01 Water Resources in northern Australia

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Ord River Dam outflow pipe
Photo: Richard Cresswell, CSIRO Land and Water
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pronounced response to extractions that does not recover under historical or future climate conditions. Only the wetter conditions of the last decade have maintained high water levels. Recharge is dominated by diffuse vertical recharge from deep drainage through the soil profile. Note the time lag of about 10 years before a new dynamic equilibrium is reached in water levels in the aquifer. The model assumes instantaneous use of all water allocations and a stationarity of climate (i.e. the future climate conditions will be purely a scaled variation of historical conditions).

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1. **KEY POINTS**

1. All water is fully in use. The water balance is closed; even “wasted” water running out to sea is needed by estuarine systems and near-shore ecosystems. Underground, groundwater supports riparian vegetation, maintains perennial reaches of many rivers and provides a dry-season source of water. Whilst current levels of use are low relative to total water stocks, any perturbation will have consequences through the hydrological cycle. The north, however, does not have a single, large, internally draining basin like the Murray-Darling Basin, but rather 55, independent, externally draining basins. The actions in one should have minimal hydrological impact on any others. Groundwater provinces (and the aquifers they contain), on the other hand, may cross beneath surface catchment boundaries and extractions may have more widespread implications.

2. The consumptive use of water during the dry season, and shauldering of the wet season, will require water storage. The north, however, does not have a climate that is conducive to year-round surface water storage. The north has: (i) a high inter-annual variability of rainfall (when compared to the rest of the world for the same (Koppen) climate class); (ii) high but highly seasonal rainfall (over 90% falling between November and April), and (iii) high potential for evaporation and plant transpiration (PET) throughout the year. These characteristics result in streamflow that mirrors rainfall patterns. Hence, there is a large variability in year-to-year flows; most streams cease to flow shortly after the wet season; there is a very short lag between peak rainfall and peak runoff and there are few perennial rivers.

3. In many areas, water required during the dry season would need to be sourced from groundwater, or from water harvesting operations. There are very few intermediate and large surface water storage sites across northern Australia. Currently, there are 23 storages with a capacity greater than 1 GL. The high inter-annual variability means that yield from large storages would be lower than one might otherwise expect. Surface water storages would need to be large due to very high evaporation rates throughout the year. Lake Argyle, for example, loses about a quarter of its storage capacity, or about half the annual demand (predominantly for hydro-power), through evaporation. The wetter regions of the far north offer most potential. Smaller, off-stream, water harvesting ventures might be beneficial to prolong water supplies into the dry season, particularly in floodplains. Management opportunities exist for storages (groundwater or within year storages) that fill each wet season, as these can give certainty of supply volumes during the subsequent dry season. Near-surface groundwater storages (aquifers), however, are extremely dynamic, with groundwater levels responding rapidly to the pronounced wet and dry seasons and commonly these resources fill and spill each year, but a run of dry years or increased extraction can reduce reliability. Shallow groundwater aquifers in carbonate rocks and alluvial sands offer most potential, though careful management is required for bores situated close to any rivers that rely on groundwater for dry season flow.

4. Groundwater flow processes are complex and are often locally variable. Negative externalities can arise from irrigation and agricultural developments associated with groundwater mis-management (e.g. dryland and irrigated salinity, double accounting/over-allocation, etc.). Groundwater processes usually occur over 'long' time periods and consequently problems can be difficult to identify and expensive to rectify. Undertaking adequately resourced hydrogeological investigations before implementing agricultural or irrigation developments would help to reduce avoidable problems (e.g. salinity resulting from failure to implement drainage in the MDB and more recently in the Lower Burdekin; the issue of double allocations or buying water back for the environment). Because groundwater pumping from shallow aquifers can lead to a reduction in nearby river flows, future developments will need to be sited far enough away from rivers to ensure groundwater drawdown does not reach the rivers before commencement of the following wet season. Understanding groundwater recharge and lateral groundwater flow processes should be a fundamental precursor to any future development.
5. In the future, it is likely that rainfall will be similar or slightly less than the historical past, and streamflow much less than the last decade, especially in the Northern Territory and northern WA. Potential evapotranspiration will be higher, so overall conditions are likely to be drier and streamflow will be slightly less than historical flows; much less than recent flows. There may be a changed pattern and amount of recharge as more intense rains are expected and these may increase recharge even if rainfall and runoff volumes do not increase.

2. **INTRODUCTION**

Australia’s north-draining rivers extend from Broome in the west to the tip of Cape York in the east and cover an area of 1,200,400 km² (Figure 1). For this project, following the analysis carried out by the Northern Australia Sustainable Yields (NASY) project, the 55 river basins (Figure 2) of the two northern drainage divisions were grouped into 12 regions (Figure 3).

Beneath these regions lies a complex architecture of geological units that form a number of distinct groundwater provinces; internally connected with distinct and definable water-bearing aquifers that are recharged via a complex interaction with the surface. These provinces can be extensive or local, and commonly extend beneath surface catchment boundaries (Figure 4). Consideration of these aquifer systems is vital when assessing water resources of northern Australia.

We can assess water resources at three levels, each offering more predictability but requiring more data and models than the one before. Not all regions have the data and models required for assessment at each level and only levels 1 and 2 have been carried out for this assessment (Figure 5).

**Level 1 – How much water is there?**

This is a water resource assessment. All regions can be assessed, using large-scale input data such as rainfall, temperature and humidity. Data can be used in temporal and spatial models to assess the patterns and quantify the amounts of water in different parts of the hydrological cycle (Figure 6).

**Level 2 – How much water can we take, where can we take it from and when can we take it?**

This is a water availability assessment. Only those regions with systems models may be assessable. These would include: the Daly region, the Ord region and part of the Van Diemen region in the Timor Sea Drainage Division; large parts of the Mitchell, South-East Gulf and Flinders-Leichhardt regions in the Gulf of Carpentaria Drainage Division (Figure 5). The Daly and Darwin Rural areas have both surface water and groundwater models available; the rest have only surface water models that are appropriate. The Lower Ord also has a groundwater model, but this is designed to assess the impact of salinisation and not for regional water resource evaluation. A groundwater model exists for the Fitzroy (WA) alluvium system, but there are insufficient data to provide confidence in the calibration for a water availability assessment.

**Level 3 – At what rate can we take water, allowing for environmental and cultural needs, and social, political and economic values?**

This represents a sustainable yield assessment and could not be carried out within the constraints of either the NASY or NALWT projects. Models developed for parts of the Lower Ord, areas within the Daly catchment and the Darwin Rural area in the Timor Sea Drainage Division can provide information that can help communities and governments make an assessment of sustainable water yields.
Figure 1. Location map for northern Australia, showing drainage divisions, Australian Water Resources Council (AWRC) river basins, major rivers and localities, overlain on a shaded relief.
Figure 2. Australian Water Resources Council (AWRC) river basins.
Figure 3. Analysis regions of the Northern Australia Sustainable Yields project.
Figure 4. Extents of groundwater provinces that (at least in part) underlie the drainage divisions of northern Australia. Note that only the north-flowing region of the Great Artesian Basin contributes to northern water resources.
Figure 5. Water assessment capability across northern Australia. Coloured areas have sufficient information, data and models to carry out the level of assessment indicated. Note the North-east Coast drainage division (grey) is not part of this assessment.

Figure 6. Elements of the hydrological cycle.
3. **CLIMATE**

The project area receives substantial rainfall each year. An average of more than 1,000,000 GL (equivalent to 100 times the capacity of Lake Argyle, or 2000 Sydney Harbours) of rain fell across the project area each year between 1930 and 2007. From year to year, however, there is great variability in this amount (Figure 7).

More than 94 percent of annual rainfall falls between November and April, with many regions receiving little or no rain for three to six months of the year (Figure 8). The potential for evaporation and for plant transpiration (‘potential evapotranspiration’) is high throughout the year. On average, for ten months of the year monthly potential evapotranspiration is greater than monthly rainfall. During a few months in the wet season, daily rainfall can exceed potential evapotranspiration and this drives the seasonal streamflow. On an annual basis, however, rainfall is insufficient to meet evaporative demand and the landscape may be described as water-limited (Figure 8). During the dry season, only a few areas along the ranges in the east and in the far north-west receive more than a few showers for the remainder of the year (Figure 9).

Averaged across the two drainage divisions, the driest year, 1952, received half (546,000 GL) the mean amount; the wettest year, 1974, received nearly twice as much (1,950,000 GL) driving a significant change in reliability (Figure 10). Averages belie this variability and a single extremely wet year (e.g. 1974) can dramatically increase the long-term mean. This variability increases away from the coast and towards the south: year-to-year variability of rainfall in the Flinders-Leichhardt region in the south is twice that of the Arafura region in the north.

![Figure 7. Annual variation from the mean average rainfall for the drainage divisions of northern Australia. The zero line represents the long-term (since 1930) mean rainfall of 868 and 779 mm/year for the Timor Sea and Gulf of Carpentaria drainage divisions, respectively. Note the significance of the extreme 1974 rainfall across northern Australia and the large number of wetter-than-average years for the last decade across the Timor Sea drainage division.](image-url)
Figure 8. Spatial distribution of historical mean annual, wet season and dry season rainfall and potential evapotranspiration and their difference (rainfall minus PET) across northern Australia. Water year: 1 September to 31 August; wet season: 1 November to 30 April; dry season: 1 May to 31 October.
Figure 9. Spatial distribution of historical dry season rainfall across northern Australia. (Note: Expanded rainfall scale compared to Figure 8).
Figure 10. Wet season rainfall surplus (positive values) and deficit (negative values) for the wettest, mean and driest years for northern Australia. Note that in dry years, only the northern tip of Cape York receives seasonal rainfall that is greater than the evaporation and transpiration demand.
4. **SURFACE WATER**

Most rain falls near the coast, on the estuaries, not in the rivers’ headwaters (unlike, for example, the Murray-Darling Basin) (Figure 11), generating an average 200,000 GL of runoff across the two drainage divisions each year. The proportion of rainfall that becomes runoff decreases from over 60 percent in the north to less than 3 percent of rainfall to the south (Figure 11). The high seasonality of rainfall is also reflected in the runoff, and hence in stream flow, with most streams running dry shortly into the dry season. The majority of northern streams have no flow for more than half of the year (Figure 12). Streams rising in the south, in particular, have a high percentage of time with no flow.

This pattern of streamflow and the high, year-round evaporation rates mean that large storages are required to ensure sufficient carry-over supply. Current storages greater than one gigalitre in capacity are shown in Figure 13.

![Comparison of mean rainfall and runoff distributions for northern Australia and the Murray-Darling Basin.](image-url)
Figure 12. Historical, mean, stream cease-to-flow determined for sub-catchments across northern Australia. The length of record used to determine the historical mean varies considerably (from a few years to a few decades) and a multiple linear regression approach was used to predict this hydrological metric across ungauged catchments. Areas in white (mostly coastal areas) have insufficient gauging information to give confidence in this metric.
Figure 13. Location of surface water storages greater than 1 GL storage capacity across northern Australia.
Across the Gulf of Carpentaria drainage division, the generally low relief of much of the coastal country compounds the problem of creating large storages, with opportunities to build diversion structures mainly in the upper reaches of catchments. In these areas, rainfall is generally lower and more sporadic, and potential evapotranspiration is higher.

The catchments surrounding Darwin have a combination of high rainfall and adequate relief and additional potential storages have been identified. Their likely development, however, is beyond the time frame of this assessment (i.e. beyond 2030).

The majority of rivers across northern Australia have largely unimpeded flow. This is reflected in the large number (87) of wetlands registered in the Directory of Important Wetlands, the proposed Heritage listing of Cape York Peninsula and the Kimberley and the Wild Rivers legislation adopted across many rivers of the Gulf of Carpentaria Drainage Division. A wild river declaration preserves a wild river’s natural values by regulating development within the wild river and its catchment area, and by regulating the taking of natural resources from the area.

The greatest single diversion occurs in the Lower Ord system around Kununurra to provide water for irrigation, hydropower and environmental flow. The level of use of water diverted for irrigation is low, but hydropower demand can require release of more than half of all inflows to Lake Argyle. Of note, the creation of Lake Argyle and Lake Kununurra through regulation of the Ord River led to their listing as Wetlands of International Importance under the Ramsar Convention.

The urban supply of Darwin is satisfied by the Darwin River Dam, but local authorities have identified that current expansion of Darwin will require further supplies and these are undergoing review and planning. In the near future, a 20% increase in the storage capacity of the Darwin River Dam will continue to provide adequate supplies for the region when combined with the more limited (~10% of supply) groundwater supplies.

The few regulated rivers generally have a low degree of regulation compared to the Murray-Darling Basin, but regulation of these rivers has had local consequences to flow regimes downstream and around regulation structures. Regulated rivers also have river system models to help guide water allocation plans. Models exist for significant reaches of: Mitchell, Gilbert, Flinders, Leichhardt, Darwin and Ord Rivers. These systems models allow an estimate of water availability within specific gauges along the rivers, and at critical diversions, storage in-flows and other specified locations (such as environmental sites of importance).

These models allow the estimation of pre-development conditions and water availability and we can generate river reach water availability estimates under a variety of input scenarios. Thus, we can model “no diversion” water availability for historical climate conditions; recent climate conditions and under the range of modelled future climate conditions (Figure 14).
Modelled streamflow transects for 4 key river systems of northern Australia, calibrated against observed gauge data. Three climate scenarios are modelled: A is mean historical (1930-2007) climate conditions; B reflects the last decade climate and C shows the range of modelled future (~2030) climate conditions. The initial N indicates a pre-development (no diversions) condition for systems that currently have major storages. Note: these are mean conditions based on 77-year sequences (23-year for the Daly sequence) based on the historical, past decade and future climate record conditions.
An assessment of potential storage locations, storage sizes and potentially exploitable (or divertible) yield (for a given reliability) were beyond the scope of the NASY project. Previous estimates of the potentially divertible yield made during past analyses were used to provide an indication of divertible yield for this study.

The most recent estimates of potentially divertible yield were made for the 1985 Australian Water Resources Review. In this review, estimates of exploitable yield were made for large storages and jurisdictions attempted to take into account factors such as: average annual flow, variability of flow, water quality and the availability of suitable sites for storage. Economic, social, cultural or environmental factors were not considered. Further, each jurisdiction employed slightly different methods in their assessments.

The ratio between the divertible yield volumes and streamflow volume estimates made by the Australian Water Resources Review were multiplied by the NASY streamflow estimates to provide an approximate NASY divertible yield (Figure 15).
Figure 15. Modelled streamflow (top) and divertible yield (bottom) across northern Australia. Note: scales are similar; values are GL/year. Streamflow is derived from rainfall-runoff models. Divertible yield is derived through comparison of the 1985 Australian Water Resources Review exploitable yield values with the Northern Australia Sustainable Yields Project-derived streamflow values.
5. **GROUNDWATER**

Water availability and divertible yield maps, whilst representing annual values, essentially represent the wet season conditions only. If water is required for dry season use, either significant surface water storages are required to compensate for no inflows and high evaporation rates during the dry season, or an alternative water resource is needed, such as groundwater, either through direct extraction, or though managed aquifer recharge (MAR), also known as aquifer storage and recovery (ASR).

The Northern Australia Sustainable Yields project has evaluated the aquifers within the groundwater provinces of northern Australia to indicate their relative groundwater prospectivity (Figure 16). Whilst absolute yields are currently conjectural for many aquifers due to a general paucity of groundwater data, there is good information on aquifer geometry, rock types and conditions, and conceptual models for recharge, transmission and discharge can be generated and potential yields estimated. Thus, high productivity aquifers may provide over 100 GL/year of supply across the entire aquifer; moderate productivity aquifers provide 10-100 GL/year and low productivity aquifers less than 10 GL/year. The actual distribution of these extractions would require further investigation and modelling. Note that these yields are at least an order of magnitude less than potential yields from surface water supplies.

Across northern Australia, only 2 regions have calibrated groundwater models: The Tindall Limestone of the Daly basin (and beyond) and the Darwin Rural area, east of Darwin.
Figure 16. Prospectivity of the groundwater provinces of northern Australia.
A few streams in northern Australia maintain flow through the dry season. These streams are maintained through groundwater discharge to the stream, either as returned stream-bank storage (Figure 17); discharge from underlying aquifers via artesian springs (Figure 18), or diffuse discharge of regional (Figure 19).

![Figure 17. Schematic of the recharge and discharge cycle that applies across most of the Timor Sea drainage division catchments, particularly in the carbonate aquifers (e.g. Daly). Note that where rivers are perennial, the groundwater level is maintained above the base of the river during the dry season (right image).](image_url)

![Figure 18. Schematic of natural (springs) and artificial (bores) discharge from the Great Artesian Basin aquifers (source GABCC, 2008).](image_url)
Figure 19. Schematic of the river-groundwater interactions in alluvial systems (e.g. Fitzroy (WA)) during wet and dry seasons.

These processes are limited in their areal extent. Hence there are only a few truly perennial reaches across northern Australia (Figure 20). There are other reaches that may flow during years of high rainfall, but will run dry during below average rainfall years. Reaches driven by groundwater discharge are more likely to continue flowing, even in dry years due to the longer time lag for groundwater discharge processes through aquifers compared to surface water flows.
Figure 20. Perennial river reaches across northern Australia maintained through groundwater discharge. There are notable associations with discharge from carbonate aquifers and associated with spring discharges from the Great Artesian Basin. An assessment has not been made for Western Australia due to insufficient data.
Many shallow aquifers exhibit a rapid response to the seasonal rainfall. These systems fill during the wet season and drain during the following dry season. This is observed most notably in the water level measurements made in shallow bores in the carbonate aquifers of the Daly basin (Figure 21) and to the east of Darwin in the McMinns lagoon area (Figure 22). The Territory agency (NRETAS) has studied the behaviours of the bores in the McMinns area and can correlate water levels with increasing and decreasing groundwater extractions, reflecting changes in extraction regimes (increasing numbers of bores) and rainfall patterns. Thus, a marked increase in the seasonal variability in water table depth was observed as increasing numbers of domestic bores were developed in the main aquifer through the late 1980s, to the extent that the aquifer water levels appeared to not completely recover each year. The following, wetter decade promoted both a decrease in domestic pumping and sufficient recharge to fill the aquifers. The last few years have again seen a decline in dry season water levels, as increased extraction takes place due to lower rainfall. The Territory has placed an embargo on further bores and has capped extractions to preserve the existing supplies.

Figure 21. Observed groundwater levels in the carbonate aquifers of the Daly river basin. RN006326 and RN029429 are both sunk in the Tindall Limestone; RN25286 draws water from the overlying, separate Ooloo Dolostone. The wetter conditions of the last decade are evident in the elevated levels achieved by the Ooloo dolostone bore (RN025286).

Figure 22. Observed groundwater levels in bore MM7424 (McMinns bore field) compared to the cumulative deviation from the mean for mean monthly rainfall. The annual cycle of rainfall creates the saw-tooth pattern, longer-term trends in increasing or decreasing rainfall is shown by the rising or falling trend in the rainfall deviation. Thus, a significant wetting phase occurred between 1993 and 1999. The variability in depth in the water table in the bore prior to 1978 illustrates the natural variability in the system. The increased variability since then is due to increased pumping as more than 3000 bores were progressively drilled in the area for domestic extraction. The variability abated during the period of increased rainfall, but rainfall levels have returned to pre-1990 levels (flattening of the deviation profile) and extractions have again increased resulting in the water levels not recovering each year.
Groundwater modelling by NRETAS in the Daly region is aimed at preserving the dry season flows of the Daly River, whilst allowing agricultural development through extraction of groundwater resources. Critically, dry season flow can be correlated with point-source discharges where the river crosses the carbonate aquifer outcrops (Figure 23). Maintenance of dry season flow through point discharge as rivers cross carbonate aquifers, appear to be a dominant mechanism across northern Australia (Figure 19).

Figure 23. Dry season flows for the Daly region. Flows recorded for drier than average and wetter than average years are indicated. Groundwater flow broadly moves to the north-west, but with local convergence at points of discharge.
Figure 24. Surface water and groundwater model reporting sites for the Daly region. Note bore Rn020614 in the north-west and RN029429 in the east. The former is sighted close to the Daly River; the latter is more than 5 km from the river bank. The modelled response of water levels at these two bores is shown below (Figures 25 and Figure 26).
Figure 25. Modelled water levels in bore RN020614, which is close to the Daly River. Levels are based on historical climate (blue line), projected forward with current full allocations, continuing the climate conditions of the last decade (green line); a future climate with current development (red line) and a future climate with increased development (grey line). As this bore is very close to the river, there is no lag in recharge and each year the aquifer re-fills, regardless of the climatic or developmental levels.

Figure 26. Modelled water levels in bore RN029429, which is approximately 5 km from the river. Levels are based on historical climate (blue line), projected forward with current full allocations (blue line), continuing the climate conditions of the last decade (green line); a future climate with current development (red line) and a future climate with increased development (grey line). There is a pronounced response to extractions that does not recover under historical or future climate conditions. Only the wetter conditions of the last decade have maintained high water levels. Recharge is dominated by diffuse vertical recharge from deep drainage through the soil profile. Note the time lag of about 10 years before a new dynamic equilibrium is reached in water levels in the aquifer. The model assumes instantaneous use of all water allocations and a stationarity of climate (i.e. the future climate conditions will be purely a scaled variation of historical conditions).
6. FUTURE SURFACE WATER POTENTIAL

Whilst a specific assessment for new surface water storages has not been carried out, it is considered that any potential intermediate and large carry-over surface water storages have already been identified.

Surface storage opportunities within the Gulf of Carpentaria drainage division occur mainly in the upper reaches of catchments; however, in these areas rainfall is lower and more sporadic, and potential evapotranspiration is highest. Sub-catchments along the Great Dividing Range may hold some potential for intermediate storages.

To increase current supply to Darwin, the Darwin River Dam is having its dam wall raised by 1.3 m. This will increase available yield by 20 percent to 49,100 ML/year. Darwin’s current demand for water is about 40,000 ML/year, and current total licensed extraction totals 46,420 ML/year. Whilst the nearby Manton Dam has an additional 7000 ML/year potential supply, recreational activities preclude its use except in emergencies.

New dam options were identified 20 years ago for consideration for long term water supplies. Three sites have potential:

1. Land for a potential future Marrakai Dam (next to Marrakai Crossing on the Adelaide River) has been bought and sub-leased for low level grazing. The extensive and generally low-lying catchment area upstream, however, would necessitate extensive engineering works and water treatment before use. The tidal limit for the Adelaide River can also extend this far upstream.

2. The catchment of the potential future Warrai Dam (about 18 km upstream of the Adelaide River township on the Adelaide River) is more compact than the other sites and good quality water might be collected without the need for chemical pre-treatment. About one third of the catchment is already protected within the Litchfield National Park. This site would also provide flood protection for the Adelaide River townsite and possibly could be configured to provide hydro-electric supply.

3. The potential future site of the Mt Bennet Dam on the Finniss River to the west of the Darwin River Dam is the site of high Indigenous values and there are environmental concerns related to the Rum Jungle mining operations.

Elsewhere in northern Australia, streamflow is largely event-driven, with a rapid rise and fall of flow. Off-stream development, supported by water harvesting, would be compromised if environmental flow rules were implemented, such as the requirement to harvest water from only the falling phase of flow. The rapid decrease in flow typical of northern Australian rivers provides for little opportunity for water take-off, following an event.

There are few rivers in northern Australia that flow all year: Most rivers cease-to-flow during the dry months. The few that maintain flow are mostly driven by shallow groundwater systems, or discharging artesian springs. Shallow groundwater systems, however, are generally variable both in storage capacity and water quality, both spatially and temporally.

Rivers across the drainage division are dominated by flood conditions during the wet season and much of the drainage division is inundated near the coast and for many kilometres inland.

The low gradients and generally flat landscape do not provide for good surface water storage, except in the headwater regions where rainfall is lower, so storages have to be large enough to withstand long periods of below average rainfall.
Many rivers in the Queensland part of the Gulf of Carpentaria drainage division have been declared as wild rivers and are to be maintained in a near-pristine state. Others have quantitative river models used for management and allocation of water resources. Future development will be undertaken under careful management regimes.

The high proportion of land under Indigenous management, combined with the significant areas of nature conservation (including the wild rivers) (Figure 27), means the majority of rivers in northern Australia will undergo relatively little hydrological change.
Figure 27. Simplified land use map of northern Australia.
7. FUTURE GROUNDWATER POTENTIAL

There are several karstic carbonate aquifers (Tindall Limestone and equivalents, and Ooloo Dolostone and equivalents) that potentially provide opportunities for large-scale (greater than 100 GL/year) groundwater development in the drainage division. These aquifers mainly occur in the Daly region in the Northern Territory. The level of groundwater extraction from these aquifers is currently low, although existing and potential future volumetric entitlements may be approaching extraction limits in some local areas, e.g. the Katherine-Douglas-Daly irrigation area. Water allocation plans undertaken, or currently being developed, in the Northern Territory – such as for the Tindall Limestone around Katherine, the Ooloo Dolostone around Daly and the Darwin-Howard East area – are all resulting in caps to groundwater extraction.

Smaller groundwater developments (i.e. 10 to 100 GL/year) are feasible within the aquifers of the Canning Basin and have been developed in the Proterozoic carbonate aquifers in the Darwin Rural Area. The latter, however, have also reached their extraction limit and there is currently a moratorium on any further groundwater development.

Even smaller extractions (i.e. less than 10 GL/year) are feasible across most of the division, and include areas of the Cretaceous sandstone aquifers. Many of the shallow groundwater resources, including alluvial aquifers bordering major rivers, are highly dynamic, responding rapidly to seasonal rainfall and river flows. The alluvial aquifers of the Fitzroy (WA) region are examples, though yields and quality is variable. The aquifer properties are poorly quantified, however.

Groundwater recharge rates are not well understood. There is little information to validate modelling of diffuse recharge, which is thought to be the dominant recharge mechanism in regions with clay and sandy soils. Over the carbonate soils of the Daly and Ord-Bonaparte regions, however, in regions where opportunities are highest, localised, indirect recharge via karstic openings and through stream beds is greater than diffuse recharge, and annually, shallow aquifers may recharge to capacity, though they often drain rapidly during the dry season (Figure 28). Each year, the aquifers fill from wet season rains, but then drain through the dry season to progressively lower levels. This fill and spill regime is being maintained due to wetter-than-average rainfall regimes experienced over the last 10 to 20 years. If climate conditions return to those experienced prior to the 1990s, it is likely that there will be years when the aquifers do not return to full capacity.

Figure 28. Recharge processes prevalent in karstic terrains (e.g. the Daly region).
Throughout the shallow aquifers (both alluvial and karstic), there is limited opportunity to augment groundwater supplies with managed aquifer recharge (MAR). Most aquifers currently in use rapidly recharge to full capacity during the wet season, but also rapidly discharge during the dry season, with large fluctuations (>10 m) in water tables made greater by increasing groundwater extraction in critical regions (e.g. Darwin Rural Area). Under current development, MAR in the alluvial aquifers would have limited applicability, as storages will be at full capacity towards the end of the wet season when surface water is available for injection. Furthermore, the low-conductivity soils that cover much of the floodplains in the drainage division preclude the use of infiltration pits for MAR. Any potential future scheme would therefore need to use injection wells to recharge the aquifer, the costs of which would be prohibitive for irrigation.

The Canning Basin sandstone aquifers probably have the greatest potential for MAR, but further investigations are required to better understand the groundwater flow and storage characteristics of these aquifers before such a scheme could be considered. Total storage in the Canning Basin aquifers has been estimated at $46 \times 10^{12} \text{ m}^3$ (46,000,000 GL), though much of this is of poor quality.

The carbonate aquifers of the Daly Basin have potential for the implementation of a MAR scheme. For carbonate aquifers the main storage and flow is in solution-enhanced fractures. Carbonate aquifers are the most suitable for consideration of MAR using borehole recharge in order to recharge water directly into the aquifer. Water can be injected into a borehole and recovered from another, some distance away, to increase travel time and benefit from the water treatment capacity of the aquifer. The technology needed to construct these structures can be quite complex in order to restrict the ingress of suspended solids that would rapidly clog the system and to restrict the inflow of contaminants that might pollute the groundwater body.

Rapid runoff of rainfall results in low rates of groundwater recharge in the higher country so there are limited storage opportunities of groundwater in this landscape. The Great Dividing Range along the eastern margin of the Gulf of Carpentaria drainage division provides recharge to the Great Artesian Basin and rejected recharge and artesian conditions result in spring discharge within the drainage division. The greatest stores of groundwater are likely in the deep aquifers. There is currently insufficient data, however, to adequately quantify the amount stored, recharge rates and sustainable extractable yields. These storages are largely undeveloped.

Beneath coastal floodplains, prolonged flooding may provide substantial opportunity for recharge, though this is tempered by generally low recharge rates through relatively impermeable sediments. The near-coastal aquifers of the Northern Territory rapidly recharge each year, often to capacity, providing reliable sources of generally good quality groundwater.

There is an intricate balance between surface and groundwater flows and the environmental regimes they support, resulting in a high level of endemic species across northern Australia.

8. SURFACE–GROUNDWATER INTERACTION

The few perennial rivers are supplied through the dry season by discharging groundwaters, mostly from Great Artesian Basin springs, particularly in the east of the drainage division. Rejected recharge along the Great Artesian Basin intake beds can supply streamflow throughout the year, especially in the north (Figure 19). Groundwater extraction in the vicinity of these springs can, therefore, have a significant impact on surface water supplies and flow.

The western catchments are typified by discharge from carbonate aquifers, particularly in the Roper, and Gregory river catchments.
9. CYCLONES AND EL NIÑO EVENTS

Cyclones are important events in producing heavy rainfall events across northern Australia. Note that the term cyclone here includes the low prior to it reaching cyclone strength and the low after it has declined below cyclone strength. An example of some cyclones that have brought heavy to very heavy rain to northern Australia: Charlotte in January 2009, Craig in March 2003, Steve in February 2000, Les in January 1998, May in February 1998, Sadie in January 1994, and Sandy in March 1985.

The following figure (Figure 29) downloaded from the BOM Internet site illustrates the importance of cyclones in northern Australia.

![Cyclone Tracks for northern Australia](source: BoM)

While cyclones are important and dramatic rainfall events, they are also often localised and intense, resulting in high local runoff. Larger, regional-scale, lows often produce larger amounts of rainfall over much greater areas and may be more important from a water resources perspective.

One of the key findings of the IPCC and its advisory committees is that it is likely that future tropical cyclones will become more intense, with larger peak wind speeds and heavier precipitation. This conclusion, however, relates to continental, regional and ocean basin scales, where numerous long-term changes in climate have been observed. These include changes in the intensity of tropical cyclones.

A link between the intensity of hurricanes (tropical cyclones) in the Atlantic Ocean with sea surface temperature triggered a flurry of research into the relationship between tropical cyclones and climate change. While the relationship between intensity of tropical cyclones and sea surface temperature is now more widely accepted, at least for the Atlantic, the continuation of the causal link into the future has been questioned. The critical issue is whether the observed increase in hurricane intensity in the Atlantic is due to the relatively higher increase in sea surface temperature in the Atlantic relative to other ocean basins or whether it is related directly to the absolute increase in sea surface temperature, regardless of what is happening in other ocean basins. If tropical cyclone intensity is linked to relative sea surface temperatures, then the intensity might relax to earlier levels as inter-ocean basin sea surface temperatures equilibrate. On the other hand, if intensity is related to absolute sea surface temperatures, then the link between climate change and cyclone intensity is strong, with even more intense cyclones expected later this century. The
observational record is not yet long enough, and the basic process-level understanding is not yet good enough, to distinguish between the two possible futures.

El Niño events appear to become more prevalent after 1977 and this has coincided with a decrease in the total number of tropical cyclones in the Queensland region. At the same time, there is some evidence that the number of severe tropical cyclones has increased.

The current, state-of-the-art coupled climate models used in the IPCC Fourth Assessment (AR4) have a typical resolution of 1.5 to 3 degrees in the atmosphere and 1 degree in the ocean. In neither component are some key aspects of the climate system (such as the influence of ocean eddies, orographic forcing of the atmosphere, tropical cyclones) adequately represented. Predicting cyclone activity is a current topic of much scientific research, and therefore not available in current GCM output used in the three Sustainable Yields Projects, and hence was not available for future climate scenarios in this project. In the absence of information on cyclonic activity under a 2030 future climate, in the NASY project the frequency of inter-tropical cyclones was assumed to be the same as the historic climate.

The AR4 documented that a robust result in high resolution model simulations of tropical cyclones in a warmer climate has been that there will be an increase in precipitation associated with cyclones. They have stated that the mechanism is simply that as the water vapour content of the tropical atmosphere increases, the moisture convergence for a given amount of dynamical convergence is enhanced.

The IPCC has also noted that the resolution of current global climate models limits the proper representation of tropical cyclones and heavy rainfall. For the modelling carried out for this project, we assessed rainfall amounts, intensity and rain days, with no reference to rainfall source, be it a cyclonic event, low pressure system or small convective cell. Hence, only rainfall processes were explicitly incorporated.
10. SUMMARY

A lot of rain falls on northern Australia, but its arrival is restricted in time and uneven in its distribution. Where and when it occurs is generally impractical for water resource development and there are large variations in how much comes year to year. There is little or no rain for three to six months every year and potential evapotranspiration rates are very high. Runoff follows a similar pattern to rainfall. The landscape is generally not amenable to storing water and the climate is not conducive to keeping it. Consequently, few rivers flow during the dry season and those that do are fed by groundwater, mostly at discrete points. Groundwater offers potential for increased extractions, but aquifers are seasonally dynamic and there is little opportunity to increase groundwater storage as the aquifers fill during the wet season and drain through the dry. Any change to surface or groundwater regimes will likely have consequences to the environment. Future rainfall is expected to be similar to that experienced historically, with future potential evapotranspiration being slightly higher throughout the year. Surface runoff and streamflow is likely to be the same or slightly less than historically; recharge to groundwaters may be slightly higher, due to greater intensity rains. The last decade has not been typical of historical climate conditions, nor of expected future conditions.

11. REFERENCES

1. This chapter draws heavily on the reports of the Northern Australia Sustainable Yields Project and references listed in (2,3). Additional data acknowledged in the text.