FLINDERS AND GILBERT AGRICULTURAL RESOURCE ASSESSMENT

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Surface water – groundwater connectivity

A technical report to the Australian Government from the CSIRO Flinders and Gilbert Agricultural Resource Assessment, part of the North Queensland Irrigated Agriculture Strategy

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The Strategy was guided by two committees:

(i) the **Program Governance Committee**, which included the individuals David Crombie (GRM International), Scott Spencer (SunWater, during the first part of the Strategy) and Paul Woodhouse (Regional Development Australia) as well as representatives from the following organisations: Australian Government Department of Infrastructure and Regional Development; CSIRO; and the Queensland Government.

(ii) the **Program Steering Committee**, which included the individual Jack Lake (Independent Expert) as well as representatives from the following organisations: Australian Government Department of Infrastructure and Regional Development; CSIRO; the Etheridge, Flinders and McKinlay shire councils; Gulf Savannah Development; Mount Isa to Townsville Economic Development Zone; and the Queensland Government.

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Some of the data interpretations and conclusions were informed by the airborne electromagnetic surveys carried out by the geophysics activity led by Tim Munday.

This report was reviewed by Dr Russell Crosbie (CSIRO), Dr Brian Smerdon (CSIRO), Dr Peter Stone (CSIRO) and Dr Cuan Petheram (CSIRO).

Director's foreword

Northern Australia comprises approximately 20% of Australia's land mass but remains relatively undeveloped. It contributes about 2% to the nation's gross domestic product (GDP) and accommodates around 1% of the total Australian population.

Recent focus on the shortage of water and on climate-based threats to food and fibre production in the nation's south have re-directed attention towards the possible use of northern water resources and the development of the agricultural potential in northern Australia. Broad analyses of northern Australia as a whole have indicated that it is capable of supporting significant additional agricultural and pastoral production, based on more intensive use of its land and water resources.

The same analyses also identified that land and water resources across northern Australia were already being used to support a wide range of highly valued cultural, environmental and economic activities. As a consequence, pursuit of new agricultural development opportunities would inevitably affect existing uses and users of land and water resources.

The Flinders and Gilbert catchments in north Queensland have been identified as potential areas for further agricultural development. The Flinders and Gilbert Agricultural Resource Assessment (the Assessment), of which this report is a part, provides a comprehensive and integrated evaluation of the feasibility, economic viability and sustainability of agricultural development in these two catchments as part of the North Queensland Irrigated Agricultural Strategy. The Assessment seeks to:

- identify and evaluate available soil and water resources
- quantify the productivity and scale of opportunities for irrigated agriculture
- quantify development costs and benefits and their distribution amongst different users.

By this means it seeks to support deliberation and decisions concerning sustainable regional development.

The Assessment differs from previous assessments of agricultural development or resources in two main ways:

- It has sought to 'join the dots'. Where previous assessments have focused on single development activities or assets – without analysing the interactions between them – this Assessment considers the opportunities presented by the simultaneous pursuit of multiple development activities and assets. By this means, the Assessment uses a whole-of-region (rather than an asset-by-asset) approach to consider development.
- The novel methods developed for the Assessment provide a blueprint for rapidly assessing future land and water developments in northern Australia.

Importantly, the Assessment has been designed to lower the barriers to investment in regional development by:

- explicitly addressing local needs and aspirations
- meeting the needs of governments as they regulate the sustainable and equitable management of public resources with due consideration of environmental and cultural issues
- meeting the due diligence requirements of private investors, by addressing questions of profitability and income reliability at a broad scale.

Most importantly, the Assessment does not recommend one development over another. It provides the reader with a range of possibilities and the information to interpret them, consistent with the reader's values and their aspirations for themselves and the region.

Peter Stone

Dr Peter Stone, Deputy Director, CSIRO Sustainable Agriculture Flagship

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Shortened forms

AEM	airborne electromagnetics
AHD	Australian Height Datum
CFC	chlorofluorocarbon
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEM	digital elevation model
GAB	Great Artesian Basin
NQIAS	North Queensland Irrigated Agriculture Strategy
NRM	natural resource management
ONA	the Australian Government Office of Northern Australia
PET	polyethylene terephthalate
TOC	top of casing

Units

MEASUREMENT UNITS	DESCRIPTION
Bq/L	becquerel per litre
ccSTP/g_{H2O}	cubic centimetres at Standard Temperature and Pressure per gram of water
dS/m	deci Siemens per metre
Fmol/L	femtomol per litre
GL	gigalitres, 1,000,000,000 litres
kL	kilolitres, 1000 litres
km	kilometres, 1000 metres
L	litres
m	metres
m^{-1}	per metre
m^2/day	metres squared per day
mAHD	metres above Australian Height Datum
meq/L	milli equivalents per litre
mg/L	milligrams per litre
ML	megalitres, 1,000,000 litres
pmol/kg	picomol per kilogram
pMC	percent Modern Carbon
dS/m	deci Siemens per metre
‰ PBD	per mille relative to Pee Dee Belemnite
‰ VSMOW	per mille relative to Vienna Standard Mean Ocean Water

Preface

The Flinders and Gilbert Agricultural Resource Assessment (the Assessment) aims to provide information so that people can answer questions such as the following in the context of their particular circumstances in the Flinders and Gilbert catchments:

- What soil and water resources are available for irrigated agriculture?
- What are the existing ecological systems, industries, infrastructure and values?
- What are the opportunities for irrigation?
- Is irrigated agriculture economically viable?
- How can the sustainability of irrigated agriculture be maximised?

The questions – and the responses to the questions – are highly interdependent and, consequently, so is the research undertaken through this Assessment. While each report may be read as a stand-alone document, the suite of reports must be read as a whole if they are to reliably inform discussion and decision making on regional development.

The Assessment is producing a series of reports:

- Technical reports present scientific work at a level of detail sufficient for technical and scientific experts to reproduce the work. Each of the 12 research activities (outlined below) has a corresponding technical report.
- Each of the two catchment reports (one for each 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 irrigated agriculture.
- Two overview reports – one for each catchment – are provided for a general public audience.
- A factsheet provides key findings for both the Flinders and Gilbert catchments for a general public audience.

All of these reports are available online at <http://www.csiro.au/FGARA>. 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.

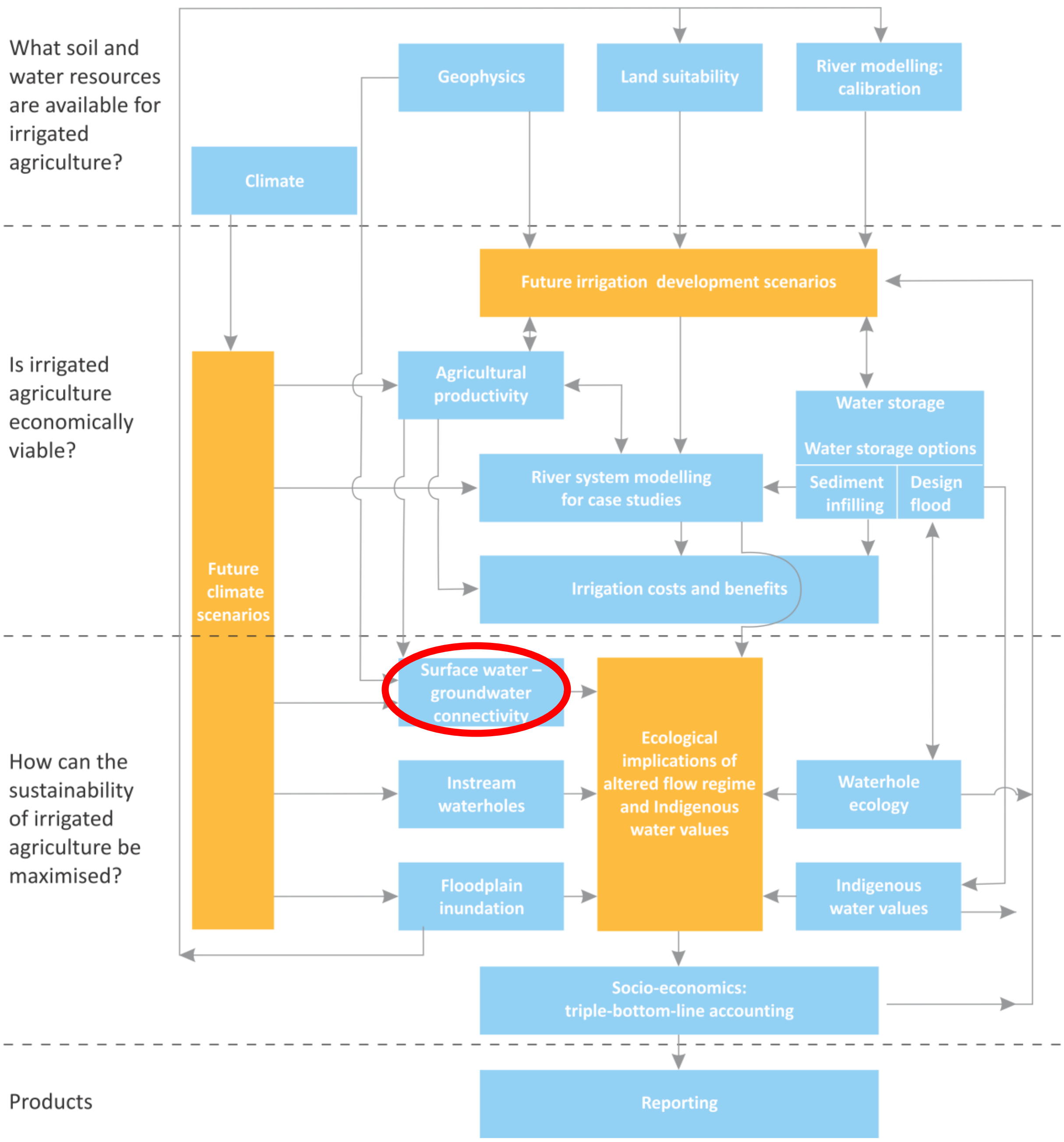
The Assessment is divided into 12 scientific activities, each contributing to a cohesive picture of regional development opportunities, costs and benefits. Preface Figure 1 illustrates the high-level linkages between the 12 activities and the general flow of information in the Assessment. Clicking on an 'activity box' links to the relevant technical report.

The Assessment is designed to inform consideration of development, not to enable particular development activities. As such, the Assessment informs – but does not seek to replace – existing planning processes. Importantly, the Assessment does not assume a given regulatory environment. As regulations can change, this will enable the results to be applied to the widest range of uses for the longest possible time frame. Similarly, the Assessment does not assume a static future, but evaluates three distinct scenarios:

- Scenario A – historical climate and current development
- Scenario B – historical climate and future irrigation development
- Scenario C – future climate and current development.

As the primary interest was in evaluating the scale of the opportunity for irrigated agriculture development under the current climate, the future climate scenario (Scenario C) was secondary in importance to scenarios A and B. This balance is reflected in the allocation of resources throughout the Assessment.

The approaches and techniques used in the Assessment have been designed to enable application elsewhere in northern Australia.



Preface Figure 1 Schematic diagram illustrating high-level linkages between the 12 activities (blue boxes)

This report is a technical report. The red oval in Preface Figure 1 indicates the activity (or activities) that contributed to this report.

The orange boxes indicate information used or produced by several activities. The red oval indicates the activity (or activities) that contributed to this technical report. Click on a box associated with an activity for a link to its technical report (or click on 'Technical reports' on <http://www.csiro.au/FGARA> for a list of links to all technical reports). Note that the Water storage activity has multiple technical reports – in this case the separate reports are listed under the activity title. Note also that these reports will be published throughout 2013, and hyperlinks to currently unpublished reports will produce an 'invalid publication' error in the CSIRO Publication Repository.

Executive summary

While potential future irrigation developments in the Flinders and Gilbert catchments in north Queensland are likely to utilise primarily surface water, there is the possibility that there may be some associated impacts on groundwater in areas where there is currently (or will develop as a result of an irrigation development) a saturated connection between the surface water and the underlying groundwater system. The sustainable management of water resources is made particularly challenging by the time lags associated with lateral groundwater flow, as many groundwater-related environmental problems can take many decades to manifest themselves (e.g. dryland salinity, overallocation). Thus it is important that the groundwater-related environmental risks are understood as early as possible in the planning process of any proposed irrigation scheme.

An extensive review of the geology, hydrogeology and surface water - groundwater interactions in each catchment was carried out and confirmed that there was a general paucity of groundwater data and knowledge. The groundwater activity therefore focussed on three main tasks that would be useful in informing water resource planners of likely groundwater impacts of future surface water and shallow groundwater irrigation developments in the Flinders and Gilbert catchments. It is important to note that the groundwater activity focussed on surface water-groundwater connectivity and groundwater was not assessed specifically for use as a resource. However, some of the results described in this report may be useful for this purpose.

Task 1 involved an assessment of whether the persistence of permanent instream and offstream waterholes through the 2012 dry season was likely to be due (at least in part) to natural groundwater inflows. The purpose of this task was to inform water resource planners and managers about the potential impact of current and future groundwater and surface water development on the hydrology and associated ecosystem health of permanent waterholes. Field sampling of six river and seventeen waterhole sites in the Flinders catchment and five river and nineteen waterhole sites in the Gilbert catchment was carried out between May and December 2012. Major ion chemistry, and naturally occurring radioactive and stable isotopes of water were used to assess the likelihood of groundwater presence in these rivers and waterholes.

The majority of river and waterhole sites sampled in both catchments had a nil or low likelihood of groundwater inflow, and so their persistence during the dry season appears to be unrelated to groundwater. It therefore is likely that there is no long term saturated connection between the rivers and the underlying groundwater systems in widespread areas of both catchments. In these situations it is unlikely that future groundwater development will have an impact on the hydrology and associated ecosystem health of permanent waterholes. However, there were several sites that had a high likelihood that groundwater inflows would be a contributor to their persistence through the dry season. All of these appear to be related to local hydrogeological conditions. In these situations, there is a possibility that future groundwater development in the alluvium/bedsands and fractured basalts may have an impact on the hydrology and associated ecosystem health of permanent waterholes. More focussed investigations will be needed at individual sites to determine the exact nature and magnitude of such impacts.

Whilst the dry season persistence of waterholes does not generally appear to be related to groundwater in most cases it is important to understand the chemistry utilised in this component of the Assessment. These methods are appropriate for detecting the inflow of groundwater to surface water that has been subject to reasonably long flow paths (has spent months to thousands of years in the sub surface) as would be expected for example in alluvial and fractured rock systems. What the chemistry is less appropriate for is identifying the inflow of other highly localised groundwater systems, where sub surface flows are in the order of days to months. These highly localised parafluvial groundwater systems exist in the fluvial plain (riverbed sediments) within the river channel. It is possible that parafluvial groundwater (surface water that enters the sub surface through the fluvial plain sediments in the river channel and discharges down plain within the river channel in areas of topographic relief or low points) could support waterholes in both catchments. However, this was not assessed and would require further investigation.

The potential impacts on alluvium/bedsands aquifers due to changes in river management will be highly dependent on the new flow regulation regime, in particular the magnitude, frequency and timing of individual water releases from storages and the subsequent extractions for use. In terms of potential river regulation there are three main possibilities: (i) year-round releases for perennial agricultural systems; (ii) supplementary releases for annual agricultural plantings in January/February that are harvested in May/June; and (ii) dry season releases for annual agricultural systems. Given that the details of each of these are yet to be determined in each catchment it is only possible to speculate as to what the potential future groundwater impacts are for dry season flows and waterhole persistence. Year-round releases that make the naturally ephemeral river systems perennial may lead to an increase in recharge to the alluvium/bedsands and a decrease in discharge of groundwater to waterholes and rivers. The impact of supplementary and dry season releases will be minimal as they will result in only short term fluctuations in river flow. These short-term changes in river flow are similar to the naturally intermittent wet season flows. Results from this Assessment indicate that these naturally intermittent flows do not appear to result in appreciable river recharge.

Task 2 involved groundwater investigations to gain a better understanding of the connection between ephemeral rivers and the shallow alluvial/bedsands aquifers, and to provide baseline groundwater information prior to any new irrigation developments. In August/September 2012 twelve existing piezometers in the alluvium/bedsands adjacent to the Flinders River between Hughenden and Maxwelton were located, sampled, and equipped with water level/salinity loggers. In October 2012 two existing piezometers in the GAB recharge beds adjacent to the Gilbert River near an irrigation area were located and equipped with water level/salinity loggers and then sampled in April 2013. Data from all loggers were downloaded in April 2013 after the wet season to attempt to determine river/aquifer connectivity. Water samples from all piezometers were analysed for major ions and a suite of naturally occurring isotopes and anthropogenic tracers to provide information on groundwater recharge such as source waters, recharge mechanisms and likely recharge rates. Unfortunately low rainfall over the 2012/2013 wet season made this work inconclusive in some areas as river levels rose only marginally.

Based on experience in southern Australia, recharge rates in alluvial/bedsands aquifers adjacent to major rivers is often higher than surrounding areas due to river recharge. However, this theory has not been tested to any great degree in northern Australia. Interpretation of the data collected in this Assessment suggests that net recharge rates to the Flinders River alluvium/bedsands were probably not very high (0.1 to >10 mm/year) and were comprised of diffuse rainfall recharge rather than direct river recharge. The low recharge rates were thought to be due to: (i) the limited spatial and temporal extent of direct river recharge because of the highly ephemeral nature of the Flinders River; (ii) the heavy-textured surface soils that limit rainfall infiltration; and (iii) the high evaporation demand in the dry season. The low net recharge rates results in spatially variable groundwater quality that is often poor. This, combined with the highly variable (and often limited) saturated thickness of the alluvial/bedsands aquifer, is why the alluvial/bedsands groundwater has only been intermittently developed in the Flinders catchment. Given the low diffuse recharge rates to the alluvial/bedsands aquifer, and the lack of evidence for high rates of direct river recharge, increased shallow groundwater usage may lead to lowering of groundwater levels, depending on local hydrogeological conditions.

It was only possible to make some qualitative interpretations of the data collected from the two piezometers in the Gilbert catchment. The interpretation for these two sites was that they received only intermittent diffuse rainfall recharge during very large rainfall events (prior to the low rainfall 2012/13 wet season) and therefore have a low mean recharge rate. Estimates of diffuse recharge rates at these sites are likely to be in the range 5 - 40 mm/year which is consistent with estimates reported elsewhere. Similar to the Flinders River alluvium/bedsands, the low recharge rates to the GAB recharge beds at these locations are thought to be due to: (i) the limited spatial and temporal extent of direct river recharge because of the highly ephemeral nature of the Gilbert River; and (ii) the high evaporation demand in the dry season. Furthermore, the alluvium/bedsands along this reach of the Gilbert River are currently used for irrigation, have a thin saturated thickness and only limited groundwater storage to supply river water to the GAB recharge beds. In the case where GAB recharge beds outcrop in the bed of the Gilbert River recharge rates may be different but this has not been investigated as part of this Assessment.

As described above the potential impacts on leakage to alluvium/bedsands aquifers due to changes in river management will be highly dependent on the new flow regulation regime. For the Flinders catchment, year-round releases may make the naturally ephemeral river systems perennial. This may lead to an increase in recharge to the alluvium/bedsands and a decrease in discharge of groundwater to waterholes and rivers. The impact of supplementary and dry season releases will be minimal as they will result in only short term fluctuations in river flow. These short-term changes in river flow are similar to the naturally intermittent wet season flows. Results from this Assessment indicate that these naturally intermittent flows do not appear to result in appreciable river recharge. Similar conclusions are likely for the lower reaches of the rivers of the Gilbert catchment where highlands adjacent to the river channels are absent. In the upper reaches of the rivers of the Gilbert catchment, where the alluvium/bedsands are thin and laterally constrained by the adjacent fractured rock highlands, the storage in these aquifers is likely to be extremely low. In the case of any of the release regimes, leakage may not, depending on local hydrogeological conditions, necessarily increase due to the low aquifer storage.

Task 3 involved the development of a new groundwater modelling method to assess the risk that root zone drainage beneath new irrigation sites may lead to watertable rise, and to evaluate the consequent impacts on the irrigation site and nearby rivers. New explicit analytical solutions were specifically developed for the groundwater modelling and were implemented as MATLAB programs. The new method has been applied in the case study sites in both the Flinders and Gilbert catchments and the results of these simulations are reported here and in the Catchment Reports (Petheram and Watson, 2013a; Petheram and Watson, 2013b).

Results from analytical modelling show that new large irrigation developments could result in groundwater table rise and the formation of groundwater mounds. Under sustained, long-term intensive irrigation such mounds may reach the ground surface. A rising water table poses the risk of secondary salinity, with the mobilised salts posing the threat of saline discharge to nearby rivers in addition to limiting plant growth. The sensitivity analyses have shown that the maximum (steady state) groundwater table rise increases with increasing recharge rate, irrigation area, distance to the river, and lower aquifer transmissivity. Irrigation developments placed further away from the river result in higher steady state groundwater table rise due to a diminishing river drainage capacity. The five case studies conducted for Cavehill, Kidston, Greenhill, O'Connell, and Dagworth sites have shown that placing large irrigation developments may lead to extreme rises in groundwater levels when crops with a high irrigation demand are introduced to areas with low-conductivity aquifers; in most cases, the groundwater table rose up to the soil surface. The time frames during which the groundwater table rises occurred varied from a few years to tens of years depending on aquifer hydraulic parameters and recharge rates. Essentially, the results from the analytical modelling show the importance of giving due consideration to siting irrigation areas in the landscape and its potential environmental impacts to both the landscape the rivers and groundwater.

As a result of the work carried out in the groundwater activity it has been possible to formulate some generalised conceptual models of surface-groundwater connectivity along the rivers of the Flinders and Gilbert catchments. These are a significant advance on those proposed in the previous Northern Australia Sustainable Yield (NASY) project. There is a default conceptual model in which there is no saturated connectivity between the rivers (and waterholes) and the underlying groundwater systems. This is likely to be the case in situations where the river or waterhole beds have such low permeability that leakage through the beds is so minimal that saturated connection between the two water bodies never occurs. In the surface water-groundwater literature this is referred to as a disconnected system. Due to the ephemeral nature of most of the rivers, the generally heavy textured surface soils, and the high rates of evaporation demand during the dry season, this conceptual model is likely to apply widely across both catchments. In situations where there is a saturated connection between the river and the underlying groundwater system (this is referred to as a connected system), four pre-development conceptual models have been defined, along with a generic conceptual model for an irrigation development adjacent to a river. Each of the five conceptual models show the surface water-groundwater flow processes during the wet season, during the early dry season, and at the end of dry season. It is important to note that these conceptual models are highly generalised and there may be many variations of each at the individual site scale.

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1 Introduction

1.1 Background

While potential future irrigation developments in the Flinders and Gilbert catchments in north Queensland are likely to utilise surface water, there is the possibility that there may be some associated impacts on groundwater in areas where there is currently (or will develop as a result of an irrigation development) a saturated connection between the surface water and the underlying groundwater system. The sustainable management of water resources is made particularly challenging by the time lags associated with lateral groundwater flow (Cook et al., 2003b), as many groundwater-related environmental problems can take many decades to manifest themselves (e.g. dryland salinity, overallocation). Thus it is important that the groundwater-related environmental risks are understood as early as possible in the planning process of any proposed irrigation scheme.

Understanding groundwater – from an environmental risk or potential resource perspective – requires an understanding of groundwater recharge, groundwater flow paths and groundwater discharge mechanisms. Unfortunately, groundwater recharge, flow and discharge are difficult to measure and can be highly variable in space. This makes understanding groundwater processes in data-sparse areas, such as the Flinders and Gilbert catchments, particularly challenging. In such areas, geophysics can be a useful tool in helping to build a rapid understanding of likely groundwater recharge areas, aquifer thicknesses and groundwater discharge mechanisms. Hence the groundwater investigations described here were informed by the findings of the geophysics activity.

Due to the general paucity of groundwater data the groundwater activity focussed on three main tasks that would be useful in informing water resource planners of likely groundwater impacts of future surface water irrigation developments in the Flinders and Gilbert catchments:

- Task 1 involved focused investigations into the nature of surface water – groundwater interactions in a selection of river and waterhole sites in both the Flinders and Gilbert catchments, with the objective of establishing the hydrogeological controls on dry-season flows and waterhole persistence.
- Task 2 involved groundwater investigations to gain a better understanding of the connection between ephemeral rivers and the shallow alluvial/bedsands aquifers, and to provide baseline groundwater information prior to any new irrigation developments. The field work for this task was undertaken adjacent to the Flinders River between Hughenden and Maxwelton, and adjacent to the Gilbert River between Prestwood and Chadshunt stations.
- Task 3 involved the development of a new groundwater modelling method to assess the risk that root zone drainage beneath new irrigation sites may lead to watertable rise, and to evaluate the consequent impacts on the irrigation site and nearby rivers. New explicit analytical solutions were specifically developed for the groundwater modelling and were implemented as MATLAB programs. The new method has been applied in the case study sites in both the Flinders and Gilbert catchments and the results of these simulations are reported in the Catchment Reports (Petheram and Watson, 2013a; Petheram and Watson, 2013b).

Table 1.1 summarises the key science questions, inputs, scale, methods and outputs for the groundwater activity. It is important to note that the groundwater activity focussed on surface water-groundwater connectivity and groundwater was not assessed specifically for use as a resource. However, some of the results described in this report may be useful for this purpose.

Table 1.1 Summary of the key science questions, input, scale, methods and outputs

KEY SCIENCE QUESTION	INPUT	SCALE	METHODS	OUTPUTS
What are the hydrogeological controls on dry-season flows and waterhole persistence?	• Analyses of major ions and natural tracers (stable isotopes of water, radon-222) from river water samples collected in the field	Waterhole	Sampling of river water from rivers and waterholes	• Locations of rivers and waterholes in the Flinders and Gilbert catchments that persist in the dry season due to groundwater inflows
Does river water leak into the shallow alluvial/bedsands aquifers and is this the major recharge source for these aquifers?	• Temporal measurements of groundwater levels and salinity with *in situ* data loggers • Temporal measurements of river levels with *in situ* data loggers • Analyses of major ions and natural and anthropogenic tracers (stable isotopes of water, chlorofluorocarbons, sulphur hexaflouride, carbon-13, carbon-14, dissolved noble gases) from groundwater samples collected in the field	Site	Existing shallow groundwater monitoring piezometers equipped with water level and salinity loggers, sampling of the groundwater in these piezometers, and water level loggers installed in the river	• Identification of which of the piezometer sites in the Flinders and Gilbert catchments has significant volumes of river water recharging the underlying shallow alluvial/bedsands aquifers
What is the risk that root zone drainage beneath potential new irrigation sites will lead to watertable rise? What is the waterlogging and salinity impact on the irrigation site and on groundwater inflows to adjacent rivers?	• Groundwater levels and salinities • Estimates of aquifer transmissivity and thickness • Estimates of root zone drainage rates	Irrigation site and river reach	Analytical modelling of vertical and lateral groundwater movements	• A new method that allows the determination of the magnitude and timing of rises in watertable beneath potential new irrigation sites and the volume and timing of the resultant movement of groundwater to the nearest river

1.2 Review of the geology, hydrogeology and surface water - groundwater interactions in each catchment

1.2.1 FLINDERS CATCHMENT

Geology

The Flinders River flows from the Great Dividing Range north-east of Hughenden in a westerly direction for 840 km, then turns north where it discharges into the Gulf of Carpentaria near Karumba. A structural basin between the uplands to the south-west and south-east is in filled with alluvial sediments from numerous streams, dissected with entrenched riverbeds. These lowland plains extend far inland to the south from the Gulf, which is in itself a down-warped part of the plain (CSIRO, 2009a). The surface geology of the uplands is highly complex and dominated by an array of igneous and metamorphic formations of various ages (Coventry, 1985), interspersed with sedimentary deposits and alluvial regolith along the channels of the major rivers and tributary streams (Twidale, 1966; Stephenson, 1986). A simplified map of the geology of the Flinders catchment is shown in Figure 1.1. There are five major structural units in the Flinders catchment (alluvium and sand plains, basalt flows, sedimentary rocks, metamorphic rocks, igneous rocks). The oldest units are the Mt Isa Inlier in the west and the Cape River Province in the east. The central part of the catchment is underlain by sedimentary rocks of the Great Artesian and Galilee Basins. Cainozoic basalt flows of the Sturgeon Province outcrop in the upper Flinders catchment and as far west as Hughenden.

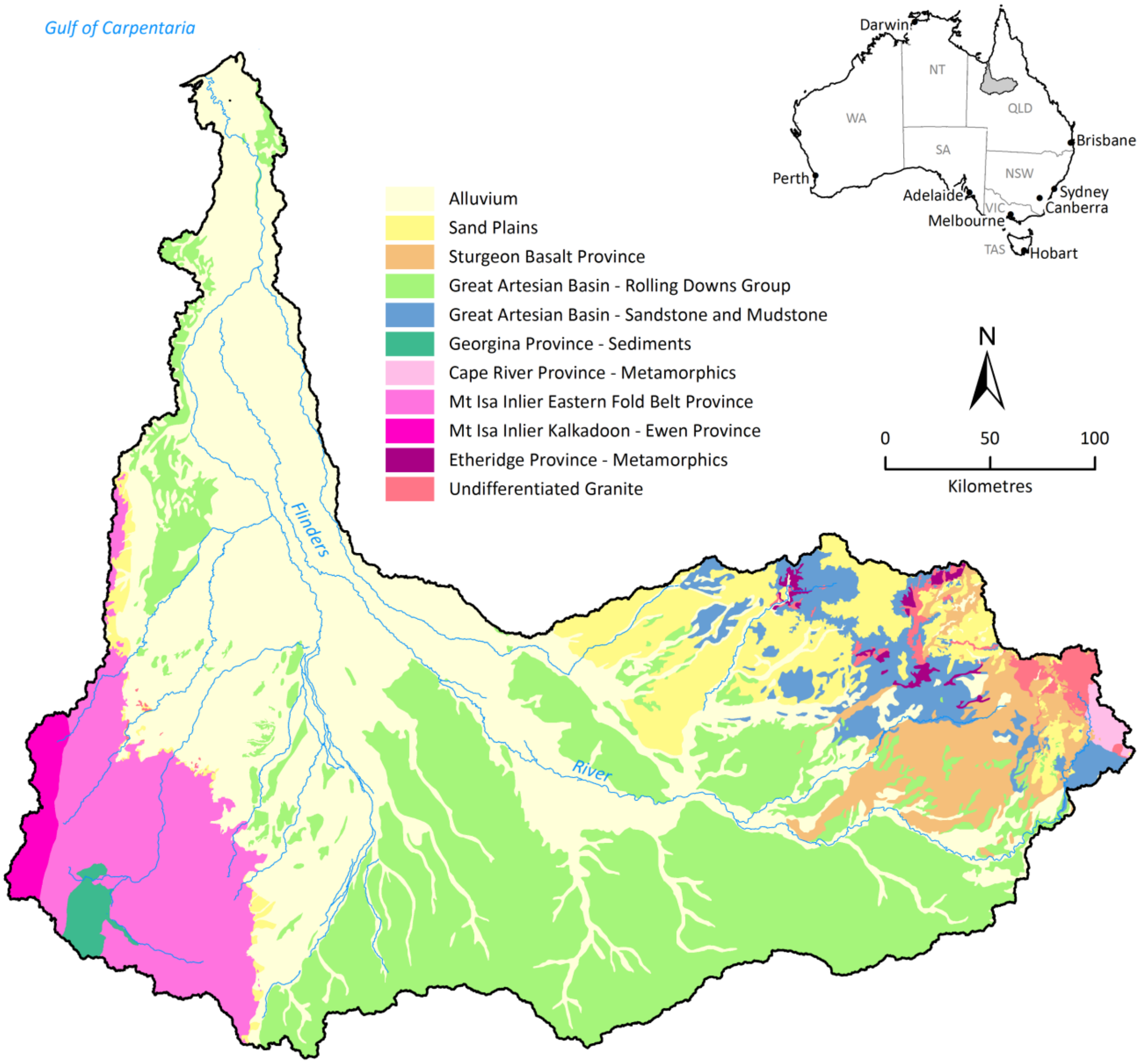

Figure 1.1 Simplified surface geology map of the Flinders catchment

Hydrogeology and groundwater use

The major aquifers of the Flinders catchment are shown in Figure 1.2. According to the Queensland Department of Natural Resources and Mines groundwater database (accessed July, 2012) there are more than 3000 registered groundwater bores in the Flinders catchment (Figure 1.3). The majority of the bores are in the Jurassic-Cretaceous age Great Artesian Basin (GAB) aquifers that supply stock and domestic water and maintains springs that host ecological assets. While there are a very large number of GAB bores, very few are being regularly monitored for either water level or water quality. There are much lesser numbers of bores in the outcropping Proterozoic and Cainozoic age fractured rocks, and in the Cainozoic age sediments that are comprised mostly of Quaternary age alluvium of the past and present rivers in the catchment (Figure 1.2). None of these bores are being regularly monitored for either water level or water quality.

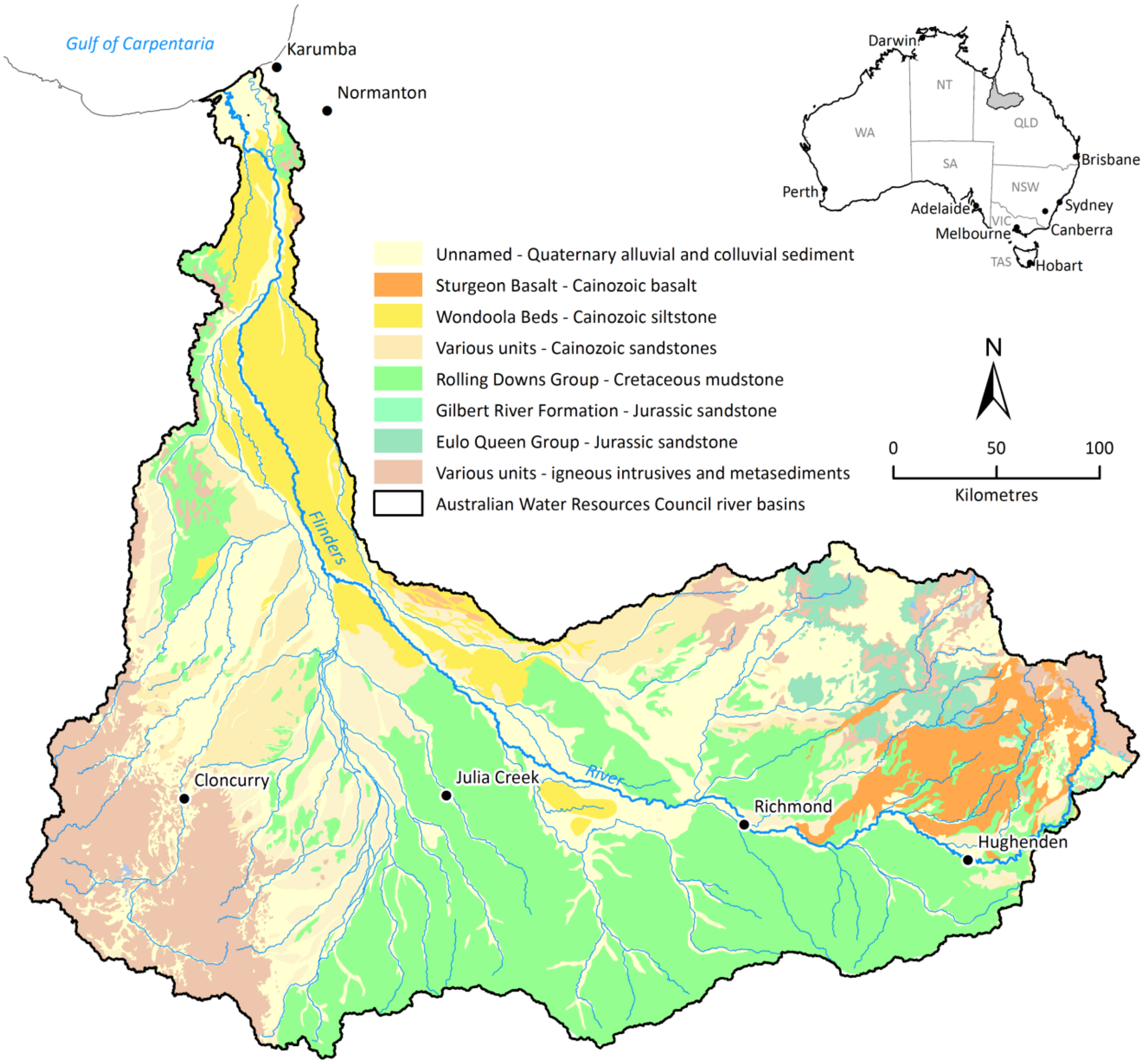

Figure 1.2 Major aquifers map of the Flinders catchment (adapted from Figure FL-2 in CSIRO (2009a))

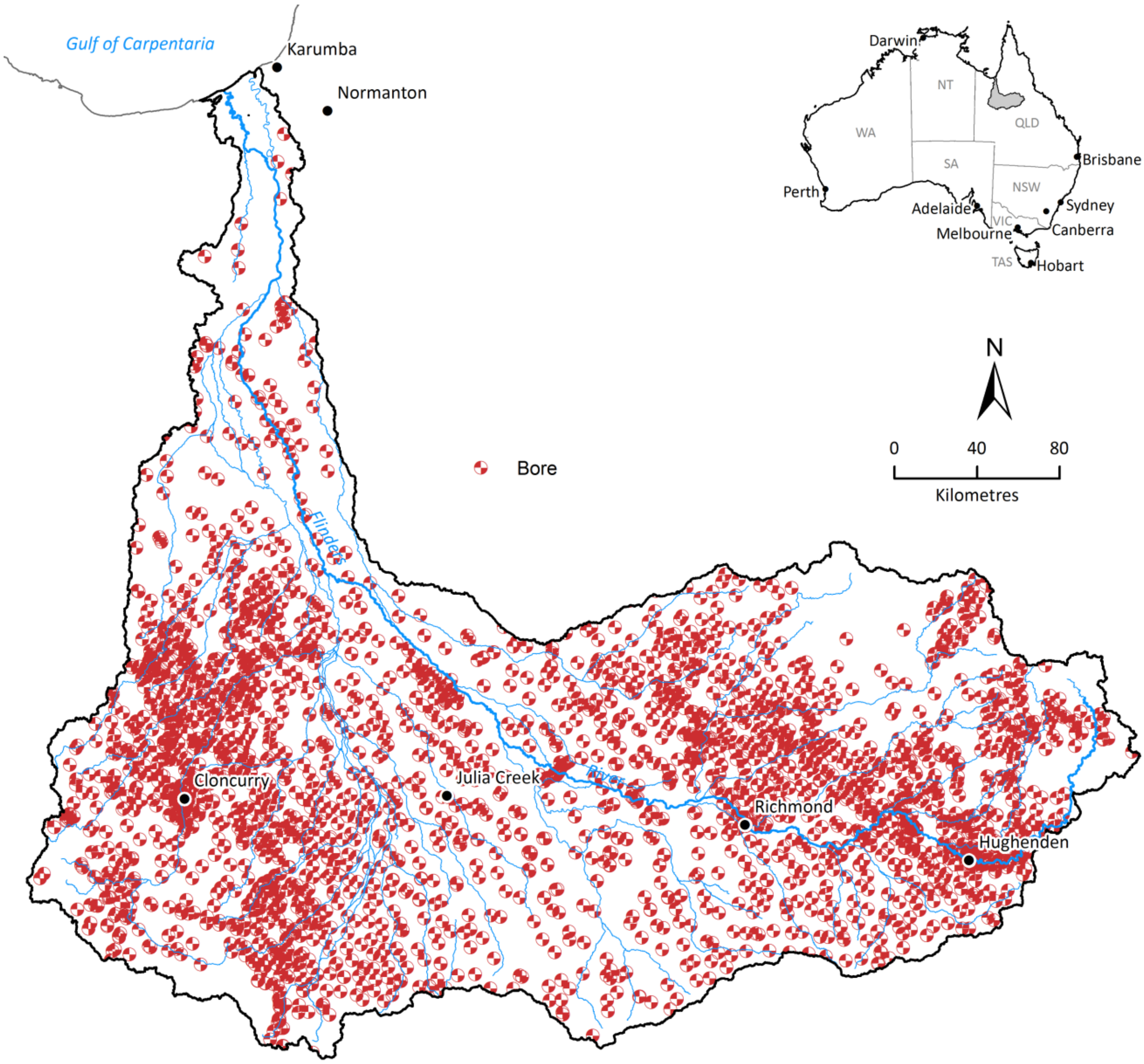

Figure 1.3 Registered bores in the Flinders catchment (data provided by the State of Queensland (Department of Natural Resources and Mines), 2012)

The Gilbert River Formation is the most widespread GAB aquifer in the Flinders catchment and it outcrops in several areas of the eastern margin. The outcrops are where it is recharged (Figure 1.4) and it has been hypothesised that rejected recharge (which occurs where water is restricted from entering the aquifer, primarily due to geology) provides baseflow to the Flinders River, albeit at generally low rates (CSIRO, 2009a). Where it does not outcrop the Gilbert River Formation is confined and often artesian in nature. The Gilbert River Formation is generally overlain by the Rolling Downs Group (Figure 1.5).

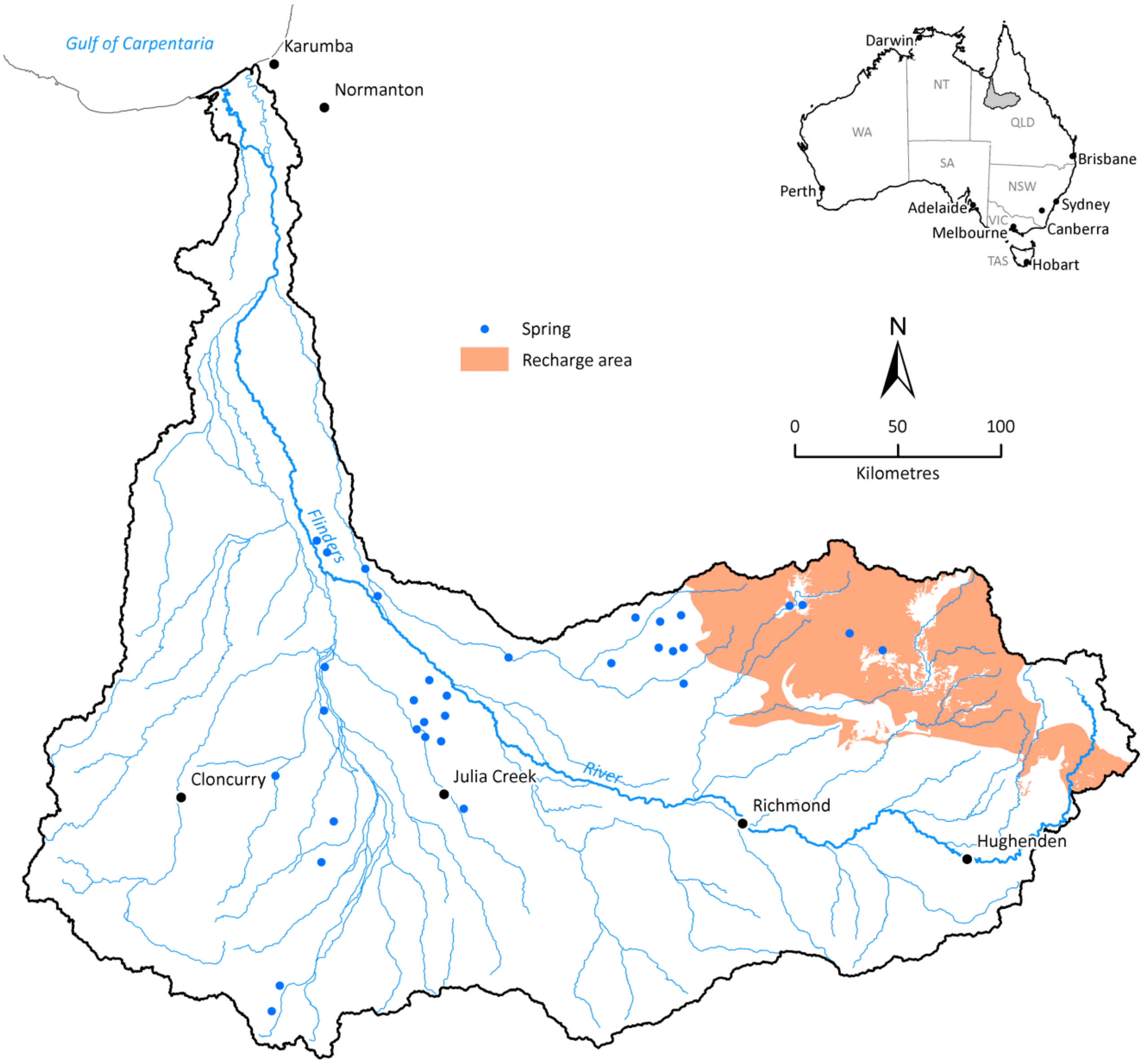

Figure 1.4 Recharge areas and springs of the Great Artesian Basin aquifers in the Flinders catchment (derived from Figure 2.1 in Smerdon et al. (2012b) and Figure 2.1 in Smerdon and Ransley (2012))

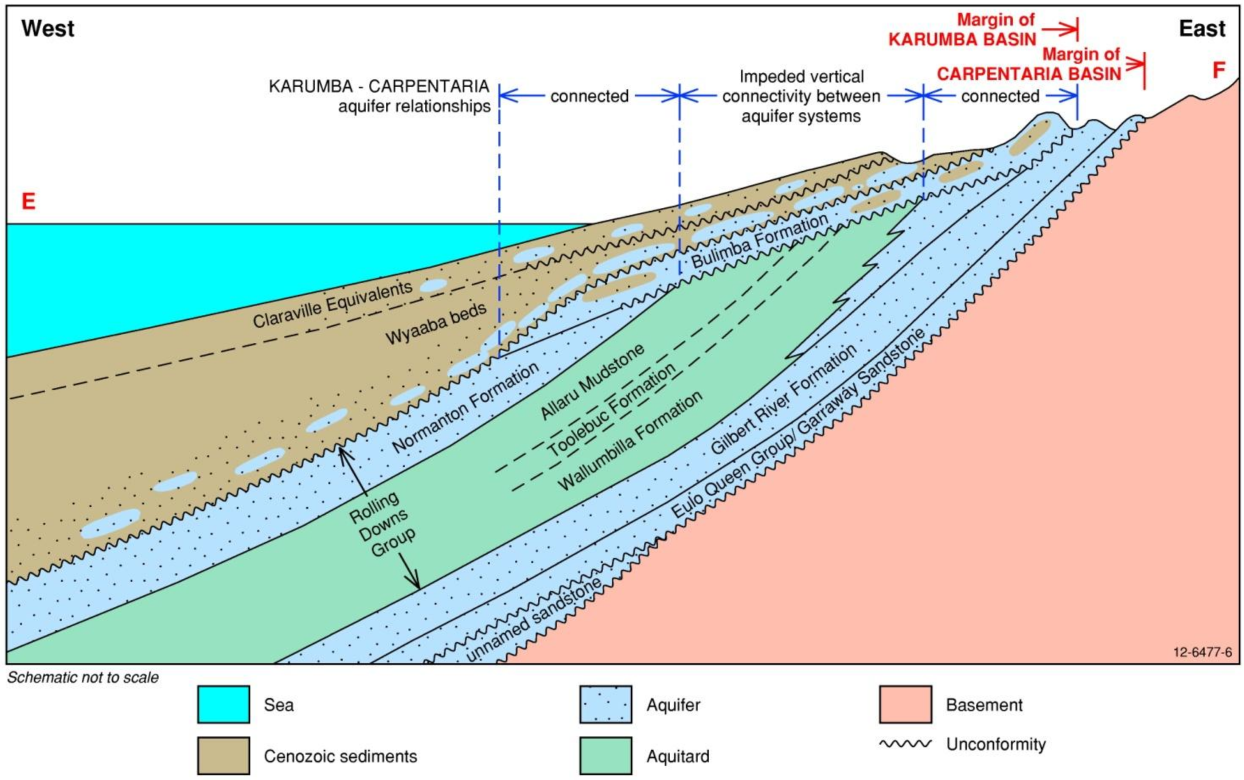

Figure 1.5 Schematic cross section highlighting the connectivity between aquifers of the Carpentaria and Karumba basins of the Great Artesian Basin (Figure 5.14 in Smerdon et al. (2012b))

The shallow alluvial/bedsands aquifers are a relatively undeveloped resource. A broad reconnaissance investigation of the groundwater in the alluvium/bedsands of the Flinders River between Hughenden and Julia Creek was carried out between 1967 and 1971 (Cochrane, 1967; Lloyd, 1970; QIWSC, 1973). From the ~150 investigation bores drilled (Figure 1.6) the mean alluvial/bedsands thickness was found to be 20 m with the saturated thickness ranging from 0 m to 6 m. Water quality was found to be fair with most bores exhibiting a high alkalinity hazard. Total dissolved salts was generally less than 800 mg/L. Bores yields were as high as 25 L/s, but due to the distinct channelling of the system, long-term stability of supply was thought to be doubtful (McEniery, 1980).

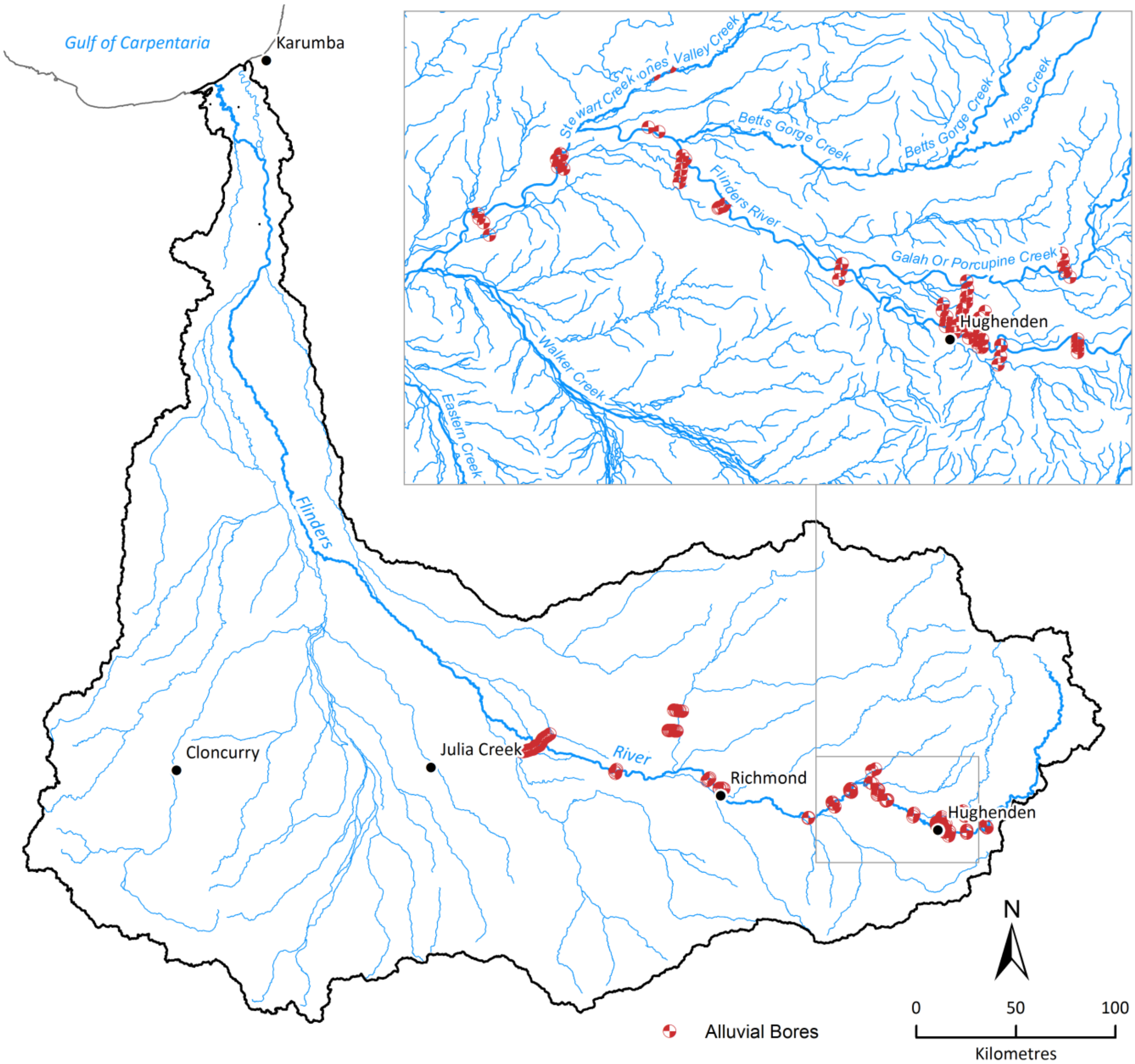

Figure 1.6 Locations of alluvial bores drilled between 1967 and 1971 in the Flinders catchment (data provided by the State of Queensland (Department of Natural Resources and Mines), 2012)

One instance where the shallow alluvial/bedsands aquifers have been utilised as a resource is for the town water supply for Cloncurry. Extraction of groundwater from a well in the alluvium/bedsands commenced in 1921 and was followed by the development of further wells and bores over the next 40 years (Laycock, 1973). A geophysical survey of ~4.8 km of the Cloncurry River valley upstream of Cloncurry was carried out in 1960 using seismic and resistivity methods (Mann and Wiebenga, 1962). The mean thickness of saturated alluvium/bedsands was inferred to be 4.87 m. However the survey also inferred that there were significant variations in the groundwater level in different sections along the valley. These were interpreted to be related to the presence of rock bars across the valley that led to groundwater gradients being greater than the mean downstream from a rock bar, and less than the mean upstream. The rock bars were speculated to act as impermeable barriers to down-river groundwater flow and hence water stored behind these barriers may not be available for downstream replenishment, i.e. the groundwater in the alluvium/bedsands may be isolated in distinct basins within the alluvium/bedsands (Laycock, 1973). Further groundwater investigations in Cloncurry occurred in the late 1980s that were primarily aimed at better defining the extent and nature of the alluvial/bedsands aquifers, determining if there were additional supplies below the existing well field, and obtaining information on groundwater quality (Huxley, 1989). A total of 65 investigation holes were drilled, with 2 completed as production bores and 26 completed as water level observation bores. This study found that there was no significant additional groundwater storage below the level of the existing well field but there may be areas in the old channel where further groundwater development could occur. It also found that while the chemistry of the water in the alluvium/bedsands varied (the laboratory-measured salinity as electrical conductivity, (EC) of the samples collected from 12 of the investigation bores ranged from 0.24 to 2.80 dS/m) it was suitable for most purposes. However, it was recommended that it should not be utilised downstream of the town because of the risk of contamination from the refuse tip and sewage outlet. The annual alluvial/bedsands groundwater yield was estimated to be 840 ML/year at a 10-20% risk of failure, and was not sufficient to meet the town water supply requirements of 1460 ML/year that existed at the time of the study.

Groundwater quality

Figure 1.7 shows groundwater salinity (as EC) for all bores contained in the Queensland Department of Natural Resources and Mines groundwater database that have either/both field or laboratory measured EC values. The bores have measurement dates of between 1900 and 2012 and screen various aquifers. Because most of the bores are screened within the GAB aquifers the map mainly reflects the salinity in those aquifers. A clear pattern is evident, with fresher groundwater (0.00 – 0.75 dS/m) in the east of the catchment, and a progression towards more saline groundwater (0.75 – 5.00 dS/m) to the north-west. However, as was noted in CSIRO (2009a), the trend may in part be due to a shift in which GAB aquifers are tapped by bores. The Gilbert River Formation becomes deeper moving towards the Gulf of Carpentaria and so more bores are likely to be completed in the shallower and more saline aquifers within the Rolling Downs Group.

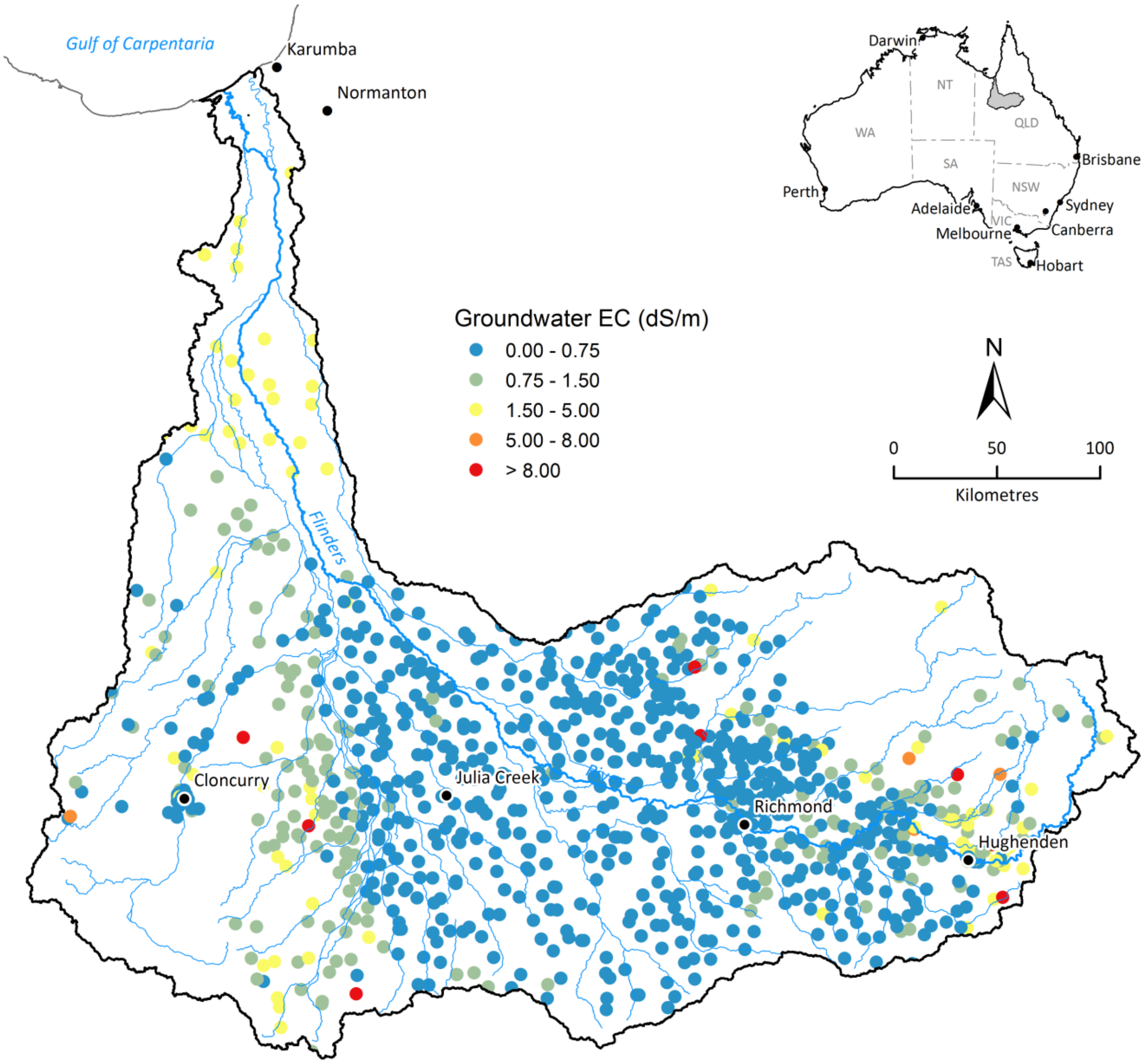

Figure 1.7 Groundwater salinity map of the Flinders catchment (data provided by the State of Queensland (Department of Natural Resources and Mines), 2012)

Groundwater recharge

Recharge is the water that replenishes underlying groundwater systems. Water that infiltrates the soil and passes below the root zone of the vegetation is commonly referred to as root zone drainage or potential recharge (Bond, 1998) and may or may not be equivalent to recharge. When a soil is wetted water flows downwards under the influence of gravity. However, when a soil is very wet water may flow laterally or water may flow upwards (i.e. capillary rise) in response to moisture gradients induced by evaporation and use of soil water by plants.

One of the challenges in quantifying recharge is that it is very difficult to measure. It is also highly variable across space and time and scale dependent. Under rain fed conditions the three factors controlling mean annual recharge across most of Australia are mean annual rainfall, land use and soil type (Petheram et al., 2002). Under irrigation root zone drainage is also heavily influenced by management practises such as method of water application, timing and amount of irrigation.

There are no known measurements of root zone drainage in the Flinders catchment and there are few measurements to parameterise and calibrate complex root zone drainage models (Crosbie et al., 2009). As such it is only possible to provide indicative information on root zone drainage rates under existing conditions in the Flinders catchment.

Figure 1.8 shows a groundwater recharge map derived using a simple regression model that relates root zone drainage to broad soil type, land use and mean annual rainfall (Leaney et al., 2011; best estimate). This map suggests that recharge rates are likely to be very low (< 5 mm/year) across the catchment, with some small areas of higher recharge (5 – 50 mm/year) in the uplands and in the lower reaches of the Flinders River. The range in values in the uplands is consistent with the estimates previously reported by McMahon et al. (2002), Kellett et al. (2003) and Smerdon and Ransley (2012) for the recharge areas of the GAB which are contained within the uplands (Figure 1.4).

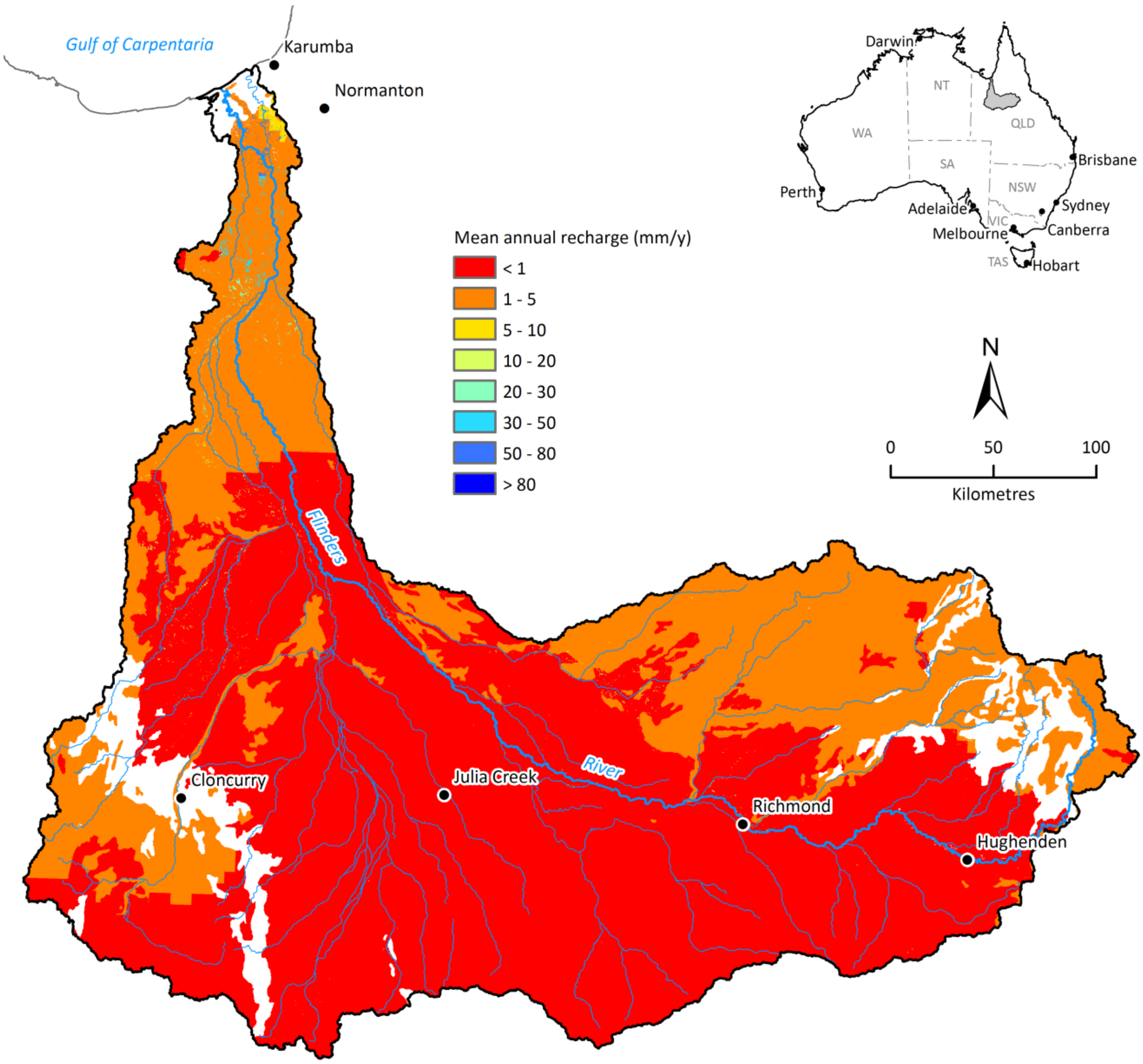

Figure 1.8 Mean annual groundwater recharge map of the Flinders catchment derived using a simple regression model that relates root zone drainage to broad soil type, land use and mean annual rainfall (Leaney et al., 2011; best estimate). The white areas do not have any recharge estimates due to a lack of suitable regressions

It is important to note that the estimates depicted in Figure 1.8 are indicative of diffuse recharge rates across the broad landscape under native vegetation and do not generally apply to areas of localised recharge such as in the alluvium/bedsands of waterholes, streams or rivers or to areas with preferential flow paths such as faults. In theory, based on experience in southern Australia, recharge rates in these localised areas are likely to be higher. However, this theory has not been tested to any great degree in northern Australia.

It is also important to note that the estimates depicted in Figure 1.8 may not generally apply to irrigation areas as application of irrigation in excess of crop water requirements leads to enhanced rates of root zone drainage and recharge.

Surface water – groundwater interactions

Prior to this Assessment there was very little existing knowledge of groundwater-surface water interactions in the Flinders catchment; what is known was reported in CSIRO (2009a). The conceptual model proposed in CSIRO (2009a) was that during the wet season water infiltrates from the river into the alluvial/bedsands aquifer (either by lateral or overbank flooding processes) and after cessation of the wet season the groundwater discharges from the alluvial/bedsands aquifer back into the river as baseflow until the groundwater level falls below the river bed. CSIRO (2009a) analysed gauged streamflow data and concluded that dry season baseflow is low in the Flinders catchment compared with other catchment in the Gulf of Carpentaria region. They found that the highest dry season baseflow occurs in the lower reaches of the Flinders River (see Figure FL-2 in CSIRO (2009a)).

CSIRO (2009a) also proposed a conceptual model in which groundwater discharges from the GAB aquifers occurs where the streams are incised into outcropping sandstones (generally where streams such as the Flinders River, Woolgar River, Hampstead Creek and Porcupine Creek intersect the Gilbert River formation) and the watertable is higher than the stream water level. CSIRO (2009a) presented a map of the locations of GAB spring groups and potential river baseflow locations (Figure 1.9) based on information in AGE (2005) and DNRM (2005). CSIRO (2009a) also speculated that there was potential for the Sturgeon Basalt to provide baseflow to tributaries such as Porcupine Creek. Note that the more recent studies of Smerdon et al. (2012b) and Smerdon and Ransley (2012) provide updated locations for GAB recharge beds and springs in the catchment (see Figure 1.4).

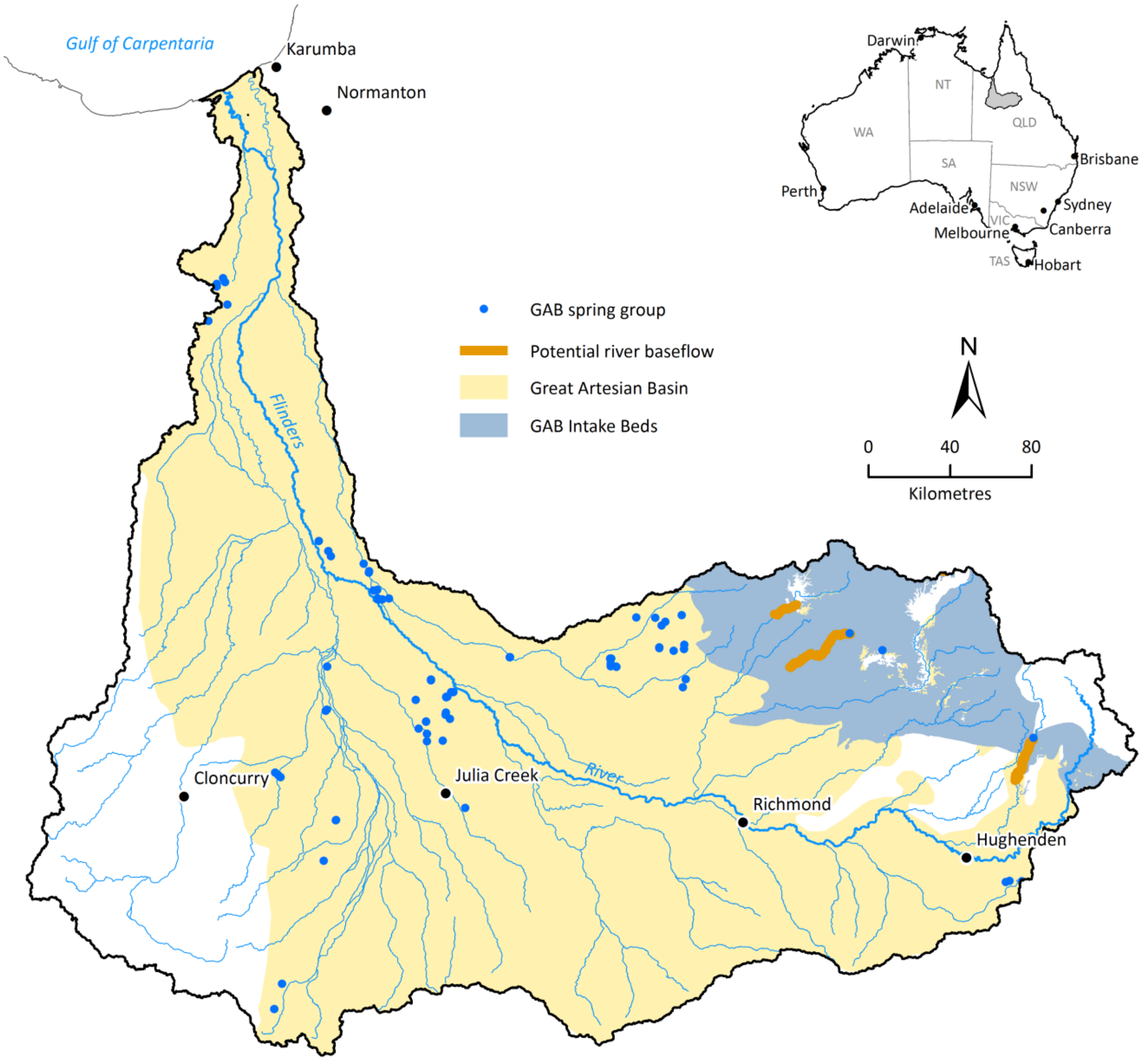

Figure 1.9 Locations of spring groups of the Great Artesian Basin and potential river baseflow in the Flinders catchment (derived from CSIRO (2009a) who derived it from DNRM (2005))

1.2.2 GILBERT CATCHMENT

Geology

The Gilbert River flows in a north-westerly direction from the Great Dividing Range, 150 km south-east of Georgetown, and is joined by its major tributary, the Einasleigh River, downstream of Strathmore, before finally entering the Gulf of Carpentaria in a river delta 100 km wide. The other main tributary, the Etheridge River, joins the Einasleigh River downstream of Georgetown (CSIRO, 2009b). The surface geology of the uplands in the south-east of the catchment is highly complex and dominated by an array of igneous and metamorphic formations of various ages, interspersed with sedimentary deposits and alluvial regolith along the channels of the major rivers and tributary streams (Twidale, 1966). The surface geology of the lowlands in the north-west of the catchment is dominated by alluvial regolith of Quaternary age (Nanson, 1991) with some coastal deposits (Warner, 1968). A simplified map of the geology of the Gilbert catchment is shown in Figure 1.10.

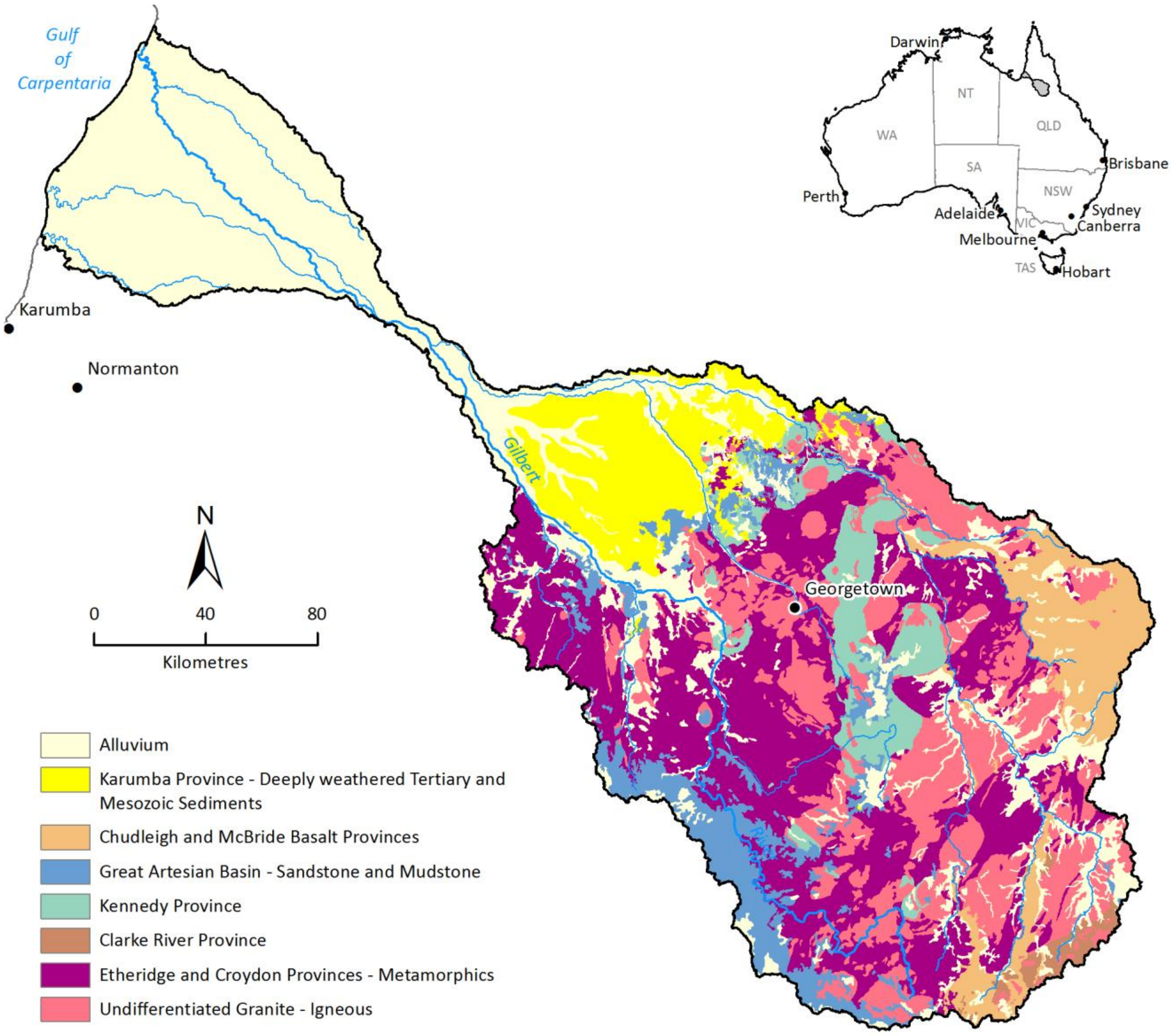

Figure 1.10 Simplified geology map of the Gilbert catchment

Hydrogeology and groundwater use

The major aquifers of the Flinders catchment are shown in Figure 1.11. According to the Queensland Department of Natural Resources and Mines groundwater database (accessed July, 2012), there are more than 400 registered groundwater bores in the Gilbert catchment (Figure 1.12). Groundwater is contained within the Jurassic-Cretaceous age GAB aquifers, in the outcropping Palaeozoic and Precambrian age fractured rocks, and in the Cainozoic age sediments that are comprised of the Tertiary age fluvial and marine deposits and the Quaternary age alluvium of the past and present rivers in the catchment (Figure 1.11). Very few of the bores in the Gilbert catchment are being regularly monitored for either water level or water quality.

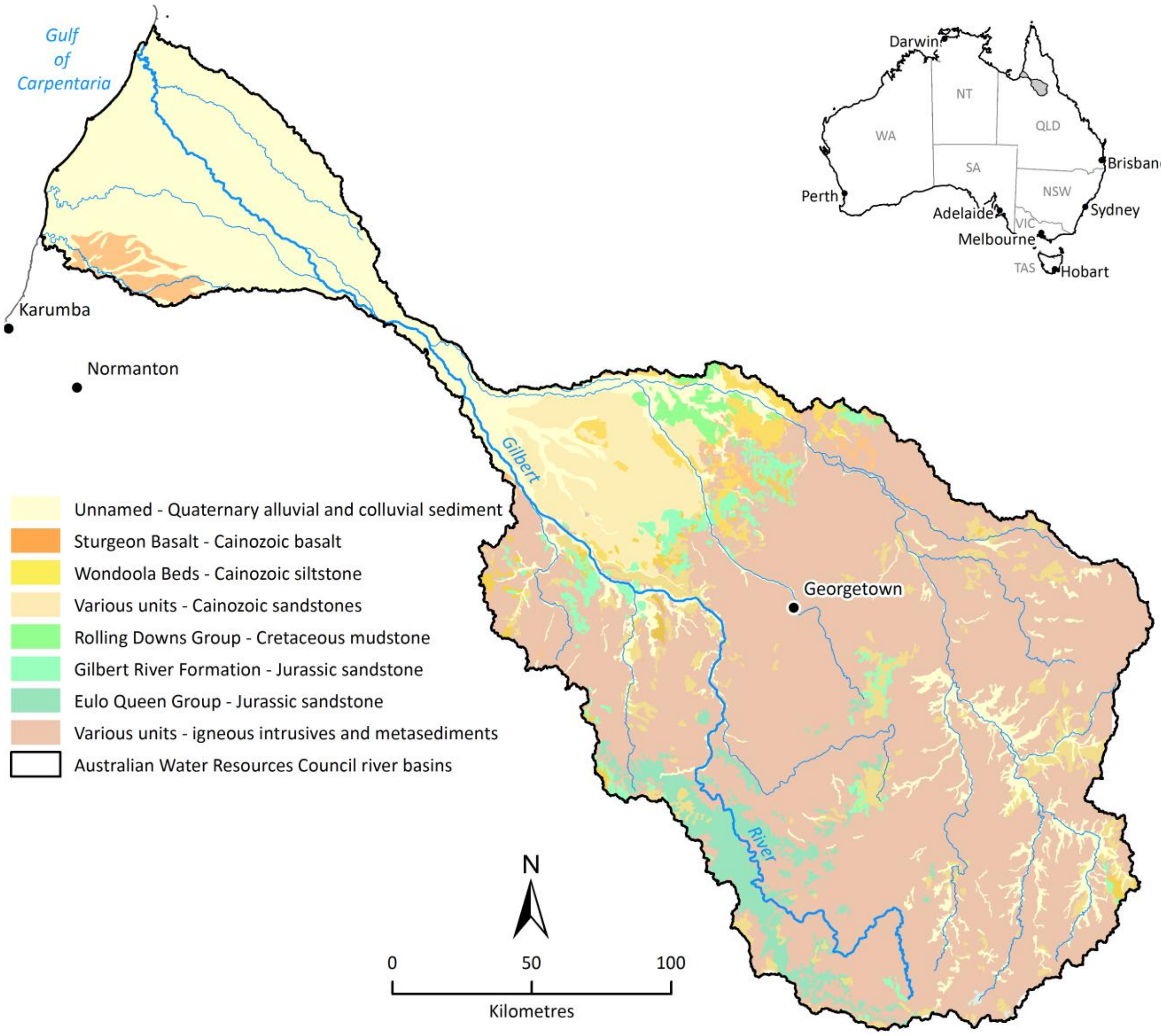

Figure 1.11 Major aquifers map of the Gilbert catchment (adapted from Figure SE-2 in CSIRO (2009b))

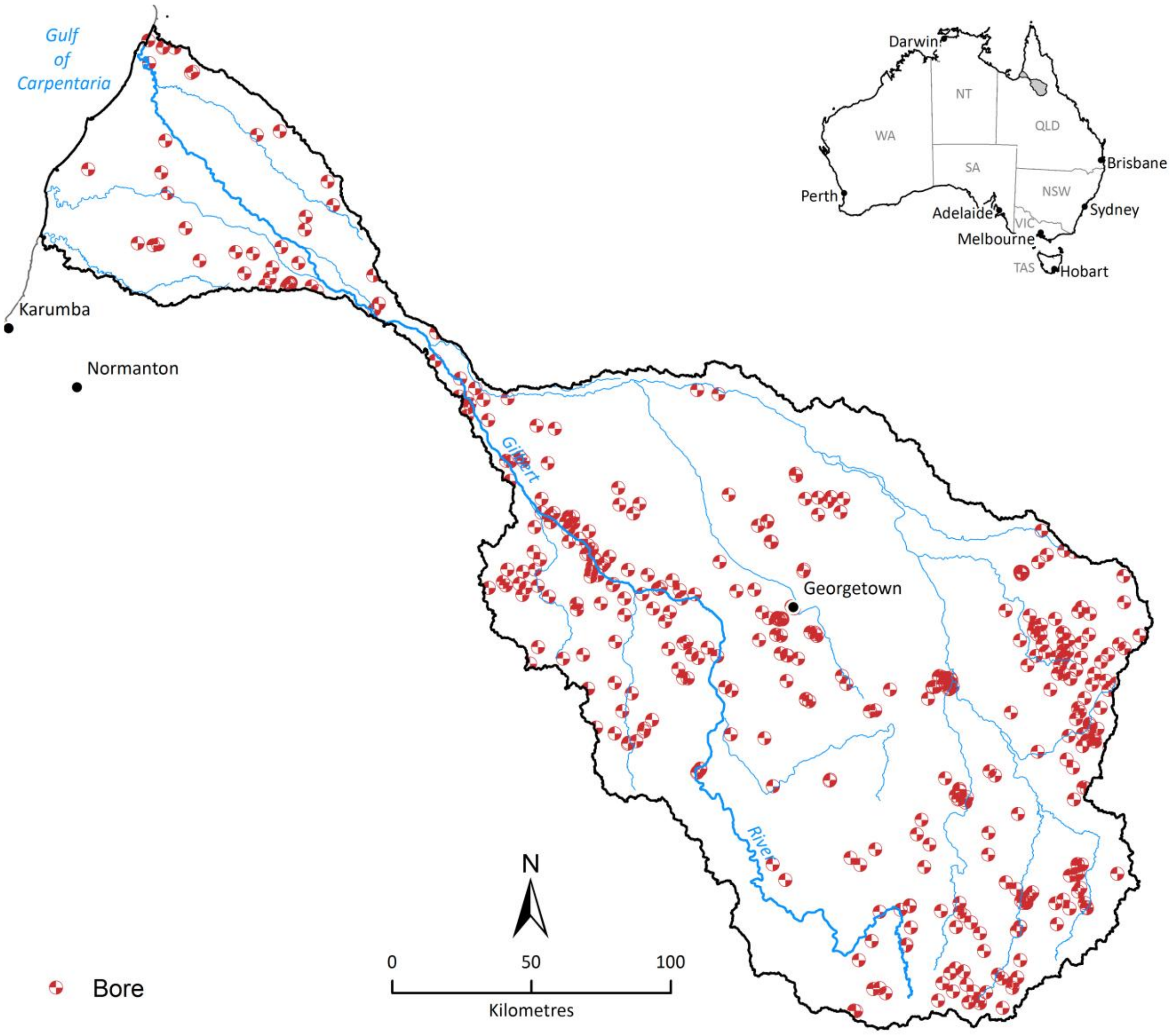

Figure 1.12 Registered bores in the Gilbert catchment (data provided by the State of Queensland (Department of Natural Resources and Mines), 2012)

The GAB aquifers in the Gilbert catchment are comprised of the outcrops of the Eulo Queen Group and Gilbert River Formation which are generally overlain by the Rolling Downs Group (Figure 1.5). It has been hypothesised that these aquifers provide baseflow to many of the rivers, albeit at generally low rates (CSIRO, 2009b). Figure 1.13 shows the locations of the recharge areas and springs of the GAB in the Gilbert catchment.

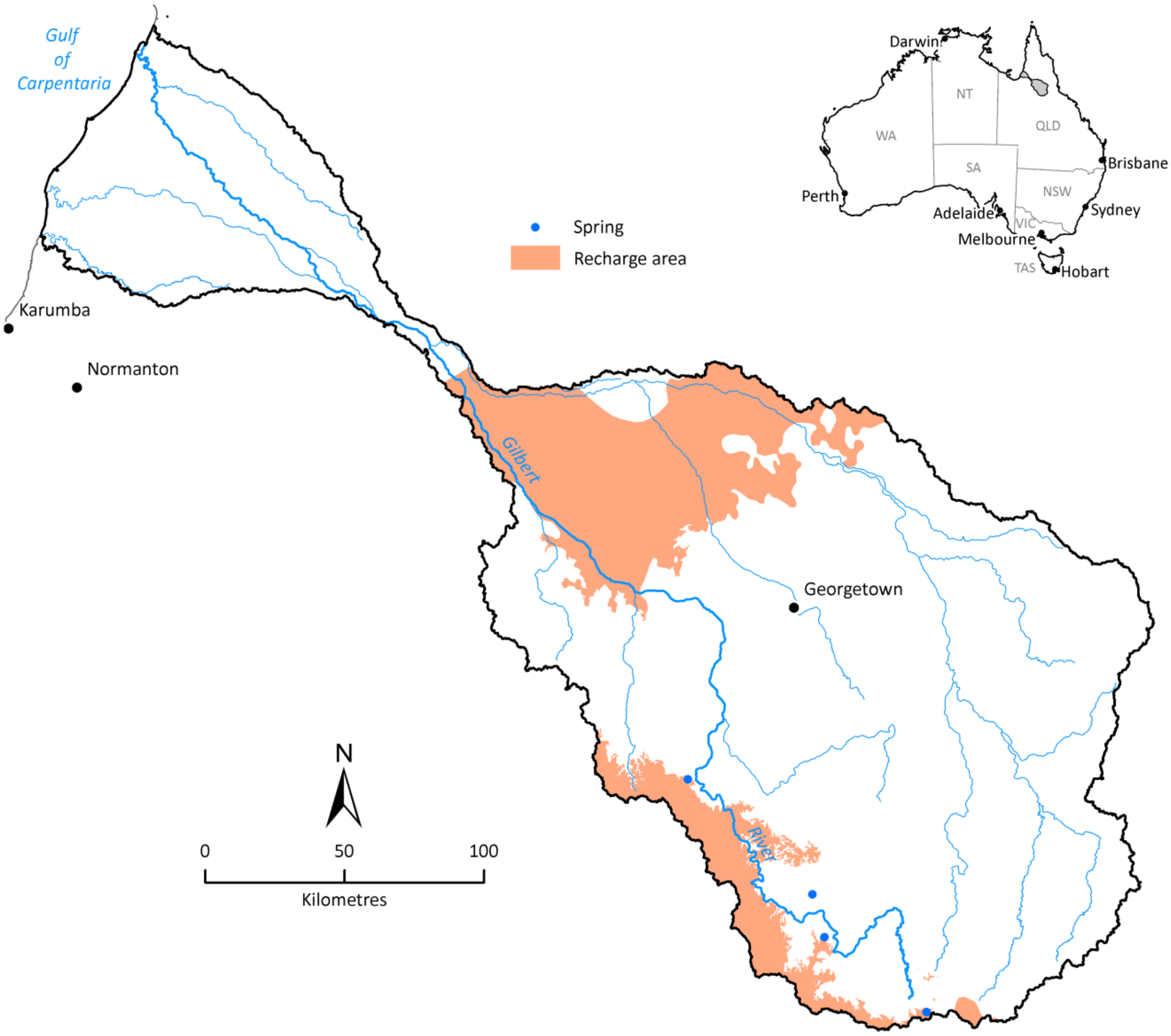

Figure 1.13 Recharge areas and springs of the Great Artesian Basin aquifers in the Gilbert catchment (derived from Figure 2.1 in Smerdon et al. (2012b) and Figure 2.1 in Smerdon and Ransley (2012))

There has been some development of the shallow alluvial/bedsands aquifers of the Gilbert River as a resource. A drilling program to explore the extent and characteristics of the alluvial/bedsands aquifer of the Gilbert River near the Gilbert River irrigation area (~ 60km west of Georgetown) was carried out 1998 (QDNR, 1998). Eight lines of bores holes (87 holes in total) were drilled in the bed of the river to determine the depth of clean sand and gravel aquifer material. At five of the sites observation bores were installed to allow watertable monitoring. It was determined that that the total saturated volume of the aquifer was between 16,980 ML and 20,370 ML. However, it was concluded that these may be conservative estimates as the drilling did not extend beyond the river bed and there was a possibility that the aquifer may extend beneath the river levees and the adjacent floodplain. In subsequent work (AGE, 1999) estimated from particle size distributions of aquifer samples that the permeability of the aquifer ranged from 10 m/day to 690 m/day. A 48 hour constant discharge pumping test carried out on a 8.65 m radius pumping hole constructed just upstream of the Georgetown-Croydon Road bridge. It was determined from the pumping test that the aquifer at this site had a vertical transmissivity, horizontal transmissivity and specific yield of 237 m^2/day, 4743 m^2/day and 0.168 respectively.

The study of PPK (1999) drilled 6 observation bores ranging in depth from 28 to 34 m in the Jurassic-Cretaceous age Gilbert River Formation sediments of the GAB that outcrop adjacent to the Gilbert River alluvium/bedsands near the Gilbert River irrigation area, and sampled them for major ions. The water levels in these observation bores ranged from being dry to 20.10 m below ground. The laboratory-measured EC of the samples collected from these observation bores ranged from 0.23 to 1.50 dS/m. The study also located 20 existing bores in the same area and measured the water level and sampled those that contained water for major ions. The water levels in these bores ranged from 4.25 m and 27.15 m below ground. The laboratory-measured EC of the samples collected from these bores ranged from 0.04 to 0.69 dS/m. The study concluded that these aquifers are low in hydraulic continuity and hence low yielding, are unconfined and in connection with the Gilbert River which acts as a sink for local groundwater flow, and that groundwater generally flows towards the northwest with a low gradient (0.001) similar to that of the Gilbert River. It was also concluded that the EC of the groundwater generally conformed to the guideline value for drinking water (0.80 dS/m) and for most of the bores only marginally exceeded the guideline value (0.65 dS/m) for irrigation of all crops.

The PPK (1999) study also drilled 8 observation bores ranging in depth from 10 to 34 m in the Einasleigh Metamorphics and/or McBride Basalt in an area known locally as the Einasleigh Common, west of Einasleigh. The water levels in these observation bores ranged from 9.48 to 21.15 m below ground. The field-measured EC of the samples collected from these observation bores ranged from 1.10 to 17.45 dS/m. The study also located 7 existing bores in the same area and measured the water level and sampled them for major ions. The water levels in these bores ranged from 7.90 m and 21.50 m below ground. The laboratory-measured EC of the samples collected from these bores ranged from 0.57 to 5.69 dS/m. The study concluded that the groundwater in the west of the investigation area generally flows to the north – north-east with a low gradient (0.002), that a groundwater divide (due to a basement ridge) exists beneath the longitudinal axis of the township which precludes direct groundwater flow to the Copperfield River, and that the generally low potentiometric gradients lead to only slow movement of groundwater. It was also concluded that the EC of the groundwater generally exceeded the guideline value for drinking water (0.80 dS/m) and for the majority of the bores the groundwater was unsuitable for irrigation.

Groundwater quality

Figure 1.14 shows groundwater salinity (as electrical conductivity, EC) for all bores contained in the Queensland Department of Natural Resources and Mines groundwater database that have either/both field or laboratory measured EC values. The bores have measurement dates of between 1966 and 1999 and screen various aquifers, and so the salinity map represents groundwater from different aquifers. However, a pattern appears evident, with fresher groundwater (0 – 1.50 dS/m) in the central and southern part of the catchment in the Gilbert River alluvium/bedsands and in the GAB recharge beds, and more saline groundwater (> 5.00 dS/m) in the regolith and coastal aquifers in the north-west of the catchment and in the Einasleigh Metamorphics and McBride Basalt west of Einasleigh.

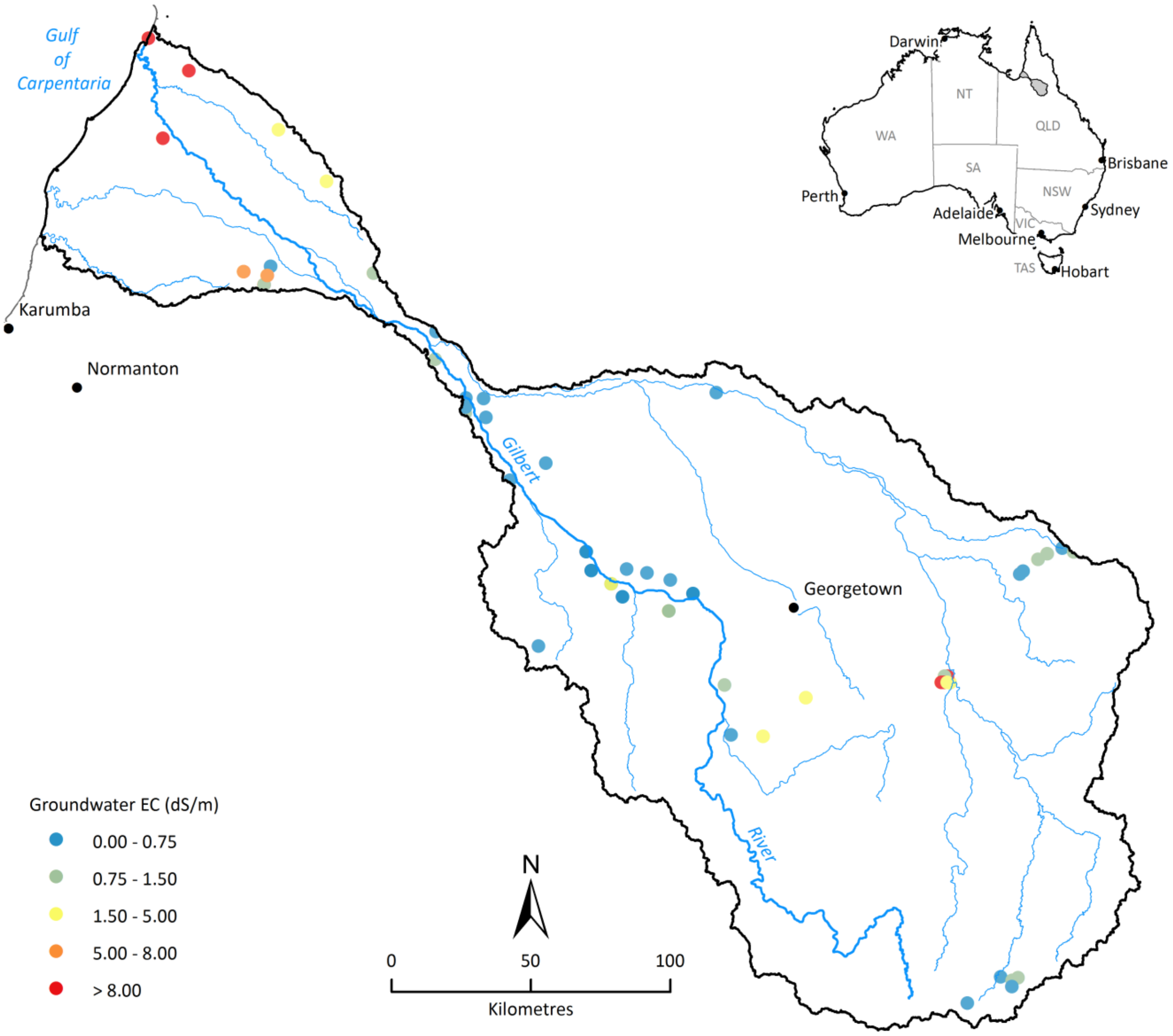

Figure 1.14 Groundwater salinity map of the Gilbert catchment (data provided by the State of Queensland (Department of Natural Resources and Mines), 2012)

Groundwater recharge

There are no known measurements of root zone drainage in the Gilbert catchment and there are few measurements to parameterise and calibrate complex root zone drainage models (Crosbie et al., 2009). As such it is only possible to provide indicative information on root zone drainage rates under existing conditions in the Gilbert catchment.

Figure 1.15 shows a groundwater recharge map derived using a simple regression model that relates root zone drainage to broad soil type, land use and mean annual rainfall (Leaney et al., 2011; best estimate). This map suggests that recharge rates are likely to be very low (<5 mm/year) across the catchment, with some areas of higher recharge (5 – 80 mm/year) beneath the coastal deposits of the lower reaches of the Gilbert River, and in the recharge areas of the GAB (Figure 1.13). The range in values in the GAB recharge areas (5 – 40 mm/year) is consistent with the estimates previously reported by Kellett et al. (2003) and Smerdon and Ransley (2012).

It is important to note that the estimates depicted in Figure 1.15 are indicative of diffuse recharge rates across the broad landscape under native vegetation and do not generally apply to areas of localised recharge such as in the alluvium/bedsands of waterholes, streams or rivers or to areas with preferential flow paths such as faults. In these localised areas recharge rates are likely to be higher. They also do not generally apply to irrigation areas as application of irrigation in excess of crop water requirements leads to enhanced rates of root zone drainage and recharge.

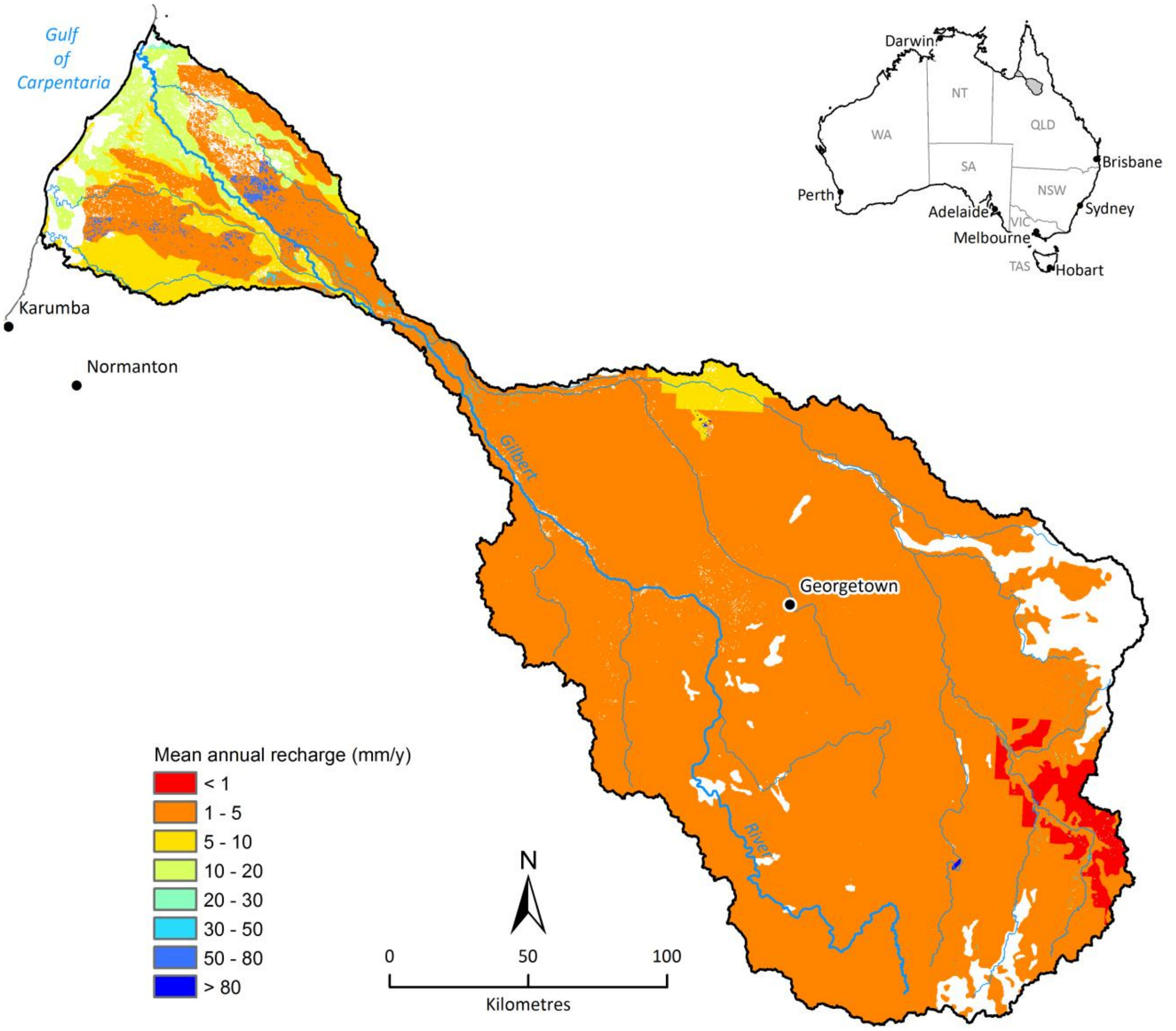

Figure 1.15 Mean annual groundwater recharge map of the Gilbert catchment derived using a simple regression model that relates root zone drainage to broad soil type, land use and mean annual rainfall (Leaney et al., 2011; best estimate). The white areas do not have any recharge estimates due to a lack of suitable regressions

Surface water – groundwater interactions

Prior to this Assessment there was also very little existing knowledge of groundwater-surface water interactions in the Gilbert catchment; what is known was reported in CSIRO (2009b). The conceptual model proposed in CSIRO (2009b) was that that during the wet season water infiltrates from the river into the surficial aquifers (either by lateral or overbank flooding processes) and after cessation of the wet season the groundwater discharges from the surficial aquifers back into the river as baseflow. CSIRO (2009b) analysed gauged streamflow data and found that dry season baseflow was highest in the Copperfield River (which could in part be due to releases from Kidston Dam (officially known as Copperfield Gorge River Dam)), Einasleigh River and Elizabeth Creek sub-catchments (see Figure SE-2 in CSIRO (2009b)).

CSIRO (2009a) also proposed a conceptual model in which spring discharge occurs in the outcrop areas of the Gilbert River Formation and Eulo Queen aquifers due to rejected recharge that occurs where water is restricted from entering the aquifer, primarily due to geology. They speculated that where streams intersect these aquifers, they receive baseflow for much of the dry season. CSIRO (2009b) presented a map of the locations of a GAB spring group and potential river baseflow locations (Figure 1.16) based on information in DNRM (2005). Note that the more recent studies of Smerdon et al. (2012b) and Smerdon and Ransley (2012) provide updated locations for GAB recharge beds and springs in the catchment (see Figure 1.13).

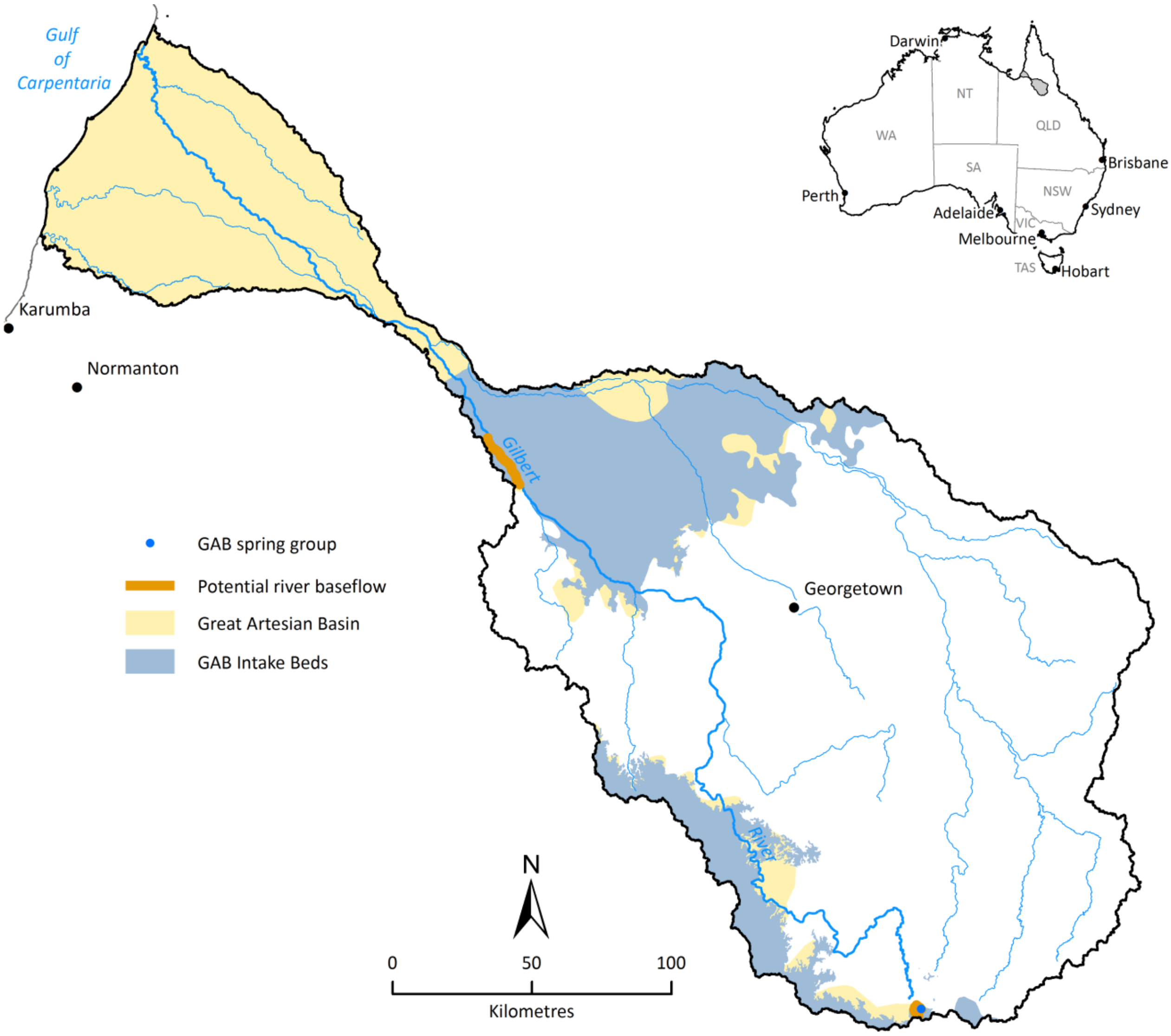

Figure 1.16 Locations of spring groups of the Great Artesian Basin and potential river baseflow in the Gilbert catchment (derived from CSIRO (2009a) who derived it from DNRM (2005))

2 Methods

2.1 Task 1 - Hydrogeological controls on dry-season flows and waterhole persistence

Task 1 involved an assessment of whether the persistence of permanent instream and offstream waterholes through the dry season was likely to be due (at least in part) to natural groundwater inflows. It was focussed on a selection of river and waterhole sites in both the Flinders and Gilbert catchments. The purpose of this task was to inform water resource planners and managers about the potential impact of current and future groundwater and surface water development on the hydrology and associated ecosystem health of permanent waterholes.

The naturally occurring radioactive gas radon-222 (^{222}Rn) was used in this task. The concentration of ^{222}Rn in groundwater increases due to the decay of uranium and radium in aquifer materials, and rapidly decreases where it equilibrates with the atmosphere. These characteristics allow ^{222}Rn to be a useful tracer for identifying groundwater discharge to surface water (e.g. Ellins et al., 1990; Cook et al., 2003a; Gardner et al., 2011; Smerdon et al., 2012a). Analyses of major ions and the stable isotopes of water (^{2}H and ^{18}O) were also used to aid in the assessment of the likelihood of groundwater presence in the rivers and waterholes.

2.1.1 SAMPLING SITES

Sampling of rivers and waterholes took place at a number of locations and times during the 2012 dry season in both the Flinders and Gilbert catchments. The river sites were sampled during an initial reconnaissance visit to the catchment and were generally targeted at reaches near existing or possible future irrigation areas. The waterhole sites were selected by the Aquatic and riparian ecology activity. They were targeted to be well spread across the Assessment area, with a specific requirement that they were located in the lower reaches of each catchment, as these waterholes represented the accumulative effect of upper catchment land use activities, and were therefore under the greatest influence of upper catchment activities (Waltham et al., 2013).

Flinders catchment

In the Flinders catchment, the Flinders River between Hughenden and Maxwelton (Hulberts Crossing) and the Stawell River at Cambridge Crossing (~20 km upstream of the confluence of the Stawell and Flinders Rivers) were sampled at six sites in May 2012. The sampling locations are shown in Table 2.1 and Figure 2.1.

A selection of instream and offstream waterholes along the Flinders River, Cloncurry River and Julia Creek were sampled between August 2012 and December 2012 by the aquatic and riparian ecology activity as part of their field campaign. Nine waterholes were sampled only once, while the remaining eight waterholes were sampled multiple times. The sampling locations are shown in Table 2.2 and Figure 2.1.

Table 2.1 River sites in the Flinders catchment that were sampled in May 2012

SITE NUMBER	SUB-CATCHMENT	STREAM	SITE NAME	DATE SAMPLED	LATITUDE (degrees)	LONGITUDE (degrees)
1	Flinders	Flinders River	Flinders River@Low level Crossing ~5 km upstream of Richmond	15/05/12	-20.743188	143.158920
2	Flinders	Flinders River	Flinders River@Ford ~40 km upstream of Richmond	15/05/12	-20.785000	143.439000
3	Flinders	Flinders River	Flinders River@Bridge in Hughenden	14/05/12	-20.840018	144.201443
4	Flinders	Flinders River	Flinders River@Alderly Crossing	15/05/12	-20.652906	143.890064
5	Flinders	Flinders River	Flinders River@Hulberts Crossing	15/05/12	-20.641479	142.628549
6	Stawell	Stawell River	Stawell River@Cambridge Crossing	15/05/12	-20.426371	142.922502

Table 2.2 Waterhole sites in the Flinders catchment that were sampled between August and December 2012

SITE NUMBER	SUB-CATCHMENT	STREAM	SITE NAME	DATE SAMPLED	LATITUDE (degrees)	LONGITUDE (degrees)
1	Flinders	Flinders River	Wondoola	06/08/12	-19.034983	140.840451
2	Flinders	Flinders River	Etta Plains Station	10/08/12	-19.735189	141.256112
3	Flinders	Flinders River	River Dale Station	11/08/12	-20.429267	142.044350
4	Flinders	Flinders River	Tentative pool 11	12/08/12	-20.742632	143.160910
5	Flinders	Flinders River	Harrogate Station	12/08/12	-20.641434	142.729511
6	Cloncurry	Cloncurry River	Cowan Downs Station	06/08/12	-18.987694	140.599778
7	Cloncurry	Off channel waterhole	Cowan Downs Station - Off channel waterhole	06/08/12	-18.974056	140.573750
8	Cloncurry	Cloncurry River	Causeway - township	07/08/12	-20.702842	140.491938
9	Cloncurry	Cloncurry River	Fort Constantine Station	08/08/12	-20.475223	140.608428
10	Flinders	Fairlight Creek	F1 - Soda Valley/Glendalough Station	13/08/12, 29/10/12, 12/12/12	-20.655902	143.894474
11	Flinders	Flinders River	F2 - River Dale Station	13/08/12, 03/11/12	-20.794137	143.444195
12	Flinders	Off channel waterhole	F3 - River Dale Station	03/11/12, 08/12/12	-20.808395	143.438154
13	Flinders	Off channel waterhole	F4 - River Dale Station	28/10/12, 08/12/12	-20.798578	143.437209
14	Flinders	Flinders River	F5 - Richmond Shire Council	04/11/12, 09/12/12	-20.663267	142.797968
15	Flinders	Flinders River	F7 - Millungera Station	25/10/12, 10/12/12	-19.973491	141.521455
16	Cloncurry	Julia Creek	F8 - Dalgonally Station	10/08/12, 25/10/12, 11/12/12	-20.134517	141.348033
17	Flinders	Cloncurry River	F9 - Dalgonally Station	08/08/12, 26/10/12, 10/12/12	-20.045600	141.088433

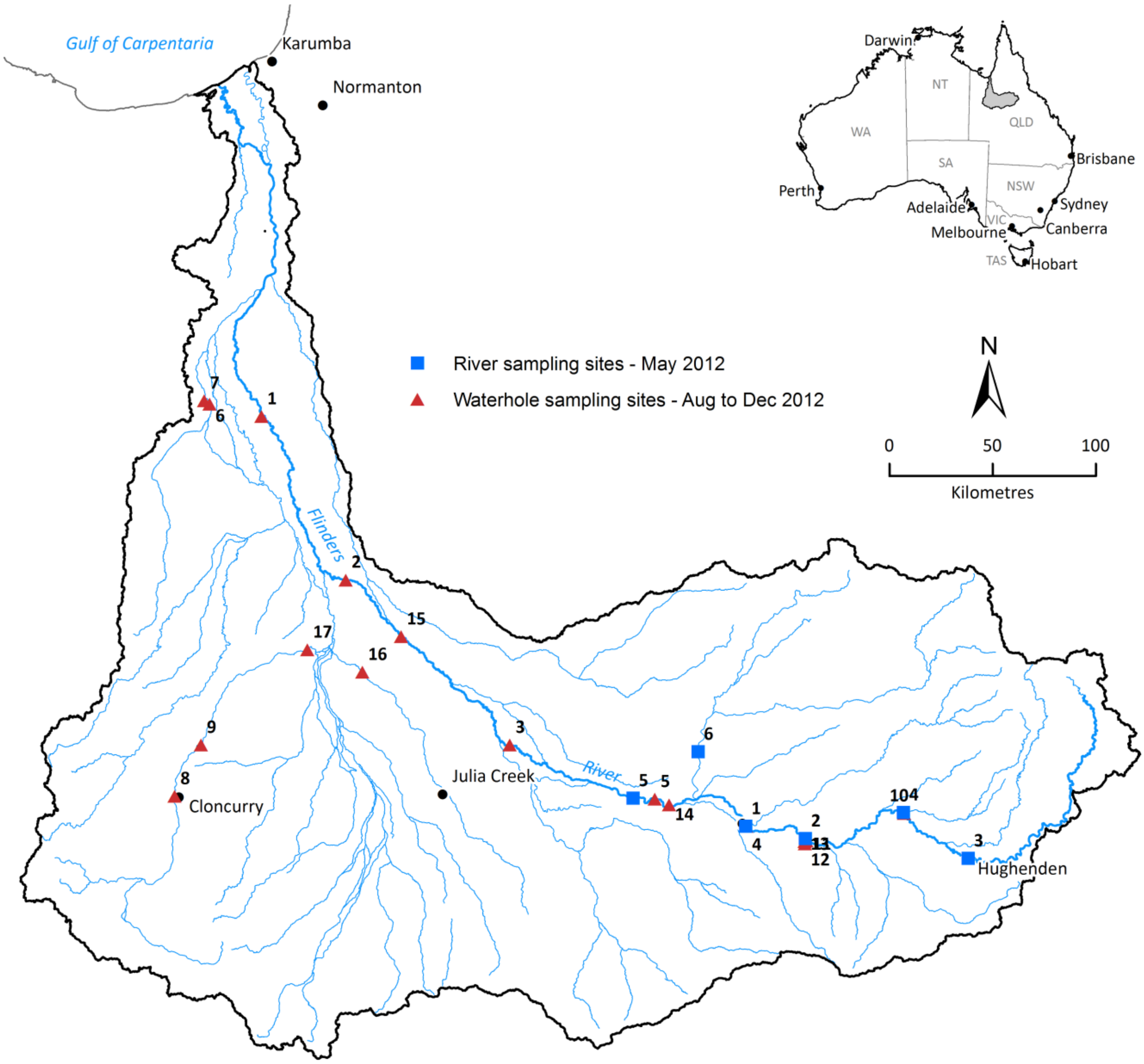

Figure 2.1 Locations of river and waterhole sampling sites in the Flinders catchment. Details for each site are in Table 2.1 and Table 2.2

Gilbert catchment

In the Gilbert catchment, the Einasleigh River, Gilbert River and Routh Creek were sampled at five sites in May 2012. The sampling locations are shown in Table 2.3 and Figure 2.2.

A selection of instream waterholes along the Gilbert River, Einasleigh River and several of the tributaries of the Einasleigh River were sampled between August 2012 and December 2012 by the aquatic and riparian ecology activity as part of their field campaign. Nine waterholes were sampled only once, while the remaining ten waterholes were sampled multiple times in that period. The sampling locations are shown in Table 2.4 and Figure 2.2.

Table 2.3 River sites in the Gilbert catchment that were sampled in May 2012

SITE NUMBER	SUB-CATCHMENT	STREAM	SITE NAME	DATE SAMPLED	LATITUDE (degrees)	LONGITUDE (degrees)
1	Gilbert	Gilbert River	Gilbert River@Bridge on Georgetown to Croydon Road	16/05/12	-18.199078	142.873533
2	Einasleigh	Routh Creek	Routh Creek@Bridge Crossing	16/05/12	-18.289169	143.714492
3	Einasleigh	Einasleigh River	Einasleigh River@Highway Bridge between Georgetown and Mt Surprise	16/05/12	-18.186322	144.007833
4	Einasleigh	Einasleigh River	Einasleigh River@Highway Bridge between Einasleigh and The Lynd Junction	17/05/12	-18.728004	143.890064
5	Einasleigh	Einasleigh River	Einasleigh River@Crossing near Einasleigh	16/05/12	-18.514777	144.111912

Table 2.4 Waterhole sites in the Gilbert catchment that were sampled between August and December 2012

SITE NUMBER	SUB-CATCHMENT	STREAM	SITE NAME	DATE SAMPLED	LATITUDE (degrees)	LONGITUDE (degrees)
1	Einasleigh	Ellendale Creek	Lynd	02/08/12	-18.409194	144.102389
2	Einasleigh	Einasleigh River	Mt Surprise	03/08/12	-18.099476	143.946431
3	Einasleigh	Bundock Creek	G1 - Lyndhurst	15/10/12, 01/12/12	-19.172855	144.441439
4	Einasleigh	McKinnons Creek	G2 - Lyndhurst	15/10/12, 01/12/12	-18.947426	144.495038
5	Einasleigh	Einasleigh River	G3 - Mt Alder Station	15/10/12, 28/11/12	-18.258821	144.061562
6	Einasleigh	Einasleigh River	G4 - Mt Surprise	15/10/12, 29/11/12	-18.221634	144.036359
7	Einasleigh	Einasleigh River	G5 - Mt Surprise	15/10/12, 28/11/12	-18.192245	144.014344
8	Einasleigh	Elizabeth Creek	G6 - Mt Surprise	02/08/12, 15/10/12, 27/11/12	-18.123503	144.291344
9	Einasleigh	Junction Creek	G7 - Mt Surprise	15/10/12, 27/11/12	-18.177855	144.241338
10	Gilbert	Porcupine Creek	G8 - Langlovale Station	15/10/12, 30/11/12	-18.271145	143.00307
11	Gilbert	Pleasant Creek	G9 - Lake Carlo Station	14/10/12, 30/11/12	-18.110617	142.796533
12	Gilbert	Gilbert River	G10 - Strathmore Station	05/08/12, 15/10/12, 30/11/12	-17.865759	142.553686
13	Einasleigh	Einasleigh River	A - main channel (shallow) east	02/11/12	-18.606507	144.189160
14	Einasleigh	Einasleigh River	B - anabranch (deep) east	02/11/12	-18.598061	144.192820
15	Einasleigh	Einasleigh River	C - anabranch (deep) east	02/11/12	-18.593372	144.189274
16	Einasleigh	Einasleigh River	D - main channel (30m up of Rd Xing, deep) east	02/11/12	-18.728646	144.313007
17	Einasleigh	Einasleigh River	E - anabranch (shallow between waterholes) west	02/11/12	-18.716949	144.314591
18	Einasleigh	Einasleigh River	Downstream Mount Noble	14/12/12	-17.983337	143.899555
19	Einasleigh	Einasleigh River	Dagworth	14/12/12	-17.719081	143.558101

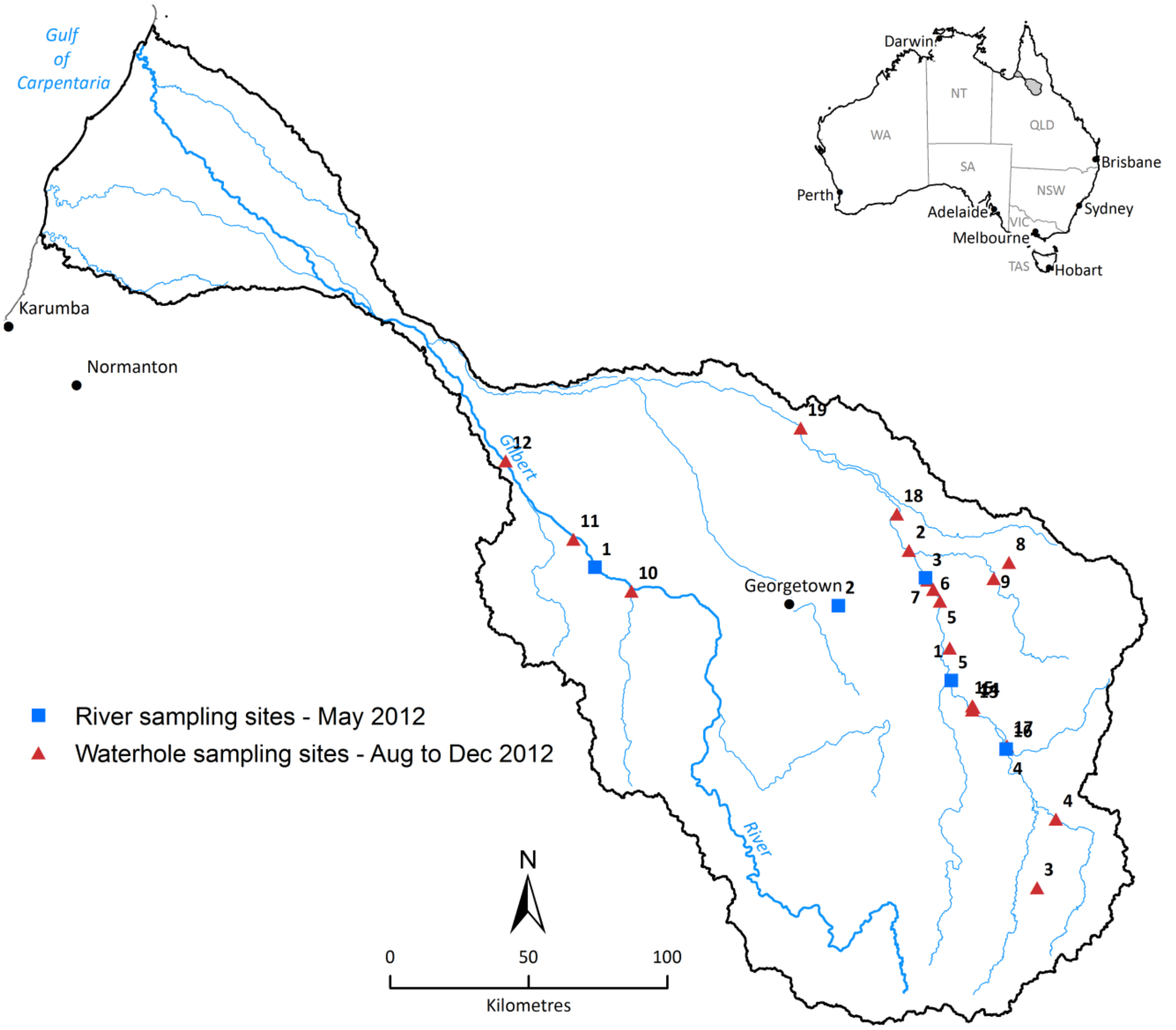

Figure 2.2 Locations of river and waterhole sampling sites in the Gilbert catchment. Details for each site are in Table 2.3 and Table 2.4

2.1.2 SAMPLE COLLECTION AND LABORATORY ANALYSES

At each river or waterhole site, samples of the surface water were collected for analyses of major ions, stable isotopes of water (δ^2H and δ^{18}O), and ^{222}Rn (Figure 2.3). The samples were collected using a small submersible pump placed in the river/ waterhole 2 to 4 m from the shore and in water at least 0.2 m deep.

Water samples for major ions were collected in well-rinsed 125 - 600 mL PET (polyethylene terephthalate) bottles. All samples were analysed at the CSIRO Analytical Chemistry Laboratory (Waite Campus, Adelaide). Laboratory EC (Meterlab CDM230) and pH (Orion 960) were measured with calibrated probes in a constant temperature room. Total alkalinity was measured by titration to a pH 4.5 end-point. Major cations were measured by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES; Spectro ARCOS) and anions by ion chromatrography (Dionex ICS – 2500).

Water samples for $\delta\,^2$H and δ^{18}O analysis were collected in 30 ml McCartney bottles and analysed via a GEO 20-20 dual inlet stable isotope gas ratio mass-spectrometer fitted with a 59 port Water Equilibration System (PDZ Europa Ltd. U.K.).

Water samples for ^{222}Rn analyses were collected in 1.25 L PET bottle by inserting the end of the pump tube into the bottom of the bottle and allowing several volumes of overflow to minimise contact with the atmosphere. The bottles were then tightly capped and the time and date of collection recorded.

^{222}Rn samples were later extracted in mineral oil following Leaney and Herczeg (2006) and ^{222}Rn activities were measured in the laboratory by liquid scintillation on a LKB Wallac Quantulus counter using the pulse shape analysis program to discriminate alpha and beta decay (Herczeg et al., 1994).

Figure 2.3 Sampling an anabranch of the Einasleigh River at Ellendale Station for major ions, ^{222}Rn, and stable isotopes of water (δ^2H and $\delta^{18}O$) during a field trip in October/November 2012

2.2 Task 2 - Leakage of water into the shallow alluvial/bedsands aquifers

Task 2 involved groundwater monitoring to gain a better understanding of the connection between ephemeral rivers and the shallow alluvial/bedsands aquifers, and to provide baseline groundwater information prior to any new irrigation developments. The field work for this task was undertaken in the alluvial/bedsands aquifer adjacent to the Flinders River between Hughenden and Maxwelton, and in the GAB recharge beds adjacent to the Gilbert River between Prestwood and Chadshunt stations.

In addition to major ions, a suite of naturally occurring isotopes and anthropogenic tracers were utilised in this task to provide information on groundwater recharge such as source waters, recharge mechanisms and likely recharge rates. The stable isotopes of water are very useful for determining mechanisms of groundwater recharge (Harrington et al., 2002), sources of recharge waters, as well as surface water-groundwater interactions (McCarthy et al., 1992). Carbon-14 (^{14}C) is a radioactive isotope which is commonly used to date groundwater that is between 500 and 20,000 years of age. When combined with the sampling depth and knowledge of aquifer geometry, the ^{14}C 'ages' can also be used to obtain estimates of recharge rate (Kalin, 2000; Harrington et al., 2002). Carbon-13 ($\delta^{13}C$) is a natural stable isotope that can provide information on the source of groundwater due to the fact that atmospheric, carbonate, and plant derived carbon-13 values all differ with respect to Pee Dee Belemnite (PDB) standard (Kalin, 2000). Chlorofluorocarbons (CFCs) are synthetic halogenated alkanes that have been used in refrigeration and other industrial purposes and several CFC compounds (including CFC-11 and CFC-12) have been released in large quantities to the atmosphere since the 1960s (Plummer and Busenberg 2000). They are used to date groundwater that is 50 years old or less. Sulphur hexaflouride (SF_6) is an anthropogenic gas which has been monotonously increasing in the earth's atmosphere for the past 50 years or so. The concentration of SF_6 measured in groundwater can be used to estimate when it was recharged. The inert nature of the dissolved noble gases helium-4 (^4He), neon-20 (^{20}Ne) and argon-40 (^{40}Ar) makes them excellent groundwater tracers. ^4He is produced by decay of uranium and thorium in aquifer minerals and accumulates in groundwater over geological time scales ($10^3 – 10^8$ years). Its concentration in 'old' groundwater is proportional to groundwater age in most settings and ^4He concentrations above atmospheric background are only found in old groundwaters (Lamontagne et al., 2011). In certain circumstances, the release of ^4He into much younger groundwater from minerals in recent geologic sediment may be used to estimate groundwater ages in the 100-10,000 year time scale. The atmospheric noble gases (^{20}Ne, ^{40}Ar) dissolve in water in the unsaturated zone and record the prevailing conditions just above the water table. They are most frequently used to estimate recharge temperatures that can be used to confirm the existence of fossil groundwater recharged under different climatic conditions of long ago. They can also be used to understand episodic recharge processes by way of estimating excess air in the groundwater. Excess air arises when there is a large amount of recharge over a short timeframe (Leaney et al., 2013).

2.2.1 SAMPLING SITES

Flinders catchment

In August/September 2012 twelve existing piezometers in the alluvium/bedsands adjacent to the Flinders River between Hughenden and Maxwelton were located, sampled, and equipped with water level/salinity loggers (Figure 2.4, Table 2.5 and Figure 2.5). The piezometers selected were a combination of those drilled between 1967 and 1971 by the Queensland government (Cochrane, 1967; Lloyd, 1970; QIWSC, 1973) and ones drilled more recently by private landowners. These were selected because there was prior knowledge of their exact locations and their bore construction details. While there may be other alluvial piezometers present in the Flinders catchment, the information available in the Queensland Department of Natural Resources and Mines groundwater database is insufficient to clarify if they are screened in the alluvium/bedsands. For each selected piezometer the water level/salinity logger was deployed within the screened interval to ensure the maximum water level fluctuation was captured. The groundwater level data from all piezometers was corrected for atmospheric pressure fluctuations using a barometric logger installed at site 9. Table 2.6 summarises the sampling and logging of these piezometers. A GAB bore (Irrigation Bore No. 2) on Glendalough station was also sampled.

Water level loggers were also installed at five locations in the Flinders River (Table 2.7; Figure 2.5). These were deployed at a height of 0.2 to 0.6 m above the river bed, with the expectation that the river would rise several metres during the wet season.

Data from all of the loggers were downloaded in April 2013 after the wet season.

Figure 2.4 Installing a water level/salinity logger in an alluvial bore near Maxwelton during a field trip in August/September 2012

Table 2.5 Locations of Queensland government alluvial piezometers (on lines drilled between 1967 and 1971 by the Queensland government; Cochrane, 1967; Lloyd, 1970; QIWSC, 1973) and private landowner alluvial piezometers between Hughenden and Maxwelton that were sampled in August/September 2012

SITE NUMBER	PIEZOMETER LINE	PIEZOMETER NAME	REGISTERED NUMBER	LATITUDE (degrees)	LONGITUDE (degrees)
1	Maxwelton	B3S4	91500089	-20.638223	142.632618
2	Not Applicable	Majuba	Unknown	-20.673010	142.646888
3	Poseidon	P3	91500074	-20.743052	143.685280
4	L-Tree Creek	L1	91500069	-20.680000	143.766106
5	L-Tree Creek	B7S5	91500066	-20.687774	143.767782
6	Glendalough	B5S5	91500054	-20.717504	143.949725
7	Not Applicable	Irrigation Bore No. 2*	118219	-20.698520	143.928051
8	Not Applicable	Shed Bore	146464	-20.709549	143.924962
9	Not Applicable	Shack Bore	146465	-20.697952	143.916806
10	Canterbury	C4	91500047	-20.779163	144.078612
11	Dog Leg	B1S1	91500041	-20.830835	144.194724
12	Dog Leg	B4S4	91500044	-20.815275	144.190557
13	Dog Leg	B5S5	91500045	-20.808333	144.191108

*This is a GAB bore not an alluvial piezometer

Table 2.6 Details of alluvial piezometers between Hughenden and Maxwelton that were sampled in August/September 2012. TOC refers to the top of casing of the piezometer

SITE NUMBER	PIEZOMETER NAME	DATE SAMPLED	PIEZOMETER DEPTH (m below TOC)	STANDING WATER LEVEL (m below TOC)	HEIGHT OF TOC ABOVE GROUND (m)	SAMPLES COLLECTED	LOGGER DEPLOYMENT
1	B3S4	30/08/12	12.90	12.48	0.48	Bailed sample for major ions	Aquatroll 200 set at 12.60 m below TOC on 01/09/12
2	Majuba	30/08/12	24.70	14.42	0.40	Pumped samples for major ions, ^{4}He, ^{20}Ne, ^{40}Ar, SF_6, $\delta^{13}C$, ^{14}C, CFCs, $\delta^{2}H$, $\delta^{18}O$	Aquatroll 200 set at 18.0 m below TOC on 01/09/12
3	P3	03/09/12	12.20	6.43	0.35	Pumped samples for major ions, SF_6, $\delta^{13}C$, ^{14}C, CFCs, $\delta^{2}H$, $\delta^{18}O$	Aquatroll 200 set at 8.0 m below TOC on 03/09/12
4	L1	02/09/12	21.80	8.76	0.35	Pumped samples for major ions, ^{4}He, ^{20}Ne, ^{40}Ar, SF_6, $\delta^{13}C$, ^{14}C, CFCs, $\delta^{2}H$, $\delta^{18}O$	Aquatroll 200 set at 10.0 m below TOC on 03/09/12
5	B7S5	02/09/12	15.45	6.71	0.45	Bailed sample for major ions	Aquatroll 200 set at 10.0 m below TOC on 02/09/12
6	B5S5	31/08/12	7.10	6.22	0.48	Bailed sample for major ions	Aquatroll 200 set at 6.5 m below TOC on 31/08/12
7	Irrigation Bore No. 2*	31/08/12	305.00	Artesian	0.00	Flowing samples major ions, $\delta^{13}C$, ^{14}C, $\delta^{2}H$, $\delta^{18}O$	None
8	Shed Bore	31/08/12	20.00	9.90	0.50	Pumped samples for major ions, ^{4}He, ^{20}Ne, ^{40}Ar, SF_6, $\delta^{13}C$, ^{14}C, CFCs, $\delta^{2}H$, $\delta^{18}O$	None
9	Shack Bore	31/08/12	17.40	9.78	0.75	Pumped samples for major ions, ^{4}He, ^{20}Ne, ^{40}Ar, SF_6, $\delta^{13}C$, ^{14}C, CFCs, $\delta^{2}H$, $\delta^{18}O$	Aquatroll 200 set at 15.0 m below TOC, including barometric logger on 01/09/12
10	C4	01/09/12	10.85	6.85	0.40	Pumped samples for major ions, ^{4}He, ^{20}Ne, ^{40}Ar, SF_6, $\delta^{13}C$, ^{14}C, CFCs, $\delta^{2}H$, $\delta^{18}O$	Aquatroll 200 set at 8.0 m below TOC on 03/09/12
11	B1S1	02/09/12	7.40	6.81	0.50	Bailed sample for major ions	Aquatroll 200 set at 7.0 m below TOC on 02/09/12
12	B4S4	03/09/12	19.00	9.43	0.50	Pumped samples for major ions, SF_6, $\delta^{13}C$, ^{14}C, CFCs, $\delta^{2}H$, $\delta^{18}O$	50m Diver set at 11.0 m below TOC on 03/09/12
13	B5S5	03/09/12	18.20	9.18	0.45	Pumped samples for major ions, ^{4}He, ^{20}Ne, ^{40}Ar, SF_6, $\delta^{13}C$, ^{14}C, CFCs, $\delta^{2}H$, $\delta^{18}O$	20m Diver set at 11.0 m below TOC on 04/09/12

*This is a GAB bore not an alluvial piezometer

Table 2.7 Details of water level loggers installed in the Flinders River in August/September 2012

SITE NUMBER	SITE NAME	LATITUDE (degrees)	LONGITUDE (degrees)	LOGGER DEPLOYMENT
1	Hulberts Crossing	-20.641477	142.628546	50m Diver set at 0.60m above bed level on 01/09/12. Installed on trunk of a Eucalypt tree in the river bed which is one of the third clump of trees ~100m upstream of the crossing on the northern side.
2	Poseidon Crossing	-20.740764	143.684356	50m Diver set at 0.20m above bed level on 02/09/12. Installed on the trunk of the second Melaleuca tree in the river bed ~200m downstream of the crossing on the southern side.
3	Alderly Crossing	-20.652906	143.890060	50m Diver set at 0.20m above bed level on 01/09/12. Installed on the root of the second Eucalypt tree ~ 30m downstream of the crossing on the northern side.
4	Canterbury Crossing	-20.779163	144.078612	50m Diver set at 0.30m above bed level on 03/09/12. Installed on the trunk of a Eucalypt tree in the river bed ~20m downstream of the bore 91500047 (C4) that has been sampled on the southern side.
5	Hughenden	-20.832023	144.193443	50m Diver set at 0.30m above bed level on 02/09/12. Installed on the trunk of the second Calitris tree in the river bed ~50m downstream of the track leading down to the river on the southern side (opposite side of the river to the Dog Leg line).

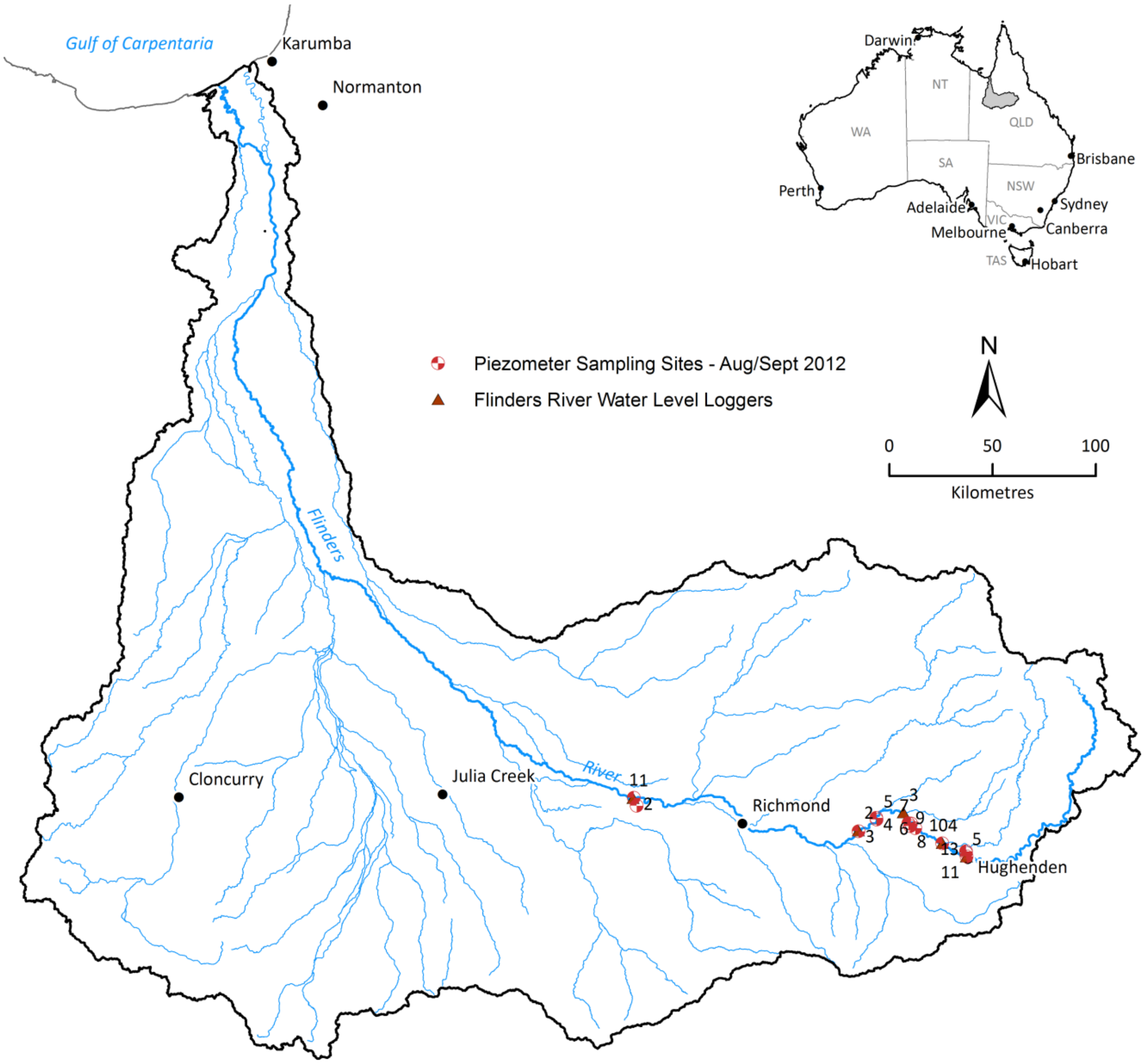

Figure 2.5 Locations of Queensland government alluvial piezometers (on lines drilled between 1967 and 1971 by the Queensland government; Cochrane, 1967; Lloyd, 1970; QIWSC, 1973) and private landowner alluvial piezometers between Hughenden and Maxwelton that were sampled in August/September 2012. Also shown are the locations of the water level loggers deployed in the Flinders River. Details for each site are in Table 2.5, Table 2.6 and Table 2.7

Gilbert catchment

The alluvium/bedsands on the Gilbert River have already been studied in some detail by QDNR (1998) and AGE (1999) and are generally well understood. Less understood are the GAB recharge beds in this area and their interaction with the Gilbert River and the associated alluvium/bedsands. In October 2012 two existing piezometers in the GAB recharge beds (Coffin Hill Member of the Gilbert River Formation) adjacent to the Gilbert River near the Gilbert River irrigation area were located and equipped with water level/salinity loggers (Table 2.8; Figure 2.6). These piezometers were drilled for the Queensland government in 1999 (PPK, 1999) and were specifically selected because they were reasonably close to the Gilbert River and their locations and bore construction details were known. The reason for sampling these GAB bores was to see if the GAB recharge beds in this area, which are not actually outcropping in the alluvium/bedsands, were being actively recharged by the Gilbert River via a lateral connection to the alluvium/bedsands. Data from these loggers were downloaded in April 2013 after the wet season, and the piezometers were also sampled at that time. The groundwater level data from both piezometers was corrected for atmospheric pressure fluctuations using a barometric logger installed at site 9 in the Flinders catchment. Table 2.9 summarises the sampling and logging of these piezometers.

Table 2.8 Locations of Queensland government GAB piezometers adjacent to the Gilbert River irrigation area that were sampled in April 2013

SITE NUMBER	PIEZOMETER LINE	PIEZOMETER NAME	REGISTERED NUMBER	LATITUDE (degrees)	LONGITUDE (degrees)
1	Not Applicable	GROB2	91700010	-18.151051	148.831137
2	Not Applicable	GROB4	91700012	-18.206529	148.850405

Table 2.9 Details of GAB piezometers adjacent to the Gilbert River irrigation area that were sampled in April 2013. TOC refers to the top of casing of the piezometer

SITE NUMBER	PIEZOMETER NAME	DATE SAMPLED	PIEZOMETER DEPTH (m below TOC)	STANDING WATER LEVEL (m below TOC)	HEIGHT OF TOC ABOVE GROUND (m)	SAMPLES COLLECTED	LOGGER DEPLOYMENT
1	GROB2	21/04/13	21.80	12.80	0.40	Pumped samples for major ions, ^{4}He, ^{20}Ne, ^{40}Ar, SF_6, δ^{13}C, ^{14}C, CFCs, δ^{2}H., δ^{18}O	Aquatroll 200 set at 18.72 m below TOC on 20/09/12
2	GROB4	30/08/12	27.50	13.62	0.43	Pumped samples for major ions, ^{4}He, ^{20}Ne, ^{40}Ar, SF_6, δ^{13}C, ^{14}C, CFCs, δ^{2}H., δ^{18}O	Aquatroll 200 set at 26.65 m below TOC on 20/09/12

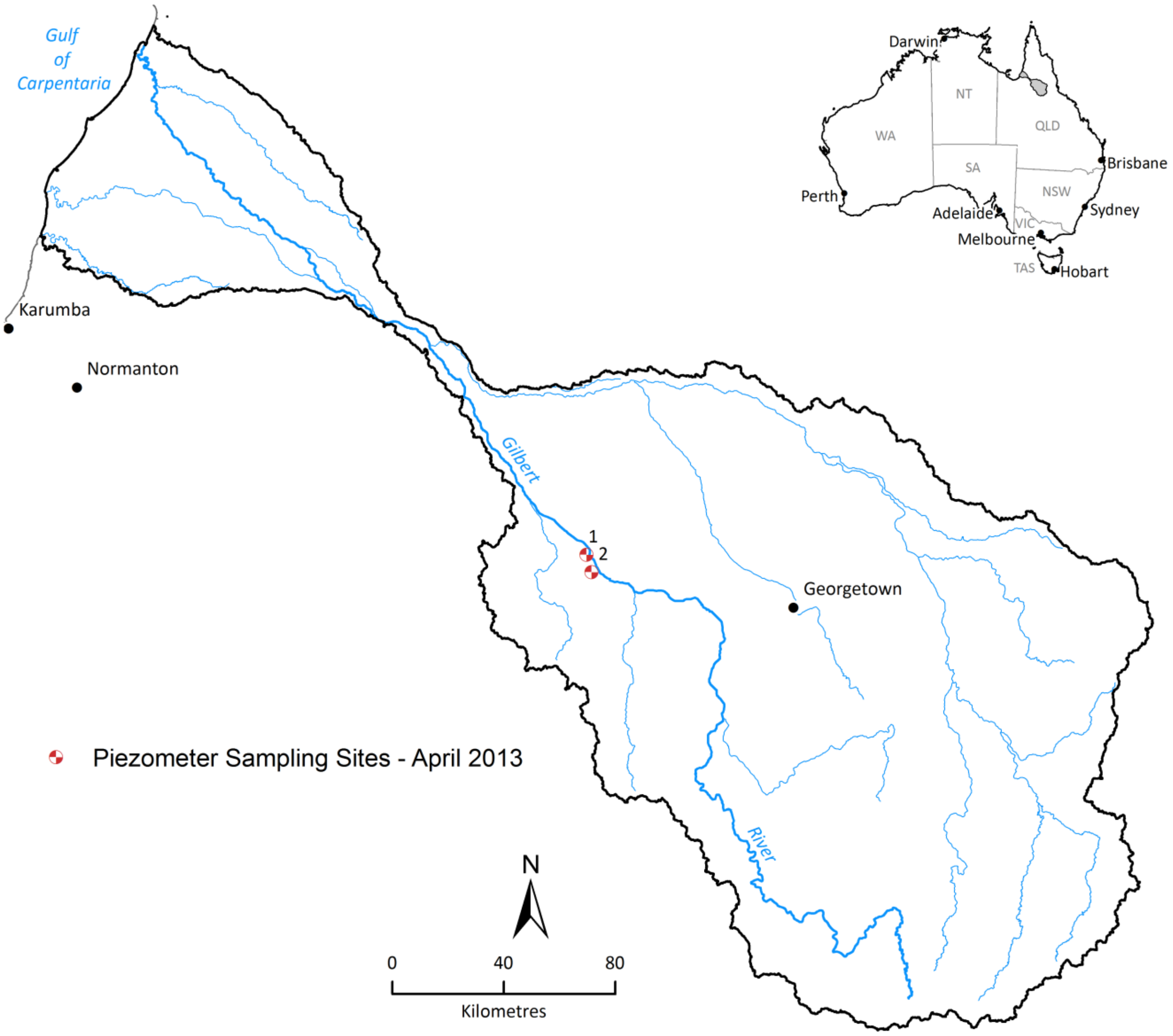

Figure 2.6 Locations of Queensland government GAB piezometers adjacent to the Gilbert River irrigation area that were sampled in April 2013. Details for each site are in Table 2.8 and Table 2.9

2.2.2 SAMPLE COLLECTION AND LABORATORY ANALYSES

At each piezometer, the standing water level was measured and the bore was purged for three bore volumes, with care taken to ensure that the water level never dropped below the top of the screen. Where purging was successful the piezometer was then sampled for analyses of major ions, stable isotopes of water (δ^2H and $\delta^{18}O$), $\delta^{13}C$, ^{14}C, chlorofluorocarbons (CFC-11 and CFC-12), SF_6 and dissolved noble gases (^4He, ^{20}Ne and ^{40}Ar). In some piezometers, water levels were only slightly above the screen presenting a challenge to successfully purge, at these sites a small sample was bailed for major ion chemistry.

Groundwater samples were 0.45 µm filtered in the field for stable isotopes of water and major ion chemistry. For the stable isotopes of water, a subsample was then stored in a gas-tight collection vessel (McCartney bottle). For major cations, a 50 mL subsample was acidified (to pH<2) and stored in a well-rinsed 125 mL PET (polyethylene terephthalate) bottles. For major anions, total alkalinity, laboratory measured EC and laboratory measured pH, another 50 mL subsample was stored in a similar manner but without acidification. A field blank for major cations and anions was also prepared by processing a distilled water sample in the same way as the field samples. All samples were analysed at the CSIRO Analytical Chemistry Laboratory (Waite Campus, Adelaide).

Samples of groundwater for δ^2H and $\delta^{18}O$ analysis were collected in 30 ml McCartney bottles and analysed via a GEO 20-20 dual inlet stable isotope gas ratio mass-spectrometer fitted with a 59 port Water Equilibration System (PDZ Europa Ltd. U.K.).

Samples of groundwater for ^{14}C analysis were collected 5 L plastic containers and the DIC precipitated as $SrCO_3$. Aliquots of CO_2, prepared via acidification of the precipitate and cryogenic purification, were sent to the accelerator mass spectrometry laboratory at the Australian National University for ^{14}C analysis. Sub-samples of CO_2 were analysed for $\delta^{13}C$ via a GEO 20-20 dual inlet stable isotope gas ratio mass-spectrometer.

Three 125 ml bottles of sample water were collected for CFC analysis (Figure 2.7) as per instructions from the USGS SF_6 and CFC laboratory (http://water.usgs.gov/lab/sf6/sampling/). The CFC-11 and CFC-12 analyses were undertaken at the CSIRO Isotope Analytical Laboratory on an aliquot of gas purged from the water using ultra high purity nitrogen and then analysed using a gas chromatograph fitted with an electron capture device.

Figure 2.7 Sampling an alluvial bore at Glendalough Station for chlorofluorocarbons during a field trip in August/September 2012

A one litre amber coloured bottle of sample water was collected for sulfur hexafluoride (SF_6) analysis as per instructions from the USGS SF_6 and chlorofluorocarbon (CFC) laboratory (http://water.usgs.gov/lab/sf6/sampling/). The SF_6 analyses were undertaken at the CSIRO Isotope Analytical Laboratory on an aliquot of ultra high purity nitrogen that had been equilibrated with ~300 mls of the water sample at 25°C and then analysed using a gas chromatograph fitted with an electron capture device.

For the dissolved noble gases and ^4He, equilibrium head space samples were collected using passive diffusion samplers (Gardner and Solomon 2009). Diffusion samplers were allowed to equilibrate with sample water (i.e., immersed in the piezometers or in the river) for 24 hours, retrieved, and clamped vacuum tight. The ^{4}He, ^{20}Ne and ^{40}Ar concentrations were measured at the CSIRO Isotope Analytical Laboratory using a quadrupole mass spectrometer with cryogenic separation (Poole et al. 1997).

2.3 Task 3 - Risk of root zone drainage beneath irrigation leading to watertable rise

Task 3 involved the development of a new groundwater modelling method to assess the risk that root zone drainage beneath new irrigation sites may lead to watertable rise, and to evaluate the consequent impacts on the irrigation site and nearby rivers.

Cook et al. (2008) and Paydar et al. (2011) previously developed modelling approaches that predict the watertable rise that occurs as a result of root zone drainage beneath an individual irrigation site and a mosaic of irrigation sites. This work showed that as the size of the irrigation site increases, the watertable rise beneath the site increases, resulting in a larger area of influence. Furthermore, the height of the watertable under the site is directly related to the time since the start of irrigation and inversely related to the spacing between sites. Furthermore, this work indicated that there is more spread and high watertable rise for a single large site than for a mosaic with the same total irrigated area. Previous work in the Murray-Darling Basin has shown that rises in groundwater levels (due to increases in root zone drainage beneath new irrigation sites) can lead to increased discharge of groundwater to adjacent rivers (Rassam et al. 2004; Rassam et al., 2005; Knight et al. (2005). This increased discharge can potentially change the baseflow regime of rivers and, if the groundwater is saline or high in other constituents, can lead to changes in river water quality. Depending on the distance of the new irrigation site from the river and the aquifer parameters, there can be long lead-in and lag times for the effect of the increase in root zone drainage to be observed as increased discharge of groundwater into the river. Task 3 developed new explicit analytical solutions that brought together these two previous pieces of work in order to predict both the rise of the watertable as a result of introducing new irrigation developments, and the subsequent increase in groundwater discharge to adjacent rivers. Steady state and transient solutions were developed for circular shaped irrigation areas.

The problem is conceptualised as shown in Figure 2.8. Groundwater flow is considered in an unconfined single-layered, homogeneous aquifer of length y and width=x_3 . A constant head boundary is located along one side of the aquifer, which represents a fully penetrating river. Irrigation developments are randomly located at (x, y) from the river, and represent a recharge sources to the aquifer. The developed solutions provide transient as well as steady state groundwater head distributions in the aquifer.

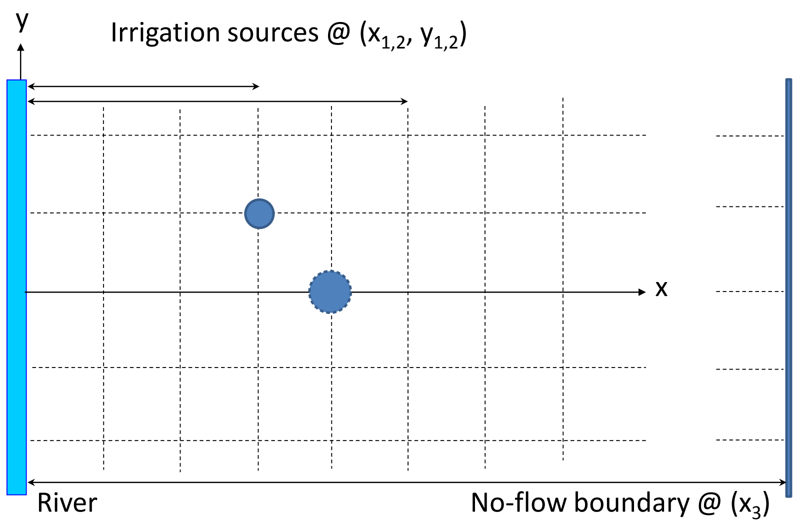

Figure 2.8 Conceptual model for estimating groundwater rise due to irrigation developments

The solutions use the linearised Boussinesq equation for unconfined groundwater free surface flow:

$$S_y \frac{\partial h}{\partial t} = K\overline{h}\left(\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2}\right) + s(x, y, t) \quad (1)$$

where *x* and *y* are Cartesian coordinates, *t* is time, *h*(*x; y; t*) is the height of the free surface above the base of the aquifer, $\overline{h}$ is a representative free surface height, K is the hydraulic conductivity, S_y is the specific yield, and *s* (*x; y; t*) is the distribution of recharge. A straight river at *x* = 0, with the boundary condition *h*(0*; y; t*) = $\overline{h}$ and the initial condition *h*(*x; y;* 0) = $\overline{h}$ is assumed. Uniform recharge of strength s_0 per unit area over a circular or a rectangular area, starting at time zero, is considered. For a circular recharge area it is taken that the recharge is to be of strength *s*0 over a circle of radius *R* with centre at (*d;* 0), with *R* < *d*. For a rectangular recharge area it is taken that the recharge is to be of strength *s*0 over a rectangle with sides of length 2*a* in the *x* direction and 2*b* in the *y* direction with centre at (*d;* 0), with *a* < *d*. Linearity implies that the impact resulting from multiple sources can simply be obtained by the superimposition of individual impacts. The applicability of this concept has been demonstrated by Rassam et al. (2004) and Rassam (2011).

For a circular recharge source, the steady state maximum height is given by:

$$h_{max} = \overline{h} + \frac{soR^2}{2K\overline{h}}\left\{\frac{d}{d+\sqrt{d^2+R^2}} + \frac{1}{2}ln\frac{(d+\sqrt{d^2+R^2})}{R}\right\} \quad (2)$$

Outside the circular recharge area, the steady state distribution of groundwater heights is:

$$h(x, y) = \overline{h} + \frac{soR^2}{4K\overline{h}}log\left\{\frac{(x-d)^2+y^2}{(x+d)^2+y^2}\right\} \quad (3)$$

Figure 2.9 demonstrates the application of Equation 3 for three random recharge sources. Note that this three-dimensional surface represents the steady state (worst case scenario) distribution of groundwater heads in the unconfined aquifer as a result of introducing new irrigation developments.

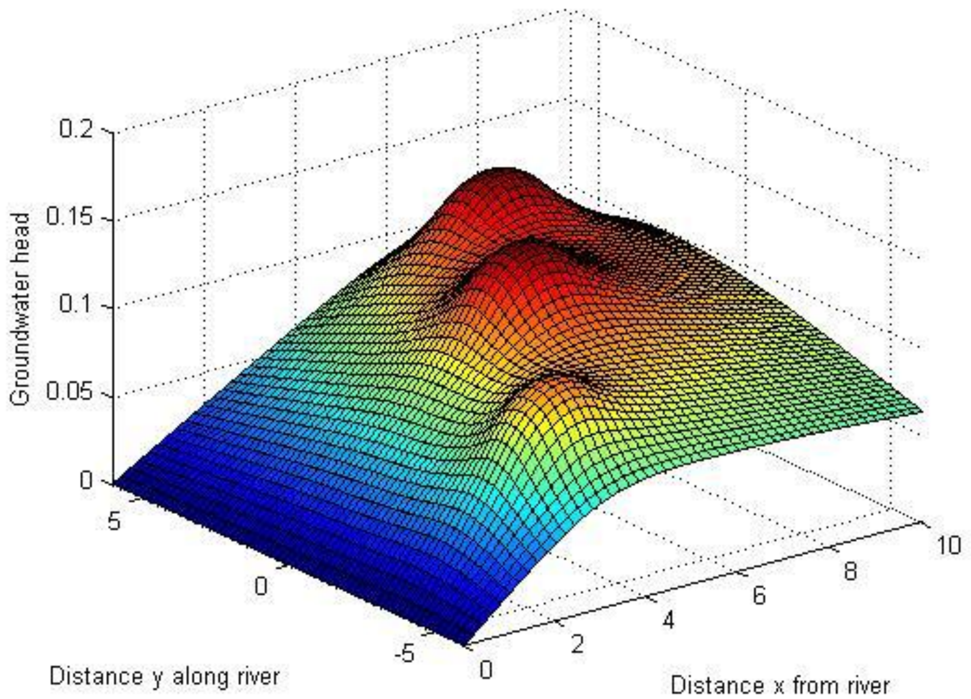

Figure 2.9 Sample result showing steady state groundwater heads due to three circular irrigation sources

The time required to realise steady state impacts might be very large depending on aquifer properties and the distance between recharge source and the river. Therefore, a transient solution, which identifies the time scales during which the impacts are realised, was required. The solution of Hantush (1967) for recharge in an unbounded (semi-infinite) aquifer was written as the integral with respect to time of a product of error function type solutions of the diffusion equation. The method of images was adopted to modify this solution to account for the presence of a no-flow boundary.

These new explicit analytical solutions were implemented as MATLAB programs and they were applied in the case study sites in both the Flinders and Gilbert catchments. The results of these simulations are reported in section 3.3 and in the Catchment Reports (Petheram and Watson, 2013a; Petheram and Watson, 2013b).

3 Results

3.1 Task 1 - Hydrogeological controls on dry-season flows and waterhole persistence

3.1.1 FLINDERS CATCHMENT

The results of the analyses of ^{222}Rn, Chloride (Cl^-), and stable isotopes of water (δ^2H and $\delta^{18}O$) for each river and waterhole site in the Flinders catchment are given in Table 3.1 and Table 3.2. The results of the analyses of EC, pH, Total Alkalinity and major ions for each river and waterhole site in the Flinders catchment are given in Apx Table A.1 and Apx Table A.2 in the Appendix.

Plots of δ^2H versus $\delta^{18}O$ are shown in Figure 3.1 and Figure 3.3 for river and waterhole sites respectively. The Local Meteoric Water Line (LMWL) depicted on Figure 3.1 and Figure 3.3 is based on rainfall analyses for Mt Isa (as reported in Crosbie et al., 2012), and the Evaporation Line depicted on Figure 3.1 and Figure 3.3 has a slope of 5 and intercept of -20 ‰ δ^2H. The LMWL defines the relationship between δ^2H and $\delta^{18}O$ of water that is derived entirely from local precipitation. The Evaporation Line defines the relationship between δ^2H and $\delta^{18}O$ for any water source that has subject to significant evaporation and hence has led to the concentration of both of these stable isotopes in the liquid phase. The plot for the river sites shows that all samples lie between the LMWL and the Evaporation Line, indicating that all have undergone some degree of evaporation. It is not possible from these data alone to determine whether this is just evaporation of surface water or is in part due to some inflow of groundwater that has an evaporative signature. The plot for the waterhole sites show that nearly all samples lie on the Evaporation Line, indicating that most have undergone a significant degree of evaporation. Most of the sites which have multiple samplings show that the degree of evaporation increased through the dry season. It is not possible from these data alone to determine whether this is just evaporation of surface water or is in part due to some inflow of groundwater that has an evaporative signature.

Plots of Chloride versus ^{222}Rn are shown in Figure 3.2 and Figure 3.4 for river and waterhole sites respectively. The plot for the river sites indicates that there is no relationship and therefore provides little insight other than the observation that two sites (Flinders River@Bridge in Hughenden and Stawell River@Cambridge Crossing) have ^{222}Rn values high enough (> 0.4 Bq/L) to suggest a high likelihood of groundwater inflow. The plot for the waterhole sites also indicates that there is no relationship and therefore provides little insight other than the observation that only two sites (Causeway – township and F1) have ^{222}Rn values high enough (> 0.4 Bq/L) to suggest a high likelihood of groundwater inflow.

Table 3.1 Results of ^{222}Rn, Cl^-, δ^2H and $\delta^{18}O$ analyses for river sites in the Flinders catchment that were sampled in May 2012

SITE NUMBER	STREAM	SITE NAME	DATE SAMPLED	^{222}Rn (Bq/L)	Cl^- (mg/L)	δ^2H (‰ VSMOW)	$\delta^{18}O$ (‰ VSMOW)
1	Flinders River	Flinders River@Low level Crossing ~5 km upstream of Richmond	15/05/12	0.268	22.0	-45.3	-5.51
2	Flinders River	Flinders River@Ford ~40 km upstream of Richmond	15/05/12	0.077	19.0	-44.8	-5.53
3	Flinders River	Flinders River@Bridge in Hughenden	14/05/12	0.490	21.0	-44.9	-5.85
4	Flinders River	Flinders River@Alderly Crossing	15/05/12	0.205	23.0	-44.5	-5.96
5	Flinders River	Flinders River@Hulberts Crossing	15/05/12	0.237	17.0	-50.7	-6.49
6	Stawell River	Stawell River@Cambridge Crossing	15/05/12	1.017	16.0	-51.8	-6.83

Table 3.2 Results of ^{222}Rn, Cl^-, δ^2H and $\delta^{18}O$ analyses for waterhole sites in the Flinders catchment that were sampled between August and December 2012

SITE NUMBER	STREAM	SITE NAME	DATE SAMPLED	^{222}Rn (Bq/L)	Cl^- (mg/L)	δ^2H (‰ VSMOW)	$\delta^{18}O$ (‰ VSMOW)
1	Flinders River	Wondoola	6/08/12	0.030	19.0	-28.1	-2.06
2	Flinders River	Etta Plains Station	10/08/12	0.060	21.0	-36.3	-3.67
3	Flinders River	River Dale Station	11/08/12	0.050	25.0	-35.3	-4.08
4	Flinders River	Tentative pool 11	12/08/12	0.310	45.0	-33.3	-4.08
5	Flinders River	Harrogate Station	12/08/12	0.140	24.0	-37.6	-4.89
6	Cloncurry River	Cowan Downs Station	6/08/12	0.090	1.6	-31.3	-4.65
7	Off channel waterhole	Cowan Downs Station - Off channel waterhole	6/08/12	0.220	6.2	7.0	6.07
8	Cloncurry River	Causeway - township	7/08/12	1.230	86.0	-30.3	-2.42
9	Cloncurry River	Fort Constantine Station	8/08/12	0.250	18.0	-37.7	-3.85
10	Fairlight Creek	F1 - Soda Valley/Glendalough Station	13/08/12, 29/10/12, 12/12/12,	0.510 0.090 0.133	46.0 74.0 97.0	-36.8 -13.4 1.1	-4.37 0.72 3.35
11	Flinders River	F2 - River Dale Station	13/08/12, 3/11/12	0.010 0.047	25.0 55.0	-31.7 37.0	-3.49 11.59
12	Off channel waterhole	F3 - River Dale Station	3/11/12, 8/12/12	0.120 0.076	7.3 15.0	-25.2 12.0	2.48 10.75
13	Off channel waterhole	F4 - River Dale Station	28/10/12, 8/12/12	0.064 0.143	12.0 44.0	25.9 84.9	11.74 23.12
14	Flinders River	F5 - Richmond Shire Council	4/11/12, 9/12/12	0.047 0.054	30.0 37.0	-11.0 0.9	0.65 3.69
15	Flinders River	F7 - Millungera Station	25/10/12, 10/12/12	0.023 0.069	29.0 36.0	-13.9 2.8	1.03 4.72
16	Julia Creek	F8 - Dalgonally Station	10/08/12, 25/10/12, 11/12/12	0.000 0.034 0.023	9.6 11.0 13.0	-69.1 -50.9 -37.6	-7.73 -4.30 -1.74
17	Cloncurry River	F9 - Dalgonally Station	8/08/12, 26/10/12, 10/12/12	0.190 0.154 0.189	6.1 8.0 11.0	-38.6 -7.2 0.8	-4.35 1.69 4.86

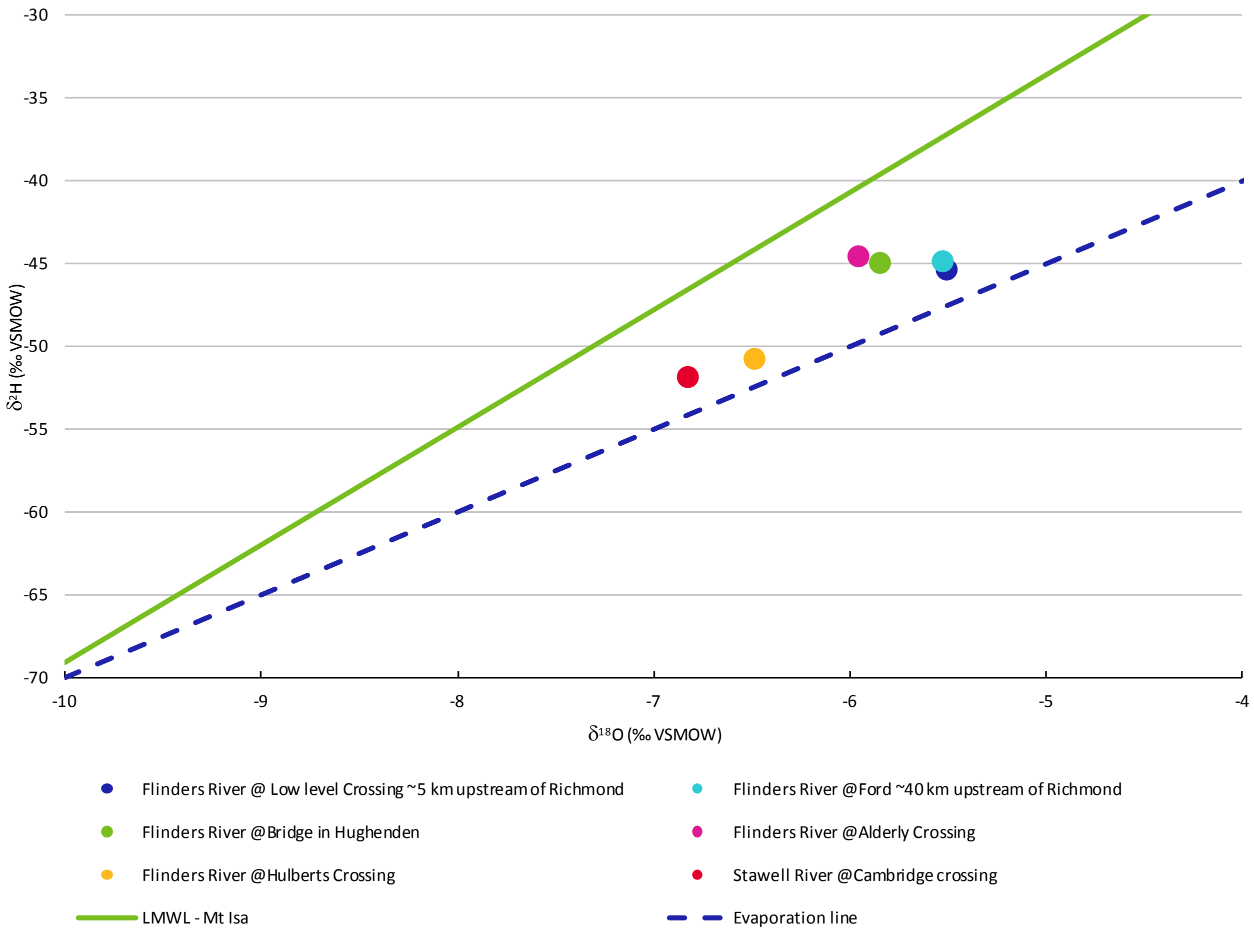

Figure 3.1 Plot of δ^2H versus δ^{18}O for river sites in the Flinders catchment that were sampled in May 2012

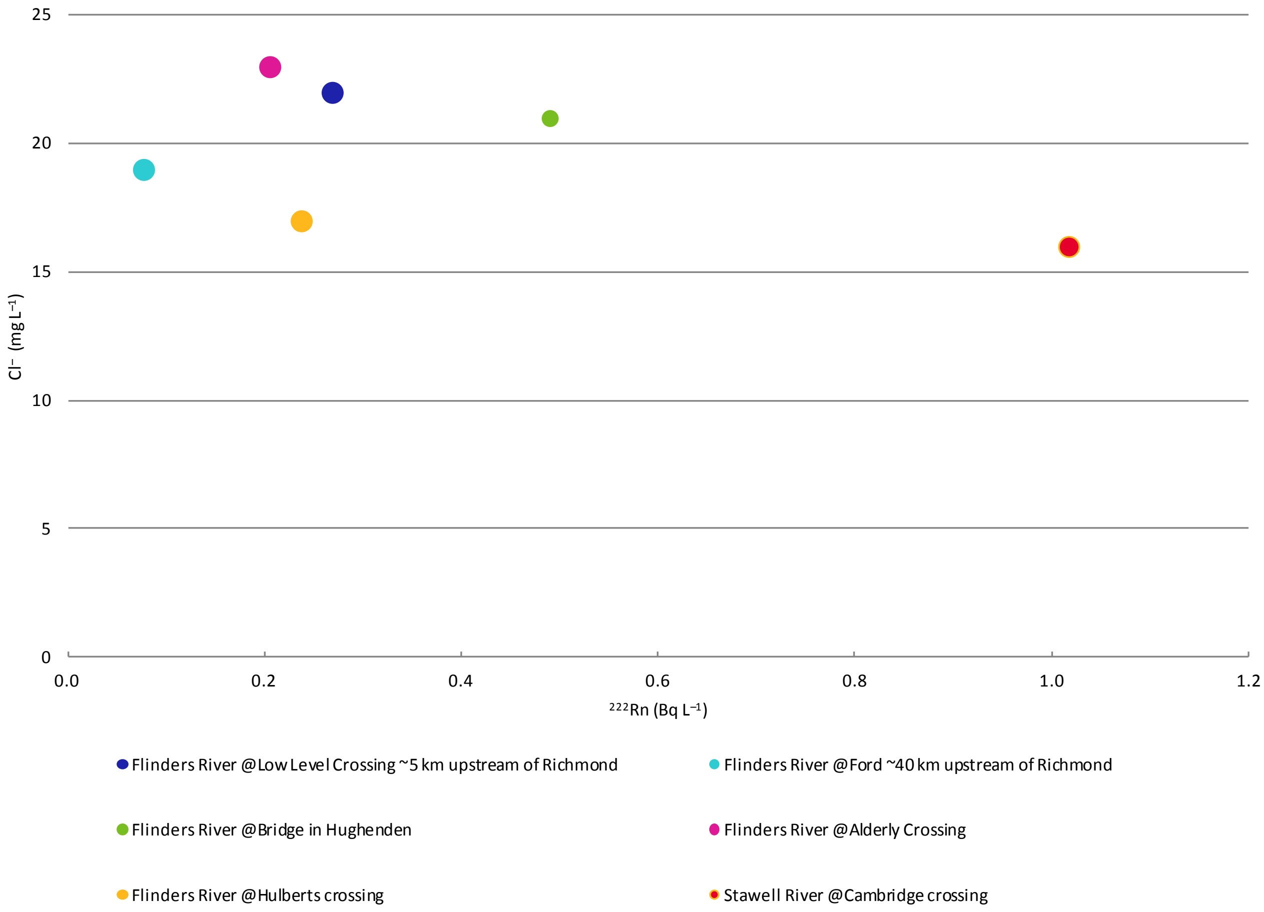

Figure 3.2 Plot of Chloride versus 222Rn for river sites in the Flinders catchment that were sampled in May 2012

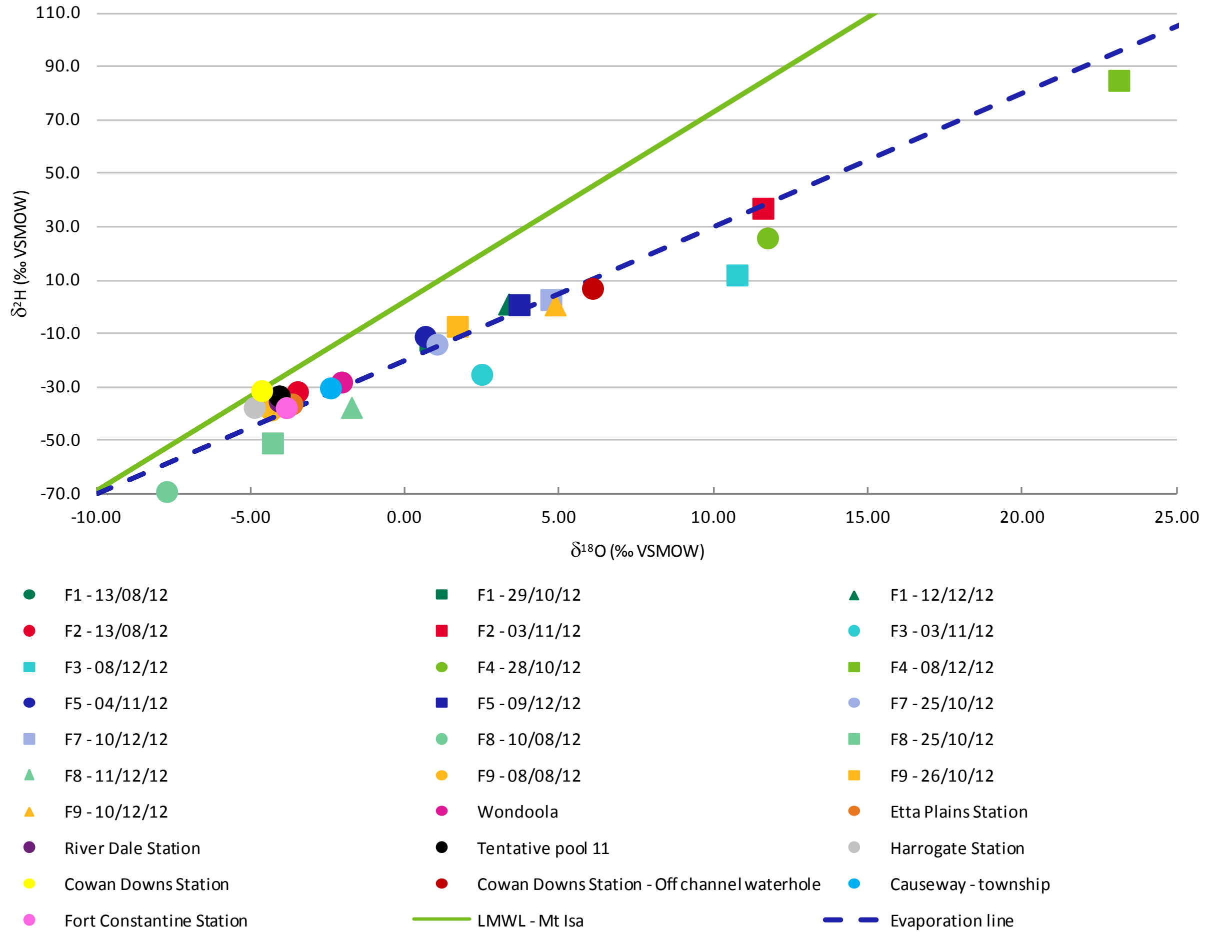

Figure 3.3 Plot of δ^2H versus δ^{18}O for waterhole sites in the Flinders catchment that were sampled between August and December 2012

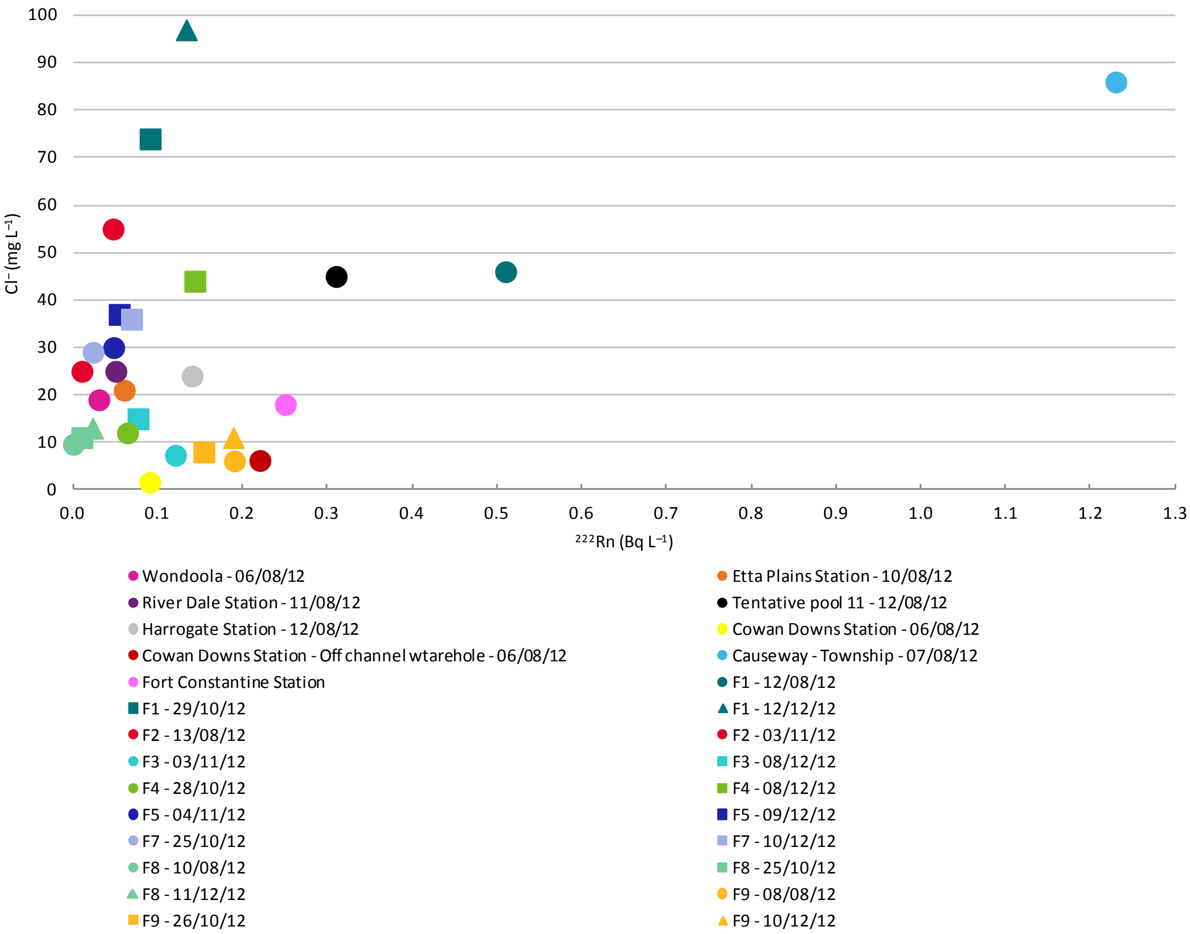

Figure 3.4 Plot of Chloride versus ^{222}Rn for waterhole sites in the Flinders catchment that were sampled between August and December 2012

3.1.2 GILBERT CATCHMENT

The results of the analyses of ^{222}Rn, Chloride (Cl^-), and stable isotopes of water (δ^2H and δ^{18}O) for each river and waterhole site in the Gilbert catchment are given in Table 3.3 and Table 3.4. The results of the analyses of EC, pH, Total Alkalinity and major ions for each river and waterhole site in the Gilbert catchment are given in Apx Table A.3 and Apx Table A.4 in the Appendix.

Plots of δ^2H versus δ^{18}O are shown in Figure 3.5 and Figure 3.7 for river and waterhole sites respectively. These plots are very similar to the those for the Flinders catchment in that all of the samples for the river sites lie between the LMWL and the Evaporation Line (indicating that all have undergone some degree of evaporation), and nearly all of the samples for the waterhole sites lie on the Evaporation Line (indicating that most have undergone a significant degree of evaporation). As is the case for the Flinders sites, it is not possible from these data alone to determine whether the results are due to just evaporation of surface water or are in part due to some inflow of groundwater that has an evaporative signature.

Plots of Chloride versus ^{222}Rn are shown in Figure 3.6 and Figure 3.8 for river and waterhole sites respectively. The plot for the river sites indicates that there is no relationship and therefore provides little insight other than the observation that one site (Gilbert River@Bridge on Georgetown to Croydon Road) has a ^{222}Rn value high enough (> 0.4 Bq/L) to suggest a high likelihood of groundwater inflow. The plot for the waterhole sites also indicates that there is no relationship and therefore provides little insight other than the observation that there are four sites (Lynd, G1,G6 and G10) that have ^{222}Rn values high enough (> 0.4 Bq/L) to suggest a high likelihood of groundwater inflow.

Table 3.3 Results of ^{222}Rn, Cl^-, δ^2H and $\delta^{18}O$ analyses for river sites in the Gilbert catchment that were sampled in May 2012

SITE NUMBER	STREAM	SITE NAME	DATE SAMPLED	^{222}Rn (Bq/L)	Cl^- (mg/L)	δ^2H (‰ VSMOW)	$\delta^{18}O$ (‰ VSMOW)
1	Gilbert River	Gilbert River@Bridge on Georgetown to Croydon Road	16/05/12	3.283	8.4	-52.2	-7.00
2	Routh Creek	Routh Creek@Bridge Crossing	16/05/12	0.138	2.7	-36.1	-3.73
3	Einasleigh River	Einasleigh River@Highway Bridge between Georgetown and Mt Surprise	16/05/12	0.113	15.0	-47.8	-6.45
4	Einasleigh River	Einasleigh River@Highway Bridge between Einasleigh and The Lynd Junction	17/05/12	0.155	13.0	-44.5	-6.42
5	Einasleigh River	Einasleigh River@Crossing near Einasleigh	16/05/12	0.069	21.0	-44.7	-5.91

Table 3.4 Results of ^{222}Rn, Cl^-, δ^2H and $\delta^{18}O$ analyses for waterhole sites in the Gilbert catchment that were sampled between August and December 2012

SITE NUMBER	STREAM	SITE NAME	DATE SAMPLED	^{222}Rn (Bq/L)	Cl^- (mg/L)	δ^2H (‰ VSMOW)	$\delta^{18}O$ (‰ VSMOW)
1	Ellendale Creek	Lynd	02/08/12	0.830	24.0	-32.3	-4.69
2	Einasleigh River	Mt Surprise	03/08/12	0.140	22.0	-39.0	-5.28
3	Bundock Creek	G1 - Lyndhurst	15/10/12, 01/12/12	0.480 0.261	9.8 9.5	-35.6 -28.9	-4.65 -2.96
4	McKinnons Creek	G2 - Lyndhurst	15/10/12, 01/12/12	0.082 0.022	21.0 25.0	-13.8 -5.4	-0.70 2.15
5	Einasleigh River	G3 - Mt Alder Station	15/10/12, 28/11/12	0.124 0.096	41.0 38.0	-16.7 -15.7	0.08 1.00
6	Einasleigh River	G4 - Mt Surprise	15/10/12, 29/11/12	0.047 0.013	41.0 65.0	-3.9 11.2	2.44 6.66
7	Einasleigh River	G5 - Mt Surprise	15/10/12, 28/11/12	0.019 0.044	39.0 51.0	-15.4 -4.8	0.45 2.47
8	Elizabeth Creek	G6 - Mt Surprise	02/08/12, 15/10/12, 27/11/12	0.550 0.613 0.701	12.0 11.0 12.0	-45.4 -45.2 -44.5	-6.36 -6.21 -6.14
9	Junction Creek	G7 - Mt Surprise	15/10/12, 27/11/12	0.053 0.055	18.0 19.0	-40.7 -38.0	-5.11 -4.55
10	Porcupine Creek	G8 - Langlovale Station	15/10/12, 30/11/12	0.153 0.043	11.0 12.0	-38.2 -28.5	-4.21 -2.42
11	Pleasant Creek	G9 - Lake Carlo Station	14/10/12, 30/11/12	0.095 0.081	12.0 17.0	-16.2 1.5	0.44 4.47
12	Gilbert River	G10 - Strathmore Station	05/08/12, 15/10/12, 30/11/12	0.570 0.057 0.046	9.4 9.7 11.0	-46.5 -34.4 -24.8	-5.57 -3.57 -1.03
13	Einasleigh River	A - main channel (shallow) east	02/11/12	1.043	38.0	-22.3	-1.32
14	Einasleigh River	B - anabranch (deep) east	02/11/12	0.114	6.7	-43.4	-3.28
15	Einasleigh River	C - anabranch (deep) east	02/11/12	0.091	7.0	-42.9	-3.32
16	Einasleigh River	D - main channel (30m up of Rd Xing, deep) east	02/11/12	0.057	24.0	-21.3	-1.44
17	Einasleigh River	E - anabranch (shallow between waterholes) west	02/11/12	0.052	63.0	-31.7	-3.31
18	Einasleigh River	Downstream Mount Noble	14/12/12	0.159	27.0	-16.5	-0.05
19	Einasleigh River	Dagworth	14/12/12	0.271	32.0	-7.8	1.80

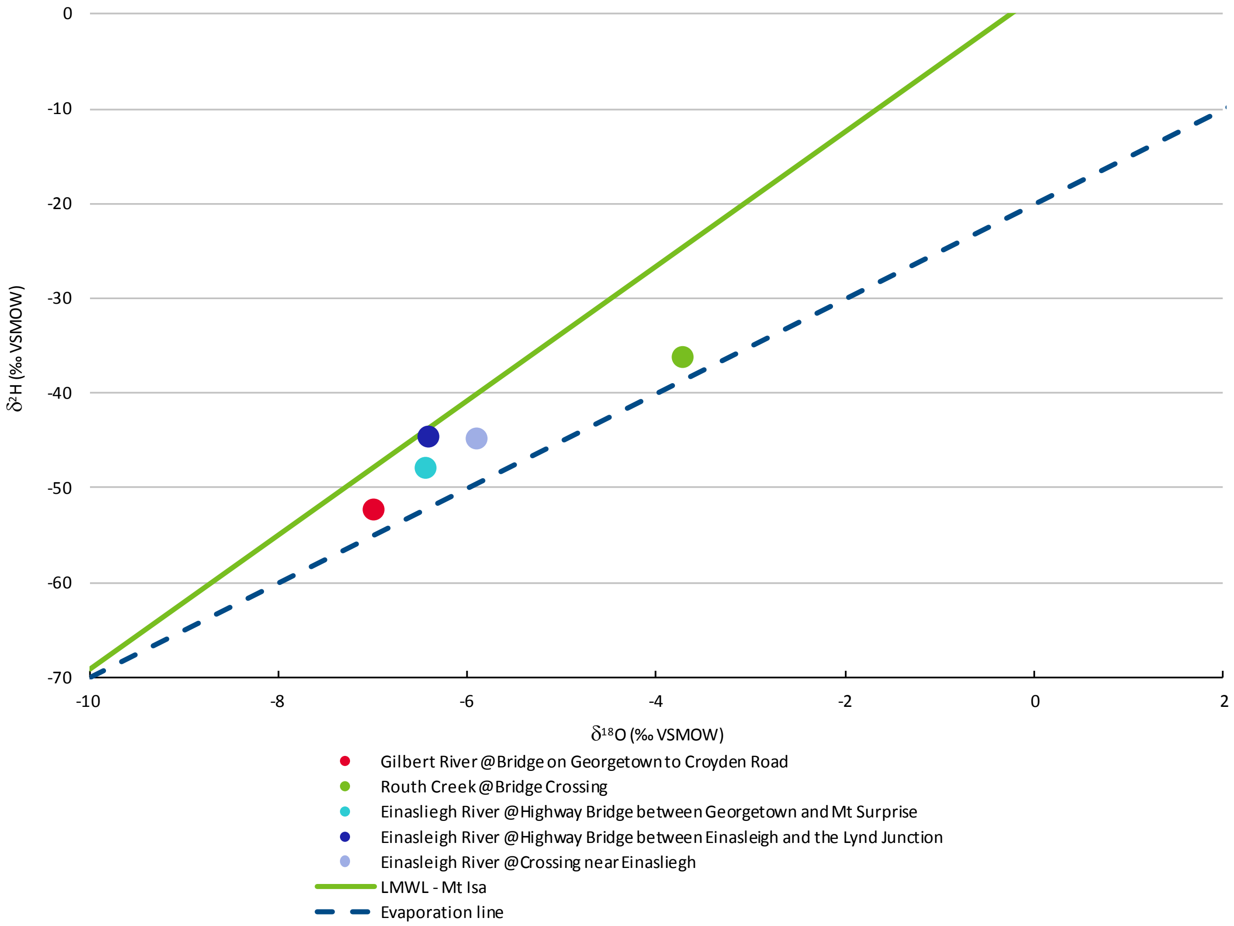

Figure 3.5 Plot of δ^2H versus $\delta^{18}O$ for river sites in the Gilbert catchment that were sampled in May 2012

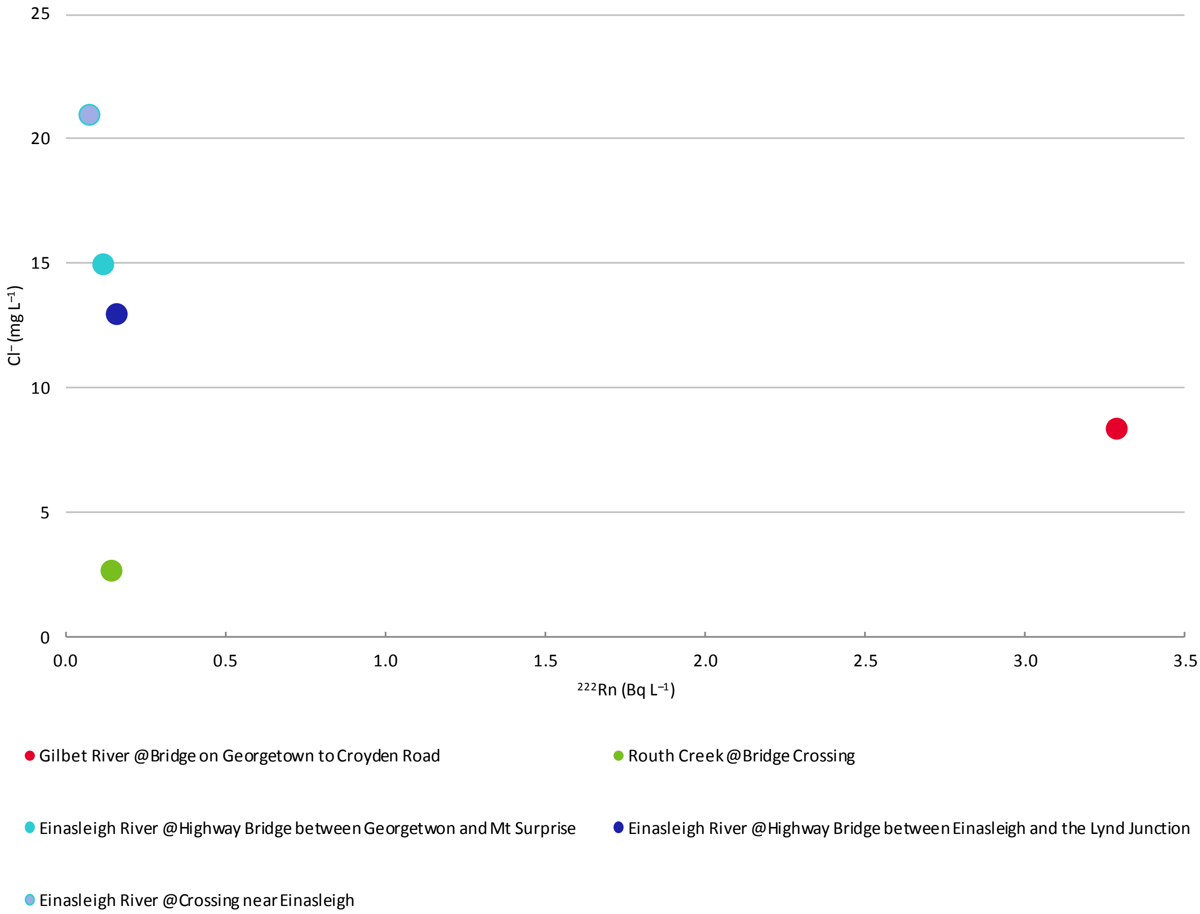

Figure 3.6 Plot of Chloride versus ^{222}Rn for river sites in the Gilbert catchment that were sampled in May 2012

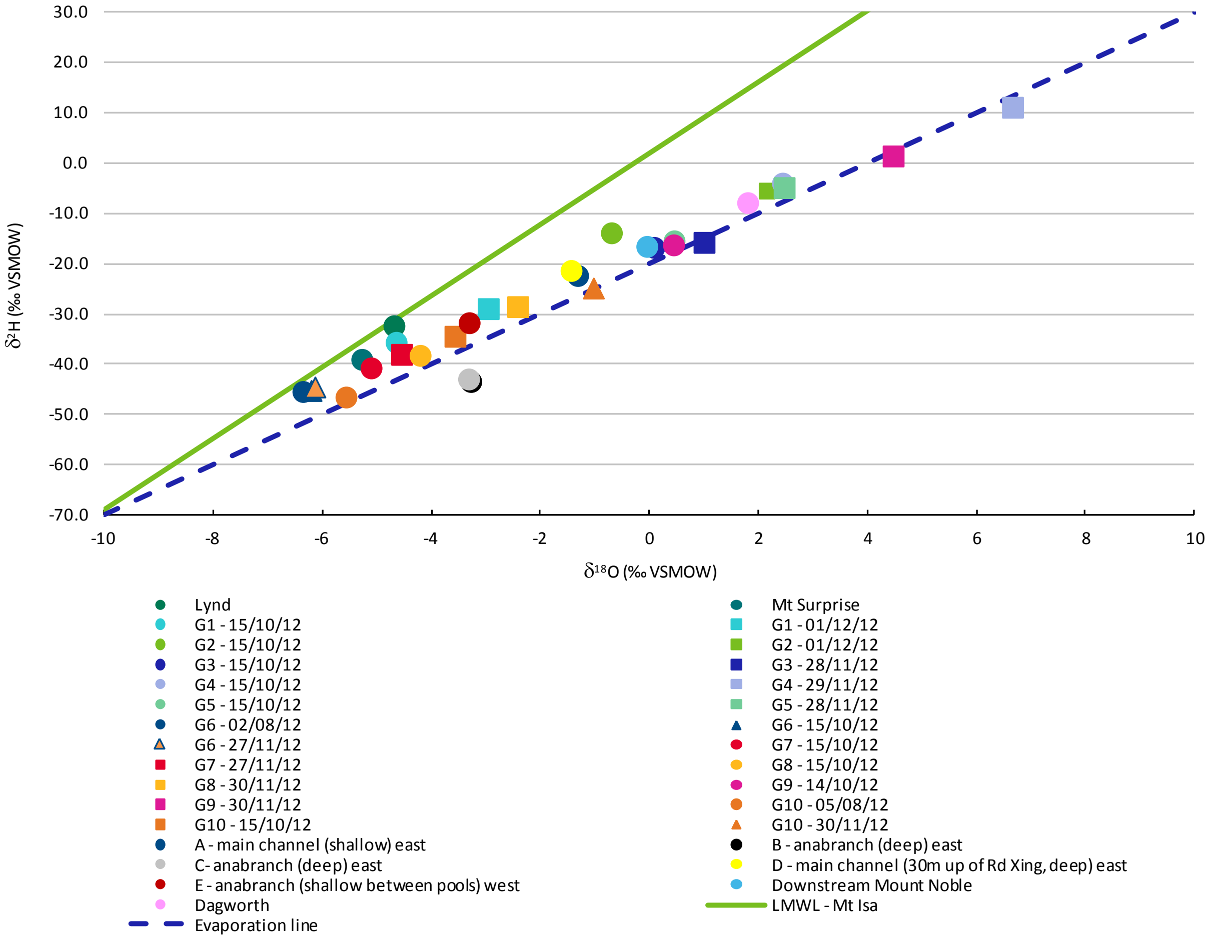

Figure 3.7 Plot of δ^2H versus δ^{18}O for waterhole sites in the Gilbert catchment that were sampled between August and December 2012

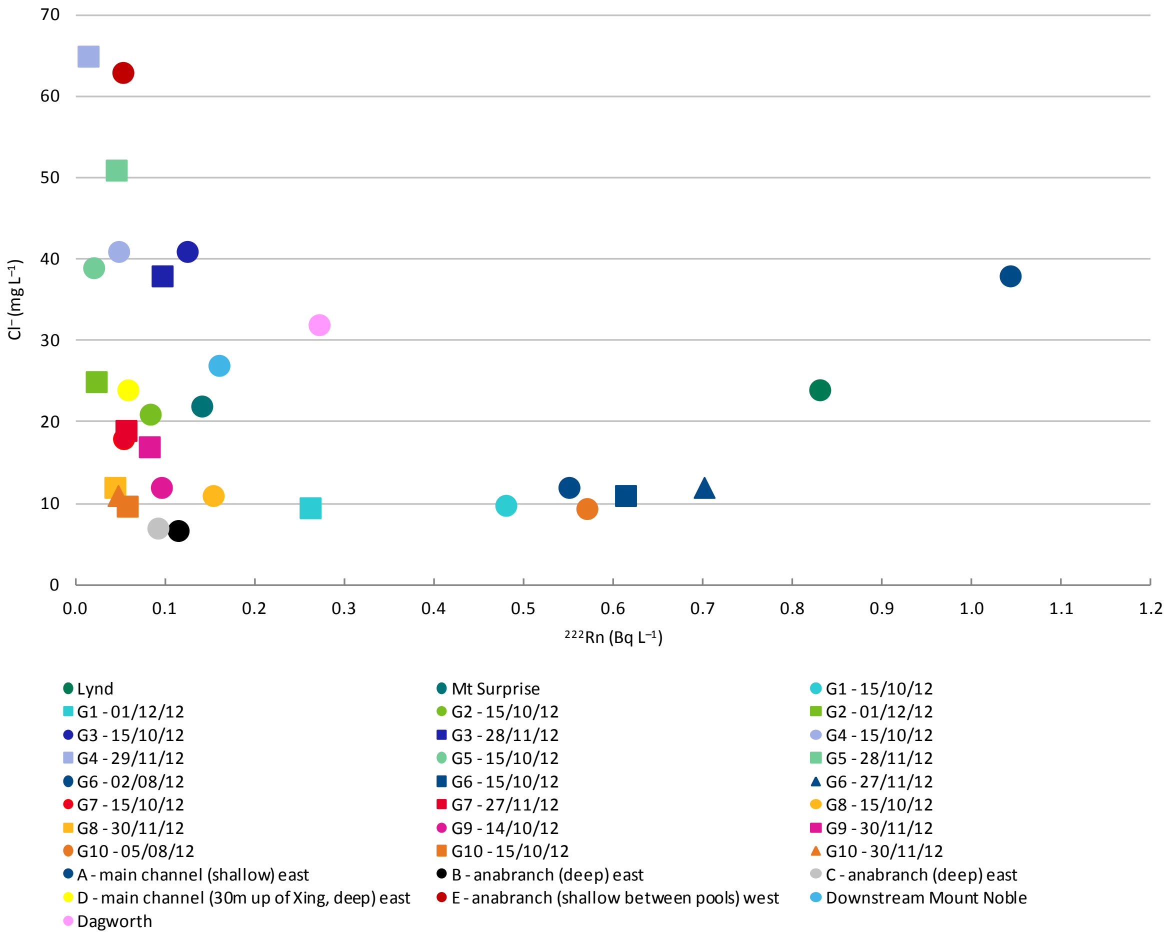

Figure 3.8 Plot of Chloride versus ^{222}Rn for waterhole sites in the Gilbert catchment that were sampled between August and December 2012

3.2 Task 2 - Leakage of water into the shallow alluvial/bedsands aquifers

3.2.1 FLINDERS CATCHMENT

Tracers and major ions

The results of the analyses of the stable isotopes of water (δ^2H and $\delta^{18}O$), chlorofluorocarbons (CFC-11 and CFC-12), sulphur hexafluoride (SF_6), selected major ions, carbon-14 (^{14}C), carbon-13 ($\delta^{13}C$) and dissolved noble gases (^4He, ^{20}Ne and ^{40}Ar) for each alluvial piezometer sampled in the Flinders catchment are given in Table 3.5, Table 3.6 and Table 3.7. The results of the analyses of EC, pH, Total Alkalinity and full major ions for each alluvial piezometer sampled in the Flinders catchment are given in Apx Table A.5 in the Appendix. A Piper diagram illustrating the major ion composition of groundwater in the Flinders catchment is shown in Figure 3.9.

Plots of δ^2H versus $\delta^{18}O$ and ^{14}C versus $\delta^{13}C$ for the alluvial piezometers sampled in the Flinders are shown in Figure 3.10 and Figure 3.11 respectively. The Local Meteoric Water Line (LMWL) depicted on Figure 3.10 is based on rainfall analyses for Mt Isa (as reported in Crosbie et al., 2012), and the Evaporation Line depicted on Figure 3.10 has a slope of 5 and intercept of -20 ‰ δ^2H.

Table 3.5 Results of δ^2H, $\delta^{18}O$, CFC-11, CFC-12 and SF_6 analyses for alluvial piezometers in the Flinders catchment that were sampled in August/September 2012

SITE NUMBER	PIEZOMETER NAME	DATE SAMPLED	δ^2H (‰ VSMOW)	$\delta^{18}O$ (‰ VSMOW)	CFC -11 (pmol/kg)	CFC -12 (pmol/kg)	SF_6 (fmol/L)
1	B3S4	30/08/12	–	–	–	–	–
2	Majuba	30/08/12	-45.2	-6.64	1.31	0.93	1.79
3	P3	03/09/12	-38.0	-5.66	<0.18	>0.16	1.87
4	L1	02/09/12	-44.7	-6.54	<0.18	0.22	0.79
5	B7S5	02/09/12	–	–	–	–	–
6	B5S5	31/08/12	–	–	–	–	–
7	Irrigation Bore No. 2*	31/08/12	-45.4	-6.50	–	–	–
8	Shed Bore	31/08/12	-43.9	-6.61	<0.18	0.84	1.64
9	Shack Bore	31/08/12	-36.4	-4.73	<0.18	0.24	0.83
10	C4	01/09/12	-43.6	-6.26	0.95	1.47	1.94
11	B1S1	02/09/12	–	–	–	–	–
12	B4S4	03/09/12	-42.8	-6.30	<0.18	0.26	0.39
13	B5S5	03/09/12	-45.2	-6.39	<0.18	<0.16	1.40

*This is a GAB bore not an alluvial piezometer

Table 3.6 Results of EC, pH, Total Alkalinity and selected major ion analyses for alluvial piezometers in the Flinders catchment that were sampled in August/September 2012

SITE NUMBER	PIEZOMETER NAME	DATE SAMPLED	EC (dS/m)	pH	Total Alkalinity (meq/L)	Cl^- (mg/L)	Ca (mg/L)	K (mg/L)	Mg (mg/L)	Na (mg/L)
1	B3S4	30/08/12	1.32	8.0	13.5	50.0	81.8	10.2	37.7	138.0
2	Majuba	30/08/12	1.37	8.0	10.7	70.0	21.2	1.7	11.7	248.0
3	P3	03/09/12	0.42	7.8	2.7	18.0	31.0	2.8	9.99	30.6
4	L1	02/09/12	0.51	8.0	3.4	16.0	29.3	1.9	9.77	55.2
5	B7S5	02/09/12	0.16	6.9	0.9	8.1	9.5	3.5	2.97	11.0
6	B5S5	31/08/12	0.66	7.9	5.8	25.0	69.3	7.2	7.05	47.3
7	Irrigation Bore No. 2*	31/08/12	0.70	7.8	6.1	53.0	33.7	5.1	33.6	46.3
8	Shed Bore	31/08/12	2.55	8.3	11.1	300.0	16.8	0.9	12.2	473.0
9	Shack Bore	31/08/12	2.20	7.6	9.2	200.0	59.0	2.1	41.1	322.0
10	C4	01/09/12	0.36	7.7	2.2	27.0	26.5	2.6	5.11	31.6
11	B1S1	02/09/12	1.77	7.5	13.9	31.0	21.7	34.1	9.22	32.3
12	B4S4	03/09/12	1.78	7.6	8.6	170.0	87.6	1.9	20.1	253.0
13	B5S5	03/09/12	2.20	7.5	11.5	170.0	110.0	2.2	26.4	320.0

*This is a GAB bore not an alluvial piezometer

Table 3.7 Results of ^{14}C, $\delta^{13}C$, ^{4}He, ^{20}Ne, ^{40}Ar and Excess Air analyses for alluvial piezometers in the Flinders catchment that were sampled in August/September 2012

SITE NUMBER	PIEZOMETER NAME	DATE SAMPLED	^{14}C (pMC)	$\delta^{13}C$ (‰ PDB)	^{4}He ($ccSTP/g_{H2O}$)	^{20}Ne ($ccSTP/g_{H2O}$)	^{40}Ar ($ccSTP/g_{H2O}$)	Excess Air# ($ccSTP/g_{H2O}$)
1	B3S4	30/08/12	–	–	–	–	–	–
2	Majuba	30/08/12	94.63	-12.8	5.40E-08	1.73E-07	3.13E-04	0.0005
3	P3	03/09/12	98.86	-13.3	–	–	–	–
4	L1	02/09/12	78.75	-13.1	6.15E-08	2.05E-07	3.43E-04	0.0023
5	B7S5	02/09/12	–	–	–	–	–	–
6	B5S5	31/08/12	–	–	–	–	–	–
7	Irrigation Bore No. 2*	31/08/12	38.42	-13.9	–	–	–	–
8	Shed Bore	31/08/12	106.56	-10.5	6.31E-08	2.23E-07	3.96E-04	0.0028
9	Shack Bore	31/08/12	97.32	-15.8	6.85E-08	2.28E-07	4.32E-04	0.0027
10	C4	01/09/12	102.38	-8.5	4.86E-08	1.75E-07	3.15E-04	0.0007
11	B1S1	02/09/12	–	–	–	–	–	–
12	B4S4	03/09/12	90.47	-12.6	–	–	–	–
13	B5S5	03/09/12	98.93	-13.5	8.10E-08	2.78E-07	5.19E-04	0.0050

*This is a GAB bore not an alluvial piezometer

Excess Air in groundwater is due to the solution of air bubbles trapped by infiltrating water in the unsaturated zone (Heaton and Vogel, 1981). Knowledge of the amount of Excess Air is required to correct the groundwater noble gas measurements for the addition of atmospheric noble gases during infiltration. Excess Air concentrations were calculated using the Unfractionated excess Air (UA) model (Kipfer et al., 2002).

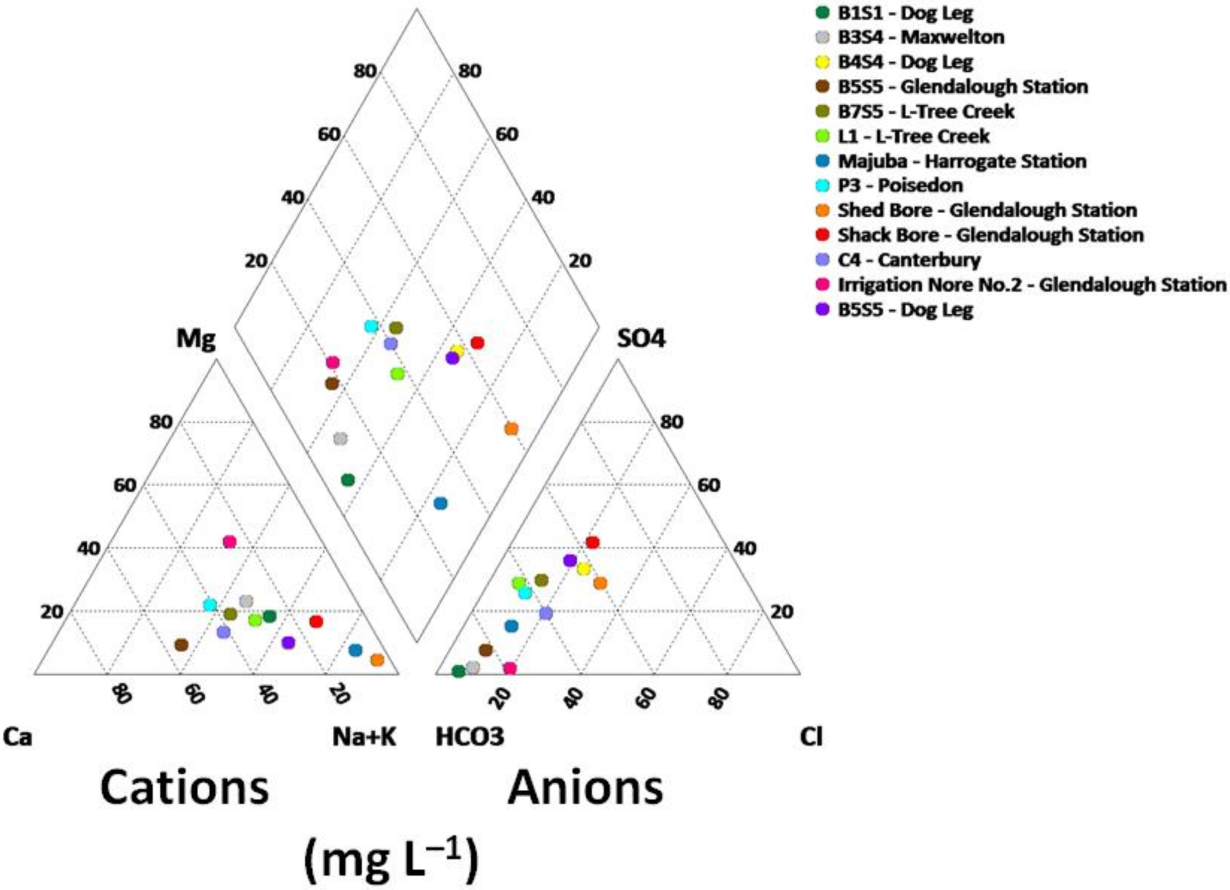

Figure 3.9 Piper diagram illustrating the major ion composition of groundwater in the alluvial aquifers adjacent to the Flinders River that was sampled in August/September 2012

In general piezometers close to the river (<500 m) have lower EC values (<1 dS/m). Most sites more than 500 m from the river have EC values >1 dS/m. The groundwater appears to have two different major ion compositions. The piezometers within 500 m of the river have Ca-HCO_3 dominated groundwater whereas piezometers located greater than 500 m from the river have Na-Cl dominated groundwater. The water in the Flinders River (see Table 3.1 and Apx Table A.1) is Ca-HCO_3 dominated which suggests that the groundwater close to the river has a contribution of river water. All piezometers except for the Shack Bore have similar stable isotope concentrations and the values lie near the LMWL for Mt Isa. This indicates that the groundwater at these sites has undergone little evaporation, which suggests that recharge, when it occurs, moves rapidly through the unsaturated zone down to the watertable. The Shack Bore has a slight evaporation signature and the reason for this is not clear.

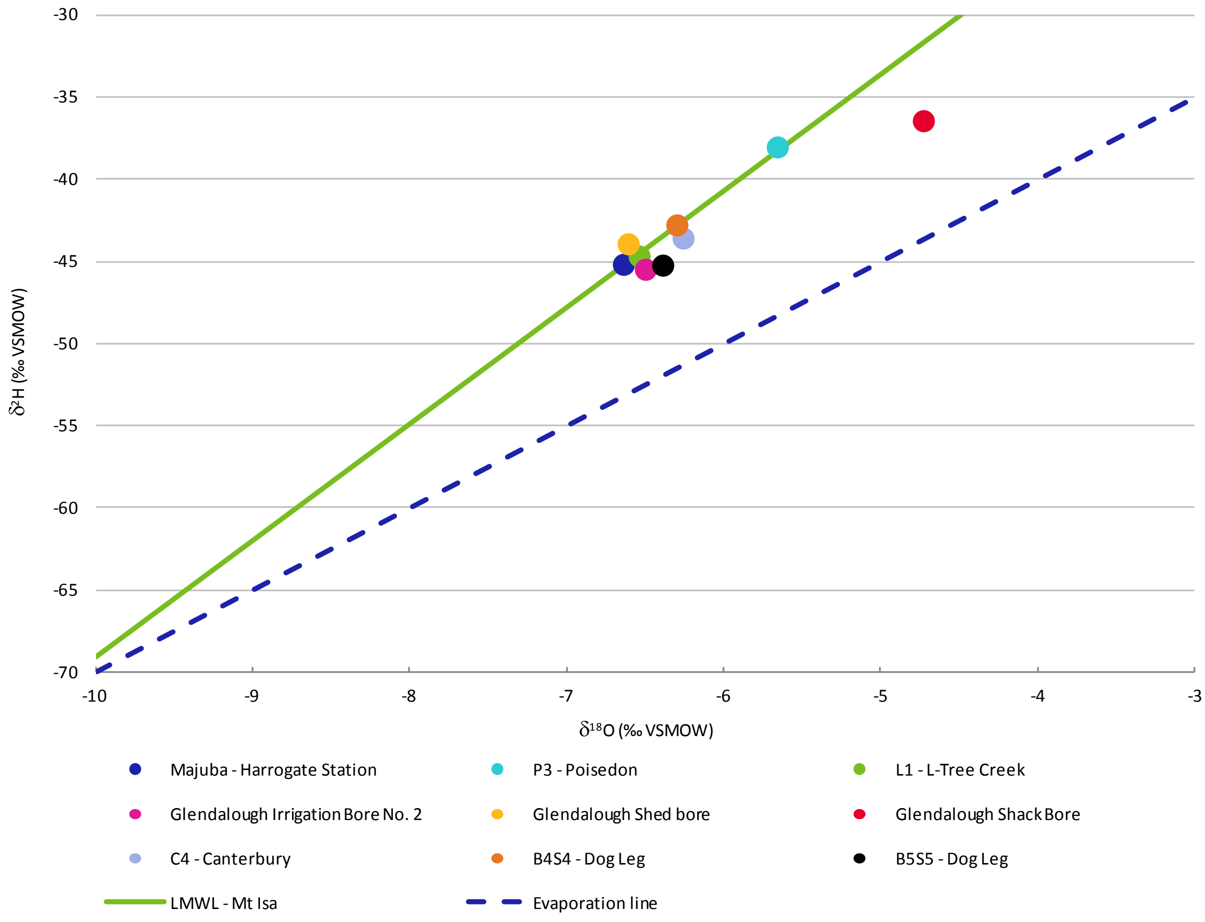

Figure 3.10 Plot of δ^{2}H versus δ^{18}O for groundwater in the Flinders catchment that was sampled in August/September 2012

The anthropogenic trace gas concentrations are variable and range from background values (e.g. CFC-12 <0.16 pmol/kg) to values that suggest modern recharge (e.g. CFC-12 >1 pmol/kg). With the exception of the GAB bore (Irrigation Bore No. 2), the ^{14}C concentrations are moderate (78 pMC) to high (106 pMC), and the δ^{13}C values are also variable. The dissolved noble gas concentrations are close to or above atmospheric concentrations and the amount of excess air in the alluvium/bedsands is highly variable. There are no clear relationships between the anthropogenic trace gas concentrations, ^{14}C concentrations and dissolved noble gas concentrations in the groundwater with distance from the river.

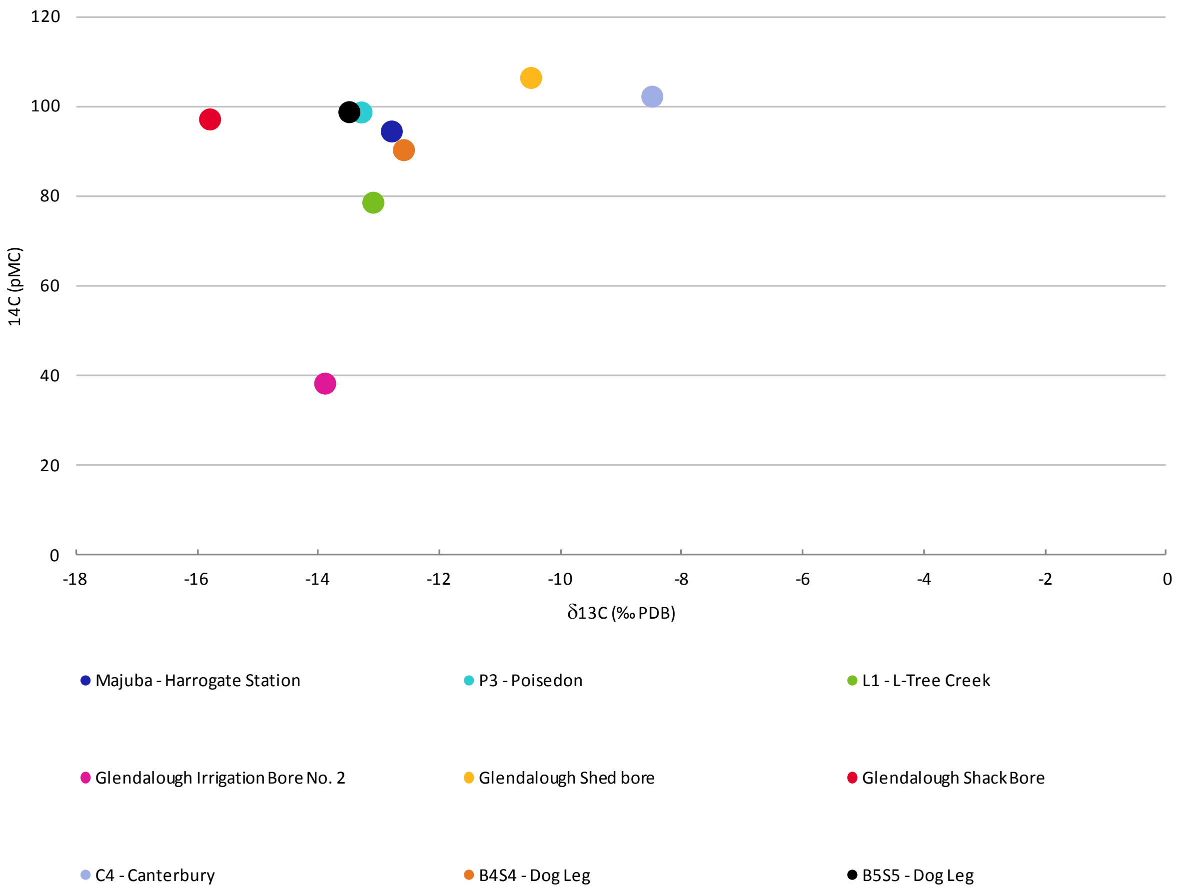

Figure 3.11 Relationship between measured $\delta^{13}C$ and ^{14}C for groundwater in the Flinders catchment that was sampled in August/September 2012

Hydrograph analysis

There was very little rainfall in the Flinders catchment during the 2012/13 wet season. As a result there were only two minor flow events in the Flinders River. Hence, the five water level loggers that were installed in the bed of the Flinders River did not record any data over the wet season as each were deployed at a height slightly above the maximum level the Flinders River rose during the 2012/13 wet season. No data from these loggers are presented.

The water level/salinity loggers installed in the piezometers B7S5 and B5S5 (site 13) malfunctioned completely and so no data for these are presented. Plots of groundwater level and salinity (as EC) data over the period 08/9/12 to 27/03/13 for each of the remaining piezometers are shown in Figure 3.12, Figure 3.13, Figure 3.14, Figure 3.15, Figure 3.16, Figure 3.17, Figure 3.18, Figure 3.19 and Figure 3.20. Note that some of these piezometers have only partial records due to the groundwater level dropping below the screened interval of the piezometer.

In each of the plot of groundwater level (left Y axis), the water level in the Flinders River (right Y axis), as measured at the Queensland government at gauging station 915008A (upstream of Richmond), is shown for comparison. While this gauging station is downstream of most of the piezometers, it is the only Flinders River gauging station in the study area that had relevant water level data during the measurement period. As such, the relative heights of the piezometer and groundwater levels cannot be directly compared, and so the plots are used only to see if the piezometer water levels responded to the river flow events. Due to the generally dry conditions during the 2012/13 wet season there was only one minor flow event in December 2012, with a smaller follow-up event occurring in January 2013. The magnitudes of both events are much smaller than would normally be expected to occur in the wet season and therefore limits the amount of information on surface water-groundwater connectivity that can be derived from the data.

Piezometer B3S4 is located approximately 150 m from the Flinders River. At this site two months of data were captured prior to the groundwater level dropping below the screened interval, and so the response to the two flow events in the Flinders River was not recorded. No useful information on surface water-groundwater connectivity can be derived from the data from this site.

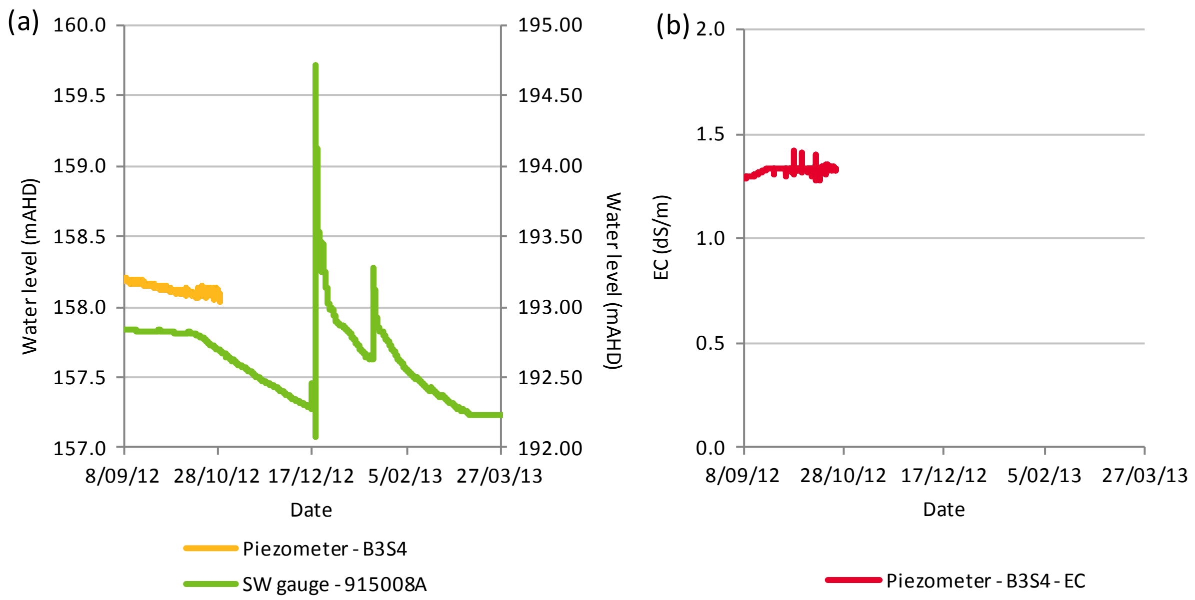

Figure 3.12 Plots of (a) groundwater level at piezometer B3S4 versus surface water level over time (data provided by the State of Queensland (Department of Natural Resources and Mines), 2013)), and (b) groundwater EC at piezometer B3S4 over time

The piezometer Majuba is located approximately 3,800 m from the Flinders River. The groundwater level and EC remained approximately constant throughout the measurement period and showed no response to the two flow events, presumably due to the distance this piezometer is from the river.

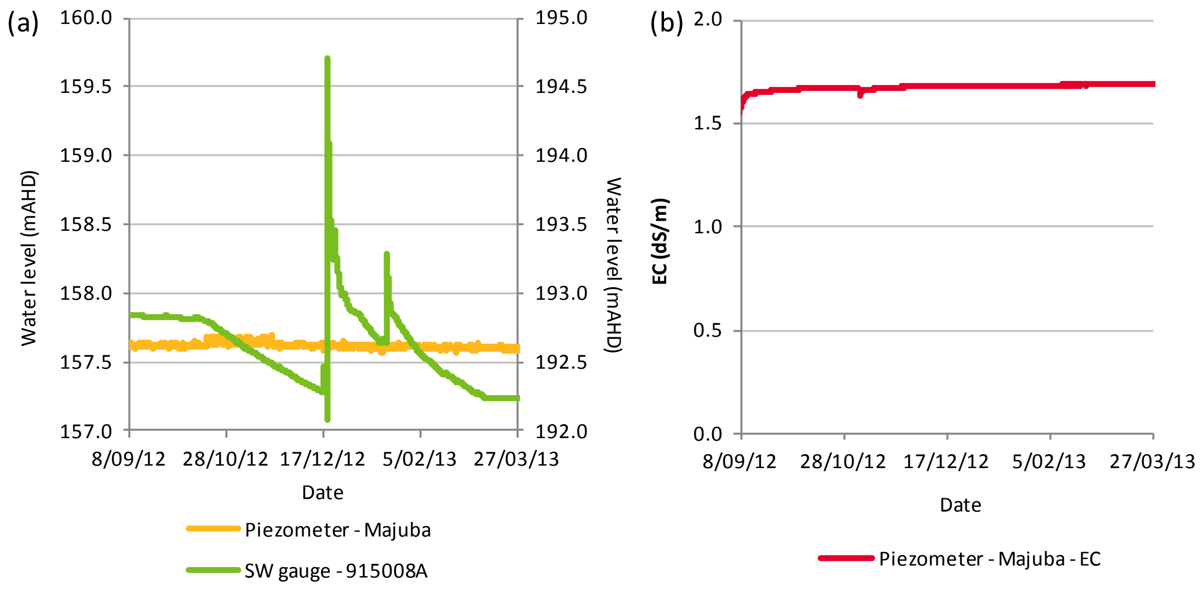

Figure 3.13 Plots of (a) groundwater level at piezometer Majuba versus surface water level over time (data provided by the State of Queensland (Department of Natural Resources and Mines), 2013)), and (b) groundwater EC at piezometer Majuba over time

Piezometer P3 is located approximately 110 m from the Flinders River. The groundwater level increased in response to the flow events but then receded to near its starting level by the end of the measurement period. The groundwater EC increased slowly until the flow event (which is presumably due to a slow recovery response after the piezometer was pumped during sampling - the groundwater level also shows a slow recovery response during this period). The groundwater EC then decreased during the flow events indicating that river water did recharge the alluvial/bedsands aquifer at this site. However, the groundwater EC increased to its pre-flow event value within approximately two months of the first flow event indicating that all of the river recharge that occurred during the flow events discharged back into the river. This observation suggests that this was a bank recharge/discharge process and therefore it was likely that there was zero net river recharge from the flow events.

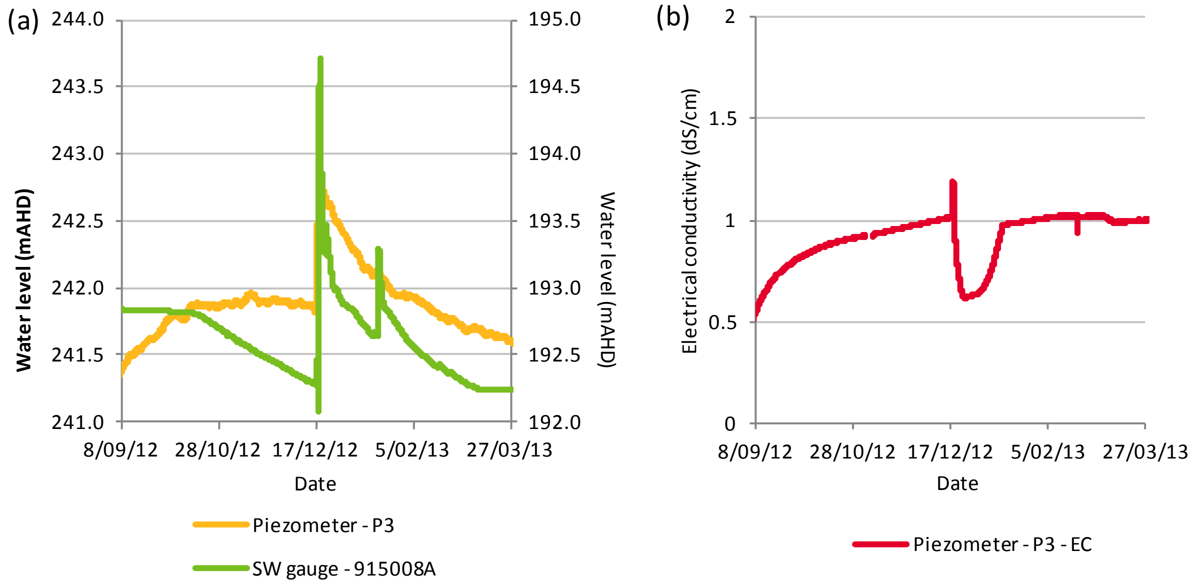

Figure 3.14 Plots of (a) groundwater level at piezometer P3 versus surface water level over time (data provided by the State of Queensland (Department of Natural Resources and Mines), 2013)), and (b) groundwater EC at piezometer P3 over time

Piezometer L1 is located approximately 40 m from the Flinders River. The groundwater level decreased slowly over the measurement period with only a very minimal response to the flow events. The groundwater EC remained approximately constant throughout the measurement period. Both of these datasets indicate that there was no river recharge at this site during the measurement period.

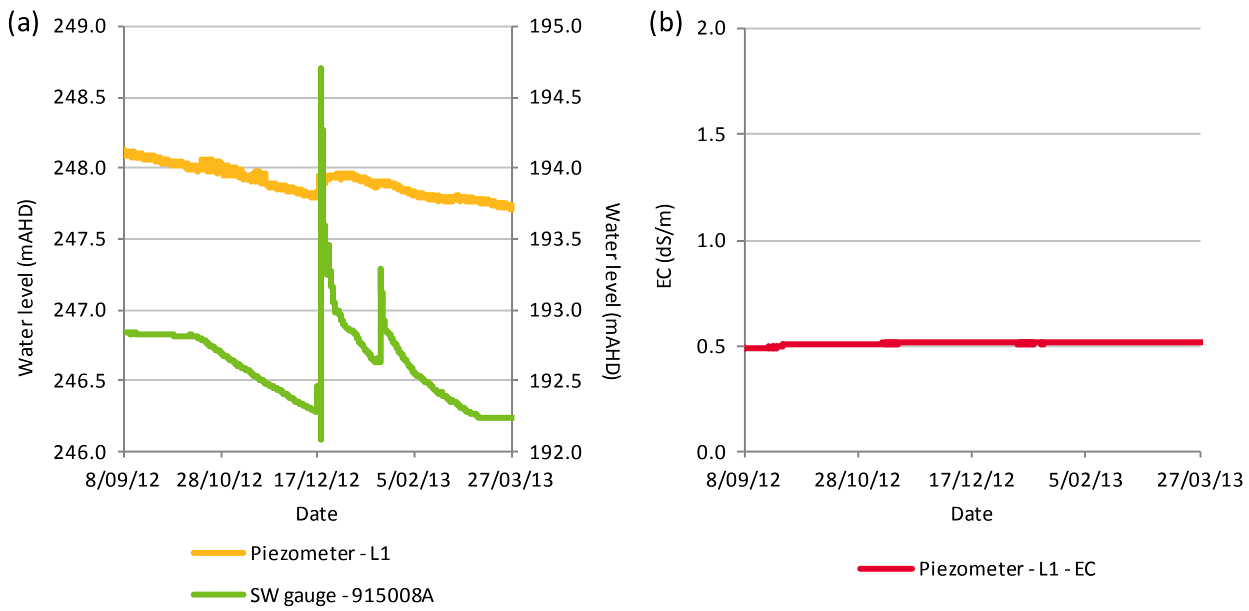

Figure 3.15 Plots of (a) groundwater level at piezometer L1 versus surface water level over time (data provided by the State of Queensland (Department of Natural Resources and Mines), 2013)), and (b) groundwater EC at piezometer L1 over time

Piezometer B5S5 (site 6) is located approximately 75 m from the Flinders River. At this site six weeks of data were captured prior to the groundwater level dropping below the screened interval, and so the response to the two flow events in the Flinders River was not recorded. As such there is no useful information on surface water-groundwater connectivity that can be derived from the data from this site.

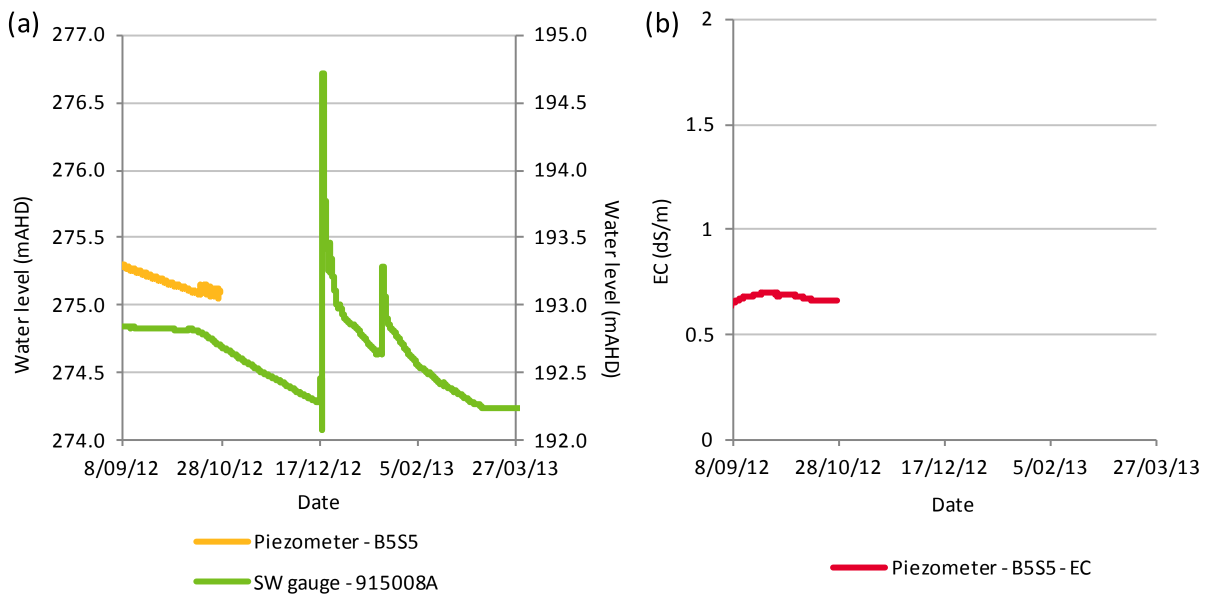

Figure 3.16 Plots of (a) groundwater level at piezometer B5S5 versus surface water level over time (data provided by the State of Queensland (Department of Natural Resources and Mines), 2013)), and (b) groundwater EC at piezometer B5S5 over time

Piezometer Shack Bore is located approximately 475 m from the Flinders River. It is also located approximately 35 m from a production bore that unfortunately began operation at the beginning of the measurement period. The groundwater level and EC fluctuated throughout the measurement period and this is most likely due to the influence of the nearby production bore. No useful information on surface water-groundwater connectivity can be derived from the data from this site.

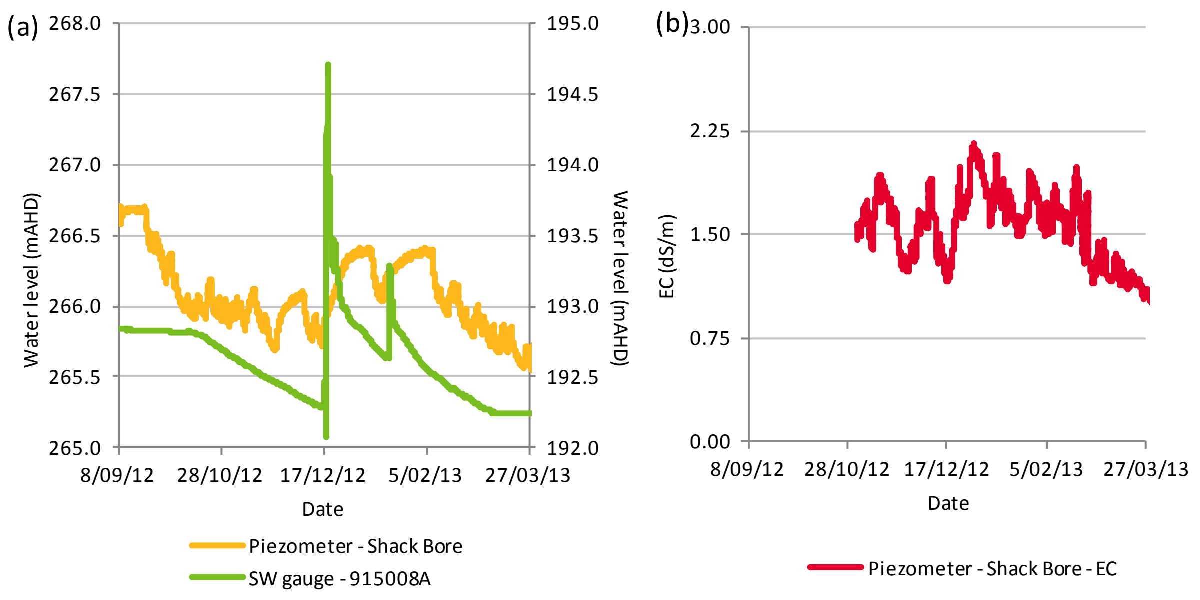

Figure 3.17 Plots of (a) groundwater level at piezometer Shack Bore versus surface water level over time (data provided by the State of Queensland (Department of Natural Resources and Mines), 2013)), and (b) groundwater EC at piezometer Shack Bore over time

Piezometer C4 is located approximately 5 m from the Flinders River. The groundwater level increased slightly in response to just the first flow event but then receded to its starting level by the end of the measurement period. The groundwater EC increased slowly until the flow event (which is presumably due to a slow recovery response after the piezometer was pumped during sampling - the groundwater level also shows a slow recovery response during this period). The groundwater EC then decreased slightly during the first flow event indicating that river water did provide a small amount of recharge to the alluvial/bedsands aquifer at this site. However, the groundwater EC increased to its pre-flow event value soon after the first flow event indicating that all of the river recharge that occurred during the first flow event discharged back into the river. This observation suggests that this was a bank recharge/discharge process and therefore it was likely that there was zero net river recharge from the flow events.

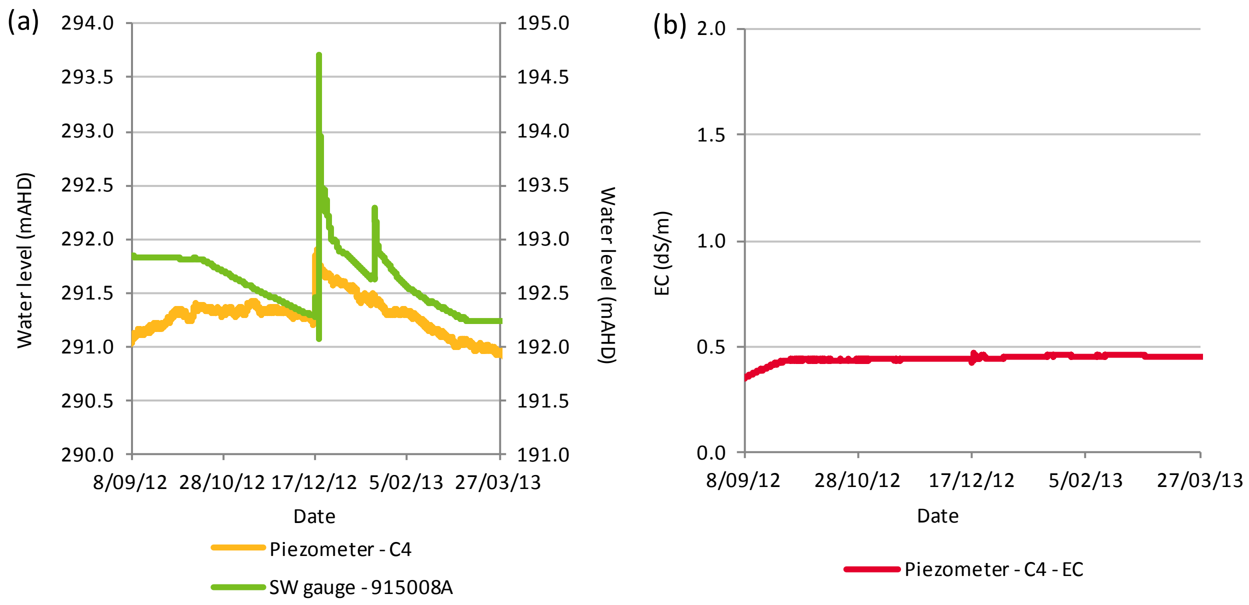

Figure 3.18 Plots of (a) groundwater level at piezometer C4 versus surface water level over time (data provided by the State of Queensland (Department of Natural Resources and Mines), 2013)), and (b) groundwater EC at piezometer C4 over time

Piezometer B1S1 is located approximately 50 m from the Flinders River. The groundwater level generally declined over the measurement period although there is some indication that it increased very slightly in response to just the first flow event. The groundwater EC generally increased over the measurement period but had periods in which it decreased (including one that corresponds with the first flow event). It is not clear exactly why the EC increased so much during the measurement period but it is possible that alluvial/bedsands groundwater from further away from the river was still flowing back past this site toward the river channel in response to the river level receding at the end of the previous wet season. The alluvium/bedsands at Hughenden is very wide and is traversed by several other streams than just the Flinders River (e.g. Galah Creek). Given the complicated surface hydrology of this area it is difficult to come to any clear conclusions as to the exact nature of the surface-groundwater connectivity of the Flinders River at this site.

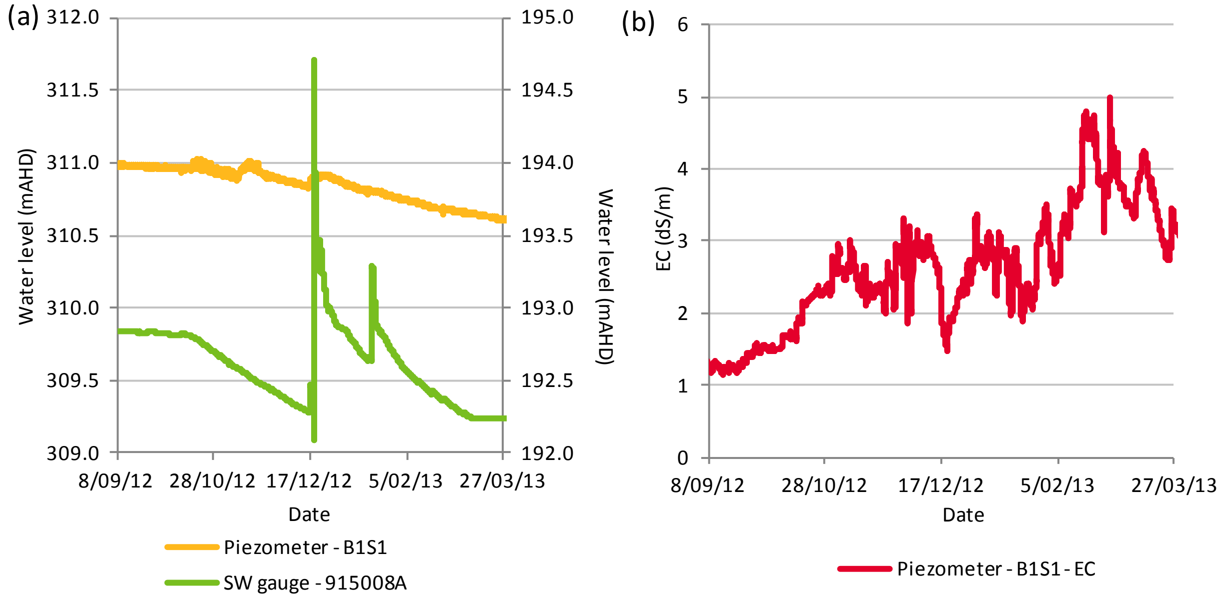

Figure 3.19 Plots of (a) groundwater level at piezometer B1S1 versus surface water level over time (data provided by the State of Queensland (Department of Natural Resources and Mines), 2013)), and (b) groundwater EC at piezometer B1S1 over time

Piezometer B4S4 is located approximately 1,600 m from the Flinders River. The logger at this site only recorded the groundwater level. The groundwater level increased early in the measurement period, possibly in response to the flow events. However it started increasing well before the flow event which in part can be explained by the fact that the gauging station is more than 100 km downstream of this site. However the groundwater level did not then recede to its starting level by the end of the measurement period. The piezometer is approximately 30 m from a creek which was dry at the beginning of the measurement period. However it appears likely that this creek may have flowed/ponded early in the wet season and this is the cause of the increase in groundwater level, particularly given how far this piezometer is from the Flinders River. However, there is evidence of a delayed response (approximately six weeks) to the two flow events in the Flinders River. As there were no EC data it is not clear whether this is just a pressure response or due to river recharge, however given the large distance of this piezometer from the Flinders River, the former is most likely.

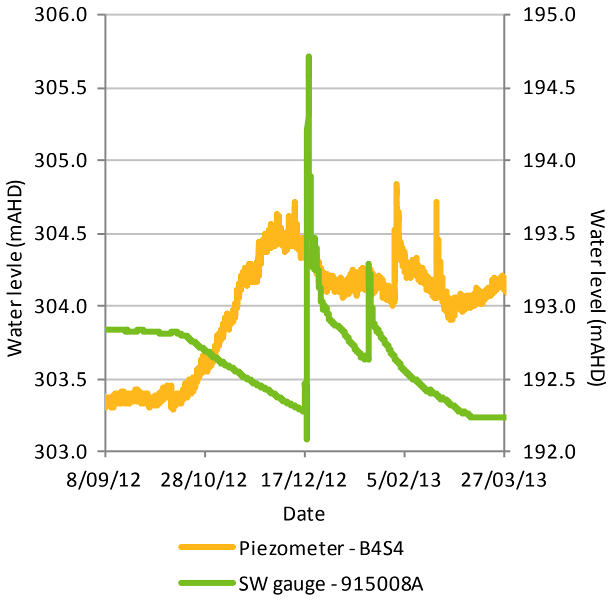

Figure 3.20 Plots of (a) groundwater level at piezometer B4S4 versus surface water level over time (data provided by the State of Queensland (Department of Natural Resources and Mines), 2013)), and (b) groundwater EC at piezometer B4S4 over time

3.2.2 GILBERT CATCHMENT

Tracers and major ions

The results of the analyses of the stable isotopes of water (δ^2H and δ^{18}O), chlorofluorocarbons (CFC-11 and CFC-12), sulphur hexafluoride (SF_6), selected major ions, carbon-14 (^{14}C), carbon-13 (δ^{13}C) and dissolved noble gases (^{4}He, ^{20}Ne and ^{40}Ar) for each GAB piezometer sampled in the Gilbert catchment are given in Table 3.8, Table 3.9 and Table 3.10. The results of the analyses of EC, pH, Total Alkalinity and full major ions for each alluvial piezometer sampled in the Gilbert catchment are given in Apx Table A.6 in the Appendix.

Both piezometers have similar stable isotope concentrations and the values lie near the LMWL for Mt Isa indicating that the groundwater at both sites has undergone little evaporation. Piezometer GROB2 has higher EC, pH, Total Alkalinity and major ion concentrations than piezometer GROB4. However, the values are low at both sites and are consistent with the fact that the groundwater has undergone little evaporation, suggesting that recharge, when it occurs, moves rapidly through the unsaturated zone down to the watertable. The major ion composition of the groundwater from both piezometers is Na-HCO_3 type which is consistent with GAB groundwater in this region (Smerdon et al., 2012). However, the water in the Gilbert River (see Table 3.3 and Apx Table A.3) also has the same major ion composition.

Piezometer GROB2 has much lower anthropogenic trace gas concentrations than piezometer GROB4 suggesting that it has older groundwater. Conversley, piezometer GROB2 has a much higher ^{14}C concentration and a slightly more enriched δ^{13}C value than piezometer GROB4, suggesting that it has much younger groundwater. The dissolved noble gas concentrations of groundwater are close to atmospheric concentrations for GROB2 suggesting it has younger groundwater. The dissolved noble gas concentrations of the groundwater from GROB 4 are slightly above atmospheric concentration suggesting older groundwater. The amount of excess air in the groundwater is higher for GROB4 than for GROB2. These apparent contradictions in the various isotopes and tracers are discussed in more detail in Section 4.2.2.

Table 3.8 Results of δ^2H, δ^{18}O, CFC-11, CFC-12 and SF_6 analyses for GAB piezometers in the Gilbert catchment that were sampled in April 2013

SITE NUMBER	PIEZOMETER NAME	DATE SAMPLED	δ^2H (‰ VSMOW)	δ^{18}O (‰ VSMOW)	CFC -11 (pmol/kg)	CFC -12 (pmol/kg)	SF_6 (fmol/L)
1	GROB2	21/04/13	-45.8	-6.68	<0.18	<0.17	0.12
2	GROB4	21/04/13	-46.9	-7.19	0.80	0.55	1.74

Table 3.9 Results of EC, pH, Total Alkalinity and selected major ion analyses for GAB piezometers in the Gilbert catchment that were sampled in April 2013

SITE NUMBER	PIEZOMETER NAME	DATE SAMPLED	EC (dS/m)	pH	Total Alkalinity (meq/L)	Cl^- (mg/L)	Ca (mg/L)	K (mg/L)	Mg (mg/L)	Na (mg/L)
1	GROB2	21/04/13	0.51	7.3	4.8	10	31.08	1.78	22.17	52.32
2	GROB4	21/04/13	0.22	6.4	0.5	22	2.92	7.13	4.16	32.05

Table 3.10 Results of ^{14}C, $\delta^{13}C$, ^{4}He, ^{20}Ne, ^{40}Ar and Excess Air analyses for GAB piezometers in the Gilbert catchment that were sampled in April 2013

SITE NUMBER	PIEZOMETER NAME	DATE SAMPLED	^{14}C (pMC)	$\delta^{13}C$ (‰ PDB)	^{4}He ($ccSTP/g_{H2O}$)	^{20}Ne ($ccSTP/g_{H2O}$)	^{40}Ar ($ccSTP/g_{H2O}$)	Excess air # ($ccSTP/g_{H2O}$)
1	GROB2	21/04/13	103.44	-10.04	8.56E-08	2.32E-07	3.70E-04	0.0002
2	GROB4	21/04/13	52.25	-12.84	4.16E-07	2.02E-07	3.21E-04	0.0020

Excess Air in groundwater is due to the solution of air bubbles trapped by infiltrating water in the unsaturated zone (Heaton and Vogel, 1981). Knowledge of the amount of Excess Air is required to correct the groundwater noble gas measurements for the addition of atmospheric noble gases during infiltration. Excess Air concentrations were calculated using the Unfractionated excess Air (UA) model (Kipfer et al., 2002).

Hydrograph analysis

The water level/salinity logger installed in the piezometer GROB2 malfunctioned completely and so no data for this piezometer are presented.

A plot of the groundwater level data over the period 02/11/12 to 11/04/13 for piezometer GROB4 is shown in Figure 3.21. In this plot of groundwater level (left Y axis), the water level in the Gilbert River (right Y axis), as measured at the Queensland government at gauging station 917001D (at Rockfields), is shown for comparison. Unfortunately the recorded EC data were erroneous due to high turbidity in this piezometer and are therefore not presented. Due to the generally dry conditions during the 2012/13 wet season there were only two minor flow events in January and in February. The magnitudes of both events are much smaller than would normally be expected to occur in the wet season and therefore limits the amount of information on surface water-groundwater connectivity that can be derived from the data. Piezometer GROB4 (site 2) is located approximately 2,300 m from the Gilbert River. The groundwater level had minor fluctuations throughout the measurement period. The only significant groundwater responses appear to be increases of ~0.1 m following the two flow events in the Gilbert River whereby the river level rose slightly above the groundwater level. As there were no EC data it is not clear whether this is just a pressure response or is due to river recharge, however given the large distance of this piezometer from the Gilbert River, the former is most likely.

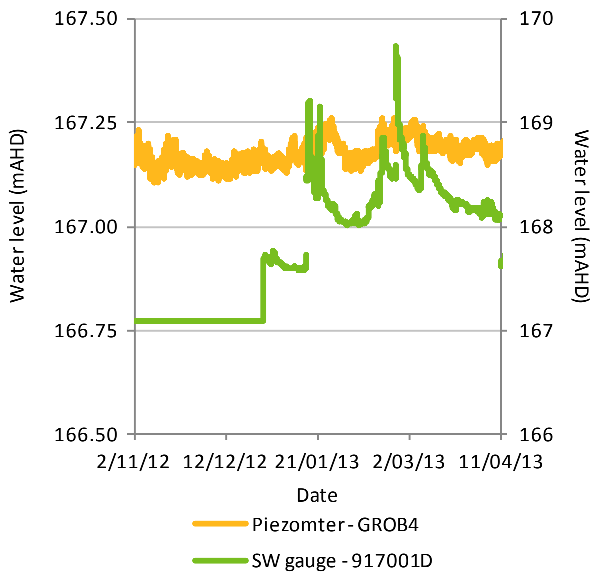

Figure 3.21 Plots of (a) groundwater level at piezometer GROB4 versus surface water level over time

3.3 Task 3 - Risk of root zone drainage beneath irrigation leading to watertable rise

3.3.1 SENSITIVITY ANALYSIS

An analytical modelling approach was adopted to evaluate the maximum (steady state) rise in ground watertable as a result of introducing new irrigation developments of varying areas situated at various distances from the river edge. A total of 420 steady state simulations of circular irrigation areas were conducted based on the combinations of parameters shown in Table 3.11. A separate transient analysis was adopted to investigate the time scales during which the head and flux responses occur.

Table 3.11 Parameters for sensitivity analysis of groundwater rise

PARAMETER	SYMBOL	UNIT	VALUES	COMMENT
Distance from centre of irrigation area to river	d	km	0.5, 1.0, 2.0, 5.0, and 10.0	River assumed to be straight
Circular irrigation area	A	ha	100, 250, 500, 1000	For radii of 564, 892, 1262 and 1784 m
Recharge rate	R	mm/yr	1, 10, 20, 50, 100, 200, and 500	Recharge rate is related to the amount of water applied and the permeability of the soil. A recharge rate of 500 mm/yr (or more) could occur under a ring tank.
Aquifer transmissivity (i.e. saturated hydraulic conductivity multiplied by aquifer thickness)	T	m^2/day	200, 500, and 2000	Representing a constant saturated aquifer thickness h=10m, and hydraulic conductivities K=20, 50, and 200 m/day
Specific yield	Sy		0.10-0.20	Only used for transient simulations

3.3.1.1 STEADY STATE WATER TABLE RISE

The simulations predict that a new irrigation development (recharge source) results in the formation of a groundwater mound, with the size of the mound being a function of the volume of the applied recharge (represented by the radius of the circular recharge area, R, and the recharge rate), the distance between the centre of the recharge source and the river (d), and aquifer drainage capacity (transmissivity/recharge rate). A sample 3-dimensional surface of the mound is shown in Figure 3.22. The point of maximal water table rise is located along the centre of the circular irrigation area (with radius R) at a distance equal to $(d^2+R^2)^{0.5}$ from the river edge, where d represents the distance from the river edge to the centre of the irrigation development.

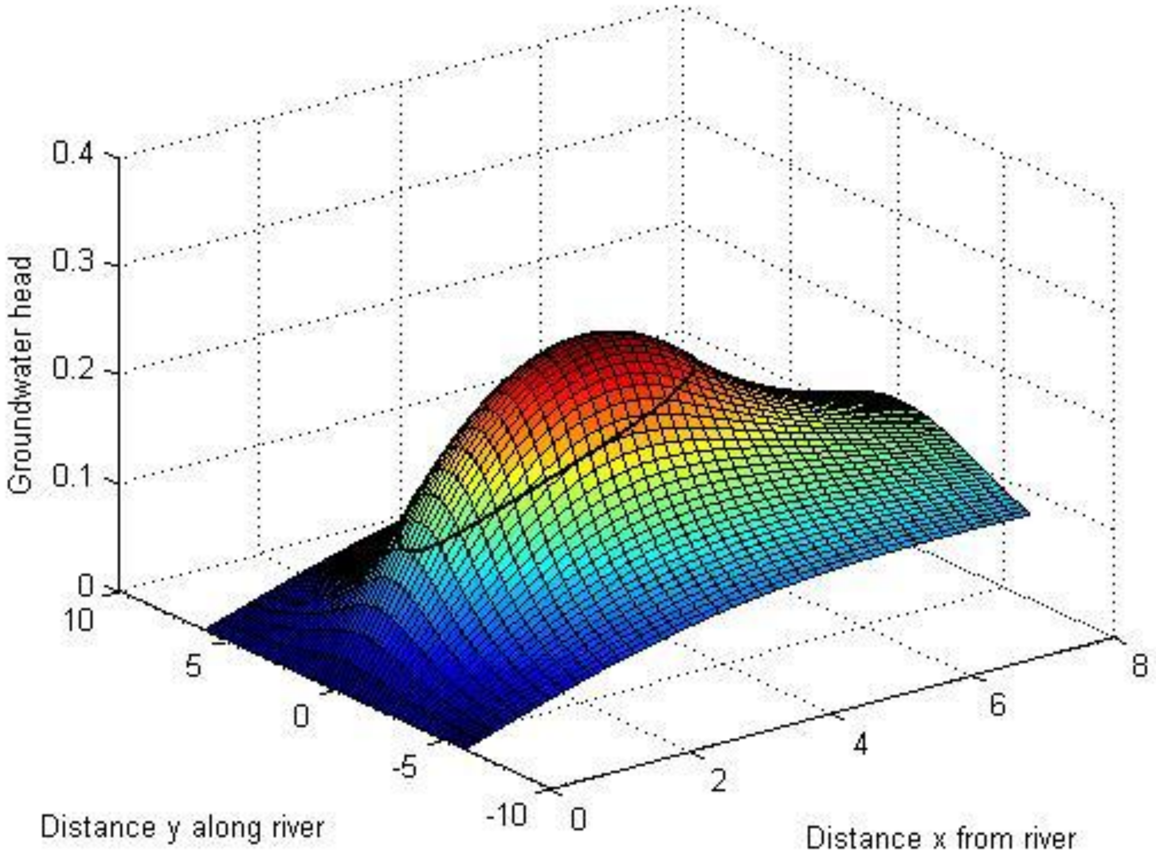

Figure 3.22 3-dimensional groundwater mound resulting from a circular recharge area

The maximum rise in water table level, increases with higher recharge rates and decreases with higher saturated hydraulic conductivity. Figure 3.23 shows the effects of saturated hydraulic conductivity (and hence aquifer transmissivity) and recharge rates are linear but opposite and perfectly correlated. Hence to simply the presentation of results and reduce the number of variables it is possible to report groundwater table level against recharge rate divided by the aquifer transmissivity.

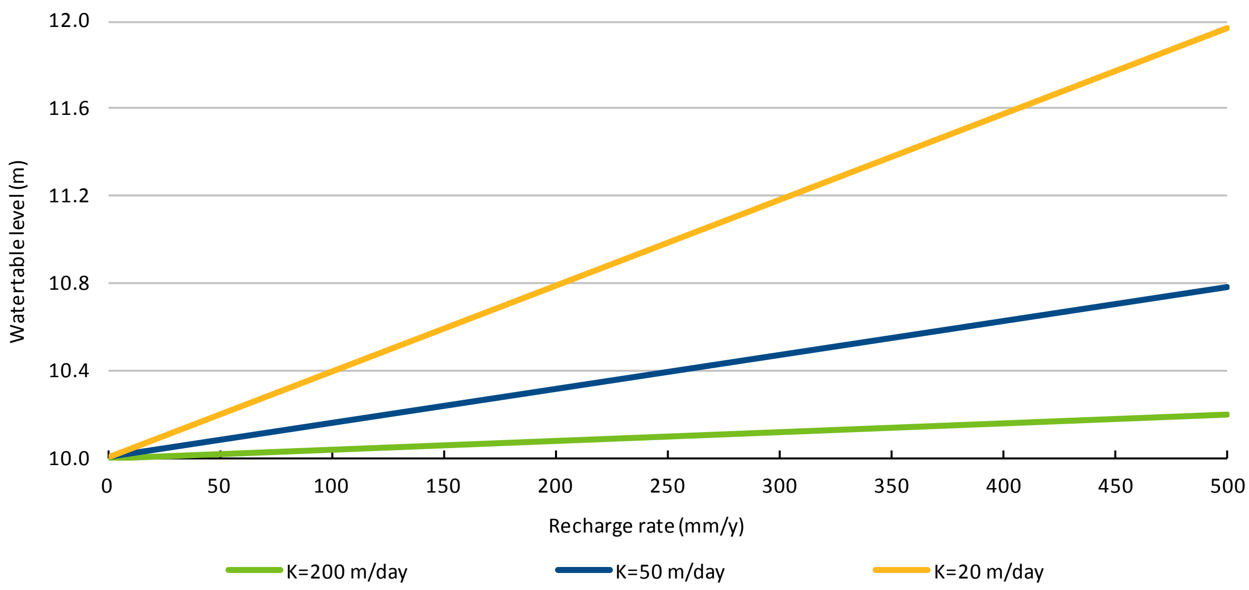

Figure 3.23 Steady state watertable levels for various recharge rates and hydraulic conductivities (K)

Figure 3.24 shows the maximum ground watertable level for a 100ha irrigation area. This figure shows the maximum watertable level decreases as the distance irrigation area to the river decreases. This is because as the irrigation area gets closer to the river, more groundwater is able to be discharged to the river. Figure 3.25 shows that the maximum water table level increases in a non-linear manner as the distance from the irrigation area to the river increases

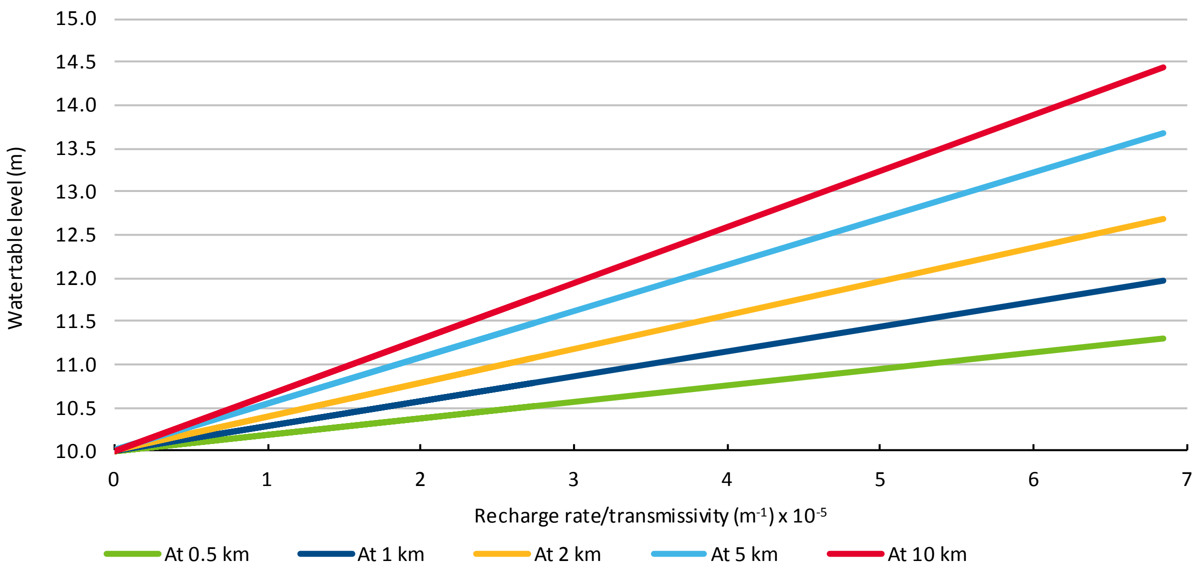

Figure 3.24 Plots of steady state water table levels; irrigation area= 100 ha

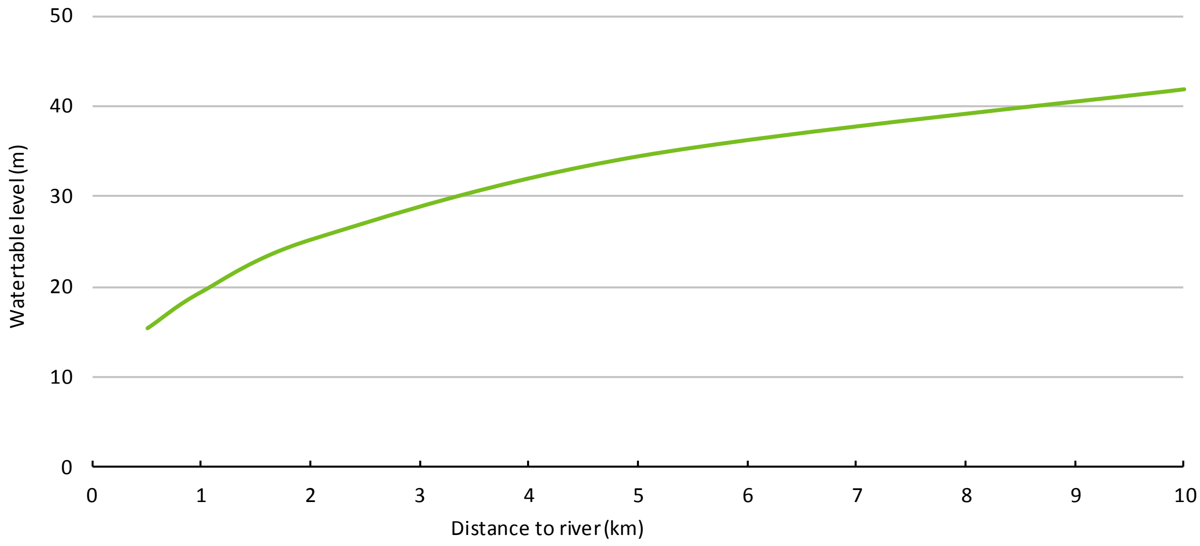

Figure 3.25 Plots of effect of distance to river on water steady state water table level (h); so/T=8.85E^{-5} m^{-1}, A=1000 ha

Figure 3.26, and 3.28 show that as the size of the irrigation area increases, the maximum water table rise also increases. For the combination of parameters considered for the Gilbert catchment, the highest point on the 'Red line' in Figure 6 shows the upper bound for groundwater rise (h_{max} =41.8-10 = 31.8 m, where 10 is the initial water table level), which represents the largest irrigation area (A=1000 ha considered in this study) located furthest from the river (d), with an aquifer having the lowest drainage capacity (highest so/T).

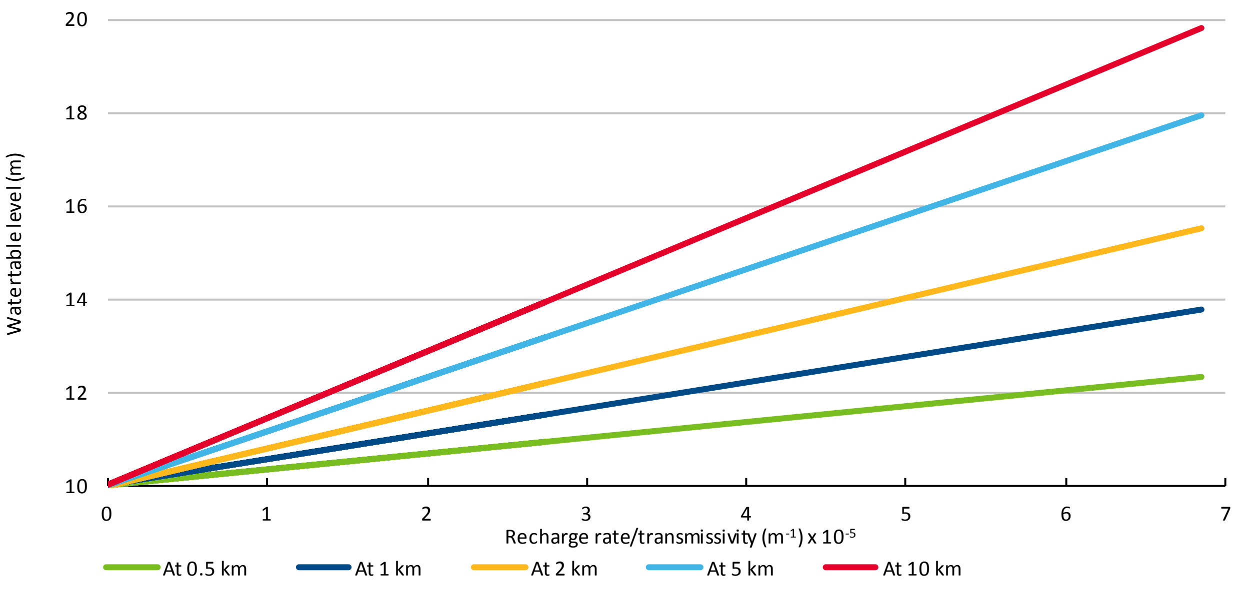

Figure 3.26 Plots of steady state water table level; irrigation area= 250 ha

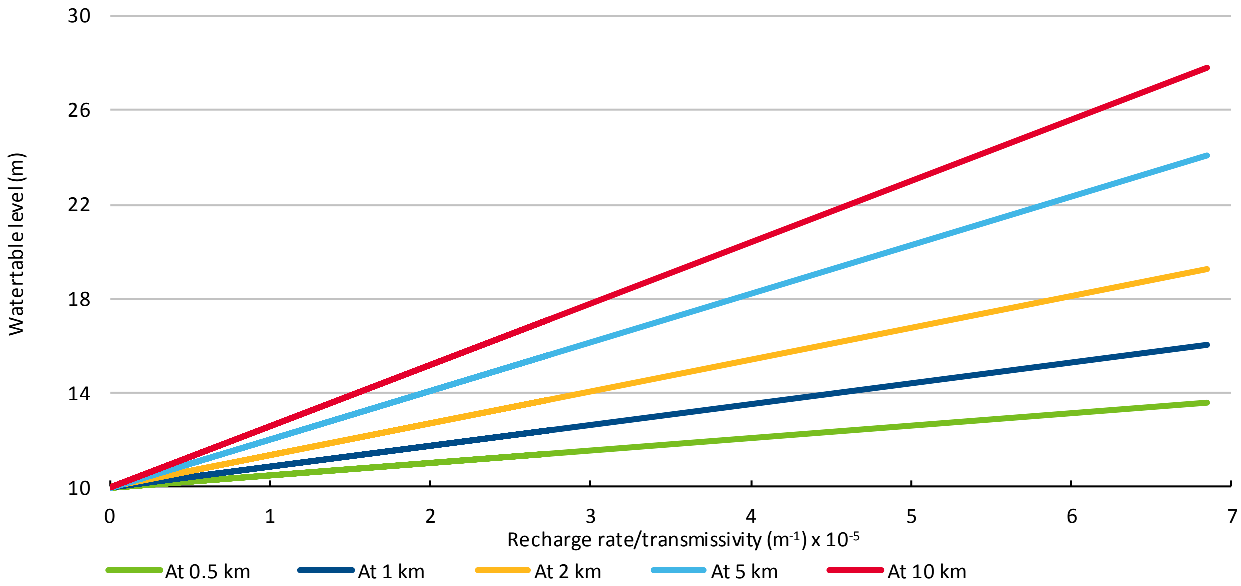

Figure 3.27 Plots of steady state water table level; irrigation area= 500 ha

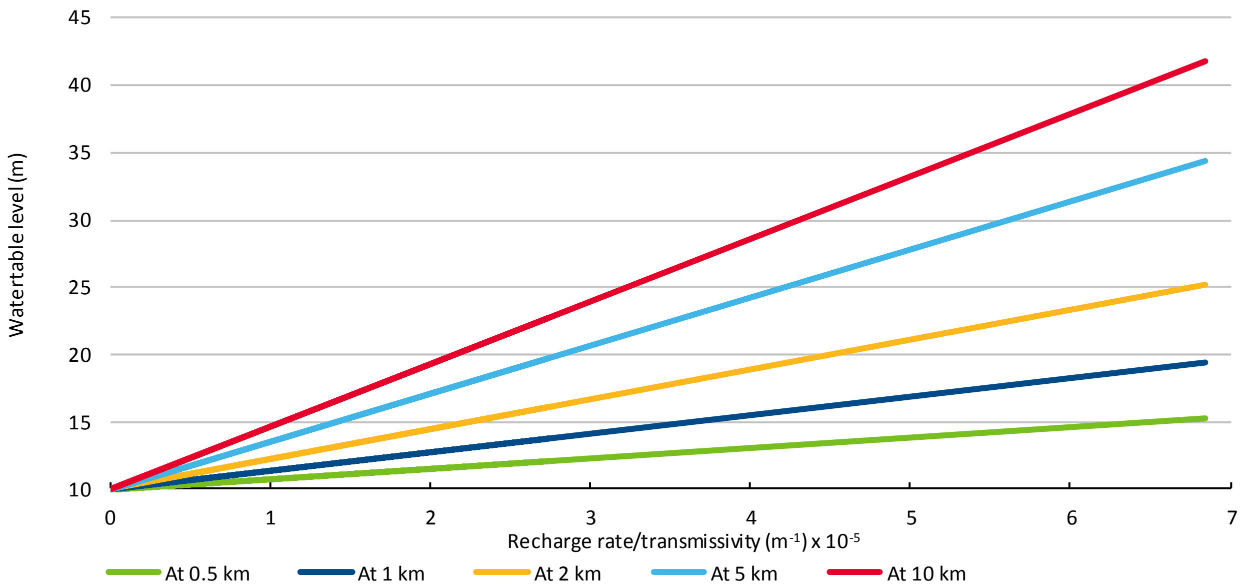

Figure 3.28 Plots of steady state water table level; irrigation area= 1000 ha

Figure 3.29 presents the same results in different form to highlights the effect of increasing the recharge area and distance to the river on water table levels.

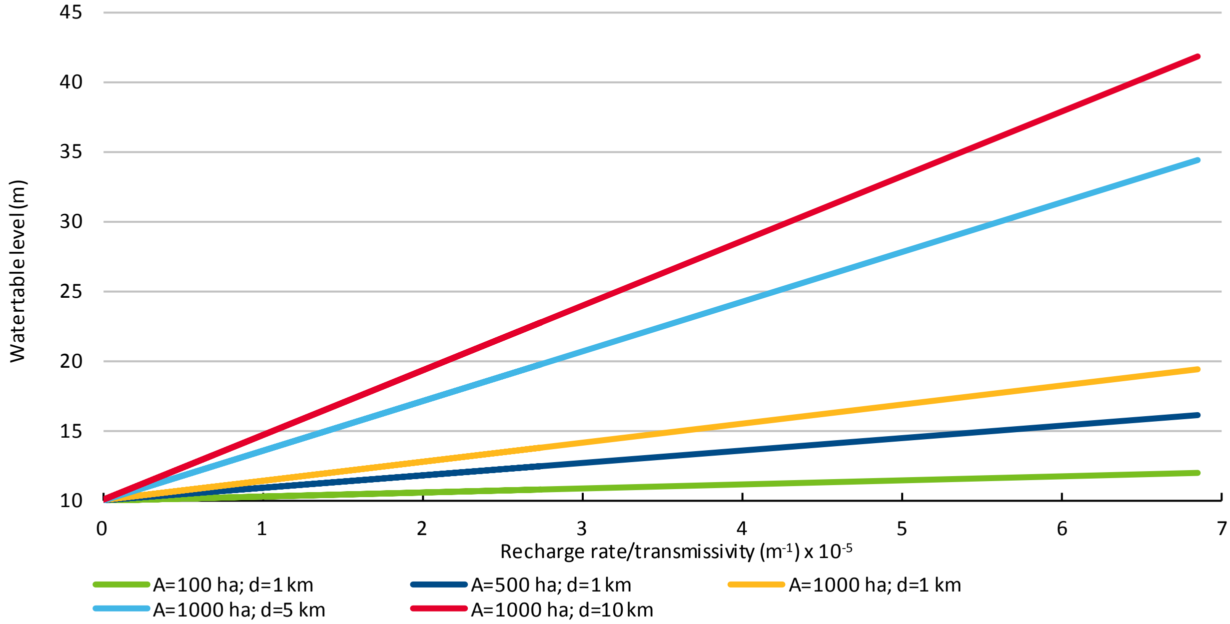

Figure 3.29 Plots of steady state water table levels for various irrigation areas and distances to the river

3.3.1.2 TRANSIENT STATE WATER TABLE RISE

The transient analysis demonstrates how the water table level evolves in time to achieve the maximum values h_{max}, which is dependent also on specific yield. Figure 3.30 represents a case where the irrigation area A=100 ha and the recharge rate so=100 mm/year. For a certain aquifer diffusivity D (aquifer transmissivity divided by specific yield), Figure 3.30 shows that at very early times the response is identical regardless of the distance to the river d. This is expected as the groundwater mound under the irrigation area builds up without the draining effect of the river. As the mound hits the river, the rate of head rise starts to decline until it reaches h_{max} at steady state. Irrigation developments placed further away from the river continue to build up head for a longer time period (see blue line in Figure 3.30).

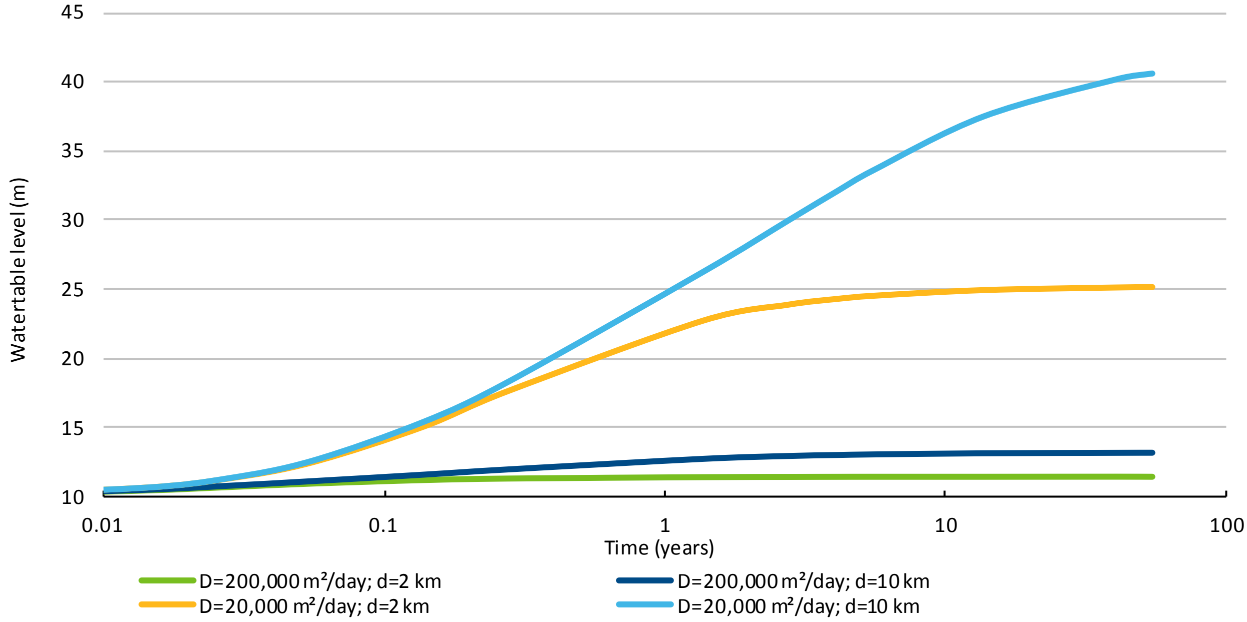

Figure 3.30 Watertable levels for various aquifer diffusivities (D) and distances to river (d), for an irrigaion area of 100 ha and recharge rate of 100 mm/year

For the high aquifer diffusivity D=200,000 m^2/day, the maximum steady state water table level is realized within a time frame of up to 13 years whereas for the low aquifer diffusivity D=20,000 m^2/day, the time frame ranges from 30-100 years. Larger irrigation areas that are placed further away from the river require longer durations to reach the maximum steady state rise. For the extreme case when d=10 km, A=1000 ha, so=500 mm/year, and D=2000 m^2/day, 92% of the steady state head rise is realized within 272 years. It is worthwhile noting that specific yield does not affect the magnitude of the steady state head rise but only changes the time scales during which this head is realized. This concept is easier understood when the water table rise is normalized with respect to the steady state head to result in a dimensionless head response. By response we mean, the ratio of the head to the maximum head, that is a response equally to unity indicates the maximum head that can ever be achieved.

Figure 3.31 shows the dimensionless head response for two aquifer diffusivities, which clearly demonstrates the effect of this aquifer property on the time scales during which h_{max} is realized.

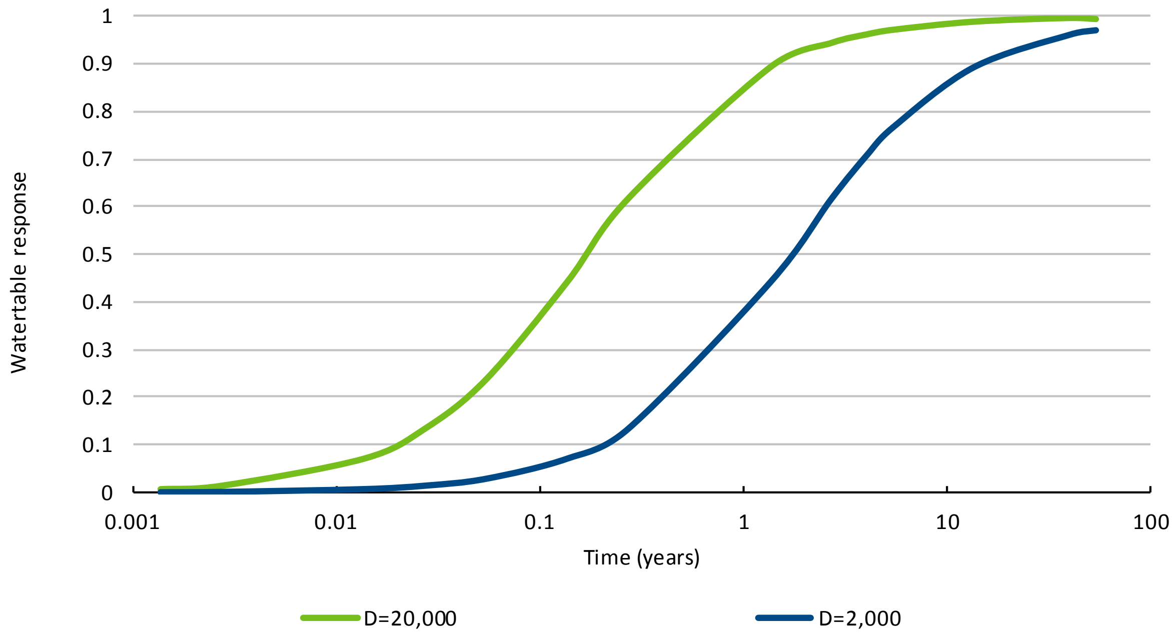

Figure 3.31 Plots of non-dimensional head response for different aquifer diffusivities

3.3.1.3 FLUX RESPONSE TO RIVER

In cases where there are concerns about the quality of water discharging to the river, the time scales of flux response become important. In the presence of a discharge boundary (a river), the applied recharge discharges to the river after a time lag, the latter depends on aquifer diffusivity D and the distance between the recharge source and the river (d). The flux response shown on the y-axis of Figure 10 represents the fraction of the applied recharge that discharges to the river at any time. Figure 3.32 shows that increased discharge to the river resulting from placing new irrigation developments might take a very long time to be realized especially when those developments are located far away from the river.

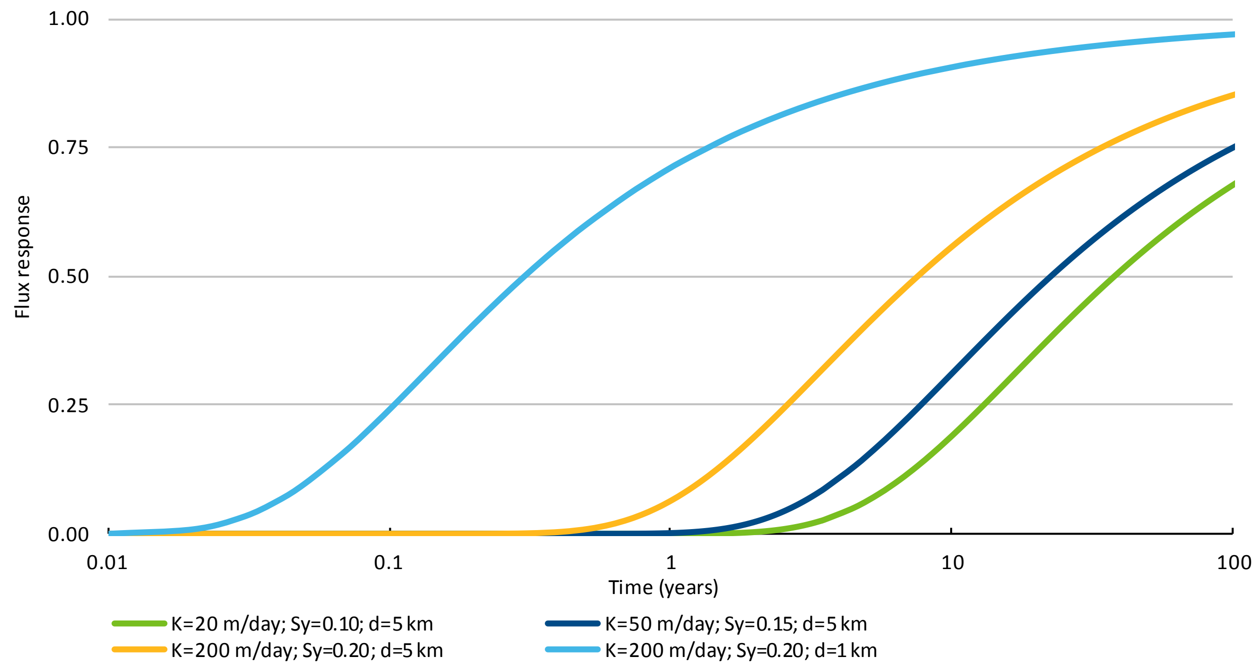

Figure 3.32 Plots of non-dimensional flux response for different aquifer diffusivities

3.3.2 CASE STUDIES

The parameters that underpin the analytical solution for evaluating groundwater table rise were derived from existing data relevant to each study case. Recharge rates were calculated from historical irrigation and rainfall data for each area. As the analytical solution only allows for a constant recharge rate, and to allow for temporal variability of recharge rates, the following procedure was followed for the modelling exercise:

1. Add rainfall to the applied irrigation to obtain the total amount of annual water available to the landscape.
2. Calculate a 20-yr moving average for the total amount of annual water available to the landscape.
3. Calculate the 10^{th}, 50^{th}, and 90^{th} percentiles for the total amount of applied water.
4. Calculate the annual recharge rate by applying a loss rate that ranges from 5% to 30% depending on site-specific conditions; these loss rates are applied in an increasing manner to the 10^{th}, 50^{th}, and 90^{th} percentiles values (i.e., higher recharge rates are associated with higher loss rates).

3.3.2.1 CAVEHILL CASE STUDY

This study assesses the rise in groundwater levels due to introducing a new irrigation development at the Cavehill site. The total area of the development is 12,000 ha, which is assumed to commence 1-km from the river, thus allowing for a riparian buffer. The development was assumed to have a length (along the river) three times the width (perpendicular to the river). Loss rates of 10%, 15%, and 20%, were applied to the 10^{th}, 50^{th}, and 90^{th} percentiles of the estimated annual applied water thus resulting in recharge rates of 67 mm/year, 118 mm/year, and 181 mm/year, respectively. To allow for uncertainty in aquifer transmissivity, three hydraulic conductivities were considered: 1 m/day, 10 m/day, and 100 m/day. Specific yield was kept constant at 0.20. Field data indicated that aquifer thickness was equal to 12 m, with a nominal depth to groundwater table equal to 9 m, which resulted in a saturated aquifer thickness of 3 m.

Figures 3.33, 3.34 and 3.35 show the evolution of groundwater table levels for the various scenarios with the purple horizontal line representing the aquifer extent (further recharge would be rejected). Note that the vertical axes in all figures range from 3 m (initial depth to groundwater) to 12 m (total thickness of the aquifer). As the hydraulic conductivity increases, so does the drainage capacity of the aquifer, which leads to lower rises in the groundwater table. For the higher conductivity range (100 m/day), the irrigation development results in a sustainable rise in groundwater table ranging from5 m only for the low recharge rate of 67 mm/year.

However, for low-conductive aquifer with k=1 and 10 m/day, the applied recharge eventually fills up the aquifer (becomes rejected recharge), this phenomenon occurs earlier as recharge rates increase. For the lower recharge rate of 67 mm/year (Figure 3.33), this occurs after 23-25 years; for the intermediate recharge rate of 118 mm/year, this occurs after 14 years (Figure 3.34); and for the higher recharge rate of 181 mm/year, this occurs after 9 years (Figure 3.35).

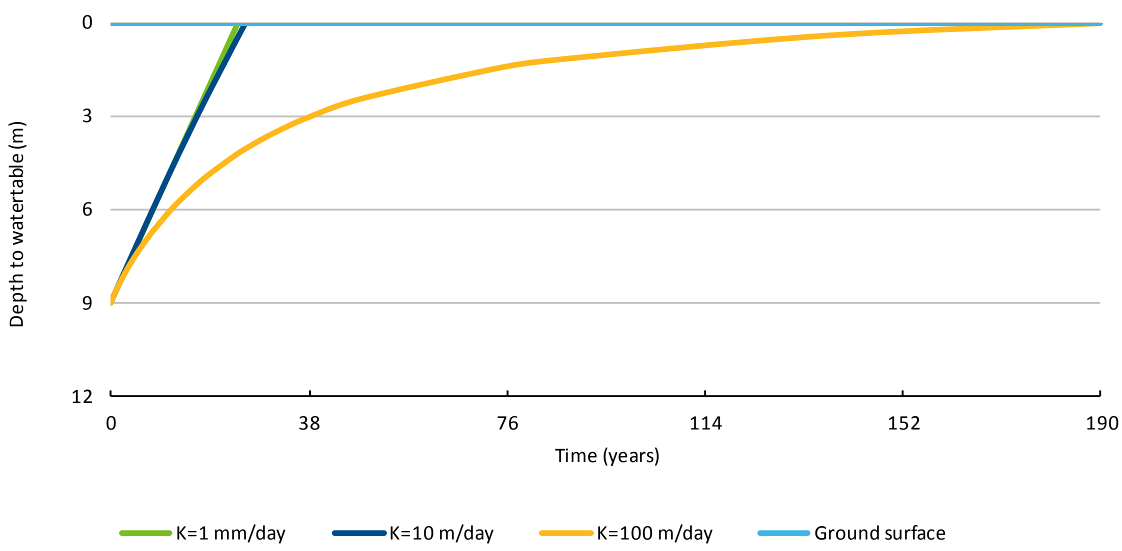

Figure 3.33 Plots of Cavehill water table levels for various hydraulic conductivities with a recharge rate=67 mm/yr

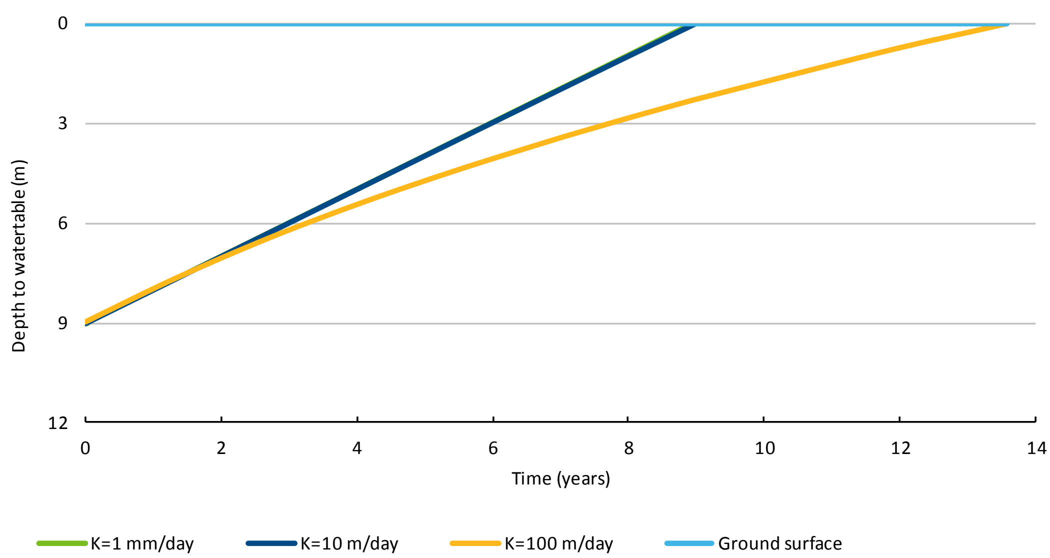

Figure 3.34 Plots of Cavehill water table levels for various hydraulic conductivities with a recharge rate=118 mm/yr

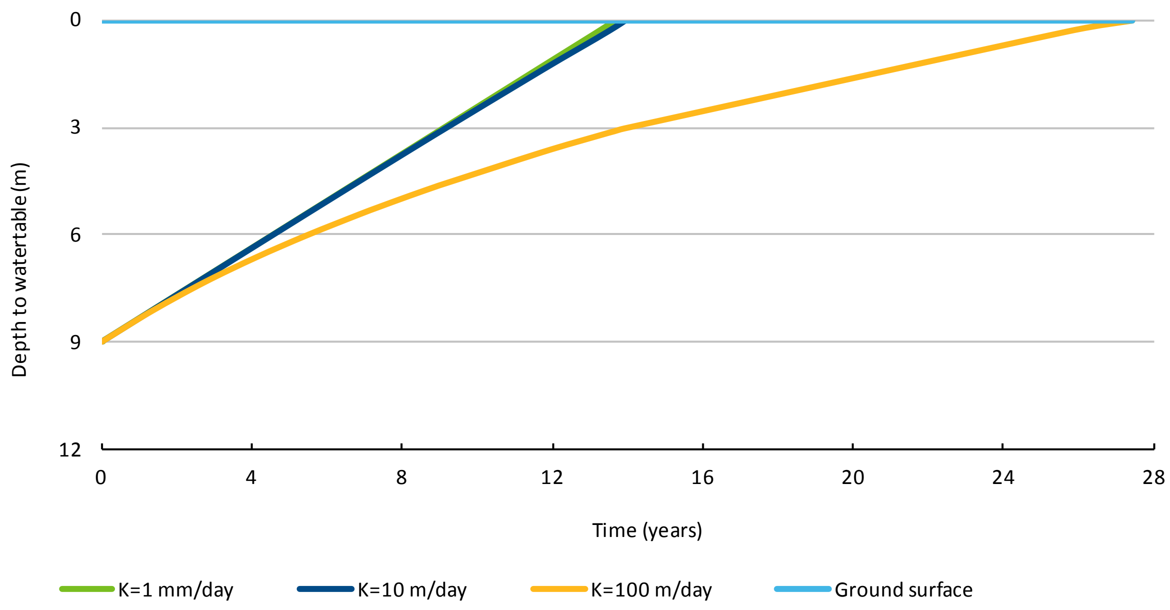

Figure 3.35 Plots of Cavehill water table levels for various hydraulic conductivities with a recharge rate=161 mm/yr

3.3.2.2 DAGWORTH STUDY

This study assesses the rise in groundwater levels due to introducing a new irrigation development at the Dagworth site. The total area of the development is 14,000 ha, which is assumed to commence 2-km from the river, thus allowing for a riparian buffer. The development was assumed to have a length (along the river) three times the width (perpendicular to the river). Loss rates of 10%, 15%, and 20%, were applied to the 10th, 50th, and 90th percentiles of the estimated annual applied water thus resulting in recharge rates of 131 mm/year, 215 mm/year, and 317 mm/year, respectively. To allow for uncertainty in aquifer transmissivity, three hydraulic conductivities were considered: 1 m/day, 10 m/day, and 100 m/day. Specific yield was kept constant at 0.18. Field data indicated that aquifer thickness was equal to 29 m, with a nominal depth to groundwater table equal to 13 m, which resulted in a saturated aquifer thickness of 16 m.

Figures 3.36, 3.37 and 3.38 show the evolution of groundwater table levels for the various scenarios with the purple horizontal line representing the aquifer extent (further recharge would be rejected). Note that the vertical axes in all figures range from 16 m (initial depth to groundwater) to 29 m (total thickness of the aquifer). As the hydraulic conductivity increases, so does the drainage capacity of the aquifer, which leads to lower rises in the groundwater table. For the higher conductivity range (100 m/day), the irrigation development results in a sustainable rise in groundwater table, ranging from 4 m to 9 m (increasing with recharge rate).

However, for low-conductive aquifer with k=1 and 10 m/day, the applied recharge eventually fills up the aquifer (becomes rejected recharge), this phenomenon occurs earlier as recharge rates increase. For the lower recharge rate of 131 mm/year (Figure 3.36), this occurs after 17-25 years; for the intermediate recharge rate of 215 mm/year, this occurs after 10-13 years (Figure 3.37); and for the higher recharge rate of 317 mm/year, this occurs after 7-8 years (Figure 3.38).

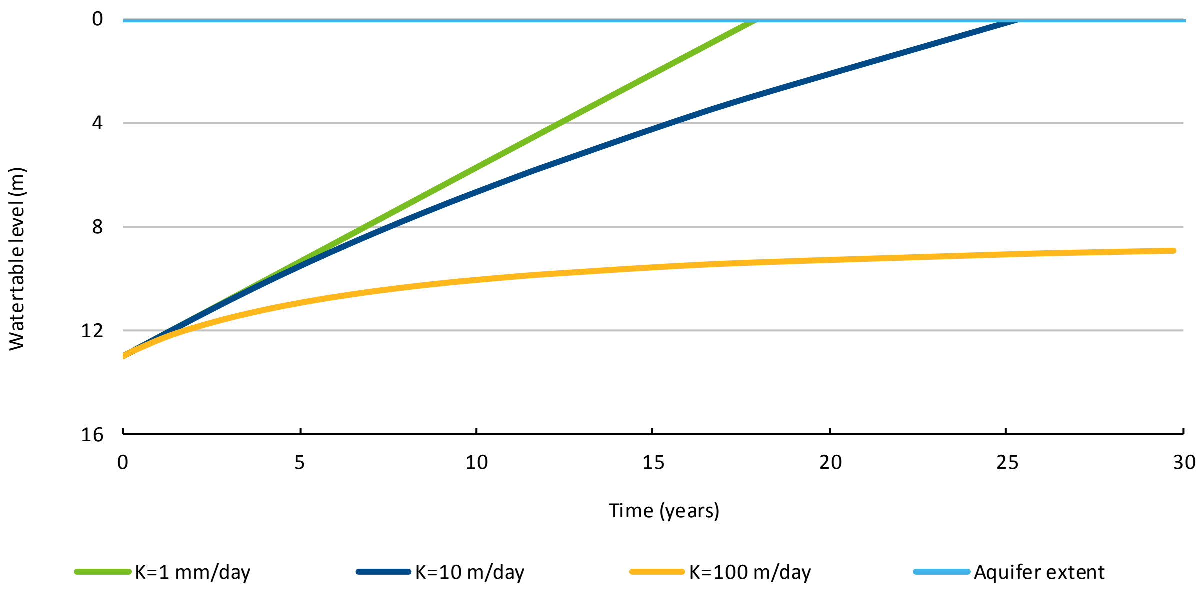

Figure 3.36 Plots of Dagoworth water table levels for various hydraulic conductivities with a recharge rate=131 mm/yr

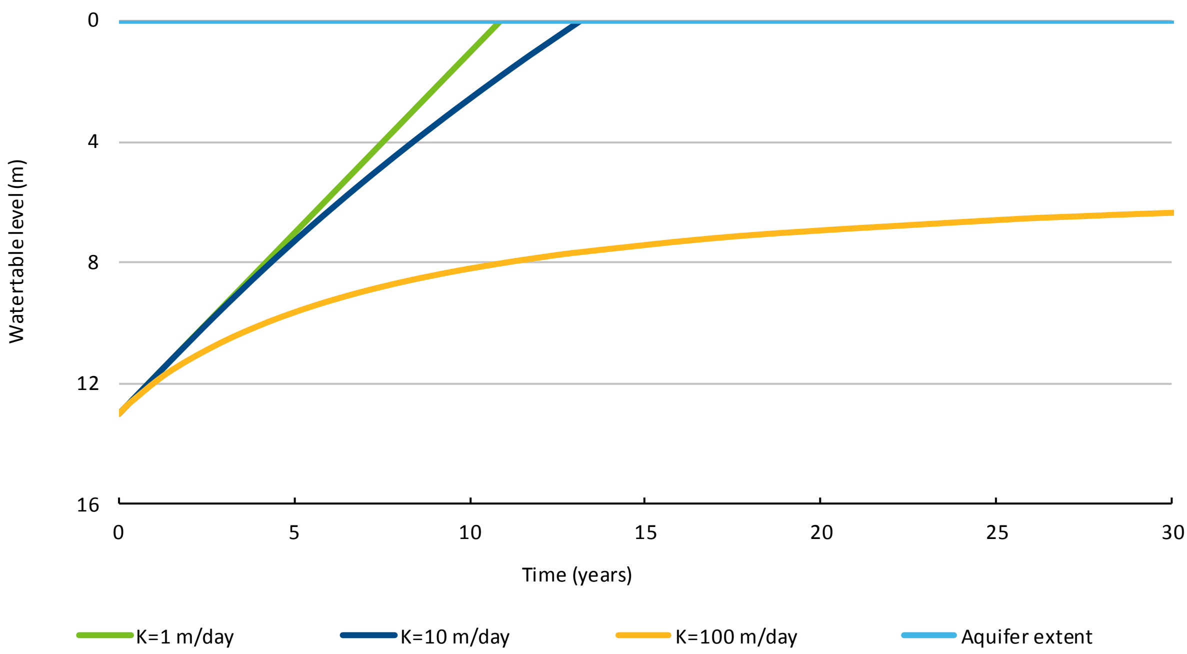

Figure 3.37 Plots of Dagoworth water table levels for various hydraulic conductivities with a recharge rate=215 mm/yr

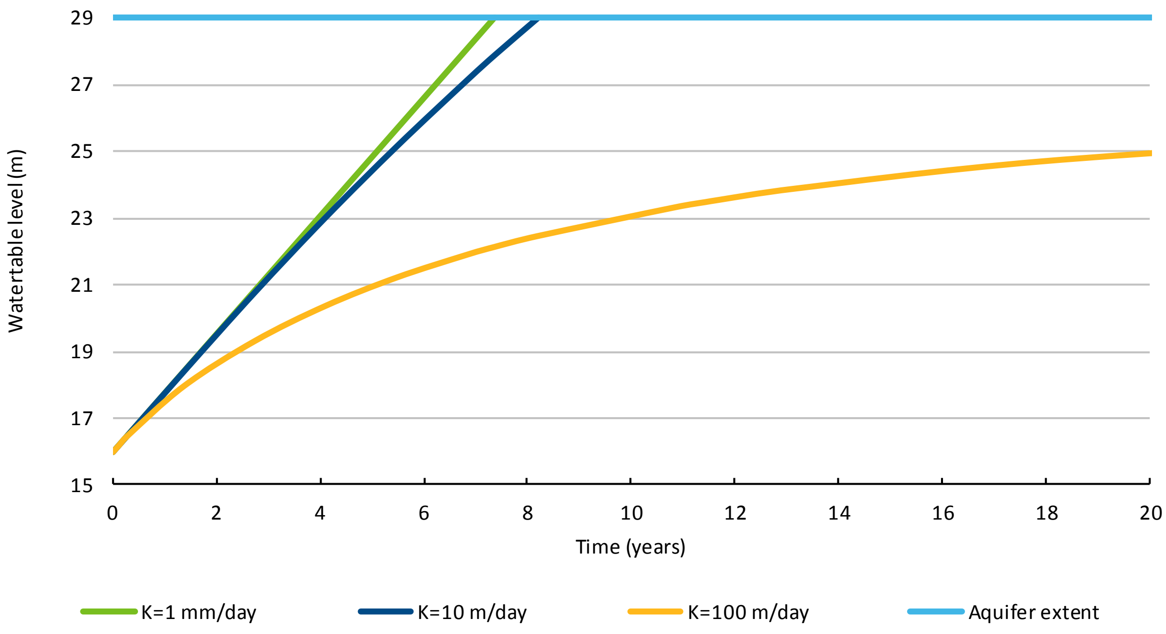

Figure 3.38 Plots of Dagoworth water table levels for various hydraulic conductivities with a recharge rate=317 mm/yr

3.3.2.3 GREENHILL STUDY

This study assesses the rise in groundwater levels due to introducing a new irrigation development at the Greenhill site. The total area of the development is 12,000 ha, which is assumed to commence 2-km from the river, thus allowing for a riparian buffer. The development was assumed to have a length (along the river) three times the width (perpendicular to the river). Loss rates of 10%, 15%, and 20%, were applied to the 10^{th}, 50^{th}, and 90^{th} percentiles of the estimated annual applied water thus resulting in recharge rates of 122 mm/year, 200 mm/year, and 285 mm/year, respectively. To allow for uncertainty in aquifer transmissivity, three hydraulic conductivities were considered: 1 m/day, 10 m/day, and 100 m/day. Specific yield was kept constant at 0.18. Field data indicated that aquifer thickness was equal to 29 m, with a nominal depth to groundwater table equal to 13 m, which resulted in a saturated aquifer thickness of 16 m.

Figures 3.39, 3.40 and 3.41 show the evolution of groundwater table levels for the various scenarios with the purple horizontal line representing the aquifer extent (further recharge would be rejected). Note that the vertical axes in all figures range from 4 m (initial depth to groundwater) to 16 m (total thickness of the aquifer). As the hydraulic conductivity increases, so does the drainage capacity of the aquifer, which leads to lower rises in the groundwater table. For the higher conductivity range (100 m/day), the irrigation development results in a sustainable rise in groundwater table ranging from 3-8 m.

However, for low-conductive aquifer with k=1 and 10 m/day, the applied recharge eventually fills up the aquifer (becomes rejected recharge), this phenomenon occurs earlier as recharge rates increase. For the lower recharge rate of 122 mm/year (Figure 3.39), this occurs after 18-29 years; for the intermediate recharge rate of 200 mm/year, this occurs after 12-15 years (Figure 3.40); and for the higher recharge rate of 285 mm/year, this occurs after 7-9 years (Figure 3.41).

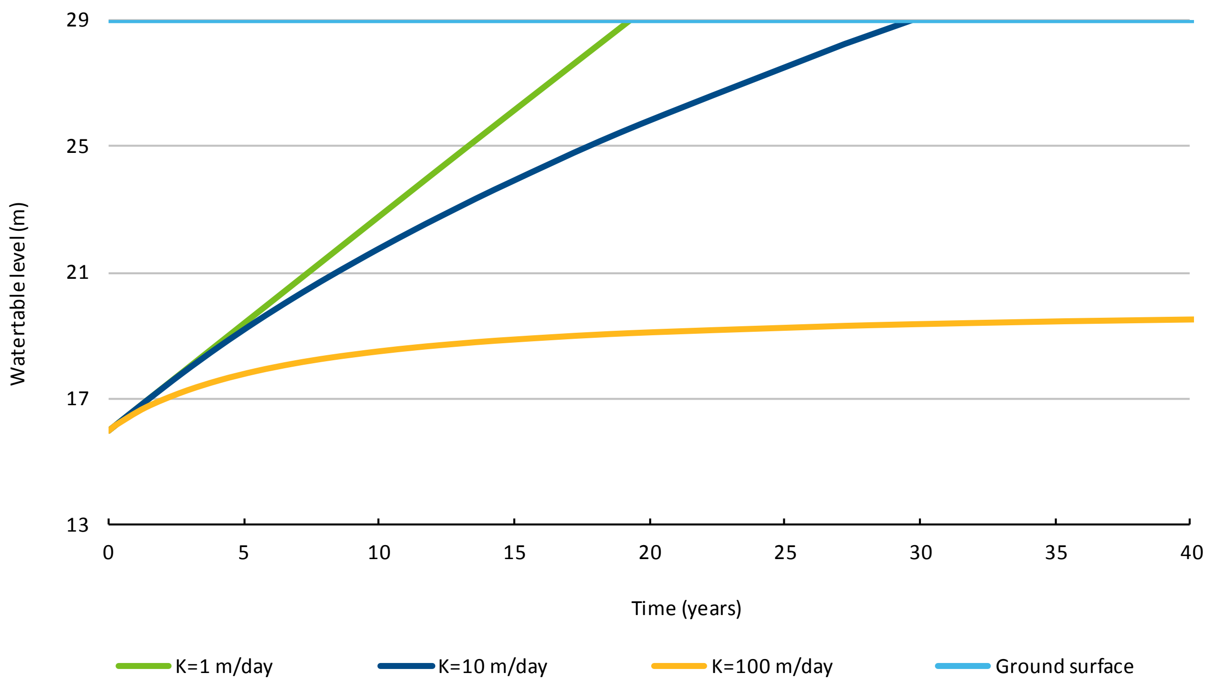

Figure 3.39 Plots of Greenhill water table levels for various hydraulic conductivities with a recharge rate=122 mm/yr

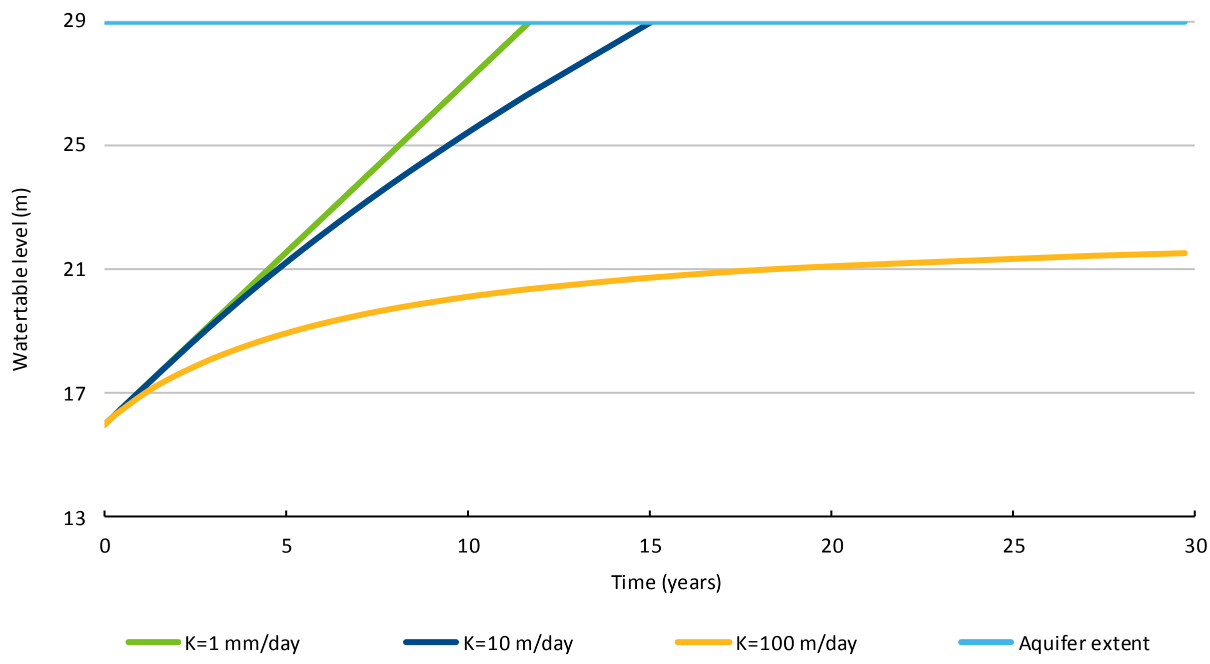

Figure 3.40 Plots of Greenhill water table levels for various hydraulic conductivities with a recharge rate=200 mm/yr

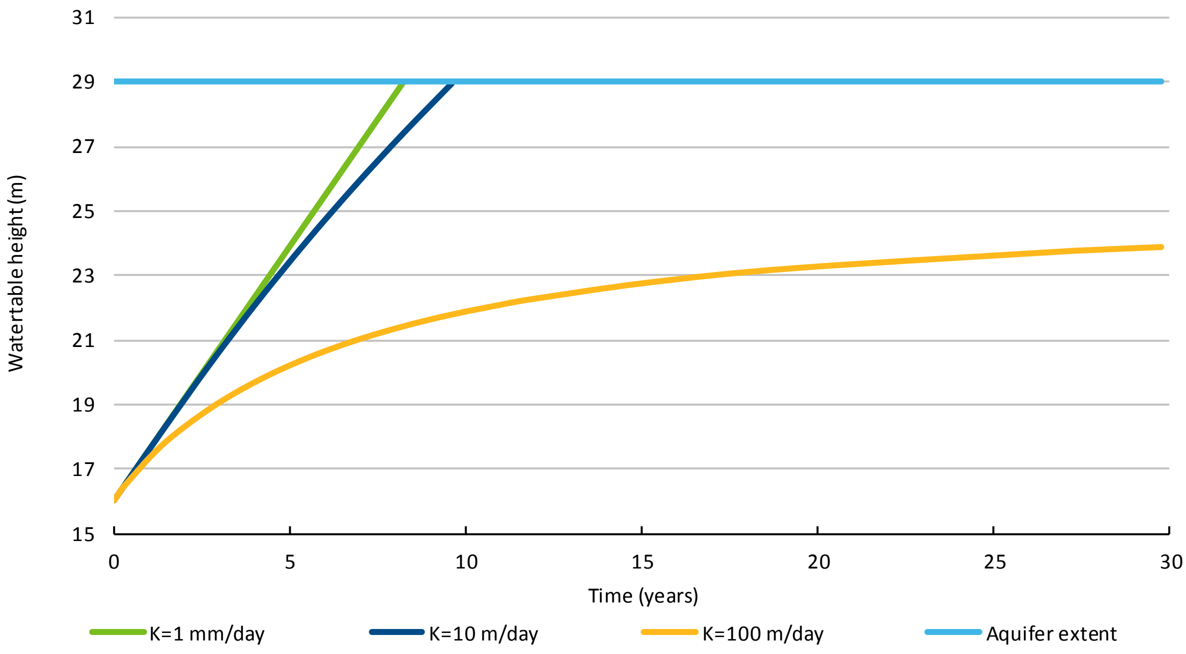

Figure 3.41 Plots of Greenhill water table levels for various hydraulic conductivities with a recharge rate=285 mm/yr

3.3.2.4 KIDSTON STUDY

This study assesses the rise in groundwater levels due to introducing a new irrigation development at the Kidston site. A representative irrigation development having an area of 1,200 ha was modeled; it was assumed to commence 100 m from the river, thus allowing for a narrow riparian buffer. Loss rates of 10%, 15%, and 20%, were applied to the 10^{th}, 50^{th}, and 90^{th} percentiles of the estimated annual applied water thus resulting in recharge rates of 78 mm/year, 136 mm/year, and 214 mm/year, respectively. To allow for uncertainty in aquifer transmissivity, three hydraulic conductivities were considered: 1 m/day, 10 m/day, and 100 m/day. Specific yield was kept constant at 0.20. Field data indicated that aquifer thickness was equal to 22 m, with a nominal depth to groundwater table equal to 13 m, which resulted in a saturated aquifer thickness of 9 m.

Figures 3.42, 3.43 and 3.44 show the evolution of groundwater table levels for the various scenarios with the purple horizontal line representing the aquifer extent (further recharge would be rejected). Note that the vertical axes in all figures range from 4 m (initial depth to groundwater) to 16 m (total thickness of the aquifer). As the hydraulic conductivity increases, so does the drainage capacity of the aquifer, which leads to lower rises in the groundwater table. For the high and intermediate conductivity range of 10-100 m/day and recharge rates of 76 and 136 mm/year, the irrigation development results in a sustainable rise in groundwater table ranging from 4-7 m.

However, for low-conductive aquifer with k=1 m/day, the applied recharge eventually fills up the aquifer (becomes rejected recharge), this phenomenon occurs earlier as recharge rates increase. For the lower recharge rate of 78 mm/year (Figure 3.42), this occurs after 38 years; for the intermediate recharge rate of 136 mm/year, this occurs after 20 years (Figure 3.43); and for the higher recharge rate of 214 mm/year, this occurs after 12 years (Figure 3.44).

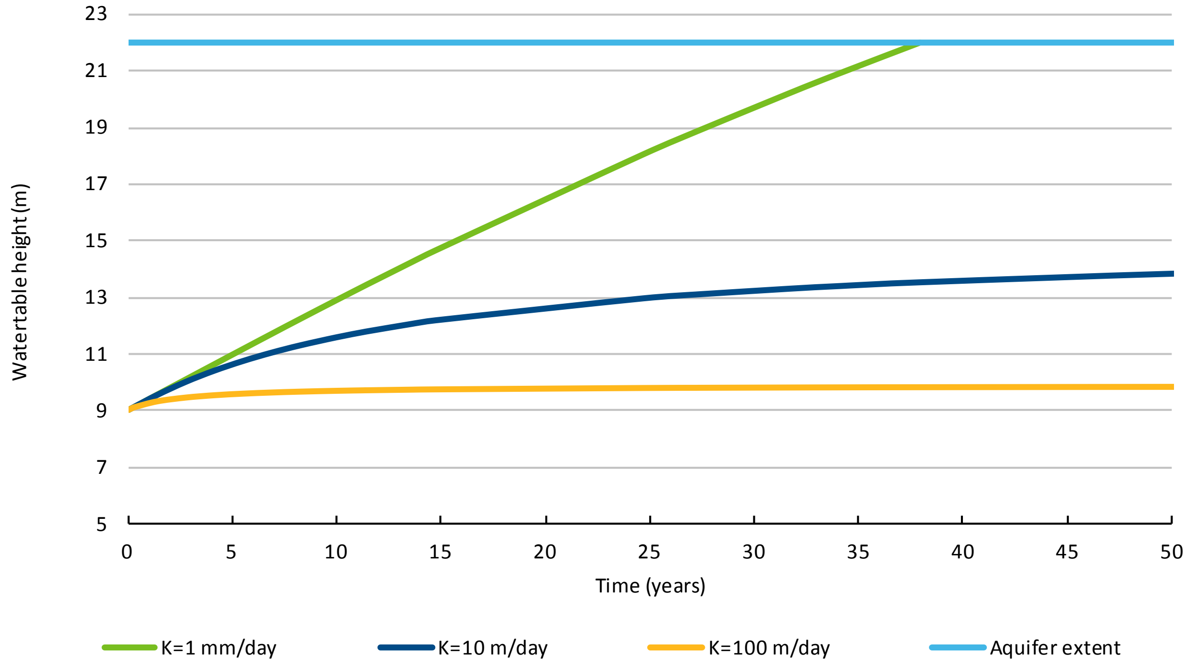

Figure 3.42 Plots of Kidston water table levels for various hydraulic conductivities with a recharge rate=78 mm/yr

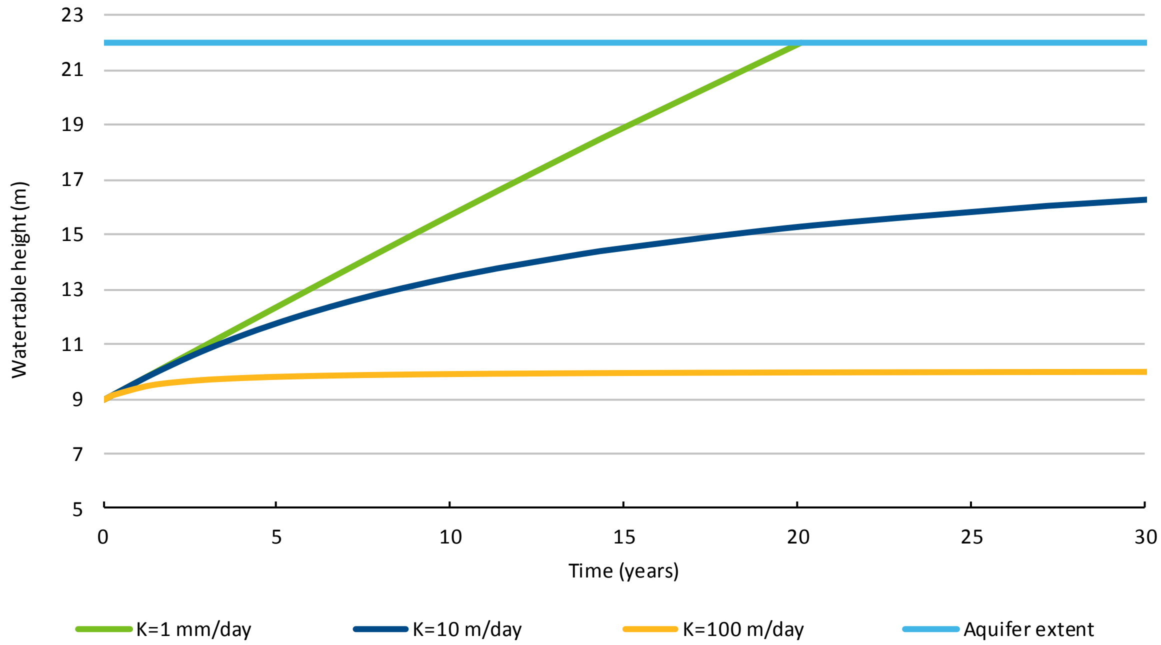

Figure 3.43 Plots of Kidston water table levels for various hydraulic conductivities with a recharge rate=136 mm/yr

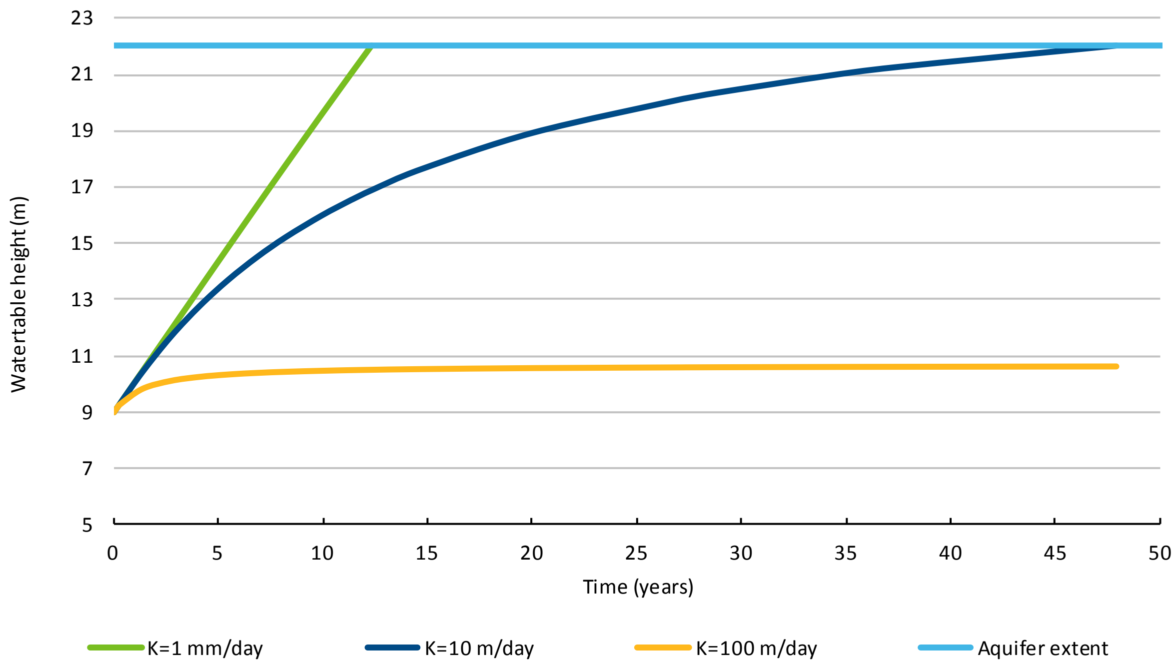

Figure 3.44 Plots of Kidston water table levels for various hydraulic conductivities with a recharge rate=214 mm/yr

3.3.2.5 O'CONNELL STUDY

This study assesses the rise in groundwater levels due to introducing a new irrigation development at the O'Connell site. The total area of the development is 6,000 ha, which is assumed to commence 3-km from the river, thus allowing for a riparian buffer. The development was assumed to have a length (along the river) three times the width (perpendicular to the river). Loss rates of 10%, 15%, and 20%, were applied to the 10th, 50th, and 90th percentiles of the estimated annual applied water thus resulting in recharge rates of 76 mm/year, 176 mm/year, and 297 mm/year, respectively. To allow for uncertainty in aquifer transmissivity, three hydraulic conductivities were considered: 1 m/day, 10 m/day, and 100 m/day. Specific yield was kept constant at 0.20. Field data indicated that aquifer thickness was equal to 16 m, with a nominal depth to groundwater table equal to 12 m, which resulted in a saturated aquifer thickness of 4 m.

Figures 3.45, 3.46 and 3.47 show the evolution of groundwater table levels for the various scenarios with the purple horizontal line representing the aquifer extent (further recharge would be rejected). Note that the vertical axes in all figures range from 4 m (initial depth to groundwater) to 16 m (total thickness of the aquifer). As the hydraulic conductivity increases, so does the drainage capacity of the aquifer, which leads to lower rises in the groundwater table. For the higher conductivity range (100 m/day), the irrigation development results in a sustainable rise in groundwater table of up to 6 m only for the case of a low recharge rate of 76 mm/year.

However, for low-conductive aquifer with k=1 and 10 m/day, the applied recharge eventually fills up the aquifer (becomes rejected recharge), this phenomenon occurs earlier as recharge rates increase. For the lower recharge rate of 76 mm/year (Figure 3.45), this occurs after 12-13 years; for the intermediate recharge rate of 176 mm/year, this occurs after 10-13 years (Figure 3.46); and for the higher recharge rate of 297 mm/year, this occurs after 8 years (Figure 3.47).

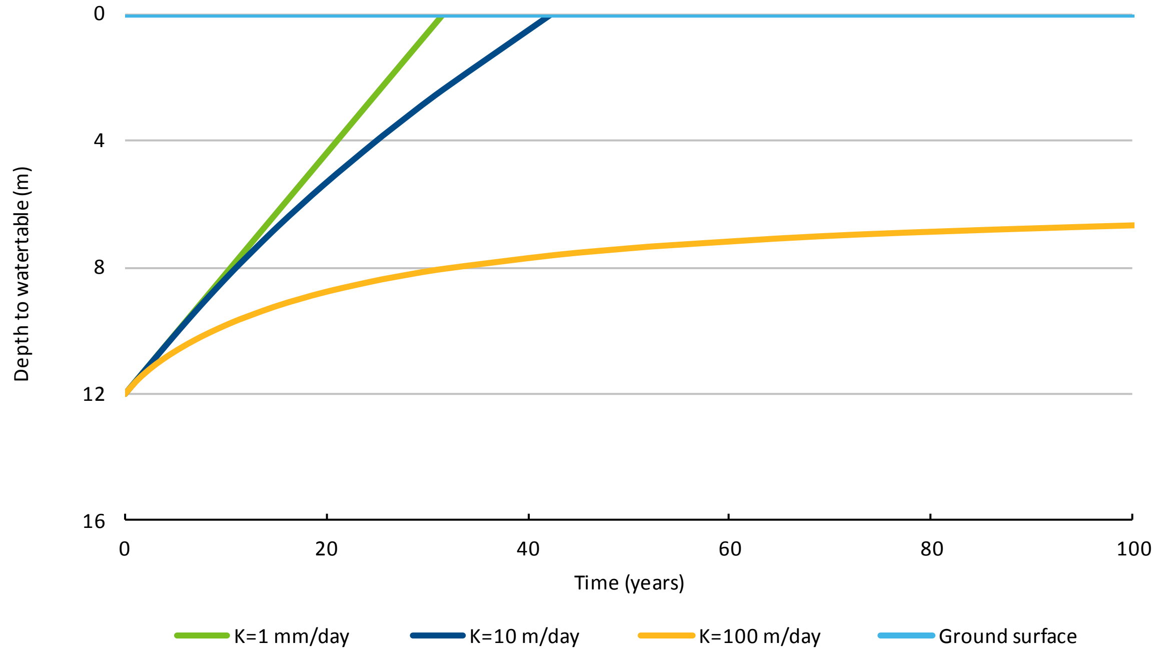

Figure 3.45 Plots of C'Connell water table levels for various hydraulic conductivities with a recharge rate=76 mm/yr

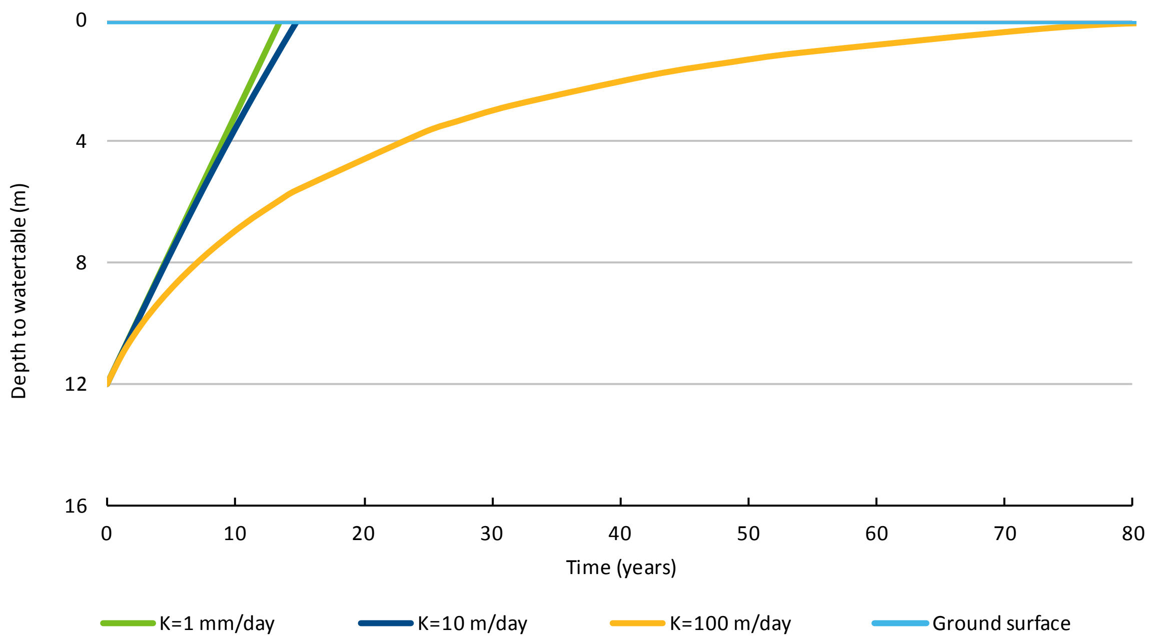

Figure 3.46 Plots of C'Connell water table levels for various hydraulic conductivities with a recharge rate=176 mm/yr

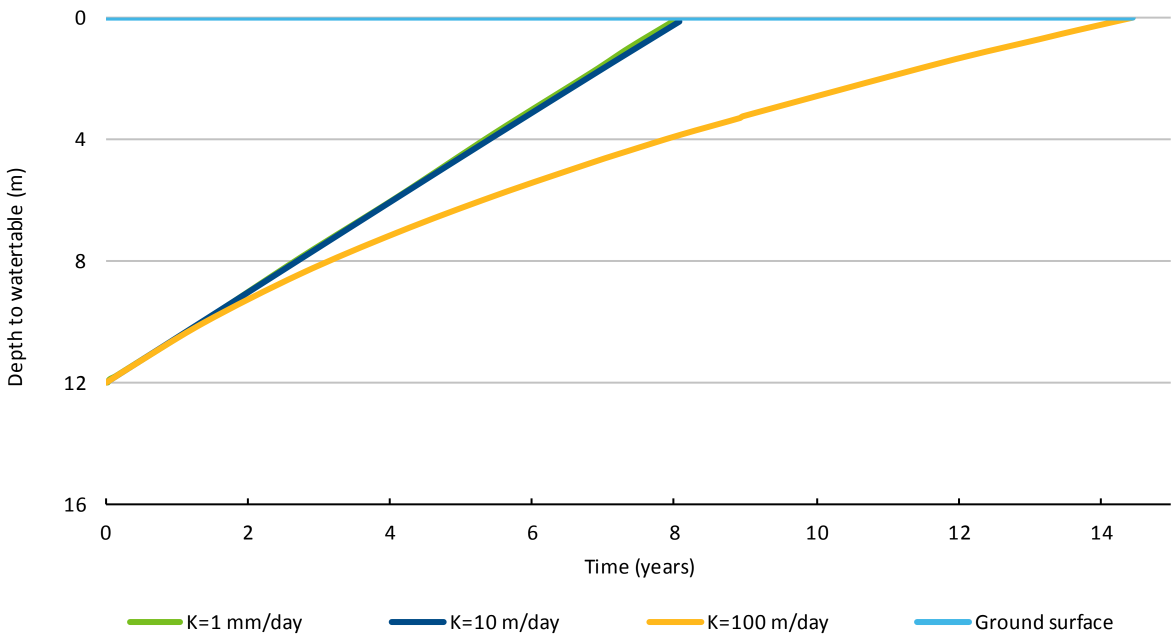

Figure 3.47 Plots of C'Connell water table levels for various hydraulic conductivities with a recharge rate=297 mm/yr

4 Discussion

4.1 Task 1 - Hydrogeological controls on dry-season flows and waterhole persistence

4.1.1 FLINDERS CATCHMENT

The data presented in Table 3.1, Table 3.2, Figure 3.1, Figure 3.2, Figure 3.3 and Figure 3.4 were interpreted to determine the likelihood that there was groundwater inflow at the time of sampling. The ^{222}Rn criteria for high likelihood was a value of >0.4 Bq/L, for low likelihood was a value of 0.1-0.4 Bq/L, and for nil likelihood was a value <0.1 Bq/L. The changes of the chloride and stable isotope values during the dry season were also used to assist in the interpretations. The outcomes of these interpretations are summarised in Table 4.1, Table 4.2 and Figure 4.1.

Only two of the river sites in the Flinders catchment (site 3 on the Flinders River and site 6 on the Stawell River) were assessed to have a high likelihood of groundwater inflow. Both are located at the downstream end of large rivers that are deeply incised into the Sturgeon Basalt and Rolling Downs Group. Similarly, only two of the waterholes sites (8 and 10) were assessed to have a high likelihood of groundwater inflow. Waterhole site 8 is located in the alluvium/bedsands of the Cloncurry River in an area where the presence of rock bars across the valley is thought to lead to groundwater levels coming closer to the surface than otherwise would be the case (see Section 1.2.1). Waterhole site 10 is located on a creek which drains the nearby Sturgeon Basalt.

Table 4.1 Likelihood of groundwater inflow at river sites in the Flinders catchment that were sampled in May 2012

SITE NUMBER	SUB-CATCHMENT	STREAM	SITE NAME	LIKELIHOOD OF GROUNDWATER INFLOW	COMMENTS
1	Flinders	Flinders River	Flinders River@Low level Crossing ~5 km upstream of Richmond	Low	Only sampled in May, ^{222}Rn is low
2	Flinders	Flinders River	Flinders River@Ford ~40 km upstream of Richmond	Nil	Only sampled in May, ^{222}Rn is negligible
3	Flinders	Flinders River	Flinders River@Bridge in Hughenden	High	Only sampled in May, ^{222}Rn is high
4	Flinders	Flinders River	Flinders River@Alderly Crossing	Low	Only sampled in May, ^{222}Rn is low
5	Flinders	Flinders River	Flinders River@Hulberts Crossing	Low	Only sampled in May, ^{222}Rn is low
6	Stawell	Stawell River	Stawell River@Cambridge Crossing	High	Only sampled in May, ^{222}Rn is high

Table 4.2 Likelihood of groundwater inflow at waterhole sites in the Flinders catchment that were sampled between August and December 2012

SITE NUMBER	SUB-CATCHMENT	STREAM	SITE NAME	LIKELIHOOD OF GROUNDWATER INFLOW	COMMENTS
1	Flinders	Flinders River	Wondoola	Nil	Only sampled in August, ^{222}Rn is negligible
2	Flinders	Flinders River	Etta Plains Station	Nil	Only sampled in August, ^{222}Rn is negligible
3	Flinders	Flinders River	River Dale Station	Nil	Only sampled in August, ^{222}Rn is negligible
4	Flinders	Flinders River	Tentative pool 11	Low	Only sampled in August, ^{222}Rn is low
5	Flinders	Flinders River	Harrogate Station	Low	Only sampled in August, ^{222}Rn is low
6	Cloncurry	Cloncurry River	Cowan Downs Station	Nil	Only sampled in August, ^{222}Rn is negligible
7	Cloncurry	Off channel waterhole	Cowan Downs Station - Off channel waterhole	Low	Only sampled in August, ^{222}Rn is low
8	Cloncurry	Cloncurry River	Causeway - township	High	Only sampled in August, ^{222}Rn is high
9	Cloncurry	Cloncurry River	Fort Constantine Station	Low	Only sampled in August, ^{222}Rn is low
10	Flinders	Fairlight Creek	F1 - Soda Valley/Glendalough Station	High	^{222}Rn is high in August but lower in October and December, $\delta^{2}H$, $\delta^{18}O$ and Cl^{-} increase between October and December, suggesting a reduction in groundwater inflow through the dry season
11	Flinders	Flinders River	F2 - River Dale Station	Nil	^{222}Rn is negligible and changes little between August and November, $\delta^{2}H$, $\delta^{18}O$ and Cl^{-} increase between August and November, suggesting evaporation of only surface water
12	Flinders	Off channel waterhole	F3 - River Dale Station	Low	^{222}Rn is low and changes slightly between August and November, $\delta^{2}H$, $\delta^{18}O$ and Cl^{-} increase between November and December, suggesting evaporation of surface water with some groundwater component
13	Flinders	Off channel waterhole	F4 - River Dale Station	Nil	^{222}Rn is negligible and changes little between October and December, $\delta^{2}H$, $\delta^{18}O$ and Cl^{-} increase between October and December, suggesting evaporation of only surface water
14	Flinders	Flinders River	F5 - Richmond Shire Council	Nil	^{222}Rn is negligible and changes little between November and December, $\delta^{2}H$, $\delta^{18}O$ and Cl^{-} increase between November and December, suggesting evaporation of only surface water

Table 4.2 continued

SITE NUMBER	SUB-CATCHMENT	STREAM	SITE NAME	LIKELIHOOD OF GROUNDWATER INFLOW	COMMENTS
15	Flinders	Flinders River	F7 - Millungera Station	Nil	^{222}Rn is negligible and changes little between October and December, $\delta^{2}H$, $\delta^{18}O$ and Cl^{-} increase between October and December, suggesting evaporation of only surface water
16	Cloncurry	Julia Creek	F8 - Dalgonally Station	Nil	^{222}Rn is negligible and changes little between August and December, $\delta^{2}H$, $\delta^{18}O$ and Cl^{-} increase between August and December, suggesting evaporation of only surface water
17	Flinders	Cloncurry River	F9 - Dalgonally Station	Low	^{222}Rn is low and changes slightly between August and December, $\delta^{2}H$, $\delta^{18}O$ and Cl^{-} increase between August and December, suggesting evaporation of surface water with some groundwater component

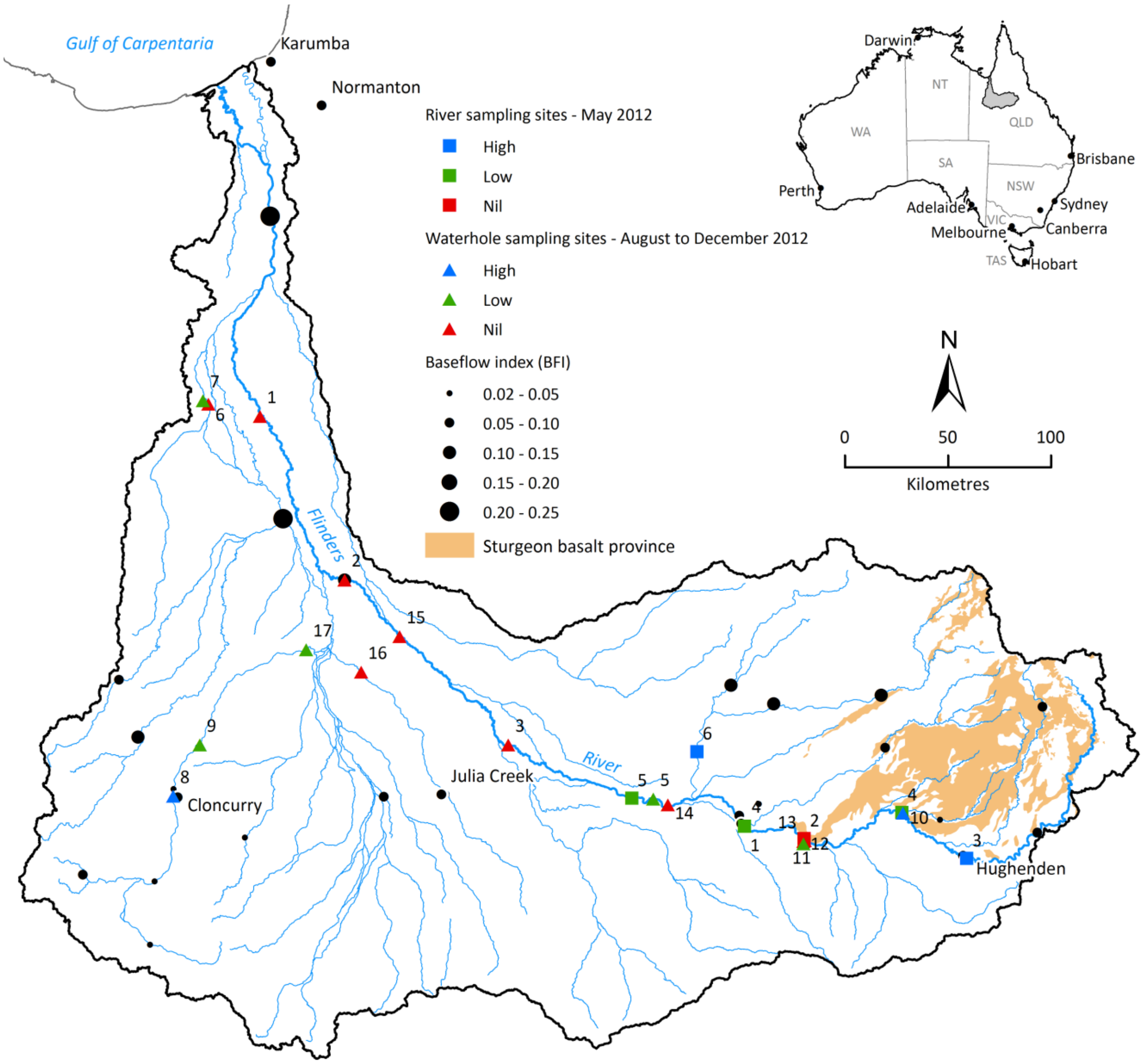

Figure 4.1 Likelihood of groundwater inflow at river and waterhole sampling sites in the Flinders catchment. Details for each site are in Table 2.1 and Table 2.2

4.1.2 GILBERT CATCHMENT

The data presented in Table 3.3, Table 3.4, Figure 3.5, Figure 3.6, Figure 3.7 and Figure 3.8 was interpreted to determine the likelihood that there was groundwater inflow at the time of sampling. The ^{222}Rn criteria for high likelihood was a value of >0.4 Bq/L, for low likelihood was a value of 0.1-0.4 Bq/L, and for nil likelihood was a value <0.1 Bq/L. The changes of the chloride and stable isotope values during the dry season were also used to assist in the interpretations. The outcomes of these interpretations are summarised in Table 4.3, Table 4.4 and Figure 4.2.

Only one of the river sites in the Gilbert catchment (site 1 on the Gilbert River) was assessed to have a high likelihood of groundwater inflow. It is located downstream of an area where the Gilbert River Formation outcrops in the alluvium/bedsands and this presumably supplies the baseflow in the dry season (as per the conceptual model of CSIRO (2009)). Four of the waterholes sites (1, 3, 8 and 12) were assessed to have a high likelihood of groundwater inflow. Waterhole site 1 is located in a highly complex geological area just to the north of Einasleigh comprised of Einasleigh Metamorphics and an intrusion of Caterpillar Microgranite. It is not clear which of these units is the origin of the groundwater. Waterhole site 3 is located in one of the upper tributaries of the Einasleigh River which drains from an area comprised of Chudleigh Basalt flows and a Dido Tonalite intrusion. It is most likely that the Chudleigh Basalt is the origin of the groundwater as recent drilling by the Queensland Department of Science, Information Technology, Innovation and the Arts (DSITIA) has suggested that the basalts are the only fractured rock units in the Einasleigh which have notable groundwater supplies (Alex Loy and Bruce Pearce, pers. comm.). Waterhole site 8 is located in one of the middle tributaries of the Einasleigh in an area dominated by the McBride Basalt flows and smaller areas of the Einasleigh Metamorphics. Results of the recent DSITIA drilling suggest that the McBride Basalt is the most likely origin of the groundwater (Alex Loy and Bruce Pearce, pers. comm.). Waterhole site 12 is similar to river site 1 in that it is located downstream of an area where the Gilbert River Formation outcrops in the Gilbert River alluvium/bedsands and this presumably supplies the baseflow in the dry season (as per the conceptual model of CSIRO (2009)).

Table 4.3 Likelihood of groundwater inflow at river sites in the Gilbert catchment that were sampled in May 2012

SITE NUMBER	SUB-CATCHMENT	STREAM	SITE NAME	LIKELIHOOD OF GROUNDWATER INFLOW	COMMENTS
1	Gilbert	Gilbert River	Gilbert River@Bridge on Georgetown to Croydon Road	High	Only sampled in May, ^{222}Rn is high
2	Einasleigh	Routh Creek	Routh Creek@Bridge Crossing	Low	Only sampled in May, ^{222}Rn is low
3	Einasleigh	Einasleigh River	Einasleigh River@Highway Bridge between Georgetown and Mt Surprise	Low	Only sampled in May, ^{222}Rn is low
4	Einasleigh	Einasleigh River	Einasleigh River@Highway Bridge between Einasleigh and The Lynd Junction	Low	Only sampled in May, ^{222}Rn is low
5	Einasleigh	Einasleigh River	Einasleigh River@Crossing near Einasleigh	Nil	Only sampled in May, ^{222}Rn is negligible

Table 4.4 Likelihood of groundwater inflow at waterhole sites in the Gilbert catchment that were sampled between August and December 2012

SITE NUMBER	SUB-CATCHMENT	STREAM	SITE NAME	LIKELIHOOD OF GROUNDWATER INFLOW	COMMENTS
1	Einasleigh	Ellendale Creek	Lynd	High	Only sampled in August, ^{222}Rn is high
2	Einasleigh	Einasleigh River	Mt Surprise	Low	Only sampled in August, ^{222}Rn is low
3	Einasleigh	Bundock Creek	G1 - Lyndhurst	High	Radon is high in October but lower in December, δ^2H, $\delta^{18}O$ and Cl^- increase little between October and December, suggesting continuous groundwater inflow that may be reducing through the dry season
4	Einasleigh	McKinnons Creek	G2 - Lyndhurst	Nil	Radon is negligible and changes little between October and December, δ^2H, $\delta^{18}O$ and Cl^- increase between October and December, suggesting evaporation of only surface water
5	Einasleigh	Einasleigh River	G3 - Mt Alder Station	Low	Radon is low and changes slightly between October and November, δ^2H, $\delta^{18}O$ and Cl^- increase between October and November, suggesting evaporation of surface water with some groundwater component
6	Einasleigh	Einasleigh River	G4 - Mt Surprise	Nil	Radon is negligible and changes little between October and November, δ^2H, $\delta^{18}O$ and Cl^- increase between October and November, suggesting evaporation of only surface water
7	Einasleigh	Einasleigh River	G5 - Mt Surprise	Nil	Radon is negligible and changes little between October and November, δ^2H, $\delta^{18}O$ and Cl^- increase between October and November, suggesting evaporation of only surface water
8	Einasleigh	Elizabeth Creek	G6 - Mt Surprise	High	Radon is high and changes little between August and November, δ^2H, $\delta^{18}O$ and Cl^- increase little between August and November, suggesting continuous groundwater inflow through the dry season
9	Einasleigh	Junction Creek	G7 - Mt Surprise	Low	Radon is low and changes slightly between October and November, δ^2H, $\delta^{18}O$ and Cl^- increase little between October and November, suggesting evaporation of surface water with some groundwater component

Table 4.4 continued

SITE NUMBER	SUB-CATCHMENT	STREAM	SITE NAME	LIKELIHOOD OF GROUNDWATER INFLOW	COMMENTS
10	Gilbert	Porcupine Creek	G8 - Langlovale Station	Low	Radon is low and changes slightly between October and November, δ^2H, $\delta^{18}O$ and Cl^- increase little between October and November, suggesting evaporation of surface water with some groundwater component
11	Gilbert	Pleasant Creek	G9 - Lake Carlo Station	Nil	Radon is negligible and changes little between October and November, δ^2H, $\delta^{18}O$ and Cl^- increase between October and November, suggesting evaporation of only surface water
12	Gilbert	Gilbert River	G10 - Strathmore Station	High	Radon is high in August but negligible in October and November, δ^2H, $\delta^{18}O$ and Cl^- increase between August and November, suggesting a reduction in groundwater inflow through the dry season
13	Einasleigh	Einasleigh River	A - main channel (shallow) east	Low	Only sampled in November, ^{222}Rn is low
14	Einasleigh	Einasleigh River	B - anabranch (deep) east	Nil	Only sampled in November, ^{222}Rn is negligible
15	Einasleigh	Einasleigh River	C - anabranch (deep) east	Nil	Only sampled in November, ^{222}Rn is negligible
16	Einasleigh	Einasleigh River	D - main channel (30m up of Rd Xing, deep) east	Nil	Only sampled in November, ^{222}Rn is negligible
17	Einasleigh	Einasleigh River	E - anabranch (shallow between waterholes) west	Nil	Only sampled in November, ^{222}Rn is negligible
18	Einasleigh	Einasleigh River	Downstream Mount Noble	Low	Only sampled in November, ^{222}Rn is low
19	Einasleigh	Einasleigh River	Dagworth	Low	Only sampled in November, ^{222}Rn is low

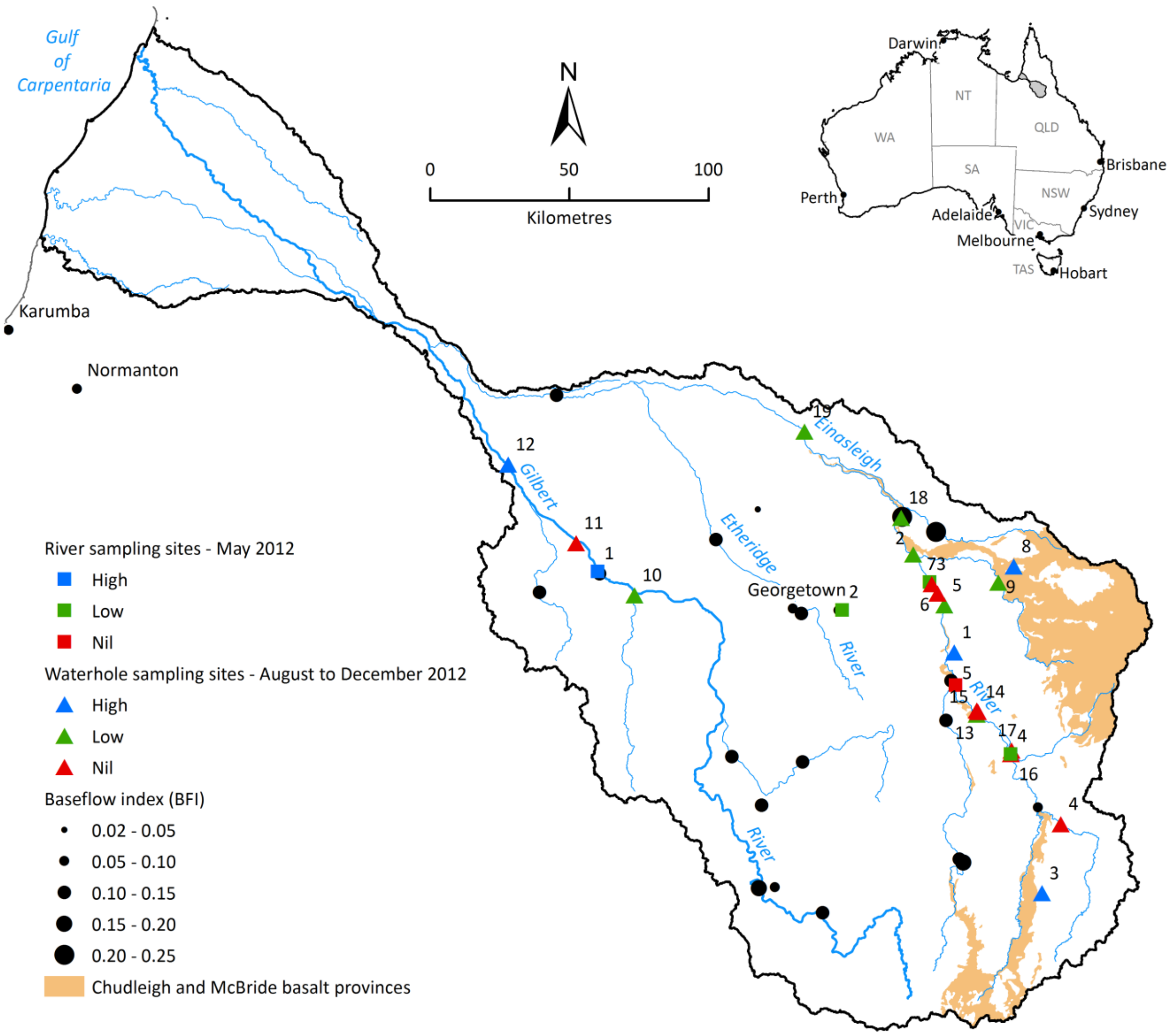

Figure 4.2 Likelihood of groundwater inflow at river and waterhole sampling sites in the Gilbert catchment. Details for each site are in Table 2.3 and Table 2.4

4.2 Task 2 - Leakage of water into the shallow alluvial/bedsands aquifers

4.2.1 FLINDERS CATCHMENT

The piezometers selected for this task were located along a 200 km reach of the Flinders River and varied in their distance from the river. It was anticipated that there would be significant wet season flows in the Flinders River and so the logger deployment would capture the alluvial/bedsands groundwater responses to the large rises and falls in river level. Hence, the data captured during this period could then be interpreted in relation to the direct river recharge of the alluvial/bedsands groundwater. Unfortunately there was very little rainfall during the 2012/13 wet season and so river flow was very minimal with only two small events. This limited the utility of the groundwater logger data. The only piezometers where groundwater responses due to the small flow events were observed were all located close to the river. The data from these suggest that in some instances (e.g. Figure 3.14 and Figure 3.18) river water flowed into the alluvial/bedsands aquifer. However, it then discharged back to the river following the flow events. These observations suggest that this was a bank recharge/discharge process and therefore it was likely that there was zero net river recharge from the flow events. The conceptual model proposed in CSIRO (2009a) was that during the wet season water infiltrates from the river into the alluvial/bedsands aquifer (either by lateral or overbank flooding processes) and after cessation of the wet season the groundwater discharges from the alluvial/bedsands aquifer back into the river as baseflow until the groundwater level falls below the river bed. However, the data collected in this Assessment suggests a much more dynamic process in which river water that infiltrates into the alluvial/bedsands aquifer during each flow event immediately discharges back into the river following the event.

The stable isotope data collected from the piezometers indicates that the alluvial/bedsands groundwater has a similar isotopic composition to that of rainfall (Figure 3.10). This suggests that any recharge to the alluvial/bedsands groundwater system occurs rapidly. The major ion composition of alluvial/bedsands groundwater in piezometers close to the river show a component of river water however this is most likely due to repeated bank recharge/discharge processes during wet seasons whereby some of the river water has mixed with the alluvial/bedsands groundwater in the aquifer. Overall, it appears from the logger, tracers and major ion data that the dominant net recharge process is probably diffuse rainfall recharge and not direct river recharge.

The anthropogenic trace gas (CFCs and SF_6) and ^{14}C data has been interpreted to estimate the likely rates of recharge to the alluvial/bedsands aquifers along the 200 km reach. Concentrations of anthropogenic trace gases in groundwater samples from bores in the Flinders catchment are shown in Figure 4.3. The fact that all but one of the CFC-11 concentrations plot to the left of the expected composition and mixing envelope with CFC-12 suggests that this tracer has been naturally degraded, which is not uncommon. Likewise, the fact that all CFC-12 concentrations plot below the expected composition and mixing envelope with SF_6 suggest that this tracer has also been degraded with respect to SF_6. Therefore, recharge rates calculated using the CFC data should be considered as lower limits.

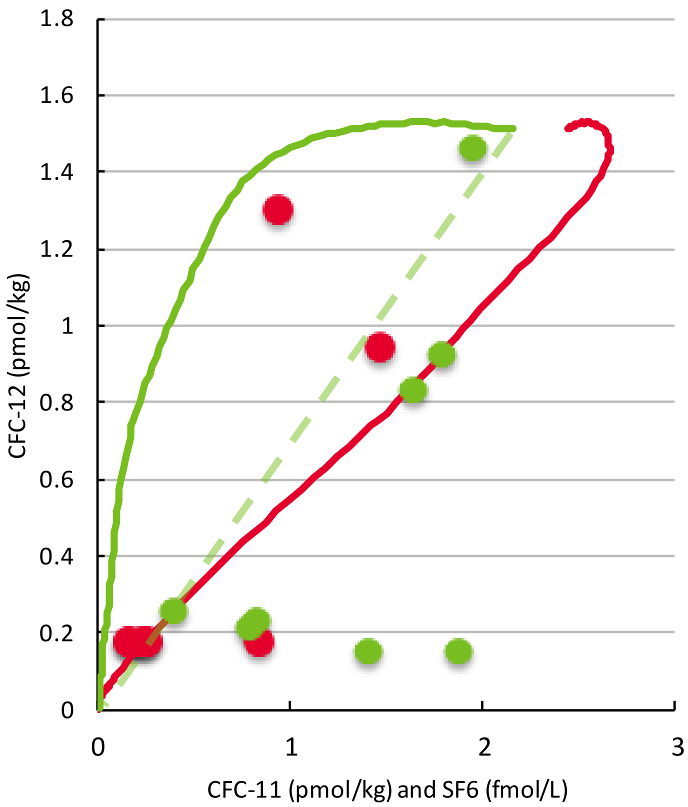

Figure 4.3 Relationship between CFC-12 concentration and either CFC-11 concentration (red) or SF_6 concentration (green). Solid lines represent expected compositions for groundwater recharged since 1940, and points represent results from Flinders bores. In both cases it was assumed that recharge temperature is 25 °C, altitude is 250 m AHD and salinity is ~1000 mg/L, while an excess air of 2.3 cc/kgH_2O was used to compute SF_6 concentrations. Dashed lines form an envelope of possible compositions due to binary mixtures of water recharged at different times

Net recharge rates have been estimated using three different tracers: CFC-12, SF_6 and ^{14}C (Figure 4.4). A simple model that considers recharge as a 1-D vertical process was used to produce theoretical curves for different recharge rates. This simplification is appropriate if either: (i) the aquifer is unconfined with a thickness that increases linearly at a slope of 1:1; or (ii) the aquifer is unconfined with a constant thickness and the sampling depth is less than 20-30% of the thickness. Whilst the former is unlikely for the alluvial/bedsands aquifers bordering the Flinders River, the latter is considered a reasonable assumption.

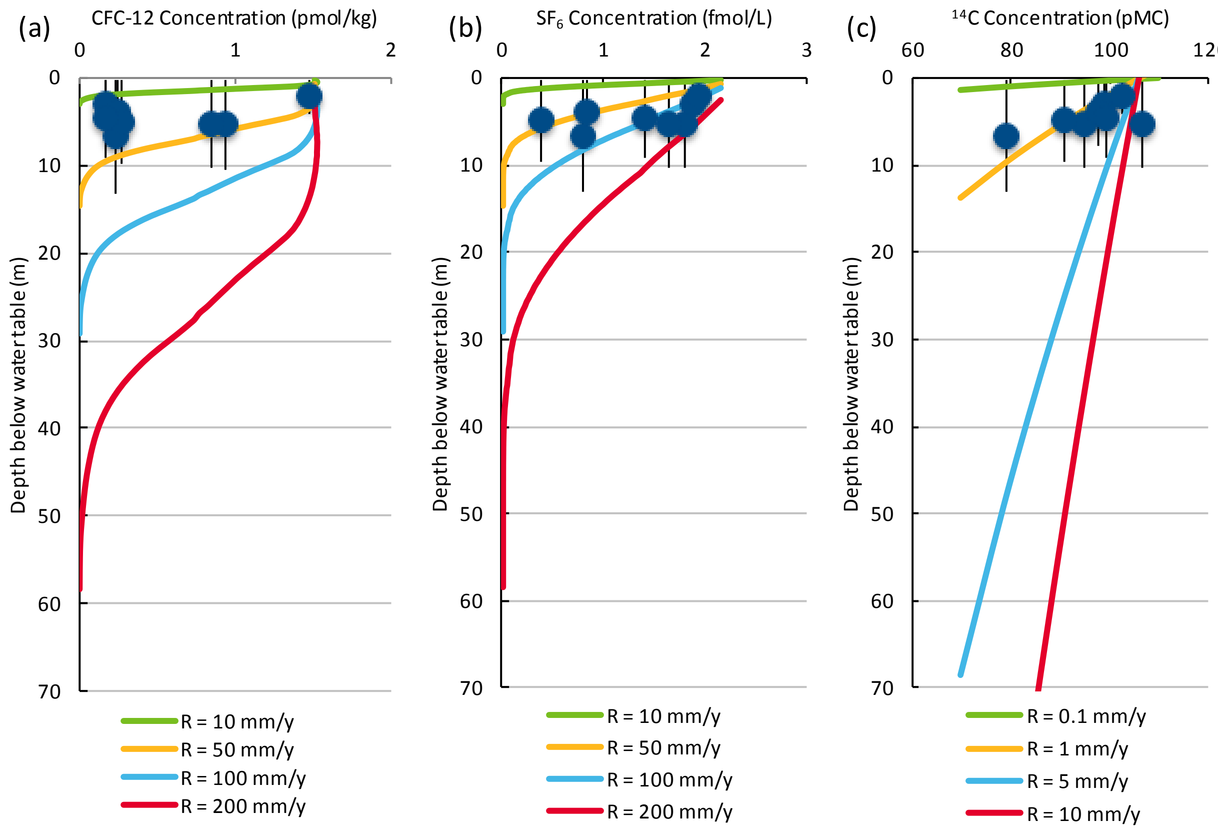

Figure 4.4 Concentrations of CFC-12, SF_6 and ^{14}C in groundwater samples versus depth below watertable. Error bars represent the maximum possible extent of the production zone in each bore, which was taken as the interval between the watertable and the total depth. Lines on each plot represent modelled relationships for different recharge rates, assuming 1-D vertical (piston) flow

In the case of CFC-12 all samples plot between recharge curves for 10 mm/year and 50 mm/year, although the error bars indicate that recharge rate could be significantly less than 10 mm/year if groundwater samples were derived entirely of water from immediately below the watertable. Regardless, these values are considered lower limits for recharge rate due to degradation of CFC-12 (Figure 4.3). In contrast, the SF_6 concentration-depth profiles are indicative of recharge rates from below 10 mm/yr up to more than 200 mm/year, with the wide range reflecting uncertainty in the production zone of the bores.

The most revealing tracer results are for ^{14}C, which suggest net recharge rates are very low and between 0.1 and 5 mm/year (although one sample from ‘Shed Bore’ on Glendalough suggests recharge is >10 mm/year). The modelled recharge curves for ^{14}C assume an initial ^{14}C concentration at the time of recharge of 106 pMC (consistent with the highest measured value) and that no carbonate weathering has occurred below the watertable, which would result in addition of ‘dead’ carbon and therefore reduce the ^{14}C concentration. This assumption is considered valid because stable carbon isotope composition ($\delta^{13}C$, Table 3.7) is relatively uniform and consistent with dissolved carbon derived mainly from soil gas. The modelled recharge curves also assume that the ^{14}C concentrations in the unsaturated zone have equilibrated to the atmospheric values. This assumption is likely to be valid in this case as the watertables are shallow and the recharge, when it occurs, appears to be rapid, as indicated by the stable isotopic composition of the groundwater mostly plotting on the LMWL (Figure 3.10). However no ^{14}C measurements of CO_2 in the unsaturated zone were measured, and so if this assumption is invalid then the recharge rates may be underestimated and may explain why these estimates are lower than those derived from CFCs and SF_6. Overall, the recharge rates determined from ^{14}C data are considered the most reliable estimates for net recharge obtained to date. Furthermore, they are consistent with the following:

- Gross recharge estimated for the Flinders-Leichhardt region using an uncalibrated soil-vegetation-atmospheric-transfer (SVAT) model in the Northern Australia Sustainable Yield (NASY) project (19 mm/year; Crosbie et al., 2009).
- Net recharge estimated for the Flinders-Leichhardt region using a steady state Chloride Mass Balance (CMB) in the NASY project (1-10 mm/year; Crosbie et al., 2009).
- Mean annual groundwater recharge rates for the Flinders catchment that were derived using a simple regression model that relates root zone drainage to broad soil type, land use and mean annual rainfall (<1-5 mm/year; Figure 1.8).
- A conceptual model in which net recharge beneath the floodplain is negligible due to: (i) the limited spatial and temporal extent of direct river recharge because of the highly ephemeral nature of the Flinders River; (ii) the heavy textured surface soils that limit rainfall infiltration; and (iii) high evaporation demand in the dry season.

Moreover, there were no obvious trends between net recharge rate and distance from river or depth to watertable. This is further evidence that the dominant recharge mechanism is spatially and temporally intermittent diffuse rainfall recharge.

4.2.2 GILBERT CATCHMENT

The two piezometers sampled in the GAB recharge areas of the Gilbert catchment were screened over the majority of the Coffin Hill Member that was intersected by each piezometer. Hence it is not possible to estimate recharge rates in the same manner as was done for the Flinders alluvial/bedsands piezometers. However, it is possible to make some qualitative interpretations of the recharge to the GAB beds in this area.

Piezometer GROB2 is located approximately 850 m from the Gilbert River. The CFC-11 and CFC-12 concentrations are low and exhibit natural degradation. The SF_6 concentration is also low. These anthropogenic trace gases suggest there has been little or no recharge in the last 50 years. However, the high ^{14}C concentration of 103.44 pMC suggests that the groundwater has some component of recent recharge. The $\delta^{13}C$ value of -10.04 **‰** PBD is consistent with dissolved carbon derived mainly from soil gas, suggesting that no carbonate weathering has occurred below the watertable, which would result in addition of 'dead' carbon and therefore reduce the ^{14}C concentration. The results suggest that the groundwater contains a mixture of recharge waters of different ages. However, it is not possible to determine the exact ratios of each recharge source as the anthropogenic trace gases concentrations are for the gas phase and do not reflect the actual masses of the tracers in the groundwater. The major ion compositions are of no use in determining if the groundwater has a river water component as GAB groundwater throughout this region is of Na-HCO_3 type, as is the Gilbert River water. There was no logger data available that could be used to determine if there were any groundwater responses to the two minor river flow events. Given that the piezometer is located a long way from the river it is unlikely there is any direct recharge from the Gilbert River via the alluvium/bedsands but this cannot be completely ruled out. The overall interpretation is that this site receives only intermittent diffuse rainfall recharge during very large rainfall events and therefore has a low mean recharge rate.

Piezometer GROB4 is located approximately 2,300 m from the Gilbert River. The CFC-11 and CFC-12 concentrations are higher than those of piezometer GROB2 but also exhibit natural degradation. The SF_6 concentration is also higher than that of piezometer GROB2. These anthropogenic trace gases suggest there has been some recharge in the last 50 years. However, the ^{14}C concentration of 52.25 pMC suggests that the groundwater is approximately 5,000 years old. The $\delta^{13}C$ value of -12.84 ‰ PBD suggests that no carbonate weathering has occurred below the watertable, which would result in addition of 'dead' carbon and therefore reduce the ^{14}C concentration. Similar to piezometer, GROB2 the results indicate that the groundwater contains a mixture of different age recharge waters. However, it is not possible to determine the exact ratios of each recharge source as the anthropogenic trace gases concentrations are for the gas phase and do not reflect the actual masses of the tracers in the groundwater. There was groundwater level logger data available for this piezometer which indicated increases of ~0.1 m following the two flow events in the Gilbert River. However, there was no logger EC data and so it was not clear whether this was just a pressure response or was due to river recharge. Given the large distance of this piezometer from the Gilbert River, the former is most likely. The overall interpretation is that this site receives only intermittent diffuse rainfall recharge during very large rainfall events and therefore has a low mean recharge rate.

While it has not been possible to quantify the diffuse recharge rates at these sites it is likely that they would be in the range 5 - 40 mm/year (as per Figure 1.15) which is consistent with the estimates previously reported by Kellett et al. (2003) and Smerdon and Ransley (2012). The low recharge rates are thought to be due to: (i) the limited spatial and temporal extent of direct river recharge because of the highly ephemeral nature of the Gilbert River; and (ii) the high evaporation demand in the dry season.

4.3 Conceptual models of surface water-groundwater connectivity

As a result of the work carried out in the groundwater activity it has been possible to formulate some generalised conceptual models of surface-groundwater connectivity along the rivers of the Flinders and Gilbert catchments. These are a significant advance on those proposed in the previous Northern Australia Sustainable Yield (NASY) project (CSIRO, 2009a, 2009b).

There is a default conceptual model in which there is no saturated connectivity between the rivers (and waterholes) and the underlying groundwater systems. This is likely to be the case in situations where the river or waterhole beds have such low permeability that leakage through the beds is so minimal that saturated connection between the two water bodies never occurs. In the surface water-groundwater literature this is referred to as a disconnected system (Brunner et al., 2009). Due to the ephemeral nature of most of the rivers, the generally heavy textured surface soils, and the high rates of high evaporation demand during the dry season, this conceptual model is likely to apply widely across both catchments.

In situations where there is a saturated connection between the river and the underlying groundwater system (this is referred to as a connected system), four pre-development conceptual models have been defined, along with a generic conceptual model for an irrigation development adjacent to a river. Each of the five conceptual models show the surface water-groundwater flow processes during the wet season, during the early dry season, and at the end of dry season. It is important to note that these conceptual models are highly generalised and there will be many variations of each at the individual site scale.

Figure 4.5 depicts the pre-development conceptual model of surface water-groundwater connectivity in lowland areas where there are no bedrock highs (comprised of either fractured rock or GAB formations) in the alluvium/bedsands. At the end of the wet season river levels are higher than the watertable level in the alluvium/bedsands (which may still be rising) and so river water recharges the alluvium/bedsands. During the dry season the river levels drop and eventually they may fall below the water table level and so some or all of the river water stored in the alluvium/bedsands discharges back into the river. By the end of the dry season when the river level is low/dry, the watertable in the alluvium/bedsands may also drop below the river bed due to evaporation losses to the riparian vegetation adjacent to the river. An example of this conceptual model was not observed during the river and waterhole sampling but it may possibly occur at locations in the lower reaches of the Flinders and Gilbert Rivers where the river beds are permeable and so there is an underlying aquifer in the alluvium/bedsands.

Figure 4.6 depicts the generic post-development conceptual model of surface water-groundwater connectivity in lowland areas with irrigation adjacent to the river. It assumes that irrigation has been taking place for sufficient time that the application of irrigation in excess of crop water requirements, causing enhanced rates of root zone drainage and recharge, has lead to the formation of a groundwater mound beneath the irrigation area. At the end of the wet season river levels are higher than the watertable level in the alluvium/bedsands (which may still be rising) and so river water recharges the alluvium/bedsands. There is also flow of groundwater from the mound towards the river and this may be impeded by the river water that is recharging into the alluvium/bedsands. During the dry season the river levels drop and eventually they may fall below the water table level and so some or all of the river water stored in the alluvium/bedsands discharges back into the river. The flow of groundwater from the mound may also then discharge into the river as it is no longer impeded by the high watertable in the alluvium/bedsands. By the end of the dry season when the river level is low/dry groundwater from the mound may still be discharging into the river and in some instances some groundwater may flow under the river if the watertable on the other side is below the river bed (due to evaporation losses to the riparian vegetation adjacent to the river). It is important to note that this conceptual model is highly generic and will vary greatly depending on the geological setting (i.e. as shown in the four pre-development conceptual models presented here) and the size, location, geometry and type of irrigation development. It is not possible at this stage to progress beyond this idealised generic conceptual model. It is however a useful pointer to the types of surface water-groundwater interactions that may occur when irrigation developments are sited close to rivers.

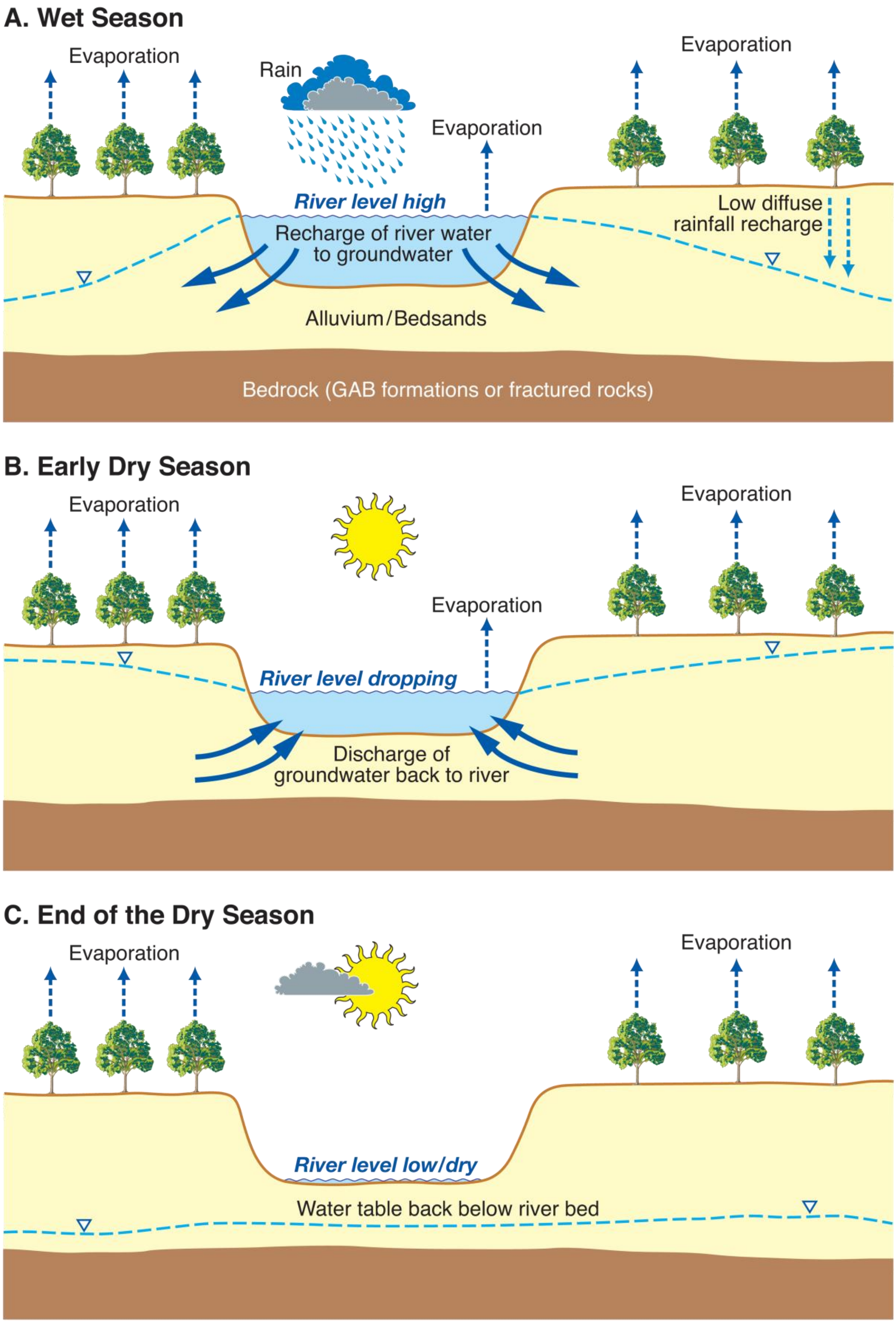

Figure 4.5 Pre-development conceptual model of surface water-groundwater connectivity in lowland areas where there are no bedrock highs in the alluvium/bedsands

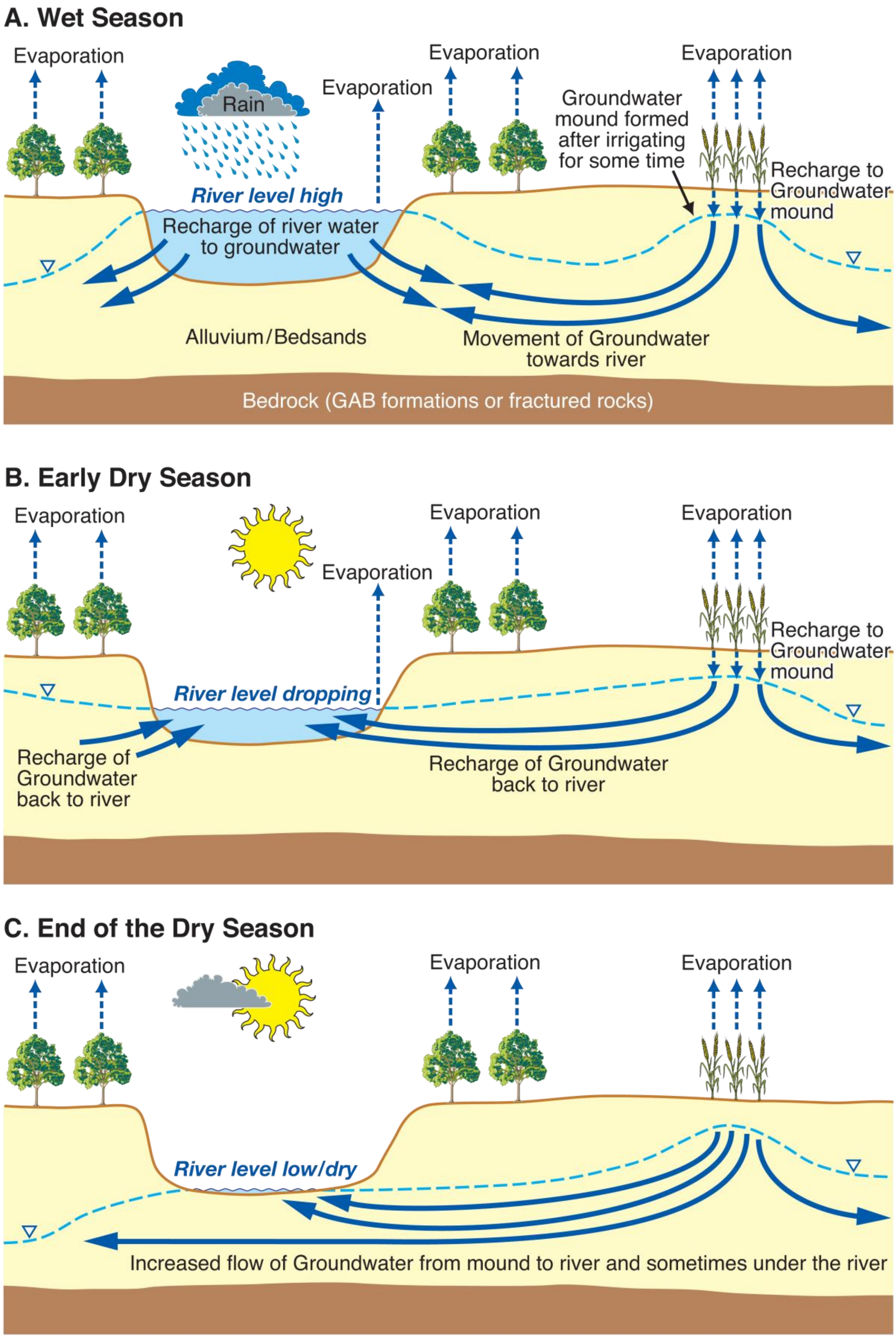

Figure 4.6 Generic post-development conceptual model of surface water-groundwater connectivity in lowland areas with irrigation adjacent to the river

Figure 4.7 depicts the pre-development conceptual model of surface water-groundwater connectivity in lowland areas where there are GAB formation(s) bedrock highs in the alluvium/bedsands. This conceptual model was first proposed in CSIRO (2009a). At the end of the wet season river levels are higher than the watertable level in the alluvium/bedsands (which may still be rising) and so river water recharges the alluvium/bedsands and also the GAB formations(s). During the dry season the river levels drop and eventually they may fall below the water table level and so some or all of the river water stored in the alluvium/bedsands discharges back into the river. By the end of the dry season when the river level is low/dry, the watertable in the alluvium/bedsands may also drop below the river bed due to evaporation losses to the riparian vegetation adjacent to the river. However, the watertable levels in the GAB formation(s) may be higher than the river bed and some of the river water that had flowed into the GAB formations during the wet season may now discharge back into the river, a process referred to as rejected recharge. Possible examples of this conceptual model are river site 1 and waterhole site 12 on the Gilbert River (see Table 2.3, Table 2.4 and Figure 2.2) which are located downstream of an area where the Gilbert River Formation outcrops in the alluvium/bedsands.

Figure 4.8 depicts the pre-development conceptual model of surface water-groundwater connectivity in lowland areas where there are fractured rock bedrock highs in the alluvium/bedsands. At the end of the wet season river levels are higher than the watertable level in the alluvium/bedsands (which may still be rising) and so river water recharges the alluvium/bedsands. During the dry season the river levels drop and eventually they may fall below the water table level and so some or all of the river water stored in the alluvium/bedsands discharges back into the river. However, some of this water may become trapped in bedrock lows and does not discharge back to the river immediately. By the end of the dry season when the river level is low/dry, the watertable in the alluvium/bedsands may also drop below the river bed due to evaporation losses to the riparian vegetation adjacent to the river. However some or all of the water that was trapped in bedrock lows may discharge back into the river during the dry season. An example of this is waterhole site 8 on the Cloncurry River (see Table 2.2 and Figure 2.1) which is located in an area where the presence of rock bars across the valley is thought to lead to groundwater levels remaining closer to the surface during the dry season than otherwise would be the case.

Figure 4.9 depicts the pre-development conceptual model of surface water-groundwater connectivity in upland fractured rock areas with shallow alluvium/bedsands. This conceptual model may apply in areas where there is high rainfall recharge through fractured rocks occurring during the wet season which leads to significant rises in watertable levels in the fractured rock aquifers. At the end of the wet season river levels may be higher than the watertable level in both the alluvium/bedsands (which may still be rising) and the adjacent fractured rock aquifers and so river water recharges the alluvium/bedsands. During the dry season the river levels drop and eventually they may fall below the watertable level and so some or all of the river water stored in the alluvium/bedsands discharges back into the river. Moreover, the watertable level in the adjacent fractured rock, which has risen as the wet season rainfall recharge reaches the water table, is much higher than the river levels and so this groundwater also flows into the river and this continues throughout the dry season. Possible examples of this conceptual model in the Gilbert catchment are waterhole site 1 on Ellendale Creek, waterhole site 3 on Bundock Creek and waterhole site 8 on Elizabeth Creek (see Table 2.4 and Figure 2.2) which are all located within the upland fractured rock areas of the Einasleigh River. Possible examples of this conceptual model in the Flinders catchment are river site 3 on the Flinders River and waterhole site 10 on Fairlight Creek (see Table 2.1, Table 2.2 and Figure 2.1) which are all located adjacent to the Sturgeon Basalt. In the latter case groundwater flow under the Flinders River may occur as the Sturgeon Basalt is only found on the north side of the river and could explain why there are good quantities of low salinity alluvial/bedsands groundwater in some locations on the southern side of the Flinders River.

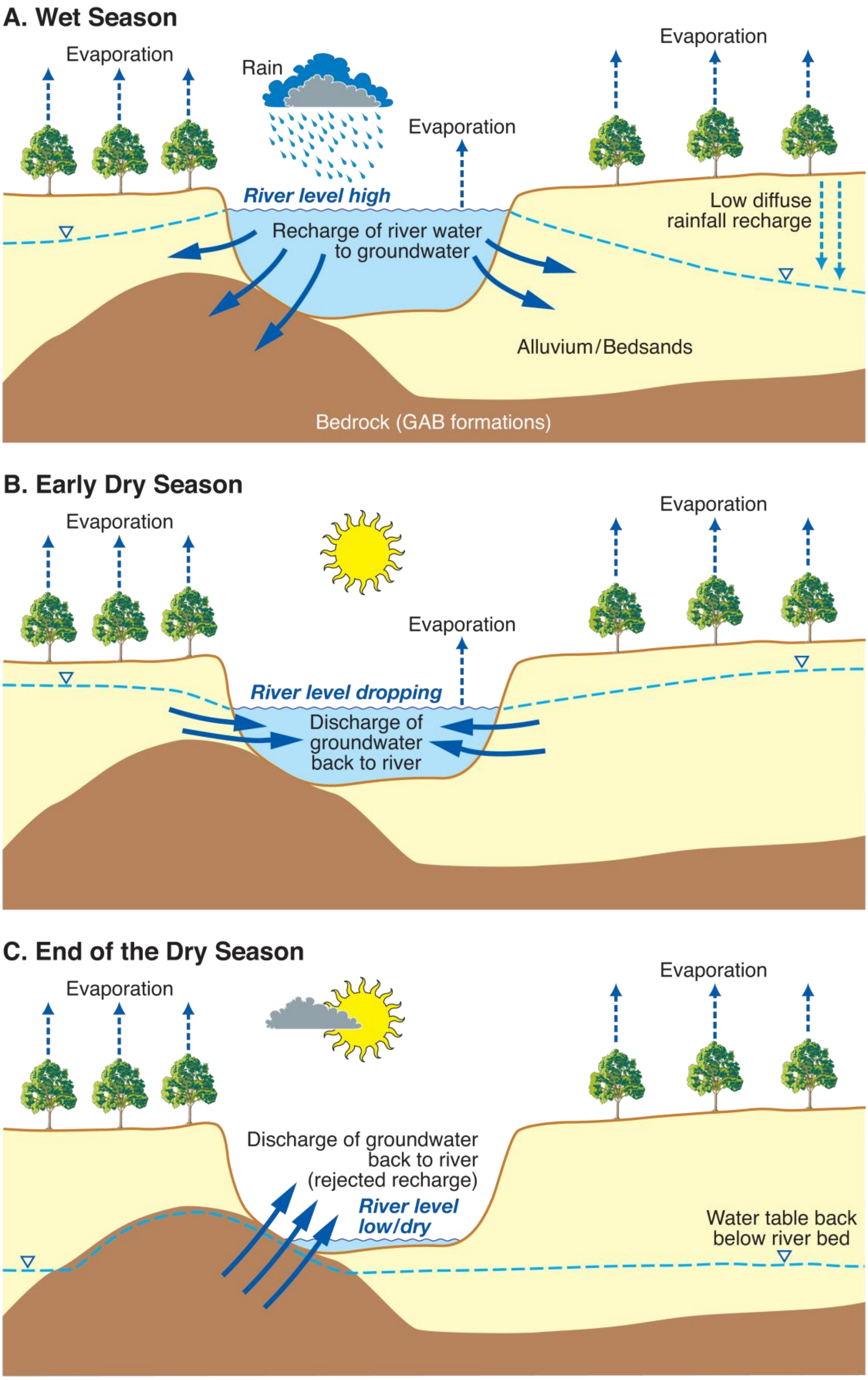

Figure 4.7 Pre-development conceptual model of surface water-groundwater connectivity in lowland areas where there are GAB formation(s) bedrock highs in the alluvium/bedsands

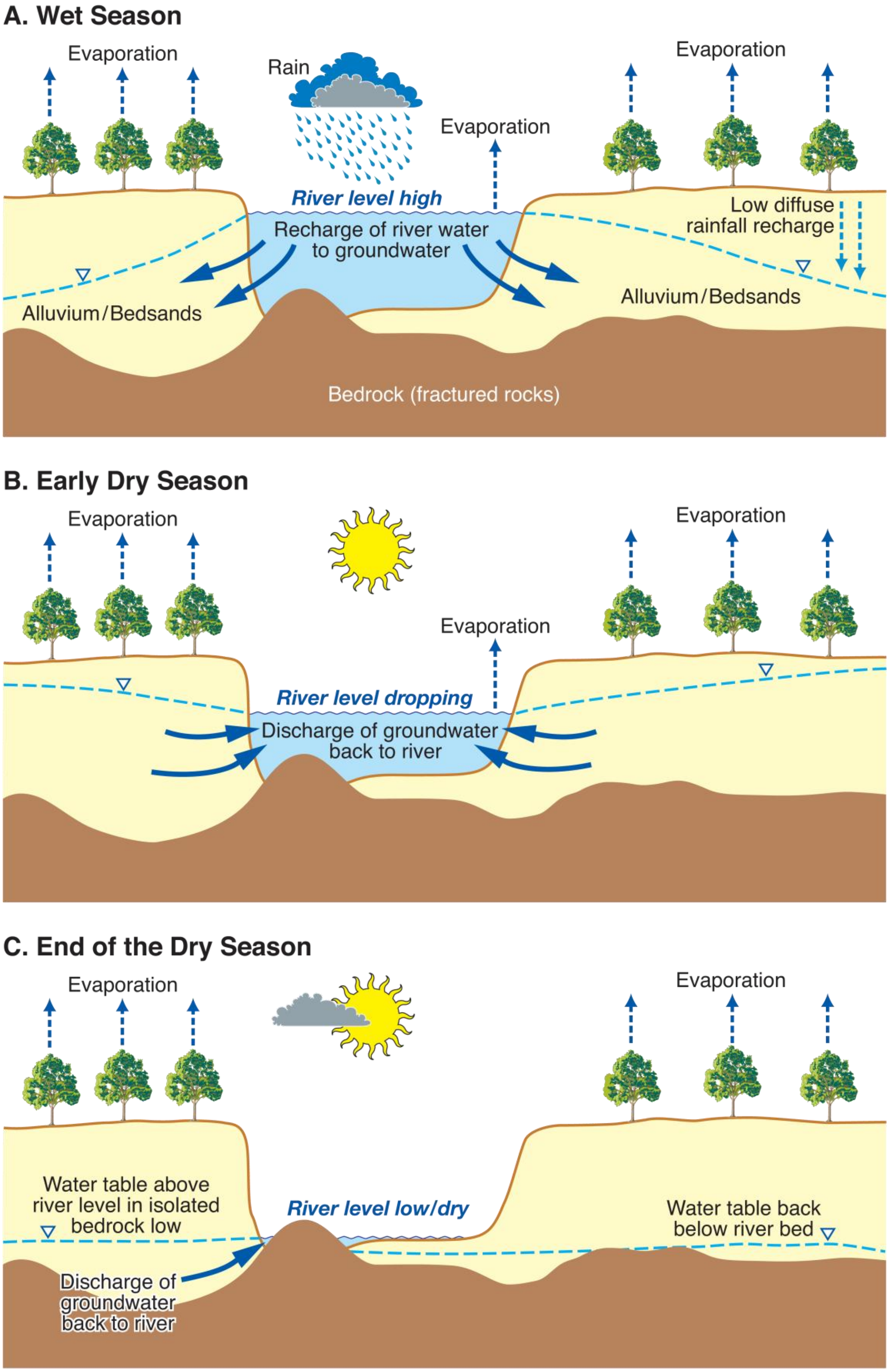

Figure 4.8 Pre-development conceptual model of surface water-groundwater connectivity in lowland areas where there are bedrock highs in shallow alluvium/bedsands

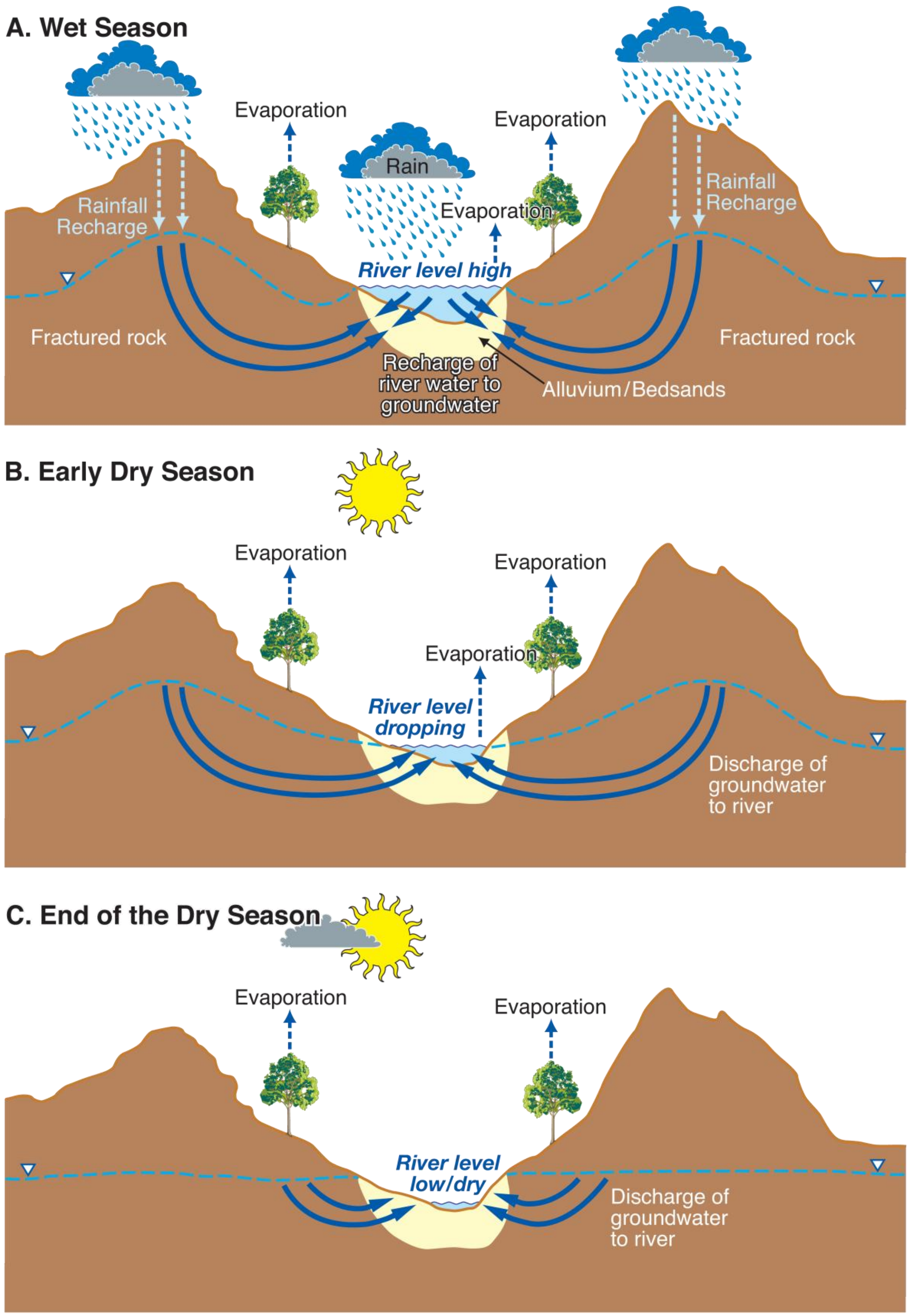

Figure 4.9 Pre-development conceptual model of surface water-groundwater connectivity in upland fractured rock areas with shallow alluvium/bedsands

4.4 Task 3 Risk of root zone drainage beneath irrigation leading to watertable rise

Newly introduced large irrigation developments result in increased root zone drainage below the root zone, which recharges the underlying aquifers. Excessive recharge results in the formation of groundwater mounds, shallow aquifers, and in extreme cases, water logging.

Salinity in soil, groundwater and river systems has long been a serious problem in many parts of Australia. Long before European settlement, Australia was dotted with naturally occurring brackish creeks, saltpans and salt marshes (Ghassemi et al. 1995). There are enormous, ancient stores of salts that are released from weathering rocks, or were carried in from surrounding oceans in rainfall, and trapped in the landscape long ago. Naturally-occurring salinity is referred to as primary salinity whereas human-induced salinity in referred to as secondary salinity. The latter can either be irrigation induced, or dryland induced resulting from changed land use in non-irrigated areas.

Rainfall and irrigation water have different salt concentrations. Over many hundreds of years, salts can be concentrated in the soil profile via evaporation. Areas most susceptible typically have low annual rainfall (i.e. less than 800 mm/yr) and low permeable soil. An example in the Gilbert catchment, are the cracking clay soils formed on the Rolling Downs group. Areas with higher annual rainfall (i.e. more than 1200 mm/yr) and highly permeable soils tend to have lower concentrations of salts in the soil profile due to the leaching of salts that eventually make its way down to the watertable. An example are the sand or loam over friable or earth clay and friable non-cracking clay or clay loam soils on the alluvial soils adjacent to the Gilbert and Einasleigh rivers.

There are three basic requirements for salt to induce environmental problem: (1) the existence of a salt source; (2) a source of water to mobilise the salt; and (3) a mechanism through which the salt gets redistributed to locations in the landscape where it can be damaging (AGS 2000). The latter is provided by rising groundwater tables. Irrigation leads to a significant increase in groundwater recharge thus resulting in: (1) rise in groundwater levels and associated increase in discharge to rivers, and (2) direct discharge to land surface and enhanced vertical evaporation through the soil when water table approaches the land surface. In areas having saline groundwater or significant salt stores in the soil profiles, the additional discharge increases the salt loads in nearby rivers. This assessment is concerned only with irrigation induced secondary salinity.

Irrigation water provides the source of water that mobilises the salts; it can also be the salt source, however, this is not the case for this study. Under irrigation, root zone drainage is significantly enhanced, thus resulting in shallow groundwater tables. Root zone drainage rates tend to be higher under coarser textured soils (Petheram et al. 2002) and poor irrigation practices. In Australia, an increase in root zone drainage under poor irrigation practices, together with leakage of water from associated irrigation water distribution networks and drainage channels, has caused watertables to rise under many intensive irrigated areas. Significant parts of all major intensive irrigation areas in Australia are currently either in a shallow watertable equilibrium condition or approaching it (Christen and Ayars, 2001). Shallow water tables (in the vicinity of 2-3 m from the land surface) pose further risks as salts concentrate over time via evaporation, thus resulting in saline root zone that limit plant growth.

The analysis conducted in this study investigated how sensitive groundwater rise is to the following factors: aquifer hydraulic parameters, recharge rate and area, and distance to the river. It was shown that the maximum rise in groundwater table increases with recharge and decreases with higher saturated hydraulic conductivity. The effects of aquifer transmissivity and recharge rates were found to be linear but opposite and perfectly correlated

The maximum groundwater table level rise decreases as the distance from the irrigation area to the river decreases. This is because as the irrigation area gets closer to the river, more groundwater is able to be discharged to the river. Figure 3 shows that the maximum watertable level increases in a non-linear manner as the distance from the irrigation area to the river increases. The time scales during which the water table rises are realised vary linearly with aquifer hydraulic parameters and non-linearly with the distance from the irrigation area to the river; high aquifer diffusivity and a shorter distance to the river speeds up the response.

The case studies have shown that one should be aware that placing large irrigation developments may lead to extreme rises in groundwater levels when crops with a high irrigation demand are introduced to areas with low-conductivity aquifers.

5 Conclusions

5.1 Task 1 - Hydrogeological controls on dry-season flows and waterhole persistence

The majority of river and waterhole sites sampled in both catchments had a nil or low likelihood of groundwater inflow, and so their persistence during the dry season appears to be unrelated to groundwater. It therefore is likely that there is no long term saturated connection between the rivers and the underlying groundwater systems in widespread areas of both catchments. In these situations it is unlikely that future alluvial/bedsands groundwater development will have an impact on the hydrology and associated ecosystem health of permanent waterholes. However, there were several sites that had a high likelihood that groundwater inflows would be a contributor to their persistence through the dry season. All of these appear to be related to local hydrogeological conditions such as: (i) bedrock highs in the alluvium/bedsands holding groundwater levels higher than otherwise would be the case (Figure 4.6); (ii) outcropping of GAB formations in the river/waterhole beds which leads to rejected wet season recharge (Figure 4.7); and (iii) close proximity to fractured basalt (Figure 4.9). In these situations, there is a possibility that future groundwater development in the alluvium/bedsands and fractured basalts may have an impact on the hydrology and associated ecosystem health of permanent waterholes. More focussed investigations will be needed at individual sites to determine the exact nature and magnitude of such impacts.

Whilst the dry season persistence of waterholes does not generally appear to be related to groundwater in most cases it is important to understand the chemistry utilised in this component of the Assessment. These methods are appropriate for detecting the inflow of groundwater to surface water that has been subject to reasonably long flow paths (has spent months to thousands of years in the sub surface) as would be expected for example in alluvial and fractured rock systems. What the chemistry is less appropriate for is identifying the inflow of other highly localised groundwater systems, where sub surface flows are in the order of days to months. These highly localised parafluvial groundwater systems exist in the fluvial plain (riverbed sediments) within the river channel. It is possible that parafluvial groundwater (surface water that enters the sub surface through the fluvial plain sediments in the river channel and discharges down plain within the river channel in areas of topographic relief or low points) could support waterholes in both catchments. However, this was not assessed and would require further investigation.

The potential impacts on alluvium/bedsands aquifers due to changes in river management needed to supply surface water for irrigation will be highly dependent on the new flow regulation regime, in particular the magnitude, frequency and timing of individual water releases from storages and the subsequent extractions for use (which will be dependent on the types of crops/pastures that may be grown and the types of infrastructure used to store and harvest the flows). In terms of potential river regulation there are three main possibilities: (i) year-round releases for perennial agricultural systems; (ii) supplementary releases for annual agricultural plantings in January/February that are harvested in May/June; and (ii) dry season releases for annual agricultural systems. Given that the details of each of these are yet to be determined in each catchment it is only possible to speculate as to what the potential future groundwater impacts are for dry season flows and waterhole persistence. Year-round releases that make the naturally ephemeral river systems perennial may lead to an increase in recharge to the alluvium/bedsands and a decrease in discharge of groundwater to waterholes and rivers. This would be due to river levels being maintained at higher levels than the underlying groundwater for longer periods of time than is presently the case. However, if this were to happen then there may be no implications for the persistence of dry season waterholes due to the increased presence of surface water. The impact of supplementary and dry season releases will be minimal as they will result in only short term fluctuations in river flow. These short-term changes in river flow are similar to the naturally intermittent wet season flows. Results from this Assessment indicate that these naturally intermittent flows do not appear to result in appreciable river recharge. For any of these flow release regimes it is important to note that local hydrogeological conditions (i.e. the physical properties of the river channel including, the level of saturation within the riverbed and riverbank sediments, the thickness of the alluvium/bedsands, and the presence or absence of bedrock highs either within the alluvium/bedsands or adjacent to the river channel) will influence the exact nature and magnitude of these impacts.

5.2 Task 2 - Leakage of water into the shallow alluvial/bedsands aquifers

Based on experience in southern Australia, recharge rates in alluvial/bedsands aquifers adjacent to major rivers is often higher than surrounding areas due to river recharge (e.g. in the alluvium of the lower reaches of the Namoi catchment; CSIRO 2007). However, this theory has not been tested to any great degree in northern Australia. The field investigation adjacent to the Flinders River between Hughenden and Maxwelton was carried out to gain a better understanding of the connection between this ephemeral river and the shallow alluvial/bedsands aquifers, and to provide baseline groundwater information prior to any new irrigation developments. Interpretation of the data collected from these piezometers suggests that net recharge rates to the Flinders River alluvium/bedsands were probably not very high (0.1 to >10 mm/year) and were comprised of diffuse rainfall recharge rather than direct river recharge. The low recharge rates were thought to be due to: (i) the limited spatial and temporal extent of direct river recharge because of the highly ephemeral nature of the Flinders River; (ii) the heavy-textured surface soils that limit rainfall infiltration; and (iii) the high evaporation demand in the dry season. The low net recharge rates results in spatially variable water quality that is often poor (Cochrane, 1967; Lloyd, 1970, QIWSC, 1973). This, combined with the highly variable (and often limited) saturated thickness of the alluvial/bedsands aquifer (data from the Geophysics activity suggests that the saturated thickness of the alluvium/bedsands in the study reach is typically 5 - 10 m), is why the alluvial/bedsands groundwater has only been intermittently developed in the Flinders catchment. Given the low diffuse recharge rates to the alluvial/bedsands aquifer, and the lack of evidence for high rates of direct river recharge, increased shallow groundwater usage may lead to lowering of groundwater levels, depending on local hydrogeological conditions.

While it was not possible to estimate recharge rates to the GAB recharge beds adjacent to the Gilbert River in the same manner as was done for the Flinders River alluvial/bedsands piezometers. However, it was possible to make some qualitative interpretations of the recharge regime. Interpretation of the data collected from the two piezometers in the Gilbert catchment was that these sites received only intermittent diffuse rainfall recharge during very large rainfall events (prior to the low rainfall 2012/13 wet season) and therefore have a low mean recharge rate. While it has not been possible to quantify the diffuse recharge rates at these sites it is likely that they would be in the range 5 - 40 mm/year (Figure 1.15) which is consistent with estimates reported elsewhere (Kellett et al. 2003; Smerdon and Ransley 2012). Similar to the Flinders River alluvium/bedsands, the low recharge rates to the GAB recharge beds at these locations are thought to be due to: (i) the limited spatial and temporal extent of direct river recharge because of the highly ephemeral nature of the Gilbert River; and (ii) the high evaporation demand in the dry season. Furthermore, the alluvium/bedsands along this reach of the Gilbert River have only a thin saturated thickness (data from the Geophysics activity suggests that the saturated thickness in this area is typically 3 - 10 m) and are currently being utilised for nearby irrigation. Therefore, there is only limited groundwater storage in the alluvium/bedsands (QDNR, 1998) that may be available to supply river water to the GAB recharge beds. In the case where GAB recharge beds outcrop in the bed of the Gilbert River recharge rates may be different but this has not been investigated as part of this Assessment.

As described above the potential impacts on leakage to alluvium/bedsands aquifers due to changes in river management will be highly dependent on the new flow regulation regime. For the Flinders catchment, year-round releases may make the naturally ephemeral river systems perennial. This may lead to an increase in recharge to the alluvium/bedsands and a decrease in discharge of groundwater to waterholes and rivers. The impact of supplementary and dry season releases will be minimal as they will result in only short term fluctuations in river flow. These short-term changes in river flow are similar to the naturally intermittent wet season flows. Results from this Assessment indicate that these naturally intermittent flows do not appear to result in appreciable river recharge. Similar conclusions are likely for the lower reaches of the rivers of the Gilbert catchment where highlands adjacent to the river channels are absent. In the upper reaches of the rivers of the Gilbert catchment, where the alluvium/bedsands are thin and laterally constrained by the adjacent fractured rock highlands, the storage in these aquifers is likely to be extremely low. In the case of any of the release regimes, leakage may not, depending on local hydrogeological conditions, necessarily increase due to the low aquifer storage.

5.3 Task 3 Risk of root zone drainage beneath irrigation leading to watertable rise

Placing large irrigation developments results in groundwater table rise and the formation of groundwater mounds; under sustained, long-term intensive irrigation such mounds may reach the ground surface. Rising water table pose the risk of secondary salinity, with the mobilised salts posing the threat of saline discharge to nearby rivers in addition to limiting plant growth. The sensitivity analyses have shown that the maximum (steady state) groundwater table rise increases with increasing recharge rate, irrigation area, distance to the river, and lower aquifer transmissivity. Irrigation developments placed further away from the river result in higher steady state groundwater table rise due to a diminishing river drainage capacity. The five case studies conducted for Cavehill, Kidston, Greenhill, O'Connell, and Dagworth sites have shown that placing large irrigation developments may lead to extreme rises in groundwater levels when crops with a high irrigation demand are introduced to areas with low-conductivity aquifers; in most cases, the groundwater table rose up to the soil surface. The time frames during which the groundwater table rises occurred varied from a few years to tens of years depending on aquifer hydraulic parameters and recharge rates. Essentially, the results from the analytical modelling show the importance of giving due consideration to siting irrigation areas in the landscape and its potential environmental impacts to both the landscape the rivers and groundwater.

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Appendix A

Apx Table A.1 Results of EC, pH, Total Alkalinity and major ion analyses for river sites in the Flinders catchment that were sampled in May 2012

SITE NUMBER	STREAM	SITE	DATE SAMPLED	EC (dS/m)	pH	Total Alkalinity (meq/L)	$NO3^-$ (mg/L)	$SO4^=$ (mg/L)	Ca (mg/L)	K (mg/L)	Mg (mg/L)	Na (mg/L)
1	Flinders River	Flinders River@Low level Crossing ~5 km upstream of Richmond	15/05/12	0.46	7.8	3.1	0.12	48	37.3	3.97	11.6	35.9
2	Flinders River	Flinders River@Ford ~40 km upstream of Richmond	15/05/12	0.39	7.8	2.8	0.33	34	30.9	3.79	10.8	29.3
3	Flinders River	Flinders River@Bridge in Hughenden	14/05/12	0.39	8.1	2.8	<0.05	32	29.4	2.96	10.2	31.6
4	Flinders River	Flinders River@Alderly Crossing	15/05/12	0.39	7.9	2.5	0.23	42	27.8	3.39	9.7	32.1
5	Flinders River	Flinders River@Hulberts Crossing	15/05/12	0.47	7.9	3.7	0.21	37	45.0	3.92	12.1	29.2
6	Stawell River	Stawell River@Cambridge Crossing	15/05/12	0.24	8.0	1.7	<0.05	13	14.6	3.19	7.6	18.6

Apx Table A.2 Results of EC, pH, Total Alkalinity and major ion analyses for waterhole sites in the Flinders catchment that were sampled between August and December 2012

SITE NUMBER	STREAM	SITE NAME	DATE SAMPLED	EC (dS/m)	pH	Total Alkalinity (meq/L)	$NO3^-$ (mg/L)	$SO4^=$ (mg/L)	Ca (mg/L)	K (mg/L)	Mg (mg/L)	Na (mg/L)
1	Flinders River	Wondoola	6/08/12	0.44	7.8	3.2	0.83	36.0	41.2	4.85	11.4	39.7
2	Flinders River	Etta Plains Station	10/08/12	0.48	7.6	3.5	0.82	45.0	45.9	4.98	14.5	47.3
3	Flinders River	River Dale Station	11/08/12	0.40	7.7	2.8	0.84	28.0	33.7	3.91	10.5	39.1
4	Flinders River	Tentative pool 11	12/08/12	0.62	7.8	3.5	0.60	71.0	50.6	4.05	15.2	63.4

5	Flinders River	Harrogate Station	12/08/12	0.42	7.9	3.1	0.34	28.0	39.3	3.58	11.4	37.2
6	Cloncurry River	Cowan Downs Station	6/08/12	0.09	6.9	0.7	1.20	4.5	7.79	2.43	1.9	6.0
7	Off channel waterhole	Cowan Downs Station - Off channel waterhole	6/08/12	0.26	7.2	2.4	2.00	3.9	28.3	6.06	8.1	15.1
8	Cloncurry River	Causeway - township	7/08/12	0.75	7.7	3.4	1.10	66.0	18.8	4.64	13.6	118.0
9	Cloncurry River	Fort Constantine Station	8/08/12	0.29	7.7	2.1	0.28	11.0	19.5	3.19	8.2	32.5
10	Fairlight Creek	F1 - Soda Valley/Glendalough Station	13/08/12, 29/10/12, 12/12/12,	0.62 0.83 0.90	7.6 7.8 7.9	3.8 4.9 5.1	2.40 0.58 <0.05	54.0 70.0 81.0	40.0 41.3 35.5	4.81 7.00 7.78	19.4 28.8 31.4	66.3 101.0 110.0
11	Flinders River	F2 - River Dale Station	13/08/12, 3/11/12	0.39 0.67	7.9 7.9	2.6 3.9	0.79 <0.05	36.0 58.0	28.8 25.8	3.76 9.24	11.9 18.1	39.2 88.4
12	Off channel waterhole	F3 - River Dale Station	3/11/12, 8/12/12	0.24 0.34	7.6 8.0	2.2 3.0	0.14 <0.05	4.7 3.7	12.2 12.1	4.90 6.40	3.6 3.6	40.6 59.2
13	Off channel waterhole	F4 - River Dale Station	28/10/12, 8/12/12	0.34 0.58	7.5 7.7	2.4 2.8	<0.05 <0.05	36.0 91.0	19.8 27.3	10.8 10.4	12.1 9.6	33.0 80.4
14	Flinders River	F5 - Richmond Shire Council	4/11/12, 9/12/12	0.44 0.49	7.9 8.3	2.9 3.2	0.53 <0.05	35.0 41.0	27.3 22.7	5.31 5.85	15.4 16.0	57.7 60.0
15	Flinders River	F7 - Millungera Station	25/10/12, 10/12/12	0.48 0.53	7.5 8.2	3.3 3.5	3.80 <0.05	40.0 47.0	35.0 31.1	6.10 6.25	13.8 14.0	51.4 60.2
16	Julia Creek	F8 - Dalgonally Station	10/08/12, 25/10/12, 11/12/12	0.24 0.28 0.31	7.2 7.4 8.1	1.9 2.2 2.5	1.10 1.40 <0.05	11.0 13.0 15.0	17.3 19.4 19.6	4.68 4.58 4.83	2.58 2.91 3.22	34.8 39.1 42.2
17	Cloncurry River	F9 - Dalgonally Station	8/08/12, 26/10/12, 10/12/12	0.24 0.31 0.36	7.5 7.6 7.7	2.1 2.9 3.3	1.30 0.91 <0.05	5.3 5.6 6.0	27.7 34.7 31.2	3.21 4.84 6.12	5.80 8.77 9.95	16.2 24.2 29.7

Apx Table A.3 Results of EC, pH, Total Alkalinity and major ion analyses for river sites in the Gilbert catchment that were sampled in May 2012

SITE NUMBER	STREAM	SITE NAME	DATE SAMPLED	EC (dS/m)	pH	Total Alkalinity (meq/L)	$NO3^{-}$ (mg/L)	$SO4^{=}$ (mg/L)	Ca (mg/L)	K (mg/L)	Mg (mg/L)	Na (mg/L)
1	Gilbert River	Gilbert River@Bridge on Georgetown to Croydon Road	16/05/12	0.17	7.6	1.4	<0.05	5.2	8.8	2.09	4.65	16.8
2	Routh Creek	Routh Creek@Bridge Crossing	16/05/12	0.04	7.1	0.4	0.34	0.1	0.6	2.02	0.45	5.9
3	Einasleigh River	Einasleigh River@Highway Bridge between Georgetown and Mt Surprise	16/05/12	0.34	8.1	3.7	0.24	1.6	18.6	3.10	16.30	25.5
4	Einasleigh River	Einasleigh River@Highway Bridge between Einasleigh and The Lynd Junction	17/05/12	0.40	8.1	4.0	<0.05	0.2	22.0	3.78	21.20	27.9
5	Einasleigh River	Einasleigh River@Crossing near Einasleigh	16/05/12	0.47	8.0	4.5	<0.05	0.9	24.4	4.27	25.90	33.2

Apx Table A.4 Results of EC, pH, Total Alkalinity and major ion analyses for waterhole sites in the Gilbert catchment that were sampled between August and December 2012

SITE NUMBER	STREAM	SITE NAME	DATE SAMPLED	EC (dS/m)	pH	Total Alkalinity (meq/L)	$NO3^{-}$ (mg/L)	$SO4^{=}$ (mg/L)	Ca (mg/L)	K (mg/L)	Mg (mg/L)	Na (mg/L)
1	Ellendale Creek	Lynd	02/08/12	0.84	7.6	8.7	0.78	2.5	61.5	2.07	44.10	75.7
2	Einasleigh River	Mt Surprise	03/08/12	0.56	8.2	5.4	1.90	1.6	26.9	5.70	37.90	43.9
3	Bundock Creek	G1 - Lyndhurst	15/10/12, 01/12/12	0.51 0.50	8.2 8.8	5.4 5.4	0.38 <0.05	0.1 0.0	30.6 29.1	7.79 7.92	35.00 36.10	33.7 37.3
4	McKinnons Creek	G2 - Lyndhurst	15/10/12, 01/12/12	0.28 0.34	7.5 7.6	2.2 3.2	1.00 <0.05	1.6 0.7	22.0 26.3	3.72 4.77	8.81 11.30	27.1 33.3
5	Einasleigh River	G3 - Mt Alder Station	15/10/12, 28/11/12	0.54 0.48	8.0 8.4	4.5 4.0	1.60 <0.05	1.3 1.5	17.6 15.5	5.69 5.45	29.00 24.90	58.9 55.0

6	Einasleigh River	G4 - Mt Surprise	15/10/12, 29/11/12	0.52 0.65	8.1 8.9	4.3 5.0	1.00 <0.05	1.1 0.5	18.8 16.3	5.57 7.86	26.80 27.50	58.9 88.7
7	Einasleigh River	G5 - Mt Surprise	15/10/12, 28/11/12	0.53 0.60	8.1 8.8	4.5 5.3	0.89 <0.05	1.3 1.0	19.3 17.5	5.48 6.69	29.60 35.40	56.9 70.2
8	Elizabeth Creek	G6 - Mt Surprise	02/08/12, 15/10/12, 27/11/12	0.63 0.70 0.72	8.1 8.3 8.2	6.8 7.8 7.9	<0.05 0.27 <0.05	0.1 0.3 0.1	38.5 44.3 44.4	4.13 4.75 5.09	49.40 58.70 60.20	35.4 37.7 38.4
9	Junction Creek	G7 - Mt Surprise	15/10/12, 27/11/12	0.75 0.70	8.3 8.8	8.1 7.8	<0.05 <0.05	0.0 0.0	28.9 23.0	9.18 9.67	67.20 62.00	56.1 53.2
10	Porcupine Creek	G8 - Langlovale Station	15/10/12, 30/11/12	0.21 0.22	7.3 7.4	1.8 1.9	<0.05 <0.05	2.5 1.8	12.6 13.0	3.46 4.32	6.95 8.20	22.8 26.0
11	Pleasant Creek	G9 - Lake Carlo Station	14/10/12, 30/11/12	0.23 0.28	7.3 7.6	1.9 2.3	1.10 <0.05	1.1 0.5	9.9 11.1	6.53 9.13	6.35 7.73	28.8 36.3
12	Gilbert River	G10 - Strathmore Station	05/08/12, 15/10/12, 30/11/12	0.18 0.20 0.22	7.5 7.5 8.0	1.5 1.7 1.9	0.52 0.68 <0.05	5.3 5.6 4.4	10.4 11.9 13.8	2.38 2.95 3.83	5.33 6.27 7.33	21.2 21.6 26.2
13	Einasleigh River	A - main channel (shallow) east	02/11/12	0.66	8.0	6.0	<0.05	0.5	25.6	4.72	32.10	45.7
14	Einasleigh River	B - anabranch (deep) east	02/11/12	0.13	7.4	1.2	<0.05	<0.1	3.4	3.58	5.08	10.1
15	Einasleigh River	C - anabranch (deep) east	02/11/12	0.18	7.7	1.6	<0.05	2.9	5.1	2.55	5.85	17.1
16	Einasleigh River	D - main channel (30m up of Rd Xing, deep) east	02/11/12	0.57	8.3	5.5	<0.05	<0.1	24.7	4.31	27.70	37.8
17	Einasleigh River	E - anabranch (shallow between waterholes) west	02/11/12	0.91	8.8	8.5	0.35	3.1	23.4	7.20	55.10	66.2
18	Einasleigh River	Downstream Mount Noble	14/12/12	0.63	9.0	6.5	<0.05	0.1	14.0	7.71	41.30	59.9
19	Einasleigh River	Dagworth	14/12/12	0.56	8.6	5.2	<0.05	0.1	14.8	5.78	28.50	58.1

Apx Table A.5 Results of EC, pH, Total Alkalinity and major ion analyses for alluvial piezometers in the Flinders catchment that were sampled in August/September 2012

SITE NUMBER	PIEZOMETER NAME	DATE SAMPLED	EC (dS/m)	pH	Total Alkalinity (meq/L)	NO_3^- (mg/L)	$SO_4^=$ (mg/L)	Cl^- (mg/L)	Ca (mg/L)	K (mg/L)	Mg (mg/L)	Na (mg/L)
1	B3S4	30/08/12	1.32	8.0	13.5	0.90	15.0	50.0	81.8	10.20	37.70	138.0
2	Majuba	30/08/12	1.37	8.0	10.7	1.10	110.0	70.0	21.2	1.65	11.70	248.0
3	P3	03/09/12	0.42	7.8	2.7	<0.05	53.0	18.0	31.0	2.77	9.99	30.6
4	L1	02/09/12	0.51	8.0	3.4	4.20	75.0	16.0	29.3	1.86	9.77	55.2
5	B7S5	02/09/12	0.16	6.9	0.9	0.45	23.0	8.1	9.5	3.51	2.97	11.0
6	B5S5	31/08/12	0.66	7.9	5.8	16.00	26.0	25.0	69.3	7.21	7.05	47.3
7	Irrigation Bore No. 2*	31/08/12	0.70	7.8	6.1	0.15	7.3	53.0	33.7	5.11	33.60	46.3
8	Shed Bore	31/08/12	2.55	8.3	11.1	2.90	380.0	300.0	16.8	0.88	12.20	473
9	Shack Bore	31/08/12	2.20	7.6	9.2	0.60	510.0	200.0	59.0	2.07	41.10	322.0
10	C4	01/09/12	0.36	7.7	2.2	0.86	34.0	27.0	26.5	2.56	5.11	31.6
11	B1S1	02/09/12	1.77	7.5	13.9	4.80	6.8	31.0	21.7	34.10	9.22	32.3
12	B4S4	03/09/12	1.78	7.6	8.6	0.30	320.0	170.0	87.6	1.90	20.10	253.0
13	B5S5	03/09/12	2.20	7.5	11.5	0.20	440.0	170.0	110.0	2.16	26.40	320.0

*This is a GAB bore not an alluvial piezometer

Apx Table A.6 Results of EC, pH, Total Alkalinity and major ion analyses for GAB piezometers in the Gilbert catchment that were sampled in April 2013

SITE NUMBER	PIEZOMETER NAME	DATE SAMPLED	EC (dS/m)	pH	Total Alkalinity (meq/L)	$NO3^-$ (mg/L)	$SO_4^=$ (mg/L)	Cl^- (mg/L)	Ca (mg/L)	K (mg/L)	Mg (mg/L)	Na (mg/L)
1	GROB2	21/04/13	0.51	7.3	4.8	13	11	10	31.08	1.78	22.17	52.32
2	GROB4	21/04/13	0.22	6.4	0.5	46	4.9	22	2.92	7.13	4.16	32.05

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