet feed (e.g. maize). There is also opportunity for the direct use of raw and processed agricultural feed ingredients into prawn and barramundi pond systems. This currently involves the addition of plant products (e.g. molasses) into the pond to promote the development of algal blooms or addition as a carbon source in bio floc systems.

Aquaculture feeds for the majority of aquaculture species are a complete feed, specifically formulated for that species. The production of a water-stable feed, and the ability to manipulate pellet buoyancy, are key characteristics. In comparison to terrestrial stock feeds, aquaculture feeds are expensive with specialised equipment required for production. There are opportunities to use agricultural products (plant and animal) as ingredients in feeds for prawn and barramundi. However, this would require a specialised feed mill to be located in northern Australia to avoid the high cost of transport of raw ingredients to mills located in Brisbane and Hobart.

Unlike most aquaculture species, the commercial feed for red claw can be produced in a less specialised terrestrial animal mill. Therefore, there is an opportunity for the establishment of a multi-purpose mill (aquaculture and livestock) in northern Australia, with close proximity a major benefit in term of transport costs.

Bio floc is a relatively new technology that involves the use of raw or processed plant materials to maintain a diverse and productive bacterial population in pond aquaculture (Avnimelech, 2009). It can be used in prawn aquaculture and enables limited or zero water exchange, stable water conditions and the provision of a secondary nutrition source (bacteria and algae). In general terms, the technology involves close monitoring of water quality conditions and the addition of carbon to the pond to change the dynamics of the pond community from algal to bacterial. Constant aeration and supplemental carbon such as molasses from sugarcane is added throughout the production cycle to maintain a stable bio floc population. There is potential for the industry to utilise hundreds of tonnes of agricultural plant materials to manage bio floc systems in northern Australia.

Novacq™ is a dry feed ingredient developed by CSIRO based on bio floc technology. The ingredient is produced in isolation in conventional marine aquaculture ponds via the bio-conversion of low-value plant waste from agriculture. The bio-conversion process involves the addition of agricultural sources such as bagasse (from sugarcane) into a marine pond containing specific concentrations of a range of nutrients. There is excellent potential for Novacq™ to be produced in northern Australia.
4.6.6 WATER AND LAND SUITABILITY

A land suitability framework for the study area was developed for marine and freshwater ponds, either earthen or plastic-lined, using the set of five land suitability classes in Table 4-1. The suitability of specific areas for aquaculture development was assessed from the perspective of soil and land characteristics for all three species (considered generically as ‘marine’ and ‘freshwater’ species) and proximity to a marine water source for black tiger prawns and barramundi (Table 4-20). Water temperature and water salinity were modelled for specific pond filling scenarios taking into account management practice, evaporation and precipitation. These limitations are directly related to the health and production characteristics of the species, which have known tolerances. The land limitations included those relevant to geotechnical considerations such as the construction and stability of the pond walls and to the extent of effort required to develop the pond locations, caused by limitations such as slope. Distance to a marine water source for marine or euryhaline species is an important consideration for the capital and operating costs of an aquaculture enterprise. For further detail see the companion technical report on land suitability (Thomas et al., 2018b). It was not possible to include proximity to fresh water due to the large number of potential locations that water could be captured and stored within the catchments. Note also that the estimates for land suitability presented below represent the total areas of the catchment unconstrained by factors such as water availability, land tenure, environmental and other legislation and regulations, and a range of biophysical risks such as cyclones and flooding. These are addressed elsewhere by the Assessment. The land suitability maps are designed to be used predominantly at the regional scale. Planning at the enterprise scale would demand more localised assessment.

Table 4-20 Rationale for limitation assessment for aquaculture land and water suitability analysis

<table>
<thead>
<tr>
<th>LIMITATION</th>
<th>BRIEF RATIONALE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water temperature</td>
<td>Water temperature is a key factor for species selection for a given region. While most species have a broad thermal tolerance, optimal production occurs across a narrow range. Pond water temperature varies seasonally.</td>
</tr>
<tr>
<td>Water salinity</td>
<td>Water salinity is a key factor for species selection. For the majority of species, optimal production occurs across a relatively narrow range, usually either marine or fresh water. However, euryhaline species are efficiently produced under marine and freshwater conditions.</td>
</tr>
<tr>
<td>Distance to marine water source</td>
<td>Pond distance from a marine water source has a large bearing on the required capital investment and ongoing crop production efficiency.</td>
</tr>
<tr>
<td>Elevation</td>
<td>Land elevation has significant bearing on ability to drain production and bioremediation ponds, which affects ongoing production efficiency.</td>
</tr>
<tr>
<td>Slope</td>
<td>Land slope has a significant bearing on required capital investment to construct ponds and channels.</td>
</tr>
<tr>
<td>Soil clay content (%)</td>
<td>The objective of the pond containment structure is to provide an impermeable layer between the pond water and the local surface and groundwater. Soil clay content (%) is a good indicator of the potential to produce an impermeable soil layer.</td>
</tr>
<tr>
<td>Soil pH</td>
<td>Soil acidity or alkalinity may lead to certain toxicities.</td>
</tr>
<tr>
<td>Acid sulfate soils</td>
<td>Acid sulfate soils are more expensive to develop, manage and can be detrimental to animal health and reduce crop production efficiency.</td>
</tr>
<tr>
<td>Soil depth</td>
<td>Soil depth has significant bearing on required capital investment to construct ponds.</td>
</tr>
<tr>
<td>Permeability</td>
<td>A measurement of the ease that the pond water can travel through the pond base and wall.</td>
</tr>
</tbody>
</table>
### Limitation | Brief Rationale
---|---
Rockiness | Rockiness has significant bearing on required capital investment to construct ponds.
Gilgai | Gilgai presence has a significant bearing on required capital investment to construct ponds.

Areas of shallow rocky soils, landscapes where slopes exceed 5% and those areas with high acid sulfate soil potential are generally precluded from aquaculture development. Earthen ponds are restricted to areas of deeper clay (>0.5 m depth) and heavier loam soils where soil compaction and stability properties are suitable for pond construction. Areas with moderate to rapid soil permeability, such as deep sands, are not suitable because loss of pond water and potential contamination of groundwater are major constraints. Marine species, including prawns, are constrained by distance from the coast or influence of marine tides, making large inland areas of the Darwin catchments unsuitable. Suitability for marine species is therefore much more restricted than for freshwater species. The most extensive areas of suitable land were those for lined ponds for freshwater species.

Sea surface temperatures from oceanic waters offshore to the Darwin catchments are ideal for the culture of a majority of tropical aquatic species from October to March. The comparatively shallow nearshore and estuarine waters in the Darwin catchments are likely to be significantly higher in temperature than adjacent oceanic waters. If the warming trend of sea surface temperatures in northern Australia continues (see companion technical report on climate (Charles et al., 2016)); this may have the potential to prolong the grow-out season for some aquatic species.

For marine ponds, a pond filled on 1 October would exhibit salinity levels that are largely buffered by rainfall during the wet season. Pond salinity progressively increases from April to September due to continuing evaporation and low rainfall. Elevated salinities during the dry season due to evaporation and low precipitation rates may be difficult to manage, as the addition of large amounts of fresh water to lower pond salinities may be impractical or too costly. For example, a standard marine pond (1 ha) receiving no precipitation and 10 mm evaporation per day would require daily addition of 100,000 L (0.1 ML) of fresh water to maintain optimal salinities. A 100-ha farm would require 10 ML of fresh water per day or 1.5 GL for a 150-day season. Evaporative influences and low precipitation periods would be considerably easier to manage by filling ponds at the lowest optimal salinity of the target species and regulating water exchanges at suitable intervals.

Pond water temperatures are optimised for most tropical aquaculture species between September and April. Minimum pond water temperatures during the mid-year dry season fall below the optimal growth threshold for tropical culture species. Distance from a marine water source is a major limiting factor, reducing suitability to the coastal parts of the catchment.

Freshwater ponds have no salt content and therefore water exchange has no effect on culture water salinity. However, there is a requirement to maintain pond volume. For example, a standard pond (1 ha) receiving no precipitation and 10 mm evaporation per day would require a daily addition of 100,000 L (0.1 ML) of fresh water to maintain pond volume. A 100-ha farm would require 10 ML of fresh water a day or 3 GL for a 300-day season.

Assuming unconstrained development, around 260,000 ha of coastal land was found to be suitable (Class 3 or better) for marine earthen ponds (Figure 4-36), the majority of which was Class 3.
Suitable areas are restricted to seasonally and permanently wet soils in the marine and coastal low-lying plains. This area extends a significant distance inland along the Adelaide River, while there is a smaller component in the lowest reaches of the Wildman River.

Assuming unconstrained development, around 420,000 ha of coastal land was found to be suitable for marine lined ponds (Figure 4-36). The area suitable for marine lined ponds extends a significant distance inland along the Adelaide River where the marine tidal influence is strong, and along much of the coastal fringe. The dominant soils for suitable areas are seasonally or permanently wet soils and to a lesser extent, red loamy soils where slope permits.

Assuming unconstrained development, around 670,000 ha of land was found to be suitable for freshwater earthen ponds (Figure 4-37). These areas are mainly associated with flatter terrain of seasonally or permanently wet soils and found in the lower parts of the catchments, particularly in the Wildman and Adelaide river catchments.
Assuming unconstrained development, around 2.4 million ha of land in the catchments is suitable for the development of freshwater lined ponds, the majority in Class 1 (Figure 4-37). The suitable areas dominate low gradient areas of the lower catchments, although a significant proportion of suitable areas are also to be found in the low gradient areas of the upper parts of the catchments. Areas less suited coincide strongly with the shallow and/or stony soils in the catchments.

4.7 References


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5 Opportunities for water resource development in the Darwin catchments

Authors: Jo Vanderzalm, Karen Barry, Phil Davies, Dennis Gonzalez, Justin Hughes, Declan Page, Cuan Petheram, Lee Rogers, Andrew R Taylor, Chris Turnadge and Ang Yang

Chapter 5 examines the opportunities for water resource development in the Darwin catchments, with a focus on the supply of water for irrigation. Evaluating the possibilities for water resource and greenfield irrigation requires an understanding of the development-related infrastructure requirements, how much water it can supply and at what reliability, and the associated costs.

The key components and concepts of Chapter 5 are shown in Figure 5-1.

Figure 5-1 Schematic diagram of key engineering and agricultural components to be considered in the establishment of a water resource and greenfield irrigation development
5.1 Summary

This chapter provides information on a variety of potential options to supply water, primarily for irrigated agriculture. The methods used to generate these results involved a mixture of field surveys and desktop analysis. The potential water yields reported in this chapter are based largely on physically plausible volumes, and do not consider economic, social, environmental, legislative or regulatory factors, which will inevitably constrain many developments. In some instances, the water yields are combined with land suitability information from Chapter 4 so as to provide estimates of areas of land that could potentially be irrigated close to the water source or storage. These estimates are similarly based on physically plausible volumes and areas of land.

5.1.1 KEY FINDINGS

Water can be sourced and stored for irrigation in the Darwin catchments in a variety of ways.

Groundwater extraction

Groundwater is already widely used in the Darwin catchments for a variety of purposes and offers year-round niche opportunities that are geographically distinct from surface water development opportunities. It is one of the most cost-effective sources of water in the Darwin catchments with an equivalent annualised unit cost of one-half to one-third of other options (Table 5-1). It is estimated that an additional 35 GL/year could potentially be extracted from a combination of the interconnected sand and dolostone aquifers in the Wildman catchment, the Koolpinyah Dolostone Aquifer east of the Adelaide River, the Kulshill Group Sandstone and the Daly River Limestone. This could potentially be used to irrigate up to 7800 ha of Asian vegetables under trickle irrigation.

Major dams

Major dams at Mount Bennett and the Upper Adelaide River are potentially the most cost-effective ways of capturing and storing large volumes of water for irrigation on the Finniss and Adelaide rivers, respectively. Together these two potential dams could release approximately 436 GL of water in 85% of years; sufficient water to irrigate 60,000 ha (2% of the area of the Darwin catchments) of dry-season Asian vegetables or 40,000 ha of mangoes after conveyance and field application losses. Collectively these two major dams would cost about $373 million.

Water harvesting and offstream storage

Water harvesting, where water is pumped from a major river into an offstream storage such as a ‘ringtank’, is the most cost-effective option of capturing and storing water from the Margaret River in the Adelaide catchment and the McKinley and Mary rivers in the Mary catchment. It is physically possible to extract 200 and 400 GL of water in 85% of years along the Margaret River and in the Mary catchment, respectively. After evaporation, conveyance and field application losses this is sufficient water to irrigate about 50,000 ha (1.7% of the Darwin catchments) of Asian vegetables. However, storing this much water in ringtanks may occupy nearly 20,000 ha of land and it is likely that land suitable for the construction of impermeable embankments will limit the scale of water-harvesting development. Although it is physically possible to pump 600 GL of water in 85% of years from the Finniss River, there is no land suitable for the construction of ringtanks that is also coincident with land suitable for irrigated agriculture.
Managed aquifer recharge

A reconnaissance assessment indicates the greatest potential for managed aquifer recharge (MAR) in the Darwin catchments is to augment recharge to sedimentary dolostones. Approximately 7700 km² of the Darwin catchments was identified as having potential for aquifers suitable for infiltration MAR techniques within 5 km of a major river, from which water could potentially be sourced for recharge. Additional recharge sources include existing and potential dams (large and farm-scale) and town water and sewer mains. However, MAR will inevitably only be developed subsequent to the development of a groundwater resource, which is cheaper than a MAR scheme, and in many cases in northern Australia groundwater extraction may be necessary to first create additional storage capacity within the aquifer. This is particularly the case in the higher rainfall areas of northern Australia, such as the Darwin catchments. In areas of groundwater extraction MAR can potentially enhance the quantity of water available for extraction and help mitigate impacts to the environment.

Five hypothetical MAR schemes are described for areas of the Darwin catchments that offer some opportunity for MAR, based on a regional-scale assessment (see Section 5.2.3). All schemes target fractured rock aquifers, which are highly variable in nature and therefore very challenging to accurately assess their suitability for MAR at a regional scale. The total equivalent annual costs for the construction and operation of the various hypothetical MAR schemes (0.6 to 5 GL/year) range between $70 and $335/ML of stored water/year. Recharge release is the lowest cost ($70/year per ML/year) as it relies on existing dam and weir structures for release and the natural river channel for infiltration. The large-scale ASR scheme is the next lowest cost at $138/ML, followed by the recharge weir ($227/year per ML/year), 1 GL/year ASTR ($315/year per ML/year) and 1 GL/year ASR ($335/year per ML/year).

Other potential sources of water

Sourcing water from large farm-scale gully dams is slightly more expensive than groundwater (Table 5-1). However, there are limited locations with suitable topography and soil for constructing embankments in the Darwin catchments. The remaining sources of water and storage options, namely weirs and natural water bodies, were estimated to be capable of reliably supplying considerably smaller volumes than major instream dams.

Nevertheless, as shown in Table 5-1, each option may have a role to play in maximising the cost effectiveness of water supply in different parts of the Darwin catchments.

Summary of investigative, capital, and operation and maintenance costs of different water supply options and potential scale of unconstrained development

Table 5-1 provides a summary of indicative investigative, capital and operation and maintenance costs of different water supply options and estimates of the potential scale of unconstrained development. The development of any of these options will impact on existing uses, including ecological systems, to varying degrees, and will depend on the level of development. This is examined in Section 7.2. All of the water source options reported in Table 5-1 are considerably cheaper than the cost of desalinisation. The initial cost of constructing four large desalinisation plants (capacity of 90 to 150 GL/year) in Australia between 2010 and 2012 ranged from $15,000/ML to $25,000/ML (AWA, 2018), indexed to 2017. This does not include the cost of ongoing operation (e.g. energy) and maintenance or the cost of conveying water to the demand.
Table 5-1 Summary of capital costs, yields and costs per ML supply, including operation and maintenance (O&M)

Costs and yields are indicative. Values are rounded. Capital costs are the cost of construction of the water storage/source infrastructure. They do not include the cost of constructing associated infrastructure for conveying water or irrigation development. Water supply options are not independent of one another and the maximum yields and areas of irrigation cannot be added together. Equivalent annual cost assumes a 7% discount rate over the service life of the infrastructure. Total yields and areas are based on physical plausibility unconstrained by economic, social, environmental, legislative or regulatory factors, which will inevitably constrain many developments.

<table>
<thead>
<tr>
<th>WATER SOURCE/STORAGE</th>
<th>GROUND-WATER†</th>
<th>MANAGED AQUIFER RECHARGE‡</th>
<th>MAJOR DAM</th>
<th>WEIR§</th>
<th>LARGE FARM-SCALE RINGTANK</th>
<th>LARGE FARM-SCALE GULLY DAM</th>
<th>NATURAL WATER BODY</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost and service life of individual representative unit</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital cost ($ million)</td>
<td>0.25–0.5</td>
<td>1</td>
<td>190</td>
<td>10–40</td>
<td>2.2</td>
<td>1.5</td>
<td>0.02</td>
</tr>
<tr>
<td>Operation and maintenance (O&amp;M) ($ million/y)*</td>
<td>0.025</td>
<td>0.06</td>
<td>0.75</td>
<td>0.2–0.8</td>
<td>0.1</td>
<td>0.03–0.05</td>
<td>~0</td>
</tr>
<tr>
<td>Assumed service life (y)</td>
<td>50</td>
<td>50</td>
<td>100</td>
<td>50</td>
<td>40</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td><strong>Potential yield of individual representative unit at water source</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield at source (GL)††</td>
<td>1</td>
<td>0.6</td>
<td>150–280</td>
<td>2–15</td>
<td>2.8</td>
<td>3</td>
<td>0.125–0.5</td>
</tr>
<tr>
<td>Unit cost ($/ML)‡‡</td>
<td>250–500</td>
<td>1,670</td>
<td>670–1,200</td>
<td>2,700</td>
<td>785</td>
<td>500</td>
<td>40–160</td>
</tr>
<tr>
<td>Equivalent annual cost ($/y per ML/y)§§</td>
<td>40–60</td>
<td>130</td>
<td>50–90</td>
<td>250</td>
<td>~100</td>
<td>55</td>
<td>5–20</td>
</tr>
<tr>
<td><strong>Potential yield of individual representative unit at paddock</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assumed conveyance efficiency to paddock (%)†††</td>
<td>95</td>
<td>90</td>
<td>65</td>
<td>80</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Yield at paddock (GL)</td>
<td>0.95</td>
<td>0.54</td>
<td>100–180</td>
<td>1.6–12</td>
<td>2.5</td>
<td>2.7</td>
<td>0.11–0.45</td>
</tr>
<tr>
<td>Unit cost ($/ML)¶¶</td>
<td>260–525</td>
<td>1,855</td>
<td>1,030–1,850</td>
<td>3,375</td>
<td>870</td>
<td>555</td>
<td>45–180</td>
</tr>
<tr>
<td>Equivalent annual cost ($/y per ML/y)¶¶¶</td>
<td>45–65</td>
<td>145</td>
<td>75–140</td>
<td>335</td>
<td>115</td>
<td>60</td>
<td>6–25</td>
</tr>
<tr>
<td><strong>Total potential yield and area (unconstrained)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total potential yield (GL/y) at source ≥85% reliability†††</td>
<td>35</td>
<td>NA</td>
<td>436</td>
<td>&lt;50</td>
<td>600</td>
<td>&lt;100</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Potential area that could be irrigated at ≥85% reliability (ha)¶¶¶</td>
<td>7,800</td>
<td>NA</td>
<td>60,000</td>
<td>&lt;5,000</td>
<td>50,000</td>
<td>&lt;10,000</td>
<td>&lt;1,000</td>
</tr>
</tbody>
</table>

†Value assumes extraction from a dolostone aquifer and cost range based on one (30 L/s) or two bores (15 L/s).
‡Based on recharge weir.
§Sheet piling weir.
*O&M cost is the annual cost of operating and maintaining infrastructure and includes cost of pumping groundwater assuming groundwater is 10–20 m below ground level and the cost of pumping water into ringtank.
††Yield at dam wall (taking into consideration net evaporation from surface water storages prior to release) or at groundwater bore. Value assumes large farm-scale ringtanks do not store water past August.
‡‡Capital cost divided by the yield.
§§Equivalent annual cost of storage/bore per ML of yield of water. Includes capital cost and O&M costs. Assumes 7% discount rate.
†††Conveyance efficiency between dam wall/groundwater bore and edge of paddock (does not include field application losses).
¶¶Likely maximum cumulative yield at the dam wall/groundwater bore. Potential yield of major dams based on yield of dams at upper Adelaide River dam site and at Mount Bennett on the Finniss River.
¶¶¶Likely maximum area that could be irrigated (after conveyance and field application losses) in at least 85% of years. Assumes a single crop of Asian vegetables in all cases.
NA = data not available.
5.1.2 INTRODUCTION

Irrigation during the dry season and other periods when soil water is insufficient for crop growth requires sourcing water from a suitable aquifer or from a water storage. However, decisions regarding groundwater extraction, river regulation and water storage are complex and the consequences of decisions can be inter-generational, where even relatively small inappropriate releases of water may preclude the development of other more appropriate (and possibly larger) developments in the future. Consequently, governments and communities benefit by having a wide range of reliable information available prior to making decisions, including the manner of ways water can be sourced and stored, as this can have long-lasting benefits and facilitate an open and transparent debate.

This chapter provides information on groundwater and subsurface storage opportunities (Section 5.2) and surface water storage (Section 5.3) opportunities in the Darwin catchments. Information is presented in a manner to easily enable the comparison of the variety of options. Section 5.4 discusses the conveyance of water from the storage and its application to the crop. Transmission and field application efficiencies and associated costs and considerations are examined.

All costs presented in this chapter are indexed to 2017.

Concepts

The following concepts are used in sections 5.2 and 5.3.

- Each of the water source and storage sections are structured around a reconnaissance-level assessment and a pre-feasibility-level assessment, where:
  - Reconnaissance-level assessments involved a review of the existing literature and a high-level desktop assessment using methods and datasets that could be consistently applied across the entire study area. The purpose of the reconnaissance-level assessment is to provide a general indication of the likely scale of opportunity and geographic location of each option.
  - Pre-feasibility-level assessments involved a more detailed desktop assessment of sites/geographic locations that were considered more promising. This involved a broader and more detailed analysis including the development of bespoke numerical models, site-specific cost estimates and site visits. Considerable field investigations were undertaken for the assessment of groundwater development opportunities (Section 5.2.2).

- Yield is a term used to report the performance of a water source or storage. It is the amount of water that can be supplied for consumptive use at a given reliability. For dams, an increase in water yield results in a decrease in reliability. For groundwater, an increase in water yield results in an increase in the ‘zone of influence’ and can result in a decrease in reliability, particularly in local- and intermediate-scale groundwater systems.

- Equivalent annual cost is the annual cost of owning, operating and maintaining an asset over its entire life. Equivalent annual cost allows a comparison of the cost effectiveness of various assets that have unequal service lives/lifespans.

Other economic concepts reported in this chapter, such as discount rates, are outlined in Chapter 6.
5.2 Groundwater and subsurface water storage opportunities

5.2.1 INTRODUCTION

Groundwater, where the water-bearing formation is at an economical depth (<300 m) and of sufficient yield to support irrigation (>10 L/second), is often one of the cheapest sources of water available, particularly where the potentiometric surface is artesian or near artesian, thereby reducing pumping costs. Even the cheapest forms of managed aquifer recharge (MAR), infiltration-based techniques, are usually considerably more expensive than developing a groundwater resource. Further to this, in the wetter parts of northern Australia many unconfined aquifers, which are best suited to infiltration-based MAR, have no ‘free’ storage capacity at the end of the wet season and consequently it is not possible to further recharge the aquifers. For these reasons MAR will inevitably only be developed subsequent to development of the groundwater resource, which is cheaper, and groundwater extraction may create additional storage capacity within the aquifer. However, if developed, MAR can enhance the quantity of water available for extraction and help mitigate impacts to the environment.

It should be noted that where water has a higher value than irrigation (e.g. mining, energy operations, town water supply), other more expensive but versatile forms of MAR, such as aquifer storage and recovery, can be economically viable and should be considered.

The Assessment undertook a catchment-wide reconnaissance assessment and at selected locations a pre-feasibility assessment of:

- groundwater resource development opportunities (Section 5.2.2)
- managed aquifer recharge opportunities (Section 5.2.3).

Unless stated otherwise, the material presented in sections 5.2.2 and 5.2.3 has been summarised from the companion technical reports on hydrogeological assessment (Turnadge et al., 2018) and on assessment of managed aquifer recharge opportunities (Vanderzalm et al., 2018), respectively.

5.2.2 OPPORTUNITIES FOR GROUNDWATER DEVELOPMENT

Introduction

Groundwater is seen as an attractive water resource in the Darwin catchments. In many locations in the study area, rivers and creeks are intermittent or ephemeral and groundwater, if available, can provide a reliable year-round water resource. Across the Darwin Rural Water Control District (DRWCD) approximately 25 GL/year is sourced from the Koolpinyah Dolostone aquifer and other dolostone aquifers for the purposes of irrigated agriculture, horticulture, public water supplies and local domestic use. However, these aquifers are considered to be fully allocated, therefore the Assessment investigated new opportunities for future groundwater resource development outside of the DRWCD.

The planning of future groundwater resource developments and authorising of groundwater allocations requires value judgments of what is an acceptable impact to receptors such as environmental assets or existing users. These decisions can be complex and typically require
considerable input from a wide range of stakeholders, particularly government regulators and communities.

Scientific information to help inform these decisions include identifying aquifers that may be potentially suitable for future groundwater resource development, characterising their depth and spatial extent, conceptualising the nature of their flow systems, estimating aquifer water balances and providing initial estimates of potential extractable volumes and associated drawdown in groundwater level over time and distance.

Unless stated otherwise, the material presented in this section has been summarised from the companion technical report on hydrogeological characterisation (Turnadge et al., 2018a).

**Reconnaissance-level assessment of groundwater resource development opportunities in the Darwin catchments**

The hydrogeological units of the Darwin catchments host a variety of local- to intermediate-scale groundwater systems, the latter being better suited for groundwater resource development. Intermediate-scale aquifers in the Darwin catchments generally contain low salinity water (<500 mg/L) and in places yield water at a sufficient rate to support irrigated agriculture (i.e. >10 L/second). Given their larger spatial extent, they also underlie and coincide with greater areas of soil suitable for irrigated agriculture (Section 4.3). The intermediate-scale aquifers contain larger volumes of groundwater in storage (i.e. gigalitres) than local-scale aquifers and therefore are less impacted by short-term (yearly) variations in recharge rates that may arise due to inter-annual variability in rainfall. Furthermore, their larger spatial extent provides greater opportunities for groundwater resource development away from groundwater-dependent ecosystems (GDEs) at the land surface such as springs, spring-fed vegetation and surface water, which can be ecologically and culturally significant. In contrast, local-scale aquifers in the Darwin catchments such as fractured rock and lateritic aquifers, host local-scale groundwater systems that are highly variable in composition, salinity and yield. They also have a smaller spatial extent and less storage compared to the intermediate-scale aquifers, limiting groundwater resource development to localised opportunities such as stock and domestic use, or as a conjunctive water resource.

The Assessment identified five hydrogeological units that offer potential for future groundwater resource development in the Darwin catchments:

1. Kulshill Group sandstone
2. Northern Daly Basin limestone
3. Daly Basin Outlier
4. Koolpinyah Dolostone in the northern Adelaide and Mary catchments
5. interconnected sand and dolostone aquifers in the northern Mary and Wildman catchments.

Reconnaissance-level estimates of the potential scale of groundwater resource development for each of these hydrogeological units are summarised in Table 5-2 and are based on a desktop evaluation of available hydrogeological data.
Table 5-2 Reconnaissance-level estimates of the potential scale of groundwater resource development opportunities in the Darwin catchments
For locations of the hydrogeological units see Figure 5-2.

<table>
<thead>
<tr>
<th>HYDROGEOLOGICAL UNIT</th>
<th>LOCATION</th>
<th>CATCHMENT</th>
<th>MEAN ANNUAL RECHARGE (GL/y)</th>
<th>LEVEL OF KNOWLEDGE</th>
<th>INDICATIVE MAXIMUM SCALE OF RESOURCE (GL/y)</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kulshill Group sandstone</td>
<td>South of Point Blaze</td>
<td>Finniss catchment</td>
<td>&lt;40</td>
<td>Low</td>
<td>&lt;10</td>
<td>Local- to intermediate-scale aquifers, good bore yields and water quality. Likely to offer potential for small-scale (1 to 2 GL/y) localised developments. Limited opportunities where there is: (i) potential for impacting dry-season flow in major rivers, and (ii) potential for seawater intrusion.</td>
</tr>
<tr>
<td>Northern Daly Basin</td>
<td>Near Tipperary</td>
<td>Finniss and Adelaide catchments</td>
<td>&lt;10</td>
<td>High</td>
<td>&lt;5 $\dagger$</td>
<td>Regional-scale aquifers, high bore yields and fresh water quality. Likely to offer potential for a few small-scale (1 GL/y) localised developments. Opportunities are likely to be limited by existing allocations for the limestone aquifer.</td>
</tr>
<tr>
<td>Daly Basin Outlier</td>
<td>South of Reynolds River near Litchfield</td>
<td>Finniss catchment</td>
<td>&lt;5</td>
<td>Low</td>
<td>&lt;2</td>
<td>Local-scale aquifers, variable bore yields and good water quality. Likely to offer potential for small-scale (&lt;1 GL/y) localised developments or as a conjunctive water resource. Limited opportunities due to the high potential for impacting dry-season flow in major rivers.</td>
</tr>
<tr>
<td>Koolpinyah Dolostone</td>
<td>Marrakai</td>
<td>Adelaide and Mary catchments</td>
<td>&lt;50</td>
<td>Medium</td>
<td>&lt;10</td>
<td>Local- to intermediate-scale aquifers, good bore yields and water quality. Likely to offer potential for numerous medium-scale (1 to 5 GL/y) localised developments. Opportunities are likely to be limited: (i) near the coast due to the potential for seawater intrusion, and (ii) potential for impacting dry-season flow in major rivers.</td>
</tr>
<tr>
<td>Interconnected sand and dolostone aquifers</td>
<td>South of Point Stuart</td>
<td>Mary and Wildman catchments</td>
<td>&lt;30</td>
<td>Medium to high</td>
<td>&lt;10</td>
<td>Local- to intermediate-scale aquifers with good bore yields and water quality. Likely to offer potential for a few small-scale (1-2 GL/y) localised developments. Limited opportunities where there is potential for impacting spring flows and spring-fed monsoon vine forest (Figure 5-3).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HYDROGEOLOGICAL UNIT</th>
<th>LOCATION</th>
<th>CATCHMENT</th>
<th>MEAN ANNUAL RECHARGE (GL/y)</th>
<th>LEVEL OF KNOWLEDGE</th>
<th>INDICATIVE MAXIMUM SCALE OF RESOURCE (GL/y)</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kulshill Group sandstone</td>
<td>South of Point Blaze</td>
<td>Finniss catchment</td>
<td>&lt;40</td>
<td>Low</td>
<td>&lt;10</td>
<td>Local- to intermediate-scale aquifers, good bore yields and water quality. Likely to offer potential for small-scale (1 to 2 GL/y) localised developments. Limited opportunities where there is: (i) potential for impacting dry-season flow in major rivers, and (ii) potential for seawater intrusion.</td>
</tr>
<tr>
<td>Northern Daly Basin</td>
<td>Near Tipperary</td>
<td>Finniss and Adelaide catchments</td>
<td>&lt;10</td>
<td>High</td>
<td>&lt;5 $\dagger$</td>
<td>Regional-scale aquifers, high bore yields and fresh water quality. Likely to offer potential for a few small-scale (1 GL/y) localised developments. Opportunities are likely to be limited by existing allocations for the limestone aquifer.</td>
</tr>
<tr>
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<td>South of Reynolds River near Litchfield</td>
<td>Finniss catchment</td>
<td>&lt;5</td>
<td>Low</td>
<td>&lt;2</td>
<td>Local-scale aquifers, variable bore yields and good water quality. Likely to offer potential for small-scale (&lt;1 GL/y) localised developments or as a conjunctive water resource. Limited opportunities due to the high potential for impacting dry-season flow in major rivers.</td>
</tr>
<tr>
<td>Koolpinyah Dolostone</td>
<td>Marrakai</td>
<td>Adelaide and Mary catchments</td>
<td>&lt;50</td>
<td>Medium</td>
<td>&lt;10</td>
<td>Local- to intermediate-scale aquifers, good bore yields and water quality. Likely to offer potential for numerous medium-scale (1 to 5 GL/y) localised developments. Opportunities are likely to be limited: (i) near the coast due to the potential for seawater intrusion, and (ii) potential for impacting dry-season flow in major rivers.</td>
</tr>
<tr>
<td>Interconnected sand and dolostone aquifers</td>
<td>South of Point Stuart</td>
<td>Mary and Wildman catchments</td>
<td>&lt;30</td>
<td>Medium to high</td>
<td>&lt;10</td>
<td>Local- to intermediate-scale aquifers with good bore yields and water quality. Likely to offer potential for a few small-scale (1-2 GL/y) localised developments. Limited opportunities where there is potential for impacting spring flows and spring-fed monsoon vine forest (Figure 5-3).</td>
</tr>
</tbody>
</table>

$\dagger$ Derived using up-scaled CMB applied to the area of each hydrogeological unit not overlain by low permeability floodplains the chloride mass balance method.

$\ddagger$CMB is the chloride mass balance method.

$\S$Future groundwater resource development in the northern Daly Basin would fall under the existing water allocation plan.
Figure 5-2 Hydrogeological units with potential for future groundwater resource development
Presents only the spatial extent of the outcropping and subcropping component of hydrogeological units. The exception is the interconnected sand and dolostone aquifers in the northern Mary and Wildman catchments where the spatial extent of the combined units in the subsurface is known from detailed desktop investigations.
Pre-feasibility-level assessment of groundwater resource development in the interconnected sand and dolostone aquifers of the Mary–Wildman area

Based on the reconnaissance-level assessment, a pre-feasibility level assessment of the interconnected sand and dolostone aquifers in the northern Mary and Wildman catchments was undertaken, which included targeted field and modelling investigations (Figure 5-4). Initially the Assessment planned to undertake targeted field and modelling investigations on the Koolpinyah Dolostone around Marrakai, but access to that area was not possible.

Figure 5-3 Monsoon vine forest in the Mary–Wildman area
Photo: CSIRO

Figure 5-4 Targeted field investigations included the drilling and installation of (a) shallow monitoring bores near springs and (b) deeper monitoring bores in the middle of the aquifers
This section presents information relevant to the cost of developing the groundwater resource in the northern Mary–Wildman catchments, including the depth to water-bearing formation (relevant to the cost of drilling) and the elevation of the potentiometric surface (relevant to the cost of pumping). Information on the spatial extent of drawdown of groundwater levels is also presented, which is relevant to the establishment of groundwater allocations.

Two intermediate-scale interconnected sand and dolostone aquifers occur in the north-western part of the Wildman catchment along the north-eastern boundary of the Mary catchment under a thin veneer of recent unconsolidated sediments but vary locally in their spatial extent in the subsurface (Figure 5-5). In this area, the aquifers are predominantly recharged by infiltration of wet-season rainfall at the land surface, though the dolostone aquifer can be preferentially recharged through dolines.

![Figure 5-5 Spatial extent of the (a) overlying Mesozoic–Cenozoic sand aquifer and (b) underlying Koolpinyah Dolostone aquifer in the Mary and Wildman catchments](image)

The sand aquifer ranges in thickness of up to 15 m and occurs as north-east striking palaeochannels at depths ranging between 50 and 100 m below the land surface (i.e. depth to top of aquifer) (Figure 5-6). The aquifers primarily occur within the coarser-grained sand units occurring at the base of the sediments deposited in these palaeovalleys. The top horizons of the base sediments deposited in the two palaeovalley sand aquifers generally occur at depths of 10 to 50 m below ground level (mBGL) (Figure 5-6). The sand aquifer is connected to the dolostone aquifer in places, however, the dolostone is patchy and information on the depth to the top of the dolostone is limited (Figure 5-6).
Maximum depths to groundwater, which occur at the end of the dry season, are less than 10 mBGL across the majority of the Mesozoic–Cenozoic sand aquifer in the Mary–Wildman catchments (Figure 5-7). Larger depths to groundwater occur in the southern part of the aquifer, where topography is elevated (i.e. >50 mAHD).
Targeted field and desktop investigations by the Assessment in conjunction with Tickell and Zaar (2017) provided a refined hydrogeological conceptual model for the aquifers. This model was implemented in a groundwater model and used to test a range of hypothetical groundwater extraction scenarios and provide initial estimates of the potential extractable volume of groundwater from the aquifers. Importantly, the hypothetical groundwater development scenarios do not provide an assessment or expert opinion of whether the potential impacts of groundwater level drawdown to receptors such as environmental assets or existing users are acceptable. Instead, they provide defensible information to inform future groundwater resource planning and investment. For more detailed information on the groundwater model see Turnadge et al., (2018b).

Three levels of groundwater extraction were tested (3, 6 and 9 GL/year) for the aquifers at three hypothetical locations (implemented as 3 x 1, 3 x 2 and 3 x 3 GL/year developments) where soils are considered suitable for irrigated agriculture, and the aquifers are spatially extensive and can be intersected by drilling and constructing bores at depths of less than 100 mBGL. In addition, two types of extraction regimes were tested: either discontinuous extraction (i.e. during the dry season only) or continuous (i.e. year-round) extraction over a 20-year period. Results of modelled drawdown in groundwater level in the semi-confined and fully confined interconnected sand and dolostone aquifers for each hypothetical scenario are summarised in Table 5-3. These results include (i) the maximum drawdown at the development sites, (ii) the maximum extent of the 2-m drawdown contour (a value that can be considered measurable and distinguishable from natural...
variations in groundwater level), and (ii) the minimum distance of the 2-m contour from the nearest spring.

Table 5-3 Modelled drawdown in groundwater level in the semi-confined and fully confined aquifers using three different extraction rates and either discontinuous or continuous extraction regimes

<table>
<thead>
<tr>
<th>CUMULATIVE EXTRACTION VOLUME (GL/y)</th>
<th>EXTRACTION TYPE</th>
<th>OBSERVATION SEASON</th>
<th>MAXIMUM DRAWDOWN AT THE DEVELOPMENT SITE (m)</th>
<th>MAXIMUM EXTENT OF THE 2-m DRAWDOWN CONTOUR FROM THE DEVELOPMENT SITE (km)</th>
<th>MINIMUM DISTANCE OF THE 2-m DRAWDOWN CONTOUR TO THE NEAREST SPRING (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Discontinuous</td>
<td>Dry</td>
<td>3.9</td>
<td>7.5</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wet</td>
<td>2.5</td>
<td>7.5</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>Continuous</td>
<td>Dry</td>
<td>3.0</td>
<td>7.5</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wet</td>
<td>3.0</td>
<td>7.5</td>
<td>6.0</td>
</tr>
<tr>
<td>6</td>
<td>Discontinuous</td>
<td>Dry</td>
<td>8.9</td>
<td>8.5</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wet</td>
<td>7.4</td>
<td>8.5</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Continuous</td>
<td>Dry</td>
<td>7.0</td>
<td>8.5</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wet</td>
<td>7.7</td>
<td>8.5</td>
<td>2.0</td>
</tr>
<tr>
<td>9</td>
<td>Discontinuous</td>
<td>Dry</td>
<td>14.3</td>
<td>9.0</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wet</td>
<td>11.5</td>
<td>9.0</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td></td>
<td>Continuous</td>
<td>Dry</td>
<td>11.5</td>
<td>9.0</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wet</td>
<td>11.8</td>
<td>9.0</td>
<td>&lt;1.0</td>
</tr>
</tbody>
</table>

At the extraction rates tested, there is a larger maximum modelled drawdown in groundwater level at the development sites at the end of the dry season for a discontinuous versus continuous extraction. This is the result of the same volume of groundwater (i.e. 3, 6 or 9 GL) being extracted over a 6-month period as opposed to throughout the entire year. When comparing the maximum modelled drawdown in groundwater level at the development sites during the wet season, there is less maximum drawdown for a discontinuous extraction for each rate tested compared to continuous extraction because some recovery is occurring during the wet season when the discontinuous extraction ceases for 6 months. For the continuous pumping scenario, at the end of the dry season there is a maximum modelled drawdown of 3 m for an extraction rate of 3 GL/year, 7 m for an extraction rate of 6 GL/year and 11.5 m for an extraction rate of 9 GL/year (Table 5-3).

There is no difference in the maximum extent of the 2-m modelled drawdown from the development sites when using either discontinuous or continuous extraction scenarios regardless of the volume tested (Table 5-3). Testing a continuous extraction rate of 6 GL/year for 20 years, the 2-m drawdown contour extends 8.5 km from the southernmost development site at the end of the dry season and 2 km from the nearest spring (Figure 5-8). At the easternmost development site, the extent of the two metre drawdown contour is less than that for the southernmost site at the same volume tested. There is very little drawdown (i.e. <2 m) around the northernmost site, though this is potentially underestimated due to the influence of the model boundary condition specified along the northern boundary, see Turnadge et al., (2018b).
The shallow surficial leaky aquitard is present across most of the model domain and hosts an extensive shallow (i.e. <10 mBGL) watertable. The semi-confined and fully confined interconnected sand and dolostone aquifers have a reduced and patchy spatial extent across the model domain. Drawdown in groundwater level in the semi-confined and fully confined aquifers is occurring at depth (i.e. > 50 mBGL) in the aquifer.

Testing a continuous extraction rate of 9 GL/year for 20 years, the 2-m drawdown contour extends 11.5 km from the southernmost development site at the end of the dry season and less than 1 km from the nearest spring (Figure 5-8). Similar to the 6 GL/year extraction scenario, the extent of the two metre drawdown contour at the easternmost site is less than that for the southernmost site at the same volume tested. Again, there is very little drawdown (i.e. <2 m) around the northernmost site despite the increase in extraction rate, though this is potentially underestimated due to the influence of the model boundary condition specified along the northern boundary, see Turnadge et al., (2018b). Similar to the 6 GL/year extraction scenario, the extent of the two metre drawdown contour at the easternmost site is less than that for the southernmost site at the same volume tested. Again, there is very little drawdown (i.e. <2 m) around the northernmost site despite the increase in extraction rate, though this is potentially underestimated due to the influence of the model boundary condition specified along the northern boundary, see Turnadge et al., (2018b).
The shallow surficial leaky aquitard is present across most of the model domain and hosts an extensive shallow (i.e. <10 mBGL) watertable. The semi-confined and fully confined interconnected sand and dolostone aquifers have a reduced and patchy spatial extent across the model domain. Drawdown in groundwater level in the semi-confined and fully confined aquifers is occurring at depth (i.e. >50 mBGL) in the aquifer.

Given the scale of the groundwater flow system in the interconnected sand and dolostone aquifers (i.e. approximately 20 × 20 km), cumulative extraction rates of greater than 10 GL/year are likely to result in drawdown extending to key springs and spring-fed monsoon vine forest (Figure 5-10). Field investigations undertaken as part of the Assessment and previously by the Department of Environment and Natural Resources (Tickell and Zaar, 2017) indicated that many springs and creeks overlying the interconnected sand and dolostone aquifers in the Mary–Wildman catchments are partly fed by groundwater discharge. In particular, groundwater discharge from springs maintains the persistence of dry-season flows at certain locations, including Opium and Jimmies creeks (see Section 2.5). Tickell and Zaar (2017) identified a range of mechanisms by which groundwater discharge occurs, including karstic collapse features, breaks in topographic slope and basement rock boundaries. Overall, results of groundwater extraction testing indicate a range of between 5 to 10 GL/year could potentially be extracted from the aquifers, though individual extraction volumes are location dependent. At each location, extraction from the aquifer will lead to spatial variations in drawdown of groundwater levels and changes to the natural flow regime that may affect GDEs.

**Groundwater development costs**

Future groundwater development of the interconnected sand and dolostone aquifers in the Mary–Wildman catchments may require investigations of the resource at two scales. At the regional
scale the regulator may be interested in further characterisation of the aquifers to better understand the resource potential, as well as current and future constraints to development. Key considerations identified in this Assessment include:

- further characterising the spatial extent and geometry of the aquifers in the north between Melaleuca and Carmor Plains stations, and in the east toward Kakadu National Park
- characterising the nature and hydraulic properties of dolines as they partly contribute to recharge of the aquifers
- monitoring groundwater levels to the north and east to better understand groundwater flow directions and magnitude
- installing four stream gauges, two each at Jimmies Creek and Opium Creek, at locations above and below the spring vents (major discharge points) of the interconnected aquifers.

Estimates of costs associated with these regional-scale investigations are summarised in Table 5-4.

Table 5-4 Summary of estimated costs to further characterise the interconnected sand and dolostone aquifers

<table>
<thead>
<tr>
<th>INVESTIGATION TYPE</th>
<th>METHOD</th>
<th>ESTIMATED COST ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characterising spatial extent and geometry</td>
<td>Near-surface geophysics, data processing and reporting</td>
<td>$60,000†</td>
</tr>
<tr>
<td>Characterising dolines</td>
<td>Shallow drilling, coring, sampling, analysis and reporting</td>
<td>$60,000‡§§§</td>
</tr>
<tr>
<td>Monitoring groundwater levels</td>
<td>Installation of data loggers</td>
<td>$20,000*</td>
</tr>
<tr>
<td>Stream gauging</td>
<td>Installation of stream gauges</td>
<td>$320,000††</td>
</tr>
</tbody>
</table>

†Assumes a two-week geophysical field survey to the north and east of the aquifers and four weeks of data processing and reporting.
‡Assumes a one-week drilling survey including: shallow drilling, coring, sub-sampling of core, laboratory testing of core material and reporting.
§ Value assumes a mobilisation/demobilisation rate of $10/km from Darwin (approximate 300-km round trip).
§§ Value assumes drilling and coring ten dolines to a depth of 20 m at a cost of $200/m and analysing four cores per doline at a cost of $400 a core sample.
*Assumes purchase and installation of ten data loggers at a cost of $2000 each.
††Assumes the installation of four gauging stations at a cost of $80,000 each.

At the local scale, individual proponents will need to undertake sufficient localised investigations in order to provide confidence around aquifer properties and bore performance. This information will also form part of an on-site hydrogeological assessment required by the regulator in order to grant an authorisation to extract groundwater. Key considerations for an individual proponent include:

- determining the location to drill a production bore
- testing the production bore
- determining the location and number of monitoring bores required
- conducting a hydrogeological assessment as part of applying for an authorisation to extract groundwater.

Estimates of costs associated with these local-scale investigations are summarised in Table 5-5.
Table 5-5 Summary of estimated costs for a small-scale (1 GL/year) mosaic-style irrigation development using groundwater from the interconnected sand and dolostone aquifers

<table>
<thead>
<tr>
<th>DRILLING, CONSTRUCTION, INSTALLATION AND TESTING OF BORES</th>
<th>ESTIMATED COST ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production bore</td>
<td>75,000†</td>
</tr>
<tr>
<td>Monitoring bores</td>
<td>12,000‡</td>
</tr>
<tr>
<td>Submersible pump</td>
<td>85,000§</td>
</tr>
<tr>
<td>Mobilisation/demobilisation</td>
<td>3,000§§</td>
</tr>
<tr>
<td>Aquifer testing</td>
<td>40,000*</td>
</tr>
<tr>
<td>Hydrogeological assessment</td>
<td>50,000**</td>
</tr>
</tbody>
</table>

†Value assumes one production bore drilled and constructed at an average depth of 75 m at a cost of $1000/m.
‡Value assumes two 150 mm PVC monitoring bores drilled and constructed at an average depth of 25 m at a cost of $250/m.
§Value assumes a pump that is rated to draw water at a rate of up to 60 L/second, as well as rated to draw water from depths of up to 50 mBGL.
§§Value assumes a mobilisation/demobilisation rate of $10/km from Darwin (approximately 300-km round trip).
*Value assumes a 72-hour aquifer test (48 hours pumping, 24 hours recovery) at a cost of $500 per hour and $4000 mobilisation/demobilisation.
** Value assumes a small-scale development away from existing users and GDEs.

Figure 5-10 Monsoon vine forest in the Darwin catchments
Photo: CSIRO
MANAGED AQUIFER RECHARGE

Introduction

MAR is the intentional recharge of water to aquifers for subsequent recovery or environmental benefit (NRMMC-EPHC-NHMRC, 2009). Importantly for northern Australia, which has a high intra-annual variability in rainfall, MAR can contribute to planned conjunctive use, whereby excess surface water can be stored in an aquifer in the wet season for subsequent reuse in the dry season (Evans et al., 2013; Lennon et al., 2014).

Individual MAR schemes are typically small- to-intermediate-scale storages, with annual extractable volumes of up to 20 GL/year currently operating predominantly within the urban and industrial, but also agricultural sectors, of Australia. This scale of operation can sustain rural urban centres, contribute to diversified supply options in large urban centres, provide localised water management options and is suited to mosaic-type irrigation developments.

The basic requirements for a MAR scheme are the presence of a suitable aquifer for storage, availability of an excess water source for recharge and a demand for water. Presence of suitable aquifers is determined from previous regional-scale hydrogeological and surface geological mapping (see companion technical report on hydrogeological assessment (Turnadge et al., 2018)). While current demand is not explicit, future demand is assumed to exist through economic development drivers. Source water availability is considered in terms of presence/absence rather than volumes with respect to any existing water management plans.

Pre-feasibility assessment was based on MAR scheme entry-level assessment in the Australian guidelines for water recycling: managed aquifer recharge (NRMMC-EPCH-NHMRC, 2009 (referred to as the ‘MAR guidelines’)). The MAR guidelines provide a framework to assess feasibility of MAR and incorporate four stages of assessment and scheme development. Stage one is entry-level assessment (pre-feasibility), stage two involves investigations and risk assessment, stage three is MAR scheme construction and commissioning, and stage four is operation of the scheme.

There are numerous types of MAR (Figure 5-11) and the selection of MAR type is influenced by the characteristics of the aquifer, the thickness and depth of low-permeability layers, land availability and proximity to the recharge source. Infiltration techniques can be used to recharge unconfined aquifers, with water infiltrating through permeable sediments beneath a dam, river or basin. If infiltration is restricted by superficial clay, the recharge method may involve a pond or sump that penetrates the low-permeability layer. Bores are used to divert water into deep or confined aquifers. Infiltration techniques are typically lower cost than bore injection (Dillon et al., 2009; Ross and Hasnain, 2018) and are generally favoured in this Assessment. The challenge in northern Australia is to identify a suitable unconfined aquifer with capacity to store more water when water is available for recharge. In the Darwin catchments, suitable unconfined aquifers are typically thought to rapidly recharge to full capacity during the wet season.

Unless stated otherwise, the material presented in Section 5.2.3 has been summarised from the companion technical report on assessment of managed aquifer recharge opportunities (Vanderzalm et al., 2018).
Figure 5-11 Types of managed aquifer recharge (MAR)
ASR = aquifer storage and recovery; ASTR = aquifer storage, transfer and recovery
Source: adapted from NRMMC-EPHC-NHMRC (2009).
Reconnaissance-level assessment of MAR in the Darwin catchments

The most promising aquifers for MAR in the Darwin catchments are within sandstones, limestones and dolostones because these formations host the major aquifer systems in the Darwin catchments (Proterozoic dolostone, Daly Basin limestone and siltstone, Bonaparte Basin sandstone, Cenozoic sandstone (Figure 2-23)). Aquifers in the Proterozoic-age dolostone include the extensive Koolpinyah Dolostone, the main water resource in the Howard East area and localised aquifers at Berry Springs and Palmerston. MAR potential was also assessed in fractured rock aquifers in dolerites and siltstones (‘other Proterozoic rocks’ (Figure 2-23)). While these fractured rock aquifers are highly variable in water yield and quality, they represent a large proportion of the Darwin catchments and currently provide small-scale water supplies. Highly heterogeneous and low-yielding fractured granite aquifers were not considered as favourable targets for MAR.

Groundwater use lowers groundwater levels and therefore creates storage capacity in the aquifer, which is required for MAR. However, the challenge remains to target aquifers with storage capacity at the end of the wet season, or to identify an available recharge source when there is sufficient storage capacity (i.e. early in the dry season). Infiltration techniques recharging unconfined aquifers are generally favoured for producing cost-effective water supplies, hence the initial focus on recharge techniques and limitations for unconfined aquifers.

MAR opportunity maps were developed from the best available data at the catchment scale (see companion technical report on assessment of managed aquifer recharge opportunities (Vanderzalm et al., 2018)) and the results are shown in Figure 5-12 and Figure 5-13. The reconnaissance assessment indicates approximately 18,400 km² (62%) of the Darwin catchments may have aquifers with potential for MAR. Most of this area, approximately 15,800 km² (~53%) of the catchments, lies within a zone of lower slope (<5%) and moderately permeable soils. Only around 3% of the Darwin catchments lie within the most favourable zone of low slope and high-permeability soils (Figure 5-12).

Major rivers were assessed as potential water sources for recharge using MAR. Proximity to water source will impact on the economic feasibility of a MAR scheme and for the purposes of a pre-feasibility assessment it was considered that distances greater than 5 km from a water source would be unlikely to be economically feasible. The geographic distribution of MAR opportunity within 5 km of major rivers within the selected aquifer types is shown in Figure 5-13. Approximately 7700 km² (26%) of the Darwin catchments may have aquifers with potential for MAR within 5 km of a major river that may be considered as the water source for recharge. Of this, approximately 6700 km² (~22%) of the catchments are within the zone of lower slope and moderately permeable soils (Figure 5-13).

Water-level data for monitoring bores across the Darwin catchments provide some insight into the potential for aquifers to store additional water (Figure 5-13). A watertable deeper than 4 m is recommended to avoid issues arising from water-level increases during MAR. Sufficient aquifer storage space is indicated where depth to water is either greater than 4 m at the end of the wet season (i.e. available for recharge year-round) or greater than 4 m at the end of the dry season (i.e. available for seasonal recharge). Bores recording depth to water of less than 4 m at the end of the dry season could be considered indicative that no storage space exists at any time of year. These bores are not identified as targeting specific aquifers, however, they plot approximately...
over corresponding regional watertable aquifers as shown by aquifer type. This is not precise, as there are doubts about the integrity of some bores as well as the potential for interaction between readings from underlying aquifers where there is layered stratigraphy, but it is considered adequate for interpretation at a regional scale.

Figure 5-12 MAR opportunities for the Darwin catchments irrespective of distance from a water source for recharge Analysis based on the permeability (Thomas et al., 2018) and terrain slope (Gallant et al., 2011) datasets, and limited to the following aquifer formations: Mesozoic sandstone, Bonaparte Basin sandstone, Daly Basin limestone and siltstone, other Proterozoic rocks and Proterozoic dolostone (Figure 2-23). Water persistence in dry seasons is shown for context; presence of water in 90% or more of dry seasons is considered indicative of perennial flow.

The available depth-to-water data suggests that, in general, there is sufficient freeboard in many areas identified as having regional MAR opportunities, particularly in the Proterozoic dolostone and the Proterozoic siltstone, sandstone and dolerite (other Proterozoic rocks). More detailed analyses of water levels in prospective areas would be required to confidently assess aquifer storage capacity.
Figure 5-13 MAR opportunities in the Darwin catchments within 5 km of major rivers
Analysis based on the permeability (Thomas et al., 2018) and terrain slope (Gallant et al., 2011) datasets, and limited to the following aquifer formations: Mesozoic sandstone, Bonaparte Basin sandstone, Daly Basin limestone and siltstone, other Proterozoic rocks and Proterozoic dolostone (Figure 2-23). Seasonal variability in depth to water in monitoring bores is shown for context.

There are a number of additional potential water sources for MAR (Figure 5-14) in the Darwin catchments. Existing sources include public water supply reservoirs (located on major rivers), potential to tap into trunk mains running from these dams to the city of Darwin, potential for stormwater harvesting and potential for mining the existing sewerage network in and around the cities of Darwin and Palmerston. Several additional potential sources include large dam sites, farm-scale gully dams and ringtanks. Some of these options may complement MAR operations where surface water capture, storage and detention offer a degree of treatment through sedimentation. Particulates in the recharge source may lead to clogging and reduce the recharge rate (infiltration or injection rate). Pre-treatment before recharge can be used to manage clogging and reduce the need for ongoing maintenance. Also, intentional release of water from surface
storage to provide groundwater recharge is an example of MAR (recharge releases (Figure 5-11)). These additional sources may provide opportunities where there are no major rivers in close proximity to suitable areas (e.g. in the Wildman catchment). Importantly, this regional-scale assessment does not capture the potential to harvest urban stormwater directly from population centres (e.g. Darwin, Palmerston and surrounds) that could be used to augment town water supplies, reduce the impacts of potential seawater intrusion or be used for crop irrigation or community amenities. These are explored in more detail in the subsequent hypothetical examples of MAR in the Darwin catchments.

Figure 5-14 Existing and potential water sources for MAR in the Darwin catchments
Analysis based on the permeability (Thomas et al., 2018) and terrain slope (Gallant et al., 2011) datasets, and limited to the following aquifer formations: Mesozoic sandstone, Bonaparte Basin sandstone, Daly Basin limestone and siltstone, other Proterozoic rocks and Proterozoic dolostone (Figure 2-23). Existing and potential large dams, potential farm dams, town water and sewer mains are shown to illustrate additional potential sources of recharge for MAR.

Based on the regional-scale potential for suitable aquifers and proximity to existing and potential water sources (Figure 5-13 and Figure 5-14), four types of MAR are described in areas of the Darwin catchments to illustrate the most prospective opportunities for MAR. These MAR
configurations include both infiltration and bore injection methods, as some of the unconfined aquifers in the Darwin catchments are better suited to MAR methods using bores for recharge. In some locations (e.g. northern part of Koolpinyah Dolostone) the dolostone aquifer is confined and therefore infiltration techniques of MAR are not possible. Where the dolostone is unconfined, the recharge rate may be limited by the storage capacity of the thin veneer of laterite at the surface.

Three types of MAR are described that could be applied to recharge the dolostone aquifer (Koolpinyah Dolostone in the Howard East area and the dolostone at Berry Springs and Palmerston, which have not been formally defined). The fourth describes a MAR type to supplement recharge to the Burrell Creek Formation (other Proterozoic rocks) at Adelaide River. Four example locations (Figure 5-13) and five hypothetical MAR schemes are used in the following sections of this chapter to demonstrate the application of each of these configurations of MAR (Figure 5-11) as follows:

- ASTR and ASR: surface water injection to augment the groundwater resource in the Koolpinyah Dolostone aquifer. Example location: Howard East
- ASR: surface water injection, storage and recovery to augment the groundwater resource in the dolostone aquifer. Example location: Palmerston
- recharge release into river to enhance natural recharge to the dolostone aquifer. Example location: Berry Springs
- recharge weir in alluvium overlying siltstone, sandstone and dolerite aquifer. Example location: Adelaide River.

Each MAR scheme is described as comprising up to seven individual components, as proposed in the MAR guidelines (NRMMC-EPHC-NHMRC, 2009):

1. ‘capture zone’ of the source of water
2. ‘pre-treatment’ if required (e.g. filtration)
3. ‘recharge’ or the type of MAR infrastructure used (e.g. recharge weir)
4. ‘subsurface storage’ or the aquifer the water is stored in
5. ‘recovery’, such as bores to recover water for use
6. ‘post-treatment’ if required, any water quality treatment needed prior to use
7. the intended ‘end use’ (e.g. irrigation).

Each component represents a step where water quantity or quality impacts can be assessed and managed as required.

It is not necessary that each of the seven components is required for each example of MAR in the Darwin catchments.

Pre-feasibility-level assessment of five potential MAR schemes (four MAR types) in the Darwin catchments

**ASR and ASTR – Howard East**

The Howard East area comprises varying sized estates and land uses. The area has experienced an increasing use of the Koolpinyah Dolostone aquifer for town water supply, rural residential and
agricultural use. MAR has potential to augment recharge to the Koolpinyah Dolostone aquifer to provide this region with ancillary water resources that could be immediately utilised for agricultural and drinking water purposes (Marsden Jacob Associates, 2012b).

Howard Springs consists of numerous individual springs that spread along both the main fault and the smaller ones, all of which are interconnected. Due to high yields and perceptions of ‘plenty of water’ by the community within this aquifer, the Howard East rural area has experienced a large increase in groundwater use to around 25 GL/year. Water supply to residents is totally reliant on groundwater extraction from the aquifer via individual bores. Furthermore, municipal bores in the McMinns and Howard East borefields contribute approximately 14% of Darwin’s water supply (Power and Water Corporation, 2013).

Within the Darwin Rural Water Control District, using a bore at less than 15 L/second does not require licensing. This means that many commercial users of the Koolpinyah Dolostone aquifer have not been licensed; therefore, there is a lack of reliable data on groundwater extraction. In addition, groundwater extraction for stock and domestic use does not require licensing.

In 2016, groundwater levels for the most part were low if not the lowest recorded for the past 10 years for most of the Howard East area (Figure 5-15a). Figure 5-15b illustrates that the dry-season groundwater levels in bore RN009421 approach the level at which Howard Springs reportedly ceases to flow (Fell-Smith and Sumner, 2011). End-of-dry-season water levels in the Howard East area can result in risk to the water supply for many groundwater users in this area. This generates considerable interest in the opportunity for MAR to help augment the groundwater resource in the Darwin rural area. The risk of the groundwater level falling below the screened interval of private bores is distributed across the Howard East area.

![Figure 5-15 Hydrograph of bores (a) RN009266 and (b) RN009421 in the Howard East area](image_url)

*Groundwater level is shown as metres below ground level (mBGL). For bore RN009421 (b), Howard Springs ceases to flow when the level in RN009421 reaches 6.71 m below ground level (mBGL).*
Groundwater modelling was undertaken to assess the potential for MAR to alleviate seasonal pressure on groundwater resources in the Koolpinyah Dolostone in the Howard East area. The Northern Territory Government’s Koolpinyah groundwater system model was used for a preliminary assessment of MAR scheme configuration and potential impact in this area. It revealed that bore injection directly into the dolostone layer was more effective than infiltration in augmenting groundwater levels. Land availability is also considered a constraint for infiltration-type MAR schemes, especially in rural residential areas. While the regional-scale model was suitable for this purpose, finer-scale modelling is required to assess the feasibility of a specific MAR scheme.

Two bore injection schemes are described in the following text: 1 GL/year ASTR and 5 GL/year ASR. ASTR refers to the use of separate bores for injection and recovery and, for the 1 GL/year ASTR scheme, injection bores are proposed to recharge the aquifer with recovery via existing groundwater extraction bores. ASTR is applied within the stressed region of the aquifer where the Koolpinyah Dolostone aquifer is unconfined. As the unconfined aquifers rapidly recharge to full capacity during the wet season, storage capacity is limited and recharge is applied from the end of the wet season until around July each year (i.e. inter-seasonal recharge and short-term storage). The components of the ASTR bore injection MAR scheme for the Howard East area are presented in Figure 5-16 and summarised in Table 5-6.

ASR refers to the use of the same well for injection and recovery and is applied within the confined portion of the Koolpinyah Dolostone aquifer, to the north of the stressed region. The confined nature of the aquifer means that water can be recharged during the wet season when it is in excess. A scheme capacity of 5 GL/year is assessed, which is comparable to the current extraction for town water supply. Stored water can be recovered each dry season, possibly offsetting the need for the municipal Howard East borefield. This would reduce extraction and decrease localised stress in parts of the aquifer but may not resolve the issue of groundwater stress and failed private bores across the entire Howard East area. Alternatively, longer storage periods could serve as a reserve for use after poor wet seasons. Therefore, this larger capacity ASR scheme can be considered as a ‘water bank’. The components of a hypothetical ASR bore injection MAR system for the Howard East area are presented in Figure 5-17 and are summarised in Table 5-7.

Bore injection types of MAR occupy a small footprint, which may be beneficial in more developed, urban areas. Operational ASR schemes across the Adelaide metropolitan area in SA have the capacity to harvest and store around 20 GL/year of urban stormwater for non-potable use. Figure 5-18 provides an example of an ASR scheme at Warruwi, NT. The ASR scheme was established to store excess drinking water supplies from the shallow laterite aquifer during the wet season in a deeper sandstone aquifer.
Figure 5-16 Schematic diagram of a hypothetical Howard East ASTR MAR scheme
Infrastructure requirements are pre-treatment (2) and ASTR bores (3). Details of the seven components are provided in Table 5-6.

Table 5-6 Components of the hypothetical Howard East ASTR MAR scheme

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>AQUIFER STORAGE TRANSFER AND RECOVERY MAR SCHEME</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Capture zone</td>
<td>Available wet- or dry-season water</td>
</tr>
<tr>
<td>2. Pre-treatment</td>
<td>Filtration; injection bores are susceptible to clogging and therefore pre-treatment is used to remove suspended solids from recharge source</td>
</tr>
<tr>
<td>3. Recharge</td>
<td>ASTR (injection bores) (assume depth ~40 m)</td>
</tr>
<tr>
<td>4. Subsurface storage</td>
<td>Koolpinya Dolostone</td>
</tr>
<tr>
<td>5. Recovery</td>
<td>Intended to be via existing groundwater extraction bores</td>
</tr>
<tr>
<td>6. Post-treatment</td>
<td>Not required for irrigation use</td>
</tr>
<tr>
<td>7. End use</td>
<td>Irrigation for horticulture and drinking water</td>
</tr>
</tbody>
</table>

Figure 5-17 Schematic diagram of the hypothetical Howard East ASR MAR scheme
Infrastructure requirements are pre-treatment (2) and ASR bores (3). Details of the seven components are provided in Table 5-7.
Table 5-7 Components of the hypothetical Howard East ASR MAR scheme

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>AQUIFER STORAGE TRANSFER AND RECOVERY MAR SCHEME</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Capture zone</td>
<td>Available wet-season water</td>
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<tr>
<td>2. Pre-treatment</td>
<td>Filtration; injection bores are susceptible to clogging and therefore pre-treatment is used to remove suspended solids from recharge source</td>
</tr>
<tr>
<td>3. Recharge</td>
<td>ASR bores (assume depth ~40 m)</td>
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<tr>
<td>4. Subsurface storage</td>
<td>Koolpinyah Dolostone</td>
</tr>
<tr>
<td>5. Recovery</td>
<td>ASR bores</td>
</tr>
<tr>
<td>6. Post-treatment</td>
<td>Not required for irrigation use</td>
</tr>
<tr>
<td>7. End use</td>
<td>Irrigation for horticulture and drinking water</td>
</tr>
</tbody>
</table>

ASR – Palmerston

Palmerston is a planned satellite city of Darwin and had a population of 33,695 at the 2016 census (ABS, 2017), making it the second-largest city in the sparsely populated NT. Palmerston is currently the fastest growing city in the NT and has been one of the fastest growing cities in Australia.

There are 18 suburbs in Palmerston, 10 of which are close to the Palmerston city centre. Palmerston is mostly residential with two light industrial areas in the north of the city. Palmerston has a large number of open space areas set aside for the community. Not all of these are irrigated parks. There are, however, 12 freshwater man-made lakes in the city as well as areas of bushland, freshwater creeks, mangroves and estuaries, which drain into Darwin Harbour. There has also been anecdotal evidence of seawater intrusion due to overextraction of the aquifer in this region.

This example considers the potential to harvest wet-season surface water (potentially urban runoff) to recharge the dolostone via ASR for the purposes of recovering irrigation supplies during the dry season as a substitute for potable supplies. The Palmerston City Council currently uses groundwater to irrigate the municipal open spaces and an opportunity exists to assess the potential for urban stormwater ASR to store wet-season urban stormwater for irrigation supplies. The components of the hypothetical ASR system in Palmerston are presented in Figure 5-19 and summarised in Table 5-8.
**Figure 5-18** ASR bore Warruwi, NT, storing excess drinking water supplies from the shallow laterite aquifer during the wet season in a deeper sandstone aquifer

*Photo: CSIRO*

**Figure 5-19** Schematic diagram of the hypothetical Palmerston ASR MAR scheme

Infrastructure requirements are pre-treatment (2) and ASR bores (3). Details of the seven components are provided in Table 5-8.
Table 5-8 Components of the hypothetical Palmerston ASR MAR scheme

<table>
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<th>COMPONENT</th>
<th>AQUIFER STORAGE AND RECOVERY MAR SCHEME</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Capture zone</td>
<td>Surface water (potentially urban runoff)</td>
</tr>
<tr>
<td>2. Pre-treatment</td>
<td>Some passive treatment would be required, potentially through geotextile fabric and 100 μm stainless steel filter, to manage the risk of bore clogging</td>
</tr>
<tr>
<td>3. Recharge</td>
<td>ASR bore (assume depth ~40 m)</td>
</tr>
<tr>
<td>4. Subsurface storage</td>
<td>Dolostone</td>
</tr>
<tr>
<td>5. Recovery</td>
<td>ASR bores</td>
</tr>
<tr>
<td>6. Post-treatment</td>
<td>Not required for irrigation use</td>
</tr>
<tr>
<td>7. End use</td>
<td>Green space irrigation</td>
</tr>
</tbody>
</table>

Recharge release – Berry Springs

Berry Springs is an outer suburban locality in Darwin. In June 2016, the Northern Territory Government put a development freeze on the Darwin rural area of Berry Springs due to the risk of overexploitation of groundwater resources.

Groundwater is used as a drinking water supply for many rural landholders and also for the main economic activities in the area, which include tourism; irrigated horticulture, particularly for food crops and cut flowers; and aquaculture. For example, Marsden Jacob Associates (2012a) estimated that the value of irrigated agriculture in the Berry Springs Water Allocation Planning Area region was approximately $20 million per year (~$14 million for fruit production and $7 million for vegetables, in 2011). Growth prospects for irrigated agriculture are relatively good, with availability of water being the key limitation to further economic growth. In addition, the prevalence of rural residential land use and likelihood of future growth in the area also create a significant risk of groundwater overextraction. Marsden Jacob Associates (2012a) estimated that under a high-growth scenario, the increase in groundwater use could be as high as 6 GL, resulting in a total use of around 14 GL by 2021. Of the 6 GL in growth, approximately 1.2 GL would be from major agriculture (metered) and around 4.6 GL would be from unmetered small horticulture (3 GL) and domestic use (1.6 GL). This growth has the potential to create a situation similar to the Howard East area, an over-stressed aquifer with few acceptable options in terms of management other than enhanced recharge.

Within the Darwin Rural Water Control District, using a bore at less than 15 L/second does not require licensing. This means that many commercial users of the Berry Springs dolomite aquifer have not been licensed, and there is a lack of reliable data on total groundwater extraction. Modelling of the aquifer system and river flows has shown that current levels of applied irrigation water reduce natural spring flow discharges from the Berry Springs aquifer by greater than 20%, which is a risk to GDEs.

The Darwin River flows through the Berry Springs area to the Timor Sea. The Darwin River has several losing and gaining portions of the stream and is known to be connected to the aquifer at several points, which provides an opportunity for enhanced recharge (Williams, 2009). In the dry season, baseflow originating from the dolomite aquifer gradually replaces surface runoff from releases from Darwin River Dam and dolomite groundwater gradually changes water quality in the river by increasing electrical conductivity, pH and ionic concentrations of bicarbonate, calcium and magnesium.
Groundwater and surface water in the Berry Springs area are highly connected with the Darwin River, alternating between losing and gaining on a seasonal basis during the year. During the wet season when the groundwater level is higher than the water level in the Darwin River, water flows into the river (making it a ‘gaining stream’). Later in the dry season and early in the wet season the river becomes a ‘losing stream’ as it loses water into the underlying aquifer as groundwater levels fall.

Conjunctive use of surface water and groundwater is a technique to augment groundwater resources with enhanced surface water flows. This method of MAR is possible where aquifers are unconfined and close to a surface water recharge source. This method can be very favourable as most of the infrastructure is likely to already exist. However, it is unknown to what extent and efficiency the released water would recharge the dolostone without further targeted investigations. Any releases from Darwin River Dam to recharge the Berry Springs aquifer could also potentially diminish the water security of Darwin.

The components of the MAR conjunctive surface water and groundwater system via recharge release are presented in Figure 5-20 and summarised in Table 5-9.

Figure 5-20 Schematic diagram of the hypothetical Berry Springs recharge release MAR scheme
Recharge release uses existing dam and weir structures. Details of the seven components are provided in Table 5-9. A dam and weir is assumed to exist for consideration of a recharge release MAR scheme.
Table 5-9 Components of the Berry Springs recharge release MAR scheme

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>RECHARGE RELEASE MAR SCHEME</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Capture zone</td>
<td>Surface water from the Darwin River Dam</td>
</tr>
<tr>
<td>2. Pre-treatment</td>
<td>Detention in the Darwin River Dam during the first part of the dry season</td>
</tr>
<tr>
<td>3. Recharge</td>
<td>Via the Darwin River, in early dry season when there is sufficient storage capacity in the aquifer</td>
</tr>
<tr>
<td>4. Subsurface storage</td>
<td>Dolostone aquifer</td>
</tr>
<tr>
<td>5. Recovery</td>
<td>Intended to be via existing groundwater extraction bores</td>
</tr>
<tr>
<td>6. Post-treatment</td>
<td>Not required</td>
</tr>
<tr>
<td>7. End use</td>
<td>Irrigation for horticulture and drinking water</td>
</tr>
</tbody>
</table>

Recharge weir – Adelaide River

The town of Adelaide River is located approximately 110 km south of Darwin on the Stuart Highway, where the highway crosses over the Adelaide River, and is a locally important transport and agricultural servicing centre. Since the 1950s the town’s water supply has been met from local groundwater resources (Dames and Moore, 1992). Elevated levels of manganese and iron concentrations are evident in some bores and recent implementation of a water treatment plant has improved the quality of drinking water through biological removal of iron and manganese (Engineers Australia, 2016).

The Burrell Creek Formation underlies most of the Adelaide River area. It comprises massive felspathic greywacke, siltstone, shale, phyllite and schists with subordinate quartz veining. A series of north–south trending fold axes run through the area, with associated shearing and fracturing particularly along the crest of anticlines. The rocks are highly weathered at the surface with weathering commonly extending to 15 m depth (Verma et al., 1991). On the northern side of the Adelaide River extending to Snake Creek, the Burrell Creek Formation underlies a 15- to 25-m thick sequence of alluvial sediments. These sediments comprise well-sorted quartz sands and gravels, which are overlain by clayey sands and sandy clays.

Dames and Moore (1992) recommended the most suitable option for MAR is a 6-m high weir with an associated spillway on Snake Creek, approximately 500 m upstream from its confluence with the Adelaide River, in addition to deepening of the creek floor to remove clays and silt to increase the infiltration area and rate. The storage capacity of the impounded area would be 400 to 600 ML. Recovery bores were proposed in an area where the Burrell Creek Formation is highly fractured and overlain by 8 to 23 m of alluvial sediments comprising coarse sands and gravels with some clay. Reported airlift yields vary between 3 and 14 L/second. Given the proximity of the proposed bores to the wastewater treatment plant, some modification of the existing wastewater treatment ponds would be required for groundwater quality protection. Figure 5-21 shows a recharge weir at Minderoo in the Pilbara, WA. A detailed analysis of the recharge weir at Minderoo is documented in the companion technical report on managed aquifer recharge, Vanderzalm et al. 2018.
Figure 5-21 Recharge weir at Minderoo in the Pilbara, WA
Recharge weirs have recently been referred to as ‘upside down dams’. Photo: CSIRO

Previous investigations by Dames and Moore (1992) reported that there is significant storage capacity in the fluvial sediments adjacent to Snake Creek. Assuming a specific yield of 0.1 (10% effective porosity), a mean aquifer thickness of approximately 10 m and a surface area of around 7.2 km², there is capacity for the storage of an additional 720 ML of recharged water.

The components of the recharge weir MAR scheme for Adelaide River are presented in Figure 5-22 and summarised in Table 5-10.

Figure 5-22 Schematic diagram of the hypothetical Adelaide River recharge weir MAR scheme
Infrastructure requirements are the recharge weir (3) and extraction bores (5). Details of the seven components are provided in Table 5-10.
Table 5-10 Components of the hypothetical Adelaide River recharge weir MAR scheme

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>RECHARGE WEIR MAR SCHEME</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Capture zone</td>
<td>Surface water from Snake Creek</td>
</tr>
<tr>
<td>2. Pre-treatment</td>
<td>Detention in the Snake Creek weir</td>
</tr>
<tr>
<td>3. Recharge</td>
<td>Via alluvium to underlying fractured rock</td>
</tr>
<tr>
<td>4. Subsurface storage</td>
<td>Adelaide River alluvium and Burrell Creek Formation</td>
</tr>
<tr>
<td>5. Recovery</td>
<td>Groundwater extraction bores (assume depth ~40 m)</td>
</tr>
<tr>
<td>6. Post-treatment</td>
<td>Chlorination, iron and manganese removal as currently undertaken for drinking water supply (existing water treatment plant, no new infrastructure required)</td>
</tr>
<tr>
<td>7. End use</td>
<td>Drinking water</td>
</tr>
</tbody>
</table>

Investigations required to assess feasibility of a MAR scheme

Several investigations are required to obtain sufficient data to assess the feasibility of a specific MAR scheme. These investigations and the associated risk-based feasibility assessment represent stage two of project assessment and development in the MAR guidelines (NRMMC-EPHC-NHMRC, 2009). For recharge weir, recharge release or infiltration basin type MAR schemes intending to store water via infiltration in an alluvial aquifer, it is necessary to:

- Assess the quality of the source water with respect to the potential for clogging, in particular the potential for suspended solids to lead to clogging and a reduction in injection or infiltration rate. Typically, higher quality water is required for bore injection schemes and thus pre-treatment by filtration is likely. If a clogging risk persists, additional pre-treatment of the source water or maintenance to mitigate clogging will be required. Recharge release involves surface detention prior to recharge, which is likely to reduce the suspended solids load of the recharge source water and thus mitigate the risk of clogging. Recharge weirs may need de-silting at regular intervals.

- Assess the suitability of the groundwater quality for the intended use, which will influence the amount of mixing between the recharge source and the ambient groundwater that can be tolerated. Salinity is the key parameter to consider with respect to limitations on mixing.

- Undertake a hydrogeological and geochemical investigation to confirm there is sufficient storage capacity within the aquifer, confirm a suitable recharge rate is viable, estimate the hydraulic impacts to connected ecosystems or nearby groundwater users and predict water quality or permeability changes that may occur due to reactive minerals.

- Undertake a hydrological assessment to confirm the volume of source water available for recharge at the time when aquifer storage capacity exists (possibly early dry season).

- Develop the project in accordance with stage three (construction and commission) and stage four (operation) of MAR guidelines (NRMMC-EPHC-NHMRC, 2009). Central to this is including a field trial to confirm all risk management strategies before progressing to an operational scheme.

MAR economic considerations

Five hypothetical MAR schemes are described in areas of the Darwin catchments that offer some opportunity for MAR, based on a regional-scale assessment. Notably, all schemes target fractured
rock aquifers, which are highly variable in nature and, therefore, very challenging to accurately assess their suitability for MAR at a regional scale.

Capital and operating cost estimates (Table 5-11) are presented in relation to the seven components of each MAR scheme to illustrate how each of these components contributes to the overall cost of a scheme. Capital costs for a 1 GL/year scheme were estimated at approximately $3,000,000 using either ASTR at Howard East or ASR at Palmerston. These costs were considerably lower at $270,000 for recharge release at Berry Springs assuming that a large dam is situated upstream and new infrastructure is not required. Capital costs for the larger 5 GL/year ASR scheme at Howard East were estimated at $4,600,000. Capital costs for a recharge weir to supply 600 ML/year at Adelaide River were estimated at $1,030,000. Given the variability in complexity of schemes, it follows that annual operation and maintenance costs ranged from $50,000 to $355,000.

Table 5-12 compares the total capital and operating cost and an equivalent annual unit cost for each of the schemes. The levelised costs (total equivalent annual costs) for the construction and operation of the various hypothetical MAR schemes range between $70 and $335/year per ML of stored water/year (Table 5-12). Recharge release is the lowest cost ($70/year per ML/year) as it relies on existing dam and weir structures for release and the natural river channel for infiltration. The 5 GL/year ASR scheme is the next lowest cost at $138 per ML, followed by the recharge weir ($227/year per ML/year), 1 GL/year ASTR ($315/year per ML/year) and 1 GL/year ASR ($335/year per ML/year).

For the purposes of the economic assessment, the following assumptions were applied:

- A 50-year infrastructure service life was adopted.
- A discount rate of 7% was used.
- Construction of all infrastructure is completed within the first year, with operations therefore assumed to commence in the second year, following construction.
- There was no volumetric water loss in the aquifer, as mixing between the source water and groundwater is not expected to limit the use of the recovered water.
- A nominal scheme size of 1 GL/year was assessed for Palmerston and Berry Springs. At Adelaide River, a 600 ML/year MAR scheme was based on a published design (Dames and Moore, 1992). The Howard East ASR water bank was considered as an alternative to the municipal borefields (5 GL/year).
- Operation and maintenance costs were assumed to be 2% of capital costs, unless specified.
- No provision was made for infrastructure to transfer water to the MAR site.
- No provision was made for infrastructure to transfer water to the end use. Typical costs to deliver groundwater from an extraction bore to an irrigation system could be around $140,000 per bore.
- Two bores are drilled for hydrogeological assessment and then subsequently used for monitoring bores aside from the Howard East ASR water bank (eight monitoring bores).
- Bore injection schemes require filtration prior to injection to manage the physical clogging risk.
• Capital costs for MAR component 3, ‘recharge’ include the recharge structure and site establishment costs such as site-access tracks, workforce accommodation, mobilisation and demobilisation of plant and land clearing.
• Capital costs for MAR component 5, ‘recovery’ include recovery bore costs where required (as outlined in the components for each scheme assessed).
• Capital costs for MAR component 7, ‘end use’ include investigations required to assess scheme viability and manage potential risks, cultural heritage management, approvals, monitoring bores and development of a risk management plan. Operating costs for component 7 include ongoing monitoring for risk management of the scheme. As noted above, the end use costs do not include the cost of reticulation to users.

Base costs are summarised in Table 5-13.

Table 5-11 Capital and operating costs for individual components of five hypothetical MAR schemes in the Darwin catchments
MAR scheme capacity varies from 0.6 to 5 GL/year.

<table>
<thead>
<tr>
<th>MAR SCHEME COMPONENT</th>
<th>COST</th>
<th>HOWARD EAST ASTR</th>
<th>HOWARD EAST WATER BANK ASR</th>
<th>PALMERSTON ASR</th>
<th>BERRY SPRINGS RECHARGE RELEASE</th>
<th>ADELAIDE RIVER RECHARGE</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Catchment</td>
<td>Capital ($)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Operating ($/y)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2. Pre-treatment†</td>
<td>Capital ($)</td>
<td>80,000</td>
<td>80,000</td>
<td>80,000</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Operating ($/y)</td>
<td>1,600</td>
<td>1,600</td>
<td>1,600</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3. Recharge‡</td>
<td>Capital ($)</td>
<td>2,620,000</td>
<td>4,132,000</td>
<td>2,620,000</td>
<td>0</td>
<td>515,200§</td>
<td>6,920</td>
</tr>
<tr>
<td></td>
<td>Operating ($/y)</td>
<td>48,000</td>
<td>76,800</td>
<td>48,000</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>4. Storage</td>
<td>Capital ($)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Operating ($/y)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>5. Recovery†</td>
<td>Capital ($)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>240,000</td>
<td>4,800</td>
</tr>
<tr>
<td></td>
<td>Operating ($/y)</td>
<td>0</td>
<td>76,800</td>
<td>48,000</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>6. Post-treatment</td>
<td>Capital ($)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0*</td>
</tr>
<tr>
<td></td>
<td>Operating ($/y)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>7. End use††</td>
<td>Capital ($)</td>
<td>270,000</td>
<td>390,000</td>
<td>235,000</td>
<td>270,000</td>
<td>270,000</td>
<td>1,030,000</td>
</tr>
<tr>
<td></td>
<td>Operating ($/y)</td>
<td>50,000</td>
<td>200,000</td>
<td>25,000</td>
<td>50,000</td>
<td>50,000</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>Capital ($)</td>
<td>2,970,000</td>
<td>4,600,000</td>
<td>2,940,000</td>
<td>270,000</td>
<td>270,000</td>
<td>1,030,000</td>
</tr>
<tr>
<td></td>
<td>Operating ($/y)</td>
<td>99,600</td>
<td>355,000</td>
<td>123,000</td>
<td>50,000</td>
<td>61,700</td>
<td></td>
</tr>
</tbody>
</table>

†Value assumes filtration is necessary prior to injection.
‡Capital costs = infiltration basin or bores and site establishment; operating costs includes basin scraping or pumping costs.
*Value assumes existing water treatment plant has capacity for treatment.
††Capital costs = investigations required for the establishment of the scheme, cultural heritage management, approvals, risk management plan; monitoring bore costs included in hydrogeological investigation; Operating costs = ongoing monitoring for risk management.
### Table 5-12 Indicative capital and operating costs for five hypothetical MAR schemes (four MAR types) in the Darwin catchments

<table>
<thead>
<tr>
<th>MAR TYPE</th>
<th>EXAMPLE LOCATION</th>
<th>VOLUME (GL)</th>
<th>CAPITAL COST ($)</th>
<th>OPERATING COST ($/ML)</th>
<th>OPERATING COST ($/y)</th>
<th>LEVELISED CAPITAL COST ($/ML)</th>
<th>LEVELISED OPERATING COST ($/ML)</th>
<th>LEVELISED COST† ($/ML)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTR</td>
<td>Howard East (unconfined)</td>
<td>1</td>
<td>2,970,000</td>
<td>2,970</td>
<td>99,600</td>
<td>215</td>
<td>100</td>
<td>315</td>
</tr>
<tr>
<td>ASR</td>
<td>Howard East water bank (confined)</td>
<td>5</td>
<td>4,600,000</td>
<td>920</td>
<td>355,000</td>
<td>67</td>
<td>71</td>
<td>138</td>
</tr>
<tr>
<td>ASR</td>
<td>Palmerston</td>
<td>1</td>
<td>2,940,000</td>
<td>2,940</td>
<td>123,000</td>
<td>213</td>
<td>122</td>
<td>335</td>
</tr>
<tr>
<td>Recharge release</td>
<td>Berry Springs</td>
<td>1</td>
<td>270,000</td>
<td>270</td>
<td>50,000</td>
<td>20</td>
<td>50</td>
<td>70†</td>
</tr>
<tr>
<td>Recharge weir</td>
<td>Adelaide River</td>
<td>0.6</td>
<td>1,030,000</td>
<td>1,710</td>
<td>61,700</td>
<td>123</td>
<td>103</td>
<td>227</td>
</tr>
</tbody>
</table>

†May also be referred to as equivalent annual unit cost, assuming a 7% real discount rate and a MAR scheme life of 50 years.  
‡Large dam is assumed to exist for consideration of a recharge release MAR scheme.

### Table 5-13 Summary of base costs used in MAR scheme costs estimates for the Darwin catchments

<table>
<thead>
<tr>
<th>ITEM</th>
<th>BASE COST IN 2017 ($)</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infiltration basin construction ($/m³)</td>
<td>4</td>
<td>Estimate</td>
</tr>
<tr>
<td>Injection or recovery bore construction cost ($/m)</td>
<td>1,000</td>
<td>Estimate based on real costs (drilling costs in catchments)</td>
</tr>
<tr>
<td>Injection bore pump and instrumentation ($/bore)</td>
<td>200,000</td>
<td>Estimate based on real costs (Vanderzalm et al., 2015)</td>
</tr>
<tr>
<td>Monitoring bore construction cost ($/m)</td>
<td>500</td>
<td>Estimate based on real costs (Vanderzalm et al., 2015)</td>
</tr>
<tr>
<td>Adelaide River MAR scheme capital ($)</td>
<td>346,000</td>
<td>Design estimate (Dames and Moore, 1992)</td>
</tr>
<tr>
<td>Filter prior to injection ($)</td>
<td>80,000</td>
<td>Pre-treatment for injection bore schemes only, to manage physical clogging risk due to particulate matter in source water (Vanderzalm et al., 2015)</td>
</tr>
<tr>
<td>Field-site establishment fixed cost ($)</td>
<td>100,000</td>
<td>Field-site establishment includes site-access tracks, workforce accommodation, mobilisation and demobilisation of plant and land clearing. Total field establishment cost = fixed cost + variable cost (for developed or remote sites, see below)</td>
</tr>
<tr>
<td>Field-site establishment variable cost – developed sites ($)</td>
<td>5% of recharge structure capital</td>
<td>Bore construction cost estimate already includes contingency for remoteness</td>
</tr>
<tr>
<td>Field-site establishment variable cost – remote sites ($)</td>
<td>20% of recharge structure capital</td>
<td>Bore construction cost estimate includes contingency for remoteness</td>
</tr>
<tr>
<td>Monitoring for risk management plan based on two monitoring bores – drinking water end use or aquifer source of drinking water supply ($/y)</td>
<td>50,000</td>
<td>Ongoing groundwater monitoring, as outlined in the risk management plan</td>
</tr>
<tr>
<td>Monitoring for risk management plan based on two monitoring bores – not drinking water end use ($/y)</td>
<td>20,000</td>
<td>Ongoing groundwater monitoring, as outlined in the risk management plan</td>
</tr>
<tr>
<td>Water quality assessment ($/water source) –</td>
<td>10,000</td>
<td>Water quality assessment recommended for</td>
</tr>
<tr>
<td>ITEM</td>
<td>BASE COST IN 2017 ($)</td>
<td>COMMENT</td>
</tr>
<tr>
<td>----------------------------------------------------------------------</td>
<td>-----------------------</td>
<td>---------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>drinking water end use</td>
<td></td>
<td>feasibility assessment</td>
</tr>
<tr>
<td>Water quality assessment ($/water source) – not drinking water end use</td>
<td>5,000</td>
<td>Water quality assessment recommended for feasibility assessment</td>
</tr>
<tr>
<td>Hydrogeological assessment including groundwater modelling</td>
<td>110,000–300,000</td>
<td>Hydrogeological assessment recommended for feasibility assessment. Two bores drilled at variable depths, which subsequently become monitoring bores (monitoring bore construction cost used)</td>
</tr>
<tr>
<td>Geochemical assessment</td>
<td>25,000</td>
<td>Geochemical assessment recommended for feasibility assessment</td>
</tr>
<tr>
<td>Development of a risk assessment plan</td>
<td>25,000</td>
<td>Establishment of an operational risk management plan</td>
</tr>
<tr>
<td>Cultural heritage management</td>
<td>15,000</td>
<td>Estimate based on real costs</td>
</tr>
<tr>
<td>Approvals</td>
<td>25,000</td>
<td>Estimate based on real costs</td>
</tr>
</tbody>
</table>

5.3 Surface water storage opportunities

5.3.1 INTRODUCTION

In a highly seasonal climate, such as that of the Darwin catchments, and in the absence of suitable groundwater, water storages are essential to enable irrigation during the dry season and other periods when soil water is insufficient for crop growth.

The Assessment undertook a pre-feasibility-level assessment of four types of surface water storage options. These were:

1. major dams that supply water to multiple properties (Section 5.3.2)
2. re-regulating structures such as weirs (Section 5.3.3)
3. large farm-scale or on-farm dams, which supply water to a single property (Section 5.3.4 and Section 5.3.5)
4. natural water bodies (Section 5.3.6).

Although natural water bodies do not require construction, their capacity may be enhanced with strategically constructed embankments.

Both major dams and large farm-scale dams can be further classified as instream or offstream water storages. In this Assessment instream water storages are defined as structures that intercept a drainage line (creek or river) and are not supplemented with water from another drainage line. Offstream water storages are defined as structures that (i) do not intercept a drainage line, or (ii) intercept a drainage line and are supplemented with water extracted from another larger drainage line. Ringtanks and turkey nest tanks are examples of offstream storages with a continuous embankment, and the former is the focus in the Assessment due to their higher storage to excavation ratios. Major dams, large farm-scale dams, offstream storages, re-regulating structures and natural water bodies are also briefly discussed below.
The performance of a dam is often assessed in terms of water yield or demand. This is the amount of water that can be supplied for consumptive use at a given reliability. For a given dam, an increase in water yield results in a decrease in reliability.

Importantly, the Assessment does not seek to provide instruction on the design and construction of farm-scale water storages. Numerous books and online tools provide detailed information on nearly all facets farm-scale water storage (e.g. QWRC, 1984; Lewis, 2002; IAA, 2007; FAO, 2010). Siting, design and construction of weirs and large farm-scale ringtanks, and gully dams is heavily regulated in Australia and should always be undertaken in conjunction with a suitably qualified professional and tailored to the nuances that occur at every site. Major dams are complicated structures and usually involve a consortium of organisations and individuals.

Unless otherwise stated, the material in Section 5.3 originates from the companion technical report on surface water storage (Petheram et al., 2017).

5.3.2 MAJOR DAMS

Introduction

Major dams are usually constructed from earth, rock and/or concrete materials, and typically act as a barrier wall across a river to store water in the reservoir created. They need to be able to safely discharge the largest flood flows likely to enter the reservoir and the structure has to be designed so that the dam meets its purpose, generally for at least 100 years. Some dams, such as Kofini Dam in Greece and Anfengtang Dam in China, have been in continuous operation for over 2000 years, with Schnitter (1994) consequently coining dams as ‘the useful pyramids’.

An attraction of major dams over farm-scale dams is that if the reservoir is large enough relative to the demands on the dam (i.e. water supplied for consumptive use and ‘lost’ through evaporation and seepage), when the reservoir is full, water can last two or more years. This has the advantage of mitigating against years with low inflows to the reservoir. For this reason major dams are sometimes referred to as ‘carry-over storages’.

Major instream versus offstream dams

Offstream water storages were among the first man-made water storages (Nace, 1972; Scarborough and Gallopin, 1991) because people initially lacked the capacity to build structures that could block rivers and withstand large flood events. One of the advantages of offstream storages is that, if properly designed, they can cause less disruption of the natural flow regime than large instream dams. Less disruption occurs if water is extracted from the river using pumps, or if there is a diversion structure it has raiseable gates, which in northern Australia need to be able to operate in remote environments, to allow water and aquatic species to pass when not in use.

The primary advantage of large instream dams is that they provide a very efficient way of intercepting the flow in a river, effectively trapping all flow until the full supply level is reached. For this reason, however, they also provide a very effective barrier to the movement of fish and other species within a river system, alter downstream flow patterns and can inundate large areas of land.
Types of major dams

Two types of major dams are particularly suited to northern Australia: embankment dams and concrete gravity dams. Embankment dams (EB) are usually the most economical, provided suitable construction materials can be found locally, and are best suited to smaller catchment areas where the spillway capacity requirement is small. Concrete gravity dams with a central overflow spillway are generally more suitable where a large capacity spillway is needed to discharge flood inflows, as is the case in most large catchments in northern Australia.

Traditionally, concrete gravity dams were constructed by placing conventional concrete in formed ‘lifts’. Since 1984 in Australia, however, roller compacted concrete (RCC) has been used, where low cement concrete is placed in continuous thin layers from bank to bank and compacted with vibrating rollers. This approach allows large dams to be constructed in a far shorter time frame than required for conventional concrete construction, often with large savings in cost (Doherty, 1999). RCC is best used for high dams where a larger scale plant can provide significant economies of scale. This is now the favoured type of construction in Australia whenever foundation rock is available within reasonable depth, and where a larger capacity spillway is required. In those parts of the Darwin catchments with topography and hydrology most suited to large instream dams, RCC was deemed to be the most appropriate type of dam.

Reconnaissance-level assessment of potential major dams in the Darwin catchments

A promising dam site requires inflows of sufficient volume and frequency, and topography that provides a physiographic constriction of the river channel, and critically, favourable foundation geology. The reconnaissance-level assessment of potential major dams in the Darwin catchments was undertaken using two approaches applied in parallel:

• a review of the literature – fifteen potential dam, weir and causeway locations in the Darwin catchments were identified from published and unpublished studies. The extent of prior investigations ranged from single reference of potential locations (e.g. Blackmore Causeway) to detailed hydrological and geotechnical investigations, such as the Adelaide River Offstream Water Storage (AROWS).

• a spatial analysis – to ensure no potential dam site had been overlooked the Assessment used a bespoke computer model, the DamSite model (Petheram et al., 2017), to assess over 20 million potential sites in the Darwin catchments for their potential as major offstream or instream dams.

Broad-scale geological considerations

Favourable foundation conditions include a relatively shallow layer of unconsolidated materials, such as alluvium, and rock that is relatively strong, resistant to erosion, non-permeable or capable of being grouted. Geological features that make dam construction challenging include the presence of faults, weak geological units, landslides and deeply weathered zones.

The best potential major dam sites in the Darwin catchments are found where rivers have eroded through meta-sedimentary volcanic or igneous rocks in the Pine Creek Orogen, particularly where there is relatively shallow rock in the valley floor. Substantial excavation may be required to provide suitable foundations where alluvium is deep. Where the rivers are tidal, the presence of soft estuarine sediments has the potential to make dam design more challenging and construction
more expensive, which may compromise the feasibility of a dam. Offstream storages may avoid some of these potential problems with deep alluvium.

Quartzite and granite in the Pine Creek Orogen are potential sources of aggregate for RCC and possibly for conventional concrete. Floodplains and colluvial slopes are potential sources of cohesive soils, sand and gravel for embankment dams, if required.

Potential dams in the coastal plains would need to have long low dams, in many cases spanning many kilometres across the floodplain (Figure 5-23. Rivers on the coastal plains are likely to be tidal and underlain by soft estuarine sediments, which will make finding a suitable foundation and construction difficult, compromising the feasibility of potential dams. Designing and constructing spillways to safely pass large floods would also be very difficult on the coastal plains.

![Coastal floodplains in the Darwin catchments](Photo: CSIRO)

**Figure 5-23 Coastal floodplains in the Darwin catchments**

**Major offstream storages for water and irrigation supply**

Figure 5-24 displays the most promising sites across the Darwin catchments in terms of topography, assessed in terms of approximate cost of construction per storage volume (ML). Favourable locations with a small catchment area and adjacent to a large river may be suitable as major offstream storages.
Figure 5-24 Potential storage sites in the Darwin catchments based on minimum cost per ML storage capacity
This figure can be used to identify locations where topography is suitable for large offstream storages. At each location the minimum cost per ML storage capacity is displayed. The smaller the minimum cost per ML storage capacity the more suitable the site for a large offstream storage. Analysis does not take into consideration geological considerations, hydrology or proximity to water. Only sites with a minimum cost to storage volume ratio of less than $4000/ML are shown. $1000/ML is equivalent to 1 GL per million dollars. Costs are based on unit rates and quantity of material and site establishment for a RCC dam. Data are underlain by a shaded relief map. Inset displays height of full supply level (FSL) at the minimum cost per ML storage capacity. For more details see companion technical report on surface water storage (Petheram et al., 2017).

In Figure 5-24 only those locations with a ratio of cost to storage less than $4000/ML are shown. This provides a simple way of displaying those locations in the Darwin catchments with the most favourable topography for a large reservoir relative to the size (i.e. cost) of the dam wall necessary to create the reservoir. This figure is particularly useful for identifying more promising sites for offstream storage (i.e. where some or all of the water is pumped into the reservoir from an adjacent drainage line). The threshold value of $4000/ML is nominal and was used to minimise the amount of data displayed. This analysis does not consider evaporation or hydrology.

This figure shows that the topography of the Darwin catchments is generally unfavourable for the construction of large dams. Those parts of the Darwin catchments with the most favourable
topography for storing water are on the Adelaide River immediately upstream of Adelaide River town. Other topographically favourable locations are immediately west of the Adelaide River south of the Arnhem Land Highway. This area coincides with AROWS (Figure 5-25).

**Major instream dams for water and irrigation supply**

In addition to suitable topography (and geology), instream dams require sufficient inflows to meet a potential demand. Potential dams that command smaller catchments with lower runoff have smaller yields. Results concerning this criterion are presented in terms of minimum cost per unit yield (ML).

The potential for major instream dams to cost effectively supply water is presented in Figure 5-26. No values less than 0.1 yield (GL) per million dollars are shown.

The highest yielding sites per unit cost are Mount Bennett on the Finniss River, Upper Adelaide River on the Adelaide River and Marrakai dam site on the Adelaide River. However, it is likely that the results presented in Figure 5-26 do not adequately reflect the poor foundations and logistical challenges of constructing a large dam at the Marrakai site.

Based on this analysis and a review of the literature, seven of the more promising and larger yielding sites were selected for the pre-feasibility analysis (see the companion technical report on surface water storage (Petheram et al., 2017)). The studies were reviewed and all locations were re-assessed using a consistent set of methods, using updated data where available.

The locations of the pre-feasibility potential dam sites are denoted in Figure 5-26 by black circles. Key parameters and performance metrics are summarised in Table 5-14 and an overall summary comment is recorded in Table 5-15. More detailed analysis of the eight pre-feasibility sites is provided in the companion technical report on surface water storage (Petheram et al., 2017).

![Figure 5-25 Looking north along the main axis of the AROWS](Photo: CSIRO)
This figure indicates those sites more suitable for major dams in terms of cost per ML yield at the dam wall in 85% of years. At each location the minimum cost per ML storage capacity is displayed. The smaller the cost per ML yield ($/ML) the more favourable the site for a large instream dam. Only sites with a minimum cost to yield ratio less than $4000/ML are shown. Costs are based on unit rates and quantity of material required for a RCC dam with a flood design of 1 in 10,000. Cost includes site establishment, fish ladders and land resumption for that area of land impounded by a flood event of annual exceedance probability 1%. Data are underlain by a shaded relief map. Left inset displays height of full supply level (FSL) at the minimum cost per ML yield and right inset displays width of FSL at the minimum cost per ML yield. See companion technical report on surface water storage (Petheram et al., 2017) for more information.

Hydro-electric power generation potential in the Darwin catchments

The potential for major instream dams to generate hydro-electric power is presented in Figure 5-27, following an assessment of more than 20 million potential dam sites in the Darwin catchments (Petheram et al., 2017). This figure provides indicative estimates of hydro-electric power generation potential but does not consider the existence of supporting infrastructure.
Costs are based on unit rates and quantity of material required for a RCC dam with a flood design of 1 in 10,000. Cost includes site establishment, fish ladders and land resumption for that area of land impounded by a flood event of annual exceedance probability 1%. Data are underlain by a shaded relief map. For more details see companion technical report on surface water storage (Petheram et al., 2017).

**Pre-feasibility-level assessment of potential major dams in the Darwin catchments**

Seven potential dam sites in the Darwin catchments were examined as part of this pre-feasibility assessment. They are summarised in Table 5-14 and Table 5-15.
Table 5-14 Potential dam sites in the Darwin catchments examined as part of the Assessment

All numbers have been rounded.

<table>
<thead>
<tr>
<th>NAME</th>
<th>DAM TYPE†</th>
<th>SPILLWAY HEIGHT ABOVE BED (m)‡</th>
<th>CAPACITY AT FSL (GL)</th>
<th>CATCHMENT AREA (km²)</th>
<th>ANNUAL WATER YIELD (GL)§</th>
<th>CAPITAL COST* (MILLION $)</th>
<th>UNIT COST†† (ML$)</th>
<th>ANNUAL EQUIVALENT UNIT COST ‡‡ ($/ML/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mount Bennett dam site on the Finniss River</td>
<td>RCC</td>
<td>20</td>
<td>343</td>
<td>1155</td>
<td>283</td>
<td>190</td>
<td>671</td>
<td>50</td>
</tr>
<tr>
<td>Upper Adelaide River dam site</td>
<td>RCC</td>
<td>23</td>
<td>298</td>
<td>616</td>
<td>153</td>
<td>182</td>
<td>1190</td>
<td>88</td>
</tr>
<tr>
<td>Acacia Gap dam site</td>
<td>EB</td>
<td>11</td>
<td>37</td>
<td>232</td>
<td>29</td>
<td>132</td>
<td>4452</td>
<td>337</td>
</tr>
<tr>
<td>AROWS</td>
<td>EB</td>
<td>18</td>
<td>68</td>
<td>34§§</td>
<td>54**</td>
<td>138§</td>
<td>2548</td>
<td>203***</td>
</tr>
<tr>
<td>Marrakai dam site on the Adelaide River</td>
<td>EB</td>
<td>15</td>
<td>1520</td>
<td>4341</td>
<td>861</td>
<td>855‡‡‡</td>
<td>992</td>
<td>73</td>
</tr>
<tr>
<td>McKinlay River dam site</td>
<td>EB</td>
<td>14</td>
<td>512</td>
<td>922</td>
<td>158</td>
<td>492</td>
<td>3114</td>
<td>231</td>
</tr>
<tr>
<td>Mary River dam site</td>
<td>RCC</td>
<td>30</td>
<td>1311</td>
<td>3063</td>
<td>492</td>
<td>756</td>
<td>1537</td>
<td>114</td>
</tr>
</tbody>
</table>

†Embarkment dam (EB), roller compacted concrete dam (RCC).
‡The height of the dam abutments and saddle dams will be higher than the spillway height.
§Water yield is based on 85% annual time-based reliability using a perennial demand pattern for the baseline river model under historical climate and current development. This is yield at the dam wall (i.e. does not take into account distribution losses or downstream transmission losses). These yield values do not take into account downstream existing entitlement holders or environmental considerations.
*Indicates manually derived preliminary cost estimate, which is likely to be –10% to +30% of ‘true cost’. □ indicates modelled preliminary cost estimate, which is likely to be –20% to +50% of ‘true’ cost. Should site geotechnical investigations reveal unknown unfavourable geological conditions, costs could be substantially higher.
††This is the unit cost of annual water supply and is calculated as the capital cost of the dam divided by the water yield at 85% annual time reliability.
‡‡Assumes a 7% real discount rate and a dam service life of 100 years. Includes operation and maintenance costs, assuming operation and maintenance costs are 0.4% of the total capital cost.
§§Catchment area of offstream storage only. Catchment area of Adelaide River at point of extraction is approximately 4500 km².
**Based on a 26 m³/s pump capacity at Adelaide River, 20:80 rule, 1 m³/s pumping threshold and extraction only permitted during the falling limb of the hydrograph. Yield at the dam wall at 95% annual time reliability is 47 GL.
†‡Includes cost of pumping water from Adelaide River into the reservoir.
†‡‡The original modelled cost ($657 million) was inflated by a nominal 30% to better reflect the likely additional costs of constructing a dam at a site with the poor foundation conditions, the additional costs involved for protecting the construction site from flooding (e.g. levees protecting the construction site) and the complex logistical challenges of constructing a large dam at this site.

Table 5-15 Summary comments for potential dams in the Darwin catchments

<table>
<thead>
<tr>
<th>NAME</th>
<th>SUMMARY COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mount Bennett dam site on the Finniss River</td>
<td>This site has the lowest cost to yield ratio of all potential dam sites in the Darwin catchments. However, the yield from the dam is likely to be larger than that required to meet Darwin’s projected water requirements over the next 30 years and for irrigation of the suitable land downstream. The quality of water flowing into the reservoir could be a potential problem because of the existence of the (closed) Rum Jungle uranium mine in the upper reaches of the catchment. Additionally, part of the Wagait Aboriginal Reserve would be inundated by a storage at this site. There are a number of registered and/or recorded sacred or cultural heritage sites known to exist in the area that would be potentially inundated. Substantial land in the area is subject to current or future native title claim.</td>
</tr>
<tr>
<td>Upper Adelaide River dam site</td>
<td>The upper Adelaide River dam site, also known as the Warrai site, is the most topographically favourable site for a dam in the Darwin catchments. It has the third lowest cost to yield ratio of all the potential dam sites in the Darwin catchments. The yield from the dam could augment Darwin’s future water demand via a supply pipeline as well as irrigate all of the land suitable for irrigated agriculture downstream of Adelaide River township and upstream of Dirty Lagoon, south of the Arnhem Highway. A recent strategy statement by the NT Land and Water Corporation concluded that of the three storage sites endorsed by the Northern Territory Government in 1988 (upper Adelaide River dam site, Marrakai dam site and Mount Bennett dam site), an Upper Adelaide River storage was preferred by the NT Land and Water Corporation since the site is the only one for which the catchment can be closed to the public, thereby reducing the level of treatment required to achieve a potable water supply.</td>
</tr>
<tr>
<td>NAME</td>
<td>SUMMARY COMMENT</td>
</tr>
<tr>
<td>------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>NAME</strong></td>
<td><strong>SUMMARY COMMENT</strong></td>
</tr>
<tr>
<td>Acacia Gap dam site</td>
<td>There are a number of registered and/or recorded sacred or cultural heritage sites known to exist in the area that would potentially be inundated. Substantial land in the area is subject to current or future native title claim.</td>
</tr>
<tr>
<td>AROWS</td>
<td>The AROWS proposal would see the storage filled by pumped diversions from the Adelaide River. This site has one of the higher cost to yield ratios of all of the potential sites in the Darwin catchments, and the highest annualised cost per ML of yield. It does, however, have various advantages over other sites as it is an offstream storage. It will not, for example, impede the movement of migratory fish species. Subject to the outcomes of further studies, NT Power and Water considers that the AROWS is the preferred medium- to long-term option to meet the water supply needs of the Darwin catchments.</td>
</tr>
<tr>
<td>Marrakai dam site on the Adelaide River</td>
<td>In 1988 this site was listed as one of three preferred storage sites adopted by the then Northern Territory Government. In 1990, the NT Cabinet approved acquisition of properties affected by the potential inundation area. The land was acquired and is currently leased for a range of low impact uses. The potential yield from a dam at this site is likely to far exceed the future demand for water from Darwin and the amount of land downstream that could potentially be irrigated. Given the very high construction risks, poor foundation conditions and the likely environmental issues involved with construction and operating a dam at this site, it was not short-listed for further consideration.</td>
</tr>
<tr>
<td>McKinlay River dam site</td>
<td>Relative to other sites in the Darwin catchments, this site is remote and would be expensive to construct relative to its potential yield due to the width of the main wall and uncertain foundation conditions. For these reasons it was not short-listed for further consideration.</td>
</tr>
<tr>
<td>Mary River dam site</td>
<td>This site offers the second highest yield of the options considered in the Darwin catchments. However, given the width of the site and the high costs of access and construction as well as potential impacts on the Mount Bundy military training area and the Kakadu and Mary national parks, this site was not short-listed for further consideration.</td>
</tr>
<tr>
<td>Manton Dam</td>
<td>Manton Dam is a small existing dam currently only used for recreational purposes. PWC have identified that their short-term water supply risks (to 2020) will be most effectively managed by the return to service of Manton Dam in combination with their Living Water Smart demand management strategy. Water quality studies indicate that significant water treatment would be necessary for the water from Manton Dam to be potable.</td>
</tr>
<tr>
<td>Darwin River Dam</td>
<td>Current annual demand for water in the Darwin catchments (i.e. between about 40–45 GL) is approaching the current water supply system yield. Of Darwin’s water, 85% is supplied by Darwin River Dam, the other 15% is sourced from the McMinns and Howard East borefields. PWC is currently investigating short- and medium-term supply augmentation options. The Darwin River Dam storage level was raised in 2010, as a short-term option at the time. There is limited opportunity to increase the yield from the Darwin River Dam by further raising the wall. Future annual water demand to 2065 is projected to be about 50 to 60 GL depending upon assumptions regarding population growth and the success of demand management programs (e.g. Living Water Smart).</td>
</tr>
</tbody>
</table>

The investigation of a potential large dam site generally involves an iterative process of increasingly detailed studies over a period of years, occasionally over as few as 2 or 3 years but often over 10 or more years. It is not unusual for the cost of the geotechnical investigations for a potential dam site alone to exceed several million dollars. For any of the options listed in this report to advance to construction, far more comprehensive studies would be needed, including geotechnical investigations, field measurements of sediment yield, archaeological surveys and ground-based vegetation and fauna surveys. Studies at that detail are beyond the scope of this regional-scale resource assessment. The companion technical report on surface water storage (Petheram et al., 2017) outlines the key stages in investigation of design, costing and construction of large dams. More comprehensive descriptions are provided by Fell et al. (2005).
Pre-feasibility-level hydro-electric power assessment

Two of the eight potential dam sites in the Darwin catchments selected for pre-feasibility analysis (Table 5-14 and Table 5-15) were also selected for a pre-feasibility-level hydro-electric power assessment (Figure 5-27). These are the upper Adelaide River dam site on the Adelaide River and Mount Bennett dam site on the Finniss River. Although the potential for hydro-electric power generation was not specifically considered in the original selection of the eight pre-feasibility sites, as illustrated in the hydro-electric power opportunity map presented in Figure 5-27, these sites are nonetheless some of better sites for hydro-electric power generation in the Darwin catchments.

Results of the pre-feasibility-level hydro-electric power assessment are presented for two release patterns:

- energy generation from irrigation releases
- energy generation with the dam operating as a hydro-electric power storage dam only.

Energy generation under the two release patterns is presented in Table 5-16 for two design discharge values. The design discharge values are based on the:

- 10th percent exceedance of daily inflows (P10)
- 30th percent exceedance of daily inflows (P30).

Capital expenditure (CAPEX) and operational expenditure (OPEX) for each design discharge includes the cost of the penstock, power plant and turbine generators, substation and (66 kV) transmission lines to interconnect to the nearest connection point on the NT distribution grid. The upper Adelaide River and Mount Bennett potential dam sites are located near existing distribution substations, which could be potential connection points pending capacity enquiries.

Further detail on the pre-feasibility hydro-electric power assessment is provided in the companion technical report on hydropower (Entura, 2017).

Table 5-16 Summary of pre-feasibility-level hydro-electric power assessment for two sites in the Darwin catchments

CAPEX is the capital expenditure, which includes the cost of the penstock, power plant and turbine generators, substation and (66 kV) transmission lines, but not the RCC dam. OPEX is the operational expenditure of the hydro-electric power infrastructure. For further detail see companion technical report on hydropower (Entura, 2017).

<table>
<thead>
<tr>
<th>POTENTIAL DAM SITE</th>
<th>PARAMETER</th>
<th>UNIT</th>
<th>P10 DESIGN DISCHARGE</th>
<th>P30 DESIGN DISCHARGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mount Bennett</td>
<td>Rated discharge</td>
<td>m³/s</td>
<td>47.9</td>
<td>8.9</td>
</tr>
<tr>
<td></td>
<td>Installed capacity</td>
<td>MW</td>
<td>4.4</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>Power generation under hydro-electric power release pattern</td>
<td>MWh</td>
<td>14,607</td>
<td>7,576</td>
</tr>
<tr>
<td></td>
<td>Power generation under irrigation release pattern</td>
<td>MWh</td>
<td>3,931</td>
<td>3,396</td>
</tr>
<tr>
<td></td>
<td>CAPEX</td>
<td>$ million</td>
<td>33.2</td>
<td>16.2</td>
</tr>
<tr>
<td></td>
<td>OPEX</td>
<td>$/y</td>
<td>695,395</td>
<td>185,102</td>
</tr>
<tr>
<td></td>
<td>Cost per MW</td>
<td>$ million/MW</td>
<td>7.5</td>
<td>16.2</td>
</tr>
</tbody>
</table>
The NT is not connected to the National Electricity Market (NEM), however, annual revenues for indicative hydro-electric power generation were calculated based on a lower bound ($60/MWh) and an upper bound ($90/MWh) of prices paid to generators in Queensland under the Australian Energy Market arrangements in 2017 (Table 5-17). Of the two potential dam sites investigated in the Darwin catchments the Mount Bennett dam site on the Finniss River had the largest generation potential, where approximately 14,600 MWh could be generated if the dam operated exclusively for hydro-electric power generation (Table 5-16). Revenue streams under a hydro-electric power release pattern, assuming the upper bound price of $90/MWh, would be $1.3 million/year (Table 5-17). With a total capital cost of dam ($190 million) and hydro-electric power infrastructure ($33.2 million) of $223 million, the total capital costs would be 172 times the annual revenue. This indicates that hydro-electric power generation under this set of conditions would not be fully commercial unless there was a substantial increase in the price paid to generators.

Under the irrigation release pattern and assuming the upper bound price of $90/MWh, approximately 3400 MWh could be generated under a P30 design discharge. If the cost of the dam was wholly attributed to irrigation the ratio of the cost of hydro-electric power infrastructure ($16 million) to revenue ($0.3 million) is 52.

Table 5-17 Indicative hydro-electric power generation revenues for two potential sites in the Darwin catchments
Assumes a P10 design discharge. Revenues have nominally been estimated for power prices at $60/MWh and at $90/MWh. These prices reflect the prices paid to Queensland generators under the Australian Energy Market in 2017.

<table>
<thead>
<tr>
<th>POTENTIAL DAM SITE (DESIGN DISCHARGE)</th>
<th>ANNUAL REVENUE AT $60/MWh</th>
<th>ANNUAL REVENUE AT $90/MWh</th>
<th>CAPITAL COST OF HYDRO-ELECTRIC POWER STATION† ($ million)</th>
<th>CAPITAL COST OF DAM ($ million)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hydro-electric power release pattern</td>
<td>Irrigation release pattern</td>
<td>Hydro-electric power release pattern</td>
<td>Irrigation release pattern</td>
</tr>
<tr>
<td>Mount Bennett (P10)</td>
<td>0.9</td>
<td>0.2</td>
<td>1.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Mount Bennett (P30)</td>
<td>0.5</td>
<td>0.2</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Upper Adelaide River (P10)</td>
<td>0.8</td>
<td>0.3</td>
<td>1.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Upper Adelaide River (P30)</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
<td>0.2</td>
</tr>
</tbody>
</table>

*Cost includes the cost of the power station at the dam and connection to the grid.
Other considerations

Ecological considerations of the dam wall and reservoir

The water impounded by a major dam inundates an area of land, drowning not only instream habitat but surrounding flora and fauna communities. Complex changes in habitat resulting from inundation could create new habitat to benefit some of these species (Figure 5-28), while other species would be affected by loss of habitat.

For instream ecology, the dam wall acts as a barrier to movements of plants, animals and nutrients, potentially disrupting connectivity of populations and ecological processes. There are many studies linking water flow with nearly all the elements of instream ecology in freshwater systems (e.g. Robins et al., 2005). The impact of major dams on the movement and migration of aquatic species will depend upon the relative location of the dam walls in a catchment. For example, generally a dam wall in a small headwater catchment will have less of an impact on the movement and migration of species than a dam lower in the catchment.

A dam also creates a large, deep lake, a habitat that is in stark contrast to the usually shallow and often flowing habitats it replaces. This lake-like environment favours some species over others and will function completely differently to natural rivers and streams. The lake-like environment of an impoundment is often used by sports anglers to augment natural fish populations by artificial stocking. Whether fish stocking is a benefit of dam construction is a matter of debate and point-of-view. Stocked fisheries provide a welcome source of recreation and food for fishers, and no doubt an economic benefit to local businesses, but they have also created a variety of ecological challenges. Numerous reports of disruption of river ecosystems (e.g. Drinkwater and Frank, 1994; Gillanders and Kingsford, 2002) highlight the need for careful study and regulatory management. Impounded waters may be subject to unauthorised stocking of native fish and releases of exotic flora and fauna.

Further investigation of any of these potential dam sites would typically involve a thorough field investigation of vegetation and fauna communities.

Potential changes to instream, riparian and near-shore marine species arising from changes in flow are discussed in Section 7.2.

Sedimentation

Rivers carry fine and coarse sediment eroded from hill slopes, gullies, banks and sediment stored within the channel. The delivery of this sediment into a reservoir can potentially be a problem because it can progressively reduce the volume available for active water storage. The deposition of coarser grained sediments in backwater (upstream) areas of reservoirs can also cause backflooding beyond the flood limit originally determined for the reservoir.

Although infilling of the storage capacity of smaller dams has occurred in Australia (Chanson, 1998), these dams had small storage capacities, and infilling of a reservoir is generally only a potential problem where the volume of the reservoir is small relative to the catchment area. Sediment yield is strongly correlated to catchment area (Wasson, 1994; Tomkins, 2013). Sediment yield to catchment area relationships developed for northern Australia (Tomkins, 2013) were found to predict lower sediment yield values than global relationships. This is not unexpected...
given the antiquity of the Australian landscape (i.e. it is flat and slowly eroding under ‘natural’ conditions).

Using the relationships developed by Tomkins (2013) potential major dams in the Darwin catchments were estimated to have about 1% or less sediment infilling after 30 years and less than 3% sediment infilling after 100 years.

**Cultural heritage considerations**

Indigenous people traditionally situated their campsites and subsistence activities along major watercourses and drainage lines. Consequently, dams are more likely to impact on areas of high cultural significance than most other infrastructure developments (e.g. irrigation schemes, roads).

No field-based cultural heritage investigations of potential dam and reservoir locations were undertaken in the Darwin catchments as part of the Assessment. However, based on existing records and statements from Indigenous participants in the Assessment, it is highly likely such locations will contain significant heritage sites of cultural, historical and wider scientific significance. There is insufficient information relating to the cultural heritage values of the potential major dam sites to allow full understanding or quantification of the likely impacts of water storages on Indigenous cultural heritage.

The cost of cultural heritage investigations associated with dam sites is high relative to other development activities.

**Cumulative yield of multiple dams in the Darwin catchments**

The combined or cumulative yield of multiple dams in the Darwin catchments is shown in Figure 5-29. Here it is shown that the total divertible yield, before losses, from four of the more promising potential dam sites was about 1100 GL in 85% of years at the dam wall and would cost approximately $1.6 billion. The construction cost per ML of yield increased from about $600/ML with the first potential dam site (i.e. Mount Bennett) to $1600/ML for all four dams.

*Figure 5-28 Magpie geese on the Darwin River Dam spillway*

*Photo: CSIRO*
Figure 5-29 Cost of water in $/ML versus cumulative divertible yield at 85% annual time reliability and change in flow at the end-of-system in the Darwin catchments
(a) Yield at the dam wall versus cost of water at the dam wall under historical climate and future development and (b) yield after river, channel (10%), on-farm (10%) and field application (15%) losses (i.e. equivalent to the amount of water available to go through the plant) versus cost of water after losses under historical climate and future development. Plot (b) is indicative of the amount of water that may be available to go through the plant. Triangles indicate combined water yield at 85% annual time reliability of one or more dams, with the colour of the dot indicating the most recently included dam in the cumulative yield calculation. Squares indicate change in (a) median and (b) mean annual streamflow at the end-of-system from the baseline (i.e. under the historical climate and current development) from the Finniss River catchment, Adelaide River catchment and Mary River catchment.

Two selected potential dam sites in the Darwin catchments

Two of the more promising potential dam sites on different rivers are summarised here. These sites were selected because they are the highest yielding and most cost effective, and are close to large continuous areas of land suitable for irrigated agriculture or for use in the Darwin area. Previous investigations of these sites date back to SMEC (1979), Gibb (1981, 1982), GHD (1988) and Paiva (1991, 1992) and were preliminary in nature. More detailed descriptions of the seven sites selected for pre-feasibility assessment and the two existing major dams in the Darwin catchments are provided in the companion technical report on surface water storage (Petheram et al., 2017).

Upper Adelaide River dam site on the Adelaide River

The upper Adelaide River dam site, also known as the Warrai site, is the most topographically favourable site for a dam in the Darwin catchments. The yield from the dam could augment Darwin’s future water demand via a supply pipeline as well as irrigate land suitable for irrigated agriculture downstream of Adelaide River township and upstream of Dirty Lagoon, south of the Arnhem Highway.

The original proposal in 1988 was for a concrete-faced rockfill dam with a spillway excavated through a right bank saddle. A RCC dam with a 180-m wide central overflow spillway is outlined here as it offers several advantages over embankment structures (Figure 5-30). A hydraulic jump-type stilling basin would be provided to protect the river bed against erosion during spillway overflows. A diversion conduit on the left bank side is proposed in which permanent outlets would be installed. This would provide for releases to the river and for a pipeline connection to a
downstream pump station and delivery main conveying supply to the Darwin area. Both the main dam abutments and the saddle dam crest have been set at the probable maximum flood peak storage level given the significant risk to the population downstream of the dam.

The full supply level with the highest yield to cost ratio was at 80 mEGM96, approximately 23 m above the river bed. At the upper Adelaide River dam site a RCC dam with a FSL 80 mEGM96 would cost approximately $182 million and yield 153 GL in 85% of years (Figure 5-32).

A dam at the upper Adelaide River site at the nominated FSL would result in little change to the area inundated downstream (5% reduction in peak inundated area) during small flood events (Figure 5-33a) and would result in negligible change under a moderate event (1% reduction in peak inundated area) (Figure 5-33b).

Creation of a barrier may limit movement, migration or colonisation of habitat by fish species (Section 3.2). Upstream of the potential barrier are some locality records of magpie geese and 16 species of water-nesting birds (Figure 5-31). Within the potential inundation area of this site there are no records of migratory or stable flow spawning fish. However, three endangered species are listed under the Territory Parks and Wildlife Conservation Act (NT), the critically endangered northern quoll (*Dasyurus hallucatus*), the vulnerable red goshawk (*Erythrotriorchis radiates*) and the partridge pigeon (*Geophaps smithii*). Each could be affected by loss of habitat as a result of inundation by the reservoir.

Substantial land in the area is subject to current or future native title claims. Several registered and/or recorded sacred and cultural heritage sites are known to exist in the inundation area. There is a high likelihood of currently unrecorded sites. The inundation area also includes a portion of Litchfield National Park.

![Figure 5-30 The upper Adelaide River dam site on the Adelaide River looking upstream](Photo: CSIRO)
Figure 5-31 Migratory fish and water-dependent birds in the vicinity of the potential upper Adelaide River dam site
FSL = full supply level.

Figure 5-32 The upper Adelaide River dam site on the Adelaide River: cost, yield at the dam wall and evaporation
(a) Dam length and dam cost versus full supply level (FSL) and (b) dam yield at 85% and 95% annual time reliability and
yield/$ million at 85% and 95% annual time reliability.
Mount Bennett dam on the Finniss River

The Mount Bennett dam site is located where the Finniss River cuts a relatively narrow gorge through the Finniss Range, approximately 107 km by road from Darwin. The proximity of the Mount Bennett potential dam site to Darwin and the Darwin River Dam make it attractive for urban water supply. However, a major limitation to using water from the potential reservoir is that the catchment area cannot be closed to the public, thereby increasing the level of treatment required to achieve a potable water supply. Furthermore, the quality of water flowing into the reservoir could be adversely affected by the existence of the (closed) Rum Jungle uranium mine located approximately 28 km upstream of the site.

It was originally proposed that a concrete-faced rockfill embankment be constructed across the main river section with a conventional concrete gravity dam incorporating a central overflow spillway constructed in the section on the northern side of the storage area known as Breakneck Pass. However, given the larger spillway capacities now required due to changes in methods of flood design, a RCC dam across the river section and a zoned earth and rockfill embankment at the Breakneck Pass saddle are outlined (Figure 5-34). The abutments would be set at the 1:10,000 annual exceedance probability (AEP) peak storage level. A hydraulic jump-type stilling basin would be provided to protect the river bed against erosion during spillway overflows. A number of low embankment saddle dams are required on the southern side of the storage. The crest level of the Breakneck Pass embankment and of the saddle dams has been set to contain the peak storage level of a 1:50,000 AEP flood. If supply to the Darwin area was required, a conduit could be constructed under the Breakneck Pass saddle dam with an intake tower in the storage with bulkhead gate control. A pump station could be located at the downstream toe of the saddle dam. Releases downstream of the dam would be via outlets installed in a diversion conduit located in the right abutment of the dam. A fish transfer facility would also be located on the right abutment.

A manual cost estimate undertaken as part of the Assessment for a RCC dam at the Mount Bennett dam site at FSL 28 mEGM96 (mEGM96 is the datum of the Shuttle Radar Terrain Mission...
digital elevation model) found the dam would cost approximately $190 million and yield 283 GL in 85% of years (Figure 5-36).

A dam at the Mount Bennett dam site at the nominated FSL would moderately alter the area inundated downstream (24% reduction in peak inundated area) during small flood events (Figure 5-37a) and would result in small changes (13% reduction in peak inundated area) during moderate flood events (Figure 5-37b).

Substantial land in the area is held as a collective and inalienable freehold title under NT-specific land rights legislation. Substantial land is also subject to future native title claims. Several registered and/or recorded sacred or cultural heritage sites are known to exist in the inundation area. There is a high likelihood of unrecorded sites occurring in the area.

At this site only one vulnerable species was listed, the partridge pigeon. A dam constructed at this site could affect the migration, movement or colonisation of a number of fish species (Section 3.2) and negatively impact important wetlands, habitat of the magpie goose and several other waterbirds such as egrets, spoonbills and herons downstream of the Finniss River. A reservoir at this site could directly impact other waterbirds (Figure 5-35). Complex changes in habitat resulting from inundation could create new habitat to benefit some of these species, while other species would be affected by loss of habitat.
Figure 5-35 Migratory fish and water-dependent birds in the vicinity of the potential Mount Bennett dam site
FSL = full supply level; GDE = groundwater-dependent ecosystem.

Figure 5-36 Mount Bennett dam site on the Finniss River: cost, yield at the dam wall and evaporation
(a) Dam length and dam cost versus full supply level (FSL) and (b) dam yield at 85% and 95% annual time reliability and yield/$ million at 85% and 95% annual time reliability.
5.3.3 WEIRS AND RE-REGULATING STRUCTURES

Re-regulating structures, such as weirs, are typically located downstream of large dams. They allow for more efficient releases from the storages and for some additional yield from the weir storage itself, thereby reducing the transmission losses normally involved in supplemented river systems.

As a rule of thumb, however, weirs are constructed to half to two-thirds of the river bank height. This height allows the weirs to achieve maximum capacity, while ensuring the change in downstream hydraulic conditions does not result in excessive erosion of the toe of the structure. It also ensures that large flow events can still be passed without causing excessive flooding upstream.

Broadly speaking, there are two types of weir structure: concrete gravity type weirs and sheet piling weirs. These are discussed below. For each type of weir, rock-filled mattresses are often used on the stream banks, extending downstream of the weir to protect erodible areas from flood erosion. A brief discussion on sand dams is also provided.

Weirs, sand dams and diversion structures obstruct the movement of fish in a similar way to dams during the dry season.

Concrete gravity type weirs

Where rock bars are exposed at bed level across the stream, concrete gravity type weirs have been built on the rock at numerous locations across Queensland. This type of construction is less vulnerable to flood erosion damage both during construction and in service.

Assuming favourable foundation conditions the cost of a 6-m high and 400-m wide concrete gravity weir is estimated to be approximately $23 million. This includes a fish lock ($1 million), bank protection ($850,000) and outlet works ($500,000), investigation and design ($650,000), on-
site overheads ($2 million) and risk adjustment ($5.6 million). It does not include acquisition and approval costs.

**Sheet piling weirs**

Where rock foundations are not available, stepped steel sheet piling weirs have been successfully used in many locations across Queensland. These weirs consist of parallel rows of steel sheet piling, generally about 6 m apart with a step of about 1.5 to 1.8 m high between each row. Reinforced concrete slabs placed between each row of piling absorb much of the energy as flood flows cascade over each step. The upstream row of piling is the longest, driven to a sufficient depth to cut off the flow of water through the most permeable material (Figure 5-38). Indicative costs are provided in Table 5-18.

![Figure 5-38 Schematic cross-section diagram of sheet piling weir](source: Petheram et al. (2013))

**Table 5-18 Estimated construction cost of 3-m high sheet piling weir**

<table>
<thead>
<tr>
<th>WEIR CREST LENGTH (m)</th>
<th>ESTIMATED CAPITAL COST ($ million)</th>
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**Sand dams**

Because many of the large rivers in northern Australia are very wide (e.g. >300 m), weirs are likely to be impractical and expensive at many locations. An alternative structure is sand dams, which are low embankments built of sand on the river bed. They are constructed at the start of each dry season during periods of low or no flow when heavy earth moving machinery can access the bed of the river. They are constructed to form a pool of depth sufficient to enable pumping (i.e. typically greater than 4 m depth), and are widely used in the Burdekin River near Ayr in Queensland, where the river is too wide to construct a weir.

Typically, sand dams take three to four large excavators about two to three weeks to construct and no further maintenance is required until they need to be reconstructed again after the wet season. Bulldozers can construct a sand dam quicker than a team of excavators but have greater
access difficulties. Because sand dams only need to form a pool of sufficient size and depth from which to pump water, they usually only partially span a river and are typically constructed immediately downstream of large, naturally formed waterholes.

The cost of 12 weeks of hire for a 20-tonne excavator and float (i.e. transportation) is approximately $80,000. Although sand dams are cheap to construct relative to a weir, they require annual rebuilding and have very high seepage losses beneath and through the dam wall. No studies are known to have quantified losses from sand dams.

The application of sand dams in the Darwin catchments is likely to be limited.

5.3.4 LARGE FARM-SCALE RINGTANKS

Large farm-scale ringtanks are usually fully enclosed circular earthfill embankment structures constructed close to major watercourses/rivers so as to minimise the cost of pumping infrastructure by ensuring long ‘water harvesting’ windows. For this reason they are often subject to reasonably frequent inundation, usually by slow-moving flood waters. In some exceptions embankments may not be circular; rather, they may be used to enhance the storage potential of natural features in the landscape such as horseshoe lagoons or cut-off meanders adjacent to a river (see Section 5.3.6 for discussion on extracting water from persistent waterholes).

An advantage of ringtanks over gully dams is that the catchment area of the former is usually limited to the land that it impounds, so costs associated with spillways, failure impact assessments and constructing embankments to withstand flood surges are considerably less than large farm-scale gully dams. Another advantage of ringtanks is that unless a diversion structure is utilised in a watercourse to help ‘harvest’ water from a river, a ringtank and its pumping station do not impede the movement of aquatic species or transport of sediment in the river. Ringtanks also have to be sited adjacent to major watercourses to ensure there are sufficient days available for pumping. While this limits where they can be sited, it means that because they can be sited adjacent to major watercourses (on which gully dams would be damaged during flooding – large farm-scale gully dams are typically sited in catchments less than 30 km²), they often have a higher reliability of being filled each year than gully dams. However, operational costs of ringtanks are usually higher than gully dams because water must be pumped into the structure each year from an adjacent watercourse, typically using diesel powered pumps (solar and wind energy do not generate sufficient power to operate high volume axial flow or ‘china’ pumps). Even where diversion structures are utilised to minimise pumping costs, the annual cost of excavating sediment and debris accumulated in the diversion channel can be in the order of tens of thousands of dollars.

For more information on ringtanks in the Darwin catchments, refer to the companion technical reports on surface water storage (Petheram et al., 2017), large farm-scale dams (Benjamin, 2018) and river model simulation (Hughes et al., 2018). A rectangular ringtank in the Flinders catchment (Queensland) is pictured in Figure 5-39.

In this section, the following assessments of ringtanks in the Darwin catchments are reported:

- suitability of the landscape for large farm-scale ringtanks
- reliability with which water can be extracted from different reaches
• indicative evaporative and seepage losses from large farm-scale ringtanks
• indicative capital, operating and maintenance costs of large farm-scale ringtanks.

Figure 5-39 Rectangular ringtank and 500 ha of cotton in the Flinders catchment (Queensland)
Channel along which water is diverted from the Flinders River to the ringtank can be seen in foreground.
Photo: CSIRO

Suitability of land for ringtanks in the Darwin catchments

Figure 5-40 displays the broad-scale suitability of large farm-scale ringtanks in the Darwin catchments. Approximately 10% of the Darwin catchments are classed as being suitable, though the majority of this land (>80%) is located on the coastal plains of the Reynolds, Finniss, Adelaide, Mary and Wildman rivers. These areas are particularly susceptible to flooding (Figure 2-41) and the soils are typically too wet to grow crops using heavy machinery. Elsewhere and less flood prone to flooding, the largest contiguous area of land suitable for offstream storages lies adjacent to the McKinlay River south (i.e. upstream) of the Arnhem Highway. Narrower areas of land suitable for farm-scale offstream storages lie adjacent to the Adelaide and Margaret rivers in the Adelaide catchment, south (upstream) of the Arnhem Highway. The remaining land in the Darwin catchments has soils that are too shallow and/or sandy to be suitable for ringtank construction.
Figure 5-40 Suitability of large farm-scale ringtanks in the Darwin catchments
Soil and subsurface data were only available to a depth of 1.5 m, hence the Assessment does not consider the suitability of subsurface material below this depth. This figure does not take into consideration the availability of water. Data are overlaid on a shaded relief map. The results presented in this figure are only indicative of where suitable locations for siting a ringtank may occur and site-specific investigations by a suitably qualified professional should always be undertaken prior to their construction.

Reliability of water extraction
The reliability at which an allocation or volume of water can be extracted from a river depends upon a range of factors including:

- the quantity of discharge and the natural inter- and intra-variability within a river system (Section 2.5.5)
- the capacity of the pumps or diversion structure (expressed here as the number of days taken to pump an allocation)
- the quantity of water being extracted by other users and their location
- conditions associated with a licence to extract water, such as:
  - a minimum threshold at which pumping can commence (pump start threshold)
— an end-of-system flow requirement, the minimum flow that must pass the lowest gauge in the system before pumping can commence.

Licence conditions can be imposed on a potential water user to ensure downstream entitlement holders are not impacted by new water extractions and to minimise environmental change that may arise from perturbations to streamflow. In some cases a pump start threshold is a physical threshold below which it is difficult to pump water from a natural pumping pool.

Figure 5-41 can be used to explore the reliability at which increasing volumes of water can be extracted ('harvested') in the Finniss, Adelaide and Mary catchments (a through g) under varying pump start thresholds, pump capacities and an end-of-system flow requirement at the lowermost streamflow gauge in each catchment. The impact of an end-of-system flow requirement on extraction reliability is examined because it is the least complex environmental flow provision to regulate and police in remote areas. Within each river reach water could be harvested by one or more hypothetical water harvesters and the water nominally stored in ringtanks adjacent to the river reach. The locations of the hypothetical water harvesters illustrated in Figure 5-41 and their relative proportion of the total system allocation (left vertical axis) were assigned based on joint consideration of crop versatility, broad-scale flooding, ringtank suitability and river discharge. The allocation assigned to each reach is shown on the right vertical axis.

At the smallest pump start threshold examined, 200 ML/day (nominally representative of a physical pumping limit), approximately 600, 600 and 500 GL of water can be extracted in the Finniss, Adelaide and Mary catchments respectively in 85% of years depending upon the location (Figure 5-41). As the total system and reach allocations increase, the reliability at which each water harvester can extract their proportion of the system allocation decreases. For example, at location (d) water harvesters can extract about 120 GL of water in 90% of years, 140 GL in 80% of years and about 170 GL in 70% of years.

At a pump start threshold of 200 ML/day, the reliability of extraction decreases with decreasing pump capacity (i.e. increasing days to pump allocation). At high system allocations (i.e. >600 GL/year) the reliability of extraction decreases more steeply with a decrease in pump capacity because at higher extraction volumes there are fewer days above the pump start threshold for pumping.

A diesel powered axial flow pump is pictured in Figure 5-42.
Figure 5-41 Reliability of extracting water up to the annual system/reach entitlement volume for a selection of seven water harvesting users for a pump start threshold of 200 ML/day.
As the pump start threshold increases (Figure 5-43), the reliability of extracting a given system/reach allocation generally decreases. This is because the time over which pumping is permitted decreases. The reduction in reliability is particularly noticeable at low pump capacities.

Under conditions where 200 GL of water has to pass the lowest streamflow gauge in each catchment before pumping can commence in a given wet season (i.e. the end-of-system requirement is 200 GL), and for a pump start threshold of 200 ML/day, approximately 200, 400 and 200 GL/year can be extracted from each of the Finniss, Adelaide and Mary catchments respectively in 85% of years (Figure 5-44).

Figure 5-45 and Figure 5-46 show the 50% and 80% annual exceedance streamflow relative to Scenario A for a 200 ML/day pump start threshold and under a range of end-of-system (i.e. lowermost gauge) flow requirements. At location (c) in the Adelaide catchment it can be seen that for a system allocation of 600 GL/year and a pump rate of 10 days the median annual flow (i.e. 50% annual exceedance flow) in the river immediately downstream of this location is slightly less than 70% of the median annual flow under Scenario A (i.e. without development) (Figure 5-45). However, at the same location and same system allocation of 600 GL/year the 80% annual exceedance streamflow is approximately 40% of the 80% annual flow under Scenario A (Figure 5-46). Implementing a lowermost gauge flow requirement appears to have little effect on the median annual flow below the point of extraction under Scenario B. However, as the lowermost gauge flow requirement increases above about 300 GL/year the impact of extractions on the 80% annual flow exceedance value decreases sharply.

These results illustrate how water harvesting/extractions have greater impact on those years of low streamflow, unless lowermost gauge flow requirements are imposed, in which case there is a trade-off with the reliability with which water can be extracted.

Figure 5-42 Diesel powered axial-flow flood-harvesting pump in Flinders catchment
Photo: CSIRO
Figure 5-43 Reliability of extracting water up to the annual system/reach entitlement volume for a selection of seven water harvesting users for a pump start threshold of 600 ML/day
Figure 5-44 Reliability of extracting water up to an entitlement volume for a selection of seven water harvesting users for a pump start threshold of 200 ML/day and end-of-system flow requirement of 200 GL/year
Figure 5.45 50% annual exceedance (median) streamflow relative to Scenario A in the Darwin catchments for a pump start threshold of 200 ML/day and a pump capacity of 10 days.
Figure 5-46 80% annual exceedance streamflow relative to Scenario A in the Darwin catchments for a pump start threshold of 200 ML/day and a pump capacity of 10 days.
Evaporation and seepage losses

Losses from a farm-scale dam occur through evaporation and seepage. When calculating evaporative losses from farm dams it is important to calculate net evaporation (i.e. evaporation minus rainfall) rather than just evaporation. Strategies to minimise evaporation include liquid and solid barriers, but these are typically expensive per unit of inundated area (e.g. $10 to $30 per m²). In non-laboratory settings liquid barriers such as oils are susceptible to being dispersed by wind and have not been shown to reduce evaporation from a water body (Barnes, 2008). Solid barriers can be effective in reducing evaporation but are expensive, at approximately two to four times the cost of constructing the ringtank. Evaporation losses from a ringtank can also be reduced slightly by sub-dividing the storage into multiple cells and extracting water from each cell in turn so as to minimise the total surface water area. However, constructing a ringtank with multiple cells requires more earthworks and incurs higher construction costs than outlined in this section.

A study of 138 farm dams ranging in capacity from 75 to 14,000 ML from southern NSW to central Queensland by the Cotton Catchment Communities CRC (2011) found mean seepage and evaporation rates of 2.3 and 4.2 mm/day, respectively. Of the 138 dams examined, 88% had seepage values of less than 4 mm/day and 64% had seepage values less than 2 mm/day. These results largely concur with IAA (2007), which states that reservoirs constructed on suitable soils will have seepage losses equal to or less than 1 to 2 mm/day and seepage losses will be greater than 5 mm/day if sited on less suitable (i.e. permeable) soils.

Ringtanks with greater average water depth lose a lower percentage of their total storage capacity to evaporation and seepage losses, however, they have a smaller storage capacity to excavation ratio. In Table 5-19 effective volume refers to the actual volume of water that could be used for consumptive purposes after losses due to evaporation and seepage. For example, if water is stored in a ringtank with average water depth of 3.5 m until December and the average seepage loss is 2 mm/day, nearly half the stored volume (i.e. 44%) would be lost to evaporation and seepage. The example provided in Table 5-19 is for a 4000 ML storage but the effective volume expressed as a percentage of the ringtank capacity is applicable to any storage (e.g. ringtanks or gully dams) of any capacity for average water depths of 3.5, 6 and 8.5 m.
Effective volume refers to the actual volume of water that could be used for consumptive purposes as a result of losses due to net evaporation and seepage, assuming a storage capacity is 4000 ML. For storages of 4000 ML capacity and average water depths of 3.5, 6 and 8.5 m, reservoir surface areas are 110, 65 and 45 ha respectively. S:E ratio is the storage capacity to excavation ratio. For more details see companion technical report on surface water storage (Petheram et al., 2017).

Table 5-19 Effective volume after net evaporation and seepage for ringtanks of three average water depths and under three seepage rates at Wildman

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<td>75</td>
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<tr>
<td></td>
<td>7.5:1</td>
<td>5</td>
<td>3283</td>
<td>82</td>
<td>2862</td>
<td>72</td>
<td>2445</td>
<td>61</td>
</tr>
<tr>
<td>8.5</td>
<td>5:1</td>
<td>1</td>
<td>3724</td>
<td>93</td>
<td>3541</td>
<td>89</td>
<td>3420</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>5:1</td>
<td>2</td>
<td>3666</td>
<td>92</td>
<td>3455</td>
<td>86</td>
<td>3291</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>5:1</td>
<td>5</td>
<td>3494</td>
<td>87</td>
<td>3197</td>
<td>80</td>
<td>2903</td>
<td>73</td>
</tr>
</tbody>
</table>

†Average water depth above ground surface.

**Capital, operation and maintenance costs of ringtanks**

Construction costs of a ringtank may vary considerably depending on its size and the way the storage is built. For example, circular storages have a higher storage volume to excavation cost ratio than rectangular or square storages. As discussed in the section on large farm-scale gully dams (Section 5.3.5) it is also considerably more expensive to double the height of an embankment wall than double its length due to the low angle of the walls of the embankment (often at a ratio of 3 horizontal to 1 vertical).

Table 5-20 provides a high-level breakdown of the capital and operation and maintenance (O&M) costs of a large farm-scale ringtank, including the cost of the water storage, pumping infrastructure and up to 100 m of pipes, and operation and maintenance of the scheme. In this example it is assumed that the ringtank is within 100 m of the river and pumping infrastructure. The cost of pumping infrastructure and conveying water from the river to the storage is particularly site-specific.

In flood-prone areas where flood waters move at moderate-to-high velocities, riprap protection may be required, and this may increase the construction costs presented in Table 5-20 and Table 5-21 by 10 to 20% depending upon volume of rock required and proximity to a quarry with suitable rock.

For a more detailed breakdown of ringtank costs see the companion technical report on large farm-scale dams (Benjamin, 2018).
Table 5-20 Indicative costs for a 4000-ML ringtank
Assumes a 4.25-m wall height, 0.75-m freeboard, 3:1 ratio on upstream slope, 3:1 ratio on downstream slope and crest width of 3.1 m, approximately 60% of material can be excavated from within storage, and cost of earthfill and compacted clay is $5/m³ and $6.50/m³ respectively. Earthwork costs include vegetation clearing, mobilisation/demobilisation of machinery and contractor accommodation. For more detail on costs see the companion technical report on large farm-scale dams (Benjamin, 2018).

<table>
<thead>
<tr>
<th>SITE DESCRIPTION/CONFIGURATION</th>
<th>EARTHWORKS ($)</th>
<th>GOVERNMENT PERMITS AND FEES ($)</th>
<th>INVESTIGATION AND DESIGN FEES ($)</th>
<th>PUMP STATION ($)</th>
<th>TOTAL CAPITAL COST ($)</th>
<th>O&amp;M OF RINGTANK ($/y)</th>
<th>O&amp;M OF PUMP STATION ($/y)</th>
<th>TOTAL O&amp;M ($/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4000-ML ringtank</td>
<td>1,602,500</td>
<td>35,500</td>
<td>76,000</td>
<td>500,000</td>
<td>2,214,000</td>
<td>17,000</td>
<td>84,000</td>
<td>101,000</td>
</tr>
</tbody>
</table>

The capital costs can be expressed over the service life of the infrastructure (assuming a 7% discount rate, see Chapter 6) and combined with O&M costs to give an equivalent annual cost for construction and operation. This enables infrastructure with differing capital and operation and maintenance costs and service lives to be compared. The total equivalent annual costs for the construction and operation of a 1000-ML ringtank with 4.25-m high embankments and 55 ML/day pumping infrastructure is about $117,100 (Table 5-21). For a 4000-ML ringtank with 4.25-m high embankments and 160 ML/day pumping infrastructure, the total equivalent annual cost is about $284,500. For a 4000-ML ringtank with 6.75-m high embankments and 160 ML/day pumping infrastructure, the total equivalent annual cost is about $402,000.

Table 5-21 Annualised cost for the construction and operation of three ringtank configurations
Assumes freeboard of 0.75 m, pumping infrastructure can fill ringtank in 25 days and assumes a 7% discount rate. Costs based on those provided for 4000 ML provided in the companion technical report on large farm-scale dams (Benjamin, 2018).

<table>
<thead>
<tr>
<th>CAPACITY AND EMBANKMENT HEIGHT</th>
<th>ITEM</th>
<th>CAPITAL COST ($)</th>
<th>LIFESPAN (y)</th>
<th>EQUIVALENT ANNUAL CAPITAL COST ($)</th>
<th>ANNUAL O&amp;M COST ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 ML and 4.25 m</td>
<td>Ringtank</td>
<td>858,000</td>
<td>40</td>
<td>64,000</td>
<td>8,600</td>
</tr>
<tr>
<td></td>
<td>Pumping infrastructure</td>
<td>200,000</td>
<td>15</td>
<td>22,000</td>
<td>4,000</td>
</tr>
<tr>
<td></td>
<td>Pumping cost (diesel)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>18,500</td>
</tr>
<tr>
<td>4000 ML and 4.25 m</td>
<td>Ringtank</td>
<td>1,714,000</td>
<td>40</td>
<td>128,500</td>
<td>17,000</td>
</tr>
<tr>
<td></td>
<td>Pumping infrastructure</td>
<td>500,000</td>
<td>15</td>
<td>55,000</td>
<td>10,000</td>
</tr>
<tr>
<td></td>
<td>Pumping cost (diesel)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>74,000</td>
</tr>
<tr>
<td>4000 ML and 6.75 m</td>
<td>Ringtank</td>
<td>3,095,000</td>
<td>40</td>
<td>232,000</td>
<td>31,000</td>
</tr>
<tr>
<td></td>
<td>Pumping infrastructure</td>
<td>500,000</td>
<td>15</td>
<td>55,000</td>
<td>10,000</td>
</tr>
<tr>
<td></td>
<td>Pumping cost (diesel)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>74,000</td>
</tr>
</tbody>
</table>

NA = not available.

*Costs include rising-main, large-diameter concrete or multiple strings of high density polypipe, control valves and fittings, concrete thrust-blocks and head-walls, dissipater, civil works and installation.

†Value assumes water is piped between river pumping infrastructure and ringtank.

Although ringtanks with an average water depth of 3.5 m (embankment height of 4.25 m) lose a higher percentage of their capacity to evaporative and seepage losses than ringtanks of equivalent capacity with average water depth of 6 m (embankment height of 6.75 m) (Table 5-19), their
annualised unit costs are lower (Table 5-22) due to the considerably lower cost of constructing embankments with lower walls (Table 5-21).

In Table 5-22 the equivalent annual cost of the water supplied from the ringtank takes into consideration net evaporation and seepage from the storage, which increase with the length of time water is stored (i.e. crops with longer growing seasons will require water to be stored longer). In these tables, the results are presented for the equivalent annual cost of water yield from a ringtank of different seepage rates and lengths of time for storing water.

Table 5-22 Equivalent annual cost per ML for two different capacity ringtanks under three seepage rates
Assumes a 0.75-m freeboard, 3:1 ratio on upstream slope, 3:1 ratio on downstream slope. Crest widths are 3.1 m and 3.6 m for embankments with heights of 4.25 m and 6.75 m respectively and assumes earthfill and compacted clay costs $5/m³ and $6.50/m³, respectively. Earthwork costs include vegetation clearing, mobilisation/demobilisation of machinery and contractor accommodation. 1000-ML ringtank reservoir has surface area of 27 ha and storage volume to excavation ratio of about 7:1. 4000-ML ringtank and 4.25-m embankment height reservoir has surface area of 110 ha and storage volume to excavation ratio of about 14:1. 4000-ML ringtank with 6.75-m embankment height reservoir has surface area of 64 ha and storage volume to excavation ratio of about 7.5:1.

<table>
<thead>
<tr>
<th>CAPACITY AND EMBANKMENT HEIGHT</th>
<th>ANNUALISED COST* $(/y)</th>
<th>SEEPAGE LOSS (mm/d)</th>
<th>UNIT COST $(/ML)</th>
<th>EQUIVALENT ANNUAL UNIT COST $(/y per ML/y)</th>
<th>UNIT COST $(/ML)</th>
<th>EQUIVALENT ANNUAL UNIT COST $(/y per ML/y)</th>
<th>UNIT COST $(/ML)</th>
<th>EQUIVALENT ANNUAL UNIT COST $(/y per ML/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 ML and 4.25 m</td>
<td>117,100</td>
<td>1</td>
<td>1271</td>
<td>141</td>
<td>1467</td>
<td>162</td>
<td>1633</td>
<td>181</td>
</tr>
<tr>
<td></td>
<td>117,100</td>
<td>2</td>
<td>1327</td>
<td>147</td>
<td>1581</td>
<td>175</td>
<td>1858</td>
<td>206</td>
</tr>
<tr>
<td></td>
<td>117,100</td>
<td>5</td>
<td>1527</td>
<td>169</td>
<td>2066</td>
<td>229</td>
<td>3170</td>
<td>351</td>
</tr>
<tr>
<td>4000 ML and 4.25 m</td>
<td>284,500</td>
<td>1</td>
<td>659</td>
<td>85</td>
<td>755</td>
<td>97</td>
<td>835</td>
<td>107</td>
</tr>
<tr>
<td></td>
<td>284,500</td>
<td>2</td>
<td>687</td>
<td>88</td>
<td>810</td>
<td>104</td>
<td>941</td>
<td>121</td>
</tr>
<tr>
<td></td>
<td>284,500</td>
<td>5</td>
<td>784</td>
<td>101</td>
<td>1038</td>
<td>133</td>
<td>1527</td>
<td>196</td>
</tr>
<tr>
<td>4000 ML and 6.75 m</td>
<td>402,000</td>
<td>1</td>
<td>993</td>
<td>111</td>
<td>1067</td>
<td>119</td>
<td>1122</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>402,000</td>
<td>2</td>
<td>1015</td>
<td>114</td>
<td>1106</td>
<td>124</td>
<td>1188</td>
<td>133</td>
</tr>
<tr>
<td></td>
<td>402,000</td>
<td>5</td>
<td>1088</td>
<td>122</td>
<td>1241</td>
<td>139</td>
<td>1442</td>
<td>161</td>
</tr>
</tbody>
</table>

Taking into consideration the cost of constructing ringtanks and net evaporation and seepage losses, the optimal embankment height will vary depending upon the capacity of the storage. Based on the cost assumptions used in this section and assuming 2 mm/day of seepage and a requirement that water is stored until August (i.e. 6 months), Table 5-23 provides an indication of how the optimum embankment height and annualised cost at the optimum embankment height vary with increasing ringtank capacity.
### Table 5-23 Annualised unit cost at optimum embankment height for ringtanks of varying capacity
Value assumes 2 mm/day of seepage and a requirement that water is stored until August (i.e. 6 months).

<table>
<thead>
<tr>
<th>CAPACITY (ML)</th>
<th>OPTIMUM EMBANKMENT HEIGHT (m)</th>
<th>ANNUALISED UNIT COST AT OPTIMUM EMBANKMENT HEIGHT ($/ML)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,000</td>
<td>3.9</td>
<td>170</td>
</tr>
<tr>
<td>2,000</td>
<td>3.95</td>
<td>125</td>
</tr>
<tr>
<td>4,000</td>
<td>4.1</td>
<td>104</td>
</tr>
<tr>
<td>6,000</td>
<td>4.25</td>
<td>94</td>
</tr>
<tr>
<td>8,000</td>
<td>4.35</td>
<td>88</td>
</tr>
<tr>
<td>10,000</td>
<td>4.45</td>
<td>84</td>
</tr>
<tr>
<td>15,000</td>
<td>4.65</td>
<td>78</td>
</tr>
</tbody>
</table>

#### 5.3.5 LARGE FARM-SCALE GULLY DAMS

Large farm-scale gully dams are generally constructed of earth or earth and rockfill embankments with compacted clay cores and usually to a maximum height of about 20 m. Dams with a crest height of over 10 or 12 m typically require some form of downstream batter drainage incorporated into embankments. Large farm-scale gully dams typically have a maximum catchment area of about 30 km² due to the challenges in passing peak floods from large catchments (large farm-scale gully dams are generally designed to pass an event with an annual exceedance probability (AEP) of 1%), unless a site has an exceptionally good spillway option.

Like ringtanks, large farm-scale gully dams are a compromise between best-practice engineering and affordability. Designers need to follow accepted engineering principles relating to important aspects of materials classification, compaction of the clay core and selection of appropriate embankment cross-section. However, costs are often minimised where possible; for example, by employing earth bywashes and grass-protection for erosion control rather than more expensive concrete spillways and rock protection as found on major dams. This can compromise the integrity of the structure during extreme events, compromise the longevity of the structure as well as increase the ongoing maintenance costs, but can considerably reduce the upfront capital costs.

In this section the following assessments are reported:

- suitability of the landscape for large farm-scale gully dams
- indicative capital, operating and maintenance costs of large farm-scale gully dams.

Net evaporation and seepage losses also occur from large farm-scale gully dams. The analysis presented in Section 5.3.4 is also applicable to gully dams.

**Suitability of land for large farm-scale gully dams**

Figure 5-47 provides an indication of where it may be more economical to construct large farm-scale gully dams in the Darwin catchments and the likely density of options. This analysis takes into consideration those sites likely to have more favourable topography and soil for the construction of the embankment and to minimise seepage from the reservoir base. In reality, dams can be constructed on eroded or skeletal soils provided there is access to a clay borrow pit.
nearby for the cut-off trench and core zone. However, these sites are likely to be less economically viable.

Figure 5-47 Most economically suitable locations for large farm-scale gully dams in the Darwin catchments

Gully dam data overlaid on agricultural versatility data (see Section 4.3). Agricultural versatility data indicate those parts of the catchment that are more or less versatile for irrigated agriculture. For the gully dam analysis soil and subsurface data were only available to a depth of 1.5 m, hence this Assessment does not consider the suitability of subsurface material below this depth. Sites with catchment areas greater than 30 km² or yield to excavation ratio less than 10 are not displayed. The results presented in this figure are modelled and consequently only indicative of the general locations where siting a gully dam may be most economically suitable. This analysis may be subject to errors in the underlying digital elevation model, such as affects due to the vegetation removal process. An important factor not considered in this analysis was the availability of a natural spillway. Site-specific investigations by a suitably qualified professional should always be undertaken prior to their construction.

This figure indicates that there are a limited number of favourable large farm-scale gully dam sites in the Darwin catchments. The favourable modelled locations are on the coastal floodplains, which have negligible agricultural value, and are likely to be remnant channels rather than genuine gully dam sites. The subdued topography in the vicinity of land more suitable for irrigated agriculture means hillslope dams (which have a lower storage to excavation ratio than gully dams) are more likely than gully dams (Figure 5-48).
Capital, operation and maintenance costs of large farm-scale gully dams

The cost of a large farm-scale gully dam will vary depending upon a range of factors including the suitability of the topography of the site, the size of the catchment area, quantity of runoff, proximity of site to good quality clay, availability of durable rock in the upper bank for a spillway and the size of the embankment. The height of the embankment, in particular, has a strong influence on cost. An earth dam to a height of 8 m is about 3.3 times more expensive to construct than a 4-m high dam, and a dam to a height of 16 m will require 3.6 times more material than the 8-m high version, but the cost may be more than five times greater, due to design and construction complexity.

As an example, actual costs for four large farm-scale gully dams in northern Queensland are presented in Table 5-24.

Table 5-24 Actual costs of four gully dams in northern Queensland
Costs are indexed to 2017.

<table>
<thead>
<tr>
<th>DAM NAME</th>
<th>LOCATION</th>
<th>CAPACITY (ML)</th>
<th>YIELD (ML/y)</th>
<th>COST ($)</th>
<th>UNIT COST ($/ML)</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sharp Rock Dam</td>
<td>Lakelands</td>
<td>3300</td>
<td>1070</td>
<td>322,800</td>
<td>302</td>
<td>Chimney filter and drainage under-blanket. Two stage concrete sill spillway. No fishway. Pump station not included</td>
</tr>
<tr>
<td>Dump Gully Dam</td>
<td>Lakelands</td>
<td>1450</td>
<td>420</td>
<td>786,000</td>
<td>1871</td>
<td>Deep and wet cut-off. Chimney filter and downstream under drainage. No fishway. Pump station was $91,000</td>
</tr>
<tr>
<td>Spring Dam #2</td>
<td>Lakelands</td>
<td>2540</td>
<td>1377</td>
<td>895,600</td>
<td>650</td>
<td>Chimney filter and drainage under-blanket. Two stage rock excavation. Spillway with fishway. Fishway was $36,500. Pump station not included</td>
</tr>
<tr>
<td>Ronny’s Dam</td>
<td>Georgetown</td>
<td>9975</td>
<td>1700</td>
<td>447,900</td>
<td>263</td>
<td>Very favourable site. Low embankment and 450-ha ponded area. Natural spillway. No pump station, gravity supply via through pipe</td>
</tr>
</tbody>
</table>

Figure 5-48 Large farm-scale gully dam (~3.75 GL capacity) in Darwin catchments
Photo: CSIRO
Performance and cost of three hypothetical farm-scale gully dams in northern Australia

A summary of the key parameters for three hypothetical 4-GL capacity farm-scale gully dam configurations is provided in Table 5-25 and a high-level breakdown of the major components of the capital costs for each of the three configurations is provided in Table 5-26. Detailed costs for the three sites are provided in the companion technical report on large farm-scale dams (Benjamin, 2018).

### Table 5-25 Cost of three hypothetical large farm-scale gully dams of capacity 4 GL
Costs include government permits and fees, investigation and design and fish passage. For a complete list of costs and assumptions see companion technical report on farm-scale dams (Benjamin, 2018).

<table>
<thead>
<tr>
<th>SITE DESCRIPTION/CONFIGURATION</th>
<th>CATCHMENT AREA (km²)</th>
<th>EMBANKMENT HEIGHT (m)</th>
<th>EMBANKMENT LENGTH (m)</th>
<th>S:E RATIO</th>
<th>AVERAGE DEPTH (m)</th>
<th>RESERVOIR SURFACE AREA (ha)</th>
<th>TOTAL CAPITAL COST ($)</th>
<th>O&amp;M COST ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Favourable site with large catchment, suitable topography and simple spillway (e.g. natural saddle)</td>
<td>30</td>
<td>9.5</td>
<td>1100</td>
<td>29:1</td>
<td>5.0</td>
<td>80</td>
<td>1,280,000</td>
<td>55,000</td>
</tr>
<tr>
<td>Unfavourable site with small catchment, challenging topography and limited spillway options (e.g. steep gully banks, no natural saddle)</td>
<td>15</td>
<td>14</td>
<td>750</td>
<td>21:1</td>
<td>6.3</td>
<td>63</td>
<td>1,474,000</td>
<td>35,000</td>
</tr>
<tr>
<td>Unfavourable site with moderate catchment, challenging topography and limited spillway options (e.g. steep gully banks, no natural saddle)</td>
<td>20</td>
<td>14</td>
<td>750</td>
<td>21:1</td>
<td>6.3</td>
<td>63</td>
<td>1,554,000</td>
<td>40,000</td>
</tr>
</tbody>
</table>

### Table 5-26 High-level breakdown of capital costs for three hypothetical large farm-scale gully dams of capacity 4 GL
Earthworks include vegetation clearing, mobilisations/demobilisation of equipment and contractor accommodation. Investigation and design fees include design and investigation of fish passage device and failure impact assessment (i.e. investigation of possible existence of population at risk downstream of site).

<table>
<thead>
<tr>
<th>SITE DESCRIPTION/CONFIGURATION</th>
<th>EARTHWORKS ($)</th>
<th>GOVERNMENT PERMITS AND FEES ($)</th>
<th>INVESTIGATION AND DESIGN FEES ($)</th>
<th>TOTAL CAPITAL COST ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Favourable site with large catchment, suitable topography and simple spillway (e.g. natural saddle)</td>
<td>1,157,500</td>
<td>36,000</td>
<td>86,500</td>
<td>1,280,000</td>
</tr>
<tr>
<td>Unfavourable site with small catchment, challenging topography and limited spillway options (e.g. steep gully banks, no natural saddle)</td>
<td>1,340,000</td>
<td>40,000</td>
<td>94,000</td>
<td>1,474,000</td>
</tr>
<tr>
<td>Unfavourable site with moderate catchment, challenging topography and limited spillway options (e.g. steep gully banks, no natural saddle)</td>
<td>1,420,000</td>
<td>40,000</td>
<td>94,000</td>
<td>1,554,000</td>
</tr>
</tbody>
</table>

In Queensland if a large farm-scale gully dam is constructed on a watercourse, as defined by the state’s legislation, then it is likely that conditions applicable to the water licence would include bed-level outlet works capable of passing a prescribed flow. This may range from relatively small volumes required to meet downstream riparian rights (stock and domestic water supplies), to relatively large volumes to meet existing entitlements of downstream irrigators. Small through-
flows of less than about 0.5 ML/day could best be achieved by means of an overbank syphon at relatively minimal cost. Releases of more than about 25 ML/day would, however, require considerable investment. Cost varies greatly, with a likely range of $50,000 to $100,000 (Benjamin, 2018).

Table 5-27 presents calculations of the effective volume for three configurations of 4-GL capacity gully dams (varying average water depth/embankment height) for combinations of three seepage losses and water storage over three time periods in the Darwin catchments.

Based on the information presented in Table 5-25 an equivalent annual unit cost including annual operation and maintenance cost for a 4-GL gully dam with an average depth of about 6 m is about $174,000 (Table 5-28 and Table 5-29).

Table 5-28 Cost of construction and operation of three hypothetical 4-GL gully dams
Assumes operation and maintenance (O&M) cost of 3% of capital cost and a 7% discount rate. Figures have been rounded.

<table>
<thead>
<tr>
<th>AVERAGE DEPTH AND RESERVOIR SURFACE AREA</th>
<th>ITEM</th>
<th>CAPITAL COST ($)</th>
<th>EQUIVALENT ANNUAL CAPITAL COST ($)</th>
<th>ANNUAL O&amp;M COST ($)</th>
<th>EQUIVALENT ANNUAL UNIT COST ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 m and 133 ha</td>
<td>Low embankment wide gully dam</td>
<td>1,000,000</td>
<td>86,000</td>
<td>30,000</td>
<td>116,000</td>
</tr>
<tr>
<td>6 m and 66 ha</td>
<td>Moderate embankment gully dam</td>
<td>1,500,000</td>
<td>129,000</td>
<td>45,000</td>
<td>174,000</td>
</tr>
<tr>
<td>9 m and 44 ha</td>
<td>High embankment narrow gully dam</td>
<td>2,000,000</td>
<td>172,000</td>
<td>60,000</td>
<td>232,000</td>
</tr>
</tbody>
</table>
Table 5-29 Equivalent annualised cost and effective volume for three hypothetical 4-GL gully dams

Dam details are in Table 5-28. Annual cost assumes a 7% discount rate.

<table>
<thead>
<tr>
<th>AVERAGE DEPTH AND RESERVOIR SURFACE AREA</th>
<th>EQUIVALENT ANNUAL COST ($/y)</th>
<th>SEEPAGE LOSS (mm/d)</th>
<th>UNIT COST ($/ML)</th>
<th>EQUIVALENT ANNUAL UNIT COST ($/y PER ML/y)</th>
<th>UNIT COST ($/ML)</th>
<th>EQUIVALENT ANNUAL UNIT COST ($/y PER ML/y)</th>
<th>UNIT COST ($/ML)</th>
<th>EQUIVALENT ANNUAL UNIT COST ($/y PER ML/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 months (March to June)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 m and 133 ha</td>
<td>116,000</td>
<td>1</td>
<td>311</td>
<td>36</td>
<td>370</td>
<td>43</td>
<td>424</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>116,000</td>
<td>2</td>
<td>327</td>
<td>38</td>
<td>407</td>
<td>47</td>
<td>502</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td>116,000</td>
<td>5</td>
<td>390</td>
<td>45</td>
<td>580</td>
<td>67</td>
<td>1123</td>
<td>130</td>
</tr>
<tr>
<td>6 m and 66 ha</td>
<td>174,000</td>
<td>1</td>
<td>416</td>
<td>48</td>
<td>448</td>
<td>52</td>
<td>472</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>174,000</td>
<td>2</td>
<td>425</td>
<td>49</td>
<td>465</td>
<td>54</td>
<td>501</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td>174,000</td>
<td>5</td>
<td>457</td>
<td>53</td>
<td>524</td>
<td>61</td>
<td>613</td>
<td>71</td>
</tr>
<tr>
<td>9 m and 44 ha</td>
<td>232,000</td>
<td>1</td>
<td>535</td>
<td>62</td>
<td>561</td>
<td>65</td>
<td>579</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>232,000</td>
<td>2</td>
<td>543</td>
<td>63</td>
<td>574</td>
<td>67</td>
<td>601</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>232,000</td>
<td>5</td>
<td>568</td>
<td>66</td>
<td>617</td>
<td>72</td>
<td>675</td>
<td>78</td>
</tr>
</tbody>
</table>

Where the topography is suitable for large farm-scale gully dams and a natural spillway is present, large farm-scale gully dams are typically cheaper to construct than ringtanks.

5.3.6 NATURAL WATER BODIES

Wetland systems and waterholes that persist throughout the dry season are natural water bodies characteristic of large parts of the northerly draining catchments of northern Australia. Many station homesteads in northern Australia use natural waterholes for stock and domestic purposes. However, the quantities of water required for stock and domestic supply are orders of magnitude less than that required for irrigated cropping and it is partly for this reason that naturally occurring persistent water bodies in northern Australia are not used to source water for irrigation.

For example, a moderately sized 5-ha rectangular water body of average depth of 3.5 m may contain about 175 ML of water. Based on the data presented in Table 5-19 and assuming minimal leakage (i.e. 1 mm/day) approximately 83, 72 and 65% of these volumes would be available if a crop were to be irrigated until July, September and December, respectively. Assuming a crop or fodder with a 6-month growing season requires 5 ML/ha of water before losses, and assuming an overall efficiency of 80% (i.e. the waterhole is adjacent to land suitable for irrigation, 95% conveyance efficiency and 85% field application efficiency), a 175-ML waterhole could potentially be used to irrigate about 20 ha of land for half a year if all the water was able to be used for this purpose. A large natural water body of 20 ha and average depth of 3.5 m could potentially be used to irrigate about 80 ha of land if all the water was able to be used for this purpose.

Although the areas of land that could be watered using natural water bodies are likely to be small, the costs associated with storing water are minimal. Consequently, where these waterholes occur in sufficient size and adjacent to land suitable for irrigated agriculture, they can be a very cost-effective source of water. It would appear that where natural water bodies of sufficient size and suitable land for irrigation coincide, natural water bodies may be effective in staging a
development (Section 6.3), where lessons are learnt and mistakes are made on a small-scale area before large capital investment occurs.

In a few instances it may be possible to enhance the storage potential of natural features in the landscape such as horseshoe lagoons or cut-off meanders adjacent to a river.

The main limitations to the use of wetlands and persistent waterholes for the consumptive use of water is that they have considerable ecological significance (e.g. Kingsford, 2000; Waltham et al., 2013), and in many cases there is a limited quantity of water contained within the water bodies. In particular, water bodies that persist throughout the dry season are considered key ecological refugia (Waltham et al., 2013).

It should also be noted that where a water body is situated in a sandy river, the waterhole is likely to be connected to water within the bedsands of the river. Hence, during and following pumping water within the bedsands of a river, the bedsands may in part replenish the waterhole and vice versa. While water within the bedsands of the river may in part replenish a depleted waterhole, in these circumstances it also means that pumping from a waterhole will have a wider environmental impact than just the waterhole from which water is being pumped.

Figure 2-46 indicates the location of (1 km) river reaches containing waterholes that persist more than 90% of the time in the Landsat TM data archive in the Darwin catchments. For the purposes of this Assessment they are referred to as ‘persistent’ waterholes.

### 5.4 Water distribution systems – conveyance of water from storage to crop

#### 5.4.1 INTRODUCTION

In all irrigation systems, water needs to be conveyed from the water source through artificial and/or natural water distribution systems, before ultimately being used on-field for irrigation. This section discusses water losses during conveyance and application of water to the crop and the associated costs.

#### 5.4.2 CONVEYANCE AND APPLICATION EFICIENCIES

Some water diverted for irrigation is lost during conveyance to the field before it can be used by a crop. These losses need to be taken into account when planning irrigation systems and developing likely irrigated areas. The amount of water lost during conveyance depends on the:

- river conveyance efficiency, from the water storage to the re-regulating structure or point of extraction
- channel distribution efficiency, from the river offtake to the farm gate
- on-farm distribution efficiency, in storing (using balancing storages) and conveying water from the farm gate to the field
- field application efficiency, which is the efficiency to which water can be delivered from the edge of the field and applied to the crop.

The overall or system efficiency is the product of these four components.
Little research on irrigation systems has been undertaken in the Darwin catchments. The time frame of the Assessment did not permit on-ground research into irrigation systems. Consequently, a brief discussion on the components listed above is provided based on relevant literature from elsewhere in Australia and overseas. Table 5-30 summarises the broad range of efficiencies associated with these components.

The total conveyance and application efficiency of the delivery of water from the water storage to the crop (i.e. the overall or system efficiency) is dependent upon the product of the four components listed in Table 5-30. For example, if an irrigation development has a river conveyance efficiency of 80%, a channel distribution efficiency of 90%, an on-farm distribution efficiency of 90% and a field application efficiency of 85%, the overall efficiency is 55% (i.e. 80% * 90% * 90% * 85%). This means only 55% of all water released from the dam can be used by the crop.

Table 5-30 Summary of conveyance and application efficiencies

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>TYPICAL EFFICIENCY (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>River conveyance efficiency</td>
<td>50–90†</td>
</tr>
<tr>
<td>Channel distribution efficiency</td>
<td>50–95</td>
</tr>
<tr>
<td>On-farm distribution efficiency</td>
<td>80–95</td>
</tr>
<tr>
<td>Field application efficiency</td>
<td>60–90</td>
</tr>
</tbody>
</table>

†River conveyance efficiency varies with a range of factors (including distance) and may be lower than the range quoted here. Under such circumstances, it is unlikely that irrigation would proceed. It is also possible for efficiency to be 100% in gaining rivers. Achieving higher efficiencies requires a re-regulating structure (see Section 5.3.3).

**River conveyance efficiency**

The conveyance efficiency of rivers is difficult to measure and even more difficult to predict. Although there are many methods for estimating groundwater discharge to surface water, there are few suitable methods for estimating the loss of surface water to groundwater. In the absence of existing studies for northern Australia, conveyance efficiencies as nominated in water resource plans and resource operation plans for four irrigation water supply schemes in Queensland were examined collectively. The results are summarised in Table 5-31.

The conveyance efficiencies listed in Table 5-31 are from the water storage to the farm gate and are nominated efficiencies based on experience delivering water in these supply schemes. These data can be used to estimate conveyance efficiency of similar rivers elsewhere.

Table 5-31 Water distribution and operational efficiency as nominated in water resource plans for four irrigation water supply schemes in Queensland

<table>
<thead>
<tr>
<th>WATER SUPPLY SCHEME IN QUEENSLAND</th>
<th>TOTAL ALLOCATION VOLUME (ML)</th>
<th>RIVER AND CHANNEL CONVEYANCE EFFICIENCY† (%)</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burdekin Haughton</td>
<td>928,579</td>
<td>78</td>
<td>The primary storage is the Burdekin Falls Dam (1860 GL), approximately 100 km upstream of Clare weir, the major extraction point. The Bowen River, a major unregulated tributary of the Burdekin River, joins the Burdekin River downstream of Burdekin Falls Dam. This may assist in reducing transmission losses between the dam and Clare weir.</td>
</tr>
</tbody>
</table>
### WATER SUPPLY SCHEME IN QUEENSLAND

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Total Allocation Volume (ML)</th>
<th>River and Channel Conveyance Efficiency† (%)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Mary</td>
<td>34,462</td>
<td>93.8†</td>
<td>The Lower Mary irrigation area is supplied from two storages, a barrage on the Mary River and a barrage on Tinana Creek. Water is drawn directly from the barrage storages to irrigate land riparian to the streams. Water distribution is predominantly via pipelines.</td>
</tr>
<tr>
<td>Proserpine River</td>
<td>87,040</td>
<td>72</td>
<td>The scheme has a single source of supply, Peter Faust Dam (491 GL). At various distances downstream of the dam, water is extracted from the river bedsands and is distributed to urban communities, several irrigation water supply boards and individual irrigators.</td>
</tr>
<tr>
<td>Upper Burnett</td>
<td>26,870</td>
<td>68</td>
<td>The Upper Burnett is a long run of river scheme with one major storage (Wuruma Dam (165 GL)) and four weir storages. The total river length supplied by the scheme is 165 km.</td>
</tr>
</tbody>
</table>

†Ignores differences in efficiency between high and medium priority users and variations across the scheme zone areas.  
‡Channel conveyance efficiency only.

**Channel distribution efficiency**

Across Australia, the average water conveyance efficiency from the river to the farm gate has been estimated to be 71% (Marsden Jacob Associates, 2003). For heavier textured soils and well-designed irrigation distribution systems, conveyance efficiencies are likely to be higher.

In the absence of larger scheme-scale irrigation systems in the Darwin catchments, it is useful to look at the conveyance efficiency of existing irrigation developments to estimate the conveyance efficiency of irrigation developments in the study area. Australian conveyance efficiencies are generally higher than those found in similarly sized overseas irrigation schemes (Cotton Catchment Communities CRC, 2011; Bos and Nugteren, 1990); therefore, Australian data should be preferentially used.

The most extensive review of conveyance efficiency in Australia was undertaken by the Australian National Commission on Irrigation and Drainage, which tabulated system efficiencies across irrigation developments in Australia (ANCID, 2001). Conveyance losses were reported as the difference between the volume of water supplied to irrigation customers and the water delivered to the irrigation system. For example, if 10,000 ML of water was diverted to an irrigation district and 8000 ML was delivered to irrigators, then the conveyance efficiency was 80% and the conveyance losses were 20%.

Figure 5-49 shows reported conveyance losses across irrigation areas of Australia between 1999 and 2000, along with the supply method used for conveying irrigation water and associated irrigation deliveries. There is a wide spread of conveyance losses both between years and across the various irrigation schemes. Factors identified by Marsden Jacob Associates (2003) that affect the variation include delivery infrastructure, soil types, distance that water is conveyed, type of agriculture, operating practices, infrastructure age, maintenance standards, operating systems, in-line storage, type of metering used and third-party impacts such as recreational, amenity and environmental demands. Differences across irrigation seasons are due to variations in water availability, operational methods, climate and customer demands.

Based on these industry data, Marsden Jacob Associates (2003) concluded that, on average, 29% of water diverted into irrigation schemes is lost in conveyance to the farm gate. However, some of
this ‘perceived’ conveyance loss may be due to meter underestimation (about 5% of water delivered to provider (Marsden Jacob Associates, 2003)). Other losses were from leakage, seepage, evaporation, outfalls, unrecorded usage and system filling.

![Figure 5-49 Reported conveyance losses from irrigation systems across Australia](image-url)

The shape of the marker indicates the supply method for the irrigation scheme: square (▪) indicates natural carrier, circle (•) indicates pipe, and diamond (♦) indicates channel. The colour of the marker indicates the location of the irrigation system (by state), as shown in the legend.


### On-farm distribution efficiency

On-farm losses are losses that occur between the farm gate and delivery to the field. These losses usually take the form of evaporation and seepage from on-farm storages and delivery systems. Even in irrigation developments where water is delivered to the farm gate via a channel, many farms have small on-farm storages (i.e. less than 250 ML for a 500-ha farm). These on-farm storages enable the farmer to have a reliable supply of irrigation water with a higher flow rate, and also enable recycling of tailwater. Several studies have been undertaken in Australia on on-farm distribution losses. Meyer (2005) estimated an on-farm distribution efficiency of 78% in the Murray and Murrumbidgee regions, while Pratt Water (2004) estimated on-farm efficiency to be 94% and 88% in the Coleambally Irrigation and Murrumbidgee Irrigation areas, respectively. For nine farms in these two irrigation areas, however, Akbar et al. (2000) measured channel seepage to be less than 5%.

### Field application efficiency

Once water is delivered to the field, it needs to be applied to the crop using an irrigation system. The application efficiency of irrigation systems typically varies between 60 and 90%, with more expensive systems usually resulting in higher efficiency.

There are three types of irrigation systems that can potentially be applied in the Darwin catchments: surface irrigation, spray irrigation and micro irrigation (Figure 5-50). Irrigation systems applied in the Darwin catchments need to be tailored to the soil, climate and crops that may be grown in the catchments and matched to the availability of water for irrigation. This is taken into
consideration in the land suitability assessment figures presented in Section 4.2. System design will also need to consider investment risk in irrigation systems as well as likely returns, degree of automation, labour availability, and operation and maintenance costs (e.g. the cost of energy).

Irrigation systems have a trade-off between efficiency and cost. Table 5-32 summarises the different types of irrigation systems, including their application efficiency, indicative cost and their limitations. Across Australia the ratio of areas irrigated using surface, spray and micro irrigation is 83:10:7, respectively. Irrigation systems that allow water to be applied with greater control, such as micro irrigation, cost more (Table 5-32) and as a result are typically used for irrigating higher value crops such as horticulture and vegetables. For example, although only 7% of Australia’s irrigated area uses micro irrigation; it generates about 40% of the total value of produce grown using irrigation (Meyer, 2005). Further details on the three types of irrigation systems follow Table 5-32.

(a) In bankless channel surface irrigation systems, application efficiencies range from 60 to 85%. (b) In spray irrigation systems, application efficiencies range from 75 to 90%. (c) For pressurised micro irrigation systems on polymer-covered beds, application efficiencies range from 80 to 90%.

Photo: CSIRO

Figure 5-50 Efficiency of different types of irrigation systems
(a) In bankless channel surface irrigation systems, application efficiencies range from 60 to 85%. (b) In spray irrigation systems, application efficiencies range from 75 to 90%. (c) For pressurised micro irrigation systems on polymer-covered beds, application efficiencies range from 80 to 90%. Photo: CSIRO
### Table 5-32 Application efficiencies for surface, spray and micro irrigation systems

Application efficiency is the efficiency with which water can be delivered from the edge of the field to the crop.

<table>
<thead>
<tr>
<th>IRRIGATION SYSTEM</th>
<th>TYPE</th>
<th>APPLICATION EFFICIENCY (%)</th>
<th>CAPITAL COST ($/ha)†</th>
<th>LIMITATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>Basin</td>
<td>60–85</td>
<td>3400</td>
<td>Suitable for most crops; topography and surface levelling costs may be limiting factor</td>
</tr>
<tr>
<td></td>
<td>Border</td>
<td>60–85</td>
<td>3400</td>
<td>Suitable for most crops; topography and surface levelling costs may be limiting factor</td>
</tr>
<tr>
<td></td>
<td>Furrow</td>
<td>60–85</td>
<td>3400</td>
<td>Suitable for most crops; topography and surface levelling costs may be limiting factor</td>
</tr>
<tr>
<td>Spray</td>
<td>Centre pivot</td>
<td>75–90</td>
<td>2500–5500</td>
<td>Not suitable for tree crops; high energy requirements for operation</td>
</tr>
<tr>
<td></td>
<td>Lateral move</td>
<td>75–90</td>
<td>2500–5000</td>
<td>Not suitable for tree crops; high energy requirements for operation</td>
</tr>
<tr>
<td>Micro</td>
<td>Drip</td>
<td>80–90</td>
<td>6000–9000</td>
<td>High energy requirement for operation; high level of skills needed for successful operation</td>
</tr>
</tbody>
</table>

Adapted from Hoffman et al. (2007), Raine and Baker (1996) and Wood et al. (2007).

†Source: DEEDI (2011a, 2011b, 2011c).

### Surface irrigation systems

Surface irrigation encompasses basin, border strip and furrow irrigation, as well as variations on these themes such as bankless channel systems. In surface irrigation, water is applied directly to the soil surface with check structures (banks or furrows) used to direct water across a field. Control of applied water is dictated by the soil properties, soil uniformity and the design characteristics of the surface system. Generally, fields are prepared by laser levelling to increase the uniformity of applied water and allow ease of management of water and adequate surface drainage from the field. The uniformity and efficiency of surface systems are highly dependent on the system design and soil properties, timing of the irrigation water and the skill of the individual irrigator in operating the system. Mismanagement can severely degrade system performance and lead to systems that operate at poor efficiencies.

Surface irrigation has the benefit that it can generally be adapted to almost any crop and usually has a lower capital cost compared with alternative systems. Surface irrigation systems perform better when soils are of uniform texture as infiltration characteristics of the soil play an important part in the efficiency of these systems. Therefore, surface irrigation systems should be designed into uniform soil management units and layouts (run lengths, basin sizes) tailored to match soil characteristics and water supply volumes.

High application efficiencies are possible with surface irrigation systems, provided soil characteristic limitations, system layout, water flow volumes and high levels of management are applied. On ideal soil types and with systems capable of high flow rates, efficiencies can be higher than 85%. On poorly designed and managed systems on soil types with high variability, efficiencies can be below 60%.

Generally, the major cost in setting up a surface irrigation system is land grading and levelling, with costs directly associated with the volume of soil that must be moved. Typical earth moving volumes are in the order of 800 m³/ha but can exceed 2500 m³/ha. Volumes greater than 1500 m³/ha are generally considered excessive due to costs (Hoffman et al., 2007).
Surface irrigation systems are the dominant form of irrigation systems used throughout the world. Their potential suitability in the Darwin catchments would be due to their generally lower setup costs and adaptability to a wide range of irrigated cropping activities. They are particularly suited to the heavier textured soils found adjacent to the Adelaide and Mary rivers and areas that have small natural topographical changes in elevation, which reduce setup or establishment costs of these systems. With surface irrigation, little or no energy is required to distribute water throughout the field and this ‘gravity-fed’ approach reduces energy requirements of these systems (Table 5-33). Surface irrigation systems generally have lower applied irrigation water efficiency than spray or micro systems when compared across an industry and offer less control of applied water; however, well-designed and well-managed systems can approach efficiencies found with alternative irrigation systems in ideal conditions.

**Spray irrigation systems**

In the context of the Darwin catchments, spray irrigation refers specifically to lateral move and centre pivot irrigation systems. Centre pivot systems consist of a single sprinkler, laterally supported by a series of towers. The towers are self-propelled and rotate around a central pivot point, forming an irrigation circle. Time taken for the pivot to complete a full circle can range from as little as half a day to multiple days depending on crop water demands and application rate of the system. Generally, lateral spans are less than 500 m.

Lateral or linear move systems are similar to centre pivot systems in construction, but rather than move around a pivot point the entire line moves down the field in a direction perpendicular to the lateral. Water is supplied by a lateral channel running the length of the field. Lateral lengths are generally in the range of 800 to 1000 m. They are advantageous over surface irrigation systems as they can be utilised on rolling topography and generally require less land forming.

Both centre pivot and lateral move irrigation systems have been extensively used for irrigating a range of annual broadacre crops and are capable of irrigating most field crops. They are generally not suitable for tree crops or vine crops or for saline irrigation water applications in arid environments, which can create foliage damage. Centre pivot and lateral move systems usually have higher capital costs but are capable of very high efficiencies of water application. Generally, application efficiencies for these systems range from 75 to 90% (Table 5-32). They are used extensively for broadacre irrigated cropping situations in high evaporative environments in northern NSW and south-west Queensland. These irrigation developments have high irrigation crop water demand requirements, which are similar to those found in the Darwin catchments. A key factor in the suitable use of spray systems is sourcing the energy needed to operate these systems, which are usually powered by electricity or diesel depending on available costs and infrastructure. Where available, electricity is considerably cheaper than diesel for powering spray systems (Table 5-33).

For pressurised systems such as spray or micro irrigation systems, the water can be more easily controlled, and potential benefits of the system through fertigation (application of crop nutrients through the irrigation system (i.e. liquid fertiliser)) are also available to the irrigator.
**Micro irrigation systems**

For high-value crops, such as horticultural crops where yield and quality parameters dictate profitability, micro irrigation systems should be considered suitable across the range of soil types and climate conditions found in the Darwin catchments.

Micro irrigation systems use thin-walled polyethylene pipe to apply water to the root zone of plants via small emitters spaced along the drip tube. These systems are capable of precisely applying water to the plant root zone, thereby maintaining a high level of irrigation control and applied irrigation water efficiency. Historically, micro irrigation systems have been extensively used in tree, vine and row crops, with limited applications in complete cover crops such as grains and pastures due to the expense of these systems. Micro irrigation is suitable for most soil types and can be practised on steep slopes. Micro irrigation systems are generally of two varieties: above ground and below ground (where the drip tape is buried beneath the soil surface). Below-ground micro irrigation systems offer advantages in reducing evaporative losses and improving trafficability. However, below-ground systems are more expensive and require higher levels of expertise to manage.

Properly designed and operated micro irrigation systems are capable of very high application efficiencies, with field efficiencies of 80 to 90% (Table 5-32). In some situations, micro irrigation systems offer water and labour savings and improved crop quality (i.e. more marketable fruit through better water control). Management of micro irrigation systems, however, is critical. To achieve these benefits requires a much greater level of expertise than other traditional systems such as surface irrigation systems, which generally have higher margins of error associated with irrigation decisions. Micro irrigation systems also have high energy requirements, with most systems operating at pressure ranges from 135 to 400 kPa with diesel or electric pumps most often used (Table 5-33).

### 5.4.3 IRRIGATION SYSTEM COSTS

The capital costs for surface irrigation reported in Table 5-32 include earthworks for a supply channel, head ditch, field land forming and drainage (including tailwater return), as well as pumps and structures. Mason and Larard (2011) reported capital costs for surface (furrow) irrigation in the Flinders catchment, north-west Queensland to be $1482/ha. This is considerably less than the $3400/ha reported for surface irrigation in Table 5-32; however, the calculation of Mason and Larard (2011) omitted expensive items such as laser levelling (which costs between $300 and $650/ha (DEEDI, 2011a)) and tailwater return ($580/ha (DEEDI, 2011a)). These items significantly increase the capital cost of surface irrigation.

The capital costs associated with the purchase of a centre pivot or lateral move in Table 5-32 include the purchase of the machine and installation costs, such as earthworks. In addition to the cost of the machine, Table 5-32 includes the cost of other items such as pipe work, pumping equipment and the power plant (either diesel or electric). The unit cost ($/ha) of both centre pivots and lateral moves is generally less for machines servicing a larger area. The most significant influence on machine price is the pipe diameter of spans (DEEDI, 2011b). As for surface irrigation, other site-specific capital costs could include power lines (and connection), supply channels, laser levelling, land clearing and road construction. Laser levelling and land forming are often limited to cut to drain as opposed to cut to grade. These additional items can add up to 50% of the system
cost (DEEDI, 2011b). Mason and Larard (2011), in a report conducted for the Flinders catchment, estimated capital costs of pivot irrigation at approximately $4470/ha (which is in the range provided in Table 5-32), with $3800/ha for the centre pivot systems, and earthworks averaging around $670/ha.

Ongoing operational costs for all systems include pumping costs and general maintenance. Operation and maintenance of irrigation equipment is often costed at about 2% of the capital cost. These irrigation systems have various trade-offs between capital, operating and labour requirements. An important consideration in selecting an irrigation system is energy requirements, and this may become a more important consideration in the future if energy prices rise. Table 5-33 shows the variation in pumping costs for diesel and electricity for different irrigation systems. In addition, there are trade-offs between these costs and efficiency factors. Surface irrigation systems, for example, tend to have lower capital and annual operating costs, but are less efficient with higher water losses (Table 5-33).

Table 5-33 Energy demands and costs by irrigation type

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>UNIT</th>
<th>FLOOD HARVESTING</th>
<th>SURFACE IRRIGATION</th>
<th>TAILWATER RETURN</th>
<th>CENTRE PIVOTS</th>
<th>LATERAL MOVES</th>
<th>SUBSURFACE DRIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate</td>
<td>ML/day</td>
<td>120</td>
<td>120</td>
<td>50</td>
<td>8.6</td>
<td>24.2</td>
<td>16.6</td>
</tr>
<tr>
<td>Total dynamic head</td>
<td>m</td>
<td>7</td>
<td>6</td>
<td>5.5</td>
<td>50</td>
<td>35</td>
<td>50</td>
</tr>
<tr>
<td>Pumping plant efficiency</td>
<td>%</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>66</td>
<td>66</td>
<td>75</td>
</tr>
<tr>
<td>Power required</td>
<td>kWh/ML</td>
<td>38.9</td>
<td>33.3</td>
<td>30.6</td>
<td>210.4</td>
<td>147.3</td>
<td>185.2</td>
</tr>
<tr>
<td>Specific fuel consumption</td>
<td>L/kWh</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Equivalent diesel requirement</td>
<td>L/ML</td>
<td>9.7</td>
<td>8.3</td>
<td>7.6</td>
<td>52.6</td>
<td>36.8</td>
<td>46.3</td>
</tr>
<tr>
<td>Pumping cost, electricity</td>
<td>$/ML</td>
<td>7.0</td>
<td>6.0</td>
<td>5.5</td>
<td>37.9</td>
<td>26.5</td>
<td>33.4</td>
</tr>
<tr>
<td>Pumping cost, diesel</td>
<td>$/ML</td>
<td>10.9</td>
<td>9.3</td>
<td>8.5</td>
<td>58.9</td>
<td>41.2</td>
<td>51.9</td>
</tr>
</tbody>
</table>

Adapted from Culpitt (2011), with costs based on assumption of $1.12/L for diesel ($1.50/L less $0.38/L rebate) and $0.18/kWh for electricity.

5.5 References


from the CSIRO Northern Australia Water Resource Assessment, part of the National Water Infrastructure Development Fund: Water Resource Assessments. CSIRO, Australia.


Marsden Jacob Associates (2012a) Socio-economic assessments to inform water resource planning in the Darwin region: Berry Springs water allocation planning area (BSWAPA). Report prepared for the Northern Territory Department of Natural Resources, Environment, the Arts and Sport, Australia.

Marsden Jacob Associates (2012b) Socio-economic assessments to inform water resource planning in the Darwin region: Howard East water allocation planning area (HEWAPA). Report prepared for the Northern Territory Department of Natural Resources, Environment, the Arts and Sport, Australia.


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Part IV Economics of development and accompanying risks

Chapters 6 and 7 describe economic opportunities, constraints and risks for water development in the Darwin catchments. This information covers:

- economic opportunities and constraints (Chapter 6)
- a range of risks to development (Chapter 7).
Chapter 6 examines which types of opportunities for irrigated agriculture development in the Darwin catchments are most likely to be commercially viable. The chapter considers the costs of building new infrastructure (both within the scheme and beyond), the financial viability of different types of schemes (considered from an investor’s perspective), and the regional economic impacts (the direct and flow-on effects for businesses across the catchment) (Figure 6-1).

The intention is not to provide a full economic analysis, but to focus on costs and benefits that are the subject of normal market transactions. Non-market impacts and risks are dealt with in chapters 3 and 7, but, given the often subjective and publicly contested nature of valuing such impacts, these are not converted to dollar amounts here. Commercial factors are likely to be one of the most important criteria in deciding between potential development opportunities. Those options that can be clearly identified as being commercially non-viable at the pre-feasibility stage could likely be deprioritised. More detailed and project-specific agronomic, ecological, social, cultural and regulatory assessments could then be focused on those opportunities identified as showing the most commercial promise.
6.1 Summary

6.1.1 KEY FINDINGS

Scheme-scale financial viability

Viable new irrigation development in the Darwin catchments would require challenging combinations of low-cost infrastructure, high-productivity farms, management of a wide range of risks, and/or off-farm value adding. The capital cost of development is the dominant factor affecting scheme viability. It is unlikely that farm gate revenue from irrigated broadacre agriculture alone would be sufficient to fully cover the development costs of irrigation schemes with capital costs above $15,000/ha (plus farm setup costs of about $7000/ha). Adding a processor to a scheme (i.e. vertical integration) could provide increases in revenues (from processed versus unprocessed goods) that are proportionally larger than the additional capital cost of the processing facility. This, or other off-farm, value-adding options, can assist in improving the commercial viability of a scheme, but can also add risk. Viable processors, particularly in remote locations, rely on secure supplies of raw farm commodities at scale. This requires upfront commitments from farmers supported by assured access to the required water and land.

Farm performance can be affected by a range of risks, including water reliability, climate variability, price fluctuations, and learning to adapt farming practices to new locations. Setbacks that occur early on after a scheme is established have the largest effect on scheme viability. There is a strong incentive to start any new irrigation development with well-proven crops and technologies, and to be thoroughly prepared for the anticipatable agronomic risks of establishing new farmland. Staging development can reduce some of the early learning risks. Risks that cannot be avoided need to be managed, mitigated where possible, and accounted for in determining the realistic returns that may be expected from a scheme, and the capital buffers that would be required.

Regional economic impacts

Justifying the costs of public investment in new water infrastructure and/or supporting community infrastructure in the Darwin catchments could well depend on indirect benefits beyond the irrigation scheme. It was found that during the initial construction phase of a new irrigation development in the Darwin catchments, there could be an additional $1.06 of indirect regional benefits, over and above the direct benefits of each dollar spent on construction within the local region. During the ongoing production phase of a new irrigation development, there could be an additional $0.46 to $1.82 of indirect regional benefits for each dollar of direct benefits from increased agricultural activity (gross revenue), depending on the type of agricultural industry. Indirect regional benefits would be reduced if there was leakage of some of the extra expenditure generated by a new development outside the catchment. Each $25 million increase in agricultural activity could create about 40 to 340 jobs, depending on the agricultural industry.
6.1.2 INTRODUCTION

Large infrastructure projects, such as new irrigation developments in the Darwin catchments, are complex and costly investments. The difficulty in accurately estimating costs and the chance of incurring unanticipated expenses during construction, or not meeting revenue projections when completed, means that there are risks to the viability of developments if they are not thoroughly planned and assessed. For example, in a global review of dam-based megaprojects, Ansar et al. (2014) found forecast costs were systematically biased downwards, with three-quarters of projects running over budget and the mean of actual costs almost double the initial estimates. In recent decades there has been growing emphasis in Australia on greater accountability and transparency in how water resources are managed and priced (e.g. the reforms under the National Water Commission (2004 to 2015)). Part of this shift has involved greater scrutiny of the commerciality of potential new dams.

Ultimately, economic factors are likely to be one of the most important criteria in deciding between potential development opportunities in the Darwin catchments. Ash et al. (2014), in an assessment of 13 agricultural developments in northern Australia, found that while the natural environments are challenging for agriculture, the most important factors determining the viability of developments were management, planning and finances. Even at a pre-feasibility stage, those options that can be clearly identified as being financially non-viable could likely be deprioritised, instead focusing expensive, more detailed and project-specific agronomic, ecological, social, cultural and regulatory assessments on more promising opportunities. This chapter aims to assist in planning and evaluating investments in large-scale irrigated development by highlighting the types of projects that are more likely to be commercially viable, quantifying the costs, benefits and risks involved. The intention is to provide a generic information resource that is broadly applicable to a range of irrigated agriculture development opportunities, rather than examining any specific options in detail. Results are presented in a way that allows readers to estimate whether particular projects they are interested in are likely to be commercially viable, using costs, risks and farm productivity specific to those particular opportunities.

Chapter 4 assessed the viability of new irrigated agriculture and aquaculture opportunities in the Darwin catchments at the enterprise level. Section 6.2 provides indicative costs for a variety of hard, post-processing and community infrastructure that may be required for large water and irrigation developments, beyond the costs presented in Chapter 5. Section 6.3 builds on this with a financial evaluation of new developments at the scheme scale (water infrastructure and associated new farms) from an investor’s perspective using a discounted cashflow framework. Section 6.4 then quantifies the regional economic impacts of irrigated development using regional input–output (I–O) analysis. Other non-market impacts were addressed in Chapter 3, and additional risks are discussed in Chapter 7.

6.2 New infrastructure costs

A range of infrastructure would be required to support development of a new irrigation scheme in the Darwin catchments, both within the scheme itself and beyond. Infrastructure can be considered ‘hard’ or ‘soft’, which within the context of a large irrigation development can be broadly defined as follows:
• Hard infrastructure refers to the physical assets necessary for the functioning of a development and can include water storage, roads, irrigation supply channels and energy, but also processing infrastructure, such as sugar mills, cotton gins, abattoirs and feedlots.

• Soft infrastructure refers to the specialised services required to maintain the economic, health, cultural and social standards of a population. They are indirect costs of a development and are usually less obvious than hard infrastructure costs. They can include expenses that continue after the construction of a development has been completed. Soft infrastructure can include:
  – physical assets, such as community infrastructure (e.g. schools, hospitals, housing)
  – non-physical assets, such as institutions, supporting rules and regulations, compensation packages, law enforcement and emergency services.

New processing infrastructure and community infrastructure are particularly pertinent to large, remote, greenfield developments, and these costs to other providers of infrastructure can be substantial even after a new irrigation scheme is developed. For example, a review of the Ord-East Kimberley Development Plan (for expansion of the Ord irrigation system by about 15,000 ha) found that there were additional costs of $114 million to the Western Australian Government, and $195 million to the Australian Government beyond the planned $220 million state investment in infrastructure to directly support the expansion (Western Australian Auditor General, 2016).

Given the systematic tendency of proponents of large infrastructure projects to substantially under estimate development costs (Wachs, 1990; Odeck and Skjeseth, 1995; Flyvbjerg et al., 2002; Ansar et al., 2014; Western Australian Auditor General, 2016), the purpose of this section is to provide a reference of component infrastructure cost estimates that are as unbiased as possible. The intention here is not to diminish the potential benefits of development and population growth in a region, but to highlight potentially overlooked costs that are required to realise those benefits.

### 6.2.1 COSTS OF HARD INFRASTRUCTURE

Establishing new irrigated agriculture in the Darwin catchments would involve the initial costs of developing water and land resources, and additional farm setup costs for equipment and facilities on each new farm. It may also involve costs associated with constructing processing facilities, extending electricity networks and upgrading road transport.

Costs of water storage and conveyance are provided in sections 5.3 and 5.4, respectively. Indicative costs for processing facilities are provided in Table 6-1 and indicative costs for roads and electricity infrastructure are provided in Table 6-2. Indicative costs for transporting goods to key markets are also listed (Table 6-3). All tables are summarised from information provided in the companion technical report on socio-economics (Stokes et al., 2017).

**Table 6-1 Indicative costs of agricultural processing facilities**

<table>
<thead>
<tr>
<th>ITEM</th>
<th>CAPITAL COST</th>
<th>OPERATING COST</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meat works</td>
<td>$33 million</td>
<td>$315/head</td>
<td>Operational capacity 100,000 head/y</td>
</tr>
<tr>
<td>Cotton gin</td>
<td>$30 million</td>
<td>$1 million/y plus $22 to $30/bale</td>
<td>Operational capacity of 2000 bales/day Operating costs depend on scale of gin and source of energy</td>
</tr>
<tr>
<td>Sugar mill</td>
<td>$396 million</td>
<td>$33 million/y</td>
<td>Operational capacity of 1000 t cane/h, 6-month crushing season Basic mill producing sugar only (no electricity or ethanol)</td>
</tr>
</tbody>
</table>
### Table 6-2 Indicative costs of road and electricity infrastructure

<table>
<thead>
<tr>
<th>ITEM</th>
<th>CAPITAL COST</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roads</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seal dirt road</td>
<td>$0.25 to $2 million/km</td>
<td>Upgrade and widen dirt road to sealed road</td>
</tr>
<tr>
<td>New floodway</td>
<td>about $20 million</td>
<td>Costs of bridges and floodways vary widely</td>
</tr>
<tr>
<td>Electricity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission lines</td>
<td>$0.4 to $1.1 million/km</td>
<td>High-voltage lines deliver bulk flow of electricity from generators over long distances</td>
</tr>
<tr>
<td>Distribution lines</td>
<td>$0.2 million/km</td>
<td>Lower-voltage lines distribute power from substations over shorter distances to end users</td>
</tr>
<tr>
<td>Substation</td>
<td>$10 to $50 million</td>
<td>Transformers and switchgear connect transmission and distribution networks</td>
</tr>
</tbody>
</table>

### Table 6-3 Indicative road transport costs between Adelaide River and key markets and ports

<table>
<thead>
<tr>
<th>DESTINATION</th>
<th>TRANSPORT COST ($/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sydney</td>
<td>507</td>
</tr>
<tr>
<td>Darwin</td>
<td>17</td>
</tr>
<tr>
<td>Brisbane</td>
<td>429</td>
</tr>
<tr>
<td>Adelaide</td>
<td>323</td>
</tr>
<tr>
<td>Melbourne</td>
<td>451</td>
</tr>
<tr>
<td>Perth</td>
<td>448</td>
</tr>
<tr>
<td>Windham Port</td>
<td>88</td>
</tr>
</tbody>
</table>

#### 6.2.2 COSTS OF SOFT INFRASTRUCTURE

The availability of community services and facilities would play an important role in attracting or deterring people from living in a new development in the Darwin catchments. If local populations increase as a result of new irrigated developments, then there would be increased demand for public services in the Darwin catchments, and provision of those services would need to be anticipated and planned. Indicative costs for constructing a range of different facilities that may be required to support population growth are listed in Table 6-4. Each 1000 people in Australia require 4.0 hospital beds served by 28 full-time equivalent hospital staff and $4.0 million/year funding to maintain current mean national levels of hospital service (AIHW, 2017). Health care services in remote locations generally focus on primary and some secondary care, while the broadest range of more specialised tertiary services are concentrated in referral hospitals that are mainly located in large cities but serve large surrounding areas. Primary schools tend to be smaller and more widespread, while larger secondary schools are more centralised.

Demand for community services is growing both from population increases in Australia and rising community expectations. New infrastructure that is built to service that demand would occur irrespective of any development in the Darwin catchments. However, if new irrigation projects shift some people to live in the Darwin catchments, this could then shift the locations of where
some services are delivered and associated infrastructure is built. The costs of delivering services and building infrastructure is generally higher in more remote locations like the Darwin catchments. The net cost of any new infrastructure that is built to support development in the Darwin catchments is the difference in the cost of shifting some infrastructure to this more remote location (not the full cost of facilities (Table 6-4) that would otherwise have been built elsewhere).

**Table 6-4 Indicative costs of community facilities**
Costs are quoted for Darwin as a reference capital city for northern Australia. Costs in remote parts of northern Australia are estimated to be about 30 to 60% higher than those quoted for Darwin. School costs were estimated separately from a range of sources across northern Australia. See companion technical report on socio-economics (Stokes et al., 2017) for details.

<table>
<thead>
<tr>
<th>ITEM</th>
<th>CAPITAL COST</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hospital</td>
<td>$0.2 to $0.5 million/bed</td>
<td>Higher end costs include major operating theatre and larger area of hospital per bed</td>
</tr>
<tr>
<td>School</td>
<td>$25,000 to $33,000 per student</td>
<td>Secondary schools tend to be larger and more centralised than primary schools</td>
</tr>
<tr>
<td>House (each)</td>
<td>$485,000 to $850,000</td>
<td>Single or double storey house</td>
</tr>
<tr>
<td>Unit (each)</td>
<td>$260,000 to $390,000</td>
<td>Unit, fewer than 10 stories, 90 to 120 m²</td>
</tr>
<tr>
<td>Offices</td>
<td>$2,200 to $2,800/m²</td>
<td>1 to 3 stories</td>
</tr>
</tbody>
</table>

### 6.3 Scheme-scale financial viability

Designing a new irrigation project in the Darwin catchments would require balancing a number of factors to find combinations that might collectively constitute a viable investment. Four key determinants of irrigation scheme financial performance examined here are:

1. capital cost of development (Section 6.3.2)
2. farm performance (Section 6.3.2)
3. risks (and associated required level of investment return) (Section 6.3.3)
4. value adding beyond the farm gate (Section 6.3.4).

Other assumptions were limited as much as possible, restricting these to factors with greater certainty and/or lower sensitivity, so that the principles derived would be as generalisable as possible.

A key finding of the irrigation scheme financial analyses is that no single factor is likely to provide a silver bullet to meet the substantial challenge of designing a commercially viable new irrigation scheme. Bridging the financial gap to viability would likely require contributions from each of the above factors, with careful selection to piece together a workable combination. The broad principles for balancing each of these factors are summarised below. However, to understand the discussions of how these factors influence irrigation scheme financial performance in the Darwin catchments, some background information is needed, and this is provided next.
6.3.1 DISCOUNTED CASHFLOW FRAMEWORK, TERMS AND ASSUMPTIONS

Scheme financial evaluations used a discounted cashflow framework to evaluate the commercial viability of irrigation developments. The framework, detailed in the companion technical report on socio-economics (Stokes et al., 2017), was intended to provide a purely financial evaluation of the conditions that would be required to produce an acceptable return from an investor’s perspective. It is not a full economic evaluation of the costs and benefits to other industries, nor does it consider ‘unpriced’ impacts that are not the subject of normal market transactions, or the equity of how costs and benefits are distributed. For the discussion that follows, a scheme was taken to be all the costs and benefits from the development of the land and water resources to the produce leaving the farm gate.

Initially, a generic ‘top-down’ approach was taken, working backwards from the costs of developing a new irrigation scheme to determine the farm gross margins that would be required to make the investment commercially viable. This approach complements the ‘bottom-up’ approach to calculating indicative farm gross margins for different farming options in Chapter 4.

A discounted cashflow analysis considers the lifetime of costs and benefits following capital investment in a new project. Costs and benefits that occur at different times are expressed in constant real dollars, with a discount rate applied to streams of costs and benefits. This section explains the terminology and standard assumptions used.

The discount rate is the percentage by which future cost and benefits are discounted each year (compounded) to convert them to their equivalent present value (PV). A discount rate of 7% is typically used when evaluating public investments.

For an entire project, the net present value (NPV) can be calculated by subtracting the PV of the stream of all costs from the PV of the stream of all benefits. The benefit–cost ratio (BCR) of a project is the PV of all the benefits of a project divided by the PV of all the costs involved in achieving those benefits. To be commercially viable (at the nominated discount rate), a project would require an NPV that is greater than zero (in which case the BCR would be greater than one).

The internal rate of return (IRR) is the discount rate at which the NPV is zero (and the BCR is 1). The project’s target IRR needs to be above the appropriate discount rate for a project to be considered commercially viable based on the risk profile of the development and alternate investment opportunities available to developers.

A project evaluation period of 30 years was used for scheme-scale assessments in this chapter. This project life was selected to reflect the life of the principal infrastructure assets in the scheme.

To simplify the tracking of assets (particularly where staged development is later considered) assets were approximated into three categories of life spans: 15, 40 and 100 years. It was assumed assets would be replaced at the end of their life, and costs were accounted for in full in the actual year of their replacement. At the end of the 30-year evaluation period, a residual value was calculated to account for assets that had not reached the end of their working life. Residual values were calculated as the proportional asset life remaining multiplied by the original asset price.

Capital costs of infrastructure were assumed to be the costs at completion (accounted for in full in the year of delivery), such that the assets commenced operations the following year. The capital costs of developing the water and land resources for irrigated farming (evaluated for costs of
$10,000/ha to $40,000/ha) were considered separately to the additional setup costs for buildings, vehicles and equipment required to establish each new farm (assumed to total $7424/ha).

The main costs for operating a large dam and associated water distribution infrastructure are fixed costs for administering and maintaining the infrastructure, expressed here as percentage of the original capital cost, and variable costs associated with pumping water into distribution channels. At the farm scale, fixed overhead costs are incurred each year whether or not a crop is planted in a particular year. For a generic broadacre crop, these costs were assumed to be $600/ha plus 1% of the original capital value of farm assets. Fixed costs were dominated by the fixed component of labour costs, assuming four full-time equivalent staff per 500 ha farm. Overheads included a lease fee to account for the use of the land prior to irrigation. Other components of overheads include maintenance, insurance, professional services and registrations.

A farm annual gross margin is the difference between the gross income from crop sales and variable costs of growing a crop each year. Net farm revenue is calculated by subtracting fixed overhead costs from the gross margin. Variable costs vary in proportion to the area of land planted, the amount of crop harvested and/or the amount of water and other inputs applied. Farm gross margins can vary substantially within and between locations, as indicated in Section 4.5. Gross margins presented here are the values before subtracting the variable costs of supplying water to farms, with these costs instead accounted for in the capital costs of developing water and land resources (and equivalent unit costs of supplying water presented separately below).

6.3.2 BREAK-EVEN ANALYSES OF DEVELOPMENT OPTIONS FOR GENERIC SCHEMES

The capital costs of developing water and land resources in the Darwin catchments vary widely, such that even when technically feasible options are found, many of these are unlikely to be profitable at the returns and over the time periods expected by many investors. The results presented below suggest that development costs above $15,000/ha (plus $7424/ha farm setup costs) would be difficult to cover from farm gate revenues alone. Gross margins (excluding water supply costs) would need to be above $3000/ha, before accounting for the negative effects of risks. There is little that potential investors can do in this regard other than focusing on the cheapest development options. However, consideration also needs to be given to ongoing maintenance and operating costs, which are typically higher for lower cost, lower life span infrastructure (particularly where assets are engineered to a lower standard).

The costs of developing water and land resources for a new irrigation development can vary substantially, depending on a wide range of case-specific factors dealt with in other parts of this Assessment. These factors include the type and nature of the water source, the type of water storage, geology, topography, soil characteristics, the water distribution system, the type of irrigation system, the type of crop to be grown, land preparation requirements, and the level to which infrastructure is engineered. Initial analyses focused on the capital costs of development, given their importance in determining the financial performance of a scheme, and the high variability in these costs between potential development opportunities. The above financial framework was applied generically, working backwards from broad assumptions about developments with different capital costs to determine the farm gross margins that would be
required for the scheme as a whole to break even (scheme NPV = zero, scheme BCR = 1). The baseline assessments considered the simplest case, where costs and farm performance stayed the same over time: first for a scheme built around a large inchannel dam, and then for an indicative on-farm water source.

**Generic scheme based on a large, off-farm dam**

**Assumptions**

The first assessment considered the case where a single developer would invest in a scheme in the Darwin catchments that included all costs and benefits from initial construction of a large dam (>25 GL/year) off-farm and land preparation up to the revenue received for produce at the farm gate. A range of development costs and target rates of return were considered. A relative breakdown of dam development costs was used to apportion infrastructure assets for dams with different costs of development (Table 6-5). This breakdown was based on costings for two indicative dams in the companion technical report on socio-economics (Stokes et al., 2017). ‘Core’ infrastructure consisted of off-farm assets, such as the dam wall, weir, main supply channel, scheme access road and costs of approvals. ‘Area-dependent’ infrastructure consisted of those assets that scaled with each extra unit of additional irrigated land, such as land development costs, farm roads, and channels for distributing water to each farm. In addition to the costs of developing land and water resources, irrigators would have setup costs for purchasing buildings, vehicles and equipment for each new farm (assumed here to total an extra $7424/ha, Table 6-5).

**Table 6-5 Assumed capital and operating costs for a new irrigation scheme with a new, large dam**

Annual operating and management (O&M) costs are expressed as a percentage of the capital costs of assets.

<table>
<thead>
<tr>
<th>SCHEME COMPONENT</th>
<th>ITEM</th>
<th>LIFE SPAN (y)</th>
<th>UNIT COST ($)</th>
<th>UNIT</th>
<th>O&amp;M COST (% capital cost)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water supplier capital and operating costs (water and land development)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital costs (split as per percentages below)</td>
<td></td>
<td></td>
<td>$10,000 to $40,000</td>
<td>ha</td>
<td></td>
</tr>
<tr>
<td>‘Core’ infrastructure %</td>
<td>100-year infrastructure</td>
<td>100</td>
<td>57%</td>
<td></td>
<td>0.4%</td>
</tr>
<tr>
<td></td>
<td>40-year infrastructure</td>
<td>40</td>
<td>9%</td>
<td></td>
<td>1.6%</td>
</tr>
<tr>
<td>‘Area-dependent’ infrastructure %</td>
<td>100-year infrastructure</td>
<td>100</td>
<td>0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>40-year infrastructure</td>
<td>40</td>
<td>34%</td>
<td></td>
<td>1.0%</td>
</tr>
<tr>
<td><strong>Operating costs (+ asset O&amp;M costs)</strong></td>
<td>Pumping from weir</td>
<td></td>
<td>$30</td>
<td>ML</td>
<td></td>
</tr>
<tr>
<td><strong>Irrigator capital and operating costs (farm buildings and equipment)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Farm setup capital costs (setup costs total $7,424/ha)</td>
<td>Buildings and structures</td>
<td>40</td>
<td>$2,190</td>
<td>ha</td>
<td>1.0%</td>
</tr>
<tr>
<td></td>
<td>Irrigation system</td>
<td>15</td>
<td>$3,960</td>
<td>ha</td>
<td>1.0%</td>
</tr>
<tr>
<td></td>
<td>Vehicles and equipment</td>
<td>15</td>
<td>$1,274</td>
<td>ha</td>
<td>1.0%</td>
</tr>
<tr>
<td>Farm overheads (annual) (+ O&amp;M costs: 1% of capital costs)</td>
<td>Labour, services etc.</td>
<td></td>
<td>$600</td>
<td>ha</td>
<td></td>
</tr>
</tbody>
</table>

Water losses affect volumes of water passing various points from the dam to the crop (see Section 5.4). The analyses required the volume of water reaching the farm gate (used as the pricing point in the next section) and volume of water being pumped from re-regulation structures
into supply channels. Analyses assumed that 6 ML/ha/year of irrigation water was used by crops (before accounting for application losses) with an application efficiency of 85%, on-farm distribution efficiency of 90% and channel distribution efficiency of 90%. On this basis, applied irrigation water at the farm gate would be 7.8 ML/ha/year (= 6 ÷ (85% × 90%) ML/ha/year, after accounting for distribution losses) and water pumped by the water supplier would be 8.7 ML/ha/year (= 7.8 ÷ 90% ML/ha/year). Water supplies were assumed to be 100% reliable and all other factors affecting farm performance were ignored for the initial baseline set of analyses. Sources of risk affecting farm performance are covered separately in Section 6.3.3 and provide a set of risk adjustment multipliers for these baseline results.

The assumed applied irrigation water has a relatively small direct effect on these analyses, by contributing to scheme operating costs. The main way in which applied irrigation water influences results below is indirectly, through the effect on development costs per hectare. A given water supply will be able to irrigate a smaller area for farming options that use more water, so scheme development costs per hectare would be higher and would need to be paid for from a smaller area of farmland.

**Break-even farm gross margins**

Cost and benefit streams, totalled across the scheme, were tracked in separate components for the water supplier and irrigator operations. For the water supplier, these streams were (i) the capital costs (including replacement costs and residual values) of developing the water and land resources, and (ii) the costs of maintaining and operating those assets. For the farm, these streams were (i) the capital costs of the farm buildings and equipment; (ii) the fixed overhead costs, applied to the full area of developed farmland; and (iii) the total farm gross margin (across all farms in the scheme), applied to the mean proportion of land in production. Table 6-6 shows farm annual gross margins that would be required for a scheme to break even (scheme NPV = zero) for a range of different capital costs of development and target IRR. The costs of supplying water to the farm gate are accounted for in the capital costs of development (rather than being subtracted as a variable cost in the farm gross margins presented).

<table>
<thead>
<tr>
<th>TARGET IRR</th>
<th>BREAK-EVEN FARM GROSS MARGIN ($/ha/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$10,000</td>
</tr>
<tr>
<td>0%</td>
<td></td>
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<tr>
<td>1%</td>
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<td>2%</td>
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<tr>
<td>3%</td>
<td></td>
</tr>
<tr>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>7%</td>
<td></td>
</tr>
</tbody>
</table>

Table 6-6 Break-even farm gross margins required for schemes with different dam development costs to meet target investment returns (IRR)

Assumes 100% farm performance in all years and an additional $7424/ha farm setup cost for buildings and equipment (Table 6-5). Gross margins exclude costs of water supply. Risk adjustment multipliers are provided in Section 6.3.3.
As expected, higher farm gross margins are required to cover higher capital costs and higher investment returns. These generic tables can be used together with information on costs and returns for particular cases. For example, Chapter 4 showed that indicative farm gross margins for broadacre crops were unlikely to exceed $3000/ha (depending on crop, location and soils), and scheme development costs for the most promising potential dam sites in this Assessment were estimated at about $18,000/ha to $25,000/ha (assuming crop applied irrigation water of 6 ML/ha, 45% water losses from dam to crop, and $11,000/ha scheme development costs after building the dam wall, before allowing for contingencies or farm setup costs). On this basis, farm gate revenues alone would fall short of reaching a 7% return on capital invested (Table 6-6).

Break-even pricing of dam water

If the water supplier and farmers were separate investors, then a price would need to be set for the delivery of water from the dam operator to the irrigators. This arrangement is broadly analogous to some large SunWater-operated irrigation schemes in Queensland, such as the Burdekin Haughton Water Supply Scheme and the Mareeba–Dimbulah Water Supply Scheme. From the water supplier’s perspective, two options for pricing water were considered. The first was on a fully commercial basis for the same combinations of development costs and target IRRs used above (Table 6-7). The second, as a lower bound, was the water pricing that would be required to cover just the ongoing maintenance and operating costs (excluding the initial capital costs of constructing the dam and developing the land) (Table 6-8).
TARGET IRR | WATER PRICE THAT WATER SUPPLIER WOULD NEED TO CHARGE TO BE PROFITABLE ($/ML AT FARM GATE)
--- | --- | --- | --- | --- | --- | --- |
14% | 223 | 318 | 412 | 507 | 602 | 792 |

Table 6-8 Minimum price water supplier would have to charge for water for schemes with different costs of development to cover annual O&M costs
Fully covers annual water supplier operating costs each year, so discount rate assumptions have no effect. Water was priced at farm gate assuming applied irrigation water of 7.8 ML/ha/year at farm gate, 8.7 ML/ha/year at weir, scheme pumping costs of $30/ML at weir, and 100% farm performance.

WATER PRICE TO COVER ONLY WATER SUPPLIER OPERATING COSTS ($/ML AT FARM GATE)

| Capital costs for water supplier to develop water and land ($/ha) |
|---|---|---|---|---|---|
| $10,000 | $15,000 | $20,000 | $25,000 | $30,000 | $40,000 |
| 43 | 47 | 52 | 57 | 61 | 71 |

Water pricing was then considered from the irrigator’s perspective and the capacity of irrigators to pay. Table 6-9 shows water prices for a farm to break even (farm NPV = zero) for a range of different farm gross margins and applied irrigation water combinations.

Under a favourable scheme for a broadacre crop with a gross margin of $3000/ha and an irrigator seeking an IRR of 7%, irrigators would be able to pay $202/ML for a crop using 6 ML/ha/year (of irrigation water before application losses, Table 6-9). Water payments from irrigators at these water prices would more than cover the ongoing operating costs of a water supplier (<$100/ML across a wide range of development costs, Table 6-8), but would fall short of covering the full costs of supplying water at a commercial rate of return (e.g. $244/ML for a 7% IRR on supplier capital development costs of $20,000/ha, Table 6-7).

Table 6-9 Break-even water pricing for the amount an irrigator could afford to pay depending on the annual gross margin of the farm, crop applied irrigation water (before application losses), and the irrigator’s target internal rate of return (IRR)
Assumes water volumes metered at the farm gate were 1.31 times the crop applied irrigation water after accounting for losses (based on 90% on-farm distribution efficiency and 85% application efficiency).

| TARGET IRR (%) | GROSS MARGIN ($/ha) | IRRIGATOR CAPACITY TO PAY FOR WATER AND STILL BE PROFITABLE ($/ML AT FARM GATE) | Crop applied irrigation water [and farm gate applied irrigation water] (ML/ha) |
|---|---|---|---|---|---|---|---|
| 3% | $1500 | 55 | 37 | 27 | 22 | 18 |
| | $2000 | 151 | 100 | 75 | 60 | 50 |
| | $2500 | 246 | 164 | 123 | 98 | 82 |
| | $3000 | 342 | 228 | 171 | 137 | 114 |
| 7% | $1500 | 15 | 10 | 8 | 6 | 5 |
| | $2000 | 111 | 74 | 56 | 44 | 37 |
| | $2500 | 207 | 138 | 103 | 83 | 69 |
| | $3000 | 302 | 202 | 151 | 121 | 101 |
| 10% | $1500 | na† | na | na | na | na |

Chapter 6 Overview of economic opportunities and constraints | 349
Generic modular development using an on-farm water source

The second baseline case considered an irrigation development in the Darwin catchments that substituted the large dam (above) with an on-farm source of water. The indicative on-farm water source was based on greenfield development using bores and pivots. A detailed breakdown of costs for this option is provided in the companion technical report on socio-economics (Stokes et al., 2017). Aside from being on-farm, this option contrasted with the dam water option in using an alternative water source (ground versus surface water) and using shorter life span infrastructure (potentially cheaper upfront capital costs but higher ongoing costs). It is also very modular, which would be more amenable to staging (Section 6.3.3), alternative models of investment (less reliant on a single large investor/developer) and developments across a wide range of scales (from part of a farm to large schemes).

Assumptions

Assumptions for the costs of developing and operating on-farm water sources were the same as for the off-farm dam example above, except that the dam water source was replaced with costs of developing and operating a series of bores (Table 6-10). Analyses initially assumed the developed water source would fully meet crop demand (with 100% reliability). Pumping costs would be part of the variable costs that would have to be included in the farm gross margin for a particular cropping option before comparing to the break-even gross margins calculated here (whereas for the dam option above, pumping costs for delivering water to the farm gate were a scheme cost, recovered through the price charged to farms for supplying water).

Table 6-10 Assumed capital and operating (O&M) costs for a new development using an on-farm water source

Modular on-farm development involves only separate ‘Area-dependent’ infrastructure for each farm, and there is no shared ‘Core’ infrastructure (as there was for the large dam).

<table>
<thead>
<tr>
<th>SCHEME COMPONENT</th>
<th>ITEM</th>
<th>LIFE SPAN (y)</th>
<th>UNIT COST ($)</th>
<th>UNIT</th>
<th>O&amp;M COST (% capital cost)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs of developing on-farm water resource and preparing land</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(split as per percentages below)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>‘Area-dependent’ infrastructure % (no ‘Core’ infrastructure)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40-year infrastructure</td>
<td>100</td>
<td>49%</td>
<td>1.0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-year infrastructure</td>
<td>40</td>
<td>51%</td>
<td>1.0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irrigator capital and operating costs (farm buildings and equipment)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Break-even farm gross margins

Table 6-11 shows the farm gross margins that would be required for the scheme to break even (NPV = zero). Note that while shorter life span infrastructure may reduce development costs of on-farm infrastructure, this leads to more frequent asset replacement, so higher farm gross margins were required for the scheme to break even relative to the same development cost per area for a large dam (Table 6-6). Thus, although some on-farm options for water development may be cheaper than building a new large dam, higher ongoing costs associated with shorter life span infrastructure offset some of that advantage. Small offstream storages, an alternative on-farm water source, can also be less reliable water sources than large instream dams, and are less able to carry water through the dry season, which limits farming options.

**Table 6-11 Break-even farm gross margins required for schemes with different costs of developing on-farm water sources to meet target investment returns (IRR)**

Assumes an additional $7424/ha farm setup costs for buildings and equipment (Table 6-11) and that the developed water source is able to fully meet crop requirements to deliver 100% farm performance in all years. Risk adjustment multipliers are provided in Section 6.3.3.

<table>
<thead>
<tr>
<th>TARGET IRR</th>
<th>$5,000</th>
<th>$10,000</th>
<th>$15,000</th>
<th>$20,000</th>
<th>$25,000</th>
<th>$30,000</th>
<th>$40,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>1,359</td>
<td>1,640</td>
<td>1,921</td>
<td>2,202</td>
<td>2,483</td>
<td>2,764</td>
<td>3,326</td>
</tr>
<tr>
<td>1%</td>
<td>1,432</td>
<td>1,743</td>
<td>2,054</td>
<td>2,365</td>
<td>2,676</td>
<td>2,987</td>
<td>3,609</td>
</tr>
<tr>
<td>2%</td>
<td>1,508</td>
<td>1,851</td>
<td>2,193</td>
<td>2,536</td>
<td>2,878</td>
<td>3,221</td>
<td>3,906</td>
</tr>
<tr>
<td>3%</td>
<td>1,588</td>
<td>1,964</td>
<td>2,339</td>
<td>2,715</td>
<td>3,090</td>
<td>3,466</td>
<td>4,217</td>
</tr>
<tr>
<td>5%</td>
<td>1,758</td>
<td>2,204</td>
<td>2,650</td>
<td>3,095</td>
<td>3,541</td>
<td>3,986</td>
<td>4,878</td>
</tr>
<tr>
<td>7%</td>
<td>1,940</td>
<td>2,461</td>
<td>2,982</td>
<td>3,503</td>
<td>4,023</td>
<td>4,544</td>
<td>5,585</td>
</tr>
<tr>
<td>10%</td>
<td>2,233</td>
<td>2,874</td>
<td>3,515</td>
<td>4,156</td>
<td>4,798</td>
<td>5,439</td>
<td>6,721</td>
</tr>
<tr>
<td>12%</td>
<td>2,438</td>
<td>3,164</td>
<td>3,890</td>
<td>4,616</td>
<td>5,342</td>
<td>6,068</td>
<td>7,519</td>
</tr>
<tr>
<td>14%</td>
<td>2,651</td>
<td>3,464</td>
<td>4,277</td>
<td>5,090</td>
<td>5,904</td>
<td>6,717</td>
<td>8,343</td>
</tr>
</tbody>
</table>

**6.3.3 RISKS ASSOCIATED WITH VARIABILITY IN FARM PERFORMANCE**

This section assessed the impacts of two types of risks on scheme financial performance: those that reduce farm performance through the early establishment and learning years, and those occurring periodically and continuously. Setbacks that occur early on after a scheme is established
were found to have the largest effect on scheme viability, particularly at higher discount rates. There is a strong incentive to start any new irrigation development with well-established crops and technologies, and to be thoroughly prepared for the anticipatable agronomic risks of establishing new farmland. Analyses showed that delaying full development for longer periods than the learning time had only a slight negative effect on IRRs, whereas proceeding to full development before learning was complete had a much larger impact. This implies that it would be prudent to err on the side of delaying full development (particularly given that in practice, it would only be possible to know when full performance was achieved in retrospect, not in advance). An added benefit of staging would be limiting losses where small-scale testing proves initial assumptions of benefits to be over-optimistic and that full-scale development could never be profitable, even after trying to overcome unanticipated challenges.

For an investment to be viable, farm gross margins need to be sustained at high levels over long periods. Thus, variability in farm performance poses risks that need to be considered and managed. Gross margins can vary between years either because of short-term initial underperformance or because of periodic shocks. Initial underperformance is likely to be associated with learning as farming practices are adapted to local conditions, overcoming initial challenges to reach their long-term potential. There would be further unavoidable periodic risks associated with water reliability, climate variability, flooding, outbreaks of pests and diseases, periodic technical/equipment failures, and fluctuations in commodity prices and market access. Periodic risks, such as reliability of water supply, are less easy to avoid. Risks that cannot be avoided need to be managed, mitigated where possible, and accounted for in determining the realistic returns that can be expected from a scheme. This would include having adequate capital buffers to survive through challenging periods. Another perceived risk for investors is that of uncertainty around future policy changes and delays in regulatory approvals. Reducing this, or any other sources of risk, would contribute to making marginal investment opportunities more attractive.

Results for analyses of both periodic and learning risks are shown below. Findings are also presented for how staging might be able to mitigate the costs of learning, and additional risks that staging could introduce. Throughout this section, farm performance in a given year is quantified as the proportion of the long-term mean gross margin a farm attains, where 100% performance is when this level is reached and zero % equates to a performance where revenues only balance variable costs (gross margin = $zero).

**Risks from periodic underperformance**

Analyses considered periodic risks generically, without assuming any of the particular causes listed above. Periodic risks were characterised in terms of three components to test their effects on scheme financial performance:

- reliability: the proportion of ‘good’ years where the ‘full’ 100% farm performance was achieved, with the remainder of years being ‘failures’ where some negative impact was experienced
- severity: the farm performance in a ‘failed’ year where some type of setback occurs
- timing: for ‘early’ timing a 10-year cycle was used where, for example, with 80% reliability failures would occur in the first 2 years of the scheme and the first 2 years of each 10 years in a cycle after that. For ‘late’ timing, the ‘failures’ came at the end of each 10-year cycle. Where
timing was not used, each year was represented as having the long-term mean farm performance of ‘good’ and ‘failed’ years (frequency weighted).

Table 6-12 summarises the effects of a range of different reliabilities and severities for periodic risks (without considering timing of impacts) on scheme viability. Periodic risks had a consistent proportional effect on break-even gross margins, irrespective of development options or costs, so results were simplified as a set of risk adjustment multipliers (which could be applied to the baseline tables of break-even gross margins presented before). These same multipliers apply to the break-even water prices that irrigators can afford to pay.

As would be expected, the greater the frequency and severity of ‘failed’ years, the greater the impact on scheme viability and the greater the increase in farm gross margins that would be required to offset these impacts. As an example, the reliability of water supply is one of the more important sources of unavoidable variability in productivity of irrigated farms. If the planted area of land was reduced in years without a full supply (‘failed’ years) so that the cropped area was always fully irrigated, then the water reliability is the same as the periodic risk reliability (Table 6-12), and the proportion of water available in a ‘failed’ year is equivalent to the mean farm performance. For example, if a water supply was 85% reliable and provided on average 75% of its full supply in ‘failed’ years, the risk adjustment multiplier that would have to be applied to baseline break-even gross margins (Table 6-6 and Table 6-11) would be 1.04 (Table 6-12). This means that a 4% higher gross margin would be required to break even than if water could be supplied at 100% reliability. For crops where the quality of produce is more important than the quantity, such as annual horticulture crops, the approach of reducing planted land area in proportion to available water in ‘failed’ years seems reasonable. However, for perennial horticulture or tree crops it may be difficult to reduce (or increase) areas on an annual basis. Farmers of these crops will therefore tend to opt for systems with a high degree of reliability of water supply (e.g. 95%). For many broadacre crops, it may be possible to deficit irrigate a larger area to slightly mitigate the impact of years with lower water allocations. As shown in Section 4.5, the agronomic optimum does not necessarily equal the economic optimum. Measures such as deficit irrigation could partially mitigate impacts on farm performance in years with reduced water availability, as could carryover effects from inputs (such as fertiliser) in a failed year that reduce input costs the following year.

Table 6-12 Risk adjustment multipliers for break-even gross margins, accounting for the effects of reliability and severity (level of farm performance in ‘failed’ years) of periodic risks
Results are not affected by discount rates. ‘Good’ years = 100% farm performance; ‘Failed’ = <100% performance. ‘Failed year performance’ is the mean farm gross margin in years where some type of setback is experienced relative to the mean gross margin when the farm is running at ‘full’ performance.

<table>
<thead>
<tr>
<th>FAILED YEAR PERFORMANCE</th>
<th>BREAK-EVEN GROSS MARGIN RISK ADJUSTMENT MULTIPLIER (VS BASE 100% RELIABILITY TABLES)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reliability (Proportion of 'good' years)</td>
</tr>
<tr>
<td>1.00</td>
<td>0.90</td>
</tr>
<tr>
<td>85%</td>
<td>1.00</td>
</tr>
<tr>
<td>75%</td>
<td>1.00</td>
</tr>
<tr>
<td>50%</td>
<td>1.00</td>
</tr>
<tr>
<td>25%</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Table 6-13 summarises how timing of periodic impacts affects scheme viability, providing break-even risk adjustment multipliers for a range of reliabilities for an impact that had 50% severity with late timing, early timing, and no (long-term frequency, weighted mean performance) timing. These results show that any negative disturbances that reduce farm performance will have a larger effect if they occur early on after the scheme is established, and that this effect is greater at higher discount rates (or higher target IRRs). For example, at a 7% discount rate and 70% reliability with ‘late’ timing (where setbacks occur in the in the last three of every 10 years) the gross margin multiplier is 1.13, meaning the annual farm gross margin would need to be 13% higher than if farm performance were 100% reliable. In contrast, for the same settings with ‘early’ timing, the gross margin multiplier is 1.23, so impacts of early setbacks are more severe and the farm gross margin would have to be 23% higher than if farm performance were 100% reliable.

Table 6-13 Risk adjustment multipliers for break-even gross margins, accounting for the effects of reliability and timing of periodic risks
Assumes 50% farm performance during ‘failed’ years, where 50% farm performance means 50% of the gross margin at ‘full’ potential production.

<table>
<thead>
<tr>
<th>TARGET IRR</th>
<th>TIMING OF FAILED YEARS</th>
<th>BREAK-EVEN GROSS MARGIN RISK ADJUSTMENT MULTIPLIER (VS BASE 100% RELIABILITY TABLES)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.00</td>
<td>0.90</td>
</tr>
<tr>
<td>3%</td>
<td>Late</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Mean – no timing</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Early</td>
<td>1.00</td>
</tr>
<tr>
<td>7%</td>
<td>Late</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Mean – no timing</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Early</td>
<td>1.00</td>
</tr>
<tr>
<td>10%</td>
<td>Late</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Mean – no timing</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Early</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Risks from initial ‘learning’ period
Another form of risk arises from the initial challenges in establishing and adapting agriculture in a new part of the Darwin catchments, and includes setbacks from delays, such as gaining regulatory approvals. Some of these risks are avoidable if investors and farmers learn from past experiences of development in northern Australia (e.g. Ash et al., 2014), avoid previous mistakes, and select farming options that are already well proven in analogous locations. However, even if developers are well prepared, there are likely to be initial challenges in adapting to the unique circumstances of a new location. Newly developed farmland can take some time to reach its productive potential as soil nutrient pools are established, soil limitations are ameliorated, suckers and weeds are controlled, and pest management systems are established.
‘Learning’ (used here to broadly represent all aspects of overcoming initial sources of farm underperformance) was assessed in terms of two simplified generic characteristics:

- initial level of performance: represented as described before, as the proportion of the long-term, mean gross margin that the farm achieves in its first year
- time to learn: the number of years taken to reach the long-term, mean farm performance. Performance was represented as increasing linearly over the learning period from the starting level to the long-term, mean performance level (100%).

The effect of learning on scheme financial viability was considered for a range of initial levels of farm performance and learning times. As before, learning had consistent proportional effects on break-even gross margins, so results were simplified as a set of risk adjustment multipliers (Table 6-14). As would be expected, the impacts on scheme viability are greater the lower the starting level of farm performance, and the longer it takes to reach the long-term performance level. Since these impacts, by their nature, are weighted to the early years of a new development, they have more impact at higher discount rates (and investors’ target IRRs). To minimise risks of learning impacts, there is a strong incentive to start any new irrigation development with well-established crops and technologies, and to be thoroughly prepared for the anticipatable agronomic risks of establishing new farmland. Higher-risk options (e.g. novel crops, equipment or practices that are not currently in profitable commercial use in analogous environments) could be tested and refined on a small scale until locally proven.

Table 6-14 Risk adjustment multipliers for break-even gross margins, accounting for the effects of learning risks

Learning risks were expressed as the level of initial farm underperformance and time taken to reach full performance levels. Initial farm performance is the initial gross margin as a percentage of the gross margin at ‘full’ performance.

<table>
<thead>
<tr>
<th>TARGET IRR</th>
<th>INITIAL FARM PERFORMANCE</th>
<th>BREAK-EVEN GROSS MARGIN RISK ADJUSTMENT MULTIPLIER (VS BASE 100% RELIABILITY TABLES)</th>
<th>Learning time (years to 100% performance)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>3%</td>
<td>85%</td>
<td>1.01</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td>75%</td>
<td>1.02</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>1.04</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td>25%</td>
<td>1.06</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td>0%</td>
<td>1.08</td>
<td>1.14</td>
</tr>
<tr>
<td>7%</td>
<td>85%</td>
<td>1.02</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>75%</td>
<td>1.03</td>
<td>1.05</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>1.06</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td>25%</td>
<td>1.09</td>
<td>1.15</td>
</tr>
<tr>
<td></td>
<td>0%</td>
<td>1.12</td>
<td>1.21</td>
</tr>
<tr>
<td>10%</td>
<td>85%</td>
<td>1.02</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>75%</td>
<td>1.04</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>1.08</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td>25%</td>
<td>1.12</td>
<td>1.20</td>
</tr>
<tr>
<td></td>
<td>0%</td>
<td>1.16</td>
<td>1.28</td>
</tr>
</tbody>
</table>
Risks and benefits of staged development

One possible strategy for dealing with learning risks could be to stage development, so that the bulk of the overall capital investment is delayed until farming systems have been tested and locally adapted to new parts of the Darwin catchments on a smaller scale. Illustrative examples are provided below to demonstrate general principles about the risks and benefits of staging.

Table 6-15 shows the effects on scheme financial returns for seven severities of learning risk: initial farm performance was set at levels from 100 to –20% and performance was increased by 10% each year so that corresponding learning times to full performance were zero to 12 years (as per the first two columns of Table 6-15).

Staging considered four options, in which initially only 5% of the total land area was developed, and the remaining area was developed after delays of zero, 4, 8 and 12 years (where the zero-year delay corresponds to no staging). Staging was considered for both the dam and on-farm water source development options used in the baseline assessments (Section 6.3.2), retaining the standard assumptions (Table 6-5 and Table 6-10). However, some extra details had to be specified in order to run the analyses. These were set towards the more favourable end of what might be possible, but with an emphasis on making relative comparisons between staging options. Both the dam and the on-farm water source developments used a farm gross margin of $2500/ha (representative of the upper range for broadacre crops, see Section 4.5) and an annual water reliability of 85%, with 77% of the full water supply available on average in the other 15% of years. The total costs at project completion were assumed to be unaffected by how the project was staged (i.e. no wasted test infrastructure from stage 1, or cost inefficiencies from developing parts of the assets at different times).

For the dam development option, staging involved building the weir first and delaying building the main dam. It was assumed that the weir and other ‘core’ off-farm infrastructure (e.g. access road, channels and approvals) required to get the test stage of development operational would cost 7% of the total project costs for ‘core’ infrastructure (Table 6-5). ‘Area-dependent’ infrastructure was scaled linearly with the area developed, so 5% of those costs (Table 6-5) were incurred in the test stage. Costs for developing water and land resources were assumed to be $20,000/ha.

The on-farm water source was assumed to be entirely modular, so that each unit of farmland could be developed entirely independently of the next, scaling total project costs to the proportion of land developed (5% in the test stage). Costs for developing water and land resources were assumed to be $10,000/ha.

A comparison of IRRs between staging options (Table 6-15) shows that the financial penalties for not staging increase as learning risks become more severe (in terms of lower starting performance and longer learning times). The impacts of learning risks could best be offset by matching the delay in proceeding to full-scale development to the learning time (i.e. completing development only once the test stage had reached full financial performance). Delaying full development for longer periods than the learning time had only a slight negative effect on IRRs, whereas proceeding to full development before learning was complete had a much larger impact. This implies that it would be prudent to err on the side of delaying full development (particularly given that in practice, it would only be possible to know when full performance was achieved in retrospect, not in advance).
Staging is complex, and a wide range of other risks and benefits would need to be considered beyond these simple, illustrative examples. An added benefit of staging would be limiting losses, where small-scale testing proves initial assumptions of costs and benefits to be over-optimistic and that full-scale development could never be profitable, even after trying to overcome unanticipated challenges. In such cases, losses could be reduced by opting not to proceed with further development. Indeed, financiers of a development might stage release of loans for this reason as a risk control measure. However, staging can transfer risks from one party to another and might not be uniformly beneficial to all parties involved in a development. For example, staged finance might delay development stages beyond what is optimal for learning times, even when development options are well proven and developers would prefer to proceed more quickly. Similarly, if staging is implemented to control risks of farm performance, while farming practices are adapted to local conditions, this could transfer risks to investors in supporting infrastructure further down the supply chain. This is particularly the case for crops such as sugarcane and cotton, where local processing is integral to the industry and requires production at large scale to be viable. Delays in development beyond optimal learning times could also be imposed for other reasons, such as logistic constraints on the rate at which land could be developed, seed material could be propagated (for clonal crops) or skilled labour could be recruited. The IRRs in Table 6-15 indicate that short-term delays (<2 years) would likely have only a minimal impact on scheme financial performance.

Table 6-15 Effect of different staging options on scheme performance for a range of learning risks

Scheme performance was measured as the internal rate of return (IRR) for each combination of staging and learning. The staging delay with the highest IRR for each level of learning risk (row) is highlighted in darker green, and delays with IRRs within 0.2% of the best IRR are highlighted in lighter green. Staging involved initially developing 5% of the farmland for testing, then allowing for learning periods of different durations before proceeding to full development.
Some of the assumptions in the illustrative examples were oversimplified. For example, staging may well incur extra costs if purchasing assets and services for development at different times is less efficient than doing so over one concentrated period, or if some of the infrastructure from the test stage does not fit with the requirements of the completed scheme. In addition, learning was considered to occur entirely at the small test scale and to then be completely scalable to full development. In reality, as highlighted by Ash et al. (2014), some of the most substantial challenges in past agricultural developments in northern Australia have come in the scaling-up phase. There is no guarantee that success at the level of an individual farm will necessarily scale easily to establishing a large, new industry in a certain location. This is particularly the case if success at the farm level is based on taking advantage of case-specific opportunities that are not easily duplicated at scale. Challenges in scaling up production could include the need for local processing facilities, access to sufficient capital, establishing and expanding markets and supply chains, training and recruiting skilled labour, availability of local support services, and building new transport and utilities infrastructure to address bottlenecks. There would be a component of learning associated with addressing these scaling challenges. An intermediate staging step, after the initial small-scale testing, might help with this learning. Such intermediate stages are better suited to developments using modular on-farm water sources than those that are based on a single, large dam.

6.3.4 POTENTIAL BENEFITS FROM INDUSTRY SYNERGIES AND INTEGRATION

Off-farm value adding and synergies could contribute to the viability of a potential new scheme in the Darwin catchments. The illustrative example explored here was adding a sugar mill to an irrigated sugarcane scheme, which demonstrated that the benefit from the higher value of the processed cane exceeds the additional costs of building and running a mill. This also suggested that an additional by-product, cogeneration of electricity, would likely be required if any such scheme were to be viable.

Sugar was used as an illustrative example because of the relatively high value adding from local processing to illustrate the upper-end potential of synergies beyond the farm gate (not because this was the most likely crop to be grown in the catchment). A wide range of other synergies could also be considered to improve scheme revenues or share costs, as listed at the end of this section. It should be noted, however, that the more complex a scheme becomes and the more strongly interdependent its components, the greater the risk that underperformance of one component could undermine the viability of the entire scheme.

Results are presented for two options for integrating a sugar mill into a scheme:

- a mill operating on a standard 6-month harvest/crushing season, producing sugar only
- a mill operating on a 6-month season with electricity cogeneration added.
Assumptions were the same as for the generic dam (Table 6-5) except that a specific scheme size was used, details of sugar cropping were added, a sugar mill was added (with associated extra streams of costs and benefits), and water supply was assumed to be 85% reliable, with 77% of the full water yield available on average in the other 15% of years (Table 6-16). Although some specific values had to be assumed for the purposes of the analysis, these should be considered as roughly indicative, and the emphasis was on the relative comparison between options rather than absolute values of results. Electricity cogeneration in remote locations is particularly difficult in this regard, given how site-specific it would be. Rough costs are provided in the assumptions below, which included a $20 million grid-connection cost. Wholesale electricity prices on the National Electricity Market (NEM) have more than doubled in the past 5 years, averaging about $90/MWh in 2017, and projected to be about $80/MWh in 2018 (AEMO, 2017). Renewable energy certificates (RECs) traded at about $85 per large-scale generation certificate (LGC, in units of MWh) in 2017, but the future of RECs is uncertain. Given the uncertainty in electricity prices over the life of the project, analyses used a conservative electricity price of $90/MWh, but also used a higher price of $165/MWh for comparison.

Table 6-16 Assumptions used for incorporating a sugar mill into an irrigation scheme
Two options for integrating a mill were explored. Cogen = cogeneration of electricity from bagasse (fibre); CCS = commercial cane sugar. Water reliability was assumed to be 85%, with a mean of 77% of the full water yield available in the other 15% of years.

<table>
<thead>
<tr>
<th>ITEM</th>
<th>UNITS</th>
<th>6-mo SEASON SUGAR ONLY</th>
<th>6-mo SEASON + COGEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheme size</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scheme area</td>
<td>ha</td>
<td>50,000</td>
<td>50,000</td>
</tr>
<tr>
<td>Capital costs of water and land development†</td>
<td>$ million</td>
<td>1,000</td>
<td>1,000</td>
</tr>
<tr>
<td>Capital costs per ha for water and land development†</td>
<td>$/ha</td>
<td>20,000</td>
<td>20,000</td>
</tr>
<tr>
<td>Cropping</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean area under cropping (1 in 5 year fallow)</td>
<td>%</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Crop applied irrigation water (before application losses)</td>
<td>ML/ha</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Crop yield (excluding fallow years)</td>
<td>t cane/ha</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Sugarcane CCS (sugar content mill can extract from cane)</td>
<td>%</td>
<td>15.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Sugarcane fibre content (affects rate mill can crush cane)</td>
<td>%</td>
<td>15.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Farm variable costs of growing crop</td>
<td>$/ha</td>
<td>1,100</td>
<td>1,100</td>
</tr>
<tr>
<td>Farm variable costs of harvesting crop</td>
<td>$/t cane</td>
<td>8.00</td>
<td>8.00</td>
</tr>
<tr>
<td>Cane price (industry formula based on sugar price)</td>
<td>$/t cane</td>
<td>44.55</td>
<td>44.55</td>
</tr>
<tr>
<td>Processing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length of crushing season</td>
<td>month</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Mill capital cost (including connection to grid for cogen)</td>
<td>$ million</td>
<td>481</td>
<td>716</td>
</tr>
<tr>
<td>Mill throughput rate</td>
<td>t/h</td>
<td>1,214</td>
<td>1,214</td>
</tr>
<tr>
<td>Mill reliability (% time operational)</td>
<td>%</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Cane transport costs (farm to mill)</td>
<td>$/t</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Processing costs</td>
<td>$ million/y</td>
<td>34</td>
<td>35</td>
</tr>
<tr>
<td>Sugar transport costs (mill to port)</td>
<td>$/t</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>
Table 6-17 Comparison of financial performance of an irrigation scheme with and without a sugar mill included

Two options for integrating a mill were explored. Cogen = cogeneration of electricity from bagasse (fibre); IRR = internal rate of return. Given the uncertainty in wholesale electricity prices, the comparison is repeated at the bottom of the table for an alternate, higher electricity price (including large-scale generation certificates for renewable energy).

<table>
<thead>
<tr>
<th>PERFORMANCE METRIC</th>
<th>UNITS</th>
<th>6-mo SEASON</th>
<th>6-mo SEASON</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SUGAR ONLY</td>
<td>+ COGEN</td>
</tr>
<tr>
<td>Scheme from dam to farm gate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Revenue from sugarcane</td>
<td>$ million</td>
<td>214</td>
<td>214</td>
</tr>
<tr>
<td>Total capital cost of development</td>
<td>$ million</td>
<td>1297</td>
<td>1297</td>
</tr>
<tr>
<td>Scheme IRR (farm gate)</td>
<td>%</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Scheme from dam to port (including processing, applies to both electricity prices below)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Revenue from raw sugar</td>
<td>$ million</td>
<td>324</td>
<td>324</td>
</tr>
<tr>
<td>Revenue from molasses</td>
<td>$ million</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Total capital cost of development</td>
<td>$ million</td>
<td>1778</td>
<td>2013</td>
</tr>
<tr>
<td>Scheme comparison: Processing vs farm gate (price for cogenerated electricity = $90/MWh)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Revenue from electricity (to node, after losses)</td>
<td>$ million</td>
<td>0</td>
<td>31</td>
</tr>
</tbody>
</table>

Source: Details for mill processing costs provided in companion technical report on socio-economics (Stokes et al., 2017)

†Water supplier development costs of $20,000/ha equate to a dam cost of $650/ML/year yielded at the dam wall (with 85% reliability), assuming overall system efficiency of 55% (18 ML/ha/year applied irrigation water at dam wall) and an additional $10,500/ha supplier development costs. ‡na = not applicable
### PERFORMANCE METRIC

<table>
<thead>
<tr>
<th></th>
<th>UNITS</th>
<th>6-mo SEASON SUGAR ONLY</th>
<th>6-mo SEASON + COGEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>% extra capital spent</td>
<td>%</td>
<td>37</td>
<td>55</td>
</tr>
<tr>
<td>% extra revenue generated</td>
<td>%</td>
<td>54</td>
<td>69</td>
</tr>
<tr>
<td>Scheme IRR (to port)</td>
<td>%</td>
<td>4.2</td>
<td>5.1</td>
</tr>
</tbody>
</table>

### Scheme comparison: Processing vs farm gate (alternate price for cogenerated electricity = $165/MWh)

<table>
<thead>
<tr>
<th>Revenue from electricity (to node, after losses)</th>
<th>$ million</th>
<th>0</th>
<th>56</th>
</tr>
</thead>
<tbody>
<tr>
<td>% extra capital spent</td>
<td>%</td>
<td>37</td>
<td>55</td>
</tr>
<tr>
<td>% extra revenue generated</td>
<td>%</td>
<td>54</td>
<td>81</td>
</tr>
<tr>
<td>Scheme IRR (to port)</td>
<td>%</td>
<td>4.2</td>
<td>6.6</td>
</tr>
</tbody>
</table>

Other synergies that could also be considered to improve scheme revenues or reduce costs would include: sequential cropping (increasing net farm revenue by producing more than one crop from the same field each year), local use of by-products (such as feed supplements for livestock), including small-scale, high-value crops in the mix of farms in a scheme; expanding the scale of a scheme, with extra dryland/opportunistic cropping around the irrigated core; improving transport infrastructure and supply chains (reducing the disadvantages of remote locations); generating hydro-electric power; and integrating farming industries (savings from synergies). Many of these options are untested, so location-appropriate details would need to be developed and proven before they could be seriously considered. Indirect costs and benefits beyond the irrigation scheme could also be important when considering public investment in new water infrastructure. Regional economic benefits are covered in the next section, while non-market impacts are covered in chapters 3 and 7, but are not converted to dollar values.

### 6.4 Regional-scale economic impact of irrigated development

A water storage development scheme to promote irrigated agriculture or aquaculture could provide economic benefits to the Darwin catchments and broader region in terms of both increased economic activity and jobs. The size of the total economic benefits experienced would depend on the scale of the development, the type of agriculture that is established, and how much spending from the increased economic activities occurs within the region. Regional economic impacts would be an important consideration for evaluating potential new water development projects.

It was estimated that each dollar spent on construction within the Darwin catchments generated an additional $1.06 of indirect benefits ($2.06 total regional benefits, including the direct benefit of each $1.00 spent on construction). Each dollar of direct benefit from new agricultural activity was estimated to generate an additional $0.46 to $1.82 in regional economic activity (depending on the particular agricultural industry).

If $2 billion capital was spent on developing an irrigated agricultural scheme within the Darwin catchments, and 50% of this capital cost was spent locally, the one-off total economic activity generated from this construction within the catchment and surrounding region would be $2.06 billion (from Table 6-21). Assuming this development directly enabled an extra $100 million of output per year on a continuing basis through the lifetime of the irrigation scheme from
irrigated cropping, then the region would benefit from $146 million of economic activity recurring annually (from Table 6-19) and generate about 160 full-time equivalent jobs (from Table 6-20).

There would be additional national benefits from expenditure flowing to other regions, and the stabilising effect of geographic diversification on agricultural production in the face of local disruptions, such as climate variability or regional water reforms.

The full, catchment-wide impact of the economic stimulus provided by an irrigated agriculture or aquaculture development project extends far beyond the impact on those businesses and workers directly involved in either the short term (construction phase) or longer term (operational phase). Those businesses directly benefiting from the project would need to increase their purchases of the raw materials and intermediate products used by their growing outputs. Should any of these purchases be made within the surrounding region, then this provides a stimulus to those businesses from which they purchase, contributing to further economic growth within the region. Furthermore, household incomes increase as a result of those local residents who are employed (as a consequence of the direct and/or production-induced business stimuli). As a proportion of their additional income is spent in the region, this expenditure further stimulates the economic activity within the region. Accordingly, the larger the initial amount of money spent within the region, and the larger the proportion of that money re-spent locally, the greater the overall benefits that will accrue to the region.

The size of the impact on the local regional economy can be quantified by regional economic multipliers (derived from I–O tables that summarise expenditure flows between industry sectors and households within the region), where a larger multiplier indicates larger regional benefits. These multipliers can be used to estimate the value of increased regional economic activity likely to flow from stimulus to particular industries, focusing here on construction in the short term and different types of agriculture in the longer term.

It is also possible to estimate the increase in household incomes in the region. From this, an estimate can be made of the approximate number of jobs represented by the increased economic activity (including both those directly related to the increase in agriculture, and those generated indirectly within other industries in the region).

Not all of the expenditure generated by a large-scale development will occur within the local region. The greater the leakage (i.e. the amount of direct and indirect expenditure made outside the region), the smaller the resulting economic benefit that will be enjoyed by the region. Conversely, the more of the initial spend and subsequent indirect spend that is retained within the region, the greater the economic benefit and the number of jobs created within the local region. However, a booming local economy can also bring with it a range of issues that can place upward pressure on prices (including materials, houses and wages) in the region, negating some of the positive impacts of the development. If some of the unemployed or underemployed people within the Darwin catchments could be engaged as workers during the construction or operational phases of the development, this could reduce pressure on local wages and reduce the leakage resulting from the use of fly-in fly-out (FIFO) or drive-in drive-out (DIDO) workers, retaining more of the benefit from the project within the local region. Census 2016 data showed an unemployment rate of 4.7% within the Darwin catchments, indicating there may be difficulties in sourcing local workers from within the region.
The overall regional benefit created by a particular development depends on both the one-off benefits from the construction phase, and the ongoing annual benefits from the operational phase. The benefits from the operational phase may take a number of years to reach the expected level, as new and existing agricultural enterprises learn and adapt to make full use of the new opportunities presented by the development. It is important to note that the results presented here are based on illustrative scenarios incorporating broad assumptions, are derived from an I–O model developed for an I–O region that is much larger than the Darwin catchments study area, and are subject to the limitations of the method.

6.4.1 ESTIMATING THE SIZE OF REGIONAL ECONOMIC BENEFITS

To develop regional multipliers for the Darwin catchments, it was necessary to use available information and models for the Northern Territory input–output (NT I–O) region (Murti, 2001), within which the Darwin catchments sit. For more detail, see companion technical report on socio-economics (Stokes et al., 2017) and Figure 6-2. Additional data are presented to show how the economic circumstances of the Darwin catchments compare to the larger I–O region (Table 6-18). Both the NT I–O region and the Darwin catchments encompass both rural and remote areas plus the major regional city of Darwin. However, the NT I–O region is larger than the Darwin catchments study area, so the economic impact within the catchment is likely to be smaller than that estimated here.

Figure 6-2 Northern Territory input–output region relative to the Darwin catchments
Table 6-18 Key 2016 data comparing the Darwin catchments with the related Northern Territory input–output region

<table>
<thead>
<tr>
<th>INDICATOR</th>
<th>DARWIN CATCHMENTS</th>
<th>NORTHERN TERRITORY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land area (ha ’000)†</td>
<td>2,985</td>
<td>135,316</td>
</tr>
<tr>
<td>Population‡</td>
<td>139,052</td>
<td>228,833</td>
</tr>
<tr>
<td>% male‡</td>
<td>52.5%</td>
<td>51.8%</td>
</tr>
<tr>
<td>% Indigenous‡</td>
<td>9.0%</td>
<td>25.5%</td>
</tr>
<tr>
<td>Median age†</td>
<td>34</td>
<td>32</td>
</tr>
<tr>
<td>Median household income§</td>
<td>$110,760/y</td>
<td>$103,116/y</td>
</tr>
</tbody>
</table>

†Data sourced from ABS (2017)
‡Data sourced from ABS (2016a)
§Data sourced from ABS (2016b)

Wide variations can be seen in the size of the multipliers for different industries within the NT I–O region (Figure 6-3). Those industries with larger local regional multipliers would be expected to benefit more from development within the I–O region. For example, the ‘Beef cattle’ industry generated a smaller multiplier than ‘Wholesale and retail trade’, but a larger multiplier than ‘Mining’. However, a simple comparison of I–O multipliers can be misleading when considering different options for regional investment, because some impacts provide a short-term, one-off benefit (e.g. the construction phase of a new irrigation development), while others provide a sustained stream of benefits over the longer term (e.g. the production phase of a new irrigation scheme). A rigorous comparison between specific regional investment options would require NPVs of the full cost and benefit streams to be calculated.
6.4.2 INDIRECT BENEFITS DURING THE OPERATIONAL PHASE OF A DEVELOPMENT

Impacts of development on the I–O region are presented for four scales of increase in gross economic output ($25, $50, $100 and $200 million/year, indicative of potential outcomes) in each of three categories of agricultural activity (‘Beef cattle’, ‘Agriculture excluding beef cattle’, and ‘Aquaculture, forestry and fishing’). Impacts are shown as the total increased economic activity (Table 6-19) in the NT I–O region and the associated estimate of increase in employment (based median incomes in the I–O region) (Table 6-20). Note that all results scale linearly as the economic output of each type of agricultural activity increases.
Table 6-19 Estimated regional economic impact per year resulting from four scales of direct increase in agricultural output (rows) for each of three different categories of agricultural activity (columns) in the Northern Territory input–output (NT I–O) region

The value of increased agricultural economic activity can be calculated by multiplying the new area under irrigation by the mean increase in farm revenue received for the new (versus previous) agricultural produce.

<table>
<thead>
<tr>
<th>DIRECT INCREASE IN AGRICULTURAL OUTPUT PER YEAR ($ MILLION)</th>
<th>TOTAL VALUE OF INCREASED ECONOMIC ACTIVITY IN NT I–O REGION – DIRECT, PRODUCTION INDUCED AND CONSUMPTION INDUCED ($ MILLION)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type of agricultural development</td>
</tr>
<tr>
<td></td>
<td>Beef cattle                                      Agriculture excluding beef cattle                           Aquaculture, forestry &amp; fishing</td>
</tr>
<tr>
<td>25</td>
<td>51.3                                              36.5                                                  70.4</td>
</tr>
<tr>
<td>50</td>
<td>102.6                                             73.0                                                  140.8</td>
</tr>
<tr>
<td>100</td>
<td>205.3                                             145.9                                                 281.5</td>
</tr>
<tr>
<td>200</td>
<td>410.5                                             291.8                                                 563.0</td>
</tr>
</tbody>
</table>

As can be seen from the economic impacts (Table 6-19), an irrigation scheme that promotes ‘Aquaculture, forestry and fishing’ could have a larger regional impact in the NT I–O region than a scheme promoting ‘Beef cattle’ or ‘Agriculture excluding beef cattle’. These differences result from the different industry multipliers estimated for the NT I–O region (Figure 6-3).

Table 6-20 Estimated number of full-time equivalent jobs from four scales of increase in agricultural output (rows) for each of three different categories of agricultural activity (columns) in the Northern Territory input–output (NT I–O) region

<table>
<thead>
<tr>
<th>DIRECT INCREASE IN AGRICULTURAL OUTPUT PER YEAR ($ MILLION)</th>
<th>TOTAL NUMBER OF ADDITIONAL JOBS IN NT I–O REGION – DIRECT, PRODUCTION INDUCED AND CONSUMPTION INDUCED</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type of agricultural development</td>
</tr>
<tr>
<td></td>
<td>Beef cattle                                      Agriculture excluding beef cattle                           Aquaculture, forestry &amp; fishing</td>
</tr>
<tr>
<td>25</td>
<td>175                                              39                                                   335</td>
</tr>
<tr>
<td>50</td>
<td>350                                              78                                                   671</td>
</tr>
<tr>
<td>100</td>
<td>699                                              157                                                  1341</td>
</tr>
<tr>
<td>200</td>
<td>1398                                             314                                                  2683</td>
</tr>
</tbody>
</table>

The results for employment (Table 6-20) are closely related to those for impacts on regional economic activity, but the two measures do reveal some differences. These additional full-time equivalent jobs arising in the NT I–O region may require additional community infrastructure (e.g. schools, health services) if workers move to fill these jobs from other parts of the country, resulting in population growth within the NT I–O region. However, should these additional jobs be filled by currently unemployed or underemployed local people, then additional infrastructure would not be necessary.
INDIRECT BENEFITS DURING THE CONSTRUCTION PHASE OF A DEVELOPMENT

While initially the building of new infrastructure (on-farm and off-farm development, including construction of related supporting infrastructure, such as roads, schools and hospitals) comes at a cost, the additional expenditure within a region (which puts additional cash into people’s and businesses’ pockets) would increase regional economic activity. This creates a fairly short-term economic benefit to the region during the construction phase, provided that at least some of the expenditure is within the region and is not all lost from the region due to leakage.

The proportion of expenditure during the construction phase that would be spent within the region depends on the different costs, including for labour, materials and equipment. For labour costs, it is likely that the wages will be paid to workers sourced from within the region and from elsewhere, with the likely proportion of labour costs relating to each source of workers being dependent on the availability of appropriately skilled labour within the region. For example, a highly populated region (more than 100,000 people) with a high unemployment rate (more than 10%) and skilled labour force is likely to be able to supply a large proportion of the workers required from within the region. However, a sparsely populated region with a low unemployment rate (less than 5%) is more likely to need to attract many workers from outside the region, either on a FIFO/DIDO basis or by encouraging migration to the region. Similarly, for materials and equipment, some regions may be better able to supply a large proportion of these items from within the region, whereas construction projects in other locations may find they are unable to source what they need locally, and instead import a significant proportion into the region from elsewhere.

Based on a review of different dam projects across the country, it would appear that the proportions of local construction spend sourced within a region (as opposed to being imported, which has no impact on the regional economy) vary significantly. Thus, analyses considered three levels for the proportion spent locally: 65% (low leakage), 50 and 35% (high leakage). However, it should be noted that for a very remote region, the potential exists for leakage to be higher than 65%.

Table 6-21 shows estimates of the regional economic benefit of the construction phase of a new development for five scales of scheme capital cost ($0.25 billion to $4 billion) and the three levels of leakage noted above.

<table>
<thead>
<tr>
<th>SCHEME-SCALE CAPITAL COST ($ BILLION)</th>
<th>TOTAL REGIONAL ECONOMIC ACTIVITY WITHIN NT I–O REGION AS A RESULT OF THE CAPITAL COST OF THE SCHEME ($ BILLION)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Proportion of total construction capital costs made locally within the I–O region</td>
</tr>
<tr>
<td></td>
<td>65%</td>
</tr>
<tr>
<td>0.250</td>
<td>0.33</td>
</tr>
<tr>
<td>0.500</td>
<td>0.67</td>
</tr>
<tr>
<td>1.000</td>
<td>1.34</td>
</tr>
<tr>
<td>2.000</td>
<td>2.68</td>
</tr>
<tr>
<td>4.000</td>
<td>5.35</td>
</tr>
</tbody>
</table>
These results show that the size of the regional economic benefit experienced increases substantially as the proportion of scheme construction costs spent within the region increases. Given the proximity of potential Darwin catchments dam sites to Darwin, leakage may be towards the middle of the range examined. For example, if $2 billion was spent on construction for a new dam project and 50% of that was spent within the NT I-O region, the construction multiplier (2.06, Figure 6-3) would only apply to the $1 billion spent locally, to give an overall regional economic benefit of $2.06 billion (with additional benefits flowing to other regions where the remaining $1 billion was spent).

6.5 References


ABS (2016a) Cultural diversity (June 2017), Findings based on use of ABS TableBuilder data.

ABS (2016b) Selected dwelling characteristics (June 2017), Findings based on use of ABS TableBuilder data.


Chapter 7 discusses a range of potential risks to be considered before establishing a greenfield agriculture or aquaculture development. These include the ecological implications of altered flow regimes, a range of biosecurity considerations, off-site impacts from sediments, nutrients and agropollutants, irrigation drainage and aquaculture discharge water and irrigation-induced salinity. The key components and concepts of Chapter 7 are shown in Figure 7-1.

Figure 7-1 Schematic diagram of the components where key risks can manifest when considering the establishment of a greenfield irrigation or aquaculture development
7.1 Summary

This chapter provides information on the ecological, biosecurity, off-site and irrigation-induced salinity risks to the Darwin catchments from greenfield agriculture or aquaculture development. It is principally concerned with the risks from these developments to the broader environment but also considers biosecurity risks to the enterprises themselves.

7.1.1 KEY FINDINGS

Ecological implications of altered flow regimes

Although irrigated agriculture in Australia typically occupies a small percentage of a catchment area (i.e. <3%), it can potentially use a large proportion of the water (i.e. greater than 30%). Consequently it was important for the Assessment to consider ecological changes to near-shore marine, estuarine, freshwater and riparian ecosystems that may result from changes in streamflow following water resource development for irrigation or other uses. It should be noted, however, that several other human-related factors can also impact on these ecosystems, including grazing, fire, disease, invasive species and changes in water quality. These factors are discussed qualitatively in the companion technical reports on ecology (Pollino et al., 2018a, 2018b).

This section overviews the outcomes from the ecology asset analysis, considering flow-related impacts of potential dams and water harvesting. It was found that the sensitivities of ecological assets to changes in flow vary. Vulnerabilities of assets change depending on their location in the catchment, the type and size of the development, volumes of water extracted and timing of water extraction. The sensitivity of assets to impacts also varies according to their dependencies on different parts of the flow regime.

The Darwin catchments encompass a variety of landscapes and ecosystems and large populations of some of northern Australia’s most iconic wildlife species, such as saltwater crocodiles, magpie geese and barramundi. The richness of biodiversity is attributed to the integrity, extent and heterogeneity of its wetland habitats.

A summary of analysis findings is presented below.

Finniss catchment

The introduction of the potential Mount Bennett dam results in moderate changes to assets at the end-of-system. Pumping or diverting volumes of water less than 350 GL results in minor change to flow metrics for all assets at the end-of-system. However, moderate change may occur for volumes greater than 350 GL with a low extraction threshold (LT).

Adelaide catchment

Results show major impacts to assets downstream of the potential Upper Adelaide River dam. Species likely to be locally impacted include migratory fish, including inland barramundi and freshwater sawfish. Moderate impacts are possible for magpie geese, riparian vegetation, waterholes and wetlands. The magnitude of changes in flow decreases with increasing distance downstream from the dam, with no change to minor change to estuarine and coastal species. Water harvesting results in no change to minor change to all species and habitats under all scenarios with a high-take threshold. With a low-take threshold, changes in flow metrics are minor.
for extraction volumes less than 350 GL. For extraction volumes greater than 350 GL, changes are moderate for sawfish and migratory fish. The Adelaide River Offstream Storage results in no change to flow metrics that are important to estuarine and coastal species and habitats.

**Mary catchment**

Changes in flow downstream of the potential Mary River dam result in local extreme change, with likely habitat and species loss. These impacts are modelled for migratory fish, including barramundi and Hyrtl’s tandan, as well as wetlands and waterholes. The magnitude of change in flow decreases with distance from the dam, with changes in flow ranging from minor to moderate for estuarine and coastal species. Water harvesting resulted in minor impacts to ecological assets.

**Biosecurity considerations**

Compared with many other countries, Australia has many advantages in terms of the opportunity to mitigate risks from pests and disease due to its isolation and sound regulatory processes. However, there have been a number of recent disease outbreaks, such as the disease of bananas, Panama disease tropical race 4, which highlight the risks to enterprises and to industries. The recent discovery of white spot syndrome virus in south-east Queensland prawn farms similarly shows the potential for disease to damage whole industries and to have a negative impact on industries which depend on wild catch. Man-made pathways include road transport, ships and planes, and the ‘carriers’ (e.g. humans, animals, plants, machinery) that facilitate the movement and incursion of new pests, diseases and weeds. In the short to medium term, biosecurity risks to the Darwin catchments are most likely to come from within Australia and, in particular, from adjacent or climatically similar parts of the country, although wind dispersal from countries to the north is also possible. The warmer, north Australian environment is more favourable than temperate climates for insects and pathogens to adapt and multiply with the introduction of a new food source (e.g. a crop). However, the environment also favours beneficial organisms that prey on pest species. A range of macro-pests also pose a risk, such as feral pigs. Pathogens pose a constant risk to aquaculture enterprises. In some cases management actions aim to prevent the introduction of the pathogen to the enterprise, in other cases the pathogen is present in the farmed population and needs to be managed through good husbandry practices. There is also potential for disease in farmed populations to escape into wild populations. Similarly, irrigated agriculture has the potential to introduce weeds into the broader environment.

**Sediment, nutrients and agropollutant loads to receiving waters**

Agriculture can affect the water quality of downstream freshwater, estuarine, and marine ecosystems. The principal pollutants from agriculture are nitrogen, phosphorus, total suspended solids, herbicides and pesticides. A relative-risk assessment approach was used to determine potential surpluses of these. Nitrogen use varied considerably but was very high for crops such as bananas and okra. Conversely, the nitrogen surplus was low or even negative for crops such as rice, maize and peanuts. Phosphorus surplus also varied substantially but was very high for crops such as melons, okra, cucumber and snake bean that have high phosphorous inputs and a low quantity of phosphorous in the harvestable product. Conversely, the phosphorous surplus was low or even negative for crops such as sweet corn, maize and soybean. Some crops, such as bananas, have high pesticide, herbicide and fungicide application rates while other crops such as mangoes have much lower application rates. Determining herbicide and pesticide surplus is difficult,
especially since technologies are changing rapidly and many newer chemicals have much lower application rates, but their active ingredients are relatively more potent than older chemicals. Nitrogen losses were also examined using a different approach, through simulation. Losses via runoff were highly dependent on the amount of runoff, which is highly dependent on rainfall amount and intensity. Simulated sediment loss showed that the use of a cover crop could minimise soil loss and therefore the amount of sediment released into water bodies downstream.

Irrigation-induced salinity

Irrigation-induced salinity requires a source of salt for salinity to manifest itself as an environmental and production problem. Areas with higher rainfall (i.e. more than 1200 mm/year), such as the Darwin catchments, and/or highly permeable soils, tend to have lower concentrations of salts in the soil profile because the salts are leached down to the watertable and flushed out of the groundwater system. Due to the absence of a source of salt in the landscape and given that water sources are typically fresh, the risk of irrigation-induced salinisation in the Darwin catchments was deemed to be low.

7.1.2 INTRODUCTION

The range of environmental changes that could potentially occur as a result of water and irrigation development is as varied as the number of developments that could be proposed. Furthermore, water and irrigation development can result in complex and in some cases unpredictable changes to the surrounding environment and communities. For instance, prior to the construction of the Burdekin Falls Dam, the Burdekin Project Committee (1977) and Burdekin Project Ecological Study (Fleming et al., 1981) concluded that the dam would improve water quality and clarity in the lower river and that para grass (Brachiaria mutica), an invasive weed from Africa that was then present at relatively low levels, could become a useful ecological element as a result of increased water delivery to the floodplain. However, the Burdekin Falls Dam has remained persistently turbid since construction in 1987, greatly altering the water quality and ecological processes of the river below the dam and the many streams and wetlands into which that water is pumped on the floodplain (Burrows and Butler, 2007). Para grass and more recently hymenachne (Hymenachne amplexicaulis), an ecologically similar plant from South America, have become serious weeds of the floodplain wetlands, rendering innumerable wetlands unviable as habitat for most aquatic biota that formerly occurred there (Tait and Perna, 2000; Perna, 2003, 2004).

Thus, there are limitations to the specific advice that can be provided in the absence of specific development proposals and for this reason this section provides general advice on those considerations or externalities that are most strongly affected by water resource and irrigation developments. It is not possible to discuss every potential change that could occur. For this reason, the chapter is structured as follows:

- Section 7.2, ecological implications of altered flow regimes; examines how river regulation affects inland and freshwater assets in the Darwin catchments and marine assets in the near-shore marine environment.
- Section 7.3, biosecurity considerations; discusses the risks presented by disease, pests and weeds to an irrigation development and the risks new agriculture or aquaculture enterprise in the Darwin catchments may present to the wider industry and broader catchment.
Section 7.4, sediment, nutrients and agropollutant loads to receiving waters; examines water quality resulting from agriculture and aquaculture enterprises and discusses agricultural or other chemical containment risks to downstream aquaculture enterprises and the environment.

Section 7.5, irrigation-induced salinity; briefly discusses the risk of irrigation-induced salinity to an irrigation development and the downstream environment in the Darwin catchments.

Other externalities associated with water resource and irrigation development discussed elsewhere in this report include:

- The direct impacts of the development of a large dam and reservoir on:
  - Indigenous cultural heritage (Section 3.4)
  - the movement of aquatic species (Section 5.3)
  - terrestrial ecosystems and species within the reservoir inundation area (Section 5.3).

The externalities listed above are rarely factored into the ‘true costs’ of water resource or irrigation development, and the reality is that even in parts of southern Australia where data are abundant, it is very difficult to express these ‘costs’ in monetary terms as perceived changes are strongly driven by values, which can vary considerably within and between communities and fluctuate over time. For this reason, the material in this chapter is presented as a standalone analysis to help inform conversations and decisions between communities and government.

It is important to note that this chapter is primarily focused on key risks from irrigated agriculture and aquaculture, although the section on biosecurity considers both risks to the enterprise and risks emanating from the enterprise into the broader environment. Other risks to irrigated agriculture and aquaculture are discussed elsewhere in this report and include risks associated with:

- flooding (Section 2.5)
- regulatory delays (Section 3.6)
- erosion (captured in the land suitability analysis described in Section 4.3)
- sediment infill of large dams (Section 5.3)
- reliability of water supply (sections 5.3 and 6.3)
- timing of runs of failed years on the profitability of an enterprise (Section 6.3).

Material within this chapter is largely based on (and further information can be found in) the companion technical reports on agricultural viability (Ash et al., 2018), aquaculture viability (Irvin et al., 2018), hydrogeological assessment (Turnadge et al., 2018) and two companion reports on ecology (Pollino et al., 2018a, 2018b).

7.2 Ecological implications of altered flow regimes

7.2.1 INTRODUCTION

As outlined in Chapter 2, the Darwin catchments are characterised by distinct wet and dry seasons, with significant variability year to year in annual rainfall. Most rivers only flow during the wet season and freshwater and marine ecosystems of northern Australia have adapted to this
seasonal variability. Changes in flow as a consequence of new water resource developments have the potential to impact on these ecosystems depending upon the location, scale and nature of regulation. This section assesses the potential ecological impacts arising from changes in flow as a result of:

- major instream dams (Section 5.3)
- water harvesting (Section 5.3), where water is pumped or diverted from a major watercourse into an offstream storage, usually a ringtank.

As described in Section 5.3, major instream dams are efficient at capturing water. However, they can dramatically change the flow patterns downstream of the dam wall. With distance downstream from the dam and the point of water extraction, the seasonality of streamflow may increasingly resemble the natural pattern and the amount of water extracted as a proportion of total streamflow decreases. Water harvesting typically causes less disruption to the high- and low-flow extremes than major instream dams. This is because during high-flow events mechanical pumps can only physically extract so much water, which is usually a small volume in relation to the volume of the flows. At low flows, pump-take thresholds constrain water take, where pumping only commences when the flow in the river is above a certain ‘threshold’ discharge. While a lower threshold results in an irrigator being able to extract their full allocation of water at a higher degree of reliability, it reduces the protection of low flows for the environment.

This section evaluates the potential impact of changes in flow on freshwater and marine ecological assets, which may result from these two water resource development options (Scenario B). Some analyses also include assessment under wet and dry extreme climate projections (Scenario C), and assessment of climate change projections and potential developments (Scenario D). Assets are defined as important habitats, species or functional groups that are of conservation, cultural, commercial or recreational value or that support ecological function (Figure 7-2). The outputs are intended to examine the sensitivity of freshwater and marine ecological assets to potential changes at locations within the catchment where the asset is located and to assist future decisions on environmental flows.

Environmental flows are used to describe the quantity, timing and quality of water flows required to sustain freshwater, estuarine and coastal ecosystems. While simple ‘rules of thumb’ approaches to defining environmental flows are desirable, they have no empirical basis and can put the integrity of ecosystems at risk (Arthington et al., 2006). Contemporary methods for defining environmental flows require the development of relationships between components of flow and ecological responses (Poff et al., 2010). This report develops such relationships to evaluate the impacts of flow alteration.

Unless specified elsewhere, the material presented in Section 7.2 has been summarised from the companion technical report on ecology (Pollino et al., 2018b).

**Contextual information**

Water-dependent ecological assets are sensitive to changes in flow, being sustained by either surface water or groundwater flows or a combination of these. Priority assets have been selected in the Darwin catchments to represent potential impacts to ecology as a consequence of surface water developments. To assess impacts, knowledge of the distribution and drivers of change of assets was synthesised and potential impacts of altered flows to assets assessed using quantitative...
and qualitative methods. By using these scenarios, the sensitivity of assets to changes in flow as a consequence of different types of flow changes was evaluated.

A two-tiered approach was used for analysis.

- The first tier evaluated changes in flow throughout the catchment where assets are known to be located. The components of the flow that are important to the asset were identified and the potential for these to change were evaluated. This was done by comparing ‘important’ components of flow (referred to as flow metrics) under Scenario B to the same components of flow under Scenario A and calculating the mean change, with the scale of change ranging from 0 and 100%.

- A subset of these assets proceeded to a second tier of analysis that provided a more detailed assessment of potential impacts. This was only undertaken for those assets for which there was a sufficient body of literature available to develop quantitative models (for more information see the companion technical report on ecology (Pollino et al., 2018b)).

Several other factors can also impact ecological systems such as water quality, access to groundwater, soil characteristics, physical changes (e.g. grazing impacts), fire, disease and invasive species. However, this analysis solely focuses on ecological changes that may result from changes in flow regimes. Other factors are discussed in Pollino et al. (2018a) but not evaluated.
A subset of hydrological model nodes was selected for assessment, representing locations in the Darwin catchments. These nodes were selected based on observational records of the location of assets within the catchment, and the likelihood that the nodes would experience changes in flow (Figure 7-3).

Under Scenario A, streamflow is simulated using the historical climate and current levels of development. This is the ‘baseline’ scenario against which other scenarios were compared.

Under Scenario B, water is extracted at different locations within the catchments and the Assessment examined how the reliability of extraction is affected by a variety of pump-related variables and other uses (Hughes et al., 2018). It also involved using major dams to store water within a catchment (Petheram et al., 2017).

Under Scenario B water harvesting (Scenario B-WH), the ecological analysis considered six whole-of-system annual extraction volumes (50, 150, 350, 550, 750 and 950 GL) at a low pump-take threshold (LT; 200 ML/day) and at a high pump-take threshold (HT; 1800 ML/day).
Under Scenario B major dams (Scenario B-D), the impacts of five potential dams on streamflow were calculated individually (Scenario B-D-I) and in combination (Scenario B-D-C):  
- In the Finniss catchment only the potential Mount Bennett dam is considered.  
- In the Adelaide catchment, the potential Upper Adelaide River dam and the Adelaide River offstream water storage (AROWS) adjacent to the Adelaide River are considered individually and in combination.  
- In the Mary catchment a potential dam on the Mary River is considered. The impact of a potential dam on the McKinlay River in conjunction with a dam on the Mary River is then assessed.  

Potential changes under scenarios Cwet and Cdry are examined. Scenarios are described in Section 1.4.  

Categories of impact used in the scenario analysis are:  
- no change – no changes are likely to be measurable (mean change in flow metrics is less than 10%)  
- minor change – minor changes that are unlikely to be measurable (mean change in flow metrics is between 10 and 30%)  
- moderate change – measurable changes but without major changes to ecosystem structure or function (mean change in flow metrics is between 30 and 60%)  
- major change – significant changes to ecosystem structure or function, no longer supporting habitat or species (mean change in flow metrics is between 60 and 90%)  
- extreme change – complete change of ecosystem structure and function (mean change in flow metrics is greater than 90%).  

The remainder of this section is structured as follows:  
- Section 7.2.2 provides a summary of changes to assets using the first-tier approach at selected locations across the study area.  
- These results form the basis of interpretation and discussion in Section 7.2.3.  
- Combined with the second-tier approach, further results are discussed in sections 7.2.4 to 7.2.6.  

7.2.2 CHANGE IN COMPONENTS OF FLOW SPECIFIC TO KEY ECOLOGICAL ASSETS AND HABITATS IN THE DARWIN CATCHMENTS

To analyse the potential for ecological change arising from potential water resource development, relative changes in streamflow under scenarios A and B were assessed at eight locations in the Darwin catchments. Data from select sites, corresponding with streamflow nodes, are presented here.  

The sites for which results are presented in this section are shown in Figure 7-3. In the Finniss River catchment results are presented for streamflow node 81500001 (Figure 7-4). In the Adelaide River catchment results are presented for nodes 81700001, 81700200, 81700050 and 81700020 (Figure 7-5, Figure 7-6, Figure 7-7 and Figure 7-8, respectively). In the Mary River catchment results are presented for nodes 81800001, 81800351 and 81800354 from the coast (end-of-
system) to inland (Figure 7-9, Figure 7-10, Figure 7-11, respectively). The figures in this section present a summary of information on aspects of change in modelled volume and timing of streamflow specific for each species and habitat at each node relative to Scenario A. The greatest changes occur at nodes immediately downstream of dams. It should be noted that under these general simulations the hydrological model was not configured to simulate irrigation releases immediately downstream of the dam. For this reason and depending upon how water is conveyed from the dam to the irrigation area (e.g. pipeline, river channel) actual streamflow patterns in the reach immediately downstream of the dam may be considerably different to the modelled flows reported in this section.

Each figure in this section corresponds to a specific node in the river model. The proximity of assets to each river model node was determined, and only assets in close proximity to a node were assessed at that node. Scenarios involving water harvesting (Scenario B-WH) and dams (Scenario B-D) are presented on the x-axis and assets are listed on the y-axis. Each number represents the percentage difference between Scenario B and Scenario A, ranging from 0 to 100%. The percentage difference is calculated as the mean of change across flow components considered important to each asset relative to Scenario A. The larger the mean percentage difference in flow components between scenarios B and A, the larger the potential for ecological change to assets. The intensity of the colour in Figure 7-4 to Figure 7-11 illustrates the magnitude of the percentage difference in flow components.
Figure 7-4 Assessment of change in flow metrics for assets at assessed location 81500001 in the Finniss catchment

The intensity of the colour represents the variability of the scenario evaluated relative to Scenario A. Water harvesting scenarios are designated by an ‘LT’ or ‘HT’ where ‘LT’ and ‘HT’ represent low (200 ML/day) and high (1800 ML/day) extraction thresholds for water harvesting, respectively. The pump rate was assigned such that the allocated volume could be extracted in 20 days. The numerals in the water harvest label correspond to the total extraction in the Finniss catchment. Upstream dams are labelled as cumulative (D-C) or individual (D-I). Numbers in cells represent mean percentage change in flow metrics for an asset (between Scenarios B and A). The bar graph at the top shows the mean of the mean change across all assets. This node represents end-of-system.
Figure 7-5 Assessment of change in flow metrics for assets at assessed location 81700001 in the Adelaide catchment
Refer to caption note in Figure 7-4 for figure explanation. This node represents the end-of-system.
Figure 7-6 Assessment of change in flow metrics for assets at assessed location 81700200 in the Adelaide catchment. Refer to caption note in Figure 7-4 for figure explanation.

Figure 7-7 Assessment of change in flow metrics for assets at assessed location 81700050 in the Adelaide catchment. Refer to caption note in Figure 7-4 for figure explanation.
Figure 7-8 Assessment of change in flow metrics for assets at assessed location 81700020 in the Adelaide catchment
Refer to caption note in Figure 7-4 for figure explanation.
Figure 7.9: Assessment of change in flow metrics for assets at assessed location 81800001 in the Mary catchment.
Refer to caption note in Figure 7.4 for figure explanation. This node represents the end-of-system.
### Figure 7-10 Assessment of change in flow metrics for assets at assessed location 81800351 in the Mary catchment
Refer to caption note in Figure 7-4 for figure explanation.

<table>
<thead>
<tr>
<th>Mean change</th>
<th>100-</th>
<th>80-</th>
<th>60-</th>
<th>40-</th>
<th>20-</th>
<th>0-</th>
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<tbody>
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<td>Barramundi</td>
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<td>Magpie geese</td>
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<td>21</td>
<td>26</td>
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<td>33</td>
</tr>
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<td>14</td>
<td>17</td>
<td>22</td>
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<td>18</td>
</tr>
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<td>Turtles</td>
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<td>17</td>
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<td>9</td>
<td>14</td>
<td>19</td>
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<td>27</td>
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</table>

### Figure 7-11 Assessment of change in flow metrics for assets at assessed location 81800354 in the Mary catchment
Refer to caption note in Figure 7-4 for figure explanation.

<table>
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<tr>
<th>Mean change</th>
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<th>60-</th>
<th>40-</th>
<th>20-</th>
<th>0-</th>
</tr>
</thead>
<tbody>
<tr>
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<td>9</td>
<td>12</td>
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<td>22</td>
</tr>
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<td>Migratory fish</td>
<td>6</td>
<td>9</td>
<td>13</td>
<td>15</td>
<td>19</td>
<td>22</td>
</tr>
<tr>
<td>Riparian vegetation</td>
<td>23</td>
<td>15</td>
<td>9</td>
<td>16</td>
<td>20</td>
<td>29</td>
</tr>
<tr>
<td>Stable flow spawners</td>
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<td>2</td>
<td>3</td>
<td>8</td>
<td>9</td>
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<td>1</td>
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<td>12</td>
<td>10</td>
<td>10</td>
<td>16</td>
<td>20</td>
<td>23</td>
</tr>
</tbody>
</table>
7.2.3 CHANGE IN MARINE ASSETS

Marine fish

Under Scenario B-WH, changes to grunter and mullet range from no change to minor, with the exception of the Finniss River. In the Finniss catchment, for the low pump-take threshold (LT), moderate impacts occur for extractions greater than 350 GL for grunter and greater than 550 GL for mullet (Figure 7-4). Flow metrics range from no change to minor impacts under the high pump-take threshold (HT). Impacts are also moderate for the potential Mount Bennett dam under Scenario B-D. Minor changes to both species occur in the Mary catchment with the potential Mary River dam, increasing to moderate with the addition of the McKinlay dam (Figure 7-9). In the Adelaide and Mary catchments, changes to marine fish range from no change to minor under Scenario B-WH, and range from no change to minor under Scenario B-D in the Adelaide catchment (Figure 7-5).

Marine fish, the grunter and mullet, were assessed at end-of-system nodes (81500001 in the Finniss catchment, 81700001 in the Adelaide catchment, 81800001 in the Mary catchment). This part of the Adelaide and Mary catchments represents estuarine habitats, which have high primary productivity and dynamic food webs, supporting abundant and diverse fish and crustacean species (Halliday et al., 2012). The estuaries and freshwater reaches of the Darwin catchments are critical habitats for juvenile and early-adult marine fish. The annual monsoon season is a critical time period for many fish species, including estuarine-dwelling species. The late dry season to early wet season is a critical period for recruitment and survival, with catchment flows reducing salinity in the estuary, allowing for optimal growth and feeding of adults and juveniles (Humphries et al., 1999). This section contains an overview of changes to grunter and mullet in the Finniss, Adelaide and Mary catchments.

Adult grunter spawn in the estuary. They prefer brackish habitats, which are sustained by late dry-season flows. Grunter reproduce in the late dry and wet season, and the estuary habitat becomes abundant with juvenile fish. Grunter are an important predator in estuary habitats, and structure fish populations in estuaries as a result. Changes in the volume of wet-season flows to the estuary would restrict grunter breeding and feeding habitat. Changes in early wet-season and wet-season flows could potentially affect the population of grunter in the estuary if changes occurred on an annual basis.

Mullet use both estuary and freshwater environments. Adult mullet spawn in estuaries and juvenile mullet migrate to the river during the late dry-season flows; flows are needed to reconnect the estuary and river channel for migration to occur (Grant and Spain, 1975; Halliday and Robins, 2005). Given the reduction in early wet-season flows, it is possible that the timing of connection is delayed, reducing the opportunities for mullet to migrate when flows are not at a high velocity. This could strand juveniles in the estuary in less optimal habitats for growth.

Under water harvest scenarios, changes to streamflow are most noticeable during the early wet-season flows. Under dam scenarios, changes to streamflow occurs throughout the year, with changes in the late dry season being highest. These changes are based on modelled flows and could vary depending upon the specific details of a development.
Snubfin dolphin

Changes to important components of flow for snubfin dolphins range from no change to moderate change. Moderate changes occur in the Finniss catchment under Scenario B-WH-LT when extraction volumes equal or exceed 550 GL (Figure 7-4). Flow metrics range from no change to minor impacts under the HT. Under Scenario B-D, the potential Mount Bennett dam, changes to snubfin are moderate at the end-of-system in the Finniss catchment. In the Mary catchment, under Scenario B-D, the potential Mary River dam results in minor changes in relevant flow metrics, increasing to moderate change with the addition of the McKinlay dam (Figure 7-9). Changes are minor in the Adelaide catchment with the potential Upper Adelaide River dam and with the addition of AROWS (Figure 7-5).

Snubfin dolphin were assessed at the end-of-system nodes (81500001 in the Finniss catchment, 81700001 in the Adelaide catchment, 81800001 in the Mary catchment). The snubfin dolphin is an estuarine- and embayment-dwelling species. They occupy near-shore marine habitats almost exclusively, and while they are found in upper estuary freshwaters, they do not venture into riverine habitats. The dependence of snubfin dolphin on river flows is via the dynamics of the annual monsoon driving a complex food web. The use of habitats in the Darwin catchments by snubfin dolphin is dependent on the seasonally dynamic annual monsoon. There is limited information available on snubfin dolphins.

Changes occur during both dry-season and wet-season flows under both water harvest and new dam scenarios. The cumulative impacts of habitat loss across seasons and over consecutive years is likely to reduce habitat availability in the estuary for snubfin dolphin. These changes are based on modelled flows and could vary depending upon the specific details of a development.

Crocodiles

In the Finniss catchment under Scenario B-WH, minor change occurs to flow metrics of importance to crocodiles, except under LT thresholds and extraction volumes of 550 GL or greater where moderate changes occur (Figure 7-4). Under Scenario B-D, changes to crocodiles in the Finniss catchment are moderate with the potential Mount Bennett dam. In the Mary catchment, changes are moderate with the potential Mary dam and the cumulative Mary and McKinlay dams (Figure 7-9). Under Scenario B-WH, changes to flow metrics important to crocodiles in the Adelaide catchment (LT 150 GL and above; HT 550 GL and above) and the Mary catchment (LT 150 GL and above; HT 550 GL and above) are minor. Changes are minor in the Adelaide catchment with the potential Upper Adelaide River dam and with the addition of AROWS (Figure 7-5).

Crocodiles were assessed at the end-of-system nodes (81500001 in the Finniss catchment, 81700001 in the Adelaide catchment, 81800001 in the Mary catchment). Flows are critical to support breeding behaviour and nesting of crocodiles, which span the wet season. Inundated areas provide suitable habitat for crocodiles. If the size or number of inundated areas increases, it could provide an opportunity for juveniles to access broader habitats. Access to a greater food supply could also boost the growth rate of crocodiles, and enable them to outcompete predators. If inundated areas decrease in size or number, it may limit the growth rate of juveniles.

Flow changes occur in wet-season flows, which have the potential to affect the survival rate of eggs and reduce the number of nesting sites available to crocodiles. These changes are based on modelled flows and could vary depending upon the specific details of a development.
**White banana prawns**

Past assessments have shown a relationship between flows at the end of a river system and the catch of white banana prawns (Bayliss et al., 2014). White banana prawn data from the Darwin catchments show that catches are likely to be affected under water harvest and dam scenarios, with flow volumes being strongly related to prawn catch. Under water harvest scenarios (Scenario B-WH), little to no change in catch is observed under the low extraction volumes. The highest water harvest scenarios (950 GL) reduce prawn catch by up to 15% on average across years. With the addition of the Mary and McKinlay dams, the reduction in prawn catch is up to 30% on average across years. The other potential dams result in changes of less than 10% on average across years. These changes are based on modelled flows and could vary depending upon the specific details of a development. For more information on this analysis see the companion technical report on ecology (Pollino et al., 2018b).

**Salt flats**

In the Mary and Adelaide catchments, under Scenario B-WH the change in flow metrics important to salt flats generally range from no change to minor change (Figure 7-5) and (Figure 7-9). Under Scenario B-D, changes are minor for the two potential dams in the Mary catchment individually and in combination. Moderate changes occur to salt flats with the Mount Bennett dam in the Finniss catchment (Figure 7-4). Under Scenario B-D, the dams predominantly affected the duration of high flows, which in turn can affect the inundation extent of salt flats.

Salt flats were assessed at the end-of-system nodes (81500001 in the Finniss catchment, 81700001 in the Adelaide catchment, 81800001 in the Mary catchment). Overbank floods extend into the estuary and they become inundated. These are colonised by a range of fish and crustacean species. A spike in primary production occurs on the inundated salt flats, which contribute to the overall dynamic production in estuaries during the monsoon season (Burford et al., 2016).

7.2.4 **CHANGE IN INLAND AND FRESHWATER ASSETS: HABITATS**

**Floodplain wetlands**

For the wetlands analysis, the Adelaide, Mary, and Wildman catchments and the Finniss catchment are considered as two separate zones. The inputs to this analysis are from inundation modelling within the Darwin catchments, see companion technical report on flood mapping and modelling Karim et al. (2018) for more information.

The floodplains of the Adelaide and Mary catchments, together with the neighbouring Alligator rivers, form a vast, interconnected, continuous wetland system (Environment Australia, 2001) that is seasonally inundated (Close et al., 2012). These freshwater coastal floodplains form a mosaic of diverse wetland habitats, including tidal flats, swamps, billabongs and mangroves that are highly productive. Floods extend over a large area, persist for an extended time and support a rich diversity of fauna and flora. The floodplain complex is a major breeding ground for magpie geese and migratory waterbirds (Close et al., 2012; Environment Australia, 2001).

The Finniss catchment supports a modified but relatively intact floodplain with seasonal and near permanent wetlands with extensive paperbark swamps. The floodplain supports floating mat...
vegetation and the permanent billabongs in the north-east are a major breeding ground for saltwater and freshwater crocodiles, and also provide important breeding habitat for magpie geese and migratory waterbirds (Close et al., 2012; Environment Australia, 2001).

An analysis of the impact of projected climate and potential dams on the connectivity of 100 wetlands in the Adelaide, Mary and Wildman catchments and 17 wetlands in the Finniss catchment was undertaken. This analysis considered (i) wetlands with no connection to the main river channel; (ii) wetlands that have one or more periods of connection to the main river channel, with a mean connection period of less than 21 days; and (iii) wetlands that had a single connection event to the main river channel that generally persisted for more than 21 days. Connectivity was analysed for flood events of a range of annual exceedance probabilities (AEP), where AEP indicates the probability of exceeding a flood of a certain magnitude in a given year.

Adelaide, Mary and Wildman catchments

In the Adelaide, Mary and Wildman catchments under Scenario Cwet, little to no change in connectivity of wetlands occurs for flood events of AEP 1 in 3 or AEP 1 in 13. Losses of connectivity occurs under Scenario Cdry, with 18% of wetlands losing connectivity. The addition of the potential Upper Adelaide River dam (i.e. Scenario Ddry) did not cause any reductions in connectivity.

Under Scenario A, for flood events that occur on average once every 3 years (AEP 1 in 3), 11% of wetlands remained unconnected, 33% of wetlands had connections for less than 21 days and 56% had connections for more than 21 days (Table 7-1, Table 7-2). This does not change under the potential Upper Adelaide River dam (Scenario B-D) scenario, under current (Scenario B) and future (Scenario D) climates (Table 7-1). Under Scenario Cdry, more wetlands have no connection to the main river channel than under Scenario A.

<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>% WETLANDS WITH NO CONNECTION</th>
<th>% WETLANDS CONNECTED &lt;21 DAYS</th>
<th>% WETLANDS CONNECTED &gt;21 DAYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario A</td>
<td>11</td>
<td>33</td>
<td>56</td>
</tr>
<tr>
<td>Scenario B-D</td>
<td>11</td>
<td>33</td>
<td>56</td>
</tr>
<tr>
<td>Scenario Cwet</td>
<td>11</td>
<td>33</td>
<td>56</td>
</tr>
<tr>
<td>Scenario Cdry</td>
<td>18</td>
<td>29</td>
<td>53</td>
</tr>
<tr>
<td>Scenario Dwet</td>
<td>11</td>
<td>33</td>
<td>56</td>
</tr>
<tr>
<td>Scenario Ddry</td>
<td>18</td>
<td>29</td>
<td>53</td>
</tr>
</tbody>
</table>

AEP = annual exceedance probability

For flood events that occur on average once every 14 years (AEP 1 in 14), under Scenario A all wetlands are connected to the main river channel, with the majority being connected for more than 21 days (Table 7-2). The potential Upper Adelaide River dam results in a small increase in the percentage of wetlands being inundated for more than 21 days, though the differences are small (Table 7-2). Under Scenario Cdry, 10% of wetlands had no connectivity. The addition of dams (i.e. Scenario Ddry) makes little difference to the percentage of wetlands with no connection (Table 7-2).
Table 7-2 Percentage of wetlands connected to the main river channel in the Adelaide, Mary and Wildman catchments for a flood event of AEP 1 in 14

<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>% WETLANDS WITH NO CONNECTION</th>
<th>% WETLANDS CONNECTED &lt;21 DAYS</th>
<th>% WETLANDS CONNECTED &gt;21 DAYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario A</td>
<td>0</td>
<td>24</td>
<td>76</td>
</tr>
<tr>
<td>Scenario B-D</td>
<td>0</td>
<td>18</td>
<td>82</td>
</tr>
<tr>
<td>Scenario Cwet</td>
<td>0</td>
<td>19</td>
<td>81</td>
</tr>
<tr>
<td>Scenario Cdry</td>
<td>10</td>
<td>14</td>
<td>76</td>
</tr>
<tr>
<td>Scenario Dwet</td>
<td>0</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>Scenario Ddry</td>
<td>11</td>
<td>13</td>
<td>76</td>
</tr>
</tbody>
</table>

AEP = annual exceedance probability

Finniss catchment

In the Finniss catchment, under Scenario Cdry there is a reduction in wetland connectivity, particularly those connected to the main river channel during moderate events (AEP 1 in 10). The potential McKinlay dam and dry climate scenarios result in a reduction in wetland connectivity. This reduction in connectivity is likely to result in diminished habitat quality and a corresponding reduction in recruitment and survival of wetlands species, including the magpie goose (Warfe et al., 2011). There is also a small increase in the proportion of wetlands inundated for increased durations. These changes are localised. A scenario of a combined potential McKinlay dam and a dry future climate (Scenario Ddry) further exaggerated changes in wetland connectivity. This would be likely to change the breeding success of magpie geese (Whitehead and Saalfeld, 2000). Increased duration of connectivity of wetlands could lead to a loss of biodiversity (Barrett et al., 2010; Kingsford et al., 1995).

Under Scenario A, for floods that occur on average once every 2 years (AEP 1 in 2), 24% of wetlands have no connection to the river during these flood events. Of the remaining wetlands, all are intermittently connected for periods of less than 21 days and no wetlands are connected for extended periods of more than 21 days (Table 7-3). Under a wetter climate scenario, more wetlands are connected, but not for more than 21 days.

The potential McKinlay dam (Scenario B-D) results in wetlands having a small reduction in connectivity under Scenario B and Scenario Dwet. The number of wetlands that are disconnected increased under Scenario Ddry, with the potential McKinlay dam (Table 7-3).

Table 7-3 Percentage of wetlands connected in the Finniss catchment under AEP 1 in 3

<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>% WETLANDS WITH NO CONNECTION</th>
<th>% WETLANDS CONNECTED &lt;21 DAYS</th>
<th>% WETLANDS CONNECTED &gt;21 DAYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario A</td>
<td>24</td>
<td>76</td>
<td>0</td>
</tr>
<tr>
<td>Scenario B-D</td>
<td>29</td>
<td>71</td>
<td>0</td>
</tr>
<tr>
<td>Scenario Cwet</td>
<td>18</td>
<td>82</td>
<td>0</td>
</tr>
<tr>
<td>Scenario Cdry</td>
<td>29</td>
<td>71</td>
<td>0</td>
</tr>
<tr>
<td>Scenario Dwet</td>
<td>29</td>
<td>71</td>
<td>0</td>
</tr>
<tr>
<td>Scenario Ddry</td>
<td>35</td>
<td>65</td>
<td>0</td>
</tr>
</tbody>
</table>

AEP = annual exceedance probability
Under Scenario A, for floods that occur on average once every 10 years (AEP 1 in 10), all wetlands are connected. This is also the case under Scenario Cwet. Under Scenario Cdry, wetlands that are connected for less than 21 days lost connection, but the proportion of wetlands connected for more than 21 days remain the same (Table 7-4). The potential Mount Bennett dam (Scenario B-D) increases the proportion of wetlands with no connectivity, but there are small increases in the proportion of wetlands connected for more than 21 days (Table 7-4). Under Scenario Dwet, there is a small reduction in wetland connectivity; however, there are small increases in the number of wetlands connected for more than 21 days (Table 7-4). Under Scenario Ddry, there is a decrease in wetland connectivity, with none being connected for more than 21 days (Table 7-4).

Table 7-4 Percentage of wetlands connected in the Finniss catchment under AEP 1 in 10

<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>% WETLANDS WITH NO CONNECTION</th>
<th>% WETLANDS CONNECTED &lt;21 DAYS</th>
<th>% WETLANDS CONNECTED &gt;21 DAYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario A</td>
<td>0</td>
<td>71</td>
<td>29</td>
</tr>
<tr>
<td>Scenario B-D</td>
<td>24</td>
<td>41</td>
<td>35</td>
</tr>
<tr>
<td>Scenario Cwet</td>
<td>0</td>
<td>71</td>
<td>29</td>
</tr>
<tr>
<td>Scenario Cdry</td>
<td>12</td>
<td>59</td>
<td>29</td>
</tr>
<tr>
<td>Scenario Dwet</td>
<td>6</td>
<td>59</td>
<td>35</td>
</tr>
<tr>
<td>Scenario Ddry</td>
<td>24</td>
<td>76</td>
<td>0</td>
</tr>
</tbody>
</table>

AEP = annual exceedance probability

Monsoon vine forest

The monsoon vine forests of the Darwin catchments are highly groundwater dependent. While monsoon vine forests occur in areas with permanent soil water, they also occur in drier sandstone escarpment and coastal thickets where deciduous species are able to cope with periods without soil water (Russell-Smith, 2001). They are distinctive stands of tall, evergreen trees that occur in small patches across the savanna, providing crucial habitat for a range of birds and animals.

Monsoon vine forests are currently confined to specific areas where water is readily available. This is the reason this ancient rainforest habitat has persisted in the otherwise vast, dry, fire-prone savanna landscape (Bowman, 1992). In the Wildman catchment, a number of important forest patches exist in the lower areas of the landscape where reliable, year-round groundwater discharge occurs in the form of springs and seepages (Tickell and Zaar, 2017). This is the result of underlying geomorphology and an annual recharge of the aquifer from reliable rainfall (Turnadge et al., 2018).

Due to their high reliance on soil water throughout the year, monsoon vine forests are highly susceptible to changes in water regimes, especially soil water and groundwater. Slight reductions in available water from the current continually available state can lead to changes, especially at the drier boundary with the surrounding savanna. This results in drying out of fuel layers and the consequent impacts of fire (including the frequent burning of the adjacent savanna) on fire-sensitive monsoon forest species. Further declines in water availability, such as springs drying up during all or part of the dry season, would exacerbate the impacts and result in the death of some individual trees, opening up the canopy and allowing for the invasion of grasses and weedy species able to carry fire into the monsoon forest patches, resulting in significant changes to the functioning of this system. A drop in the level of the watertable below the mature tree rooting depth for even part of the year could result in extreme changes, with the death of the critical
mature canopy species and the system likely replaced by fire- and drought-tolerant savanna species with a grassy understory.

In the Mary–Wildman rivers area, available groundwater measurements during 2016–17 indicated that groundwater levels below monsoon rainforest patches typically vary by less than 5 m below ground surface all year. In comparison, groundwater levels below areas of eucalypt savanna (which represent the majority of vegetation present in the Mary–Wildman rivers area) vary by up to 10 m (Turnadge et al., 2018). Monsoon rainforest patches are likely to be affected by water resource and agricultural developments located within a few kilometres distance.

Numerical soil–vegetation–atmosphere modelling indicates that an increase in the depth to groundwater of 2 m beneath these rainforest patches results in a 2% and 10% reduction in leaf area index and transpiration, respectively. Modelled reductions in leaf area index of about 7% and 14% and reductions in stand transpiration of 22% and 36% occur when groundwater levels fall over the long-term by 5 and 10 m, respectively (Turnadge et al., 2018). Based on these results it is thought likely that reductions in groundwater levels of between 5 and 10 m beneath a monsoon vine forest patch would result in a moderate to major change to its composition and function over the long-term.

![Figure 7-12 Modelled change in monsoon vine forest patch transpiration rate and leaf area index with change in groundwater elevation (relative to no drawdown scenario)](image)

### 7.2.5 CHANGE IN INLAND AND FRESHWATER ASSETS: FISH

#### Stable flow spawners

Stable flow spawners are a functional group of fish that spawn in the dry season, in association with stable flows (low flow, baseflow and cease-to-flow). The species in the group include the freshwater longtom (Strongylura kreffitii); mouth almighty (Glossamia aprion); bony herring (Nematalosa erebi); barred grunter (Amniataba percoide); flyspecked (Craterocephalus stercusmuscarum stercusmuscarum) and freckleheaded (Craterocephalus lentiginosus) hardyhead; and the eastern (Melanotaenia splendida splendida), chequered (Melanotaenia splendida inornata) and western (Melanotaenia australis) rainbowfish. Stable flow spawners were assessed at four nodes in the Adelaide and Mary catchments (nodes 81700020 and 81700050 in the Adelaide catchment; 81800351 and 81800354 in the Mary catchment). Stable flow spawners are
typically small and sedentary, and are prey for a range of larger species, such as barramundi. Despite stable flow spawners not requiring high flows to initiate spawning, recruits do benefit from exploiting the nutrient-rich floodplains during the wet season and they require flows for habitat maintenance and condition.

A reduction in the extent of inundation would increase competition between species because of the decrease of available resources and space. Overbank floods in the wet season provide dispersal routes for fish species to migrate to exploit the nutrient-rich inundated floodplains (Karim et al., 2012). Wet-season floods also inundate important offchannel habitats that function as refugia habitat in the dry season (Karim et al., 2012; King et al., 2015; Pusey et al., 2004). Changes in ‘condition’ are described as changes in the area, quality and persistence of habitat for species. Changes in habitat condition can affect recruitment rates, dispersal and range, body condition and persistence of stable flow spawners.

Tier 1 screening analysis indicates that under Scenario B-WH, no or minor changes to the habitat of stable flow spawners occur. Under Scenario B-D, the potential Upper Adelaide River dam, minor changes to habitat in the Adelaide catchment result. The potential Mary River dam results in moderate changes at node 81800354 (immediately below the dam) and minor changes at node 81800351 (downstream of the dam at the confluence of the Mary and McKinlay rivers).

Further analysis (Tier 2) was undertaken at nodes 81700050, 81700200, 81800351 and 81800354 for water harvest scenarios and 81700001, 81700020, 81700050, 81700200, 81800001, 81800351 and 81800354 (Figure 7-3) for dam scenarios. The results of the Tier 2 analysis are consistent with those of the Tier 1 analysis.

Minimal changes in the condition score of all stable flow spawners are found in the Adelaide catchment in response to the addition of two potential dams (the Upper Adelaide River and AROWS dams). The addition of the potential Mary River dam in the Mary catchment results in a more dramatic change in condition of stable flow spawners immediately below the dam. Dams affect the connectivity of a river system. Although stable flow spawners do not migrate to the extent of some other fish species such as barramundi, a single dam is likely to alter flows, which affects habitat maintenance and persistence, which in turn affects the overall condition of stable flow spawners, as evidenced by node 81800354. The potential dams could alter the connection and disconnection periods of offchannel and main channel habitat. A reduced connection period (through reduced inundation and flows) could hinder the ability of stable flow spawners to migrate to suitable dry-season refugia habitat and inundated floodplains in the wet season. This could have detrimental effects on stable flow spawners as they would be forced to remain in main channel habitats where competition and predation effects would be greater. In contrast, an increased connection period (through river regulation and introducing permanency of water in a previously ephemeral reach) could facilitate the dispersal of species that would normally not occupy offchannel habitats. This could alter fish assemblage structures and increase competition and predation of stable flow spawners.

Migratory fish

A fish group vulnerable to inchannel barriers and changes to flows is freshwater migratory fishes. Migratory fish are distributed throughout the Darwin catchments. While there are many species in this group, barramundi (*Lates calcarifer*), bull shark (*Carcharhinus leucas*), black catfish (*Neosilurus*
ater) and Hyrtl’s tandan (*Neosilurus hyrtlii*), sooty grunter (*Hephaestus fugilinosus, H. jenkinsi*), freshwater longtom (*Strongylura kreffti*) and spangled perch (*Leiopotherapon uniclor*) are used here for analysis.

Migratory fish were assessed at five nodes in the Adelaide and Mary catchments (nodes 81700020, 81700050 and 81700200 in the Adelaide catchment; 81800351 and 81800354 in the Mary catchment) (Figure 7-3). Tier 1 screening analysis found that under Scenario B-WH in the Adelaide catchment there are minor changes under the lowest extraction scenarios, but moderate changes under the higher (550 GL and above) scenarios for the LT. Changes are minor under Scenario B-WH HT. With the potential Upper Adelaide River dam, changes are minor at node 81700200 (just below the junction of the Adelaide and Margaret rivers), and moderate at node 81700050 (on the Adelaide River above the junction of the Adelaide and Margaret rivers). Changes are major at node 81700020 (immediately downstream of the potential dam). Major changes would have substantial impacts on the habitat for migratory fish.

In the Mary catchment, the changes in the flow regime under Scenario B-WH LT are minor, from 150 GL onwards at node 81800351 and 350 GL onwards at node 81800354. Under Scenario B-WH HT changes are minor, from 550 GL onwards at node 81800351 and 750 GL onwards at node 81800354. Under Scenario B-D, the potential Mary River dam, changes are major at node 81800351 and extreme at node 81800354. With extreme changes, habitat for migratory fish would no longer be suitable.

**Detailed flow analysis**

Further analysis (Tier 2) was undertaken at nodes 81700050, 81700200, 81800351 and 81800354 under Scenario B-WH and 81700001, 81700020, 81700050, 81700200, 81800001, 81800351 and 81800354 under Scenario B-D (Figure 7-13 and Figure 7-14). Analysis shows minimal change in the condition of migratory fish under Scenario B-WH, with the exception of barramundi, which had moderate changes.

Under Scenario B-D, there is no change or minimal changes in condition within the Adelaide catchment, with the exception of node 81700020, which is located at the node with the potential Upper Adelaide dam. Small to moderate changes are found for all migratory fish at this node. In the Mary catchment, a dramatic change in the condition score for all migratory fish is found at node 81800354, located at the potential Mary River dam site (Figure 7-14). This change extends down to node 81800351, where the change is minor to moderate.

Changes in flows as a consequence of water harvesting results in reduced dry-season flows, which replenish waterhole habitats utilised by migratory fish. Reduced late dry-season flows would compromise water quality and the persistence of habitats. The movement of migratory fish into high primary-productivity estuarine habitats would also be limited. These habitats support productive food webs and high growth rates (King et al., 2015). Other flow changes in the early wet season would affect spawning and movement.

Dams compromise the movement of fishes, preventing access to distant or adjacent habitats (Roscoe and Hinch, 2010). The potential dams in the Darwin catchments are likely to have localised impacts on migratory fishes by limiting movement within the river channel. Impacts could extend to fish populations, particularly as migratory species are top predatory species, which structure fish communities. Dams also have the potential to reduce available habitat,
increasing competition between and within species and reducing the carrying capacity of a river system.

Figure 7-13 Maximum condition scores of sooty grunter and black catfish, considering dam scenarios at nodes 81700001, 81700200, 81700050 and 81700020 in the Adelaide catchment.
Barramundi

The barramundi is a large fish that occurs throughout northern Australia in rivers, lagoons, swamps and estuaries and is arguably the most important fish species to cultural, recreational and commercial fisheries. Barramundi is found extensively throughout the Darwin catchments. Barramundi has the potential to be affected by barriers to movement and changes in the flow regime. Spawning occurs in estuaries, juveniles migrate up rivers and the first few years of a
barramundi’s life are spent in freshwater habitats. In the dry season, barramundi use permanent waterholes as a refuge.

Barramundi were assessed at seven nodes in the Adelaide and Mary catchments (nodes 81700001, 81700020, 81700050 and 81700200 in the Adelaide catchment; 81800001, 81800351 and 81800354 in the Mary catchment) (Figure 7-3). Tier 1 screening analysis in the Adelaide catchment indicates that Scenario B-WH LT results in minor changes to flow metrics important to barramundi, with moderate changes occurring at extraction volumes equal to or greater than 550 GL at node 81700200 and 750 GL at node 81700050. Changes are minor under Scenario B-WH HT, other than for extraction volumes equal to or greater than 950 GL at node 81700050. Under Scenario B-D, the potential Upper Adelaide River dam, changes to flow metrics important to barramundi are moderate at node 81700050, and are minor at node 81700020.

In the Mary catchment, under Scenario B-WH LT, changes are minor for extraction volumes greater than 150 GL at node 81800351 and greater than 350 GL at node 81800354. Under Scenario B-WH HT, changes are minor, for extractions greater than 550 GL at node 81800351 and greater than 750 GL at node 81800354. Under Scenario B-D, the potential Mary River dam, changes in flow metrics important to barramundi are major at node 81800351 and extreme at node 81800354. Major changes would have substantial impacts on the habitat for barramundi. With extreme changes, the habitat for barramundi would no longer be suitable.

**Detailed flow analysis**

Further analysis (Tier 2) was undertaken at nodes 81700050, 81700200, 81800351 and 81800354 under Scenario B-WH and 81700001, 81700020, 81700050, 81700200, 81800001, 81800351 and 81800354 under Scenario B-D.

The potential Upper Adelaide River dam results in a dramatic decline in habitat at node 81700020, which is located immediately below the potential dam site (Figure 7-15). The potential Mary River dam results in an extreme decline in habitat at node 81800354, also immediately below the potential dam, with the change decreasing with distance downstream to node 81800351 and to the end-of-system node 81800001 (Figure 7-16). Extreme changes would result in the habitat for barramundi no longer being suitable.

Water harvest scenarios have the potential to reduce dry-season flows and the duration of wet-season flows. Dam scenarios can increase the duration of low-flow periods in the dry season. In the dry season, adult barramundi in near-shore marine habitats spawn and the juveniles migrate to estuaries and freshwater river reaches where they forage and grow for several years. Barramundi spawned during the late dry season move upstream to inchannel waterhole habitats as juveniles. Connectivity via river flows is required to access these habitats. Late dry-season flows are important to reconnect the estuary to the river channel and allow juvenile barramundi to move to riverine habitats. For inland juvenile barramundi, the loss of freshwater habitats may represent a critical bottleneck for barramundi populations in the catchment. Decreases in the extent, depth and productivity of waterholes would reduce the extent of dry-season habitat and food abundance. In addition to changes in habitat, cues and productivity, dams are also a physical barrier. Flow changes as a consequence of the potential dams are likely to have an impact on barramundi, with changes throughout the year negatively affecting habitat. This is more evident in
nodes close to potential dams. Dams will compromise the movement of barramundi, preventing access to distant or adjacent habitats (Roscoe and Hinch, 2010).

Figure 7-15 Maximum condition scores of barramundi, considering dam scenarios at nodes 81700001, 81700020, 81700050 and 81700200 in the Adelaide catchment
Sawfish

The freshwater sawfish (*Pristis pristis*) is distributed throughout the Darwin catchments. There are few observation records for sawfish in the Darwin catchments, with observations only in the Adelaide catchment, reflecting a data gap. Inchannel barriers along migration routes of the Darwin catchments pose a threat to the freshwater sawfish. The freshwater sawfish has a marine adult phase while the juvenile phase is in estuaries and rivers, and juveniles and adults occupy large pools and waterholes of large rivers.
Sawfish were assessed at four nodes in the Adelaide catchment (nodes 81700001, 81700200, 81700050 and 81700020). Sawfish are a subset of the migratory fish and a species of conservation significance. Tier 1 screening analysis in the Adelaide catchment under Scenario B-WH results in changes in flow metrics that range from minor to moderate under the lowest volume water harvest scenarios. Under Scenario B-WH LT, moderate changes are evident at extraction volumes equal to or greater than 550 GL. Changes are minor under Scenario B-WH HT. Under Scenario B-D, the potential Upper Adelaide dam, changes to flow metrics relevant to sawfish are minor at nodes 81700001 and 81700200. Changes are moderate at node 81700050 and major at node 81700020. Major changes have substantial impacts on the habitat for sawfish.

### 7.2.6 CHANGE IN INLAND AND FRESHWATER ASSETS: MAGPIE GOOSE

**Magpie goose**

The Darwin catchments contain highly significant populations of the magpie goose (*Anseranas semipalmata*). The magpie goose breeding and foraging habitat consists of sub-coastal wetlands where, during the wet season, magpie geese make nests from emergent vegetation. Years with high wet-season rainfall and flooding are associated with increases in both nesting success and dry-season survival of magpie geese. The inputs to this analysis are from inundation modelling within the Darwin catchments as per the companion report on flood mapping and modelling (Karim et al., 2018).

Under Scenario A in the Adelaide, Mary and Wildman catchments, 28% of sites where magpie geese had been observed are inundated during a small flood event (Figure 7-17a) and 36% are inundated during a moderate to large flood event (Figure 7-18a). With the potential Upper Adelaide River dam, the percentage of sites inundated where magpie geese had been historically observed reduced by 28% and 33% for small and large flood events, respectively (Table 7-5). Under Scenario D, a further decrease was observed, with 14% and 29% of historical observation sites inundated during small and large flood events, respectively. These changes suggest minor impacts would occur to magpie geese populations under Scenario B-D (i.e. Adelaide River dam).
Figure 7-17 Flood extent and percentage of sites inundated where magpie geese had historically been observed for a small annual flood event (AEP 1 in 3) under (a) Scenario A and (b) Scenario B-D
Figure 7-18 Flood extent and percentage of sites inundated where magpie geese had historically been observed for a moderate to large annual flood event (AEP 1 in 14) under (a) Scenario A and (b) Scenario B-D

Table 7-5 Maximum percentage of sites with magpie goose observations that are inundated under different scenarios

<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>MAXIMUM PERCENTAGE OF MAGPIE GOOSE OBSERVATIONS INUNDATED FOR ZONE 1 (%)</th>
<th>MAXIMUM PERCENTAGE OF MAGPIE GOOSE OBSERVATIONS INUNDATED FOR ZONE 2 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario A</td>
<td>28.24</td>
<td>36.44</td>
</tr>
<tr>
<td>Scenario B-D</td>
<td>27.90</td>
<td>33.40</td>
</tr>
<tr>
<td>Scenario Cwet</td>
<td>28.72</td>
<td>39.74</td>
</tr>
<tr>
<td>Scenario Cdry</td>
<td>16.43</td>
<td>29.74</td>
</tr>
<tr>
<td>Scenario Dwet</td>
<td>17.87</td>
<td>37.46</td>
</tr>
<tr>
<td>Scenario Ddry</td>
<td>14.49</td>
<td>29.43</td>
</tr>
</tbody>
</table>

AEP = annual exceedance probability
7.3 Biosecurity considerations

7.3.1 INTRODUCTION

Diseases and pests, due either to pathogens endemic to farming regions or introduced through translocations of animals from other regions, have had, and continue to have, major impacts on global agriculture and aquaculture production. For example, the resultant economic loss to global aquaculture industries alone was estimated to be US$6 billion/year (World Bank, 2014).

Compared with many other countries, Australia has many advantages in terms of the opportunity to mitigate risks from pests and disease through sound regulatory processes controlling translocation, technological knowledge and capability, and the greater geographic spread between farming operations in many regions. However, the recent discovery of the highly pathogenic white spot syndrome virus (WSSV) in south-east Queensland prawn farms has had a devastating effect on parts of the industry. There have also been serious outbreaks of diseases in agricultural crops in recent years across northern Australia, including green cucumber mottle mosaic virus on melons in the Katherine region in the NT; the fungal rice blast affecting rice production in the Ord, WA; Panama disease tropical race 4 affecting bananas in northern Queensland and the NT; and banana freckle in the NT. These serve as contemporary reminders of the impact that a pathogen can have at the point of infection as well as on an entire industry.

From a biosecurity point of view, risk is defined as the product of the likelihood of an invasion by a pest or pathogen and the impact that species will have. With both likelihood and impact there is a great deal of uncertainty and difficulty in making clear predictions.

This section examines biosecurity risk from an agriculture and aquaculture perspective, with the discussion structured around:

- the biosecurity risk to new farming enterprises in the Darwin catchments
- the biosecurity risk that new farming enterprises in the Darwin catchments may present to the broader industry across Australia.

Agriculture and aquaculture production systems can be threatened by generalist or specialised pests. The relative isolation of small areas of agriculture and aquaculture may, under some circumstances, provide some protection from certain pests and diseases but the opposite may also be the case; extensive areas of natural or less intensively managed vegetation may provide refuge for pests and diseases as well as beneficial organisms. For example, the Darwin catchments are far removed from the WSSV outbreaks in prawn production systems in south-east Queensland but such isolation does not preclude the very real prospect of a biosecurity risk should such production systems be established there.

Generally, both dryland and irrigated cropping systems have relatively well-developed pest management protocols and the economics of such systems is such that they can bear the cost of controlling the pests that are of concern to them. This is especially the case for high-value crops. Less-intensive agricultural industries and environmental interests are likely to be in a less-favourable economic position when it comes to pest management. Irrigation and other intensive agricultural industries can thus increase the risks from pests faced by less-intensive industries and the natural environment.
Unless stated otherwise, material in the agriculture biosecurity (Section 7.3.2) and aquaculture biosecurity (Section 7.3.3) sections have been summarised from the companion technical reports on agricultural viability (Ash et al., 2018) and aquaculture viability (Irvin et al., 2018), respectively.

7.3.2 AGRICULTURAL BIOSECURITY

Irrigated agriculture in the Darwin catchments will be exposed to existing and new pests and diseases. Although a tropical environment is conducive to a wide range of pests and diseases, the long dry season and the loss of green vegetation that characterises the Darwin catchments provide an unfavourable environment for many pests and diseases and act as a natural break to their year-round persistence. However, areas of irrigation with year-round green foliage may increase the risk of insect pests and diseases persisting throughout the year. Further, new incursions are more likely because of increased human activity and the transport of new vectors on equipment, people or through seeds.

In the short to medium term, biosecurity risks to the Darwin catchments are most likely to come from within the country and, in particular, from adjacent or climatically similar parts of Australia. The catchments already experience impacts from introduced plants and the Darwin catchments have probably been subject to a broader array of introduced pests than many other parts of northern Australia. This is due partly to climate factors, such as relatively high and reliable rainfall, and partly because the catchments include Darwin, one of northern Australia’s largest cities, and the relatively intensive agricultural and peri-urban areas around it. One of Australia’s Weeds of National Significance, mimosa (*Mimosa pigra*), was first introduced into the botanical gardens of Darwin, from whence it spread to become a serious pest of Top End wetlands. Not all parts of the catchment are equally vulnerable to invasive species. In northern Australia, riparian zones are vulnerable to invasion by many different non-native plants because these zones are relatively moist, have generally higher nutrient levels and experience naturally high levels of disturbance.

New risks will mostly be associated with insect pests and diseases. Understanding and managing this increased risk will be important. For these catchments, the types of pests and diseases that provide a risk to the various agricultural industries that could be established are many and varied. Annual weeds are a risk to crop production but they can generally be controlled through herbicides, use of cover crops and stubbles, and cultivation. They tend to not be an acute problem like pests and diseases and thus represent an ongoing management challenge rather than a threat to viability. For example, ongoing weed management in sugarcane costs around $338/ha.

Identifying potential pest and disease problems that can occur in greenfield agricultural areas can be problematic. The warmer, north Australian environment provides a more favourable environment in which insects and pathogens can multiply with the introduction of a new food source (i.e. a crop). However, the environment also favours beneficial organisms that prey on pest species. Production systems that recognise the ecological realities of the natural environment are recommended; the collapse of the cotton industry in the Ord in WA during the 1970s is one example of a failure to do this. Irrigating a number of crops each year in rotation can provide a year-round food source for pests and carry-over of pathogens between crops.
Biosecurity risks to new agricultural enterprises and the risks from these enterprises to the broader environment

This discussion examines pathways of entry to the Darwin catchments and then specifically discusses disease, pests and weeds in turn.

Pathways of entry

Pathogens, pests and weeds can enter a catchment via man-made pathways or natural pathways. Man-made pathways include road transport, ships and planes, and the ‘carriers’ (e.g. humans, animals, plants, machinery) that facilitate the movement and incursion of new pests, diseases and weeds. Published work has shown that the most likely human-facilitated pathway for bringing invasive species is either general trade, or live plant or animal trades. While it is not currently possible to determine the actual or relative risk to the Darwin catchments from these forms of human-facilitated trade, it is possible to look at the historical rate of invasions (also referred to as incursions) in Australia. Studies have shown that the incursion rate in Australia for four orders of insects (beetles, bugs, flies, and moths and butterflies) has been about 15 species per year. Given the low human population in the Darwin catchments it is not likely that they will be exposed to regular incursions facilitated by humans. However, they do occur and can be very damaging, for example the green cucumber mottle mosaic virus in the NT.

The risk of arrival of fungal pathogens and insect pests directly from South-East Asia into the Darwin catchments is small and only during a relatively narrow period. Wind dispersal modelling work undertaken in this Assessment shows that there is no risk from a fungal pathogen or insect pest landing in the Darwin catchments from Sumatra or the middle and northern coast of Papua (Table 7-6). The greatest risk of a fungal pathogen arriving to this region is from the southern coasts of Papua New Guinea and Timor-Leste. For insect pests, the only threat is from Indonesia and Timor-Leste. Where risks exist they are only present for part of the year. From late April to late September, the prevailing winds are generally southerly through to easterlies, i.e. blowing offshore. As a result, there are no arrivals from any points in South-East Asia to the Darwin catchments during this period.

Table 7-6 Proportion of simulations (1 per week = 52), in which a fungal pathogen or insect pest could have been transported from a location in South-East Asia to the Darwin catchments

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>FUNGAL PATHOGEN</th>
<th>INSECT PEST</th>
</tr>
</thead>
<tbody>
<tr>
<td>PNG (south coast)</td>
<td>0.19</td>
<td>0.00</td>
</tr>
<tr>
<td>PNG (mid and north coast)</td>
<td>0.06</td>
<td>0.00</td>
</tr>
<tr>
<td>Indonesia (Papua – south coast)</td>
<td>0.12</td>
<td>0.00</td>
</tr>
<tr>
<td>Indonesia (Papua – mid and north coast)</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Indonesia (Java and Bali)</td>
<td>0.00</td>
<td>0.02</td>
</tr>
<tr>
<td>Indonesia (Sumatra)</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Timor-Leste</td>
<td>0.15</td>
<td>0.12</td>
</tr>
</tbody>
</table>

PNG = Papua New Guinea

Threats to agriculture in the Darwin catchments are not just from new arrivals from overseas but also from human-mediated dispersal from other areas within Australia. There are many different human-mediated vectors within Australia that have been shown to spread invasive species. These
include tourists, livestock, vehicles, machinery, trains and transport containers. For example, the movement of cattle has been shown to spread the prickly acacia weed (*Acacia nilotica*) in western Queensland and parthenium weed (*Parthenium hysterophorus*) is spread by the movement of vehicles, machinery, livestock and stock feed. Those two examples are woody, perennial weeds that negatively affect extensive, pastoral operations as there is limited documentation of weed spread into irrigated cropping areas in northern Australia.

**Pests**

Pests are not limited to insects and pathogens, with macro-pests such as birds (cockatoo; galah, *Eolophus roseicapilla*; brogla, *Grus rubicunda*; and magpie geese, *Anseranas semipalmata*) and macropods (kangaroos and wallabies) considered a risk to introduced irrigated crops, particularly during the drier winter months when native food sources may be scarce. Locally developed and adaptive integrated pest and pesticide resistance management plans are an essential component of best practice and must be implemented pre-emptively.

Pigs can be a significant problem for agriculture in the Top End. Pigs can cause indirect damage, for example by carrying weed seed from watercourses to open country, and can cause direct and major physical damage to a wide range of crops and even to cultivated ground. Pigs have a daily water requirement, which means that during the dry season their range is generally restricted to watercourses and man-made water supplies so as the dry season progresses areas of irrigated crops become increasingly attractive. Apart from direct damage to crops and being agents of weed dispersal, pigs can carry a range of exotic diseases. Of particular concern to the northern cattle industry is foot-and-mouth disease. Pig control is expensive and so selection of crops not attractive to pigs (e.g. cotton) is desirable where their numbers are high.

**Weeds**

The Darwin catchments, along with other parts of northern Australia, are subject to invasion by a wide variety of weeds, many of them deliberately introduced (Cook and Dias, 2006). Neither annual crops (cereals, pulses, cotton, melons, Asian vegetables etc.) nor tree fruits (mango, banana etc.) pose a weed risk. However, some of the weeds that can establish in these crops can spread and pose some risk to the environment or domestic livestock. Some are more generally problematic while others are problematic for specific industries, sectors or land users. Riparian zones and other more mesic parts of the landscape are prone to a greater variety of weeds than elsewhere but even drier parts of the landscape provide niches for some invasive species. Greater levels of disturbance, such as those that occur in association with any cropping system, provide opportunity for particular types of weeds.

Some plants which are now weeds, were deliberately introduced to support agricultural industries. For example, Gamba grass (*Andropogon gayanus*), a Weed of National Significance, was imported for use as a cattle forage but is now problematic in Darwin’s peri-urban areas because its high levels of biomass present a fire risk, and it also threatens environmental assets such as Litchfield National Park.
7.3.3 AQUACULTURE BIOSECURITY

Aquatic diseases are the main biosecurity risk to aquaculture and are caused by a range of pathogenic agents such as viruses, bacteria, fungi and parasites that have varying impacts across species, geographies, rearing systems and life stages.

Biosecurity risk to new aquaculture farming enterprises in the Darwin catchments

This section briefly examines pathways by which pathogens could enter an operation in the Darwin catchments. It then discusses disease and other biosecurity issues relating to the two main tropical farmed species, black tiger prawns (*Penaeus monodon*) and barramundi (*Lates calcarifer*). However, it should be noted that there are significant, and often different, experiences and issues posed by pathogens and disease for all Australian aquaculture industries.

Pathways of entry

The introduction of pathogens into aquatic farming systems comes from two main routes, the first being vertical transmission from parent to progeny, and the second being horizontal transmission from an infected environment, equipment, worker, or animal coming into contact with an uninfected animal during the rearing process. Horizontal transmission can occur through many vectors that harbour the pathogen such as the rearing water, other animals, dead tissues that are consumed, or animal faeces which are consumed or touched. Understanding the primary mode of transmission for each pathogen is critical to understanding how to mitigate disease risks. Applying preventative biosecurity measures that mitigate risks of all routes of transmission for all likely problematic pathogens is key to managing disease. Importantly, the existence of pathogens in the farming system does not necessarily equate to disease, and so disease management in aquaculture needs to both exclude those pathogens that can be excluded, and manage those pathogens that cannot be excluded.

Pathogens

As with all agricultural industries, there are a range of pathogens that pose risks to and may impact aquaculture. Fortunately, Australia is free of many of the aquatic pathogens that affect other aquaculture farming regions of the world.

For prawns, the disease agents that have most affected farming have been viruses. There are a large number of different viruses that can infect prawns, which vary significantly in their ability to cause disease and affect production. Fortunately, most of the highly pathogenic viruses are exotic to Australia. However, the recent discovery of the highly pathogenic WSSV in south-east Queensland farms has led to investigations to determine whether WSSV is in fact endemic, or the result of an aberrant localised introduction (QDAF, 2017). Several endemic viruses can also have an effect on Australian prawn production, particularly when detrimental pond conditions, such as poor water quality, inflict environmental stress on the prawns and trigger disease episodes (QDPIF, 2006).

Bacteria pathogens can also reduce production, but are also often believed secondary to other stressors (QDPIF, 2006). Recently, syndromes caused by toxicity associated with bacteria have had significant impacts on prawn production both in Australia (*Penaeus monodon* mortality syndrome (QDAF, 2016)) and even more so overseas (acute hepatopancreatic necrosis disease (NACA,
Fungi and a range of other microbial and parasitic agents can also cause disease at various life stages and have a negative effect on the appearance of harvested prawn products, but have rarely affected Australian farming in recent decades due to better health and pond management practices.

For barramundi, a range of viral, bacterial, fungal and parasitic pathogens can also affect hatcheries and grow-out. The predominant viral pathogens of concern for barramundi farming in Australia are the nodaviruses, which can cause major mortalities in larval and juvenile barramundi. Bacterial diseases, such as streptococciosis, can also cause high mortalities in both fresh and marine farming systems. Vibriosis and other bacterial pathogens, which infect the gut (causing ‘bloat’) and the gills, also reduce production in fresh and marine waters but are typically secondary to other environmental and dietary stresses. Fungal diseases causing ulceration also periodically affect production in the freshwater and estuarine phases, and typically cause fish to become lethargic and prone to cannibalism. Parasitic protozoans residing in the skin and gills can increase in numbers at times and cause disease, and a blood protozoan has also been associated with major mortalities in sea-caged barramundi. In addition to these non-infectious diseases, particular deformities can reduce production, typically due to nutritional inadequacies in the diet.

A comprehensive knowledge of pathogen agents is essential for developing and implementing risk-based biosecurity measures to mitigate against disease impacts in aquaculture. Understanding of the diseases and disease agents that are likely present in various jurisdictions, or through the process of acquiring animal stocks, and which may have adverse effects, is also important in developing a biosecurity plan. Government departments have important roles in the ongoing surveillance of pathogens, in controlling translocation of stocks based on pathogen risks, and in undertaking investigations where potential disease episodes have been identified (Department of Agriculture and Fisheries Queensland, 2013).

Due to increasing awareness of pathogen risks and the need for biosecurity, and the increasing professionalism of farming operations, it is becoming more common for individual farms to undertake their own pathogen monitoring to minimise the disease risks to their operations. The key elements to effective biosecurity and disease management at the farm level are to access clean and healthy stock; to provide a clean and healthy rearing environment (e.g. good quality water); to provide an adequate quality and quantity of diet; and to control access to water, equipment and people that may introduce pathogens into the farming system.

Treatment actions once diseases are present typically provide few options, particularly for viral pathogens, and are also costly to implement and rarely as effective as prevention. Consequently, for aquaculture, the most important component of disease management is prevention. Important components of prevention are hygiene and biosecurity in the earliest hatchery stages of production, as well as decontamination processes between crops to ensure the environment is clean before the next crop is commenced. Another very important aspect of disease management is to maintain a quality rearing environment, as both the introduction of pathogens, and more importantly the increase of pathogens in the environment and their manifestation to a disease episode, is typically triggered by increased stress on the animals caused by a poor rearing environment.

Due to the rudimentary immune system of crustaceans, there is limited ability to manage the most serious diseases once established, and so pathogen management has typically focused on
exclusion through pathogen screening of broodstock and postlarvae prior to stocking ponds. Some treatments for external bacterial and fungal pathogens are employed, particularly for broodstock, eggs and larvae within the hatchery (FAO, 2007). During the rearing of larvae, control of bacterial pathogens is typically focused on maintaining a good environment and through pre- and probiotics, with antibiotics used only in exceptional circumstances.

**Biosecurity risks that new aquaculture farming enterprises in the Darwin catchments may present to the broader catchment or industry**

**Risk to other aquaculture enterprises**

A major risk pathway with the development of new and established marine aquaculture enterprises is associated with sharing of a water source (usually a river). The risk of contamination between enterprises is highest when there is limited distance (<2 km) between the location of the discharge point from one farm and the supply point of another farm.

**Risk to wild populations**

There is potential for disease transfer between aquaculture species (e.g. prawns and barramundi) and their respective wild populations. The main transfer routes are discharge waters containing disease or from infected animals (escapees) in discharge water or transferred by predatory vectors (e.g. seabirds). The potential impact of disease on wild populations will depend on pathogen volume, ability of the pathogen to survive without a host, proximity of a significant susceptible host population and the health and tolerance of the host to the disease. In general, susceptible animals in the wild occur only in low-density populations adjacent to land-based aquaculture operations.

The effect that exotic or endemic disease outbreaks from aquaculture have on wild stocks is difficult to evaluate. In Australia, impacts of disease transferred from aquaculture to wild populations have not been widely reported and are difficult to detect. In overseas countries where WSSV is endemic there is little evidence that the disease has any effect on wild prawn populations. In Australia, the response to a suspected outbreak of exotic disease (e.g. WSSV) involves the farm notifying the relevant authorities, isolation of affected ponds and preventing water flow from the ponds to the surrounding environment. The authority (e.g. Biosecurity Queensland) provides advice, which depending on the diagnosis may include destruction and disposal of stock and decontamination of the site. In the case of the recent WSSV discovery in south-east Queensland, a surveillance program commenced (post decontamination) that requires 24 months of no detection of infection in the wild before farming can recommence (DAF, 2018). Since the introduction of the surveillance program in Queensland only very small numbers of infected wild crustaceans have been detected, the vast majority sampled in the vicinity of the original discovery.

The discovery of exotic disease may have a larger impact on the fisher than the wild fishery. For example, in the case of WSSV in Queensland, local commercial and recreation prawn fishers have been constrained by a ban on the movement of uncooked prawns within a restriction zone, which stretches from Caloundra to the NSW border (DAF, 2018). If an exotic disease (e.g. WSSV) was to be identified in aquaculture enterprises located in the Darwin catchments, commercial fishers operating in waters adjacent to the catchment would likely face similar restrictions in the movement of prawns.
Biosecurity regulatory impacts on development

The aquaculture industry is managed by numerous agencies at the local, state and federal levels of government. To date, significant development of marine aquaculture in northern Australia has in part been constrained by complex legislation and the absence of aquaculture-specific policy, particularly relating to biosecurity issues. A parliamentary inquiry into the development of northern Australia identified the regulatory environment as a serious impediment to major expansion of the prawn farming industry (Parliament of Australia, 2014).

In general, large areas of low-value land located away from populated coastal areas are likely to be suitable for freshwater ponds. In contrast, marine ponds require higher value coastal land, often located in close proximity to towns or regional centres. Compared to marine pond aquaculture, freshwater pond aquaculture is ranked as a low environmental risk option for development. There is no difference in the probability of marine or fresh pond water escaping containment and seeping into the groundwater or surrounding environment. However, marine water discharged into groundwater or freshwater bodies has greater potential to cause negative environmental and ecological impacts.

The approval process for an aquaculture licence is simple for freshwater pond-based farming. This is reflected in the number of licence approvals. For example, in Queensland in 2014–15 there were 158 development approvals for freshwater red claw production compared to 58 approvals for marine prawn production. The disconnection between the number of licence approvals and value of the respective industries ($1 million for red claw and $86 million for prawns) is due to the greater difficulty in obtaining an aquaculture licence for marine pond-based farming (Savage, 2016). The approval process will vary depending on the state or territory and jurisdiction of water source. Specific details on the approvals required for a land-based aquaculture operation can be found at the website of the relevant authority. Two reviews undertaken in 2013 and 2014 by the Centre for International Economics (CIE) provide a good overview of the regulatory framework for aquaculture in Queensland (CIE, 2013, 2014). The 2014 CIE review provides a comparative assessment of Queensland with three southern jurisdictions, highlighting the degree of difference in regulatory approaches across jurisdictions (CIE, 2014).

7.4 Sediment, nutrients and agropollutant loads to receiving waters

7.4.1 INTRODUCTION

Agriculture can affect the water quality of downstream freshwater, estuarine, and marine ecosystems. The principal pollutants from agriculture are nitrogen, phosphorus, total suspended solids, herbicides and pesticides (Lewis et al., 2009; Kroon et al., 2016; Davis et al., 2017). Losses via runoff or deep drainage are the main pathways by which agricultural pollutants enter water bodies. The climate, location (e.g. soils and topography), land use (e.g. cropping system) and management (e.g. conservation and irrigation practices) influence the type and quantity of pollutants lost from an agricultural system.

The development of agriculture in northern Australia has been associated with declining water quality (Lewis et al., 2009; Mitchell et al., 2009; De’ath et al., 2012; Waterhouse et al., 2012; Thorburn et al., 2013; Kroon et al., 2016). Since the 1850s it has been estimated that pollutant
loads in north-eastern Australian rivers (typically those in which agriculture as a land use dominates) have increased considerably for nitrogen (2 to 9 times baseline levels), phosphorus (3 to 9 times), suspended sediment (3 to 6 times) and pesticides (~17,000 kg) (Kroon et al., 2016). Degraded water quality can cause a loss of aquatic habitat, biodiversity, productivity and ecosystem services. Increased nitrogen and phosphorus can cause plankton blooms and weed infestation, increased hypoxia, and result in fish deaths. Suspended sediment can smother habitat and aquatic organisms, reduce light penetration and reduce dissolved oxygen levels. Pesticides may be toxic to aquatic organisms (Pearson and Stork, 2009; Brodie et al., 2013; Davis et al., 2017).

Northern Australian river systems are distinctive as they have highly variable flow regimes, unique species composition, low human population densities and, in some cases, naturally high turbidity (Brodie and Mitchell, 2005). Primary influences on water quality include increased sediment loads associated with land clearing, grazing, agriculture and late dry-season fires, and nutrient pollution from agricultural and pastoral land use (Dixon et al., 2011).

Unless specified otherwise, material in sections 7.4.2 and 7.4.3 are summarised from the companion technical report on agriculture viability (Ash et al., 2018) and sections 7.4.4 and 7.4.5 are summarised from the companion technical report on aquaculture viability (Irvin et al., 2018).

7.4.2 AGRICULTURE POLLUTANT LOSSES AT THE PADDOCK SCALE

Two approaches were used to quantify the likely losses of key pollutants (nitrogen, phosphorus, total suspended solids, and chemicals such as herbicides, pesticides and fungicides) from potential agricultural development in the Darwin catchments:

1. The first approach was a relative-risk assessment of the crops using potential nutrient surpluses arising from recommended tillage management and herbicide, pesticide and fungicide application rates in these cropping systems as indicators of risk of losses of the key pollutants.

2. The second approach involved a more detailed estimate of pollutant losses for some specific crops for agricultural development based on Agricultural Production Systems sIMulator (APSIM) simulations of the cropping systems for those crops.

Relative-risk assessment of pollutant losses

To estimate the risk of losses of nitrogen, phosphorus, total suspended solids and chemicals from a range of crops and cropping systems, information on a wide range of factors was collated or calculated including information on nutrient surpluses, number of tillage operations, and application rates of herbicides, pesticides and fungicides (Ash et al., 2018).

Central to the relative-risk assessment is nutrient surpluses, which occur when a greater amount of nutrient (e.g. nitrogen, phosphorous) is applied to the crop than is removed from the field in the harvested product. Nutrient surpluses are an indicator of potential nutrient losses from fields and have been used to assess the risk of nutrient discharges from agricultural areas in other parts of northern Australia (Thorburn and Wilkinson, 2013). The risk of herbicide, pesticide, fungicide and sediment losses was assessed from the amount of chemical applied and the number of tillage operations, respectively.

Nitrogen use varied considerably for crops grown in the Darwin catchments (Table 7-7). The nitrogen surplus was very high for crops such as bananas or okra that have high nitrogen inputs,
and a low quantity of nitrogen in the harvestable product. Conversely, the nitrogen surplus was low, or even negative, for crops such as rice, maize and peanuts. A negative nitrogen surplus indicates that nitrogen inputs are less than the nitrogen in the harvestable product. In these instances, nitrogen from mineralisation of soil nitrogen would be required to meet crop nitrogen demands (Angus, 2001).

Table 7-7 Nitrogen (N) surplus for multiple crops grown in the Darwin catchments based on risk assessment
Data calculated using APSIM output and values from literature (see the companion technical report on agricultural viability (Ash et al., 2018)).

<table>
<thead>
<tr>
<th>CROP</th>
<th>N APPLIED TO CROP (kg/ha)</th>
<th>N FERT GREEN MANURE CROP (kg/ha)</th>
<th>N FIXED (kg/ha)</th>
<th>TOTAL N INPUTS (kg/ha)</th>
<th>N IN HARVESTABLE PRODUCT (kg/ha)</th>
<th>N SURPLUS (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Banana</td>
<td>500</td>
<td>0</td>
<td>0</td>
<td>500</td>
<td>71</td>
<td>429</td>
</tr>
<tr>
<td>Rockmelon</td>
<td>125</td>
<td>89</td>
<td>0</td>
<td>214</td>
<td>12</td>
<td>202</td>
</tr>
<tr>
<td>Honeydew melon</td>
<td>125</td>
<td>89</td>
<td>0</td>
<td>214</td>
<td>14</td>
<td>200</td>
</tr>
<tr>
<td>Watermelon</td>
<td>125</td>
<td>89</td>
<td>0</td>
<td>214</td>
<td>31</td>
<td>183</td>
</tr>
<tr>
<td>Okra</td>
<td>350</td>
<td>89</td>
<td>0</td>
<td>439</td>
<td>76</td>
<td>363</td>
</tr>
<tr>
<td>Cucumber</td>
<td>250</td>
<td>89</td>
<td>0</td>
<td>339</td>
<td>109</td>
<td>230</td>
</tr>
<tr>
<td>Sweet corn</td>
<td>195</td>
<td>0</td>
<td>0</td>
<td>195</td>
<td>42</td>
<td>153</td>
</tr>
<tr>
<td>Snake bean</td>
<td>205</td>
<td>89</td>
<td>0</td>
<td>294</td>
<td>164</td>
<td>130</td>
</tr>
<tr>
<td>Soybean</td>
<td>18</td>
<td>0</td>
<td>180</td>
<td>198</td>
<td>150</td>
<td>48</td>
</tr>
<tr>
<td>Rice</td>
<td>160</td>
<td>0</td>
<td>0</td>
<td>160</td>
<td>122</td>
<td>38</td>
</tr>
<tr>
<td>Maize</td>
<td>155</td>
<td>0</td>
<td>0</td>
<td>155</td>
<td>159</td>
<td>–4</td>
</tr>
<tr>
<td>Peanut</td>
<td>14</td>
<td>0</td>
<td>124</td>
<td>138</td>
<td>105</td>
<td>33</td>
</tr>
</tbody>
</table>

Phosphorus surplus varied substantially for crops grown in the Darwin catchments (Table 7-8). The phosphorus surplus was very high for crops such as melons and okra that have high phosphorus inputs and a low quantity of phosphorus in the harvestable product. Conversely, the phosphorus surplus was low or even negative for crops such as soybean, maize and sweet corn. A negative phosphorus surplus indicates that phosphorus inputs are less than the phosphorus in the harvestable product. In these instances, phosphorus from mineralisation of organic phosphorus would be required to meet crop phosphorus demands (Stewart and Tiessen, 1987).

Table 7-8 Phosphorus (P) surplus for multiple crops grown in the Darwin catchments based on risk assessment
Data calculated using APSIM output and values from literature (see the companion technical report on agricultural viability (Ash et al., 2018)).

<table>
<thead>
<tr>
<th>CROP</th>
<th>P FERT CROP (kg/ha)</th>
<th>P FERT GREEN MANURE CROP (kg/ha)</th>
<th>TOTAL P INPUTS (kg/ha)</th>
<th>P IN HARVESTABLE PRODUCT (kg/ha)</th>
<th>P SURPLUS (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Honeydew melon</td>
<td>68</td>
<td>22</td>
<td>90</td>
<td>3</td>
<td>87</td>
</tr>
<tr>
<td>Rockmelon</td>
<td>68</td>
<td>22</td>
<td>90</td>
<td>3</td>
<td>87</td>
</tr>
<tr>
<td>Watermelon</td>
<td>68</td>
<td>22</td>
<td>90</td>
<td>3</td>
<td>87</td>
</tr>
<tr>
<td>Okra</td>
<td>131</td>
<td>22</td>
<td>153</td>
<td>15</td>
<td>138</td>
</tr>
<tr>
<td>Cucumber</td>
<td>192</td>
<td>22</td>
<td>214</td>
<td>23</td>
<td>191</td>
</tr>
<tr>
<td>Snake bean</td>
<td>131</td>
<td>22</td>
<td>153</td>
<td>21</td>
<td>132</td>
</tr>
</tbody>
</table>
The total herbicide, pesticide and fungicide application rates per crop varied substantially for crops grown in the Darwin catchments (Table 7-9). Some crops, such as bananas, have high pesticide, herbicide and fungicide application rates while other crops, such as mangoes, have much lower application rates. It should be noted that this analysis is quite limited as it is simply reporting total amounts applied rather than the impact of the active ingredients. Many newer herbicides and pesticides have much lower application rates but their active ingredients are relatively more potent than older chemicals. For example, the pesticide chlorantraniliprole (Alatacor, Dupont Chemicals) is a recent pesticide that is highly effective against caterpillars in pulse crops and is applied at a rate of just 70 g/ha.

<table>
<thead>
<tr>
<th>CROP</th>
<th>P FERT CROP (kg/ha)</th>
<th>P FERT GREEN MANURE CROP (kg/ha)</th>
<th>TOTAL P INPUTS (kg/ha)</th>
<th>P IN HARVESTABLE PRODUCT (kg/ha)</th>
<th>P SURPLUS (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Banana</td>
<td>101</td>
<td>0</td>
<td>101</td>
<td>9</td>
<td>92</td>
</tr>
<tr>
<td>Rice</td>
<td>53</td>
<td>0</td>
<td>53</td>
<td>25</td>
<td>28</td>
</tr>
<tr>
<td>Peanut</td>
<td>31</td>
<td>0</td>
<td>31</td>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>Soybean</td>
<td>18</td>
<td>0</td>
<td>18</td>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>Maize</td>
<td>30</td>
<td>0</td>
<td>30</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>Sweet corn</td>
<td>44</td>
<td>0</td>
<td>44</td>
<td>70</td>
<td>–26</td>
</tr>
</tbody>
</table>
### Table 7-9 Herbicide, pesticide and fungicide application rates for multiple crops grown in the Darwin catchments

<table>
<thead>
<tr>
<th>CROP</th>
<th>TOTAL HERBICIDE APPLICATION (L/ha/CROP)</th>
<th>TOTAL PESTICIDE APPLICATION (L/ha/CROP)</th>
<th>TOTAL FUNGICIDE APPLICATION (L/ha/CROP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Okra</td>
<td>5.0</td>
<td>8.6</td>
<td>3.4</td>
</tr>
<tr>
<td>Snake bean</td>
<td>5.0</td>
<td>8.6</td>
<td>3.4</td>
</tr>
<tr>
<td>Bitter melon</td>
<td>5.0</td>
<td>8.6</td>
<td>3.4</td>
</tr>
<tr>
<td>Hairy melon</td>
<td>5.0</td>
<td>8.6</td>
<td>3.4</td>
</tr>
<tr>
<td>Long melon</td>
<td>5.0</td>
<td>8.6</td>
<td>3.4</td>
</tr>
<tr>
<td>Luffa</td>
<td>5.0</td>
<td>8.6</td>
<td>3.4</td>
</tr>
<tr>
<td>Cucumber</td>
<td>4.0</td>
<td>5.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Watermelon</td>
<td>1.5</td>
<td>1.5</td>
<td>2.4</td>
</tr>
<tr>
<td>Rockmelon</td>
<td>1.5</td>
<td>1.5</td>
<td>2.4</td>
</tr>
<tr>
<td>Honeydew melon</td>
<td>1.5</td>
<td>1.5</td>
<td>2.4</td>
</tr>
<tr>
<td>Banana (ratoon)</td>
<td>25.3</td>
<td>78.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Cashew</td>
<td>2.0</td>
<td>10.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Mango Calypso</td>
<td>3.0</td>
<td>0.1</td>
<td>1.8</td>
</tr>
<tr>
<td>Mango KP</td>
<td>3.0</td>
<td>0.1</td>
<td>1.8</td>
</tr>
<tr>
<td>Tahitian lime</td>
<td>12.4</td>
<td>0.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Maize</td>
<td>5.5</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Peanuts</td>
<td>10.7</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Rice (aerobic dryland)</td>
<td>7.2</td>
<td>1.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Rice (aerobic wet)</td>
<td>7.2</td>
<td>1.4</td>
<td>0.0</td>
</tr>
<tr>
<td>Rice (anaerobic)</td>
<td>7.2</td>
<td>1.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Rice (aromatic, aerobic, wet)</td>
<td>7.2</td>
<td>1.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Rice (aromatic, anaerobic)</td>
<td>7.2</td>
<td>1.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Rice (aromatic, aerobic, dry)</td>
<td>7.2</td>
<td>1.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Soybean</td>
<td>13.1</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Sweet corn</td>
<td>1.5</td>
<td>4.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Forage (Cavalcade)</td>
<td>0.3</td>
<td>2.4</td>
<td>0.0</td>
</tr>
<tr>
<td>Forage (Jarra grass)</td>
<td>6.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Forage sorghum</td>
<td>3.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

The number of tillage operations varied substantially for crops grown in the Darwin catchments. The greater the number of tillage operations, the greater the risk of loss of soil to the environment, which has the potential to end up as suspended sediment in waterways. Intensive tillage operations pose a greater risk than minimal tillage operations. Thus, crops such as melons and bananas that have a high number of both total and intensive tillage operations pose the greatest risk. Crops such as rice and sweet corn that have a low number of both total and intensive tillage operations pose the least risk.
Simulated pollutant losses

Simulated annual loss of nitrogen via runoff varied depending on crop but simulated annual totals were low (Figure 7-19a). Mean annual simulated loss of nitrogen was 0.1 kg/ha and the maximum annual loss was 0.9 kg/ha from a soybean crop.

Simulated annual losses of leached nitrogen tended to be higher than losses via runoff and varied depending on crop (Figure 7-19b). Mean annual simulated nitrogen loss was 14 kg/ha and the maximum annual loss was 84 kg/ha from a forage sorghum crop. In general, losses of leached nitrogen were higher in forage sorghum than in other crops.

Simulated annual soil losses varied depending on crop (Figure 7-19c). Mean simulated annual loss was 4 t/ha and the maximum annual loss was 23 t/ha from a mungbean crop. In general, soil loss from mungbean and soybean was higher than for forage sorghum and rice.

Pollutant losses varied considerably based on rainfall as nitrogen loss via runoff and soil erosion are driven by frequency and intensity of rainfall, while nitrogen leaching is driven by water drainage. For example, for a forage sorghum crop simulated under an Adelaide River climate and on a Vertosol in 2001 and 2002 with 1866 mm and 995 mm of annual rainfall, respectively, simulated annual nitrogen losses via runoff were 0.3 kg/ha and 0.1 kg/ha, respectively. Nitrogen losses via leaching were 57 kg/ha and 31 kg/ha, respectively, and soil losses were 4.1 t/ha and 1.2 t/ha, respectively. These results are based on a single annual crop and do not include a cover crop or other form of rotational cropping system.

Climate is also a driver of pollutant losses. Comparison of years with considerably different annual rainfall found nitrogen losses via runoff or leaching were greater in years with high rainfall than with low rainfall. Soil texture also plays a role in driving pollutant losses, with sandy soils more prone to nitrogen losses via leaching than clay soils (Gaines and Gaines, 1994). Future agricultural development could minimise pollutant losses by prioritising development on soils with lower potential for pollutant losses.
Reducing pollutant losses

There is a large body of literature that has investigated approaches to minimising pollutant losses from farming systems in Australia. Refining application rates of fertiliser to better match crop requirements and improving irrigation management are effective ways to minimise nitrogen losses (Brodie et al., 2008; Thorburn et al., 2008, 2011a, 2011b; Webster et al., 2012; Biggs et al., 2013; Thorburn and Wilkinson, 2013). Lower fertiliser application rates has reduced losses of nitrogen via leaching from banana crops (Armour et al., 2013). The use of ‘best management practices’ including controlled traffic and banded application of herbicides can substantially reduce the loss of herbicides (Masters et al., 2013; Silburn et al., 2013). Furthermore, crop rotation, particularly the use of a cover crop, can minimise soil loss (Carroll et al., 1997; Dabney et al., 2001). In a simulated example of a cropping rotation that includes a summer cover crop, simulated annual nitrogen loss via leaching was reduced from 6.3 kg/ha for a single rice crop, to between 0.4 and 1.1 kg/ha for a rice–soybean or rice–sorghum rotation (Figure 7-20).
7.4.3 MANAGING IRRIGATION DRAINAGE

Surface drainage water is water that runs off irrigation developments as a result of over-irrigation or rainfall. This excess water can potentially affect the surrounding environment by modifying flow regimes and changing water quality. Hence, management of irrigation or agricultural drainage waters is a key consideration when evaluating and developing new irrigation systems and should be given careful consideration during the planning and design process. Regulatory constraints on the disposal of agricultural drainage water from irrigated lands are being made more stringent as this disposal can potentially have significant off-site environmental effects (Tanji and Kielen, 2002). Hence, minimising drainage water through the use of best-practice irrigation design and management should be a priority in any new irrigation development in northern Australia. This involves integrating sound irrigation systems, drainage networks and disposal options so as to minimise off-site impacts.

Surface drainage networks need to be designed to cope with the runoff associated with irrigation, and also the runoff induced by rainfall events on irrigated lands. Drainage must be adequate to remove excess water from irrigated fields in a timely manner, and hence reduce waterlogging and salinisation, which can seriously limit crop yields. In best-practice design, surface drainage water is generally reused through a surface drainage recycling system where runoff tailwater is returned to an on-farm storage or used to irrigate subsequent fields within an irrigation cycle.

The quality of drainage water will vary depending upon a range of factors including water management and method of application, soil properties, method and timing of fertiliser and
pesticide application, hydrogeology, climate and drainage system (Tanji and Kielen, 2002). These factors need to be taken into consideration when implementing drainage system water recycling and also when disposing of drainage water to natural environments.

A major concern with tailwater drainage is the agropollutants derived from pesticides and fertilisers that are generally associated with intensive cropping and are found in the tailwater from irrigated fields. Crop chemicals can enter surface drainage water if poor water application practices or significant rainfall events occur, after pesticide or fertiliser application (Tanji and Kielen, 2002). Tailwater runoff from pesticides and fertilisers can contain phosphate, organic nitrogen and pesticides that have the potential to adversely affect flora and fauna and ecosystem health, on land waterways, estuaries or marine environments. Tailwater runoff may also contain elevated levels of salts, particularly if the runoff has been generated on saline surface soils. Training of irrigators in responsible application of both water and agrochemicals is therefore an essential component of sustainable management of irrigation.

As tailwater runoff is either discharged from the catchment or captured and recycled it can result in a build-up of agropollutants that may ultimately require disposal from the irrigation fields. In externally draining basins, the highly seasonal nature of flows in northern Australia does offer possibilities to dispose of poor-quality tailwater during high-flow events. However, downstream consequences are possible and no scientific evidence is available to recommend such disposal as good practice. Hence, consideration should be given to providing an adequate understanding of downstream consequences of disposing of drainage effluent and options must be provided for managing disposal that minimise impacts on natural systems.

7.4.4 CHEMICAL CONTAMINANT RISK TO AQUACULTURE AND THE ENVIRONMENT

Hundreds of different chemicals, including oils, metals, pharmaceuticals, fertilisers and pesticides (e.g. insecticides, herbicides, fungicides) are used in different agricultural, horticultural and mining sectors, and in industrial and domestic settings, throughout Australia. The release of these chemical contaminants beyond the area of target application can lead to the contamination of soils, sediments and waters in nearby environments. In aquatic environments, including aquaculture environments, fertilisers have the potential to cause nonpoint source pollution. This eutrophication is caused by nutrients that trigger excessive growth of plant and algal species, which then form hypoxic (low oxygen) ‘dead zones’ and potentially elevated levels of toxic un-ionised ammonia (Kremser and Schnug, 2002). This can have a significant impact on the health and growth of animals in aquaculture operations, as well as in the broader environment. For example, health indicators are lower in barramundi collected from agriculturally affected rivers in Queensland relative to those collected at more pristine sites.

Of concern to aquaculture in northern Australia are the risks posed to crustaceans (e.g. prawns and crabs) by some of the insecticides in current use. These insecticides can be classified based on their specific chemical properties and modes of action. The different classes of insecticides have broad and overlapping applications across these different settings.

The first class is organophosphate insecticides of which toxicity is not specific to target insects, raising concerns about the impacts on non-target organisms, such as crustaceans and fish. Despite concerns about human health impacts and potential carcinogenic risks, organophosphates are still
one of the most broadly used insecticides globally and are still used in Australia for domestic pest control (Weston and Lydy, 2014; Zhao and Chen, 2016). Pyrethroid insecticides have low toxicity to birds and mammals, but higher toxicity to fish and arthropods. Phenylpyrazole insecticides are another class that also pose risks to non-target crustaceans (Stevens et al., 2011). Neonicotinoid insecticides are a class being used in increasing amounts because they are very effective at eliminating insect pests, yet pose low risks to mammals and fish (Sánchez-Bayo and Hyne, 2014). Monitoring data from the Great Barrier Reef catchments indicate that concentration of neonicotinoid insecticides in marine water samples is rapidly increasing with widespread use. One significant concern for aquaculture is the risk that different insecticides, when exposed to non-target organisms, may interact to cause additive or greater than additive toxicity.

An awareness and knowledge of the potential exposures, risks, and impacts that chemical contaminants may pose in a location is valuable when establishing and operating a commercial aquaculture enterprise, to ensure exposures are best mitigated. For the most vulnerable life cycle stages of production, such as the larval stages of rearing within the controlled hatchery environment, water treatment systems can be employed to mitigate risks of exposure to contaminants. However, for broadacre pond systems, the best approach is to understand the risks of exposure in an area, and ideally to establish farms in areas of lower exposure.

7.4.5 AQUACULTURE DISCHARGE WATER AND OFF-SITE IMPACTS

Discharge water is effluent from land-based aquaculture production. Discharge water is water that has been used (culture water) and is no longer required in a production system. In most operations (particularly marine), bioremediation is used to ensure that water discharged off-farm into the environment contains low amounts of nutrients and other contaminants. The aim is for discharge waters to have similar physiochemical parameters to the source water.

Discharge water from freshwater aquaculture can be easily managed and provides a water resource suitable for general or agriculture-specific irrigation. Marine discharge water is comparatively difficult to manage, with limited reuse applications. The key difference in discharge management is that marine (salty) water must be discharged at the source, whereas location for freshwater discharge is less restrictive and potential applications numerous (e.g. irrigation). Specific water discharge guidelines vary with species and jurisdiction. For example in Queensland, water discharge policy minimum standards for prawn farming include minimum standards for physiochemical indicators (e.g. oxygen and pH) and nutrients (e.g. nitrogen, phosphorus and suspended solids) and total volume (EHP, 2013).

A large multidisciplinary study on intensive Australian prawn farming, which assessed the impact of effluent on downstream environments (CSIRO, 2013), found that Australian farms operate under world best practice in regards to the management of discharge water. The study found that discharge water had no adverse ecological impact on receiving water and that nutrients could not be detected 2 km downstream from the discharge point.

While Australian prawn farms are reported as being among the most environmentally sustainable in the world (CSIRO, 2013), location of the industry adjacent to the listed Great Barrier Reef and related strict policy on discharge has been a major constraint to expansion of the industry. Strict discharge regulation, which requires zero net addition of nutrients in waters adjacent to the Great Barrier Reef.
Barrier Reef, has all but halted expansion in the last decade. An example of the regulatory complexity in this region is the 14-year period taken to obtain approval to develop a site in the Burdekin shire in north Queensland (APFA, 2016). Over the last decade, increases in production have been due to improvements in production efficiency rather than any expansion of the industry footprint.

In a report to the Queensland Government (Department of Agriculture and Fisheries Queensland, 2013) it was suggested that less-populated areas in northern Australia, which have less conflict for the marine resource, may have potential as areas for aquaculture development. The complex regulatory environment in Queensland was a factor in the decision by Project Sea Dragon to investigate greenfield development in WA and NT as an alternative location for what would be Australia’s largest prawn farm (Seafarms, 2016).

Today most farms (particularly marine) use bioremediation ponds to ensure that water discharged off-farm into the environment contains low amounts of nutrients and other contaminants. The prawn farming industry in Queensland has adopted a code of practice to ensure that discharge waters do not result in irreversible or long-term impacts to the receiving environment (Donovan, 2011).

Pump stations are used to distribute water around the farm (Figure 7-21). Marine water is pumped from a primary pump station located near the water source (usually a river) to a raised supply channel engineered to gravity-deliver water to the ponds. During production and at final harvest water is discharged from production ponds via gravity into a waste water channel. A secondary pump station is then used to pump the water from the waste water channel to the bioremediation pond. The role of the bioremediation process is to reduce suspended solids and nutrients (nitrogen and phosphorus) in the water to meet discharge water quality standards set by regulators. Water treated in the bioremediation pond is either recirculated to the production pond via a third pump station and the supply channel or discharged by gravity to the river. The specifications of each pump station are in keeping with the volume of water required to fill the ponds and to service water exchange requirements. Farm layout should be designed to minimise the chance of reintroducing discharged water to the ponds via the primary pump station. The location of the primary pump station and the discharge channel should be separated by as large a physical distance as practical. In general, best practice involves access of source water at high tide and discharge of water at low tide.
The volume of water required to be discharged or possibly diverted to a secondary application (e.g. agriculture) is equivalent to the total pond water use for the season, minus total evaporative losses and the volume of recycled water used during production.

7.5 Irrigation-induced salinity

7.5.1 INTRODUCTION

Prior to European settlement, Australia was dotted with naturally occurring brackish creeks, salt pans and salt marshes. In these areas of ‘primary salinity’, ecosystems evolved that were adapted to the high concentrations of salt in the water and soil. Areas where the effects of salinity are now evident as a consequence of European settlement, are referred to as ‘secondary salinity’. Secondary salinity manifests itself in two main forms: that which occurs in irrigation regions and salinity occurring in dryland regions.

There are three basic requirements for salt to become an environmental problem: (i) a source of salt, (ii) a source of water in which to mobilise the salt, and (iii) mechanisms by which the salt is redistributed to locations in the landscape where it causes damage.
Salts can be concentrated by in situ weathering of rock and minerals in the soil, and in some instances, salt can originate from low quality irrigation water. However, in many places in Australia, salt in the soil originates from rainfall.

Rainfall contains small quantities of salt. Over many hundreds of years, salts from rainfall can become concentrated in the soil, through evaporation. Areas most susceptible typically have relatively low annual rainfall (i.e. less than 800 mm/year) and low soil permeability. Areas with higher rainfall (i.e. more than 1200 mm/year), such as the Darwin catchments, and/or highly permeable soils, tend to have lower concentrations of salts in the soil profile because the salts are leached down to the watertable and flushed out of the groundwater system. In a dryland salinity hazard mapping of the NT, Tickell (1994) determined that the dryland salinity hazard over most of the NT is low, predominantly due to relatively low salt storages occurring in areas where deep-rooted vegetation is present, and that the low salt storages in the landscape were mainly due to small salt inputs from rainfall.

Due to the absence of a source of salt in the landscape and that water sources are typically fresh, the risk of irrigation-induced salinisation in the Darwin catchments was deemed to be low and consequently no further assessment of salinity risk was undertaken.

7.6 References


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Appendices
Appendix A

Assessment products

More information about the Northern Australia Water Resource Assessment can be found at [https://www.csiro.au/en/Research/Major-initiatives/Northern-Australia/Current-work/NAWRA](https://www.csiro.au/en/Research/Major-initiatives/Northern-Australia/Current-work/NAWRA). The website provides readers with a communications suite including factsheets, multimedia content, FAQs, reports and links to other related sites, particularly about other research in northern Australia.

In order to meet the requirements specified in the contracted ‘Timetable for the Services’, the Assessment provided the following key deliverables:

- Technical reports present scientific work at a level of detail sufficient for technical and scientific experts to reproduce the work. Each of the activities of the Assessment has at least one corresponding technical report.

- Each of the three catchment reports (i.e. this report and another for the Mitchell catchment and Fitzroy catchment) synthesises key material from the technical reports, providing well-informed but non-scientific readers with the information required to make decisions about the opportunities, costs and benefits associated with water resource development.

- A case study report, with case studies which show how information produced by the Assessment can be assembled to help readers ‘answer their own questions’. They are also used to help readers understand the type and scale of opportunity for irrigated agriculture or aquaculture in selected parts of the Assessment area, and explore some of the nuances associated with greenfield developments in the study area. Case studies are provided for each study area.

- Three overview reports – one for each of the three study areas – are provided for a general public audience.

- Three factsheets provide key findings for each study area for a general public audience.

This appendix lists all such deliverables.

Please cite as they appear.

Methods reports


Technical reports


the Australian Government from the CSIRO Northern Australia Water Resource Assessment, part of the National Water Infrastructure Development Fund: Water Resource Assessments. CSIRO, Australia.


Catchment reports


Overview reports


Factsheets on key findings


Appendix B

Shortened forms

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<thead>
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<th>SHORT FORM</th>
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<tr>
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<td>AWRC</td>
<td>Australian Water Resources Council</td>
</tr>
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<td>CGE</td>
<td>Computable General Equilibrium</td>
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<td>digital elevation model</td>
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<tr>
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<td>global climate model output empirically scaled to provide catchment-scale variables</td>
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<td>Integrated Quantity-Quality Model – a river systems model</td>
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<td>NRM</td>
<td>natural resource management</td>
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<tr>
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<tr>
<td>TRaCK</td>
<td>Tropical Rivers and Coastal Knowledge Research Hub</td>
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## Units

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Data sources and availability

The Northern Australia Water Resource Assessment obtained a range of data for use under licence from a number of organisations, including the following:

- **State of Queensland (Business Queensland)**
  - Digital Cadastral Database - The Digital Cadastral Database (DCDB) contains the property boundaries and related property description of all land parcels in Queensland. It provides the base for searching, planning and analysing land related information and is primarily used by most local governments for these purposes.
    - Licence: Data downloaded via QSpatial as open data is provided under a Creative Commons CC-By licence.

- **State of Queensland**
  - Queensland’s Regional Ecosystem Description Database
    - Licence: This work is licensed under a Creative Commons Attribution 3.0 Licence
    - Conditions of use statement: The database was developed using data compiled by the State of Queensland as represented by the Queensland Herbarium, Department of Environment and Science. While every effort has been made to ensure that the material contained in the database is accurate, the State of Queensland accepts no liability and gives no assurance in respect of its accuracy and shall not be liable for any loss or damage arising from the use of the database.

- **Australian Government (Geoscience Australia)**
  - GEODATA Topo 250K Series 3 – spatial data for mapping
    - Licence: Creative Commons Attribution 3.0 Australia, [http://creativecommons.org/licenses/by/3.0/au/](http://creativecommons.org/licenses/by/3.0/au/), (c) Commonwealth of Australia (Geoscience Australia) 2014
  - SRTM-derived 3 Second Digital Elevation Models Version 1.0
    - Licence: The 3 second DEMs were released under Creative Commons attribution licensing in ESRI Grid format
  - GEODATA 9 second DEM and D8: Digital Elevation Model Version 3
    - Licence: Creative Commons Attribution 4.0 International Licence
• Esri
  – *World Imagery Map Service* – map service of satellite imagery for the world and high-resolution imagery for the United States and other areas around the world. Imagery is sourced from GeoEye IKONOS, Getmapping, AeroGRID, IGN Spain, IGP Portugal, i-cubed, USGS, AEX, Aerogrid, Swisstopo and by the GIS User Community.
    - https://www.arcgis.com/home/item.html?id=10df2279f9684e4a9f6a7f08febac2a9
• Atlas of Living Australia - a collaborative, national project that aggregates biodiversity data from multiple sources and is freely available and usable online.
• Australian Wetlands Database - online access to information on Australia’s Ramsar wetlands and sites listed in the Directory of Important Wetlands of Australia, Australia’s internationally and nationally important wetlands respectively.
Glossary and terms

**Anthropogenic:** a human impact on the environment.

**Aquifer:** a permeable geological material that can transmit significant quantities of water to a bore, spring, or surface water body. Generally, ‘significant’ is defined based on human need, rather than on an absolute standard.

**Aquitard (confining layers):** a saturated geological unit that is less permeable than an aquifer, and incapable of transmitting useful quantities of water. Aquitards often form a confining layer over an artesian aquifer.

**Artesian:** a general term used when describing certain types of groundwater resources. Artesian water is underground water confined and pressurised within a porous and permeable geological formation. An artesian aquifer has enough natural pressure to allow water in a bore to rise to the ground surface. Subartesian water is water that occurs naturally in an aquifer, which if tapped by a bore, would not flow naturally to the surface. Artesian conditions refer to the characteristics of water under pressure.

**Basement:** the crust below the rocks of interest. In hydrogeology it means non-prospective rocks below accessible groundwater. Commonly refers to igneous and metamorphic rocks which are unconformably overlain by sedimentary beds or cover material, and sometimes used to indicate ‘bedrock’ (i.e. underlying or encasing palaeovalley sediments).

**Benthic:** the ecological region at the lowest level of a body of water such as an ocean or a lake, including the sediment surface and some sub-surface layers.

**Current development:** the level of surface water, groundwater and economic development in place as of 1 July 2013. The Assessment assumes that all current water entitlements are being fully used.

**Development:** see entries for ‘current development’ and ‘future irrigation development’.

**Discount rate:** the percentage by which future cost and benefits are discounted each year (compounded) to convert them to their equivalent present value (PV)

**Drainage division:** the area of land where surface water drains to a common point. There are 12 major drainage divisions in Australia. At a smaller scale, surface water drainage areas are also referred to as river basins, catchments, or watersheds.

**Drawdown:** the lowering of groundwater level resulting from the extraction of water, oil or gas from an aquifer.

**Ecosystem services:** the contributions that ecosystems make to human wellbeing.

**Eutrophication:** the ecosystem response to the addition of artificial or natural substances, such as nitrates and phosphates, through fertilizers or sewage, to an aquatic system. One example is an ‘algal bloom’ or great increase of phytoplankton in a water body as a response to increased levels of nutrients.

**Environmental flows:** describe the quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well being that depend on these ecosystems.
Flow regime: the entire pattern of flow in a river – from how long it lasts, to how frequently it flows and how large it is.

Fecundity: the potential reproductive capacity of an individual or population.

Fertigation: application of crop nutrients through the irrigation system (i.e. liquid fertiliser)

Future irrigation development: is described by each case study storyline (see chapters 8 to 10); river inflow and agricultural productivity are modified accordingly.

Geological basin: layers of rock that have been deformed by mega-scale geological forces to become bowlshaped. Often these are round or oblong with a depression in the middle of the basin.

Geological formation: geological formations consist of rock layers that have common physical characteristics (lithology) deposited during a specific period of geological time.

Groundwater (hydrogeology): water that occurs within the zone of saturation beneath the Earth’s surface. The study of hydrogeology focuses on movement of fluids through geological materials (e.g. layers of rock).

Groundwater basin: a groundwater basin is a non-geological delineation for describing a region of groundwater flow. Within a groundwater basin, water enters through recharge areas and flows toward discharge areas.

Groundwater divide: a divide that is defined by groundwater flow directions that flow in opposite directions perpendicular to the location of the divide.

Groundwater flow (hydrodynamics): within a groundwater basin, the path from a recharge area to a discharge area is referred to as a groundwater flow system, where travel time may be as short as days or longer than centuries, depending on depth. The mechanics of groundwater flow – the hydrodynamics – are governed by the structure and nature of the sequence of aquifers.

Groundwater flow model: a computer simulation of groundwater conditions in an aquifer or entire groundwater basin. The simulations are representations based on the physical structure and nature of the sequence of aquifers and rates of inflow – from recharge areas – and outflow – through springs and bores. Groundwater level: in this report refers to the elevation of equivalent freshwater hydraulic head at 25 °C

Groundwater recharge and discharge: recharge occurs where rainfall or surface water drains downward and is added to groundwater (the zone of saturation). Discharge occurs where groundwater emerges from the Earth, such as through springs or seepage into rivers.

Hydrodynamics: the study of liquids in motion.

Internal rate of return (IRR): the discount rate at which the net present value (NPV) is zero.

Legume: pulse crop.

Lithology: the character of a rock; its composition, structure, texture, and hardness.

Net present value: a standard method for using the time value of money to appraise long-term projects by measuring the differences between costs and revenues in present value terms.
**Palaeochannel**: refers to the main channel of ancient rivers, sometimes called the ‘thalweg’, the lowest point of incision along the river bed where coarser sediments are commonly deposited. Former river channels that are recognised in the surface (from aerial or satellite images) or subsurface (typically in aerial electromagnetic surveys or drilling).

**Permeability**: a measurement describing the ability of any fluid (water, oil) to pass through a porous material. Values vary widely, with higher values corresponding to aquifers (i.e., highly permeable) and lower values corresponding to aquitards (i.e. less permeable).

**Refugia**: habitat for species to retreat to and persist in.

**Regolith**: weathered upper layer.

**Residual value**: calculated as the proportional asset life remaining multiplied by the original asset price.

**Riparian**: of, on, or relating to the banks of a watercourse. A riparian zone is the area of land immediately adjacent to a stream or river. Plants found within this zone are collectively known as riparian vegetation. This vegetation frequently contains large trees that stabilise the river bank and shade part of the river.

**River reach**: an extent or stretch of river between two bends.

**Streamflow**: is the flow of water in rivers and other channels (creeks, streams etc.). Water flowing in channels comes from surface runoff, from groundwater flow, and from water discharged from pipes. There are a variety of ways to measure streamflow – a gauge provides continuous flow over time at one location for water resource and environmental management or other purposes; it can be estimated by mathematical equations. The record of flow over time is called a hydrograph. Flooding occurs when the volume of water exceeds the capacity of the channel.

**Triple-bottom-line**: an accounting framework that incorporates three dimensions of performance: social, environmental and financial.

**Watertable**: the surface where the groundwater level is balanced against atmospheric pressure. Often, this is the shallowest water below the ground.
Appendix C

List of figures

Figure 1.1 Mangoes in the Darwin catchments ................................................................. iii
Figure 1.1 Map of Australia showing Assessment area ...................................................... 4
Figure 1.2 Schematic diagram of key components and concepts in the establishment of a
greenfield irrigation development ..................................................................................... 8
Figure 1.3 The Darwin catchments .................................................................................... 12
Figure 2.1 Schematic diagram of key natural components and concepts in the establishment
of a greenfield irrigation development .............................................................................. 18
Figure 2.2 Major geological provinces of the Darwin catchments ..................................... 21
Figure 2.3 Surface geology of the Darwin catchments ....................................................... 23
Figure 2.4 The soil generic groups of the Darwin catchments produced by digital soil mapping 26
Figure 2.5 Field soil sampling to 1.5 m depth of DSM chosen sites for modelling and chemical
analysis carried out by CSIRO and the NT Department of Environment and Natural Resources 28
Figure 2.6 Surface soil pH of the Darwin catchments ....................................................... 29
Figure 2.7 Minimum soil depth of the Darwin catchments ............................................... 30
Figure 2.8 Soil surface texture of the Darwin catchments ................................................ 31
Figure 2.9 Soil permeability of the Darwin catchments ..................................................... 32
Figure 2.10 Plant available water capacity in the Darwin catchments ............................... 33
Figure 2.11 Rockiness in soils of the Darwin catchments ................................................ 34
Figure 2.12 Rainfall during the wet season in the Darwin catchments ............................... 36
Figure 2.13 Historical rainfall, potential evaporation and rainfall deficit ......................... 37
Figure 2.14 Monthly rainfall in the Darwin catchments at Darwin and Wildman station under
Scenario A ......................................................................................................................... 39
Figure 2.15 Monthly potential evaporation in the Darwin catchments at Darwin and Wildman
station under Scenario A ......................................................................................... 39
Figure 2.16 Annual rainfall at Darwin and Wildman station under Scenario A ............... 40
Figure 2.17 (a) Coefficient of variation of annual rainfall and (b) the coefficient of variation of
annual rainfall plotted against mean annual rainfall for 96 rainfall stations around Australia ... 40
Figure 2.18 Runs of wet and dry years at Darwin and Wildman station under Scenario A .... 42
Figure 2.19 Percentage change in mean annual rainfall and potential evaporation under
Scenario C relative to under Scenario A ........................................................................... 43
Figure 2.20 Spatial distribution of mean annual rainfall across the Darwin catchments under scenarios Cwet, Cmid and Cdry.

Figure 2.21 Monthly rainfall and potential evaporation for the Darwin catchments under scenarios A and C.

Figure 2.22 Schematic diagram of terrestrial water balance in the Darwin catchments.

Figure 2.23 Spatial extent of six key hydrogeological units in the Darwin catchments.

Figure 2.24 Groundwater bore yields for different aquifers in the Darwin catchments.

Figure 2.25 Two-dimensional conceptual schematic of the interconnected aquifer system and its variability.

Figure 2.26 Groundwater salinity for different aquifers in the Darwin catchments.

Figure 2.27 Annual recharge estimates for the Darwin catchments.

Figure 2.28 Summary of recharge statistics to areas of key hydrogeological units.

Figure 2.29 Spatial distribution of springs and monsoon vine forest patches across the Darwin catchments.

Figure 2.30 Modelled streamflow under natural conditions.

Figure 2.31 Mary River floodplain.

Figure 2.32 Streamflow observation data availability in the Darwin catchments.

Figure 2.33 Median annual streamflow (50% exceedance) in the Darwin catchments under Scenario A.

Figure 2.34 Adelaide River at the potential Marrakai dam site looking upstream during the dry season.

Figure 2.35 20% and 80% exceedance of annual streamflow in the Darwin catchments under Scenario A.

Figure 2.36 Catchment area and elevation profile along the Adelaide River from its mouth to its source.

Figure 2.37 Catchment area and elevation profile along the Mary River from its mouth to its source.

Figure 2.38 Mean annual rainfall and runoff across the Darwin catchments under Scenario A.

Figure 2.39 Maps showing annual runoff at 20%, 50% and 80% exceedance across the Darwin catchments under Scenario A.

Figure 2.40 Runoff in the Darwin catchments under Scenario A.

Figure 2.41 Flood inundation map of the Darwin catchments.

Figure 2.42 Spatial extent and temporal variation of inundation in the Adelaide, Mary and Wildman catchments.

Figure 2.43 Relationships between peak flood discharge, maximum inundated area and annual exceedance probability.
Figure 2 44 Instream waterhole evolution .......................................................................................... 70
Figure 2 45 Persistent waterhole in the Darwin catchments ............................................................. 70
Figure 2 46 Location of river reaches containing permanent water in the Darwin catchments.. 71
Figure 3 1 Schematic diagram of key components of the living and built environment to be 
considered in the establishment of a greenfield irrigation development........................................... 78
Figure 3 2 Distribution of important wetlands, important bird areas and protected areas 
within the Darwin catchments............................................................................................................... 83
Figure 3 3 Distribution of mangroves and salt flats in the coastal area of the Darwin 
catchments........................................................................................................................................... 89
Figure 3 4 Distribution of monsoon vine forest in the Darwin catchments ....................................... 91
Figure 3 5 Distribution of focal migratory freshwater fishes in the Darwin catchments .......... 93
Figure 3 6 Distribution of focal stable flow spawning fishes in the Darwin catchments ............... 94
Figure 3 7 The freshwater sawfish (Pristis pristis) ........................................................................... 95
Figure 3 8 Distribution of freshwater sawfish (Pristis pristis) in the Darwin catchments .......... 96
Figure 3 9 Distribution of barramundi (Lates calcarifer) in the Darwin catchments....................... 97
Figure 3 10 Distribution of magpie goose (Anseranas semipalmata) in the Darwin catchments 99
Figure 3 11 Mary River, showing floodplains, wetlands, riparian areas and terrestrial systems100
Figure 3 12 Distribution of species listed under the EPBC Act (Cth) and by the Northern 
Territory Government in the Darwin catchments.............................................................................. 101
Figure 3 13 Land use classification for the Darwin catchments ..................................................... 106
Figure 3 14 Map of regions in the Northern Prawn Fishery (NPF) .................................................. 108
Figure 3 15 Tourism is a major contributor to the economy of the Darwin catchments............. 109
Figure 3 16 Tourism Research Australia and Australian Bureau of Statistics (ABS) statistical 
regions relevant to the Darwin catchments ............................................................................................ 110
Figure 3 17 Mining licences, tenements and major resources in the Darwin catchments ......... 113
Figure 3 18 Road rankings and conditions for the Darwin catchments........................................ 114
Figure 3 19 Vehicle access restrictions for the Darwin catchments............................................. 115
Figure 3 20 Typical vehicle combinations used for agriculture transport in Australia.......... 116
Figure 3 21 Road speed restrictions for the Darwin catchments.................................................. 116
Figure 3 22 Agricultural enterprises in the Darwin catchments....................................................... 117
Figure 3 23 Extent of the electricity network serving the Darwin catchments, illustrating 
transmission and distribution networks and generation facilities .................................................... 120
Figure 3 24 Overview of Darwin catchments water supply network ......................................... 122
Figure 3 25 Darwin River Dam looking upstream ........................................................................... 123
Figure 3.26 Manton Dam looking upstream ................................................................. 124
Figure 3.27 Current groundwater allocations for the Darwin catchments ............... 125
Figure 3.28 Rainbow diagram classifying stakeholders according to their likely support of irrigated agriculture in a greenfield site in the Darwin catchments. Stakeholders to the right of the diagram are more likely to be supportive ......................................................... 128
Figure 3.29 Indigenous freehold (Aboriginal Land) in the Darwin catchments as at July 2017. 134
Figure 3.30 Indigenous native title claims and determinations in the Darwin catchments as at July 2017 .................................................................................................................. 135
Figure 3.31 General location of registered Indigenous cultural heritage sites in the Darwin catchments as at July 2017 ........................................................................................................ 137
Figure 3.32 Median length of each stage of the assessment process under the Environmental Assessment Act (NT), 2006–2018 ................................................................. 148
Figure 3.33 Median length of each stage of the assessment and approval process under the EPBC Act, all projects in the Northern Territory over the period 2010-2018 .................. 148
Figure 3.34 Total length of EPBC Act assessment and approval process, Northern Territory projects from 2010-2018, by industry and length of process ........................................... 149
Figure 4.1 Schematic diagram of agriculture and aquaculture enterprises as well as crop and/or forage integration with existing beef enterprises to be considered in the establishment of a greenfield irrigation development .................................................. 164
Figure 4.2 Area (ha) associated with each land suitability class in the Darwin catchments for 14 potential crop land uses ............................................................................................. 171
Figure 4.3 Agricultural versatility index map for the Darwin catchments ..................... 172
Figure 4.4 A mungbean crop ready to be harvested ..................................................... 176
Figure 4.5 Annual cropping calendar for agricultural options in the Darwin catchments .......... 177
Figure 4.6 Probability of exceedance graph of simulated dryland sorghum yields (t/ha) for fortnightly sowing dates from January to April on a Red Kandosol at Wildman River ........... 179
Figure 4.7 Probability of yield potential for dryland and fully irrigated mungbean sown in Wildman River climate on a Red Kandosol in February/March (dryland) and in August (irrigated) .................................................................................................................. 180
Figure 4.8 Probability of yield potential for dryland and fully irrigated grain sorghum sown in Wildman River climate on a Red Kandosol in January to March (dryland) and March (irrigated) .................................................................................................................. 181
Figure 4.9 Crop yield plotted against applied irrigation water in Wildman River climate for peanut planted in April ......................................................................................................... 181
Figure 4.10 Crop yield plotted against applied irrigation water in Wildman River climate for peanut planted in August ...................................................................................................... 182
Figure 4.11 Modelled land suitability for (a) dry-season rice using furrow irrigation and (b) wet-season grain sorghum using furrow irrigation .......................................................... 189
Figure 4.37 Land suitability in the Darwin catchments for freshwater species aquaculture; (a) earthen ponds and (b) lined ponds ................................................................. 237

Figure 5.1 Schematic diagram of key engineering and agricultural components to be considered in the establishment of a water resource and greenfield irrigation development. 242

Figure 5.2 Hydrogeological units with potential for future groundwater resource development ........................................................................................................ 250

Figure 5.3 Monsoon vine forest in the Mary–Wildman area ................................................................. 251

Figure 5.4 Targeted field investigations included the drilling and installation of (a) shallow monitoring bores near springs and (b) deeper monitoring bores in the middle of the aquifers. 251

Figure 5.5 Spatial extent of the (a) overlying Mesozoic–Cenozoic sand aquifer and (b) underlying Koolpinyah Dolostone aquifer in the Mary and Wildman catchments. 252

Figure 5.6 Elevation of the top of the Mesozoic–Cenozoic sand aquifer in the Mary–Wildman rivers area (mAHĐ) ...................................................................................................................................................... 253

Figure 5.7 Depth to groundwater values measured (a) at the end of the 2016 dry season and (b) at the peak of the 2016–17 wet season in the Mary–Wildman rivers area ............... 254

Figure 5.8 Modelled drawdown in groundwater level in (a) model layer 1 (b) model layer 2 for a 6-GL/year extraction over a 20-year period ................................................................. 256

Figure 5.9 Modelled drawdown in groundwater level in (a) model layer 1 (b) model layer 2 for a 9 GL/year extraction rate over a 20-year period .................................................................................. 257

Figure 5.10 Monsoon vine forest in the Darwin catchments .................................................................. 259

Figure 5.11 Types of managed aquifer recharge (MAR) ................................................................... 261

Figure 5.12 MAR opportunities for the Darwin catchments irrespective of distance from a water source for recharge .................................................................................................. 263

Figure 5.13 MAR opportunities in the Darwin catchments within 5 km of major rivers .................. 264

Figure 5.14 Existing and potential water sources for MAR in the Darwin catchments .................. 265

Figure 5.15 Hydrograph of bores (a) RN009266 and (b) RN009421 in the Howard East area ...... 267

Figure 5.16 Schematic diagram of a hypothetical Howard East ASTR MAR scheme ......................... 269

Figure 5.17 Schematic diagram of the hypothetical Howard East ASR MAR scheme ...................... 269

Figure 5.18 ASR bore Warruwi, NT, storing excess drinking water supplies from the shallow laterite aquifer during the wet season in a deeper sandstone aquifer ........................................ 271

Figure 5.19 Schematic diagram of the hypothetical Palmerston ASR MAR scheme ......................... 271

Figure 5.20 Schematic diagram of the hypothetical Berry Springs recharge release MAR scheme .......................................................................................................................... 273

Figure 5.21 Recharge weir at Minderoo in the Pilbara, WA .................................................................. 275

Figure 5.22 Schematic diagram of the hypothetical Adelaide River recharge weir MAR scheme .......................................................................................................................... 275
Figure 5.23 Coastal floodplains in the Darwin catchments ........................................................ 283
Figure 5.24 Potential storage sites in the Darwin catchments based on minimum cost per ML storage capacity .................................................................................................................................................. 284
Figure 5.25 Looking north along the main axis of the AROWS ........................................................................................................................ 285
Figure 5.26 Potential storage sites in the Darwin catchments based on minimum cost per ML yield at the dam wall .................................................................................................................................................. 286
Figure 5.27 Darwin catchments hydro-electric power generation opportunity map ........................................................................................................................................................................... 287
Figure 5.28 Magpie geese on the Darwin River Dam spillway ........................................................................................................................................................................... 293
Figure 5.29 Cost of water in $/ML versus cumulative divertible yield at 85% annual time reliability and change in flow at the end-of-system in the Darwin catchments ................................................................................................................... 294
Figure 5.30 The upper Adelaide River dam site on the Adelaide River looking upstream ........................................................................................................................................................................... 295
Figure 5.31 Migratory fish and water-dependent birds in the vicinity of the potential upper Adelaide River dam site ........................................................................................................................................................................... 296
Figure 5.32 The upper Adelaide River dam site on the Adelaide River: cost, yield at the dam wall and evaporation ........................................................................................................................................................................... 296
Figure 5.33 Comparisons of modelled inundated area with and without construction of upper Adelaide River dam under historical climate ........................................................................................................................................................................... 297
Figure 5.34 The Mount Bennett dam site on the Finniss River looking upstream ........................................................................................................................................................................... 298
Figure 5.35 Migratory fish and water-dependent birds in the vicinity of the potential Mount Bennett dam site ........................................................................................................................................................................... 299
Figure 5.36 Mount Bennett dam site on the Finniss River: cost, yield at the dam wall and evaporation ........................................................................................................................................................................... 299
Figure 5.37 Comparisons of inundated area with and without construction of Mount Bennett dam under historical climate ........................................................................................................................................................................... 300
Figure 5.38 Schematic cross-section diagram of sheet piling weir ........................................................................................................................................................................... 301
Figure 5.39 Rectangular ringtank and 500 ha of cotton in the Flinders catchment (Queensland) ........................................................................................................................................................................... 303
Figure 5.40 Suitability of large farm-scale ringtanks in the Darwin catchments ........................................................................................................................................................................... 304
Figure 5.41 Reliability of extracting water up to the annual system/reach entitlement volume for a selection of seven water harvesting users for a pump start threshold of 200 ML/day ........................................................................................................... 306
Figure 5.42 Diesel powered axial-flow flood-harvesting pump in Flinders catchment ........................................................................................................................................................................... 307
Figure 5.43 Reliability of extracting water up to the annual system/reach entitlement volume for a selection of seven water harvesting users for a pump start threshold of 600 ML/day ........................................................................................................... 308
Figure 5.44 Reliability of extracting water up to an entitlement volume for a selection of seven water harvesting users for a pump start threshold of 200 ML/day and end-of-system flow requirement of 200 GL/year ........................................................................................................................................................................... 309
Figure 7.13 Maximum condition scores of sooty grunter and black catfish, considering dam scenarios at nodes 81700001, 81700200, 81700050 and 81700020 in the Adelaide catchment ................................................................. 395

Figure 7.14 Maximum condition scores of sooty grunter and black catfish, considering dam scenarios at nodes 81800001, 81800351 and 81800354 in the Mary catchment ................................. 396

Figure 7.15 Maximum condition scores of barramundi, considering dam scenarios at nodes 81700001, 81700020, 81700050 and 81700200 in the Adelaide catchment .............................. 398

Figure 7.16 Maximum condition scores of barramundi, considering dam scenarios at nodes 81800001, 81800351 and 81800354 in the Mary catchment ............................................................... 399

Figure 7.17 Flood extent and percentage of sites inundated where magpie geese had historically been observed for a small annual flood event (AEP 1 in 3) under (a) Scenario A and (b) Scenario B-D ........................................................................................................ 401

Figure 7.18 Flood extent and percentage of sites inundated where magpie geese had historically been observed for a moderate to large annual flood event (AEP 1 in 14) under (a) Scenario A and (b) Scenario B-D ................................................................. 402

Figure 7.19 Simulated annual nitrogen N losses via runoff or leaching and soil loss from Adelaide River climate station and a Vertosol for four crops (forage sorghum, mungbean, rice and soybean) for the Darwin catchments ............................................................................... 416

Figure 7.20 Simulated annual nitrogen N losses via runoff or leaching and soil loss from Adelaide River climate station and a Vertosol for rice, rice–sorghum, and rice–soybean crop rotations ................................................................................................................................. 417

Figure 7.21 Cross-section of a marine aquaculture farm detailing optimal land elevation, water flow and discharge ................................................................................................................................. 421
List of tables

Table 2.1 Soil generic groups (SGG) for the Darwin catchments .................................................. 24
Table 2.2 Projected sea-level rise for the coast of the Darwin catchments ................................. 45
Table 2.3 Streamflow metrics at gauging stations in the Darwin catchments under Scenario A ..................................................................................................................................... 61

Table 3.1 Asset types and asset names in the Darwin catchments .............................................. 86
Table 3.2 Definition of threatened categories under the EPBC Act (Cth) and the Northern Territory wildlife classification system .............................................................................................. 102
Table 3.3 Major demographic indicators for the Darwin catchments ........................................ 104
Table 3.4 SEIFA scores of relative socio-economic advantage for the Darwin catchments ...... 104
Table 3.5 Key employment data in the Darwin catchments in relation to state and national means .......................................................................................................................................... 105
Table 3.6 Key 2015 tourism data relevant to the Darwin catchments ....................................... 111
Table 3.7 Key statistics relating to the mining industry in the Darwin catchments ................... 112
Table 3.8 Overview of agriculture commodities transported into and out of the Darwin catchments .................................................................................................................................. 118
Table 3.9 Energy generation facilities in the Darwin catchments .............................................. 119
Table 3.10 Constructed large dams in the Darwin catchments .................................................. 123
Table 3.11 Hospitals servicing the Darwin catchments .............................................................. 127
Table 3.12 Number and percentage of unoccupied dwellings and population for the Darwin catchments .................................................................................................................................. 127
Table 3.13 Summary of published stakeholder and interest group values relevant to the development of greenfield irrigated agriculture in northern Australia ................................................. 129
Table 3.14 Stakeholder engagement typology for the Darwin catchments, as determined via influence/interest matrices related to the development of irrigated agriculture in a greenfield site. ............................................................................................................................... 130
Table 3.8 Overview of agriculture commodities transported into and out of the Darwin catchments.

Table 3.9 Energy generation facilities in the Darwin catchments.

Table 3.10 Constructed large dams in the Darwin catchments.

Table 3.11 Hospitals servicing the Darwin catchments.

Table 3.12 Number and percentage of unoccupied dwellings and population for the Darwin catchments.

Table 3.13 Summary of published stakeholder and interest group values relevant to the development of greenfield irrigated agriculture in northern Australia.

Table 3.14 Stakeholder engagement typology for the Darwin catchments, as determined via influence/interest matrices related to the development of irrigated agriculture in a greenfield site.

Table 4.1 Land suitability classification used in the Assessment.

Table 4.2 Qualitative land evaluation observations for locations in the Darwin catchments shown in Figure 4.3.

Table 4.3 Yields (20th, 50th (median), 80th percentile) of three crops at Wildman River under dryland and irrigated conditions.

Table 4.4 Crop types and crops explored in the Assessment.

Table 4.5 Soil water content at sowing and rainfall for the 90-day period following sowing for three sowing dates (Wildman River), based on a Red Kandosol soil type.

Table 4.6 Sowing date, crop yield, price, variable cost, gross margin and break-even crop yield for dryland crops in the Darwin catchments, with data shown for a Vertosol at Adelaide River and a Red Kandosol at Wildman River.

Table 4.7 Cropping season, applied irrigation water, crop yield, price, variable cost, gross margin and break-even yield for crops in the Darwin catchments, with data shown for a Vertosol soil type at Adelaide River and a Red Kandosol soil type at Wildman River.

Table 4.8 Cropping season, irrigation water requirement, crop yield, price, variable cost, gross margin and break-even crop yield for horticultural and tree crops in the Darwin catchments, assuming a Red Kandosol soil type.

Table 4.9 Sorghum (grain) (Sorghum bicolor).

Table 4.10 Mungbean (Vigna radiata).

Table 4.11 Soybean (Glycine max).

Table 4.12 Peanut (Arachis hypogaea).

Table 4.13 Rhodes grass (Chloris gayana).

Table 4.14 Cavalcade (Centrosema pascuorum ‘Cavalcade’).

Table 4.15 Cotton (Gossypium spp.).

Table 4.16 Sugarcane (Saccharum).
Table 5.20 Indicative costs for a 4000-ML ringtank

Table 5.21 Annualised cost for the construction and operation of three ringtank configurations

Table 5.22 Equivalent annual cost per ML for two different capacity ringtanks under three seepage rates

Table 5.23 Annualised unit cost at optimum embankment height for ringtanks of varying capacity

Table 5.24 Actual costs of four gully dams in northern Queensland

Table 5.25 Cost of three hypothetical large farm-scale gully dams of capacity 4 GL

Table 5.26 High-level breakdown of capital costs for three hypothetical large farm-scale gully dams of capacity 4 GL

Table 5.27 Effective volumes and cost per ML for a 4-GL storage with different average depths and seepage loss rates at Wildman in the Darwin catchments

Table 5.28 Cost of construction and operation of three hypothetical 4-GL gully dams

Table 5.29 Equivalent annualised cost and effective volume for three hypothetical 4-GL gully dams

Table 5.30 Summary of conveyance and application efficiencies

Table 5.31 Water distribution and operational efficiency as nominated in water resource plans for four irrigation water supply schemes in Queensland

Table 5.32 Application efficiencies for surface, spray and micro irrigation systems

Table 5.33 Energy demands and costs by irrigation type

Table 6.1 Indicative costs of agricultural processing facilities

Table 6.2 Indicative costs of road and electricity infrastructure

Table 6.3 Indicative road transport costs between Adelaide River and key markets and ports

Table 6.4 Indicative costs of community facilities

Table 6.5 Assumed capital and operating costs for a new irrigation scheme with a new, large dam

Table 6.6 Break-even farm gross margins required for schemes with different dam development costs to meet target investment returns (IRR)

Table 6.7 Break-even water pricing required for schemes with different dam development costs to meet target investment returns (IRR) for the water supplier (developer of dam, water distribution infrastructure and land)

Table 6.8 Minimum price water supplier would have to charge for water for schemes with different costs of development to cover annual O&M costs

Table 6.9 Break-even water pricing for the amount an irrigator could afford to pay depending on the annual gross margin of the farm, crop applied irrigation water (before application losses), and the irrigator’s target internal rate of return (IRR)
Table 6.10 Assumed capital and operating (O&M) costs for a new development using an on-farm water source ................................................................. 350

Table 6.11 Break-even farm gross margins required for schemes with different costs of developing on-farm water sources to meet target investment returns (IRR) .......................................................... 351

Table 6.12 Risk adjustment multipliers for break-even gross margins, accounting for the effects of reliability and severity (level of farm performance in ‘failed’ years) of periodic risks 353

Table 6.13 Risk adjustment multipliers for break-even gross margins, accounting for the effects of reliability and timing of periodic risks ................................................................. 354

Table 6.14 Risk adjustment multipliers for break-even gross margins, accounting for the effects of learning risks .................................................................................. 355

Table 6.15 Effect of different staging options on scheme performance for a range of learning risks ................................................................................................................. 357

Table 6.16 Assumptions used for incorporating a sugar mill into an irrigation scheme .. 359

Table 6.17 Comparison of financial performance of an irrigation scheme with and without a sugar mill included ................................................................. 360

Table 6.18 Key 2016 data comparing the Darwin catchments with the related Northern Territory input–output region ................................................................. 364

Table 6.19 Estimated regional economic impact per year resulting from four scales of direct increase in agricultural output (rows) for each of three different categories of agricultural activity (columns) in the Northern Territory input–output (NT I–O) region ................................................................................. 366

Table 6.20 Estimated number of full-time equivalent jobs from four scales of increase in agricultural output (rows) for each of three different categories of agricultural activity (columns) in the Northern Territory input–output (NT I–O) region ................................................................................. 366

Table 6.21 Estimated regional economic benefit of the construction phase of a development designed to promote an irrigated agricultural development within the Northern Territory input–output (NT I–O) region ................................................................................. 367

Table 7.1 Percentage of wetlands connected to the main river channel in the Adelaide, Mary and Wildman catchments for a flood event of AEP 1 in 3 ................................................................. 389

Table 7.2 Percentage of wetlands connected to the main river channel in the Adelaide, Mary and Wildman catchments for a flood event of AEP 1 in 14 ................................................................. 390

Table 7.3 Percentage of wetlands connected in the Finniss catchment under AEP 1 in 3 .......... 390

Table 7.4 Percentage of wetlands connected in the Finniss catchment under AEP 1 in 10 ...... 391

Table 7.5 Maximum percentage of sites with magpie goose observations that are inundated under different scenarios ................................................................................................................. 402

Table 7.6 Proportion of simulations (1 per week = 52), in which a fungal pathogen or insect pest could have been transported from a location in South-East Asia to the Darwin catchments ................................................................................................................. 405
Table 7.7 Nitrogen (N) surplus for multiple crops grown in the Darwin catchments based on risk assessment .......................................................................................................................... 412

Table 7.8 Phosphorus (P) surplus for multiple crops grown in the Darwin catchments based on risk assessment ...................................................................................................................... 412

Table 7.9 Herbicide, pesticide and fungicide application rates for multiple crops grown in the Darwin catchments .......................................................................................................................... 414
Appendix D

Detailed location map of the Darwin catchments and surrounds
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