Feasibility assessment of managed aquifer recharge for cotton irrigation in the Gilbert: Final case study

Milestone 4.2 draft report for *Feasibility study of manager aquifer recharge for improved water productivity for Australian cotton production*

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NOTE: This case study technical report scopes the feasibility of managed aquifer recharge in the Gilbert River Agricultural Precinct (GRAP). Three potential MAR scenarios and, for comparison, three alternate surface water management options are identified and evaluated against seven feasibility assessment criteria. It is important to note that these scenarios, or the suggested enhancements to the current representation of bed sands in eWater Source river model, do not constitute endorsement from local or state government stakeholders for a particular course of action. While every effort has been made to ensure the accuracy and completeness of this report, no guarantee is given nor responsibility taken by the Australian National University (ANU) for errors or omissions and the ANU does not accept responsibility in respect of any information or advice given in relation to or as a consequence of anything contained herein.

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Executive summary

Background

The project *'Feasibility study of managed aquifer recharge* [MAR] *for improved water productivity for Australian cotton production'* is investigating the potential to implement MAR at a regional scale in established and emerging irrigated cotton growing regions of Australia. The broad aim of the project case studies was to evaluate how MAR might be feasible for irrigated cotton production and associated cropping systems in the focus regions, and make recommendations on further work to evaluate local hydrogeological conditions, plan the necessary site-specific infrastructure, and establish the legal, social and organisational conditions for implementation of MAR.

The focus of this report is the second case study of the MAR feasibility project, the Gilbert River Agricultural Precinct (GRAP) in the Gilbert River catchment. The study has concentrated on identifying how potential interventions that might provide timely and reliable water yields from the alluvial bed sands adjacent to the Gilbert River might work, and what information would be needed to support investment in the sustainable active management of bed sands.

The broad approach taken was to draw on evidence from a holistic feasibility assessment to scope the most promising opportunities ("scenarios") for MAR, within an active management paradigm, and to test and refine these scenarios with local stakeholders and state government stakeholders. The key questions we have addressed in the context of seven feasibility criteria are:

1. How might potential strategies (e.g., leaky weirs, recharge weirs, infiltration basins) be applied in the Gilbert River to maximise storage, top up and/or slow down drainage from the bed sands to provide water for irrigation when needed?
2. What are the policy and implementation implications of active management of bed sands? What environmental, social and/or hydrological impacts would need to be tracked?
3. How could an active management approach operate? What governance and information sharing arrangements might be needed?

In addressing these questions, we have identified limitations in the current conceptualisations used in the models underpinning Water Resource Plans (WRP) for the Gulf catchments and, from this, opportunities to improve conceptual understanding of the bed sands.

Active management of bed sands

Bed sands are already in use for agriculture and other purposes, though water policy would need to change to permit use for storage and later extraction. Governance of water in the Gilbert catchment provides opportunity to obtain new water entitlements. The current flow conditions required for granting of entitlements from general unallocated water reserves do not allow water extraction during low flows in the dry season, limits time available for water extraction and MAR and so additional legislation would need to be considered when planning water development.

Active management is proposed to make progress without complete and perfect information, by building understanding over time and stewardship of the water resources. Such an approach would avoid lock-in to particular interventions but would provide transparency and vision to attract investment. Active management of the alluvial bed sands would require shifting to a regulatory system where rules are based on staying within pre-defined conditions rather than limiting extraction directly. It has the potential to allow incremental change from existing use subject to demonstrable acceptable impacts from a water provision, social licence and environmental risk perspective.

Opportunities for MAR in the Gilbert River Agricultural Precinct

Potential recharge strategies

Recharge strategies aim to increase infiltration or delay outflows in local areas of the bed sands. Leaky weirs aim to slow the flow of water to rehydrate the land; they could possibly be constructed across small streams off the Gilbert River. Recharge weirs aim to slow flows in order to increase recharge into unconfined aquifers. Multiple recharge weirs could be installed along one or multiple river courses in a catchment (allowing for incremental development) and possible locations could be small streams off Gilbert River targeting the horizontal extent of bed sands. Infiltration basins aim to recharge unconfined aquifers through pumping or diverting water from the river into off stream storage. In the Gilbert, possible locations are the bed sand deposits that extend beyond the river channel. Recharge release is a strategy suggested by CSIRO FGARA reports in other North Queensland catchments, which would work in conjunction with the proposed Greenhills Dam to service the bed sands downstream of the dam (through to Strathmore). The aim would be to strategically release surface water from dams for infiltration through the downstream natural river channel and the dam would act as a settling pond (treatment). The siting of infrastructure needs to account for site-specific hydrogeological and hydraulic properties, as well as practicalities, including access and site- and infrastructure-specific impacts of wet season flows.

Scenario: Farm-scale MAR

MAR, on a single farm and run by an individual owner or land manager, would use the bed sands to provide supplementary irrigation at the start of the dry season, and would actively manage the local bed sands to maximise water availability with targeted recharge infrastructure and adjustments to pumping regimes and locations. This would be an incremental change for existing spear bore users, but may require substantial investment, planning, and approvals for prospective new users. In addition to actively tracking spear bore water levels, new monitoring to plan these changes would be primarily led by the landholder, but may involve partnership with other landholders and organisations. Collaboration between local stakeholders and government would work towards establishing appropriate rules for recharge and later extraction of surface water into bed sands, approvals for the establishment or replacement of infrastructure, and monitoring of impacts.

As the bed sands are intended as an actively managed storage of entitlements managed under the Water Plan (Gulf) 2007, the alternative to farm-scale MAR is investment in off-stream surface water storages (e.g. gully dams or ring tanks). Construction of off-stream storages is an established technology with defined institutional and compliance procedures. While previous work has noted the high infiltration and evapotranspiration rates, infiltration could benefit bed sands and losses from short term storages may be acceptable for the purpose of finishing crops and bridging events. At farm scale, different farms may benefit from different storage solutions.

Scenario: Regional-scale MAR

A regional scale MAR scheme, that could provide sufficient water to irrigate an area of cotton that would support a viable gin in the region, would utilise water entitlements set aside under the Gulf Water Plan as a general reserve to support water infrastructure for regional development. Existing new cotton planting outside the GRAP means that substantial reductions in transport costs may be achieved even if the gin is not located in Georgetown, and that the Gilbert River would not need to be the sole water source. The operation of the MAR scheme could be achieved through the establishment of an organisation that would partner with other agencies but ultimately operate on a user pays cost recovery basis based on assessable area charges from the agriculture industry. Investments in studies to improve understanding of the aquifer storage capacity of the alluvial sands would over time build knowledge and capacity in the region for managing water in the bed sands, allowing local and state governments to play a more active role in assisting landholders to plan and coordinate their pumping from bed sands, and address risks associated with pumping riverbeds dry during the dry season and recharging during high flows.

An alternative (without MAR) is the proposed Greenhills dam that would service the Gilbert River Irrigation Project (GRIP); a Detailed Business Case (DBC) was prepared for this scheme in 2020 although it has not yet progressed to preparation of an Environmental Impact Statement (EIS). While the supply capacity of the bed sands is still uncertain, it is likely that the capacity of Greenhills dam would be on the order of 10 times larger, such that a focus on bed sands development would imply a smaller agricultural development or an incremental development as part of a whole-of-system view of dry season water storage.

The third scenario for a regional scale irrigation scheme would combine MAR and the proposed Greenhills dam. The dam could be used as a temporary storage or sedimentation tank prior to releasing water to recharge the alluvial river sands. Alternately, the dam could be used to deliver immediate water demands from entitlements with the excess used to recharge bed sands using MAR, for extraction in the dry season or in years of low rainfall. Impacts from recharge and pumping the sand beds in the dry season would need to be tracked. The states to be monitored, and the information and infrastructure needed to do so, to identify unacceptable impacts from the dam, recharge releases and riverbed pumping are as for the regional-scale MAR scenario.

Improved conceptualisation of river bed sand aquifers adjacent to the Gilbert River

There are multiple possible options to explore regarding the use of water from bed sands but any actions are currently constrained by concerns about risks. Regulation cannot be relaxed without better identifying risks, but obtaining better information about the system can also help better articulate water needs and opportunity, and optimise existing pumping. Investment in monitoring and improving conceptual understanding of the bed sands and their representation in river models used in water management in the Gulf region would likely also benefit impact assessment for any dam, and develop and demonstrate stewardship capabilities for sustainable development of the resource.

Recommendations

Given the early stage of agricultural development and knowledge of bed sands dynamics, the first step towards implementation of managed aquifer recharge and active management of the bed sands as a water storage involves 1) improving knowledge systems, and 2) elaboration of management arrangements. The scenarios operate at multiple scales in terms of stakeholders involved and consideration of storage solutions beyond the bed sands. Similarly, recommendations cover next steps that can be taken at multiple scales from both knowledge and management perspectives (Table 1). While the recommendations were developed with a focus on the Gilbert River Agricultural Precinct, the recommendations also apply to other monsoonal areas with bed sands at a similar stage of agricultural development and scientific knowledge.

Table 1 Recommendations for agents of change in the Gilbert catchment at multiple levels

	Landholders	Local organisations, including Etheridge Shire Council, Gulf Savannah Natural Resource Management Group	State government	R&D organisations (e.g., CRDC)
Improving knowledge systems	Evaluate current water use arrangements, especially spear bore use; plan monitoring to resolve gaps and identify improvements	Build capacity for site-specific assessment and planning of water storage management, including regional datasets	Partner to improve monitoring, conceptualisation and modelling of bed sands and associated impacts to inform assessment of active management arrangements	Build capacity for landholder groundwater use and status monitoring, and monsoonal water storage options assessment
Elaboration of management arrangements	Keep records of water levels and use of spear bores and consider opportunities to share information and collaborate on planning	Investigate possible business models and scope of a potential local water management organisation, considering possible partnerships and a systems view of storage options	Co-design requirements for MAR, including active management of bed sands, for consideration in 2027 review of the Gulf Water Plan (2007). This would include consideration of condition-based limits, MEL framework, and guidelines for approvals, water accounting and impact reporting	Support development of public-private information sharing arrangements and coordination mechanisms, to go beyond extraction limits and encourage active management and stewardship of resources

Acronyms and Organisations

AIRR	anticipation-inclusion-reflexivity-responsiveness
AMTD	adopted middle thread distance
ANU	Australian National University
ASR	aquifer storage and recovery
ASTR	aquifer storage treatment and recovery
BOM	Bureau of Meteorology
CPI	Consumer Price Index
CRDC	Cotton Research and Development Corporation
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAF	Queensland Department of Agriculture and Fisheries
DBC	detailed business case
DNRME	Department of Natural Resources, Mines and Energy
DSITIA	(Queensland) Department of Science, Information Technology, Innovation and the Arts
EIS	Environmental Impact Statement
EPA	Environment Protection Authority
EPHC	Environment Protection Heritage Council
ESC	Etheridge Shire Council
FGARA	Flinders and Gilbert Agricultural Resource Assessment
GAB	Great Artesian Basin
GABORA	Great Artesian Basin and other regional aquifers
GDE	groundwater dependent ecosystems
GHD	GHD Group Pty Ltd (previously Gutteridge Haskins & Davey)
GL	gigalitre
GM	genetically modified
GRAP	Gilbert River Agricultural Precinct
GRIP	Gilbert River Irrigation Project
GSNRM	Gulf Savannah Natural Resource Management Group
GW	groundwater
IAH	International Association of Hydrogeologists
IAHS	International Association of Hydrological Sciences
IAR	Impact Assessment Report
ILUAS	Indigenous land use agreements
IWMI	International Water Management Institute
MAR	managed aquifer recharge
MDB	Murray Darling Basin
MIPP	Maturing the Infrastructure Pipeline Program
MITEZ	Mount Isa to Townsville Economic Development Zone
ML	megalitre
MODIS	Moderate Resolution Imaging Spectroradiometer
MSES	(Queensland) Matters of State Environmental Significance
NAIF	Northern Australia Infrastructure Facility
NAWRA	Northern Australian Water Resource Assessments
NGIS	National Groundwater Information System
NGRMG	Northern Gulf Resource Management Group (now the GSNRM)
NHMRC	National Health Medical Research Council
NRM	Natural Resource Management
NRMMC	Natural Resource Management Ministerial Council
NSW	New South Wales
NWGA	National Water Grid Authority
NWIDF	National Water Infrastructure Development Fund
ORIA	Ord River Irrigation Area
QLD	Queensland
RCI	resource condition indictor

RDMW	(Queensland Department of) Regional Development, Manufacturing and Water
RIC	Regional Investment Corporation
ROP	Resource Operations Plan
RRI	Responsible Research and Innovation
RTNBC	Registered Native Title Body Corporate
SA	South Australia
SGG	soil generic group
SIF	State Infrastructure Fund
SKM	Sinclair Knight Merz
SW	surface water
US	United States
WA	Western Australia
WMIP	Water Monitoring Information Portal
WRP	Water Resource Plan
WUE	water use efficiency

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1. Introduction

1.1 The Australian cotton industry

The cotton industry is an important sector of Australia's agricultural and rural landscape. The industry is focused mainly on the south-east coast, from central and southern Queensland (QLD), throughout New South Wales (NSW) and into northern Victoria[1]. However, emerging cotton growing areas can be found in North Australia[2]. The majority of cotton farms are family owned and the industry employ over 12,000 people[3]. Australia cotton is exported around the world, with average earnings of $2 billion annually[4].

1.2 The implications of water reforms and climate variability on irrigated cotton production

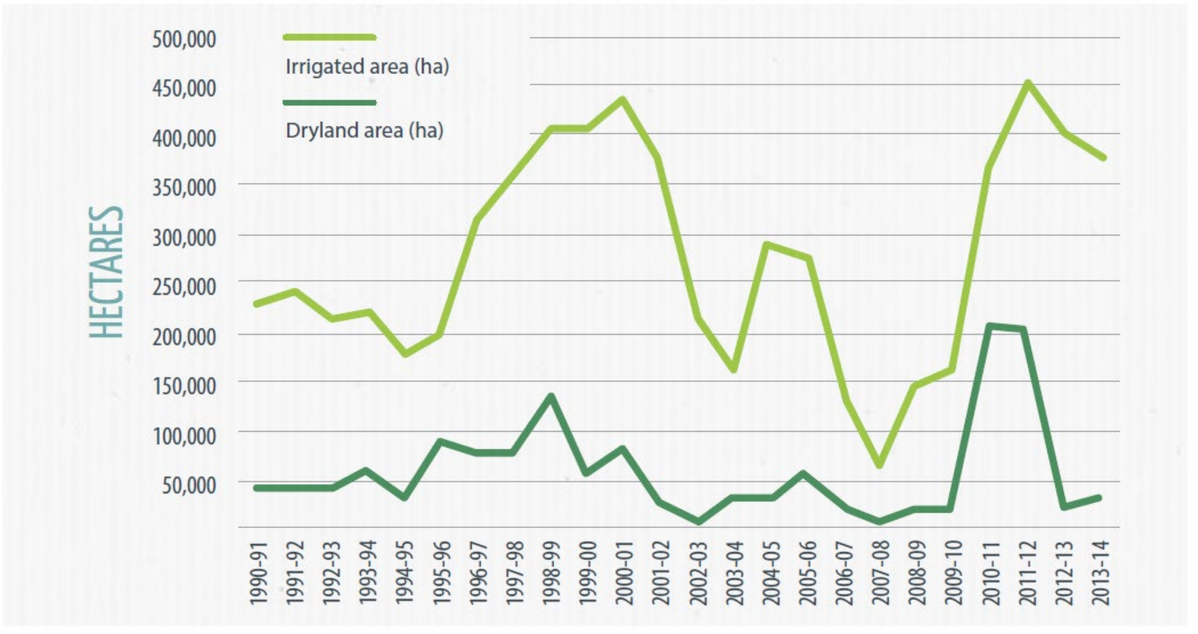
The majority of cotton is produced from irrigated systems. In the past, the high water use of the Australian cotton industry attracted criticism, but the industry is now one of the most water efficient cotton industries in the world[5]. Between 2002 and 2012, the industry increased yields as a result of improved crop management, advances in plant breeding and the adoption of genetically modified varieties, while being more efficient users of water. These changes improved industry wide water use efficiency (WUE) by 40% (Roth et al., 2014). Select examples of farm management changes that lead to the observed improvements in WUE, described in The Australian Grown Cotton Sustainability Report 2014 (Cotton Australia and CRDC, 2014), include:

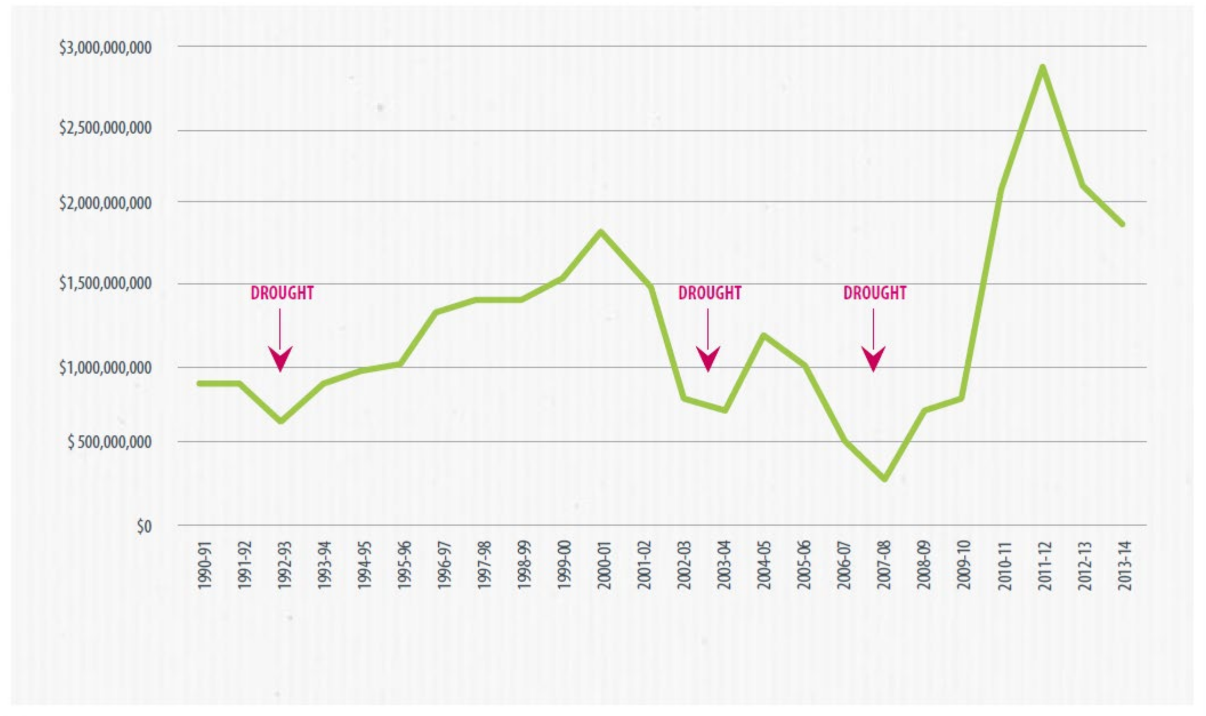
- A 30% increase in the use of soil moisture probes since 2006, which are now used by 70% of irrigators
- 96% of furrow irrigation systems have been improved or changed to alternative systems
- 49% of irrigators have updated the flow or size of siphons
- 35% of irrigators have redesigned fields; for example, decreasing the distance between dams and fields to reduce evaporation losses

Even after the recent improvements in WUE, irrigated cotton production varies substantially between years (Figure 1), depending on water volumes available for irrigation (Cotton Australia and CRDC, 2014). The gross value of cotton lint is strongly associated with the area of irrigated crop production (Figure 2), decreasing in times of low water availability (Cotton Australia and CRDC, 2014). It follows that a key limiting factor on the cotton industry in Australia is water security, exacerbated by the potential for further policy changes to water access and entitlements and future climate unknowns.

On average, groundwater contributes 15% of water used for the production of irrigated cotton (Cotton Australia and CRDC, 2014). In dry periods, dependence on groundwater to increases. Managed aquifer recharge (MAR) could be used in this context by the Australian cotton industry; as a management strategy in the face of future surface water scarcity. Is it also possible that MAR has a place in 'greenfield' production areas to increase water security from the onset of industry development, limiting the unintended water scarcity seen in established regions.

[1] https://cottonaustralia.com.au/industry-overview, accessed 30 August 2020
[2] https://cottonaustralia.com.au/industry-overview, accessed 30 August 2020
[3] https://cottonaustralia.com.au/industry-overview, accessed 30 August 2020
[4] https://cottonaustralia.com.au/industry-overview, accessed 30 August 2020
[5] https://cottonaustralia.com.au/industry-overview, accessed 30 August 2020





1.3 A brief history of cotton production in Northern Australia

Cotton production in North Australia has been both spatially and temporally limited, due to a number of factors (Matz, 2020, Andrews, 2015).

The Ord River Irrigation Area (ORIA) in Western Australia (WA) was initiated in the 1960s and included wet season cotton production (Matz, 2020). Issues relating to poor quality and pest damage resulted in commercial cotton production ceasing by the mid-1970s (Ash and Watson, 2018). Recently, there has been renewed interest in cotton in the region with the focus of research and development on dry season cropping where planting occurs in February and harvesting in October (Matz, 2020). This change in season avoids damage from pest species that contributed to the failure of cotton crops during the 1960s and

1970s, particularly *Spodoptera* cluster caterpillars and pink bollworm (Yeates et al., 2014). Production potential has also benefited from the development of transgenic cotton varieties, and the ongoing breeding of shorter season cotton varieties that are better suited to the north (Matz, 2020).

Recent research and development into cotton production in north west Queensland, including the Gilbert catchment, has focused on collaborative trials with growers and researchers (Matz, 2020). Despite interest in the potential of cotton, the current lack of production in this region of Queensland is attributed to significant transports costs resulting from distant processing facilities as well as a lack of year round water availability (Matz, 2020).

1.4 A brief history of MAR schemes in Australia

MAR involves the purposeful recharging of aquifers using surface water, whether from rivers and other water bodies or recycled water, to be extracted when needed. Overseas MAR has been used to increase water security, with interest in MAR continuing to grow in Australia. MAR projects in Australia date back to the 1960s and the focus of these schemes are mostly urban (Dillon, 2009); MAR remains in its infancy in Australia in an agricultural setting.

South Australia (SA) and Western Australia (WA) are home to the majority of Australia's MAR schemes (Dillon, 2009). The longest running MAR project in Australia is in Queensland's Burdekin Delta. The infiltration based system has maintained groundwater levels in the regions, preventing the intrusion of seawater, for decades (Dillon, 2009). Infiltration systems have also been used in WA since the 1980s as a way to recycle wastewater to irrigate public spaces, including playing fields (Vanderzalm et al., 2015). Multiple regions in SA inject stormwater runoff into aquifers, to be recovered as a water supply for irrigation and industry (Barnett et al., 2000, Miotliński et al., 2014, Yuan et al., 2016). Several MAR sites around Adelaide (SA) treat stormwater via artificial wetlands before injection into saline aquifers (Barnett et al., 2000). Water recovered as part of this project is of reduced salinity compared to the levels of the native aquifer, and can be used for irrigation purposes (Barnett et al., 2000). The Salisbury aquifer storage treatment and recovery (ASTR) scheme in SA spatially separates injection and recovery wells, allowing for the treatment of injected water during residence in the aquifer (Miotliński et al., 2014, Yuan et al., 2016). Pre-injection artificial wetlands are used to filter out total suspended soils, reducing clogging of wells (Yuan et al., 2016).

The MAR schemes currently operating in Australia show that well-planned projects can be successful. Although uptake in agricultural settings is limited, some have suggested that more MAR developments would increase water storage capacity and water security in a way that is economically viable compared to dams and other surface storages (Dillon, 2009, Khan et al., 2008).

1.5 The MAR Feasibility project

The *'Feasibility study of managed aquifer recharge for improved water productivity for Australian cotton production'* project (here-on-in referred to as the MAR Feasibility project) was funded by the Cotton Research and Development Corporation (CRDC) to investigate the feasibility of MAR at a regional scale in established and developing cotton growing regions in Australia. MAR has been discussed as an option in cotton regions previously, so the MAR Feasibility project has focused on whether MAR is a more feasible option then the current or alternate surface water options. Seven feasibility criteria based on those developed by Ticehurst and Curtis (2017) are used in conjunction with scenario development. Further research and resources should be directed to the more feasible options (scenarios), whether it be MAR or other water management options.

Three case study regions were selected in consultation with the project steering committee: the Murrumbidgee region in southern NSW, the Namoi region in northern NSW and the Gilbert region in northern Queensland (Figure 3). The Namoi and Murrumbidgee regions were selected as representing agricultural settings where the likelihood of MAR being feasible should be high, based on what was previously known about these systems across the different feasibility criteria. If the outcomes of these case studies did not support MAR, it would suggest that MAR should be ruled out as a water management option for the cotton industry. The Gilbert case study, however, considers the feasibility of using MAR in a region with relatively small extent of agricultural development, and where there is the potential to compare MAR against traditional surface water storage options before large-scale water development.

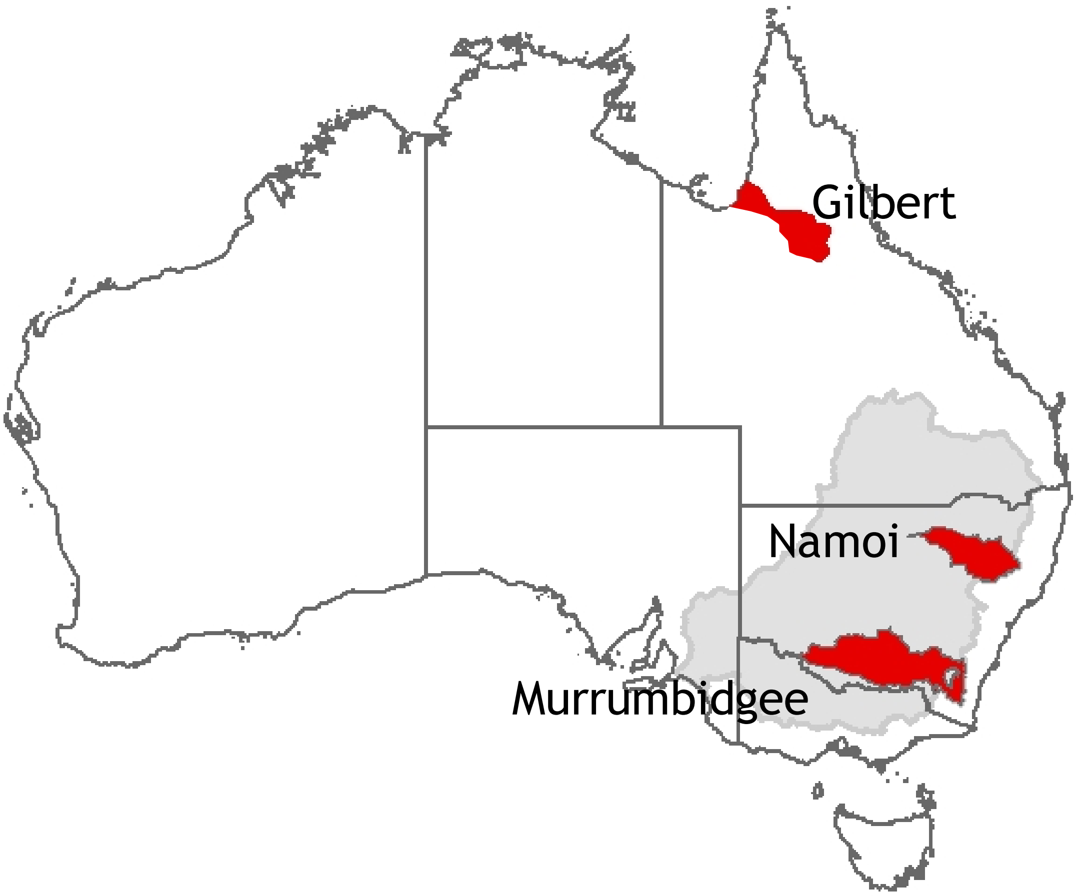


Figure 3 Location of the project case study areas. This report focuses on the Gilbert case study.

Northern Australia has previously been highlighted as a region suited to the development of an irrigated agriculture industry, with cotton identified as a potential crop option (Petheram et al., 2013, Queensland, 2007). In Queensland, most focus has been on surface water storage infrastructure with the exceptions being the MAR scheme in the Burdekin Delta and more recently the CSIRO Northern Australia Water Resource Assessment project in the Mitchell catchment (Petheram et al., 2018). The potential benefits of MAR to irrigated agriculture industry in northern Queensland is two-fold. Storing water underground will avoid the evaporative losses experienced when using surface storages. The recharged water can then be extracted to even out the seasonal difference in water supply seen in North Australia which would enhance certainty to a developing sector. The need for sustainable development, that considers environmental, cultural and community aspects, as well as financial gain, has been highlighted (Petheram et al., 2013, Barber, 2018, Waltham et al., 2013, Crossman and Bark, 2013). The feasibility criteria used in this assessment aims to address the above aspects, which a focus on sustainability over all criteria.

1.6 Structure of this report

The Gilbert River case study seeks to investigate and resolve some uncertainties associated with potential irrigation development in northern Australia by identifying plausible options for investment in conjunctive use of surface and groundwater and agro-ecological approaches to irrigated agriculture. Past investigations have focused primarily on surface water schemes, with groundwater considerations limited to impacts of the surface water schemes on the groundwater system. This report draws on existing investigations and stakeholder expertise to critically assess the potential feasibility of MAR in the region and to identify next steps for research and development to guide investment by government or other funders. The approach and methods used to assess the feasibility of MAR is provided in Section 2. This is followed in Section 3 by a description of the Gilbert River catchment system and the Gilbert River Agricultural Precinct (GRAP), which is the focus of the case study. Five scenarios representing MAR options or alternative surface water storage options are identified and evaluated in Section 4. The development and evaluation of these scenarios drew on the detailed results of the feasibility criteria assessment provided in Section 5. This research has identified that limitations in the conceptualisation of river bed sands in available river system models constrains the extent to which impacts of MAR on (or extraction of water from) bed sands can be assessed. Section 6, therefore, considers how this conceptualisation could be improved in future water modelling and management. The report concludes in Section 7 with a statement of the potential for MAR in the region and recommendations for the CRDC and local and state-level stakeholders going forward.

2. Overarching approach

An argumentation approach has been used to guide the case study development. This reflects the high uncertainty in both project requirements and consequences associated with MAR innovations. A staged approach is more suitable in these situations, rather than trying to eliminate all uncertainty in one go. By firstly using available information to identify whether it's worth taking the next step in investigating the innovation, strategies that incrementally address critical uncertainties around the potential innovation can be identified. In this case study, our intent is to identify scenarios that support the hypothesis that MAR could be part of an irrigation development strategy centred on conjunctive use that supports a culturally and socially acceptable, environmentally sensitive, and viable irrigated agriculture industry. The questions guiding the 11 steps of the argumentation approach are shown in Figure 4; while represented as distinct steps in the diagram the process was highly iterative and underpinned by engagement throughout the duration of the case study.

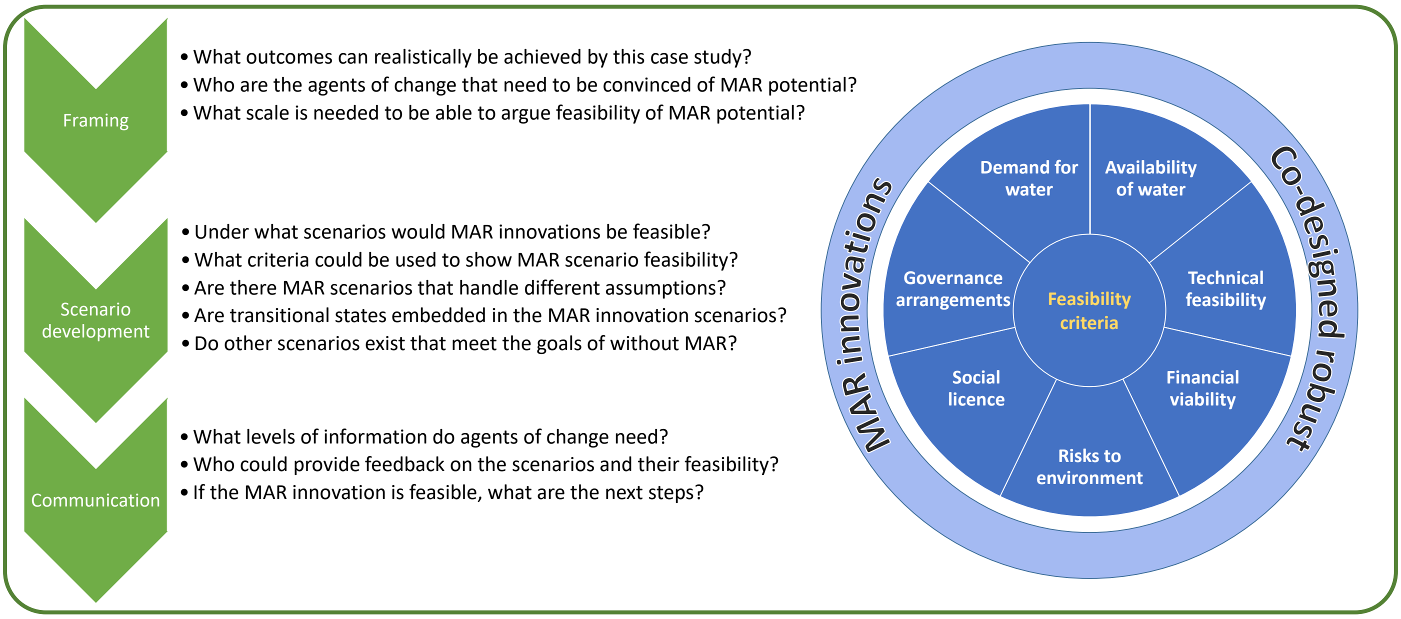


Figure 4 Argumentation approach used to investigate the potential feasibility of MAR in the Gilbert River case study.

The ***Framing*** phase identifies what we could achieve in the project, who needed to be convinced of the potential viability of MAR (the 'agents of change'), and what part of the Gilbert River catchment we would focus on. With no scope to conduct in-depth field research, this project centred on analysis of existing investigations, the development of scenarios, and the conceptualisation of bed sand aquifers. Given the relatively small extent of irrigated agriculture and the limited exposure to MAR as a concept in the region, the project needs to convince investors/funding bodies, state government representatives or local government representatives that MAR is worth investigating further as a development strategy. This in turn requires addressing any concerns around social license, environmental impacts and water governance. The case study considers both farm-level and regional MAR within the area covered by the GRAP.

In the ***Scenario development*** phase, we developed MAR innovation scenarios and alternate scenarios that do not have a MAR component. These scenarios were supported by a systematic feasibility criteria assessment against the seven feasibility criteria of (Ticehurst and Curtis, 2017): Demand for Water, Water availability, Technical feasibility, Financial viability, Environmental risks, Social acceptability & social license, and Governance arrangements. This assessment involved the synthesis of available literature and data for the system; key resources are listed in Table 2. Initial investigations highlighted that the bed sands of the Gilbert River were the most promising aquifer system for MAR. From this, we explored how interventions that aim to provide timely and reliable water yields from the alluvial bed sands adjacent to the Gilbert River might work. Interventions were considered to operate at a farm or regional scale and stand-alone or in conjunction with surface water development schemes. We contend that there are multiple possible options to explore regarding the use of water from bed sands but any actions are currently constrained by concerns about risks (e.g. to hyporheic ecosystems).

Table 2 Key resources used in the potential feasibility assessment and definition of plausible MAR and alternative scenarios

Resource
Publications and datasets from the Flinders and Gilbert Agricultural Resource Assessment (FGARA) projects • https://www.csiro.au/en/research/natural-environment/water/Flinders-Gilbert/Overview
Mitchell River catchment reports from the Northern Australian Water Resource Assessments (NAWRA) • https://www.csiro.au/en/research/natural-environment/water/nawra
Water Plan (Gulf) 2007 • https://www.business.qld.gov.au/industries/mining-energy-water/water/catchments-planning/water-plan-areas/gulf • https://www.legislation.qld.gov.au/view/html/inforce/current/sl-2007-0268
Gulf Resource Operations Plan • https://www.resources.qld.gov.au/__data/assets/pdf_file/0005/293927/gulf-rop-amendment-august-2015.pdf
Great Artesian Basin and other regional aquifers (GABORA) plan 2021 • https://www.business.qld.gov.au/industries/mining-energy-water/water/catchments-planning/water-plan-areas/gabora • https://www.legislation.qld.gov.au/view/html/inforce/current/sl-2017-0164

The ***Communication*** phase documented, and sought feedback on, the developed scenarios and feasibility assessment, and established recommendations that address the next steps for assessment and implementation of the innovation. Over the life of the case study, we engaged with state government agencies (RDMW, DAF), CSIRO, the Etheridge Shire Council (ESC), the Gulf Savannah Natural Resource Management Group (GSNRM), the chair of the Tagalaka Aboriginal Corporation RTNBC, and local landholders (through two phone interviews and in-person at the Gilbert River Agricultural Forum facilitated by the ESC).

We have built upon the current representation of bed sands used in the models underpinning Water Resource Plans (WRP) for the Gulf catchments. This improved conceptual model of the alluvial aquifers in the Gilbert River catchment could inform future work aimed at improving the capacity to represent river bed sands in water management models of the Gilbert River system. It could help communicate how, over time and space, the bed sands fill and empty and the nature and extent of impacts of current and future extractions of water from these alluvial systems.

3. Gilbert River catchment

3.1 Background

The Gilbert River catchment, with a catchment area of approximately 46,354 km^2 (Webster et al., 2013), drains into the Gulf of Carpentaria in North Queensland (Figure 5). Neighbouring catchments, collectively termed the Gulf region, include Settlement Creek, Nicholson, Leichhardt, Morning Inlet, Flinders, Norman, Gilbert, Staaten, Mitchell and Coleman (Figure 5).

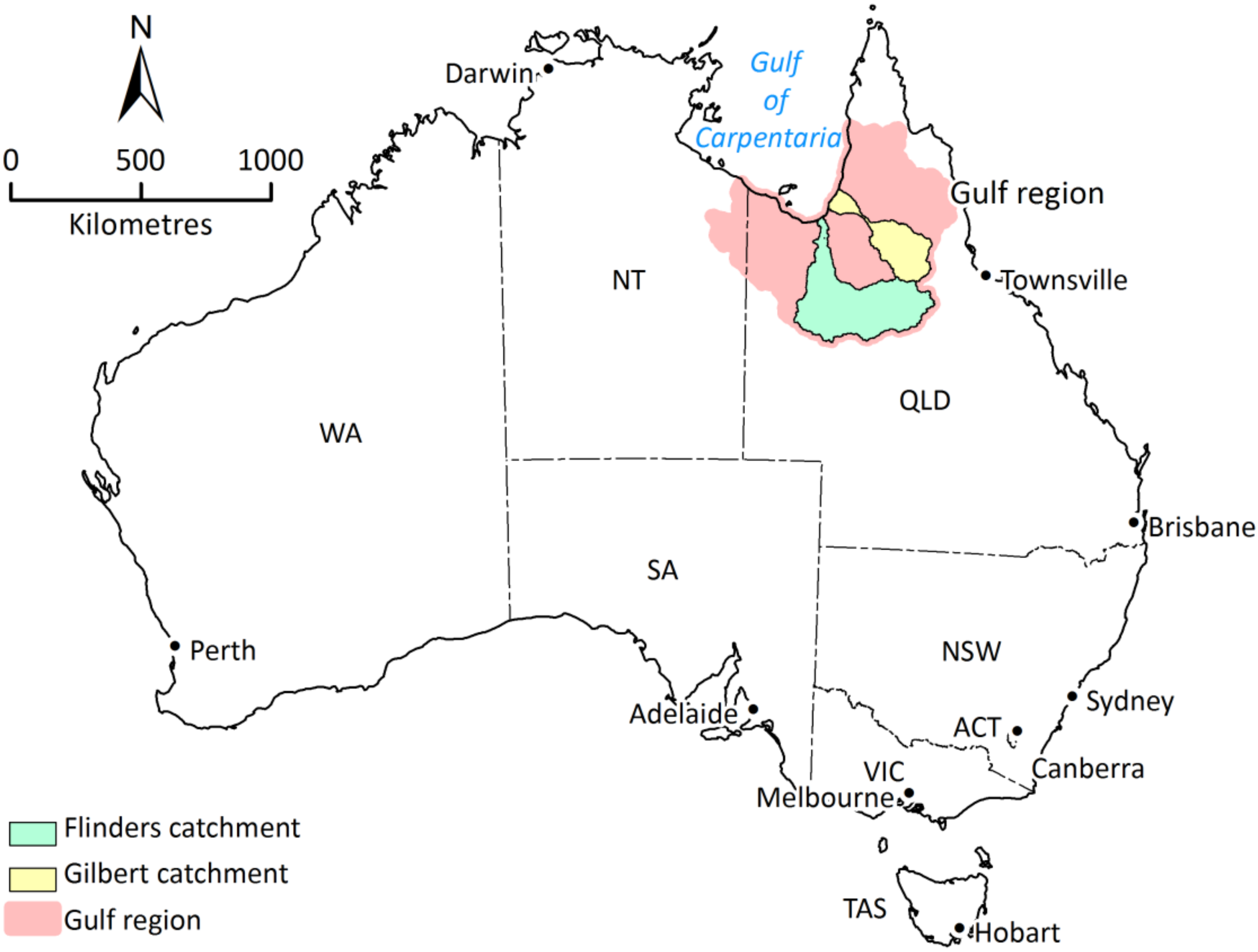


Figure 5 Gilbert catchment, Gulf region and Flinders catchment (Source: Petheram et al., 2013).

The climate in the Gulf region is hot, semi-arid and highly seasonal, with two distinct seasons, wet and dry (Figure 6). The wet season is the six-months between 1 November and 30 April, with the dry season from 1 May to 31 October. Average annual rainfall in the catchment is 755 mm (Figure 7), with 93% falling during the wet season (Petheram et al., 2013). Rainfall variation between years is high (Figure 7). Generally, rainfall declines moving away from the coast, but is also highly localised. Potential evaporation is more than double the average annual rainfall, over 1800 mm/year (Petheram et al., 2013). The Gilbert catchment is not immune to the dry spells experienced elsewhere in Australia, with dry periods of similar length but greater intensity then other parts (i.e. south-east and south-western Australia) (Petheram et al., 2013).

A range of soil types are present in the Gilbert catchment (Figure 8), reflecting the various geologies and geological process in the area (Section 5.3.2).

The surface hydrology of Gilbert is driven by the strong seasonality of the climate and high evaporation rates. The two major rivers in the catchment are the Einasleigh and Gilbert (Figure 9), with an average combined streamflow of 3706 GL/year and a median of 2585 GL/year (Petheram et al., 2013). The large variation between mean and median streamflow illustrates the large impact that years of very high streamflow (associated with high rainfall) have on skewing the mean. Many of the rivers and their tributaries are ephemeral, flowing less than 50% of the time (Petheram et al., 2013). This can be observed in the hydrograph from the middle reaches of the Gilbert (Figure 10). During the dry season, these rivers and creeks form a series of waterholes, most of which are uninfluenced by groundwater inflows based on ion and isotope analysis (Petheram et al., 2013, Jolly et al., 2013). However, some locations in the mid-reaches of the Gilbert River suggested a high likelihood of groundwater inflow at both river and waterhole sampling sites (Figure 4.2, Table 4.3 and Table 4.4 in Jolly et al. (2013)).

Although groundwater resources and recharge are poorly understood in the area, it has been suggested that groundwater resources are limited and that recharge rates are low over the majority of the catchment, albeit with localised areas of high recharge rates. This is further explored in Section 5.3.1.

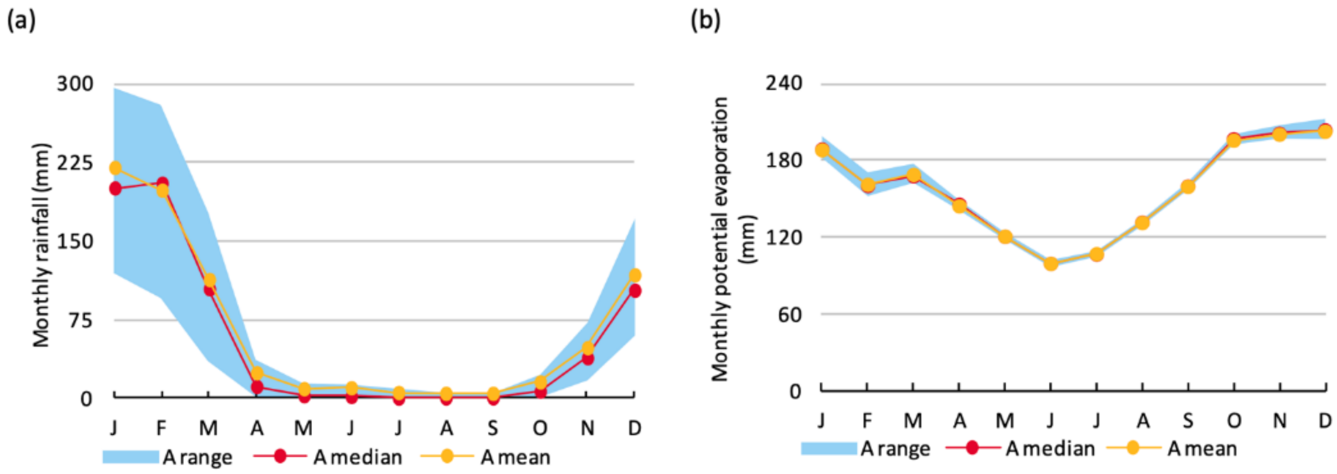


Figure 6 (a) Monthly rainfall and (b) monthly potential evaporation, based on data from 1890 – 2011, average across the Gilbert catchment. The A range is the 20th to 80th percentile exceedance (Source: Petheram et al., 2013).

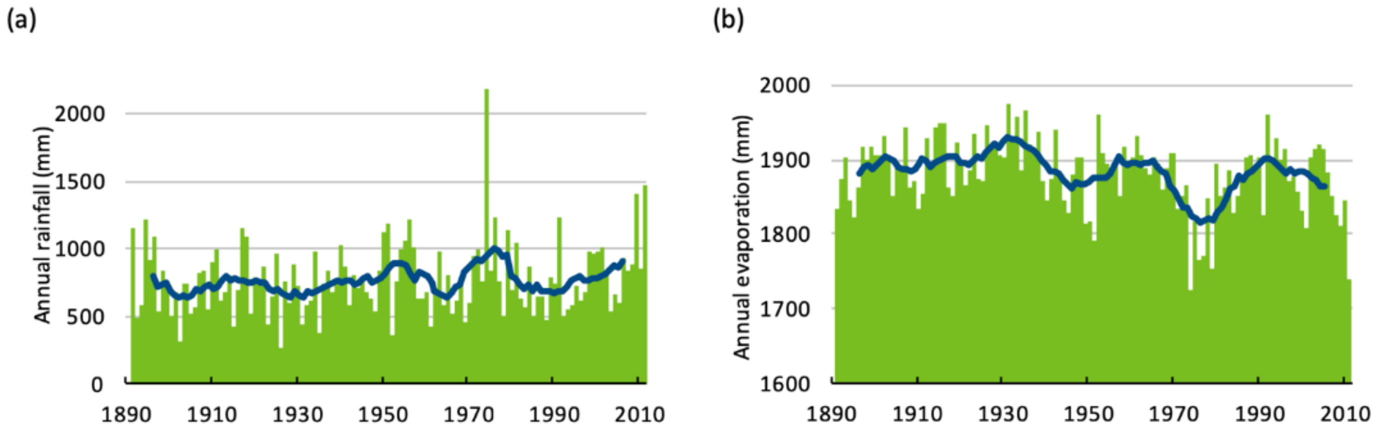


Figure 7 (a) Mean annual rainfall and (b) mean annual potential evaporation, based on data from 1890 – 2011, average across the Gilbert catchment. The blue line represents the 10-year running mean (Source: Petheram et al., 2013).

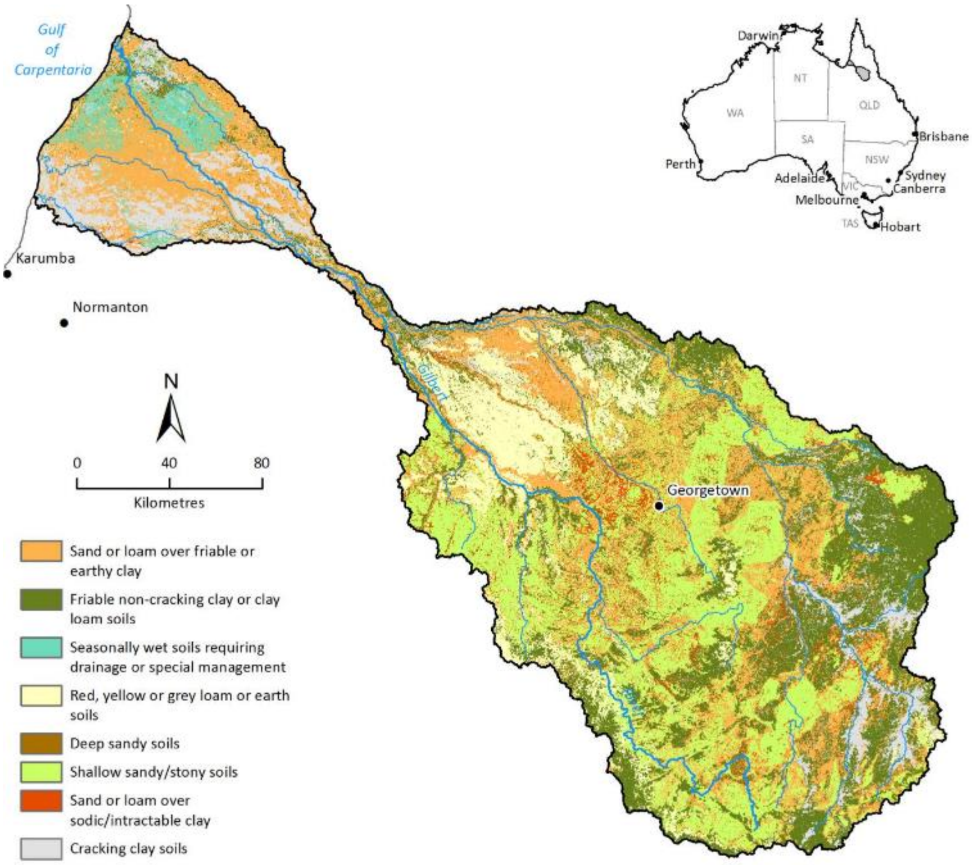


Figure 8 Map of soil generic group (SGG) classes for the Gilbert catchment (Source: Petheram et al., 2013).

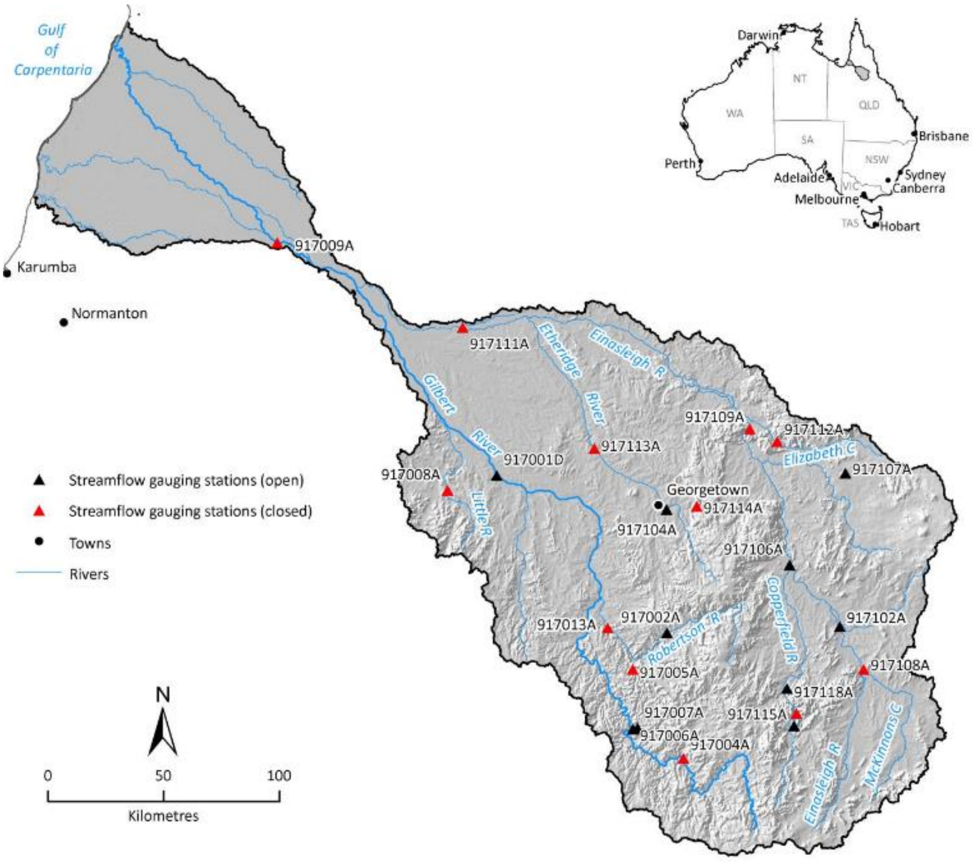


Figure 9 Main rivers and tributaries of the Gilbert catchment (Source: Petheram et al., 2013).

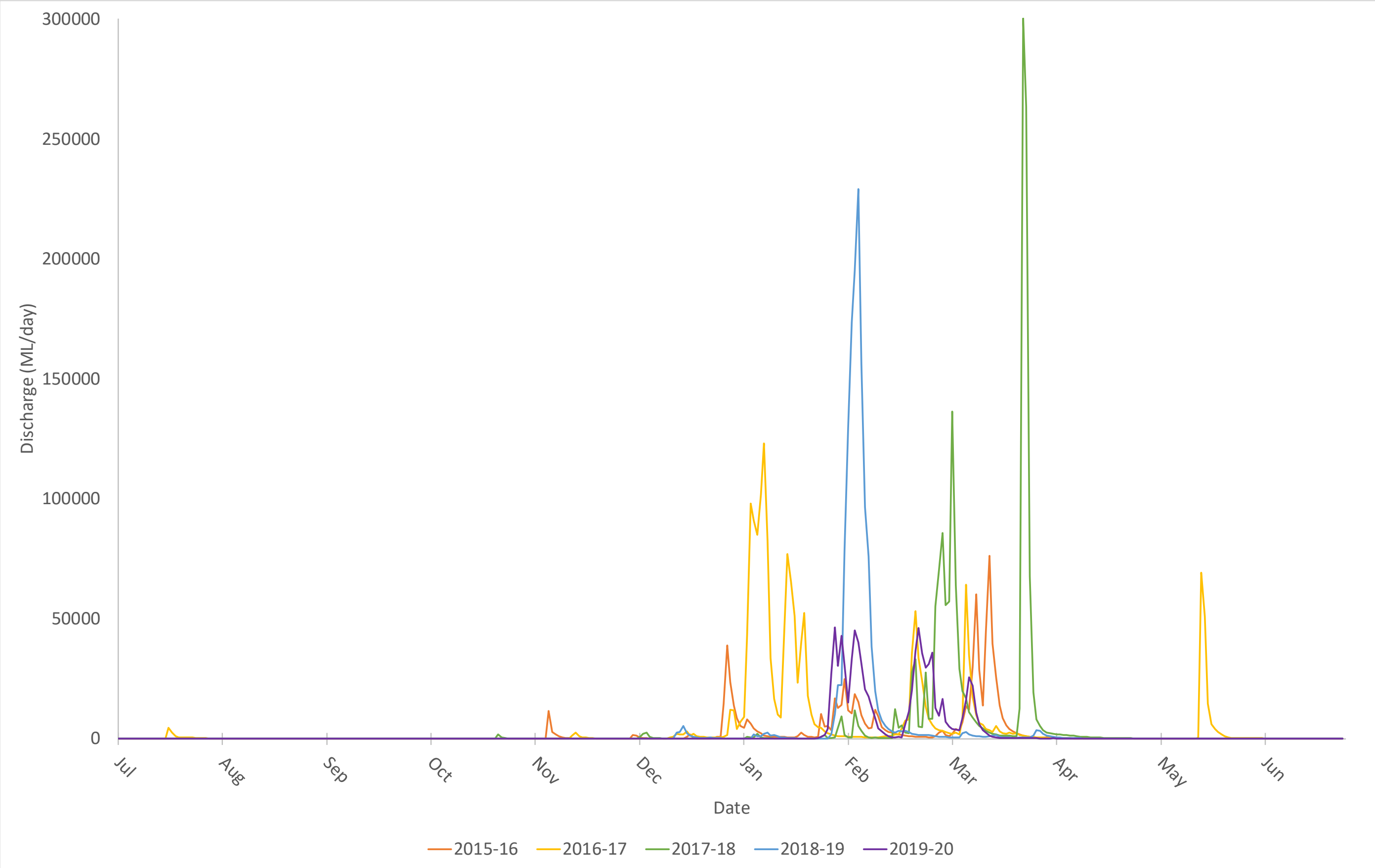


Figure 10 Hydrograph of the Gilbert River at Rockfields (gauge: 917001D). Data source: https://water-monitoring.information.qld.gov.au/

The Indigenous nations present in the Gilbert catchment are Tagalaka, Ewamian, and Kurtijar peoples (Petheram et al., 2013). The traditional owners of the land, rivers, and saltwater country in the south-east Gulf of Carpentaria are the Kurtijar People (https://kurtijaraboriginalcorporation.com.au/, accessed 12 May 2021). Tagalaka Country covers Gulf Savannah lands around the townships of Croydon, Normanton and East Hayden (https://www.tagalaka.com/who-we-are, accessed 12 May 2021). The Country of the Ewamian peoples are the savannah lands in the upper Gilbert and Einasleigh River catchments, primarily lying within the Etheridge Shire Local Government Area (https://www.ewamian.com.au/countryculture, accessed 12 May 2021).

Covering the Etheridge Shire and part of the Carpentaria shire, the Gilbert catchment has a population of approximately 1,200 people (Petheram et al., 2013). The largest town in the catchment, Georgetown, has a population of 301 (based on 2016 census data) [6].

The two key ecological considerations in the area are wetland connectivity through flooding in the wet season and waterhole persistence in the dry season (Petheram et al., 2013). The coastal floodplains of the Gilbert flood regularly (Figure 11). These floods serve an important ecological purpose, allowing for connection and nutrient exchange between the main channel and normally disconnected wetlands. However, flooding can cause damage to crops and infrastructure. Many of the rivers in the Gilbert are ephemeral, breaking up during the dry season into the series of waterholes (Figure 12). These waterholes provide refugee for many aquatic species to survive the dry season.

The major activity in the region is pastoralism (cattle grazing), with tourism, mining and commercial fishing also economically important (Petheram et al., 2013). Cropping, both dryland and irrigated, are smaller contributors, occupying less than 0.02% of the landscape (Petheram et al., 2013). As cropping is not a

[6] https://quickstats.censusdata.abs.gov.au/census_services/getproduct/census/2016/quickstat/UCL322050?opendocument, accessed 3 June 2020

major industry in the region, processing facilities for industrial crops (e.g. cotton, sugar) are absent. The closest cotton gin is ~ 900 km south-east in Emerald. However, there has been a growing interest to establish an irrigated agriculture industry in the catchment (Jacobs Australia Pty Limited., 2020), but the ephemeral nature of most rivers in the catchment requires the storage of water during the wet season for irrigation during the dry season is to take place (Petheram et al., 2013).

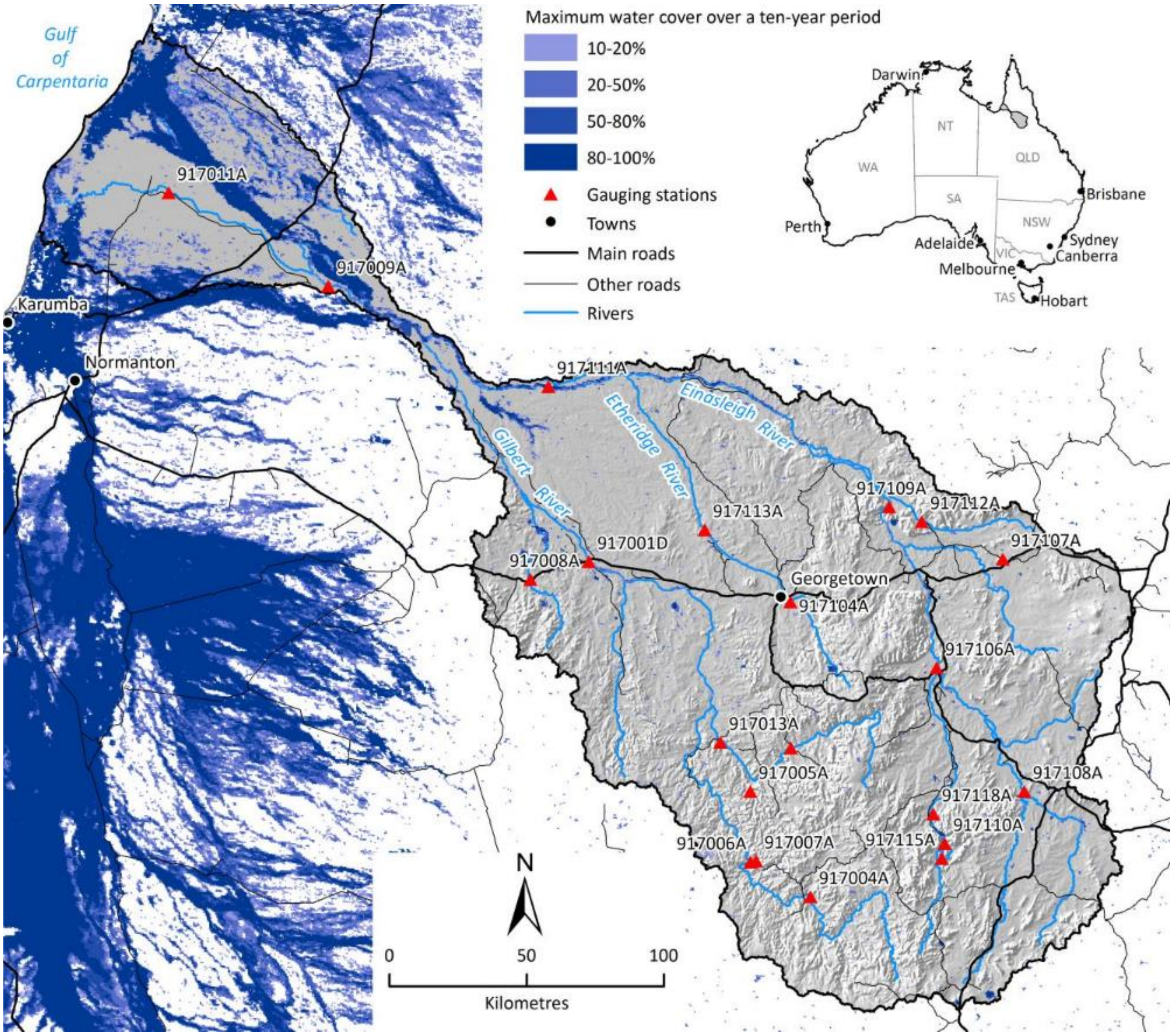


Figure 11 Flood inundation in the Gilbert Catchment, based on MODIS data from 2000 – 2010 (Source: Petheram et al., 2013).

3.2 Water infrastructure, regulation and use

3.2.1 Current situation

The rivers of the Gilbert are largely unregulated, with one large instream dam (20.6 GL) in the catchment located on the Copperfield River near Kidston, 60km south of Einasleigh [7]. The Kidston Dam (Figure 13), officially the Copperfield River Gorge Dam (Table 3), was constructed in 1984 to provide water for the now closed Kidston gold mine (Petheram et al., 2013). The dam is now managed by Queensland Department of Resources, providing stock and domestic water to limited downstream properties and some homes in Kidston via the original mine supply pipeline (Petheram et al., 2013). The dam is also used for recreational activities (e.g. fishing) [8].

[7] https://www.qld.gov.au/environment/water/catchments/state-owned-dams, accessed 16 June 2020
[8] https://www.qld.gov.au/environment/water/catchments/state-owned-dams, accessed 16 June 2020

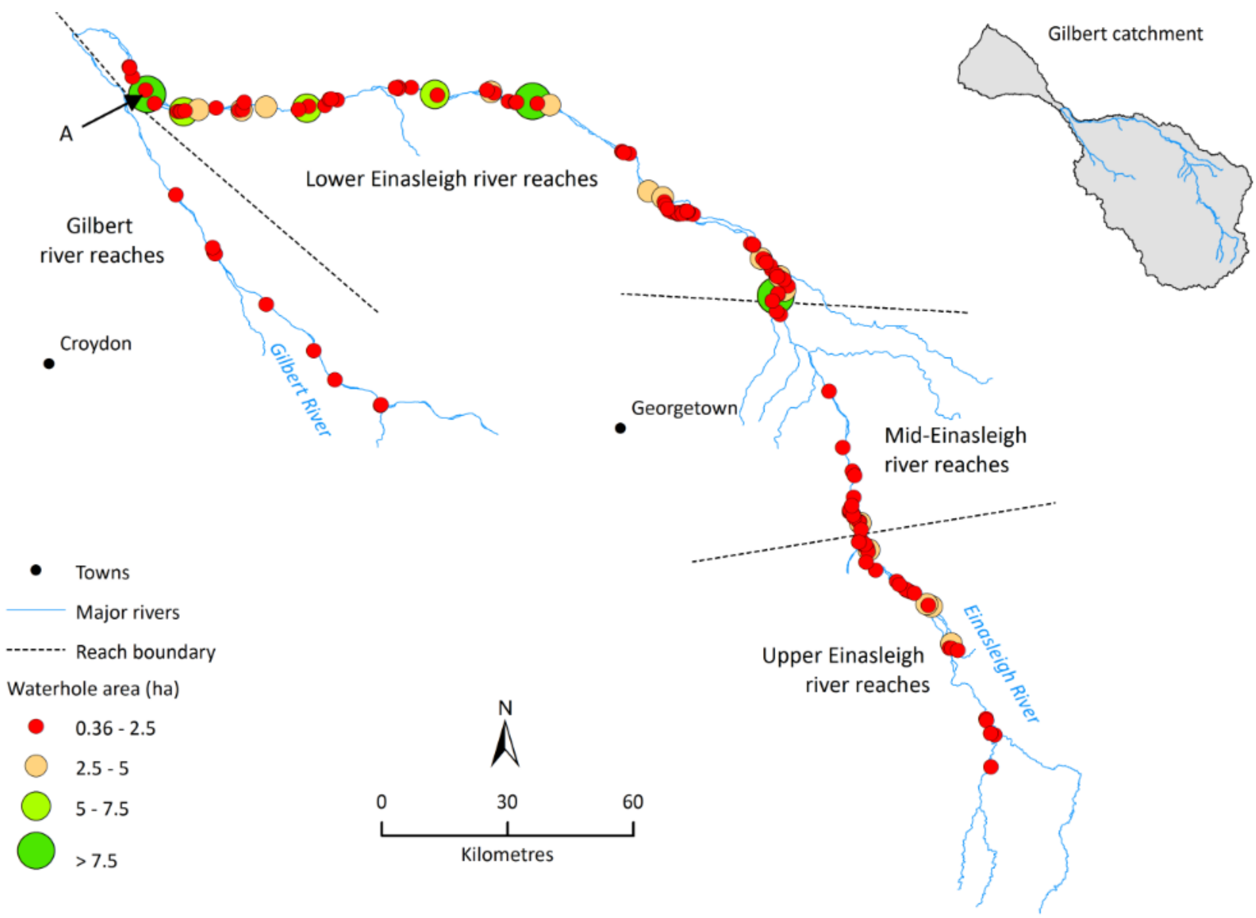


Figure 12 Waterholes in the Gilbert catchment. Please note that exact locations and size do change year to year. Insert shows the river reaches examined (Source: Petheram et al., 2013).

Figure 13 Aerial photograph of Kidston Dam (Source: https://nla.gov.au/nla.obj-149777813/view, accessed 16 June 2020)

Table 3 Summary of the Kidston Dam (Source: Petheram et al., 2013)

Name of Dam	Nearest Town	Type of Dam	Original Purpose	Year Constructed	Height Above Bed Level (m)	Storage Capacity at Full Supply Level (GL)	Annual Water Yield (GL)
Copperfield River Gorge Dam	Kidston	Concrete gravity – roller compacted concrete	Mining	1984	38	20.6	15

The largest city in the Gilbert catchment, Georgetown, is able to access water supply via nearby bores on the Etheridge River (Jacobs Australia Pty Limited., 2020, Cummings, 2015). Due to the large seasonality of the catchment and substantial differences in rainfall between years it was not uncommon for water to be severely limited by the end of the dry season and during rainfall years (Cummings, 2015). In extreme circumstances, water has been carted in by truck to maintain minimum supplies for the town (Cummings, 2015). The situation, prior to construction of the Charleston Dam, was that the water infrastructure in the catchment did not allow for substantial population or industry growth (Cummings, 2015).

The Charleston Dam, downstream of Forsayth and upstream of Georgetown on the Delaney River [9,10], was completed in late 2020. The purpose of the dam is primarily water supply to both towns with the provision of recreational facilities a secondary benefit [11]. However, local agriculture, as well as other industries, have also been suggested as beneficiaries of the project [12]. Town water licences were granted from the Gilbert River strategic reserve and the granting of a water licence for the dam was associated with release of water from strategic reserve in accordance with the Water Resource (Gulf) Plan 2007 rules.

Landholders within the Gilbert catchment currently hold 40 GL of allocations (Table 8), however, very little of this is used for irrigated agriculture (Jacobs Australia Pty Limited., 2020). The cropping that does occur commonly uses water drawn from aquifers in the sand beds of the Gilbert River (Cummings, 2015), which is classed as surface water and managed under the Gulf Water Plan. There is currently an open unallocated water release process [13] although uptake has been low (see Section 5.2).

In the Gilbert catchment, the use of groundwater resources managed under the Great Artesian Basin and other regional aquifers (GABORA) water plan is primarily for stock and domestic purposes; bores for this use do not have associated entitlements. The one (out of 507) registered bores that does have authorised use for irrigation purposes has an entitlement of 13 ML per water year (see Section 5.2).

3.2.2 Planned Changes to Water Infrastructure

There are proposed projects intended to allow for the development of an irrigated agriculture industry in the Gilbert catchment, to support both the community and economy in the region.

Large-scale surface water irrigated developments are limited to relatively few locations (Ash and Watson, 2018). The largest streamflows are typically in lower parts of the catchments that are of low relief; they are

[9] https://www.etheridge.qld.gov.au/development/economic-development/charleston-dam, accessed 20 August 2020
[10] https://www.northweststar.com.au/story/6757066/charleston-dam-gets-3m-from-feds-to-complete-the-project/, accessed 20 August 2020
[11] https://www.etheridge.qld.gov.au/development/economic-development/charleston-dam, accessed 20 August 2020
[12] https://www.northweststar.com.au/story/6757066/charleston-dam-gets-3m-from-feds-to-complete-the-project/, accessed 20 August 2020
[13] https://www.business.qld.gov.au/industries/mining-energy-water/water/catchments-planning/unallocated-water/gulf, accessed 29 November 2021

unsuitable for dams and prone to seasonal flooding and secondary salinisation. In upper reaches of the catchment, rainfall tends to be lower and the catchment upstream of the potential impoundments that are capable of storing large volumes of water. The locally preferred site is that of the the Gilbert River Irrigation Project (GRIP) [14]. This scheme would deliver 130 GL of water entitlements per year, split into both high and medium priority allocations (Jacobs Australia Pty Limited., 2020). The irrigation area hoping to be developed as a result of this project is the fertile soils that run along the Gilbert River, downstream of the dam, with a total area of 17,900 ha (Jacobs Australia Pty Limited., 2020). Community and economic benefits of this project are the diversification of industry in the area, which is currently dominated by cattle grazing, and the creation of new jobs, which would slow or reverse the current decreases in population seen in the region (Jacobs Australia Pty Limited., 2020). A local Indigenous Cooperation has given their support for the GRIP [15].

The dam wall is planned to cross the Gilbert River about 3.5 km downstream of the Carnes Road crossing (Jacobs Australia Pty Limited., 2020). The total storage capacity of the dam will be 323,577 ML, inundating an area of 5,847 ha. The area to be inundated is currently used for cattle grazing (Jacobs Australia Pty Limited., 2020).

However, to support the construction of large dams (or other water infrastructure) in the catchment there is a need for water to be available to be stored. Under the Gulf Water Pan, there is the potential for up to 467,000 ML of water entitlements to be issued from general reserve, for example to support water infrastructure (Section 5.2.3), as well as smaller allocations available for individuals (Section 5.2.2). Section 5.2 provide further details on water availability to support both water infrastructure and irrigated agriculture enterprises.

3.3 Farming systems in the north

Due to the greenfields nature of the Gilbert catchment, the ability of the catchment, and the GRAP particularly, to support an irrigated agriculture (cotton) industry is imperative to evaluate, alongside MAR feasibility. It has been suggested that farming practices from southern Australia cannot be simply transferred to the north (Yeates et al., 2014), but instead new practices must be developed. Genetically modified (GM) cotton has been previously grown in the Gilbert catchment (Petheram et al., 2013). Moving forward, developing shorter season cotton varieties should be a priority in the north (Matz, 2020).

Based on past analysis on the feasibility of irrigated cotton production in Australia's tropical north (Yeates et al., 2014), the Gilbert catchment spans the areas likely to support dry-season and wet-season cotton production (Figure 14). The differences between dry-season and wet season cropping in the north is detailed in Table 4.

Figure 14 Likely boundary between dry-season (north of black line) and wet-season (south of dashed line) cotton production areas with the production season unknown between the lines. The Gilbert catchment is circled (Source: Yeates et al., 2014).

[14] https://www.etheridge.qld.gov.au/development/economic-development/gilbert-river-agricultural-scheme, accessed 15th August 2020

[15] https://www.etheridge.qld.gov.au/downloads/file/199/lether-1pdf, accessed 8th December 2020

Table 4 Comparison of dry-season and wet-season cotton production in the north. Data sources: Yeates et al. (2014) and Petheram et al. (2013).

	Dry-season	Wet-season
Sowing	March-April	December-February
Harvest	August-October	May-July
Irrigation	7.5 ML/ha – 5.5 ML/ha	3.2 ML/ha Supplementing rainfall to finish crop.
Pests	Avoids main pests. Easy to incorporate integrated pest management.	Similar to elsewhere in QLD, however, Pink Bollworm is absent in the Georgetown area, unlike other regions of north Australia.
Limitations	If the wet season runs long sowing is delayed, increasing the chance of rainfall at picking and reducing yield. Not suitable for areas with cold nights during the dry season.	If wet-season cloud cover is prolonged and occurs during boll filling yields are reduced.

Dryland systems in the north have been predicted to be opportunistic (Ash et al., 2017, Petheram et al., 2013), with past analysis suggesting that break-even crop yields of dryland cotton could be expected fewer than 2 in 10 years (Petheram et al., 2013). This is due to the combinations of low soil water storage being common and highly variable rainfall (Petheram et al., 2013). The ability to predict a favourable season can be done with a high degree of confidence at time of sowing (Petheram et al., 2013), encouraging opportunistic dryland cropping when conditions permit.

Rotational cropping systems have also been proposed for the Gilbert catchment (Petheram et al., 2013, Ash et al., 2017), however managing such a system adds complexity where crop stages must be matched with seasonal conditions (Ash et al., 2017). For example, times of low soil trafficability due to waterlogging would limit when machinery can be used (Ash et al., 2017). Suggested crop rotation for cotton in the north include lablab, mungbean, peanuts and sorghum (Petheram et al., 2013).

There have been multiple barriers to expanding agriculture in north Australia, including:

- High transport costs to reach processing facilities or markets (Ash et al., 2017, Ash and Watson, 2018, Matz, 2020)
- Accessing land and water resource (Ash and Watson, 2018)
- Obtaining the required approvals (Ash and Watson, 2018)
- Sourcing capital costs required to establish a greenfields agriculture area (Ash and Watson, 2018)
- Gaining support from the local community (Ash and Watson, 2018)

Due to the large rainfall events experienced in the north, erosion is possible, especially in poorly managed systems (Petheram et al., 2013). Practices including minimum or zero tillage (as opposed to intensive tillage) and stubble retention have been suggested at a method of erosion control, where the aim is to maintain natural suspended sediment loads (Petheram et al., 2013). However, rainfall in the North commonly occurs before the late crop development phase, which minimises the likelihood of late rainfall downgrading the cotton fibre quality and therefore price (Petheram et al., 2013).

3.4 Case study area of interest

The area of interest for this case study is the Gilbert River Agricultural Precinct (GRAP; Figure 15) which corresponds to the area that the proposed Greenhills Dam would service.

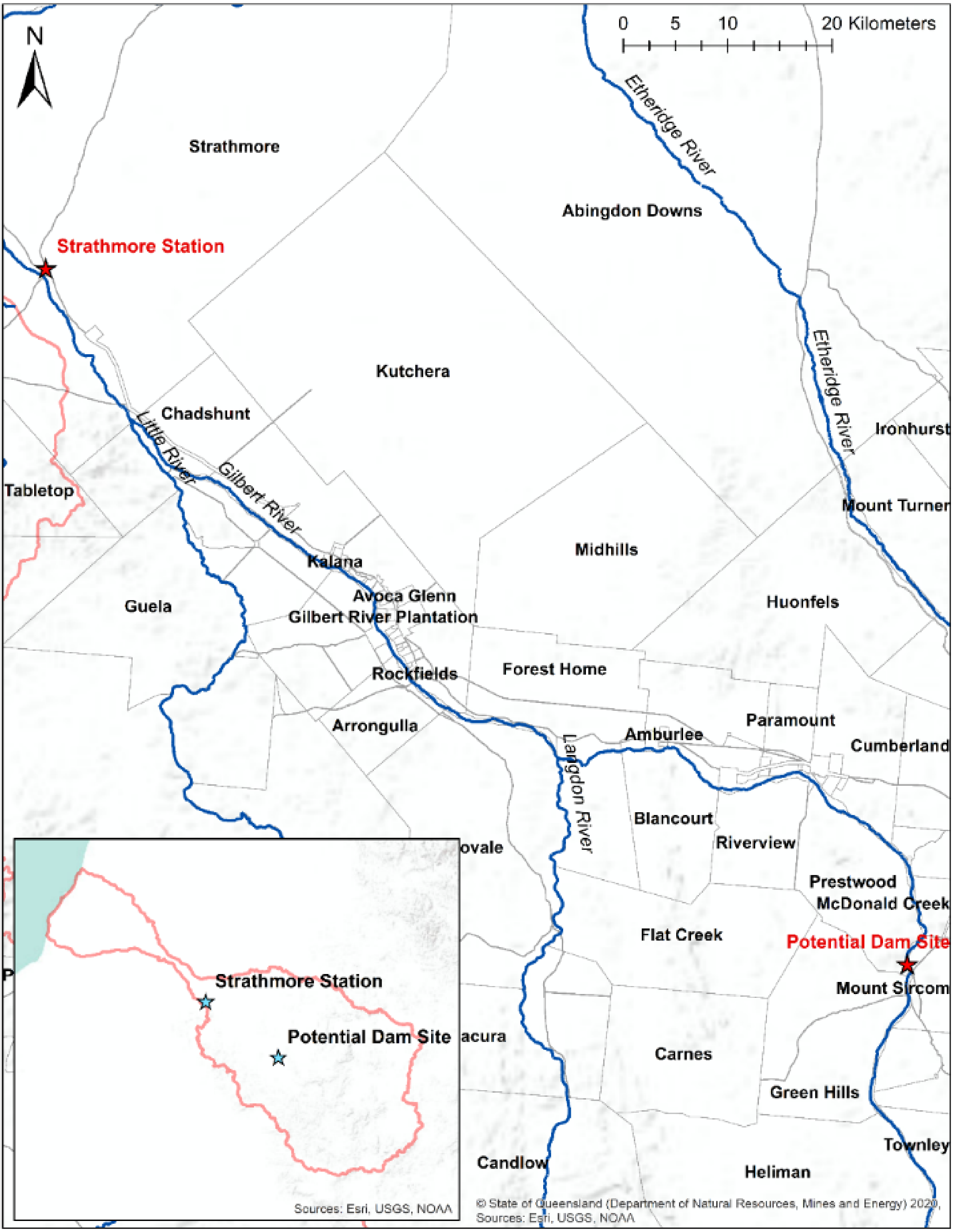


Figure 15 The Gilbert River Agricultural Precinct (Source: https://nla.gov.au/nla.obj-149777813/view, accessed 16 June 2020)

4. Scenarios

The proposed scenarios were initially drafted in late 2020 from preliminary feasibility analyses pertaining to MAR in the Gilbert River catchment and were refined based on discussions with local stakeholders and further assessment of potential feasibility. Note that these scenarios do not constitute an endorsement for a particular course of action. Rather, they highlight possible opportunities for MAR in the Gilbert River catchment, contrasting scenarios without a MAR component, and a scenario with both MAR and surface water elements (conjunctive water management). They were used to guide the finalisation of the potential feasibility assessment for the Gilbert case study (Section 5) and to develop recommendations for CRDC and other stakeholders to support any efforts to proceed with MAR, and conjunctive use of water more broadly, should they wish to invest further in investigating MAR (Section 7.2).

Currently, the cropping that does occur in the Gilbert River catchment tends to be irrigated using water drawn from the aquifers in the sand beds of the Gilbert River [16]. Some farms currently irrigating (for cropping trials or forage) pump into a tank on the river to build up head, filling the tank either during the day (or night) and running the pivot in the night (or day); other farms are able to pump straight from the bed sands into their irrigation systems [17]. Given that the typically low yields of underlying sandstone aquifers will constrain MAR in these systems [18], the most promising prospect appears to be MAR interventions designed to provide timely and reliable water yields from the bed sands. These interventions would aim to top up the bed sands and/or slow the drainage from the sands.

The coarse scale of data on the alluvium in the Gilbert River catchment [19] means that further data collection and ongoing monitoring would be required to assess the full potential for MAR and gain confidence that risks can be addressed within developed governance arrangements in a socially acceptable manner. Focus is therefore on active management of bed sands, that is aiming to build understanding of the system through incremental development under the current framework for water management in the catchment, with a view to building evidence to support the state government to revise or refine rules currently limiting extraction, recharge, and infrastructure development.

Associated with all scenarios is the development of renewable energy infrastructure which, for regional scale development could open up the possibility of co-investment as well as benefits to electricity for the whole region. All scenarios would need to seek approvals for, and address environment impacts, of vegetation clearing and to avoid deleterious impacts on culturally significant sites.

4.1 Farm scale MAR

This scenario focuses on active management of the bed sands through the capture and banking of water licences during wet periods by individual farms, run by an individual owner or land manager. The intention would be to use the bed sands to provide supplementary irrigation at the start of the dry season and use recharge structures to maximise water levels at the end of the wet season using entitlements managed under the Water Plan (Gulf) 2007.

Landholders in the Gilbert catchment collectively hold 40 GL of water licences although little of this water is currently used for irrigated agriculture [20] (Jacobs Australia Pty Limited., 2020)(Jacobs Australia Pty Limited., 2020)(Jacobs Australia Pty Limited., 2020)(Jacobs Australia Pty Limited., 2020)(Jacobs Australia Pty Limited., 2020). There is a total of 85 GL per year of unallocated entitlements aimed at individual

[16] Cummings, W. S. 2015. Charleston Dam Project Water Supply Augmentation for Georgetown and Forsayth: Economic Impact/ Benefit Cost Analysis. Cairns, Australia Cummings Economics

[17] Stephen Yeates (*pers. comm.* 6 November 2020)

[18] Underlying sandstone aquifers would be regulated under the GABORA water plan.

[19] See Section 5.3.1

[20] See Section 5.2.1

properties in the catchment under the 2020 Terms of Release which is being released from the 467,000 ML general reserve [21]. Purchasers of entitlements commit to installing infrastructure capable of taking at least 50% of the yearly entitlement within three years of issue [22]. Given the monsoonal climate, there is ample water available in most years, but dry season storage is the key challenge that bed sands could help address.

The existing use of spear bores for domestic and irrigation purposes by landholders in the Gilbert demonstrates that the infrastructure needed for extracting water from the bed sands works [23]. As there is limited established water delivery infrastructure, farmer managers would locate MAR operations adjacent to agriculturally suitable soils in order to reduce initial capital costs. On-farm strategies and infrastructure to recharge water into the bed sands could include regenerative agriculture techniques such as leaky weirs which could be constructed across small streams off the Gilbert River and would slow water flow and facilitate local wetting of the landscape and alluvial sands [24]. Construction materials and earthworks would be needed for the construction of leaky weirs. Infiltration basins aim to recharge unconfined aquifers through pumping or diverting water from river into an off-stream storage. In the Gilbert, possible locations are the bed sand deposits that extend beyond the river channel. The requirements of infiltration basins are for land adjacent to the river with permeable soils that facilitate quick recharge of water, the ability to fill the basin by gravity, and the cost of earthworks. Methods taking place in the river will be costlier due to annual maintenance costs and higher regulation requirements.

Within an active management paradigm, the aim is for land managers to progressively improve their water use strategies and management of the bed sands over time, rather than aiming for a single major recharge infrastructure investment. The starting point is to keep records of water use and state of the water resource (e.g. spear bore water levels), and to seek to collaborate with other landholders and organisations to gain a more complete understanding of the system and identify and evaluate possible improvements. If the land manager has an existing spear bore entitlement, they could use these initially (and expand over time as needed) and implement measures to manage risks as part of their existing operations as they arise.

In setting entitlement volumes, the Gulf Water (2007) Plan has considered environmental flows, avoiding impacts on water holes, and maintaining riparian and in-stream vegetation. Restrictions on extraction prevent new licenses from taking water during dry season low flows, and there is no established procedure tailored to approvals of recharge infrastructure specifically. Changes to the Gulf Water (2007) Plan would therefore be required in the 2027 review, and landholders would need to engage with state government early to start exploring options for changing the plan to adopt condition-based management, emphasizing avoidance of impacts to allow more flexibility in extraction. Collaboration between local stakeholders and government would work towards establishing appropriate rules for recharge and later extraction of surface water into bed sands, approvals for the establishment or replacement of infrastructure [25,26], and monitoring of impacts. Any localised impacts of pumping from the riverbeds in the dry season would be tracked by monitoring water levels and yields from sand beds, streamflow, and vegetation condition. It is anticipated that monitoring would need to extend to the full width of the bed-sands and at least a

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[21] See Section 5.2.2 and https://www.business.qld.gov.au/industries/mining-energy-water/water/catchments-planning/unallocated-water/gulf, accessed 18 June 2021

[22] See Section 5.2.2

[23] See Section 5.3.6

[24] See Section 5.3.5

[25] https://www.business.qld.gov.au/industries/mining-energy-water/water/bores-and-groundwater/construction-approvals; https://www.business.qld.gov.au/industries/farms-fishing-forestry/agriculture/rural-disaster-recovery/repairs-watercourses-infrastructure/groundwater-bores-spears

[26] In-stream infrastructure may need approval under the water act and water plan as well as other legislation (e.g. fishway barrier works approval).

kilometre upstream and downstream[27], such that collaboration and establishment of information sharing arrangements is important even with a farm scale focus.

4.2 Farm scale surface water storage

An alternative to farm-scale MAR is investment in off-stream surface water storages (e.g. gully dams or ring tanks) on a single farm that the land manager could use to capture water during the wet season to provide supplementary irrigation when needed at the start of the dry season. The source of water and requirements for installation of infrastructure (50% capacity within three years) are as outlined in the farm scale MAR scenario, although under the Water Plan (Gulf) 2007 there is also the ability to take overland flow in surface storages up to 250 ML without a water licence and larger volumes with a water licence [28,29].

Construction of off-stream storages is an established technology with defined institutional and compliance procedures. However, as they retain water above ground, the highly seasonal climate of the Gilbert catchment could lead to substantial evaporation losses. Also, the soils adjacent to the Gilbert River are highly permeable and typically considered to be less suitable for off-stream storages [30], especially if they are not lined to prevent leakage. While leakage may recharge the bed sands in some circumstances, leakage and evaporative losses from off-stream storages have been estimated to add an additional cost of $140/ML to $240/ML to store water for 4 to 12 months, respectively [31]. Land and operational factors determine the physical storage dimensions and storage capacity.

Surface storages may still present the best option in circumstances where costs can be minimised or losses may not be significant [32]. Costs can be minimised in locations with pockets of low infiltration soils located close to good agricultural land, or where sites that act as natural surface storages could be enhanced. Losses may not be significant for high value uses of smaller volumes of water such as bridging of water supply between rainfall events and finishing a wet-season crop. Based on discussions with stakeholders in the area the development of on-farm small scale surface storages was of greater interest than what could be gauged from previous reports [33]. Stakeholders also had themselves scoped areas that they felt were most suitable for surface storages on their properties [34].

Without changes in policy to allow MAR, the need for associated infrastructure to accompany new entitlements suggests that off-stream surface water storages are being promoted by previous water releases. This focus on surface flows for use is further complemented by the Water Plan's ecological outcome of limiting dry season low flow extraction from the bed sands in the Gilbert River [35], highlighting that expanding groundwater use in aquifers outside the GABORA is currently not an option in the catchment. In the Gilbert catchment, there has been little analysis of systems implications of widespread new surface water storages, e.g. for low flows, such that environmental and subsequent regulatory risk may remain an issue when investing in off-stream surface water storages [36].

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[27] Section 6.3.2
[28] See Section 5.7.1
[29] Any off-stream works that take overland flow water need to be assessed for consistency with either an entitlement or water plan authority for taking overland flow water using limited capacity works https://www.rdmw.qld.gov.au/?a=109113:policy_registry/code-self-assessable-development-limited-capacity-works.pdf, accessed 3 December 2021.
[30] See Figure 39
[31] See Section 5.4.2
[32] See Section 5.4.2
[33] See Section 5.1.2
[34] See Section 5.1.2
[35] See Section 5.7.1
[36] Although not with a MAR component, some proponents have investigated options for accessing shallow (alluvial or other unconsolidated sediments) groundwater, along with other sources of water (namely overland flow), in other catchments

Further investigation of off-stream water storages as an alternative to MAR is outside the scope of this project but it appears that both may be viable in different locations or for different farms. Therefore, both should be considered when taking a systems view of dry season water storage in the Gilbert.

4.3 Regional scale MAR and establishment of a local gin

This scenario describes a regional scale MAR scheme that could provide sufficient water to irrigate an area of cotton that would support a viable cotton gin servicing the Gilbert and adjacent catchments. A gin in the region has been shown to be critical for profitability of local cotton production [37] but existing new cotton planting outside the Gilbert River Agricultural Precinct (GRAP), namely in St Ronans, Mount Garnet, and Innot Hot Springs, means that substantial reductions in current transport costs may be achieved even if the gin is not located in Georgetown, and the Gilbert River would therefore not need to be the sole water source. A recent estimate of the land area and yields needed to support a cotton gin are a minimum of 7,000 hectares of cotton yielding 9 bales per hectare (i.e., ~67,500 bales) [38]; other estimates of the number of bales needed to support a local gin have ranged from about 50,000 to 100,000. Irrigation is needed to maximise cotton yields in the Gilbert with estimates that full irrigation (with a median irrigation requirement of 3.2 ML/ha) would double yields [39]. A report focused on feasible cotton gin locations in North Queensland is currently being prepared on behalf of the Mount Isa to Townsville Economic Development Zone (MITEZ) [40].

Multiple strategies could be implemented within a regional-scale MAR scheme, with the Burdekin MAR scheme providing examples of the range of possible interventions [41]. Recharge weirs could be incrementally constructed along the length of the water courses adjacent to the Gilbert River and the GRAP to detain water and increase the time for it to infiltrate into the riverbed sands. Similarly, infiltration basins could be utilised to provide recharge for later extraction by multiple users. Structures such as underground, sand dams and recharge weirs have been used internationally (e.g., Africa) in ephemeral systems to retain flood flows in alluvium to provide regional scale water supply. Pooling behind the structure could lead to the desired impact of longer recharge periods for the alluvial aquifer, but wet season flows and discharge into the Gulf might be reduced, and sediment retention in the system increased as water flows are slowed by structures. Such impacts can be tracked by monitoring levels and yields from sand beds, sediment loads before and after installation of weir(s), and changes in streamflow just downstream of the weir(s) and near the Gulf. Currently there are two groundwater monitoring bores in the catchment, one in the GRAP [42]. However, the monitoring bore is located in the GAB sandstone

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managed under the Gulf water plan. An example is the 15 Mile Irrigated Agricultural Development project. The Coordinator-General's evaluation on the impact assessment report provides an example of the processes and approvals required for a regional scheme. http://eisdocs.dsdip.qld.gov.au/15%20Mile%20Irrigated%20Agricultural%20Development/CGER/15-mile-irrigated-agricultural-development-coordinator-generals-evaluation-report.pdf, accessed 6 December 2021

[37] See Section 5.4.1

[38] Matz, J. 2020. Northern Australian broadacre cropping situational analysis. CRCNA.

[39] Petheram, C., Watson, I. & Stone, P 2013. Agricultural resource assessment for the Gilbert catchment. A report to the Australian Government from the CSIRO Flinders and Gilbert Agricultural Resource Assessment, part of the North Queensland Irrigated Agriculture Strategy. CSIRO Water for a Healthy Country and Sustainable Agriculture flagships. Australia.

[40] As of the finalisation of this Milestone report, the MITEZ report was not available online. The North West Star reported in September 2021 that "Richmond and Hughenden were identified as preferred locations for a gin, which the assessment said would be viable in a five-year horizon." https://www.northweststar.com.au/story/7436935/nq-cotton-gin-is-viable-says-mitez-study/, accessed 6 December 2021.

[41] See Section 5.4.4

[42] See Section 5.3.7

aquifer, not the near surface alluvial aquifer. There are several bores in the area, most of which are used for stock and domestic water supply [43] and are located in the GAB aquifers [44].

The operation, maintenance and monitoring of MAR schemes could be achieved through the establishment of a local water management organisation that would partner with other agencies but ultimately operate on a user pays cost recovery basis based on assessable area charges from the agriculture industry [45]. Lessons can be learnt from the governance arrangements for the Burdekin system whereby the water boards have responsibilities for day-to-day operation of the scheme and setting a broad strategic framework, business targets and operational controls, with the state government providing the policy framework and technical support [46].

Through partnerships such an organisation could be set up to have an incremental mandate, starting with local data collection, knowledge management and sharing, moving on to daily support of landholder water management, and then to development and operation of larger schemes. Given the coarseness of data on the alluvium in the Gilbert, initial steps would require investment in studies to improve understanding of the aquifer storage capacity of the alluvial sands and to build knowledge and capacity in the region for managing water in the bed sands. Understanding of the use of water in the river and bed sands over time could allow local and state governments to play a more active role in assisting landholders to plan and coordinate their pumping from bed sands, and address risks associated with pumping riverbeds dry during dry season and recharging during high flows. An element of this would be a network of monitoring bores used to track water depths in the bed sands during and after periods of recharge and extraction. A water management organisation and its partners would play a critical role in working with state government to co-create appropriate rules for recharge and later extraction of surface water into bed sands, approvals for the establishment or replacement of infrastructure [47], and monitoring of local and regional impacts. Substantial changes are required in the 2027 review given that current unallocated water entitlements up for tender in the Gilbert catchment are associated with flow conditions [48], and therefore cannot be used in the way that current bed sand entitlements are used (i.e., extraction approved when there are low or no flows of the Gilbert River). An organised, coordinated, regional perspective provides a critical mass that would facilitate and accelerate discussion around these changes.

4.4 Surface water management and establishment of a local gin

This scenario describes the proposed Gilbert River Irrigation Project (GRIP) for which a Detailed Business Case (DBC) was prepared in 2020 [49]. The development would see a 323,577 ML dam constructed near Georgetown on the Gilbert River that would be able to deliver 130 GL of water entitlements per year for use as irrigation to an area of 17,900 ha on the fertile soils along the Gilbert River (Jacobs Australia Pty Limited., 2020). In this scenario the GRIP is associated with the development of a cotton gin to support the viability of an irrigated agriculture industry in the Gilbert (as per the Regional MAR scenario). In the DBC it was suggested that the GRIP development would be of a size to support the establishment of a local cotton gin.

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[43] See Figure 20

[44] See Figure 75

[45] In the Burdekin Delta, partnerships between the growers and millers of sugar exists such that growers pay two-thirds of the charges and millers one-third. A similar arrangement could exist between cotton growers and the operators of a local gin.

[46] This scheme has the benefit of providing rate payers access to water for irrigation but one of the main purposes of the board is to replenish groundwater to levels preventing ingress of salt water.

[47] https://www.business.qld.gov.au/industries/mining-energy-water/water/bores-and-groundwater/construction-approvals; https://www.business.qld.gov.au/industries/farms-fishing-forestry/agriculture/rural-disaster-recovery/repairs-watercourses-infrastructure/groundwater-bores-spears

[48] See Section 5.2.2

[49] Jacobs Australia Pty Limited. 2020. Gilbert River Irrigation Project Detailed Business Case. Australia.

The surface water infrastructure for the proposed GRIP encompasses the dam wall, pipelines, ring tanks and fully lined channels to avoid seepage losses. The DBC consider three scenarios for funding the GRIP: no, medium and high government funding. Under these scenarios, total customer charges of these scenario range from 54.50 and 77.78 $/ML for medium and high priority water, respectively, with high government contributions, to 272.42 $/ML and 404.66 $/ML with no funding provided by government.

The maintenance of environmental flows is a requirement of the Gulf Water Plan, so for example, the proposed Gilbert River Irrigation Project dam would need to be able to release up to 136,830 ML per day to meet the Gulf Water Plan's environmental flow objectives [50]. Impacts on bed sands would likely need to be assessed as part of the Environmental Impact Assessment prior to approval of the dam, which would likely still require further investment in bed sands monitoring. The dam volume is potentially on the order of 10 times larger than the bed sands storage volume[51], and therefore involves larger investment in agricultural development that would be transformational for the region. In contrast to the more incremental approach of regional scale MAR, attracting this investment and managing this transformation is therefore critical, including investment in urban infrastructure. State significant listing of the project was also considered important in the DBC, in particular to gain exemptions needed to clear vegetation [52].

Given political support and investor interest, policy considerations surrounding a dam would perhaps be more straightforward then implementing MAR due to the long history of in-stream surface water storages throughout Queensland and Australia. However, dam construction would likely need to satisfy policy beyond the water sphere, for example, the Queensland Fisheries Act on account of a structure being erected in a waterway. Details about additional policy related to water development can be found in Section 5.7.3.

4.5 Conjunctive water management and establishment of a local gin

This scenario describes a regional scale irrigation scheme that combines MAR and the proposed GRIP scheme, again with establishment of a local gin.

MAR might be used in conjunction with the proposed GRIP dam in two ways. The dam could be used as a temporary storage or sedimentation tank prior to releasing water to recharge the alluvial river sands. Alternately, the dam could be used to deliver immediate water demands from entitlements with the excess used to recharge bed sands using MAR, which can then be extracted when required in the dry season or in years of low rainfall. As the intent is to recharge the bed sands, the dam wall would be retained in this scenario but not necessarily the pipelines, ring tanks and channels. Avoiding concreting channels could save costs, increase recharge, and retain control over gravity-fed delivery. Delivering water solely by releases to the bed sands would reduce capital costs but increase pumping costs and changes to instream flow patterns. Combining the strategies may also reduce initial investment by allowing for a smaller initial dam wall and later expansion, though costing of this approach was out of scope of this project.

As the dam would hold back (flood) water during wet season there will be some impacts of reduced wet seasons flows and discharge into the Gulf and the inundation of an area upstream of dam would have impacts on native vegetation. Any potential impacts of pumping the sand beds in the dry season would need to be tracked. The states to be monitored, and the information and infrastructure needed to do so, to identify unacceptable impacts from the dam, recharge releases and riverbed pumping are as for the Regional MAR and dam scenarios. Once again, the Burdekin scheme could be looked at to provide

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[50] Jacobs Australia Pty Limited. 2020. Gilbert River Irrigation Project Detailed Business Case. Australia.

[51] See Section 6.1

[52] See Section 5.7.3

examples of how policy can allow for conjunctive water use to support irrigated agriculture [53]. Similar to any regional scale scenario, many policy approvals outside the water sphere would be required [54]. Despite their potential complexity relative to narrower or more familiar developments, hybrid solutions of this type are worth including in any systems analysis of dry season water storage in the Gilbert given the flexibility and adaptive capacity they provide, and therefore the opportunity to approach sustainable irrigation development as an incremental rather than potentially disruptive step-change transformation.

[53] See Section 5.7.4

[54] See Section 5.7.3

5. Feasibility Criteria Analysis

This section presents the data, information, analysis and assumptions that have been made in order to inform the potential feasibility of the five scenarios presented in Section 4 across the seven criteria outlined in Table 5. An overview of key points for each scenario and feasibility criteria is given in Table 6.

Table 5 The seven feasibility criteria of Ticehurst and Curtis (2017).

Criteria	Example questions and considerations
Demand for Water	• Is there demand for more water, or a greater water security? • Who wants the water and when?
Water availability	• Is water available to be banked underground (e.g. unused surface water shares, surface water traded in when prices are low)?
Technical feasibility	• Is there space in the aquifer systems to store surface water for drier times? • How can the water be recharged, stored and extracted?
Financial viability	• Financial viability and profitability of MAR schemes are influenced by many factors including the MAR type, water source, infiltration and recovery rates, groundwater depth, water markets, crop prices and yields, groundwater pumping costs
Environmental risks	• Are there any significant effects on water quality & quantity (positive or negative)? • What are the consequential impacts of any change on farm land and ecosystems?
Social acceptability	• Is it a socially acceptable option to irrigators, stakeholders and the wider community? • What are people's values, knowledge and beliefs about MAR? • Do they perceive risks about its implementation in their region?
Governance arrangement	• Are the legislative and policy settings appropriate to support a MAR system? • If not, how would they need to be changed?

5.1 Effective demand for products

To catalyse innovative water management there must be 'demand' for change. In the Gilbert catchment, demand for change could include calls for:

- increasing the volume of water available for irrigation, especially to allow for industry development, and/or
- evening out water availability between the wet and dry season, to create greater year-round water security.

To assess if there is demand for such changes in the Gilbert catchment, first the seasonal variability in water availability is explored (Section 5.1.1), followed by findings and feedback for the demand for change to water management from an irrigators perspective (Section 5.1.2) and community/industry perspective (Section 5.1.3).

5.1.1 Variability of water availability

The seemingly abundant water supply in Northern Australia has sparked development interest in the area (Petheram et al., 2010). This notion overlooks the areas 'unfavourable streamflow characteristics, storage constraints and large evaporative losses' and that seasonality is a limiting factor to development (Lennon et al., 2014).

Table 6 Summary of the scenario feasibility

Scenario	Farm scale MAR	Farm scale surface water storage	Regional scale MAR	Regional scale surface water storage	Regional scale MAR + surface water storage
Effective demand for products [5.1]	There is some interest from farmers to diversify from traditional pastoralism only enterprises [p96]. Some farmers have already started cropping, either dryland or irrigated using water entitlements [5.1.2].		Beyond interest from farmers in the region [5.1.2], there is also support for expansion of irrigated agriculture from the Etheridge Shire [5.1.3]. Demand for water also exists from actors from southern farming regions expanding to the north [5.1.3].		
Water availability [5.2]	There are currently unallocated water entitlements out for tender [5.2.2]. These entitlements are associated with flow conditions.		There are substantial volumes of unallocated general reserve water beyond those currently out for tender that could be used for regional scale projects [5.2.3].		
Technical feasibility [5.3]	*Surface storage:* Many past reports describe the region as unsuitable for surface storage due to the highly permeable soils and high evaporative demands [5.3.2, 5.4.2], however there are possibly situations where these impediments can be navigated. *MAR:* Recharge of bed sands occurs naturally [5.3.1]. The ability to complement this is unknown and would need to be explored through active management and monitoring of the bed sands [5.3.4]. Many modes of MAR have been suggested to target alluvial aquifers elsewhere [5.3.4, 5.3.5].			CSIRO's Flinders and Gilbert Agricultural Resource Assessment identified several possible dam sites over both the catchments, including the Greenhills Dam on the Gilbert River. This is the upper bound of both the proposed Gilbert River Agricultural Precinct [5.1.2] and the area of interest of this feasibility assessment [3.3].	A recharge release scheme [5.3.5], where water is purposefully released from an upstream dam to recharge the Gilbert River bed sands could top up the bed sands throughout the dry season. This MAR method was suggested for the Mitchell catchment [5.3.4].
Financial viability [5.4]	*Surface storage:* Due to losses, water costs increase substantially with increasing storage time [5.4.2]. *MAR*: Initial estimates of the costings of potential MAR schemes in North Queensland are available, with levelized costs ranging from $48 - $172 per ML [5.3.4]. The only operating MAR scheme in Queensland (in the Burdekin) has a levelized costs in the lower half of those estimated above ($80/ML) [5.4.4].			A detailed business case exists for a large in-stream surface storage in the Gilbert River [5.4.3]. Estimated water costs range from $54.50 - $404.66 per ML depending on priority (high, medium) and funding sources [5.4.3].	The cost of establishing all the required infrastructure for a recharge release scheme (i.e., dam and MAR infrastructure) is unknown as past assessments assumed that the dam was already constructed [5.3.4]. However, using the river as a natural delivery network would reduce costs if a pipeline/lined channel delivery network was to be built [5.4.3].

<table>
<tr><th>Scenario</th><th>Farm scale MAR</th><th>Farm scale surface water storage</th><th>Regional scale MAR</th><th>Regional scale surface water storage</th><th>Regional scale MAR + surface water storage</th></tr>
<tr><td>Environmental risk [5.5]</td><td colspan="3">Surface storage: Systems implications of multiple off-stream water storages, e.g. for low flows, may pose an environmental risk

MAR: Active management of extractions, with condition-based regulations, is needed to ensure outflows into the Gulf are not adversely reduced [5.5.3], and to build knowledge about hyporheic ecosystems and any impacts of extraction from the bed sands of the Gilbert River [p81].</td><td>There are many environmental assets [5.5.1] and processes [5.5.2] that rely on the substantial wet season flows. Multiple methods have been suggested to minimise the impact of water development on the environment [5.5.3], including allowing first flush events to proceed unimpeded.</td><td>The combined use of MAR and an instream dam could pose risks to the hyporheic ecosystem of the bed sands [p81] and wetland and floodplain processes [5.5.2].</td></tr>
<tr><td>Social acceptability [5.6]</td><td colspan="5">All options provide substantial changes to the status quo. A large dam represents a potentially disruptive, transformational change for the whole community. Even though MAR and surface water storage options are more incremental [5.3.5], they are also highly uncertain and require development of high-level trust and coordination. Given that changes are possible at the earliest with the review of the Gulf Plan in 2027, bringing the community along for the journey is critical, feasible, and already being pursued by the Etheridge Shire Council [5.1.3, p95].</td></tr>
<tr><td>Governance arrangements [5.7]</td><td>Changes to existing policy, co-created with state government, would be needed to allow for sustainable water extraction from the bed sands and MAR during dry season low-flow conditions [p98].</td><td>250 ML of overland flow can be taken without a licence [5.7.1], promoting small scale on-farm surface storage.</td><td colspan="3">Beyond water related policy, there are other legislative hurdles to establishing water infrastructure and irrigated agriculture in the region [5.7.3].</td></tr>
</table>

Reflecting the extreme seasonality of the Gilbert catchment, where ~ 95% of rainfall and ~ 99% of runoff occurs during the wet season (Lennon et al., 2014), Figure 16 illustrates that demand for water peaks towards the end of the dry season (Lennon et al., 2014). In other words, demand and supply are inverse, with storage required to bridge this gap (Lennon et al., 2014). If a substantial year-round irrigation industry was to develop in the region, it would follow that future water demand would also be larger than what is currently seen.

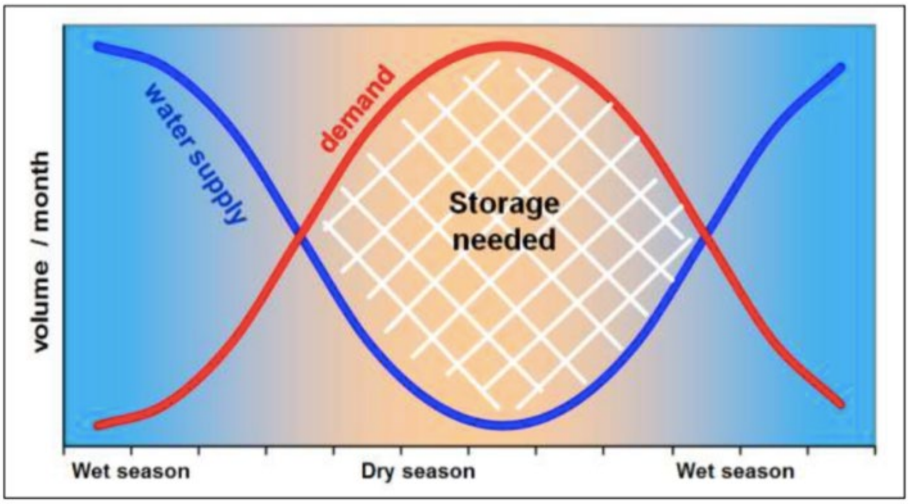

Figure 16 Supply vs. Demand for water in Northern Australia (Source: Lennon et al., 2014)

5.1.2 Irrigators demand for water

Agriculture in the Gilbert catchment is dominated by pastoralism with only small areas of cropping (Petheram et al., 2013, Álvarez-Romero, 2015). There has been interest from some farmers in the region to incorporate irrigated agriculture into their enterprise, which has been accompanied by called for water infrastructure in the catchment. For example, in 2017 a farmer in Georgetown planted sorghum and corn to assess the suitability of cropping on their land and diversification [55]. After a successful harvest, this farmer called for support to establish a large-scale irrigation project to get the critical mass onboard, possibly unlocking economic gains not yet realised on the region. The farmer suggested that the major barrier to this was a lack of water licences. However, based on the Gulf unallocated water release, there are water licences available, albeit with associated flow conditions (See Section 5.2).

Neither water development in the Gilbert River or shifting to a regulatory system of active water management is a priority of the state government. The Gilbert River Agricultural Precinct (GRAP) lies to the west of Georgetown in a monsoonal climate where substantial volumes of water are typically available in the wet, yet storage is required to access water in the dry. The region has struggled to attract investment in the proposed Green Hills dam, and water releases have seen low sales. At face value this appears to indicate low interest for water development and therefore low need for additional investment. However, anecdotal evidence at the Gilbert River Agricultural Forum (April 2021) suggests that there is instead a latent demand for water and water storage, hidden behind water-related and other barriers, information gaps regarding system operation, management options and pathways for investment [56] (see page 96).

In conversations with landholders and other stakeholders at the Gilbert River Agricultural Forum in April 2021, there was some interest in on-farm surface water storages. Based on reports, the feasibility of such infrastructure in the region generally is low (see Section 5.4.2), although some landholders indicated that

[55] https://www.northqueenslandregister.com.au/story/4647549/gilbert-irrigators-seek-water/, accessed 22nd June 2020.

[56] From this Gilbert case study, the Queensland Water Modelling Network (QWMN) has funded a project led by ANU in collaboration with Gulf Savannah Natural Resource Management (GSNRM) which aims in part to assess the extent of latent water and water storage demand in the Gilbert.

regions of their property would be suitable for turkey nest dams or structures that use the natural contours of the land. They said they could use such storages to ‘finish off’ current or hypothetical crops at the end of the wet season. This water management timeline would minimise evaporative losses by not holding water long post wet season. Other persons at the forum expressed interest in having some flexibility in planting times at the start of the wet season. By having water stored, the planting could still occur in a late onset wet season or in a wet season with a large gap between rainfall events. These conversations support those from a farmer interview conducted in March 2019 when scoping the potential CRDC MAR project case studies. He noted that whilst their bed sand licenses allowed them access to a lot of water early in the season, it peters out into the dry season when they need the water to finish off their cotton crops. There are five spear bores with entitlements where water is actively being extracted from the bed sands (see Section 5.2.1); from speaking with three landholders or land managers the reliability of access to water over time from the bed sands varies between the bores (even over quite small distances between bores).

In summary, there is demonstrable demand from irrigator landholders to ***even out*** *water availability in the lead-up and to and end of the wet season where water security is not guaranteed from year to year. The need for* ***more*** *water volumes is not as clear-cut given storage limitations and other barriers may be constraining demand.*

5.1.3 Industry and community perspective

Industries usually associated with the southern Australian farming regions (e.g., MDB), including the cotton industry, are looking to boost irrigated agriculture in the Gilbert River region, with water entitlements and infrastructure being highlighted as major requirements to support this development [57]. There is interest from players in the horticultural industry to establish trials or plantings in the region [58]. For example, one table grape producer is conducting a trial in the Gilbert catchment with a vision to be the first to achieve year-wide production across their Australian holdings

The Etheridge Shire Council, one of the local councils in the Gilbert catchment, has long supported the expansion of the limited irrigation infrastructure in the area [59,60]. A detailed business case (DBC) was recently released in support of a large dam on the Gilbert River (Jacobs Australia Pty Limited., 2020). The current council remains supportive of irrigation to support diversification and value-adding to existing grazing, horticulture and cropping in the catchment. They are deliberately taking a broader look at water management and agriculture in the catchment, rather than the previous focus on the proposed dam, to ensure they had landholder support to grow the precinct sustainably [61]. Local participants at the Gilbert River Agricultural Forum, expressed the desire that future agricultural development would retain the character of the catchment and support local development and jobs. *This suggests some tension with some calls for broadscale agricultural development and retaining the pastoral identity of the catchment.*

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[57] https://www.queenslandcountrylife.com.au/story/4891553/cotton-backs-nq-water-announcement/, accessed 24 June 2020

[58] https://www.northqueenslandregister.com.au/story/7188113/gilbert-river-forum-to-step-cattlemen-through-ag-options/, accessed 17 May 2021

[59] https://www.etheridge.qld.gov.au/development/economic-development/gilbert-river-agricultural-scheme, accessed 24 June 2020

[60] https://www.etheridge.qld.gov.au/downloads/file/599/gilbert-river-irrigation-project-brief, accessed 24 June 2020

[61] https://www.northqueenslandregister.com.au/story/7188113/gilbert-river-forum-to-step-cattlemen-through-ag-options/, accessed 17 May 2021

5.2 Water availability

Surface water in the Gilbert catchment is managed and allocated based on the Water Plan (Gulf) 2007 [62] overseen by the Department of Regional Development, Manufacturing and Water (RDWM), from here referred to as the Plan. Groundwater in Great Artesian Basin aquifers in the Gilbert catchment are managed based on the Great Artesian Basin and other regional aquifers (GABORA) plan [63]. Groundwater that does not fall under the management of the GABORA is managed by the Plan [Water Plan (Gulf) 2007: Section 11 (2)].

5.2.1 Current Water Licences

Surface Water

Table 7 outlines the entitlements, both allocated and unallocated, in the Plan [64]. The Plan includes the Settlement Creek, Nicholson, Leichardt, Morning Inlet, Flinders, Gilbert, Norman and Staaten catchments (Figure 17). As per Section 8 (1) of the Plan 'Groundwater in an aquifer under a prescribed watercourse, or under land within 1 km of a prescribed watercourse, is declared to be water in the watercourse'. The Gilbert River, the river that runs through the GRAP for this research, is identified as a prescribed watercourse [Section 8 (4)]. This indicates that water in the bed sands of the Gilbert River is classified as surface water, rather than groundwater, and be allocated as such.

Current entitlements in the Gilbert River catchment, as reported in the Minister's Performance Assessment Report (DNRME, 2018a), are outlined in Table 8. The metered usage for the 2016/17 water year is also included in Table 8 to highlight the gap between entitlements and usage. One of the entitlements in the Gilbert catchment is the water licence granted to Etheridge Shire Council (ESC) from the strategic unallocated reserve (DNRME, 2018a). Additional to the entitlements [65] in Table 8, maximum annual volumetric limits are set in specified areas of the catchment (Figure 18, Figure 19, Table 9). For these areas, there are five entitlements actively extracting water from the bed sands (Zones 3, 4 & 5 in Figure 18 and Figure 19), with usage varying between 178 – 2894 ML/year between 2010 – 2017 (DNRME, 2018a). This is below the total volumetric limit for these three zones (5082 ML/year; Table 9).

Table 7 Entitlements per the Water Plan (Gulf) 2007 which encompasses the catchment areas shown in Figure 17.

Water Allocation Type	Volume (ML)
Supplemented Surface Water	75,150
Unsupplemented Surface Water	268,911
Unallocated Surface Water	707,706
Supplemented Groundwater	0
Unsupplemented Groundwater	0
Unallocated Groundwater	0

Table 8 Entitlements in the Gilbert catchment and usage in the 2016/17 water year. Data from DNRME (2018a).

Water Volume (ML)			
Total licence entitlement	Surface water entitlement	Groundwater entitlement	Total usage
39,972	39,959	13	240.54 (2016/17 water year)

[62] https://www.business.qld.gov.au/industries/mining-energy-water/water/catchments-planning/water-plan-areas/gulf, accessed 11 January 2021

[63] https://www.business.qld.gov.au/industries/mining-energy-water/water/catchments-planning/water-plan-areas/gabora, accessed 11 January 2021

[64] https://qgsp.maps.arcgis.com/apps/MapSeries/index.html?appid=610e67fd52e24dbf9168ed812137ff5c, accessed 11 January 2021

[65] Note that the entitlements in Table 8 do change over time

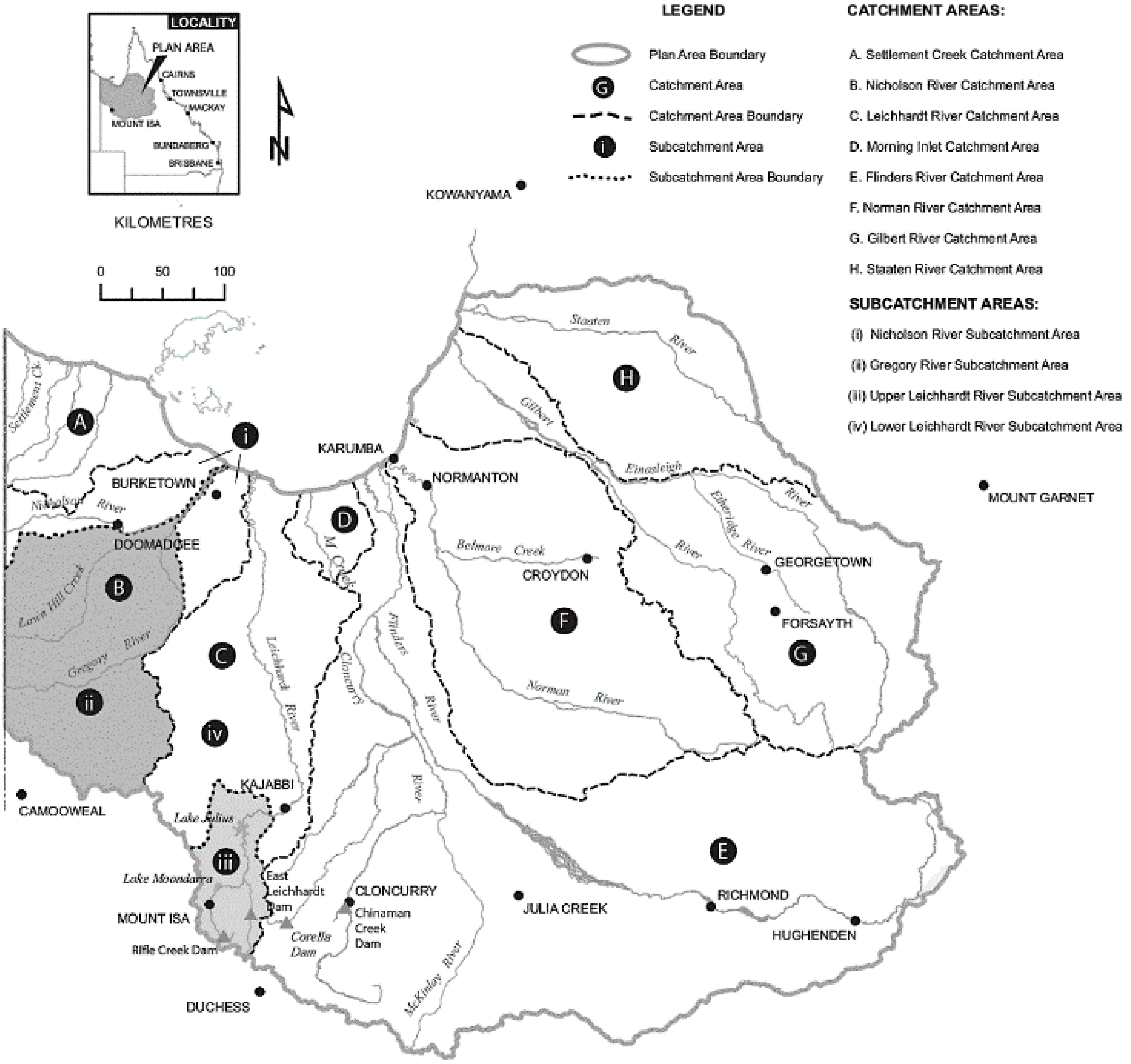

Figure 17 Catchments managed under the Water Plan (Gulf) 2007 (Source: https://www.legislation.qld.gov.au/view/pdf/2017-09-02/sl-2007-0268, accessed 13 January 2021)

Groundwater

Of the 507 registered bores with assigned 'authorised purpose' in the Gilbert catchment only one is authorised to be used for irrigation purposes (Figure 20). The entitlement for this bore is 13 ML per water year (as reflected in Table 8) which is managed under the GABORA water plan rules. This bore is described as being in the Gilbert River Formation. The remaining bores are used for stock and/or domestic supply and therefore do not have associated entitlements. The prevalence of stock and domestic bores throughout the catchment would result in relatively small groundwater use volumes. This is confirmed by the work of Kent et al. (2020) shown in Figure 21.

Map A Gilbert River WMA—zones 3, 4, 5 and 6

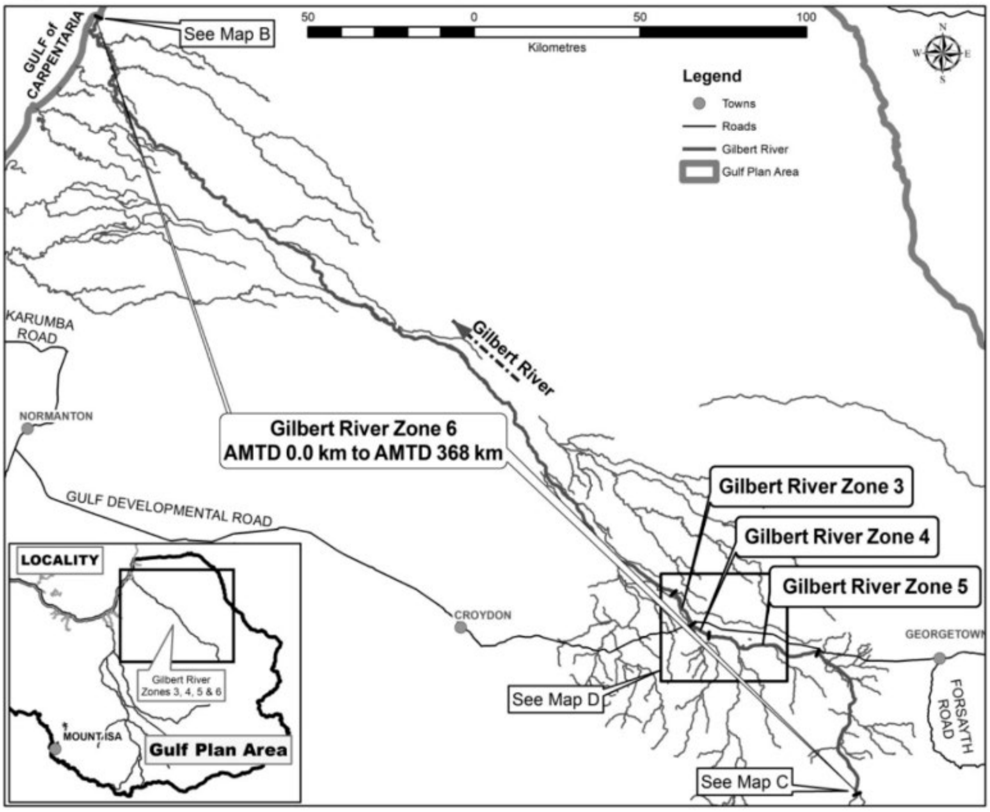

Figure 18 Zones of the Gilbert River (Source: DNRME, 2015).

Map D Gilbert River WMA—zones 3, 4 and 5

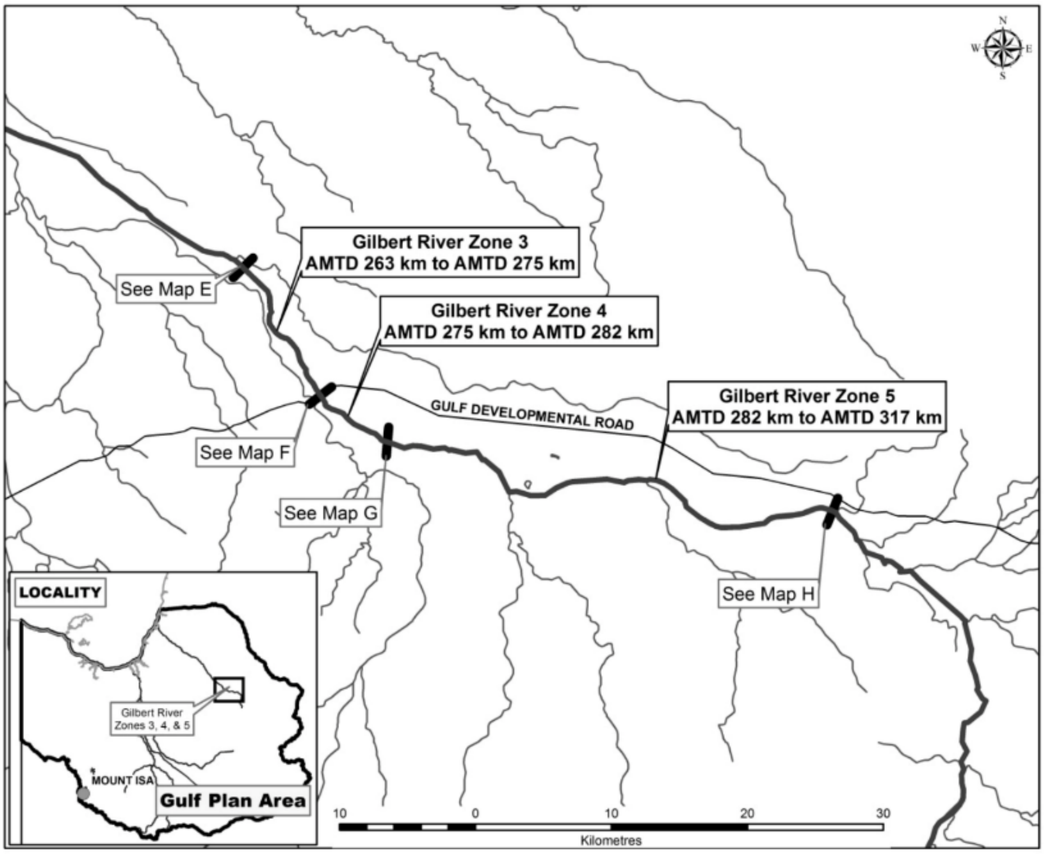

Figure 19 Zones 3, 4 and 5 of the Gilbert River (DNRME, 2015).

Table 9 Maximum annual volumetric limit (ML/year) for each zone of the Gilbert River. Adopted from: Table 6A in Gulf Resource Operations Plan June 2010 Amendment August 2015 (DNRME, 2015).

Maximum annual volumetric limit (ML/year)			
Zone 3	Zone 4	Zone 5	Zone 6
1800	600	2,682	25,242

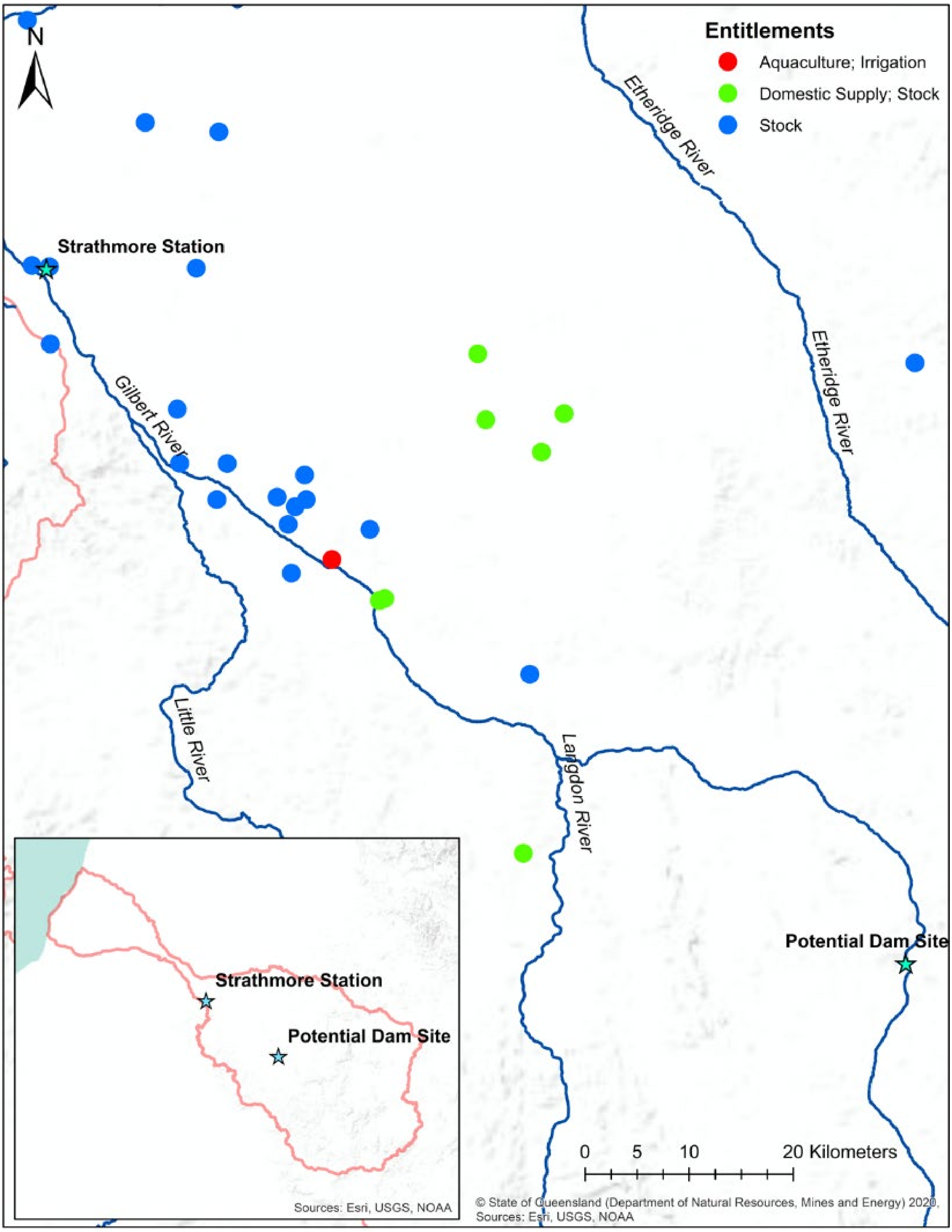

Figure 20 Authorised purpose of bores in the GRAP

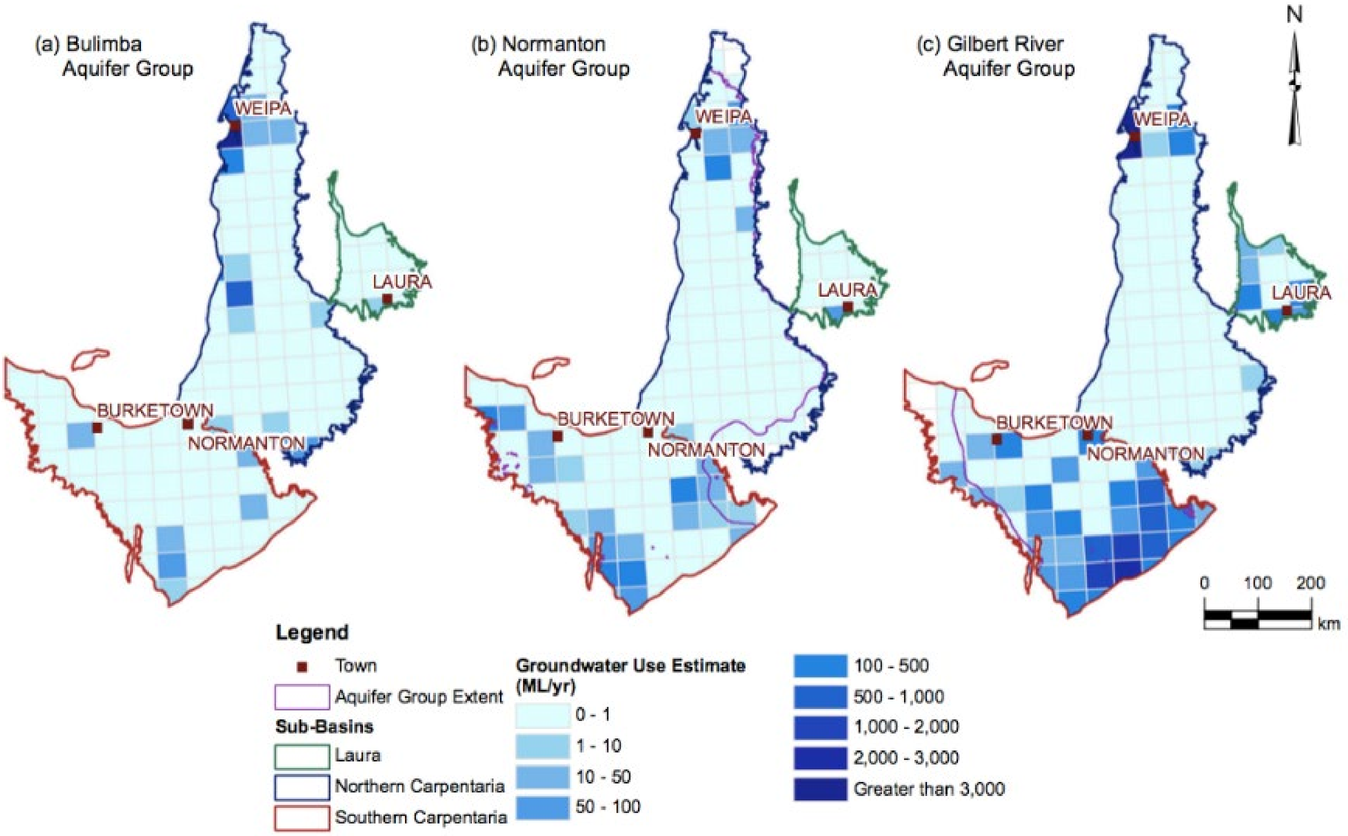

Figure 21 Estimated groundwater use in 2015 across GAB aquifer groups (Source: Kent et al., 2020)

5.2.2 Farm Scale to Support Irrigated Agriculture

The types of unallocated water for the Gilbert catchment are outlined in Section 5.2. Under the Gulf Water Plan there are currently unallocated entitlements aimed at individual properties that total 85 GL per year [66]. These entitlements were last updated 29 June 2020. Table 10 provides outlines the details of the entitlements and Figure 22 displays the zones of allocations. Figure 23 and Figure 24 show when flow conditions are met based on discharge data from the last three years.

The release of these entitlements for individual properties is aimed at landholders either entering into or expanding existing irrigation activity [67]. It is hoped that this will support economic growth, business diversification and sustainable agriculture in the region. It is envisaged that irrigated agriculture projects will begin or expand soon after securing water. This is reflected in one of the license conditions which requires infrastructure capable of taking at least 50% of the yearly entitlement to be installed within 3 years of issue. The individual and total allocated volumes have been selected as a way to ensure rapid assessment of an application while reflecting demand and development needs. Also considered is the need to retain water for large scale water infrastructure proposals/developments.

The available entitlements also consider any impacts on existing entitlements and the environment [68,69]. The annual volumes and rate of take limits listed in Table 10 are intended to ensure that the reliability of

[66] https://www.business.qld.gov.au/industries/mining-energy-water/water/catchments-planning/unallocated-water/gulf, accessed 15 August 2020
[67] https://www.business.qld.gov.au/industries/mining-energy-water/water/catchments-planning/unallocated-water/gulf, accessed 15 August 2020
[68] https://www.business.qld.gov.au/industries/mining-energy-water/water/catchments-planning/unallocated-water/gulf, accessed 15 August 2020
[69] Other impacts of proposed development, such as those on cultural heritage sites and vegetation management constraints is considered when the entitlement application is assessed.

existing entitlements are not compromised. The flow conditions outlined in Table 11 have been put in place to ensure that ecosystems dependent on peak flows (e.g., waterholes, floodplains, estuaries) still receive the flow they require. For example, in the lower section of the catchment (Zone 6 (0 km – 171 km AMTD) in Figure 22) water can only be extracted when flow is in excess of 15,100 ML per day (Table 10, Figure 23). On average, since 1967, such conditions have been met 15 days a year (Jacobs Australia Pty Limited., 2020). Two payment options are available for these farm scale entitlements (Table 11).

Table 10 Release of unallocated water in the Gilbert Catchment (Source: https://www.rdmw.qld.gov.au/__data/assets/pdf_file/0007/1486600/gulf-water-release-terms.pdf, accessed 29 November 2021)

Location (see Figure 22)	Annual volume available (ML/year)	Rate of take (ML/Day)	Water source options	Volumetric limit	Conditions (see Figure 23 & Figure 24)
Zone 6 0 km – 171 km AMTD	Up to 75,000	5% of annual volume	Watercourse only Watercourse and overland flow combined	Up to 25,000 ML per property	Taking water will be permitted when the flow in the Gilbert River at Burke Development Road exceeds 15,100 ML per day
Unzoned or Zone 6 171 km – 368 km AMTD	Up to 10,000	10% of annual volume	Watercourse only Watercourse and overland flow combined Overland flow only	Up to 2,000 ML per property	Taking water will be permitted when the flow in the Gilbert River at Rockfields exceeds 2,592 ML per day

Table 11 Cost of unallocated entitlements (Source: https://www.business.qld.gov.au/industries/mining-energy-water/water/catchments-planning/unallocated-water/gulf)

Option	Cost
Full Value Amount	$125.00 per ML upfront
Annual Installment Amount	$13.00 per ML per annum for 10 years (includes prorated CPI and administration charges)

5.2.3 Catchment Scale to Support Water Infrastructure

As part of the Gulf Water Plan, there is additional general unallocated water beyond the farm scale unallocated entitlements. The total unallocated volume is 467,000 ML (section 39 and schedule 8) [70]; outlined in Table 12. Jacobs Australia Pty Limited. (2020) noted the potential for up to 200,000 ML of entitlements to be issued for the support of water infrastructure.

In line with the conditions outline above, the maintenance of environmental flows is a requirement of the Gulf Water Plan, so any larger entitlements would be required to abide by the Plan. For example, the proposed Gilbert River Irrigation Project dam would need to be able to release up to 136,830 ML per day to meet the Gulf Water Plan’s environmental flow objectives (Jacobs Australia Pty Limited., 2020).

Table 12 Unallocated water available in the Gilbert Catchment based on the Water Plan (Gulf) 2007 [reprinted in September 2017]

Unallocated Water in the Gilbert Catchment	Volume (ML)
Indigenous[a]	17,500
State Purpose[b]	5,000
General[c]	467,000

[a] may be granted only for helping indigenous communities achieve their economic and social aspirations
[b] may be granted to a coordinated project (see https://www.statedevelopment.qld.gov.au/coordinator-general/assessments-and-approvals/coordinated-projects), a project of regional significance (see Section 27 of Water Plan (Gulf) 2007) or town water supply
[c] may be granted for any purpose

[70] https://www.legislation.qld.gov.au/view/html/compare/2016-12-06/2017-09-02/sl-2007-0268, accessed 30 April 2020

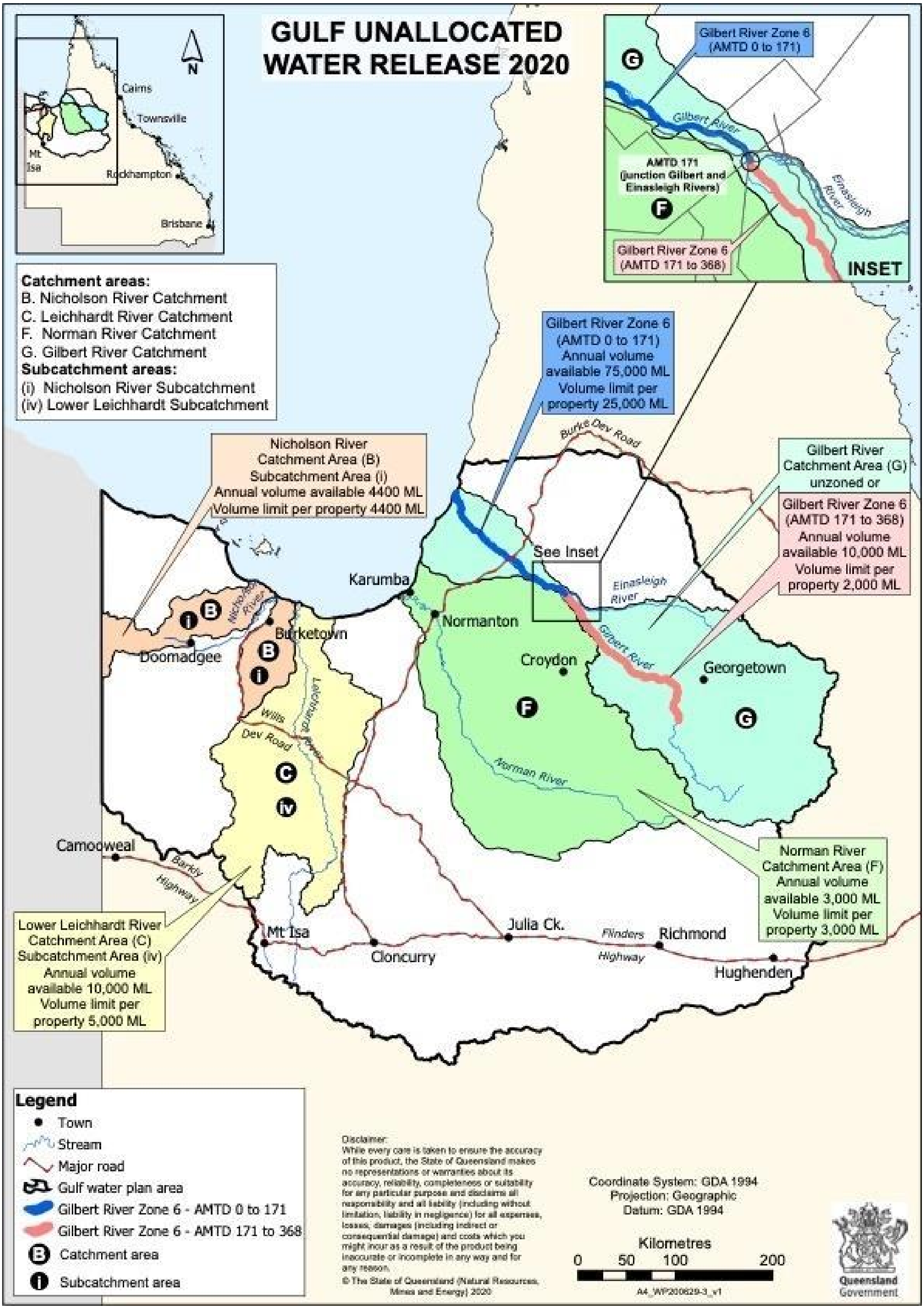

Figure 22 Zones for unallocated water in the Gilbert catchment, as defined by the Gulf Water Plan (Source: https://www.business.qld.gov.au/industries/mining-energy-water/water/catchments-planning/unallocated-water/gulf, accessed 23 April 2021)

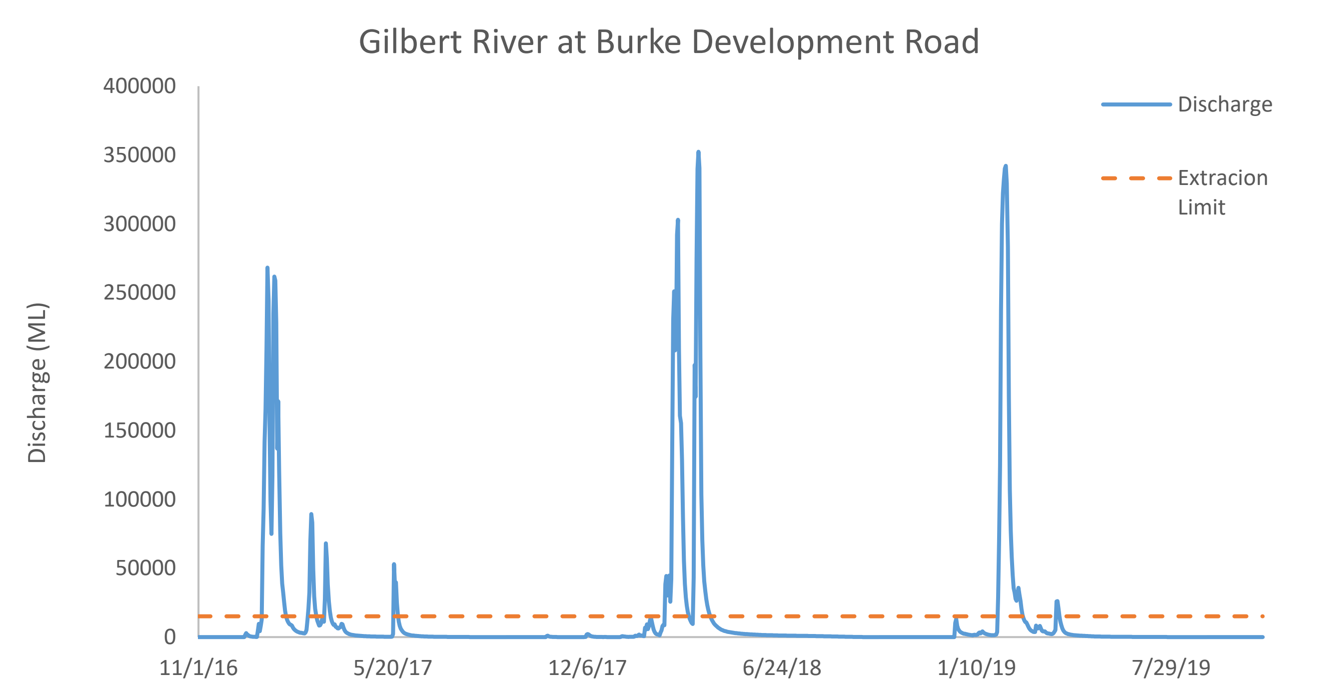

Figure 23 Discharge of Gilbert River at Burke Development Road, showing when flow condition for extraction are met (Extraction Limit)

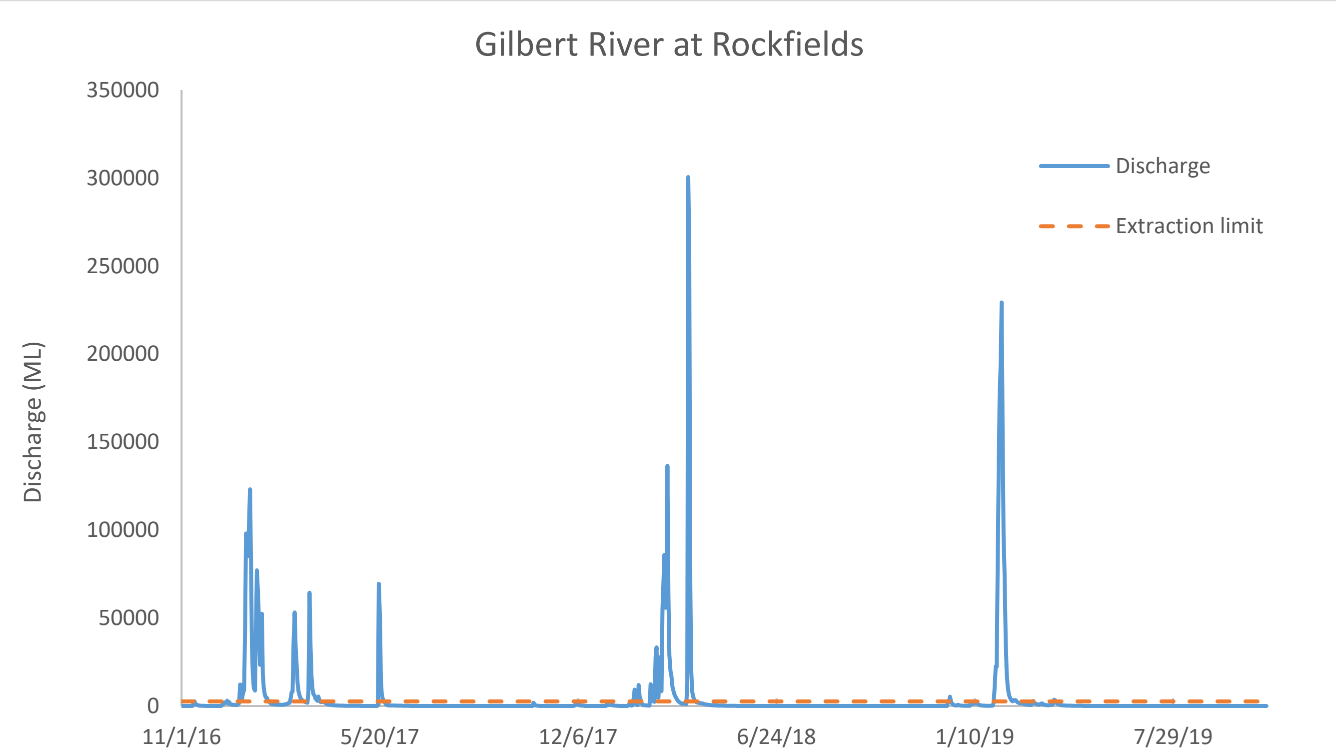

Figure 24 Discharge of Gilbert River at Rockfields, showing when flow condition for extraction are met (Extraction Limit)

5.3 Technical feasibility

The seasonality and large evaporative losses highlighted in Section 5.1 raise the possibility that dams and other irrigation infrastructure may not be well suited and result in large losses (Lennon et al., 2014). Alternative water management techniques, including conjunctive surface and groundwater use and MAR, have been suggested as possible methods to meet demand during the dry season (Lennon et al., 2014).

This section is structured to provide information of aquifer and soil characteristics (Section 5.3.1 and Section 5.3.2) and then to inform the design, planning and implementation of MAR strategies (Sections

5.3.3, 5.3.4, 5.3.5, 5.3.6, and 5.3.7). Conjunctive water management, which MAR can be part of, is potentially simpler in less developed agricultural areas compared to regions with already developed surface water infrastructure (CSIRO, 2009).

The following subsections present information on both the catchment scale and the area encompassing the GRAP.

5.3.1 How much water can be recharged or extracted?

Aquifer characteristics across the Gilbert catchment

Alluvial Sediments: Unconsolidated alluvial sediments overlay the deeper groundwater system throughout the Gilbert catchment, especially in current and old riverbeds (e.g. Gilbert River bed sands) (Petheram et al., 2013). It is possible for local groundwater systems to form in these sediments (Petheram et al., 2013). The Gilbert River bed sands have been developed for local agriculture and therefore are the most characterised of the alluvial aquifers.

The Gilbert River bed sands have an estimated total saturated volume of 17 – 20 GL and good water quality (Petheram et al., 2013, Department of Natural Resources, 1998). Other areas of alluvial sediments (e.g., Einasleigh Common) in the Gilbert catchment are associated with poor water quality and high salinity (Petheram et al., 2013).

Great Artesian Basin (GAB): A portion of the Gilbert catchment is located within the Great Artesian Basin (GAB) groundwater system (Figure 25). The GAB sub-basin that part of the Gilbert River is located within is the regional scale groundwater system known as the Carpentaria Basin (Petheram et al., 2013). The Carpentaria Basin is comprised of a series of aquifers and aquitards (sedimentary rock formations), characterised by large distances between recharge and discharge zones (hundreds of kilometers or more) and residence times of the order of centuries (Petheram et al., 2013). Aquifers and aquitards within the Carpentaria Basin include the Gilbert River Formation and Eulo Queen Group, overlain by the Rolling Down Group (Figure 27, Figure 28) (Petheram et al., 2013). Many of the formation have direct connectivity, for example, the Bulimba Formation exhibits connectivity to both the Normanton and Gilbert River Formations (Figure 28) (Radke and Ransley, 2020). Recharge occurs where these aquifers outcrop (Figure 29). Where no outcropping occurs, the recharge is estimated to be low (< 5 mm/year) (Petheram et al., 2013), however precise recharge volumes are unknown (Jolly et al., 2013). However, it has been suggested that the bed sands are not connected to underlying aquifers (DNRME, 2006b, DNRME, 2018b).

Yields from GAB formations are often too low to support irrigated agriculture (Figure 30). Vanderzalm et al. (2018) found similar yields from rock aquifers in the neighboring Mitchell catchment. There are two monitoring bores in the GAB aquifers in the Gilbert catchment. Bore levels and rainfall are shown in Figure 31 and Figure 32.

Other Aquifers: In areas not included in the GAB, basalt aquifers associated with the Chudleigh and McBride Provinces dominate (Figure 26). These are fractured rock formations with notable groundwater supplies, that is likely to discharge into adjacent waterholes.

Underlying Aquifers: Based on the work of Radke and Ransley (2020), there is minimal connectivity between the GAB aquifers in the Gilbert catchment and the underlying basins (Figure 33).

Groundwater Salinity: Groundwater salinity varies across the Gilbert catchment (Jolly et al., 2013, Petheram et al., 2013) (Figure 29). The central and southern part of the catchment, associated with Gilbert River alluvium and GAB recharge beds, display fresher groundwater, while the regolith and coastal aquifers are more saline. The Einasleigh Metamorphics and McBride basalt west of Einasleigh are also more saline then elsewhere in the catchment. Due to the high permeability of the alluvial sediments adjacent to the

Gilbert River, an increase in irrigation there would be unlikely to result in large water table rises and salinity issues (Jolly et al., 2013).

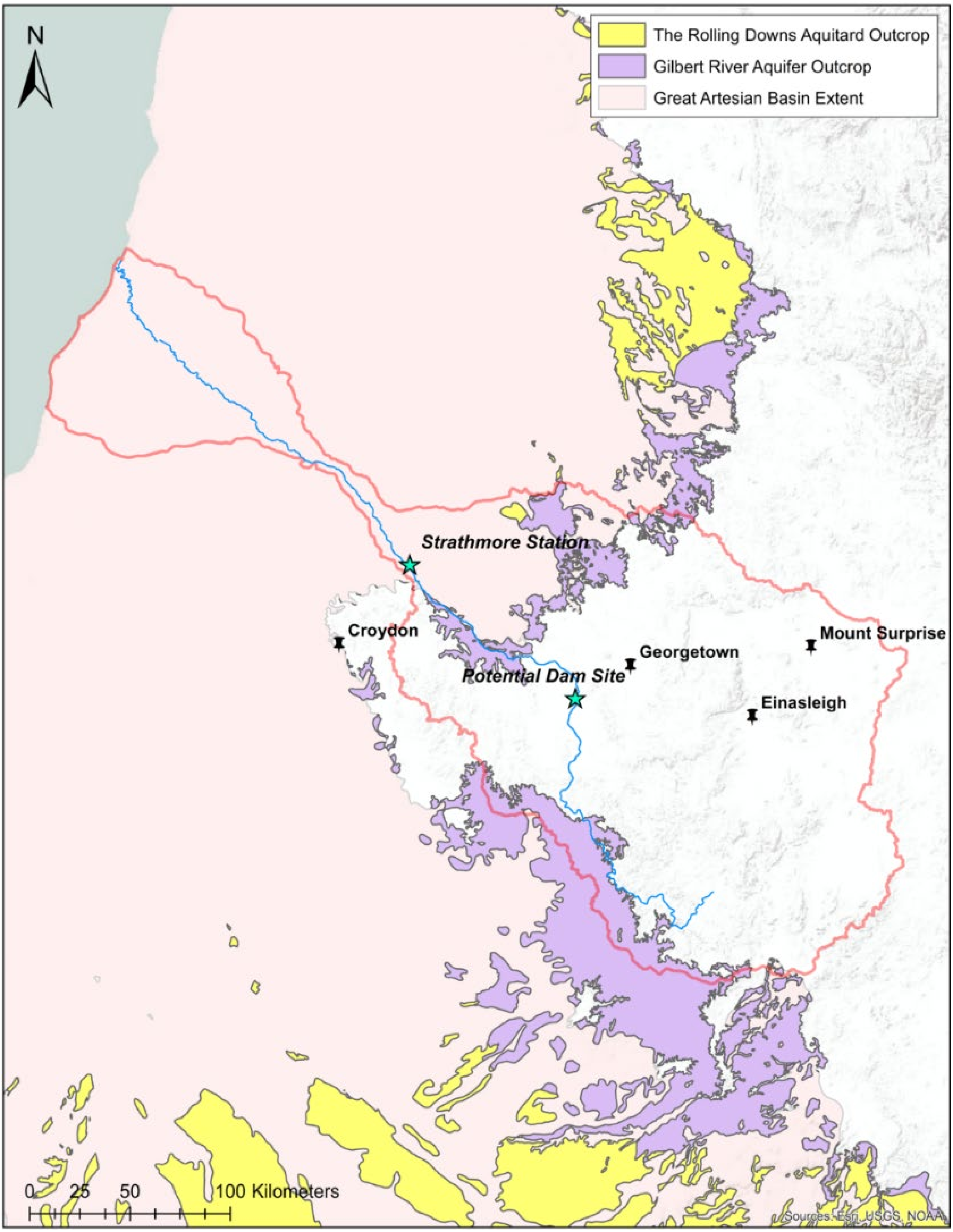

Figure 25 The extent of the Great Artesian Basin (GAB) in the Gilbert catchment, with outcropping aquifer layers shown. The Gilbert River is also shown. Data from Geoscience Australia [71,72,73].

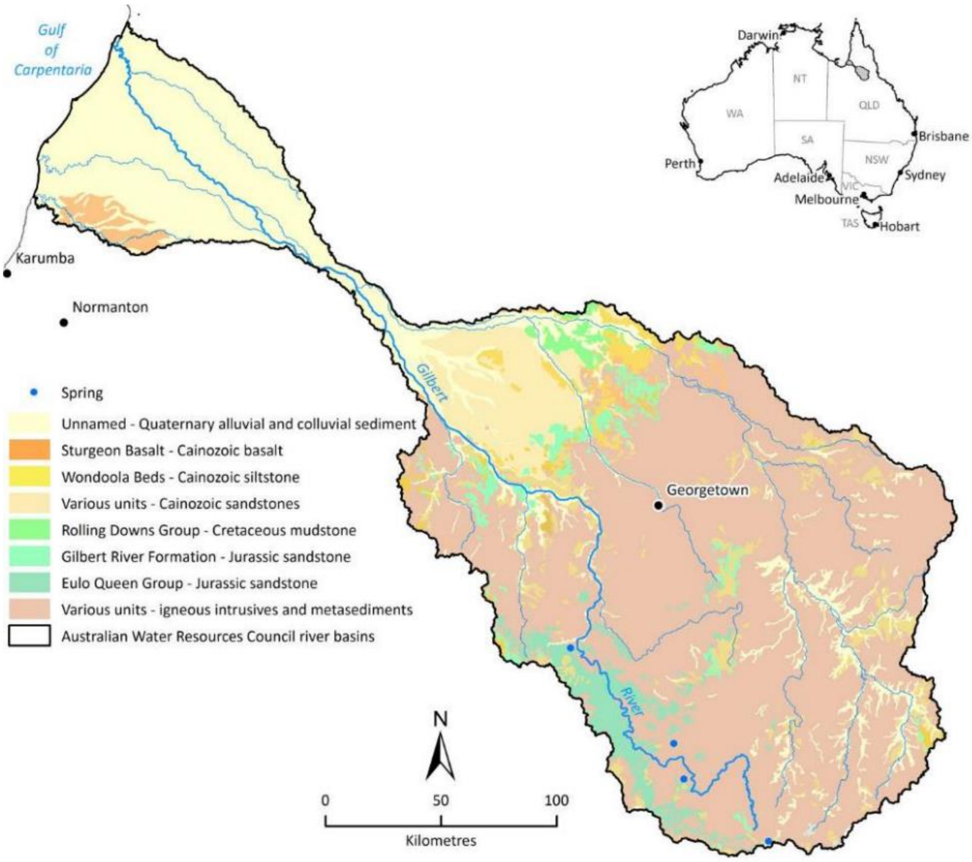

Figure 26 Major aquifers of the Gilbert catchment (Source: Petheram et al., 2013).

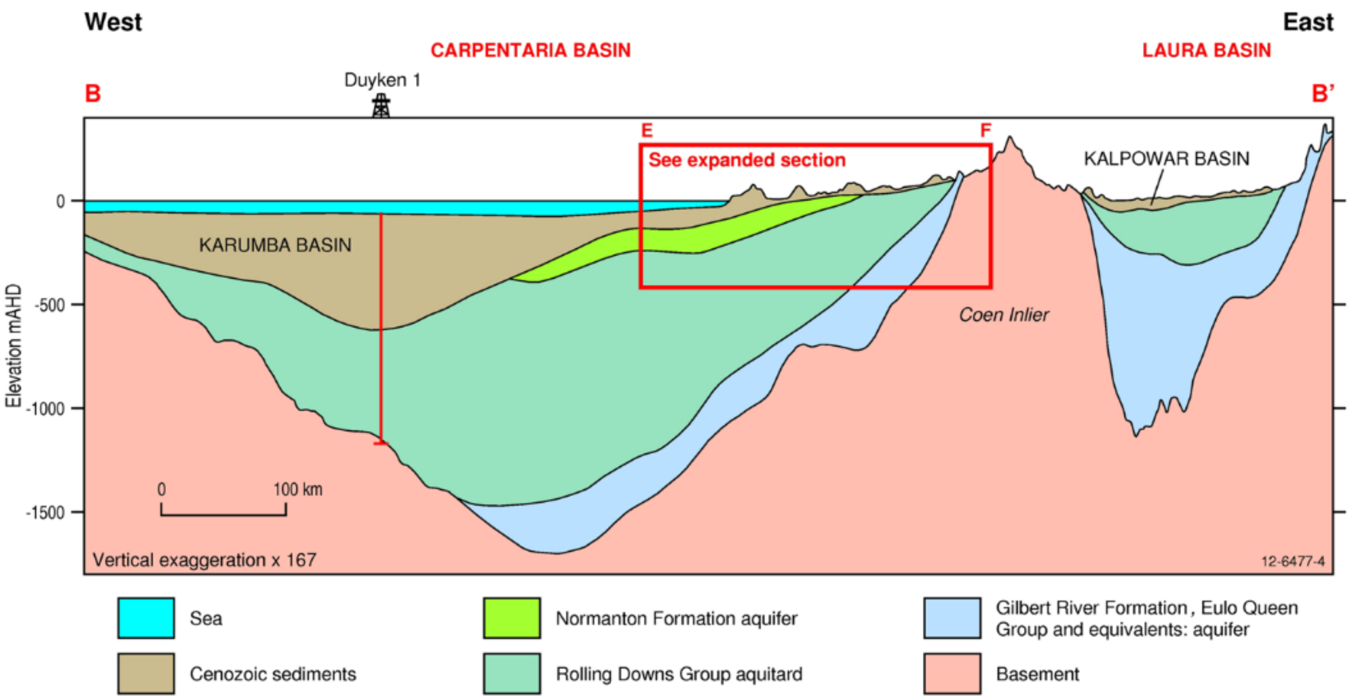

Figure 27 West-east section contrasting basin architecture, structure and aquifer configurations between the Carpentaria-Karumba and Laura-Kalpowar basins (Source: Smerdon et al., 2012). For expanded section E–F refer to Figure 18.

71 http://pid.geoscience.gov.au/dataset/ga/81672, accessed 1st November 2020
72 http://pid.geoscience.gov.au/dataset/ga/81677, accessed 1st November 2020
73 http://pid.geoscience.gov.au/dataset/ga/81678, accessed 1st November 2020

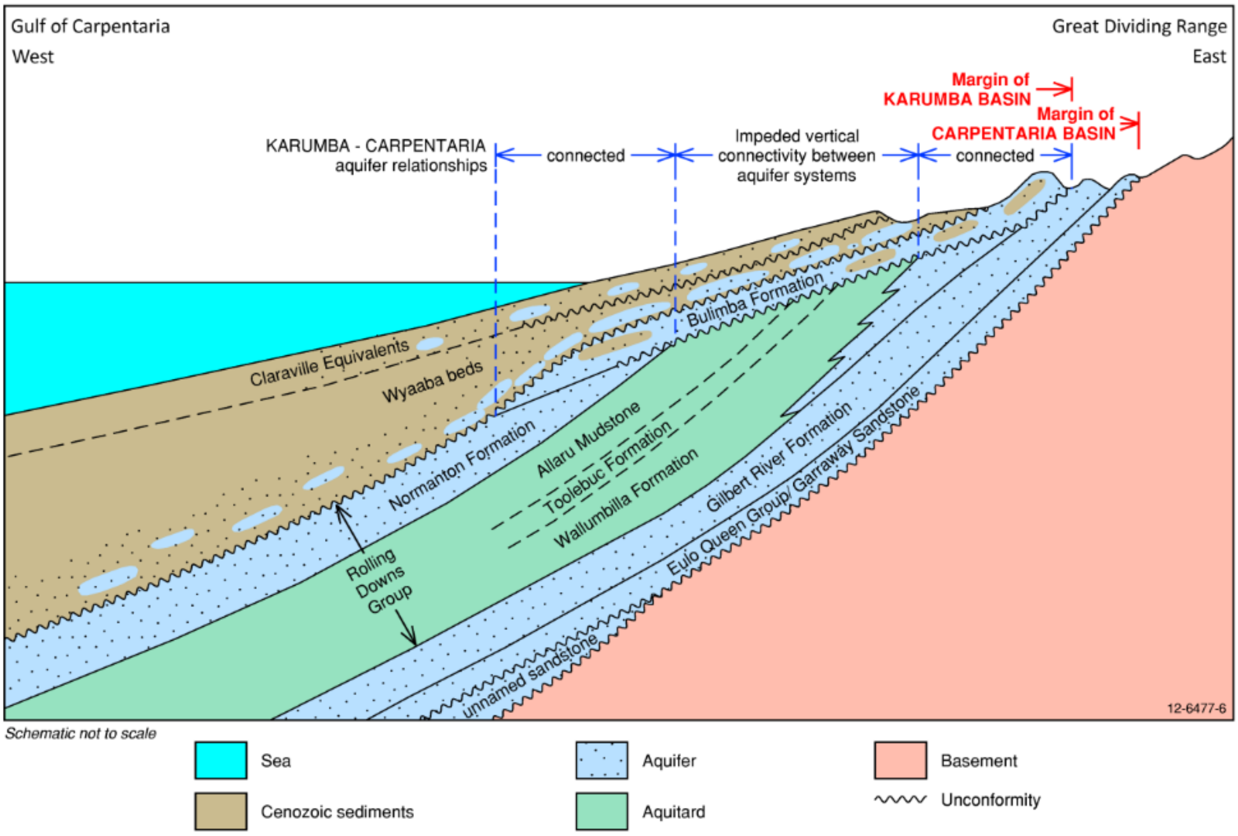

Figure 28 Cross-section highlighting the connectivity between aquifers of the Carpentaria and Karumba basins of the Great Artesian Basin (Source: Smerdon et al., 2012)

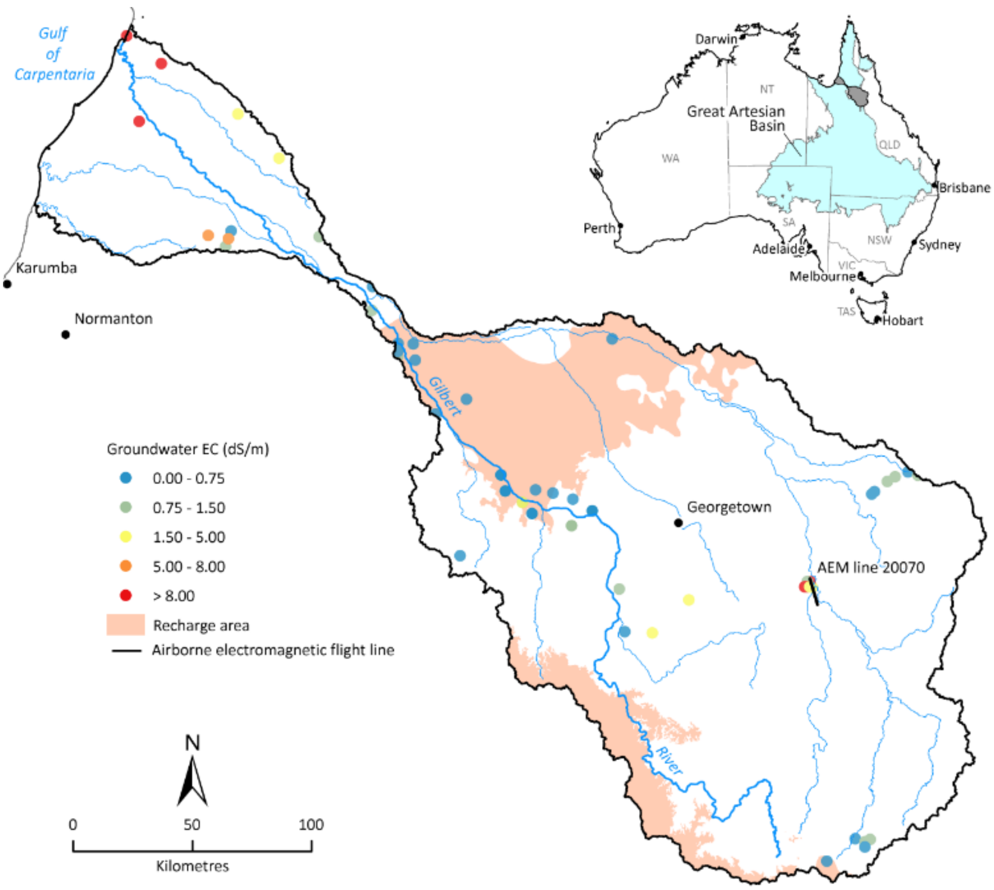

Figure 29 Groundwater salinity in the Gilbert catchment with the recharge area of the Great Artesian shown (Source: Petheram et al., 2013).

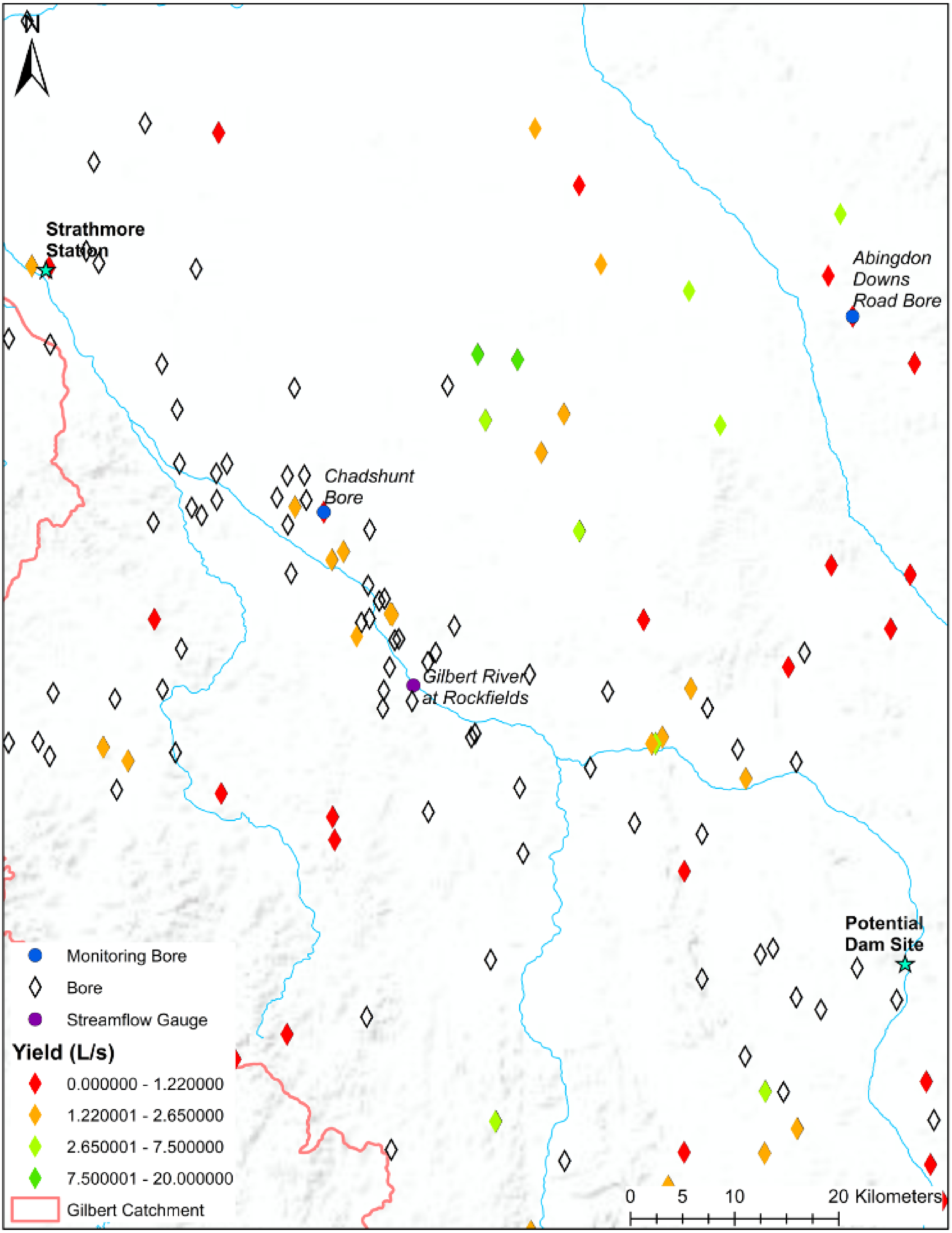

Figure 30 Bores in the GRAP, with associated yield data where available.

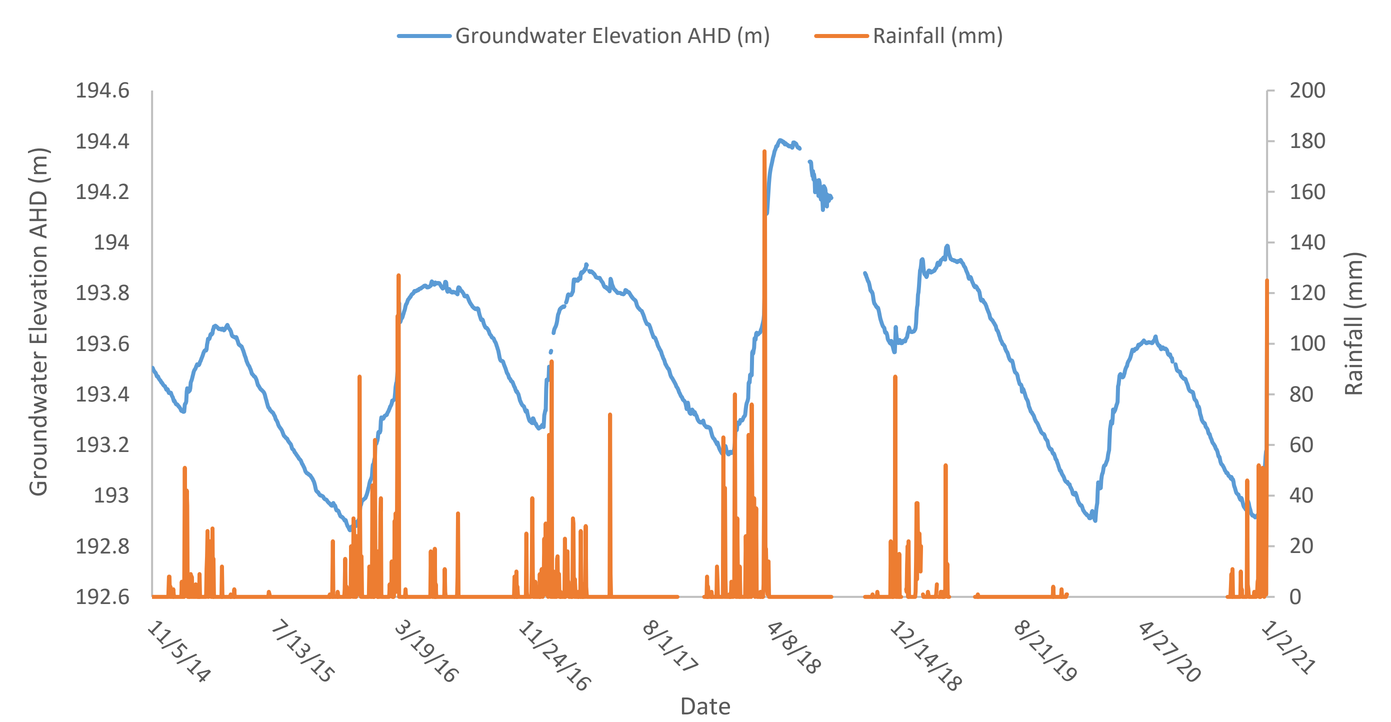

Figure 31 Mean daily groundwater elevation above Australian Height datum (AHD) (meters) at Abingdon Downs Road Bore (91710019). Data source: https://water-monitoring.information.qld.gov.au/

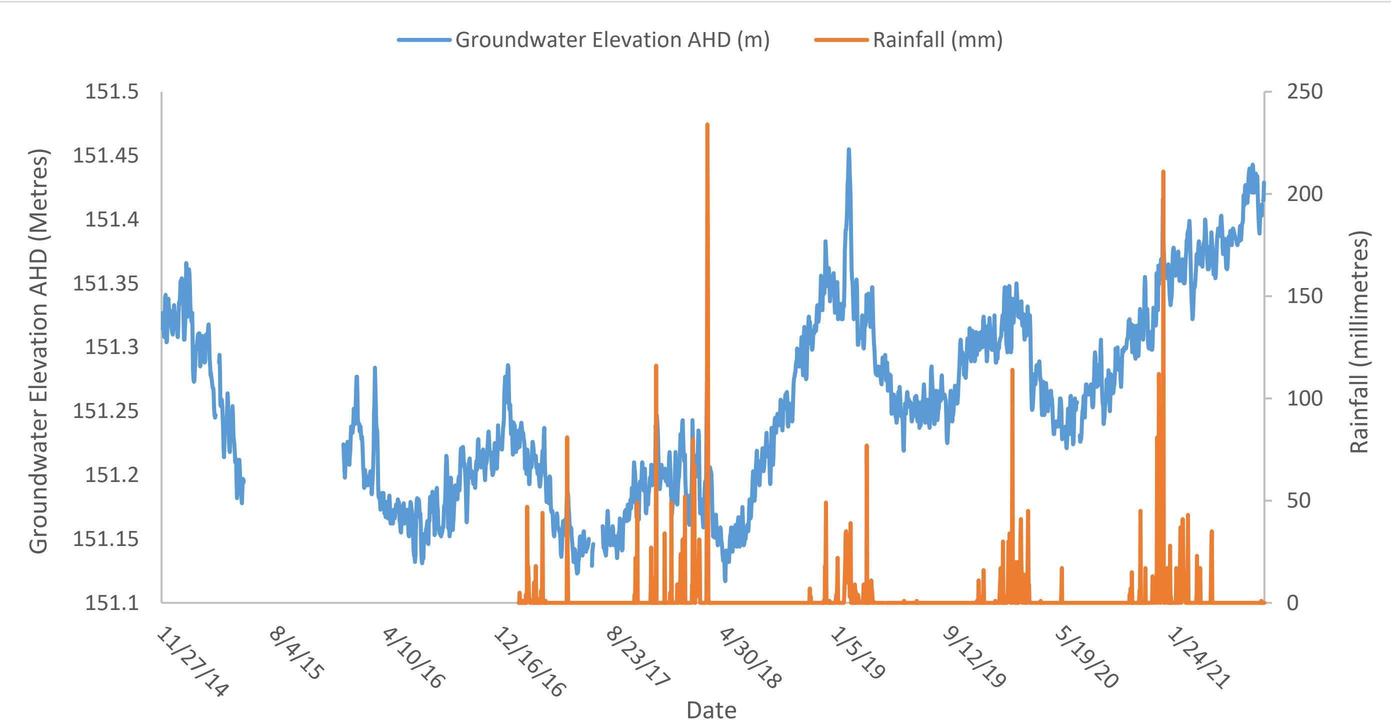

Figure 32 Mean daily groundwater elevation above Australian Height datum (AHD) (meters) at Chadshunt Bore (91700015). Note: Rainfall data is unavailable before 30/01/2017. Data source: https://water-monitoring.information.qld.gov.au/

Focus aquifer in the GRAP

The focus aquifer for this study is the alluvial aquifer (bed sands) of the middle reaches of the Gilbert River. The aquifer occupies a U-shaped valley over 50 km in length and 400 m wide (DNRME, 2006b). Aquifer material in this reach is comprised of moderately to poorly sorted sand and gravel (Department of Natural Resources, 1998), to depths ranging between 1 and 15 m (DNRME, 2006b). The (conservatively) estimated volume of the aquifer is 67,909,000 m^3 (Department of Natural Resources, 1998). Expected porosity is between 25 – 30% (Department of Natural Resources, 1998). Permeability of the bed sands has been estimated to be up to 700 mm/day and measured at 255 mm/day (DNRME, 2006b). Based on particle size distribution analysis, permeability of the aquifer is between 10 m/day (1000 mm/day) to 690 m/day (690000 mm/day) (Jolly et al., 2013), substantially greater than the above estimates. The lower permeability is due to underlying sediments that have increased clay content or are sandstone (DNRME, 2006b). Characterisation of this bed sands would show if this lower permeability was widespread (i.e., a layer resulting from sedimentation sequences) or localised. Based on a pumping test, vertical transmissivity was 237 m^2/day, horizontal transmissivity was 4743 m^2/day and specific yield was 0.168 (Jolly et al., 2013).

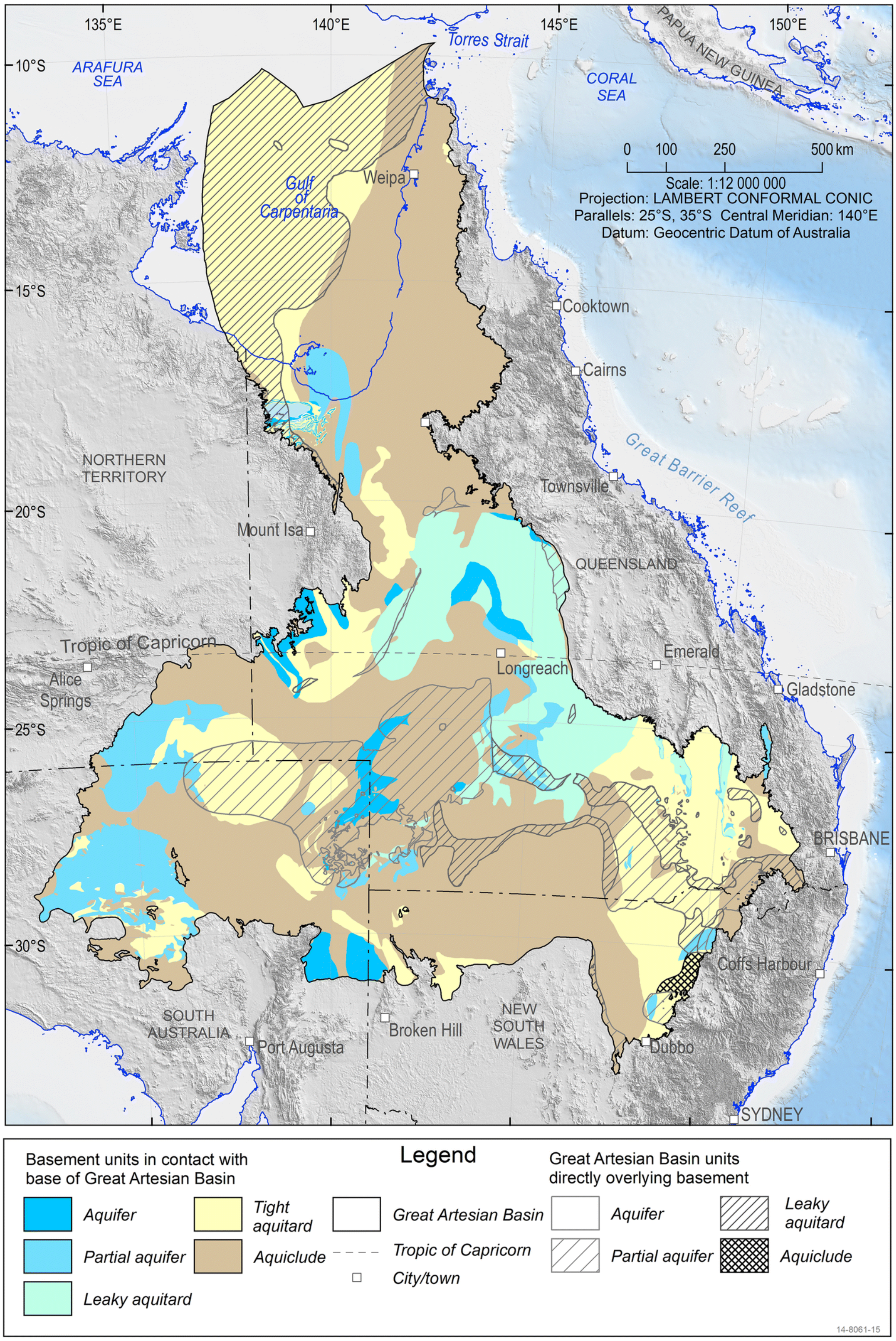

Figure 33 Inferred hydraulic connectivity across the base of the Great Artesian Basin (Source: Radke and Ransley, 2020)

The primary recharge mechanisms for this aquifer are rainfall and streamflow (DNRME, 2006b). There is very little connectivity between the underlying rock aquifers and the bed sands (DNRME, 2006b, DNRME, 2018b). However, the contribution, if any, of old water sources to flows in the bed sands is not known with certainty (DNRME, 2006a). To move forward with bed sand development (MAR or otherwise) it would be advisable to further investigate whether changes to bed sand dynamics would have consequences for underlying and surrounding aquifers. On a catchment scale, groundwater discharge constitutes a small proportion of overall streamflow (Petheram et al., 2013).

There are distinct geological features scattered throughout the bed sands (Department of Natural Resources, 1998), for example, rock bars (DNRME, 2006b). These are presumed to act as physical barriers to groundwater flow through the bed sands, decreasing hydraulic connectivity (DNRME, 2006b), particularly as the dry season progresses (Department of Natural Resources, 1998). This could cause the formation of discrete subsurface pools within the bed sands (Department of Natural Resources, 1998). Groundwater from the bed sands is low salinity and otherwise of good quality (DNRME, 2006b).

An exploratory drilling program in the area of interest, aiming to quantify the water resources in the Gilbert River bed sands (Department of Natural Resources, 1998), focused on a region of the Gilbert deemed to have potentially arable soils; the 59 km length of river between 'Prestwood' and 'Chadshunt' stations (Figure 34). This is roughly the area targeted by the proposed Gilbert River Irrigation Project (Jacobs Australia Pty Limited., 2020) and, consequently, the focus area of the scenarios described in Section 4. Water is being drawn from the Gilbert River bed sands currently, using shallow interception galleries, sand-spears and gravel-packed bore-holes.

Bore holes were drilled across the riverbed at multiple locations in the study area to determine the depth and composition of the bed material to assess its potential as a groundwater aquifer. The drilling occurred in the active river channel after surface flow ceased. Results are summarised by location in Table 13. It was estimated that the bed sands in this area contained between 16,980 ML to 20,370 ML of water (Department of Natural Resources, 1998). From this estimate it was recommended that water licences for irrigation should consider that the bed sands would store a volume of 18,000 ML when surface flow ceases. This drilling survey did not extend very far from the riverbed, making these estimates conservative as the alluvial aquifer may extend onto the adjacent floodplain (Jolly et al., 2013).

It is common for unconfined aquifers in North Queensland to fill to full capacity during the wet season and drain in the dry season (Knapton et al., 2019). Specifics on this process in the Gilbert River bed sands is unknown.

5.3.2 Soils

Soils suitable for MAR

Soil type can be a limiting factor when assessing the plausibility of infiltration-based MAR schemes. It is common for infiltration basins to be located on soils with sandy textures (Beganskas and Fisher, 2017, Smith and Pollock, 2012) to maximise permeability and take advantage of high infiltration rates (Rahman et al., 2012, Russo et al., 2015). This would facilitate the quick infiltration of recharge water. The quick recharge of water is especially important in the Gilbert due to the seasonality of streamflow (i.e. source water), where water availability is temporally limited.

MAR schemes that utilise injection are less dependent on soil type. The characteristics of the target aquifer are instead more important, and can be limiting (Yuan et al., 2016). Confined or semi-confined aquifers are generally more suitable for direct injection wells (Yuan et al., 2016), whereas unconfined aquifers are generally better suited to infiltration basins.

In the Gilbert catchment, where there is an absence of already established water delivery infrastructure, there is added importance of operating a MAR scheme near agriculturally suitable soils in order to minimise capital costs. Therefore, it is important look for areas that could both support an expansion into irrigated agriculture and support an associated MAR scheme.

Table 13 Results of the Gilbert River Bed sand Investigation Exploratory Drilling Programme, as summarised from Department of Natural Resources (1998).

Location	Description	Interpretation
Prestwood	Low flow channel Total width of river bed ~325 m	Depth of aquifer material below the normal water table level is minimal
Riverview	River has a broad, fairly uniform sandy bed with a narrow low-flow channel Granite outcrops Total width of riverbed ~ 325 m Standing water level of about 2m below natural surface	Sand/gravel to 3.3 – 13.5 m, then clayed sand/gravel (to about 15 m), then dense gravelly clay (15.3 – 22.5 m)
Blancourt	River is fairly narrow low-flow channel about 100 m wide Free water was evident at the lowest point of the river bed	Depth of clean sand/gravel from 4.5 m – 6 m, underlain by clayed sand/gravel, bottom out in dense cemented clayey gravel between 15 – 25 m Saturated sand/gravel appears to extend beneath both river banks beyond the limits of the section drilled
Forest Home	River is broad near level channel almost 300 m wide Free water was evident at the lowest point of the river bed	Clean sand/gravel ranged from 1.3 – 7.5 m, underlain by clayed sand/gravel, to bottom out in dense silt or clay between 12 m – 22.5 m
Rockyview	River is narrow, about 80 m wide Out crops of sandstone and siltstone Free water was evident in a water hole adjacent to the lowest point	Depth of clean sand/gravel ranged from 1m – 6.9 m in the centre of the channel, underlain by clayed sand and gravel, bottom out in samdstone between 1 – 7.3 m Suggestion that saturated sand and gravel may extend beneath the right bank beyond the limits drilled Aquifer material below the normal water table is minimal
Gilbert Bridge	River at this location has a broad channel (190 m wide); total width of river bed ~ 192 m Exposed sandstone out crops Free water was evident in the low-flow channels	Clean sand/gravel was encountered in the bed (up to 12 m), underlain by clayed sand/gravel and cemented granite sands
Neem Trees	Three channels Free water was evident in a small channel at the lowest point of the river bed	Depth of clean sand/gravel ranged from 2 – 6.6 m, underlain by clayed sand and gravel, bottom out in hard rock (generally granite) between 8 – 25.3 m
Godfrey's	Standing water level was approximately 0.8 m below the bed	Depth of clean sand/gravel ranged from 3.6 – 7 m There was also clayed sand/gravel over dense mottled clay

Soil characteristics of the Gilbert

Figure 8 (in Section 3.1) showed the multiple soil types in the Gilbert catchment (Petheram et al., 2013). The spatial distribution of both soil texture and permeability are provided in Figure 35 and Figure 36. The proportion of the soil groups in the catchment and management consideration for irrigated agriculture and MAR are outlined in Table 14. It has been suggested that the deep alluvial soils on the catchment's two major rivers, Gilbert and Etheridge, upstream of their confluence, are most suitable for irrigated agriculture (Petheram et al., 2013).

Soil characteristics of the GRAP

The soil properties of the GRAP are shown in Figure 37 to Figure 41. The region between the Gilbert and Etheridge Rivers is characterised by soils with a sandy texture class and low clay percentage (Figure 37, Figure 38). This results in moderate to high soil permeability (Figure 39).

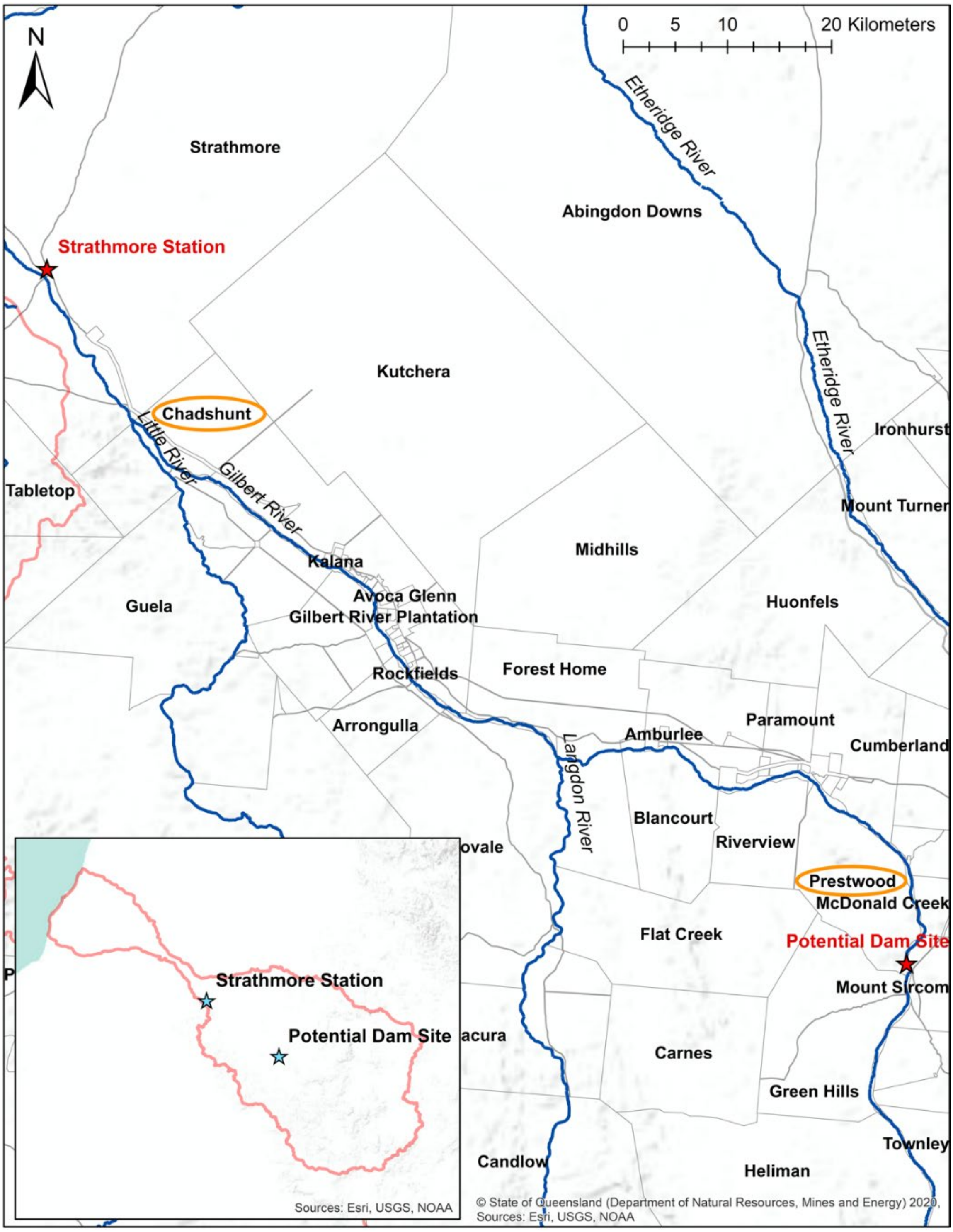

Figure 34 The area that the exploratory drilling program surveyed, with approximate start and finish points along the Gilbert River circled.

Land suitability

A land suitability assessment for a variety of crops and irrigation types as part of the FGARA report series (Bartley et al., 2013f). Furrow and spray wet season cotton were assessed (Figure 42), where irrigation would supplement rainfall.

The assessment was based largely on soil attributes and also incorporated climate and local landscape characteristics. Social, economic, flooding and salinity information was not included in the assessment. Land suitability was indicated by class (1 – 5), with the most limiting suitability subclass determining the final land suitability class in a particular area.

In the Gilbert catchment, less than 1% of the land was classified as highly suitable or suitable with minor limitations for cotton, under either furrow or spray irrigation (Bartley et al., 2013f). The main limitations that reduced the suitability for cotton in the region were rockiness, slope and the resulting possibility of erosion, and limited soil moisture capacity in areas with shallow/light textured soils. Spray irrigation was reported as more moderately suitable then furrow irrigation based on area, 43% and 19%, respectively (Bartley et al., 2013f). Permeability was raised as an issue for furrow irrigations systems, with sandy, free draining soils requiring more frequent irrigation with greater water usage (Bartley et al., 2013f). This would put pressure on the already surface water limited environment (Petheram et al., 2013).

Table 14 The soil groups (grouped by soil generic group (SGG)), occurrence throughout the catchment and management consideration for irrigated agriculture and MAR. Data (with the exception of the management considerations) from Petheram et al. (2013).

Soil Group	Description	Associated Landforms	Occurrence	Irrigated Agriculture and MAR Management Considerations
Sand or loam over friable or earth clay	- associated with less resistant igneous/metamorphic geologies - 0.5 – 1.5+ m in depth	- gentle slopes - alluvial plains	27%	- potentially suitable for agriculture
Friable non-cracking clay or clay loam soils	- associated with less resistant igneous/metamorphic geologies - 0.5 – 1.5+ m in depth	- gentle slopes - alluvial plains	24%	- high suitability for agriculture
Seasonally wet soils	- associated with unconsolidated sediments, especially alluvium	- coastal areas - inland wetlands, swamps and depressions	2%	- unsuitable for cropping - may be associated with salinity problems
Red, yellow or grey loamy soils	- shallow to deep (0.5 to 1.5 m) - little clay increase with depth	- plains and plateaus	10%	- often hard setting
Deep sandy soils	- possibly gravelly isolated	- sandplains - beach ridges - aeolian and fluvial sediments	0.5%	- excessive drainage - poor water holding capacity - low soil nutrients - low agricultural potential
Shallow sandy/stony soils	- associated with resistant igneous/metamorphic geologies - <0.5 m in depth	- uplands - crests and slopes of hilly landscapes - scarps	24%	- steep slopes - presence of rock
Sand or loam over sodic/intractable clay	- strong texture contract with depth	- lower slopes - plains	4%	- restricted drainage - high erosion risk
Cracking clay soils	- slow permeability - decomposed rock at depth	- floodplains - alluvial plains	8.5%	- moderate to high agricultural potential - risk of flooding - risk of salinity issues

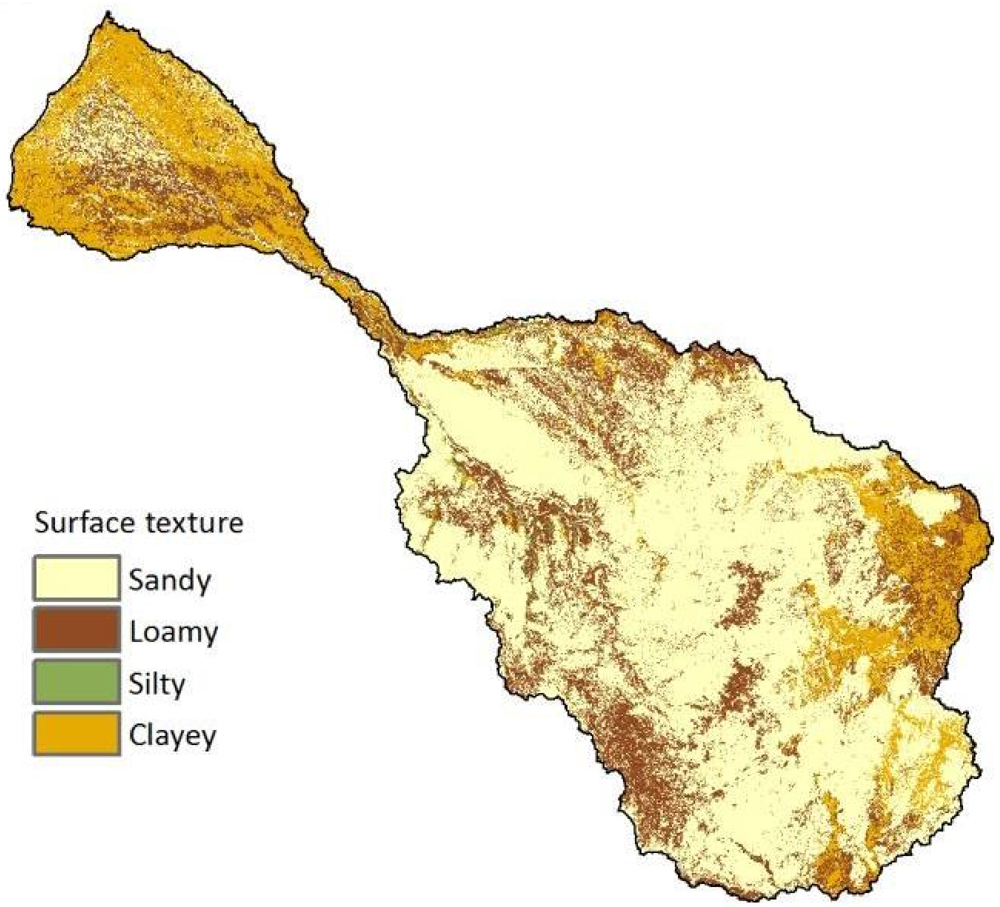

Figure 35 Modelled surface texture for the Gilbert catchment (Source: Bartley et al., 2013f).

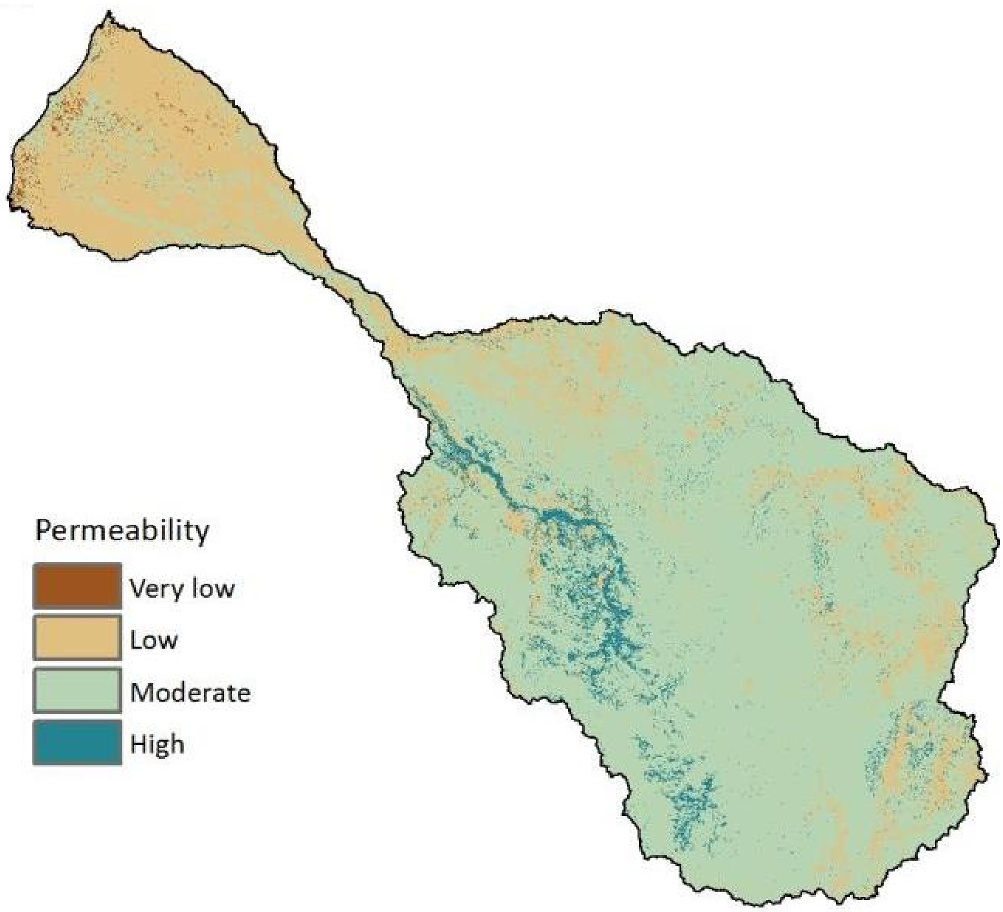

Figure 36 Modelled permeability for the Gilbert catchment. (Source: Bartley et al. (2013f))

Figure 37 Surface soil texture for the area of interest, based on modelled date from Bartley et al. (2013d).

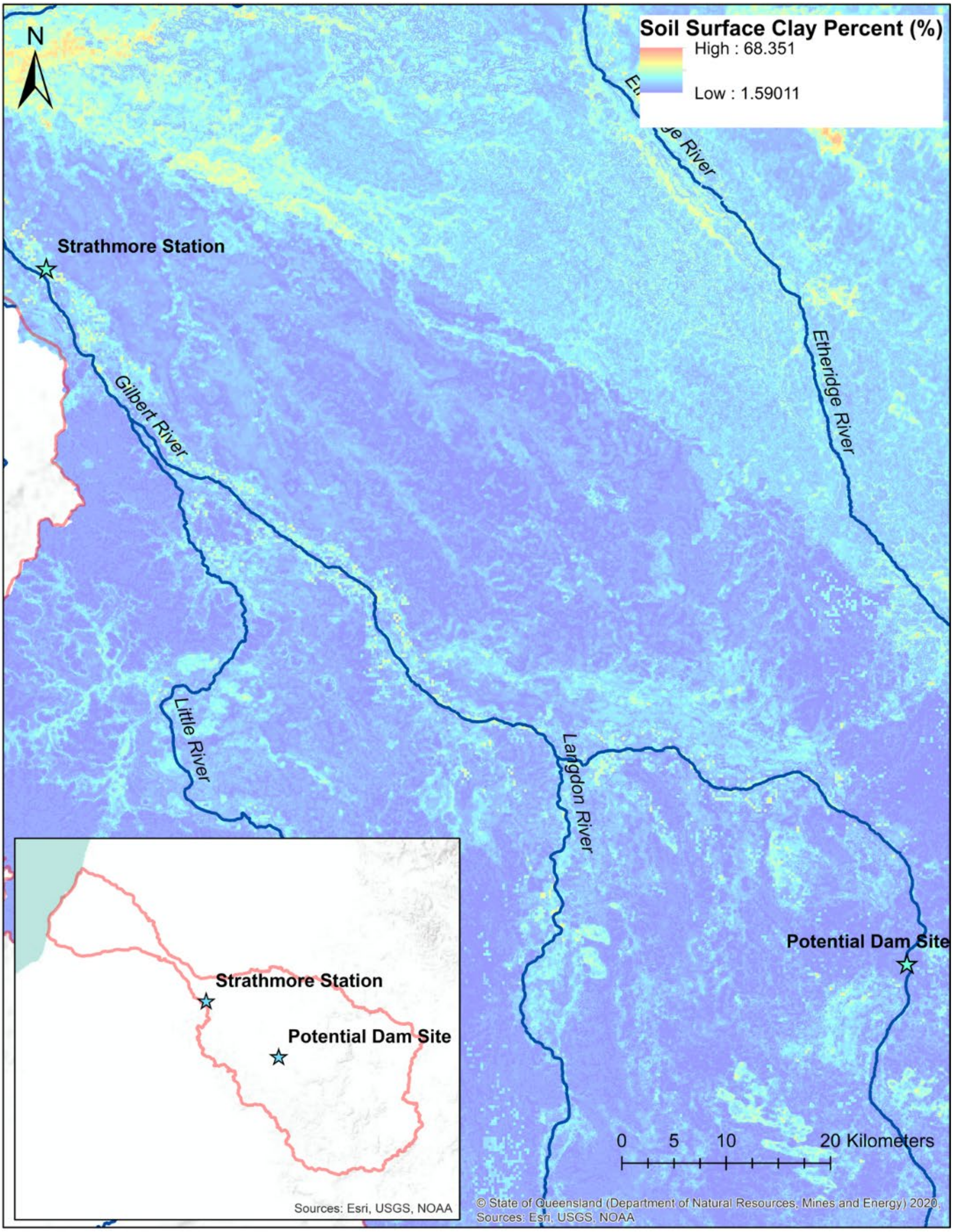

Figure 38 Soil surface clay percentage (%) for the area of interest, based on modelled date from Bartley et al. (2013c).

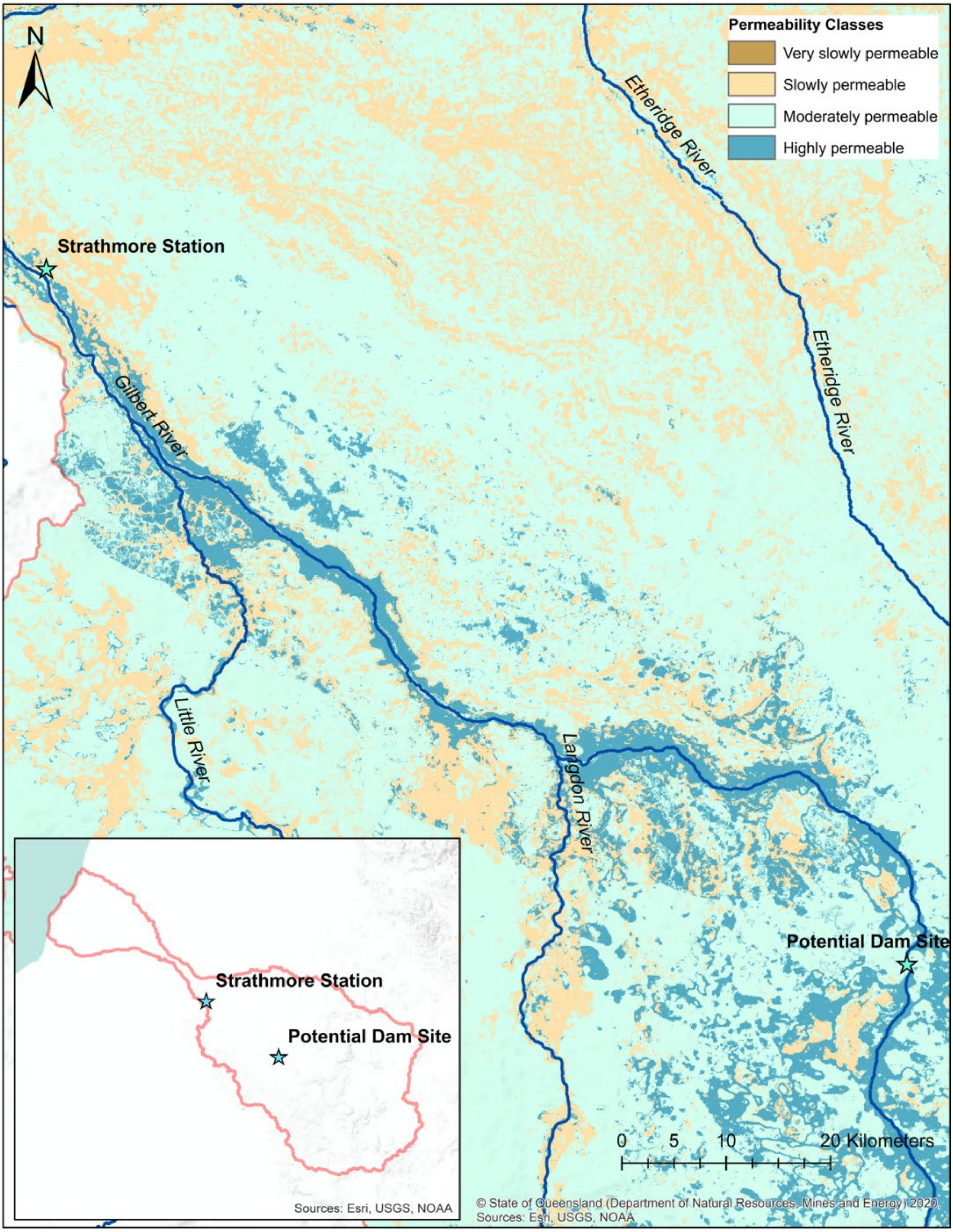

Figure 39 Soil permeability for the area of interest, based on modelled data from Bartley et al. (2013b).

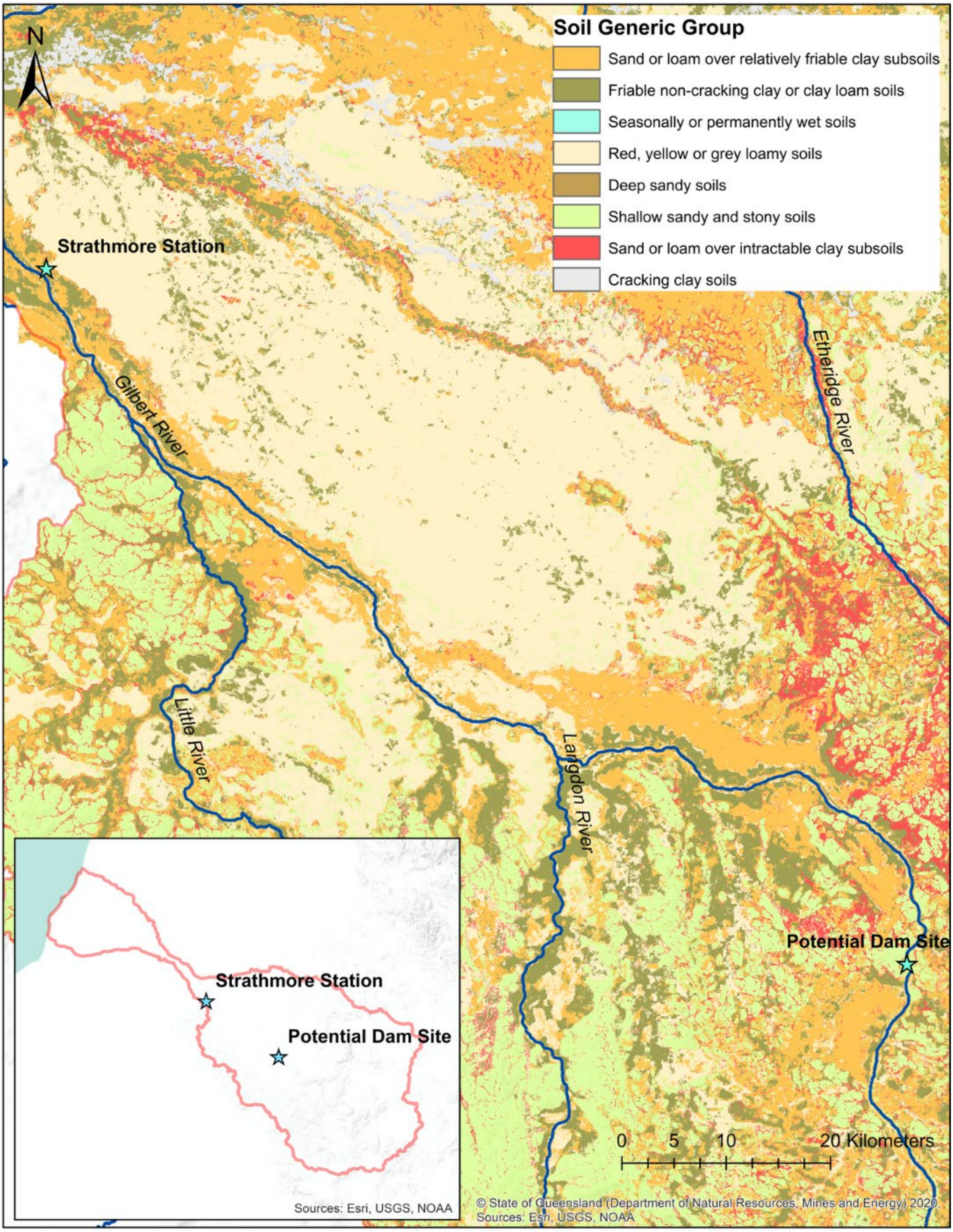

Figure 40 Map of soil generic group (SGG) classes for the area of interest, based on data from Bartley et al. (2013a).

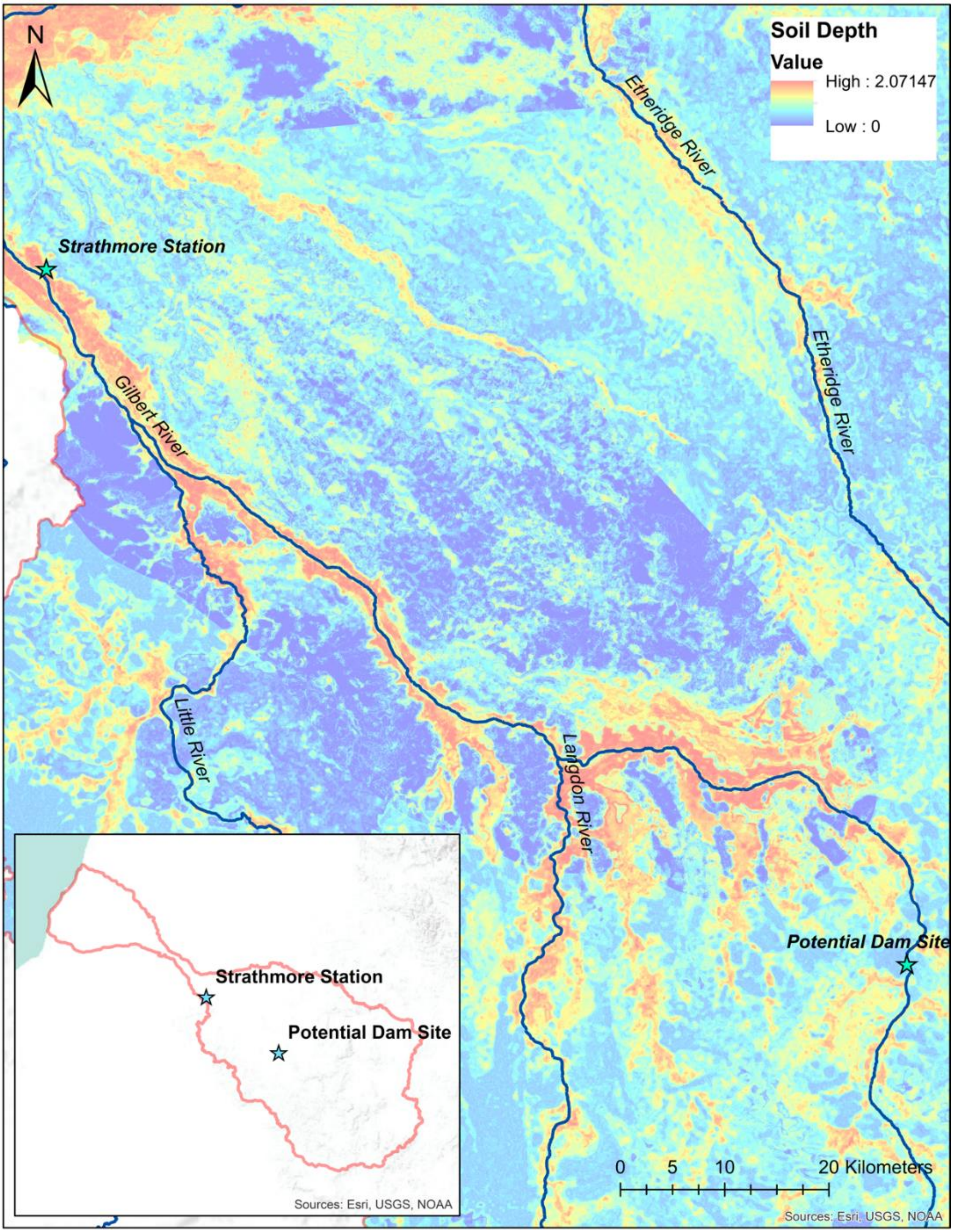

Figure 41 Soil depth for the GRAP based on modelled data from Bartley et al. (2013b).

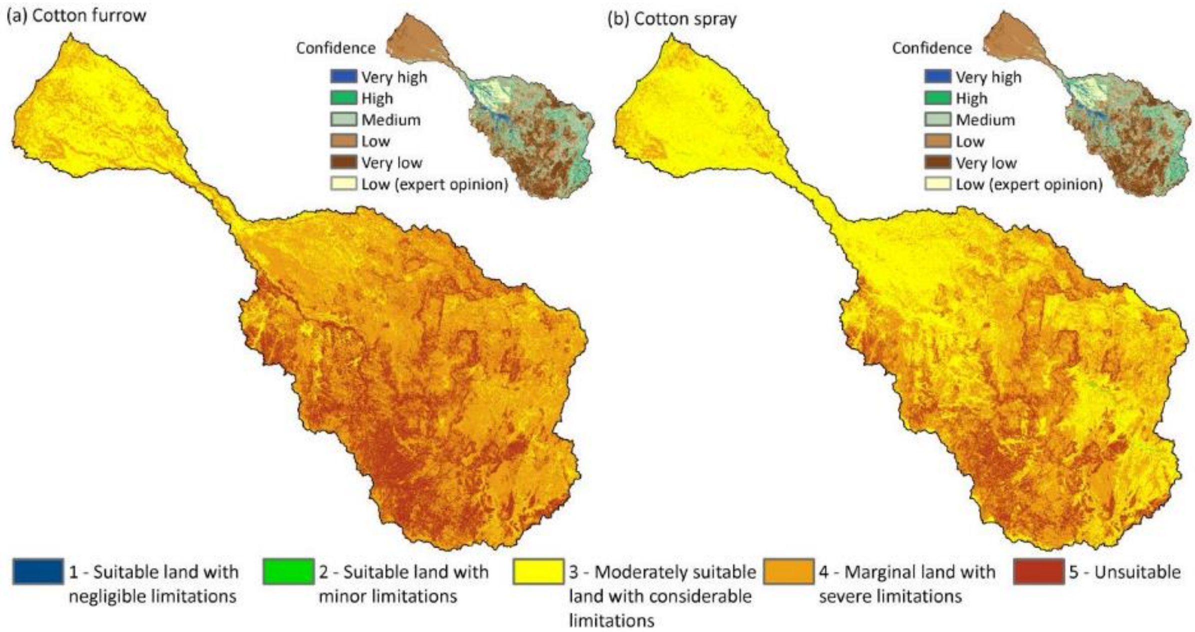

Figure 42 Predicted suitability for growing (a) cotton using furrow irrigation and (b) cotton using spray irrigation (Source: Bartley et al., 2013f).

Similar to the suitability for the catchment as a whole, spray systems are better suited to the GRAP compared to furrow systems (Figure 43, Figure 44). This is due to the limitations outlined above, particularly the perceived issue of permeability. Along the Gilbert River, furrow irrigation of cotton would be considered conventionally unsuitable for this 'low irrigation efficiency' (Figure 43). However, furrow irrigation could be used with potential MAR infiltration schemes, especially in the soils around the Gilbert River, the theory being that the bed sands could be recharged, which would allow for extraction of groundwater after the wet season.

5.3.3 MAR in a highly seasonal setting

MAR has been employed, developed and investigated overseas in climates similar to the Gilbert being characterised by a dry and wet/monsoon season.

In Southern Florida, there are 30+ aquifer storage and recovery (ASR) wells (MAR using injection; Table 16, Figure 54) to recharge the Floridan aquifer system (Reese and Alvarez-Zarikian, 2004). This region is associated with both hurricanes (Missimer et al., 2017) and a distinct wet and dry season (Lascody and Melbourne, 2002). The aim of this ASR scheme is to store excess water that is available during the wet season, to be recovered during the dry season (Reese and Alvarez-Zarikian, 2004). The end uses of this scheme are varied, including agriculture, recreation and municipal water supply. When drinking water is the end goal, the water quality requirements are stricter and non-saline areas of the aquifer are targeted. Issues identified during the operation of this scheme were the mixing of native aquifer water with recharge water limiting recovery and captured water quality concerns. A successful ASR site within this scheme is Boynton Beach. In total, 16 recharge-recovery cycles have been conducted with an average of 2 cycles per year. The quality of water recovered increased considerably over these cycles.

Throughout India there is a need to manage monsoon runoff to boost water resources for the dry season and limit flood damage, for which MAR has been employed using both infiltration and well structures (Holländer et al., 2009). The deliberate lowering of groundwater tables to assist in recharge during the monsoon season is a method used (Holländer et al., 2009). Although there are many positive experiences with MAR in India as well as promising research (Khan et al., 2014, Massuel et al., 2014, Brindha and Pavelic, 2016, Pavelic et al., 2015, Alam et al., 2020, Holländer et al., 2009), clogging is a problem highlighted again and again, due to the large amounts of suspended sediments present in monsoon runoff (Holländer et al., 2009, Soni et al., 2020). Not collecting the runoff from the initial heavy rain event has been suggested as a way to reduced sediment loads (Soni et al., 2020). The economic feasibility of some types of MAR schemes in an Indian setting have been questioned, with recharge structures using wells being suggested as economically unfeasible (i.e., present value of costs exceed the present value of benefits) (Soni et al., 2020). However, check dams which are an infiltration MAR scheme similar to a recharge weir (Table 16, Figure 46) have shown benefit/cost ratios > 1 (Dashora et al., 2019).

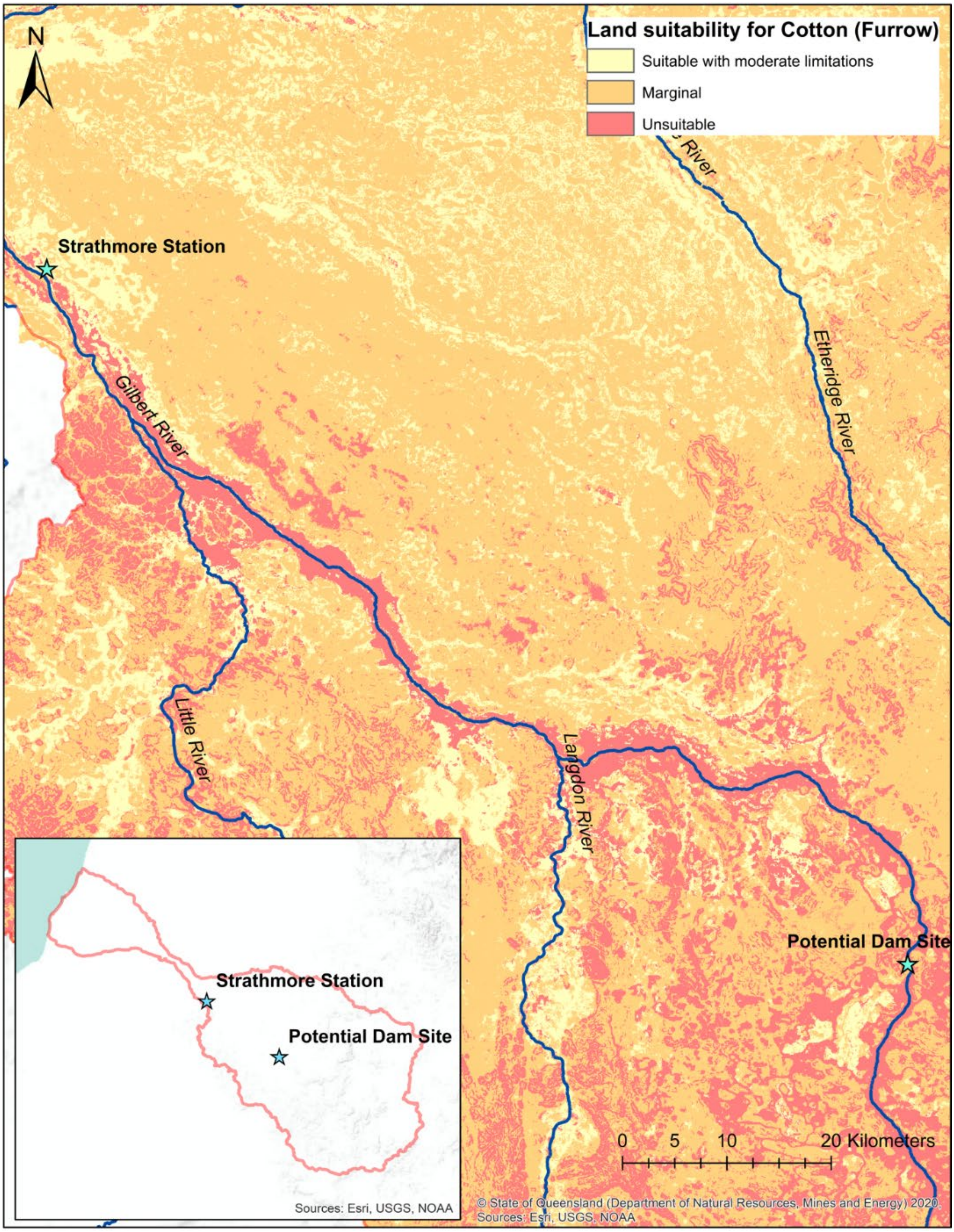

Figure 43 Predicted suitability for growing cotton using furrow irrigation in the area of interest, based on data from Bartley et al. (2013e).

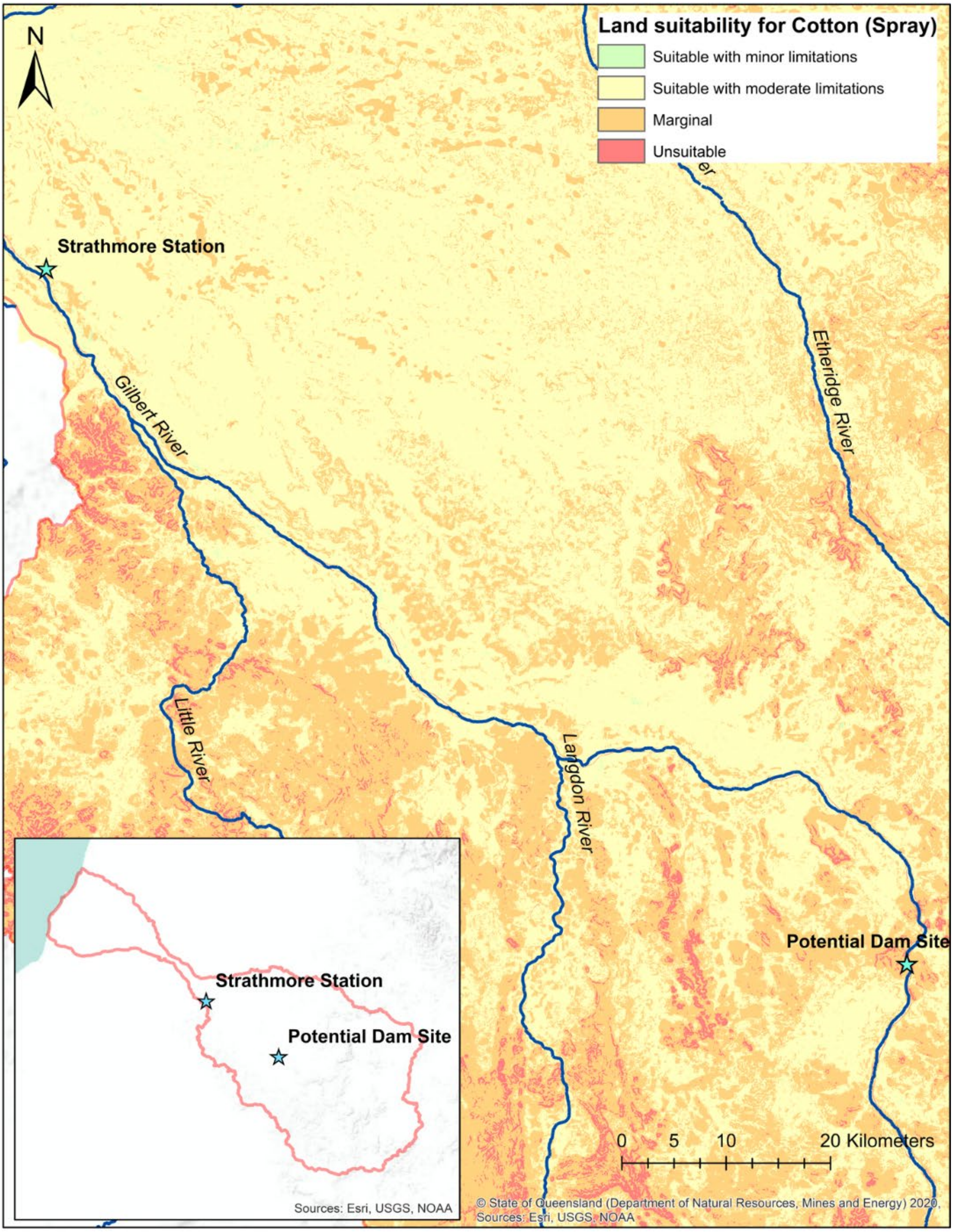

Figure 44 Predicted suitability for growing cotton using spray irrigation in the area of interest, based on data from Bartley et al. (2013e).

MAR has also been suggested as a future water management strategy for Thailand (Pavelic et al., 2012) and Brazil (Shubo et al., 2020), where flooding during the wet season and water shortages during the dry season are common.

5.3.4 Past MAR assessments in the northern Gulf region

There has been one previous MAR suitability assessment conducted for the Gilbert catchment (Lennon et al., 2014). It argues for embracing conjunctive use of groundwater and surface water resources during the strategic development of water resources in Northern Australia, for which MAR is incorporated.
The alluvial aquifer surrounding the catchments main rivers was highlighted as having the greatest MAR potential. Extraction occurs from this aquifer currently. Based on calculations, the aquifer would be able to hold 8 GL/year of water recharged via MAR. However, it is not clear whether the recharged water would reside in the aquifer for a substantial amount of time, or if it would discharge into the river. Recharging further from the river may assist in increasing residence time.

There has been an additional MAR opportunity assessment in the Mitchell catchment (Table 15) (Vanderzalm et al., 2018), a catchment neighbouring the Gilbert. The suitability assessment was based predominantly on physical aspects (e.g. soil permeability, depth of regolith, slope and source water quality, quantity and proximity). Alluvium in the region’s non-perennial streams was deemed the most suitable, and therefore the focus of this research. However, the assessment was limited by the lack of data on the area’s alluvium and, therefore, aquifer storage capacity would have to be confirmed before MAR potential could be determined with any certainty.

The schemes put forward by both Lennon and Vanderzalm would aim to recharge relatively low volumes compared to what would be required to establish an irrigation industry at a site that has a heavy dependence on groundwater. Another limitation of these studies was that existing water management plans (and ‘entitlements’) were not considered in order to determine source water availability or extraction of recharge water.

Table 15 Summary of schemes investigated in the Mitchell (Source: Vanderzalm et al. (2018): Executive Summary Table 2).

MAR type	Location	Volume (GL)	Capital cost ($)	Operating cost ($/yr)	Levelised capital cost ($/ML)	Levelised operating cost ($/ML)	Levelised cost ($/ML)*
Recharge release (from potential dam)	Lynd River	1	285000	27000	21	27	48#
Infiltration Basin	Ten Mile Creek	1	687000	32200	50	32	82
Recharge weir	Rosser Creek	1	1695000	49000	123	49	172

* Costs include recovery bore costs as there is currently very little groundwater extraction; this cost will be reduced if groundwater resource development occurs prior to implementation of the MAR scheme as additional recovery bores may not be required.
* Levelised cost may also be the equivalent annual cost assuming a 7% discount and MAR life of 50 years.
# Large dam is assumed to exist for consideration of a recharge release MAR scheme.

5.3.5 Managed recharge strategies

The potential strategies that could be used to recharge water into the bed sands are listed in Table 16.

Leaky weirs aim to slow the flow of water to rehydrate the land and are a regenerative agriculture technique (not specifically a MAR technique); they could possibly be constructed across small streams off the Gilbert River. Recharge weirs aim to slow flows in order to increase recharge into unconfined aquifers. Multiple recharge weirs could be installed along one or multiple river courses in a catchment (allowing for incremental development) and possible locations could be small streams off the Gilbert River targeting the horizontal extent of bed sands. Infiltration basins aim to recharge unconfined aquifers through pumping or diverting water from river into off stream storage. In the Gilbert, possible locations are the bed sand deposits that extend beyond the river channel. Recharge release is a strategy suggested by CSIRO FGARA reports in other North Queensland catchments, which would work in conjunction with the proposed Greenhills Dam to service the bed sands downstream of the dam (through to Strathmore). The aim would be to strategically release surface water from dams for **infiltration** through the downstream natural river channel and the dam would act as as a settling pond (treatment).

Table 16 Summary of managed aquifer recharge strategies

Type	Aims to…	Notes
Leaky Weir (**Figure 45**)	slow flow to rehydrate land.	- not an explicit MAR technique; linked to regenerative agriculture practices
Recharge Weir (**Figure 46**)	slow flow to increase recharge.	- weirs built to detain water, allowing increased time to infiltrate - targets unconfined aquifer - clogging can be a management issue - opportunity for multiple recharge weirs to be installed along one or multiple river courses in a catchment (could occur incrementally)
Sand Dam [Overseas] (**Figure 47**, **Figure 48**)	gradually build up sand behind a dam wall to store water in.	- dam wall is built gradually over dry seasons - requires: an ephemeral river, sandy sediment, (shallow) bedrock to anchor the dam to - bedrock has to be impermeable to stop the water held in the built-up sediment from being lost - bonus of limiting sediment discharge at mouth of river
Sands Dams [Burdekin, QLD] (**Figure 49**)	hold back releases from upstream storages creating levels that are practical for pumping.	- suited to large rivers where weirs would be impractical and expensive - the low embankments of sand are constructed (and reconstructed) in the dry season when periods of low/no flow allow machinery access - cheap but require annual rebuilding associated with seepage losses
Underground Dam (**Figure 50**)	retain flood flows in alluvium via the use of an underground impediment.	- used in ephemeral settings - unconfined aquifer above the underground dam in confined horizontally
Recharge Release (**Figure 51**)	strategically release surface water from dams for infiltration through the downstream natural river channel.	- release rates typically match the infiltration capacity into underlying unconfirmed aquifers - dam acts as settling pond (treatment)
Infiltration Basin (**Figure 52**, **Figure 53**)	recharge unconfined aquifers through infiltration via pumping or diverting water from river into off stream storage.	- basin scrapping (picture below) often required to remove built up sediment
Injection Well (**Figure 54**)	inject water into a confined or semi-confined aquifer via a well.	- water can be injected under pressure or under gravity - wells can become clogged with sediment so pre-treatment of water to be injected or backwashing of well can be used

Figure 45 Comparison of a landscape pre- and post-leaky weir installation. (Source: https://themullooninstitute.org/projects, accessed 15 February 2021)

Figure 46 Recharge weir on Ashburton River (Source: Vanderzalm et al., 2018)

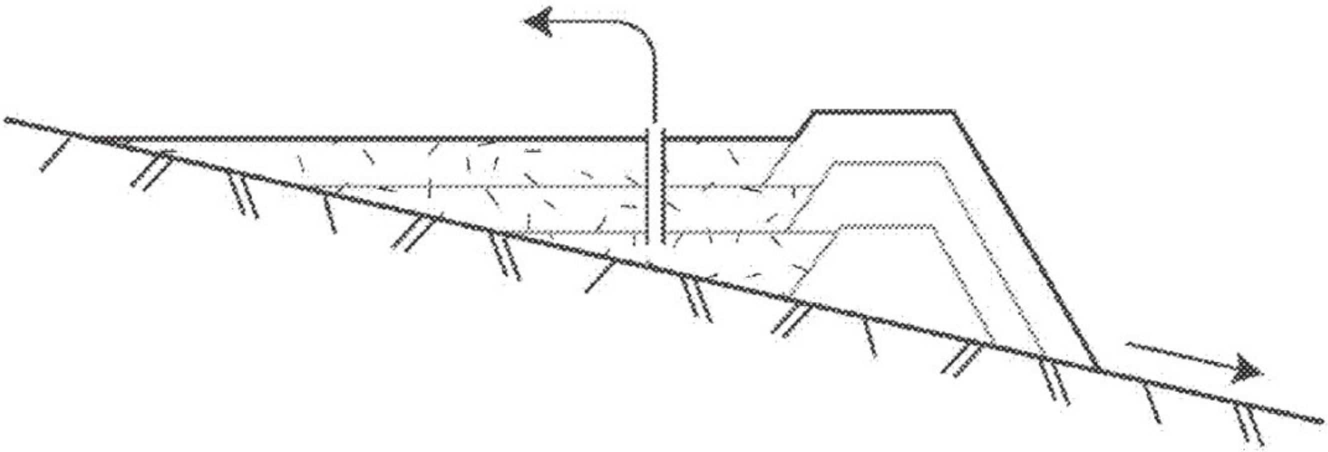

Figure 47 Basic diagram depicting a sand dam (Source: Dillon, 2005).

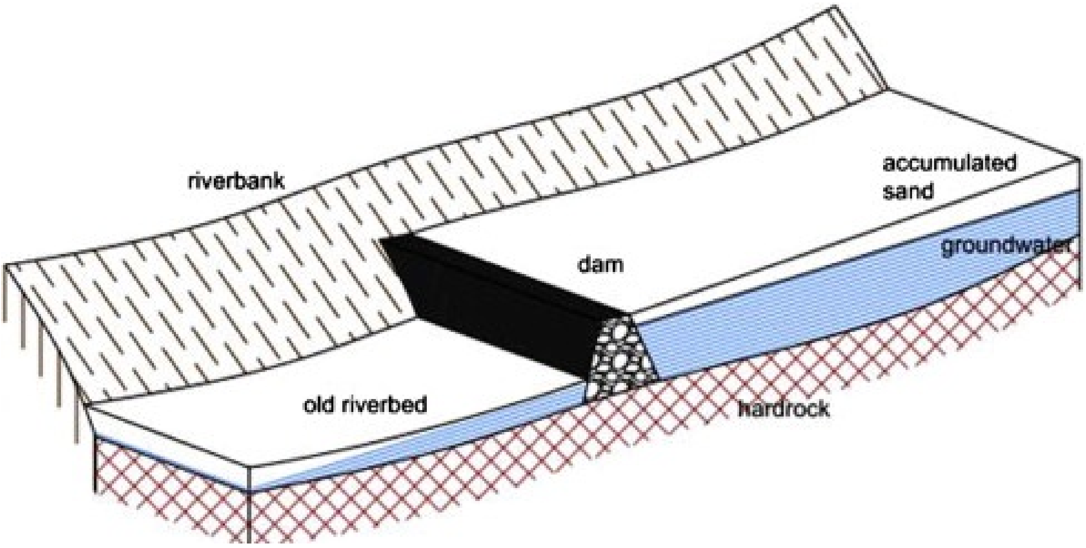

Figure 48 Graphic representation of a sand dam, showing the accumulation of sand upstream of the dam wall (Source: Quilis et al., 2009).

Figure 49 Sand dams in the Burdekin system (Source: Dillon et al., 2009b).

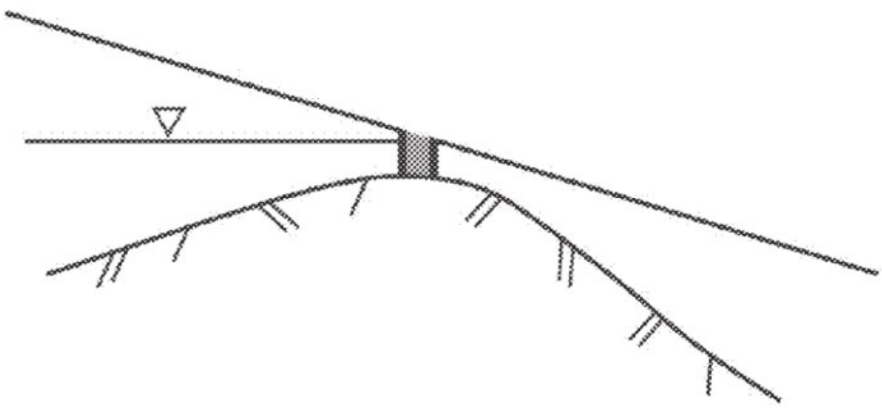

Figure 50 Basic diagram depicting an underground dam (Source: Dillon, 2005).

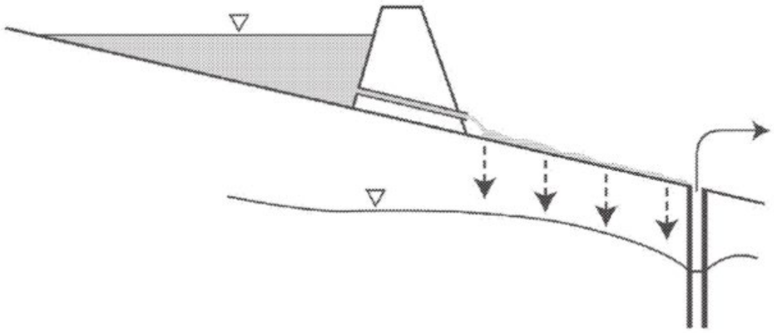

Figure 51 Basic diagram depicting a recharge release system (Source: Dillon, 2005).

Figure 52 Infiltration basin in the Burdekin system (Source: Vanderzalm et al., 2018).

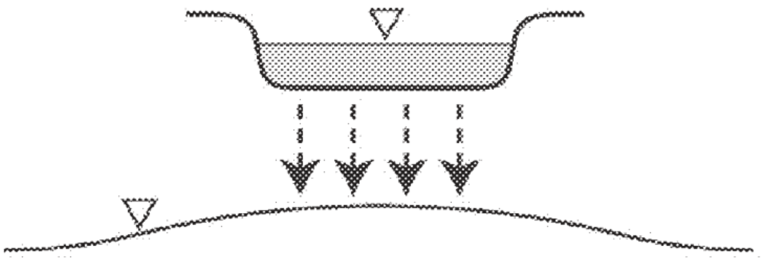

Figure 53 Basic diagram depicting an infiltration basin (Source: Dillon, 2005).

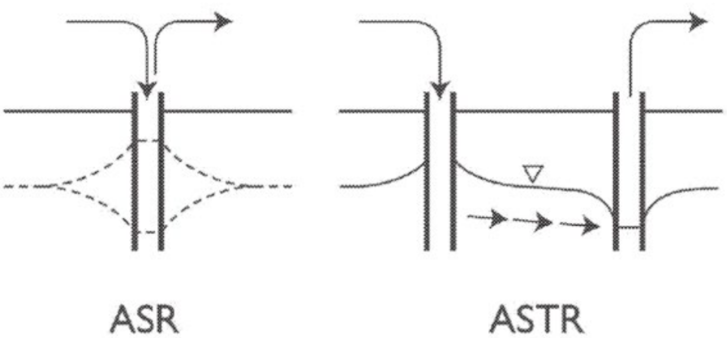

Figure 54 Basic diagram depicting two forms of injection well systems for MAR. Aquifer storage and recovery (ASR) involves using the same well for both recharge and recovery. Aquifer storage, transport and recovery (ASTR) involves allowing the recharged water to travel within the aquifer and be recovered from another well (Source: Dillon, 2005).

5.3.6 Recovery efficiency

Low yields of the order of 1-3 L/s in the consolidated sandstones (see Figure 30) are, if they are the maximum potential, not suitable for the irrigation of crops such cotton unless there is some capacity to pump into temporary storage in the lead up to irrigation scheduling. Given the limited hydrogeological information available, some localised areas with greater yields are possible. However, overall, these sandstone aquifers do not hold much promise in terms of supporting irrigated agricultural development.

Bore yields from the alluvial bed sands hold more potential. In a phone interview in March 2019, one farmer in the region thought that from his irrigation system – three spear bores in the river bed and one out of the river bed – he could extract 30 L/s (2.6 ML/day) within his license of up to 20 ML/day. At the Gilbert River Agricultural Forum in April 2021, spear bores were being used to irrigate research trial plots of cotton, mung beans and other crops on this property and a table grape trial and established mango orchard on other properties. As noted in Section 5.1.2, yields from these bores can vary over time and space as the dry season progresses.

Salinity should not be a constraint to recovery efficiency as there are no reports of elevated salinities in the alluvial or other aquifers with the GRAP. Recovery efficiency is likely to be constrained by the need to guarantee ecological outcomes (see Section 5.5).

5.3.7 Monitoring design to manage effects

There are over 400 registered bores in the catchment (Figure 55) and many in the GRAP (Figure 56) that could be used for monitoring groundwater depths during/after periods of recharge and extraction. If the bed sands were to be the target aquifer of the MAR scheme, there would likely need to be an investment in monitoring due to the absence of information in this area. Reviews of the Water Plan (Gulf) 2007 identify localized measurements of bed sands water levels in the Gilbert River as a key knowledge gap (DNRME, 2018b). Further reports reviewing water managed under the Water Plan (Gulf) mirror this, highlighting that no monitoring data is available to assess the impact of water extraction on bed sand ecosystems (DNRME, 2018a). The expansion of monitoring into the groundwater managed under the Water Plan (Gulf) 2007 is in line with Plan requirements (Chapter 6 Section 91).

There are currently two monitoring bores in the catchment (Chadshunt and Abingdon Downs Road [74]) (Figure 56), with data collection commencing in 2014 for both sites. Both of these bores are located in the deeper sandstone aquifers.

Monitoring design could be driven by the 'action-state-consequence' framework (Figure 57), which was developed after consulting the relevant literature (summarised in 5.5.4). This framework asks a range of questions based on the action that is proposed to be taken:

- What consequences might we expect?
- What states might we want to monitor?
- Who might be involved? How and why?

An example of the complete framework based on the recharge release scenario is provided in Figure 58.

[74] https://water-monitoring.information.qld.gov.au, accessed 1st November 2020

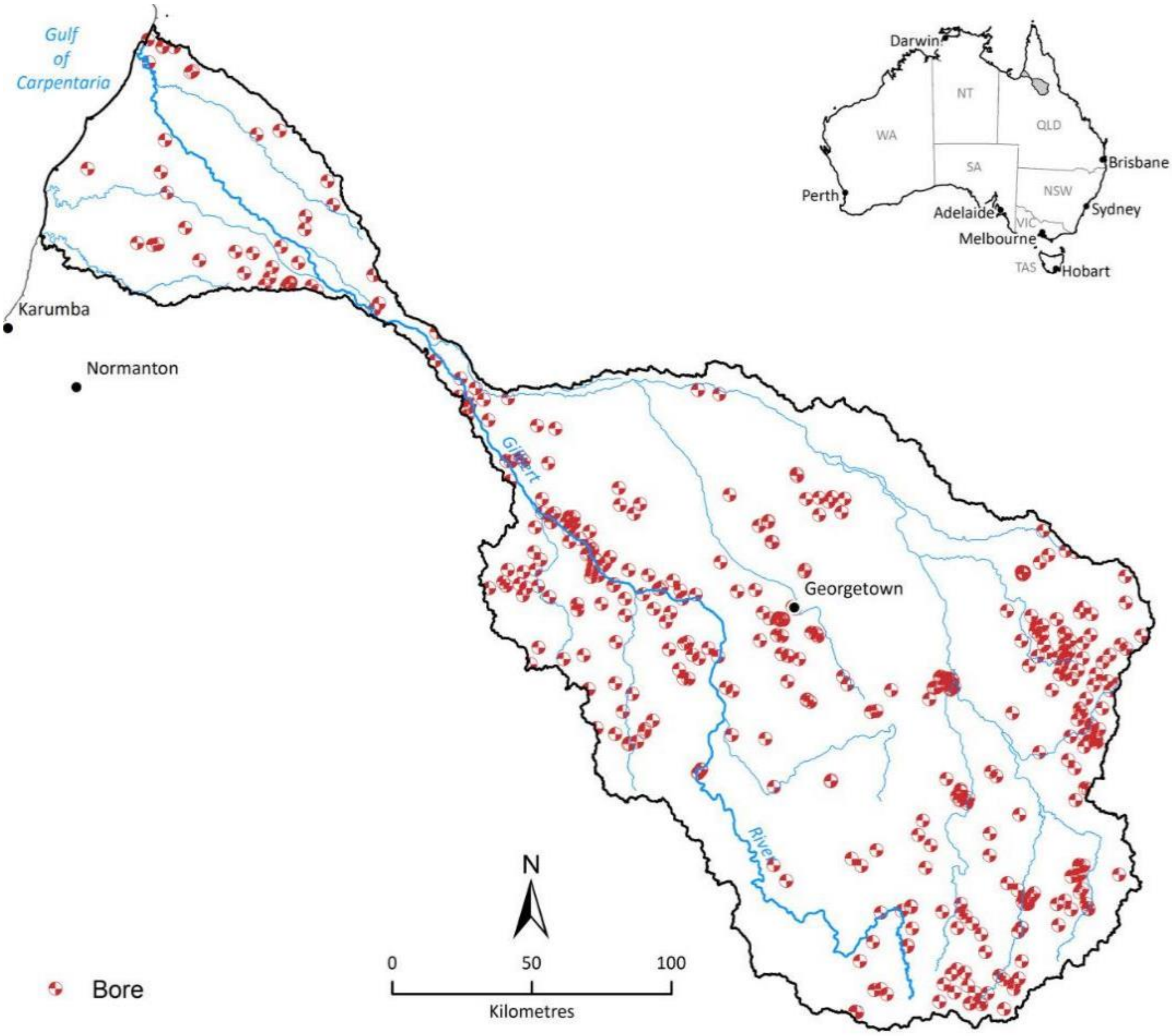

Figure 55 Bores in the Gilbert catchment (Source: Jolly et al., 2013).

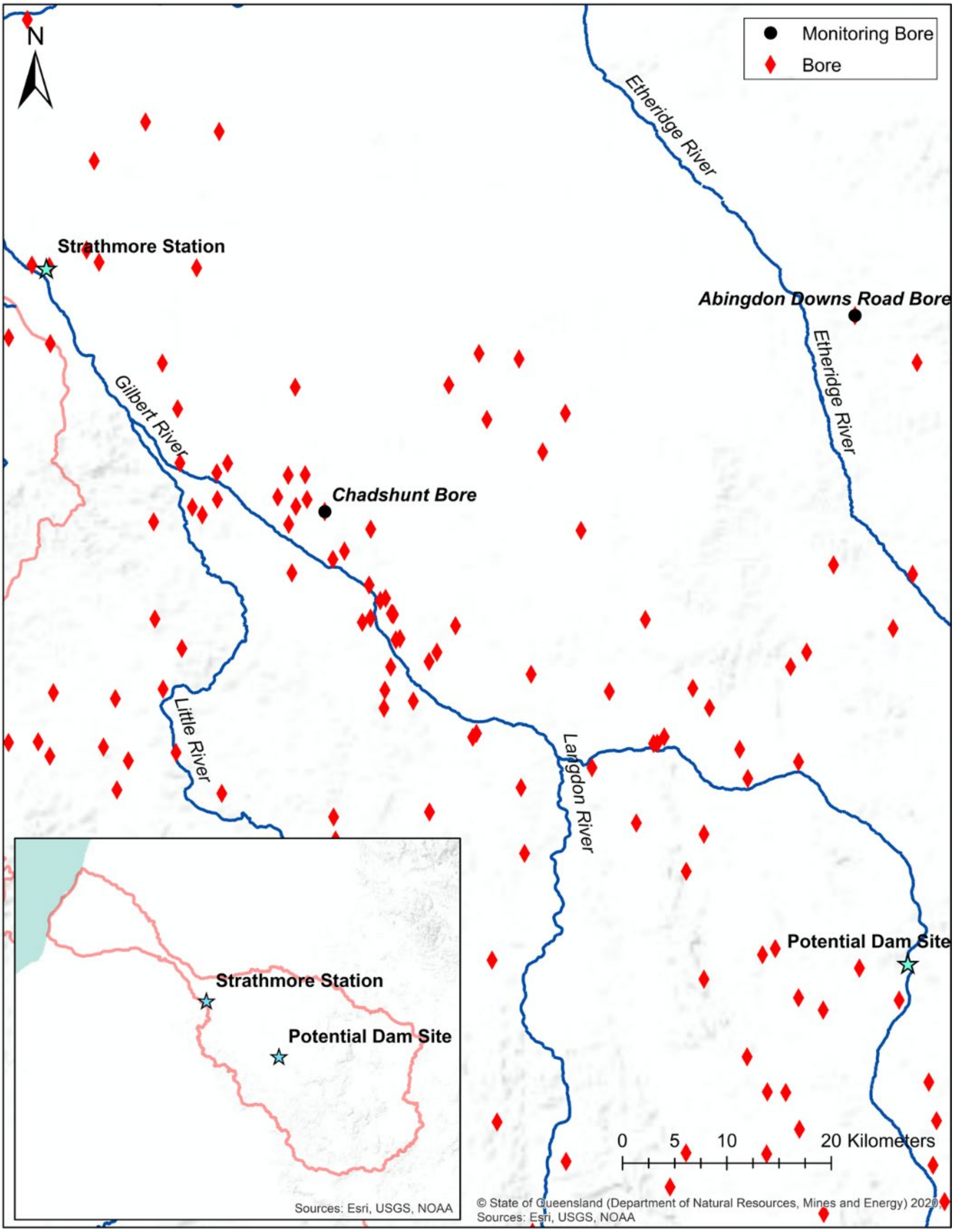

Figure 56 Bores in the area of interest, including monitoring bores. Data from: National Groundwater Information System (NGIS) [75] and QLD Water Monitoring Information Portal (WMIP) [76], respectively.

[75] http://www.bom.gov.au/water/groundwater/ngis/, accessed 1st November 2020
[76] https://water-monitoring.information.qld.gov.au, accessed 1st November 2020

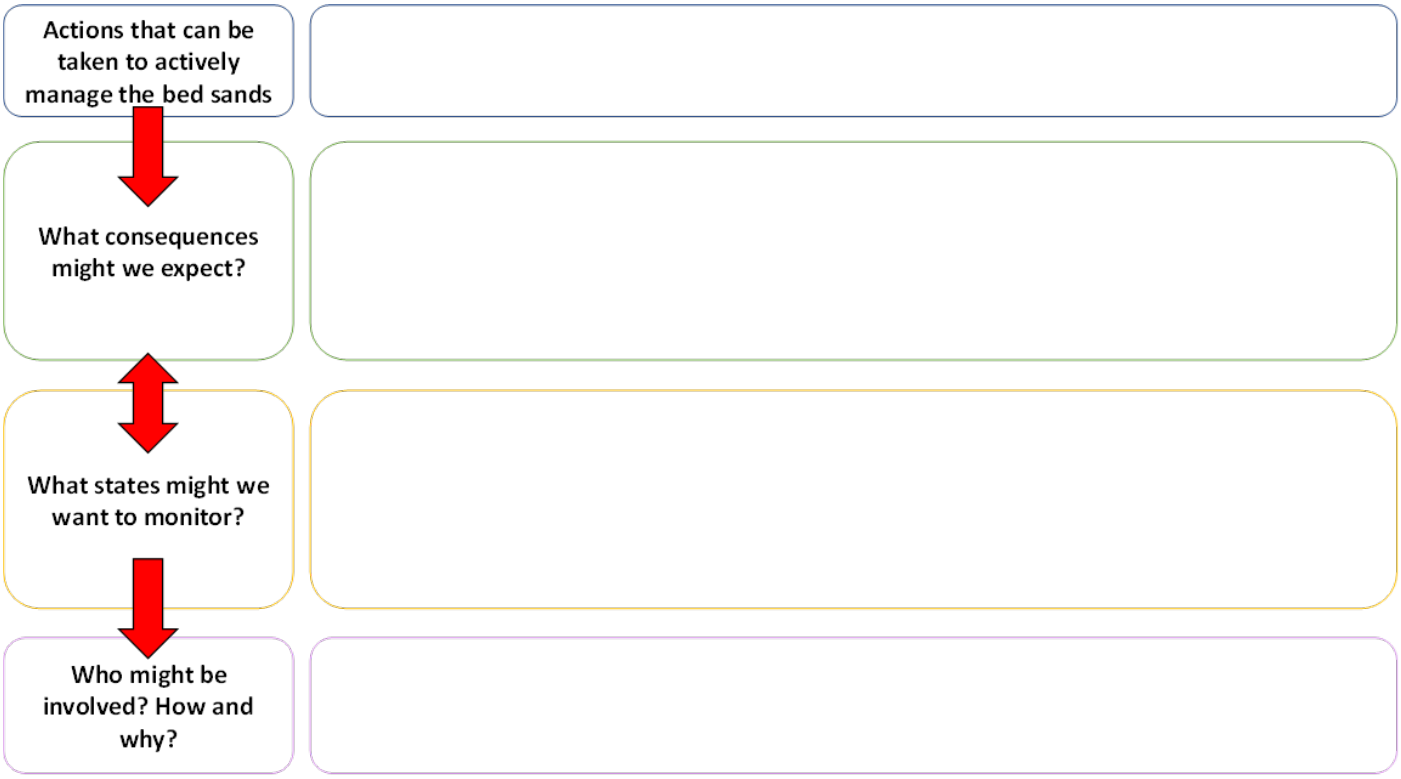

Figure 57 Outline of action-consequence-state framework

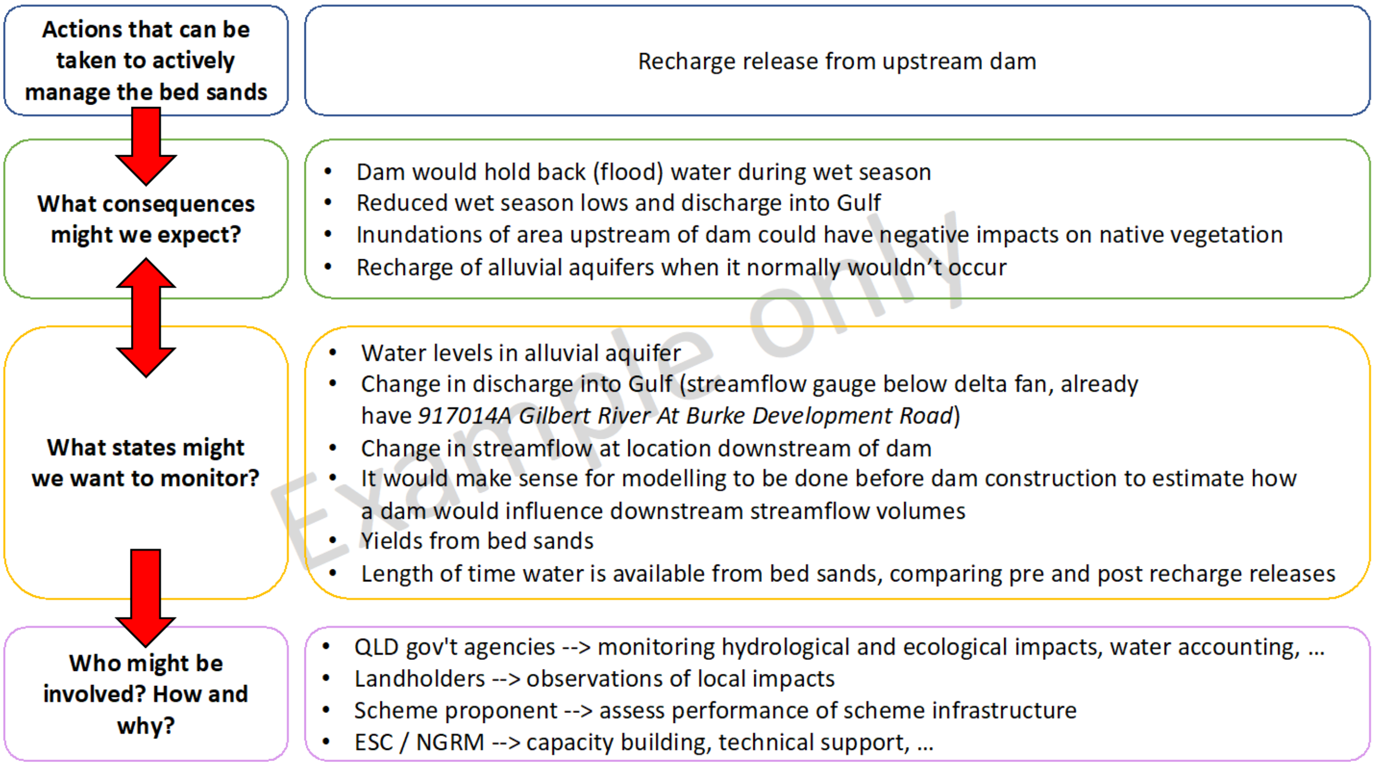

Figure 58 Example using the action-consequence-state framework

5.4 Financial viability

This section considers the three different water management types proposed in the scenarios: off-stream storage (Section 5.4.2), in-stream storage (Section 5.4.3) and MAR (Section 5.4.4). The MAR costs are based on the Burdekin scheme, a developed water management scheme in QLD that employs infiltration basins to replenish the aquifers below agricultural land, dominated by sugarcane cropping (Bristow et al., 2000). Due to the 'greenfields' nature of irrigated agriculture in the Gilbert catchment, all water infrastructure types would incur significant capital costs and be required to set up water distribution networks. Establishing local processing facilities is also not without risk (Ash et al., 2017). However, this is a benefit for MAR as significant investment hasn't already been directed to infrastructure to support surface storage, unlike in established irrigation regions (Evans and Dillon, 2017).

Of major importance to the development of an irrigated agriculture industry in the region, regardless of water delivery mechanism, is the establishment of local processing facilitates, to overcome the regions remoteness (Ash et al., 2017). Petheram et al. (2013) estimated that the break-even crop yield for irrigated cotton produced in the Gilbert catchment would more than half if a local cotton gin was established. Multiple scenarios, with varying details (e.g., area planted, yield), are presented in Section 5.4.1. All presented scenarios would theoretically produce enough cotton to support a local gin. The financial viability of cotton in particular could be further improved by using the by-product of ginning, cottonseed, as supplement fodder for cattle, the main industry in the catchment (Petheram et al., 2013, Álvarez-Romero, 2015).

5.4.1 Local cotton gin

The financial viability of a local irrigated agriculture industry has been suggested to depend on the establishment of local processing facilities, for example, a local cotton gin (Jacobs Australia Pty Limited., 2020, Petheram et al., 2013, Ash and Watson, 2018). With the ability to process at a local gin, farmers could pay up to $263/ML for water and break even (Jacobs Australia Pty Limited., 2020). It is estimated that establishing a cotton gin in the region would cost $30 – 40 million (Matz, 2020).

Multiple scenarios have been developed based on published values to understand how irrigation requirements, area under irrigation and yields influence the gross value of the hypothetical irrigation industry (Table 17). The average price of cotton per bale is set at $500, based on the average value proposed by Cluff (2017). The irrigation requirement is also kept constant based on the median irrigation requirement of 3.2 ML/ha (Petheram et al., 2013). The median potential yield is based on the value proposed by Petheram et al. (2013) for irrigated cotton – 8.5 bales/ha. In scenario 5, a substantially smaller potential yield is used based on results from a trial of non-irrigation cotton in the Gilbert catchment (Cluff, 2017). This is used as a worse-case yield scenario.

The major variation between the scenarios is the area of cotton that is planted (Table 17). Both scenario 1 and 5 use the value of 35,000 ha, based on the area estimated to be required to support a local gin by Cluff (2017). A much smaller planted area was used in scenario 2, with the aim of producing the minimum bales suggested to support a local gin by Petheram et al. (2013). Similar bale numbers (67,500) are proposed by Ash and Gleeson (2014), as referenced in Matz (2020). Scenarios 3 and 4 are based on the land deemed moderately suited for spray and flood irrigated cotton cropping, respectively (Petheram et al., 2013). These areas are best case scenarios where all moderately suitable land is sown.

At the Gilbert River Agricultural Forum, in April 2021, a presentation was given that outlined a scoping study looking at different locations for a cotton gin in North Queensland (*North Queensland Cotton Gin Feasibility Study*). This study is being undertaken on behalf of the Mount Isa to Townsville Economic Development Zone (MITEZ) and will suggest the most feasible locations for cotton gins in North Queensland to service the developing cotton industry in the region. The report is due to be delivered in the middle of 2021. As of the submission of this final report the study has not been published but the North

West Star has reported that Hughenden and Richmond are the preferred locations for the gin. [77] These sites would reduce the travel time from Georgetown by about half from the nearest gin currently in operation (located in Emerald).

Table 17 Scenarios based on published values to assess possible yields and values of cotton cropping in the Gilbert River catchment.

Scenario	Median Irrigation Requirement (ML/ha)	Median Potential Yield (bales/ha)	Cotton in Area (ha)	Water Needs (ML)	Yield (bales)	Average price of cotton per gin bale ($)	Gross Value ($)
Scenario 1	3.2	8.5	35,000	112,000	297,500	500	148,750,000
Scenario 2	3.2	8.5	6,000	19,200	51,000	500	25,500,000
Scenario 3	3.2	8.5	2,000,000	6,400,000	17,000,000	500	8,500,000,000
Scenario 4	3.2	8.5	900,000	2,880,000	7,650,000	500	3,825,000,000
Scenario 5	3.2	2	35,000	112,000	70,000	500	35,000,000

5.4.2 Estimated costs of off-stream storage

Off-stream storages (i.e. farm dams) have been suggested as more challenging and costly than larger in-stream storages in the Gilbert catchment due to the need to mitigate sandy textured soils with, for example, synthetic liners (Figure 36) (Jacobs Australia Pty Limited., 2020, Petheram et al., 2013). This is of particular importance in the GRAP (Figure 37, Figure 39), where Petheram et al. (2013) suggested that there are few locations adjacent to the Gilbert River that are suitable for off-stream storage (Figure 59).

Short term off-stream water storage (4 months) has been suggested to cost at least $140/ML, increasing to $240/ML when storage time is increased to 12 months (Jacobs Australia Pty Limited., 2020, Petheram et al., 2013). These costs are higher than larger in-stream dams (Section 5.4.3) due to increased evaporative and seepage losses (Jacobs Australia Pty Limited., 2020). However, even when accounting for 12-month storage, it may still be possible for a cotton farmer to make a small profit using off-stream storage if a local gin was to be built [78].

The construction and operation cost of a 1000 ML ring tank (form of surface storage) and pumping system are outlined in Table 18. The cost of the pumping infrastructure outlined in Table 18 would fill the ring tank in five days as a way to capture the full entitlement in the majority of years. It is therefore possible to use a smaller and lower cost pump, but this would increase the number of days to fill the ring tank and therefore decrease the possibility of the full entitlement being taken up. The cost of supply channels are not included, as are highly situation dependent. It should also be that this analysis was completed in 2013, so prices would be reflective of that time.

There are situations where off-stream surface water storage may be more technically and financially feasible than what is suggested above. The characteristics that would improve the feasibility of off-stream storages are:

- if there was a natural dam site that could be further enhanced
- sites with soil of low infiltration
- sites close to good agricultural soil to minimise pumping costs (if required)

[77] https://www.northweststar.com.au/story/7436935/nq-cotton-gin-is-viable-says-mitez-study/, accessed 6 December 2021
[78] Section 5.4.1 With a gin in Georgetown, farmers could pay $263/ ML for water and break-even

- water captured by overland flow to remove capital cost of canal construction from the river and on-going pumping costs to extract water from the river
- captured water is used completely within a short period after the completion of the wet season (e.g., to finish crop) to minimise evaporation losses

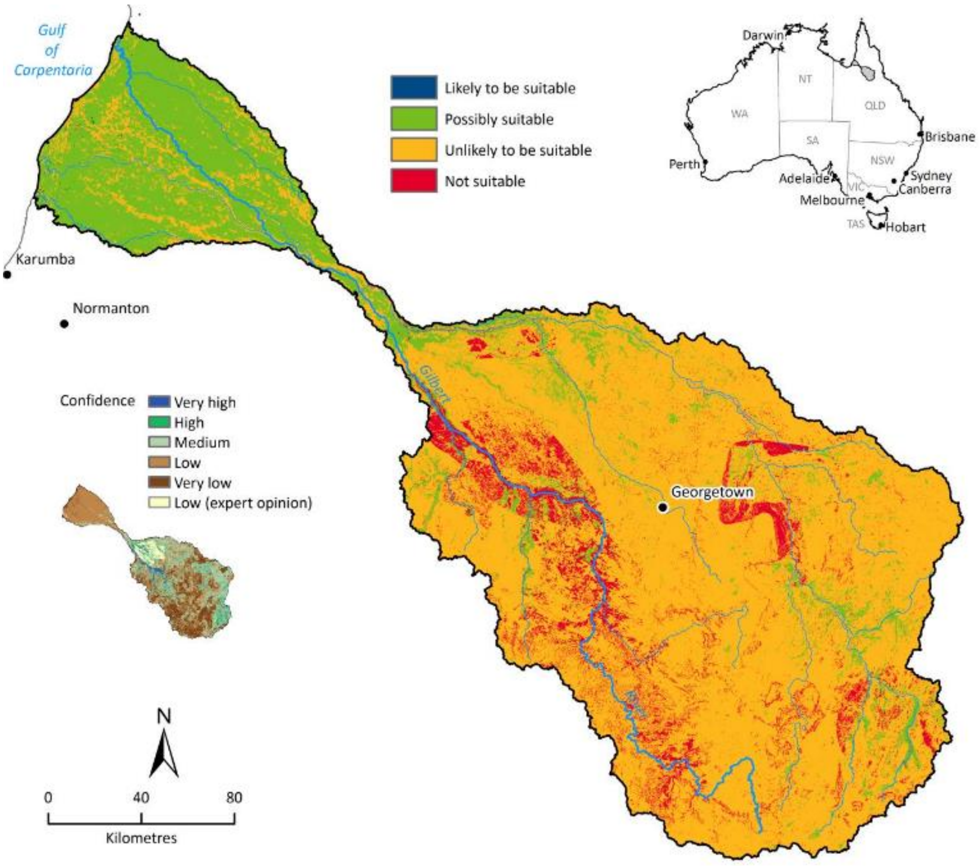

Figure 59 Suitability for off-stream water storages in the Gilbert catchment. Here suitability is based on landscape and soil attributes (Source: Petheram et al., 2013).

Table 18 Estimated construction and operation costs for a surface storage in the Gilbert catchment, assuming a discount rate of 7% (Source: Petheram et al., 2013).

Item	Capital cost ($)	Lifespan (Years)	Equivalent annual capital cost ($)	Annual operation and maintenance cost ($)
Off-stream storage (ring tank)	1,000,000	40	75,000	10,000
Pumping infrastructure	170,000	15	18,650	3,400
Pumping cost (diesel)	-	-	-	16,000

5.4.3 Estimate costs of large in-stream storage

The recent detailed business case (DBC) for the proposed Gilbert River Irrigation Project outlined the costs, both of construction and operation/maintenance, of a large in-stream dam on the Gilbert River (Jacobs Australia Pty Limited., 2020). Water entitlements costs and economic benefit were also defined (Jacobs Australia Pty Limited., 2020).

The estimated capital cost of the project is $785 million, $429 million for dam construction and $355 million for the delivery network and water purchase cost (Table 19) (Jacobs Australia Pty Limited., 2020).

Table 19 Estimated capital expenditure for the Gilbert River Irrigation Project dam, as set out in the detailed business case (Jacobs Australia Pty Limited., 2020)

Description	Capital cost ($ million)
Dam	429.3
Distribution network	342.3
Water purchase	13
Total	784.6

The annual operating cost was estimated to be $5.6 million. The annual refurbishment cost was estimated to be $3.8 million (Jacobs Australia Pty Limited., 2020). These costs are planned to be met through annual water charges (Jacobs Australia Pty Limited., 2020).

The project is set to deliver 130 GL of water entitlements per year, split into 90 GL of high priority allocations available between February and December (~330 days) and 40 GL of medium priority allocations delivered between February and May (~100 days) (Jacobs Australia Pty Limited., 2020). The payment structure for entitlements is divided into two stages; an up-front capital contribution (Table 20) and annual water charges (Table 21) (Jacobs Australia Pty Limited., 2020). Based on demand assessment it is expected that 100% of the allocations would be pre-sold for the prices listed (Table 20) (Jacobs Australia Pty Limited., 2020). The annuals charges are below those estimated by CSIRO of $100/ML per annum - $140/ML per annum (Jacobs Australia Pty Limited., 2020, Petheram et al., 2013).

Table 20 Up-front customer capital contributions for the Gilbert River Irrigation Project dam, as set out in the detailed business case (Jacobs Australia Pty Limited., 2020)

Priority of Allocation	Cost ($/ML)
High	3,000
Medium	1,000

Table 21 Annual water charges for the Gilbert River Irrigation Project dam, as set out in the detailed business case (Jacobs Australia Pty Limited., 2020)

Charge	Cost
Fixed (Part A)	$60/ML per annum
Variable (Part B)	$20/ ML of metered water use
Total	$80/ML per annum

The total economic benefit of the project is estimated to be $839 million, resulting in a net economic benefit of $108 million and a benefit cost ratio of 1.15 (Jacobs Australia Pty Limited., 2020). This, and the above charges, are based on the assumptions that:

- 100% of water entitlements are sold pre-construction, bringing in capital contributions of $310 million
- The funding shortfall for construction will be covered via government funding to keep the price of annual charges low and support uptake
- Initial purchase of the water allocation from the QLD Government, via unallocated reserve as per the Gulf Water Plan, cost $100/ML, for a total of $13,000,000. (This price reflects similar recent transactions)

However, the modelled water prices for irrigators vary substantially based on government contributions (Table 22) (Figure 60) (Jacobs Australia Pty Limited., 2020). The proposed funding sources, both grants and loans, are outlined in Table 23.

Table 22 Funding scenarios, the breakdown of funding sources and resulting total customer charges in $/ML (Source: Jacobs Australia Pty Limited., 2020)

Funding Source and User Chargers	Scenario 1: High Government Funding	Scenario 2: Medium Government Funding	Scenario 3: No Government Funding
Water user contributions ($ million)	310.0	310.0	310.0
QLD & Australian Government Capital Grant Funding ($ million)	683.7	504.3	-
Concessional Loans ($ million)	-	194.3	740.6
High Priority Annual Charges ($/ML)	**77.78**	**163.55**	**404.66**
Medium Priority Annual Charges ($/ML)	**54.50**	**111.68**	**272.42**

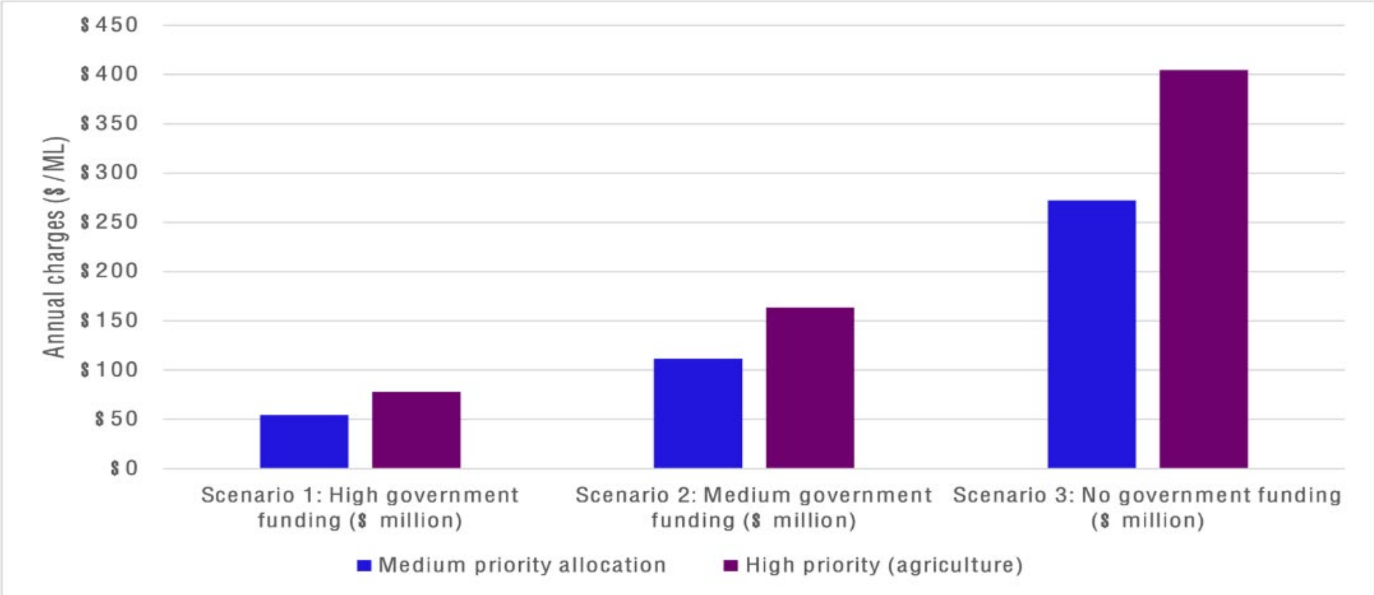

Figure 60 Water charges by funding scenario (Source: Jacobs Australia Pty Limited., 2020).

5.4.4 Indicative costs of MAR

An established MAR scheme exists in the Burdekin region of Queensland (Bristow et al., 2000), providing a financial reference.

The Burdekin Delta is home to a well-established but growing irrigation industry, expanding from 35,000 ha at the turn of century (Bristow et al., 2000) to 90,000 ha recently, making it the largest irrigated agricultural area in north Australia (Ash and Watson, 2018). The major groundwater supplies that underly the region[79] are heavily relied upon as a source of irrigation water (Bristow et al., 2000).

[79] http://lowerburdekinwater.com.au/about-us-2/about-us/, accessed 4th March 2021

Table 23 Funding sources suggested in Jacobs Australia Pty Limited. (2020).

Funding Sources	Program/Loan Name	Details	Link(s)
Queensland Government grant funding	State Infrastructure Fund (SIF)	A core allocation from the SIF was $20 million for the Maturing the Infrastructure Pipeline Program (MIPP), part of which was used to fund the Gilbert River Irrigation Project Detailed Business Case (Jacobs Australia Pty Limited., 2020). The MIPP intended to further infrastructure planning only, which further no commitments of does further funding from Queensland Government for a project.	https://www.statedevelopment.qld.gov.au/industry/infrastructure/infrastructure-planning-and-policy/state-infrastructure-fund https://www.statedevelopment.qld.gov.au/industry/infrastructure/infrastructure-planning-and-policy/state-infrastructure-fund/maturing-the-infrastructure-pipeline-program
Australian Government grant funding	National Water Infrastructure Development Fund (NWIDF), now administered through the National Water Grid Authority (NWGA)	The NWIDF has been established to fund water infrastructure investments. In the 2020/21 Federal Budget an additional $2 billion in funding was announced for the NWIDF, bringing the total funding commitment to $3.5 billion. Funding for the Charleston Dam Facility, to provide water to the towns of Forsayth and Georgetown, was obtained under this funding source, with co-funding from the Etheridge Shire Council.	https://www.agriculture.gov.au/water/national/national-water-infrastructure-development-fund https://www.nationalwatergrid.gov.au/program https://www.nationalwatergrid.gov.au/program/charleston-dam-facility
Concessional loans (from the Australian Government)	National Water Infrastructure Loan Facility (NWILF)	Administrator: Regional Investment Corporation (RIC) Amount: $10 million + Who can apply: State and Territory governments When: Apply anytime Investment: No more than 49 per cent of total project cost (including all Australian Government Funding) Interest Rate: On request Term of loan: Up to 30 years (5-year construction period can be interest only, then principal and interest for up to 25 years)	https://www.ric.gov.au/states-territories
	Northern Australia Infrastructure Facility (NAIF)	Administrator: Northern Australia Infrastructure Facility (NAIF) Amount: No minimum Who can apply: Private and Public Sector (Project benefits mainly in Northern Australia) When: Apply anytime Investment: Can lend up to 100 per cent of the debt Interest Rate: Concessional—cannot be below the combined cost of Australian borrowing and administration costs Term of loan: Up to 30 years (different concessions available – reviewed on a case-by-case basis) Eligibility: Be of public benefit; be located in, or have significant benefit for, northern Australia; Have an Indigenous Engagement Strategy, among other criteria.	https://naif.gov.au

Lower Burdekin Water manages the delta, preventing seawater intrusion via aquifer replenishment and delivering irrigation water (Bristow et al., 2000). The replenishment occurs at multiple locations via the use of infiltration basins (Figure 52) and on-farm practices such as ‘recycling’, ‘water spreading’ and recharge channels (Bristow et al., 2000). The infiltration basins in the scheme have a very high recharge capacity - up to 20 ML/day (Dillon et al., 2009b). ‘Recycling’ refers to the use of private production bores to return excess irrigation water back to the groundwater storage through the soil (Bristow et al., 2000). ‘Water spreading’ is where river water that is too turbid to be infiltrated in the basins is made available to irrigators, which some of this water recharging the aquifer past irrigation. Water spreading is managed by Lower Burdekin Water, and prevents to silting up of infiltration basins, instead spreading the silt load across the scheme area (Bristow et al., 2000). The estimates of artificial recharge range from 45 GL/year (Dillon et al., 2009b) to 96 GL/year (Bristow et al., 2000).

The operational, maintenance and infrastructure costs for the scheme are funded by the players of the benefiting irrigated agricultural industry, namely growers and millers of sugarcane, the dominant crop of the region (Bristow et al., 2000). The dominance of sugarcane in the region results in four sugar mills servicing the area (Ash and Watson, 2018). The long-term viability of the mills is ensured via contractual agreements with growers and the establishment of minimum quotas (Ash and Watson, 2018).

Table 24 provides a breakdown of costs, both capital and operational, for the Burdekin scheme, compiled from numerous sources. The levelized cost is similar to the water costs for the proposed dam (Table 21, Table 22, Figure 60). The operating costs of the MAR, based on the calculated operational costs of the 51 infiltration basins managed by Lower Burdekin Water (Table 24), is less than the estimate for the proposed dam (Section 5.4.3).

Table 24 Breakdown of costs in the Burdekin scheme

Capital/Activity	Cost	Cost Reference Year	Source
Construction of two infiltration basins	$2.1 million	2009	(Dillon et al., 2009b)
Operation and maintenance costs of two infiltration basins	$85,000	2009	(Dillon et al., 2009b)
Operation and maintenance costs of the 51 infiltration basins of scheme based in value for two basins in Dillon et al. (2009b)	$2.17 million	2009	http://lowerburdekinwater.com.au/about-us-2/history/north-board/ http://lowerburdekinwater.com.au/about-us-2/history/south-board/
Recharge and recovery of unconfined aquifer via infiltration basins	$0.07/kL ($0.05/kL recharge + $0.02/kL recovery from high yielding bores)	-	(Dillon et al., 2009b)
Water base rate	$16.48/ML - $19.75/ML	2020/21	http://lowerburdekinwater.com.au/wp-content/uploads/2020/08/ADM012-Schedule-of-Rates-Charges-2020-21.pdf, accessed 5th March 2021
Aquifer Maintenance – Infiltration base scrapping	$18,167 Cost for two-year period as scrapping occurs every 2 years (Dillon et al., 2009b)	2018/19	http://lowerburdekinwater.com.au/wp-content/uploads/2019/08/QAO-Approved-Annual-Financial-Statements-2018-19.pdf, accessed 5th March
Levelised cost	**$80/ML**	2017	(Vanderzalm et al., 2018)

Estimated costs of three scheme types (recharge release, infiltration basin and recharge weir) in the Mitchell Catchment were provided in Table 15. Levelised costs of $48/ML for a scheme based on recharge release reflect the assumed existence of a large dam; the higher capital costs and operational costs for schemes based on infiltration basins or recharge weir account for the higher estimated levelised costs ($82/ML and $172/ML). It should be noted that schemes based on either or both of these two recharge strategies could be incrementally developed.

5.4.5 Potential benefits for community

The building of water infrastructure and the expansion of agricultural production in the region would bring economic benefits to the community. Based on the availability of additional water resulting from the proposed dam, over 2,000 jobs are forecast to the be created, both directly in the agriculture industry and indirectly in other industries (Jacobs Australia Pty Limited., 2020). The establishment of a local processing facility (e.g., cotton gin) would assist in providing new employment opportunities for the region (Jacobs Australia Pty Limited., 2020).

Based on financial analysis, the proposed dam would have a 1:1.15 direct economic return to the community (Jacobs Australia Pty Limited., 2020). This analysis excluded employment created by the project.

5.5 Environmental risks

This section considers the potential implication of water development for agriculture in the Gilbert River with emphasis on the ecosystems and fauna and flora that rely (at least in part) on the bed sands adjacent to the Gilbert River in the GRAP. An overview of the environmental importance and ecological characteristics of the catchment is provided in Section 5.5.1. This is followed by a discussion of wetland and floodplain processes (Section 5.5.2) and the constraints on water extractions that are needed to minimise environmental impacts (Section 5.5.3). This leads into a summary of approaches and frameworks from the literature that have been used to design or inform ‘sustainable irrigation development’ (Section 5.5.4).

5.5.1 Environmental assets

Vegetation

The majority of the vegetation communities in the Gilbert catchment are classified as ‘not of concern’ (Figure 61), based on the biodiversity codes from the *Vegetation Management Act 1999* (Petheram et al., 2013). This category is defined as: Remnant vegetation is over 30% of its pre-clearing extent across the bioregion, and the remnant area is greater than 10,000 ha. The categories here are based exclusively on current remnant vegetation extent compared to its pre-clearing extent and the current remnant vegetation area (Petheram et al., 2013). Ford (2010) identified threatened species in a 1,190 km^2 area towards the headwaters of the Gilbert River and into the Einasleigh Uplands Bioregion, identifying pockets of near threatened and vulnerable species based on the threatened species list produced by Queensland Government. Regions of regulated vegetation, which determine clearing requirements [80], for the GRAP are shown in Figure 62.

[80] https://www.resources.qld.gov.au/__data/assets/pdf_file/0006/1447098/general-guide-vegetation-clearing-codes.pdf, accessed 17 March 2021

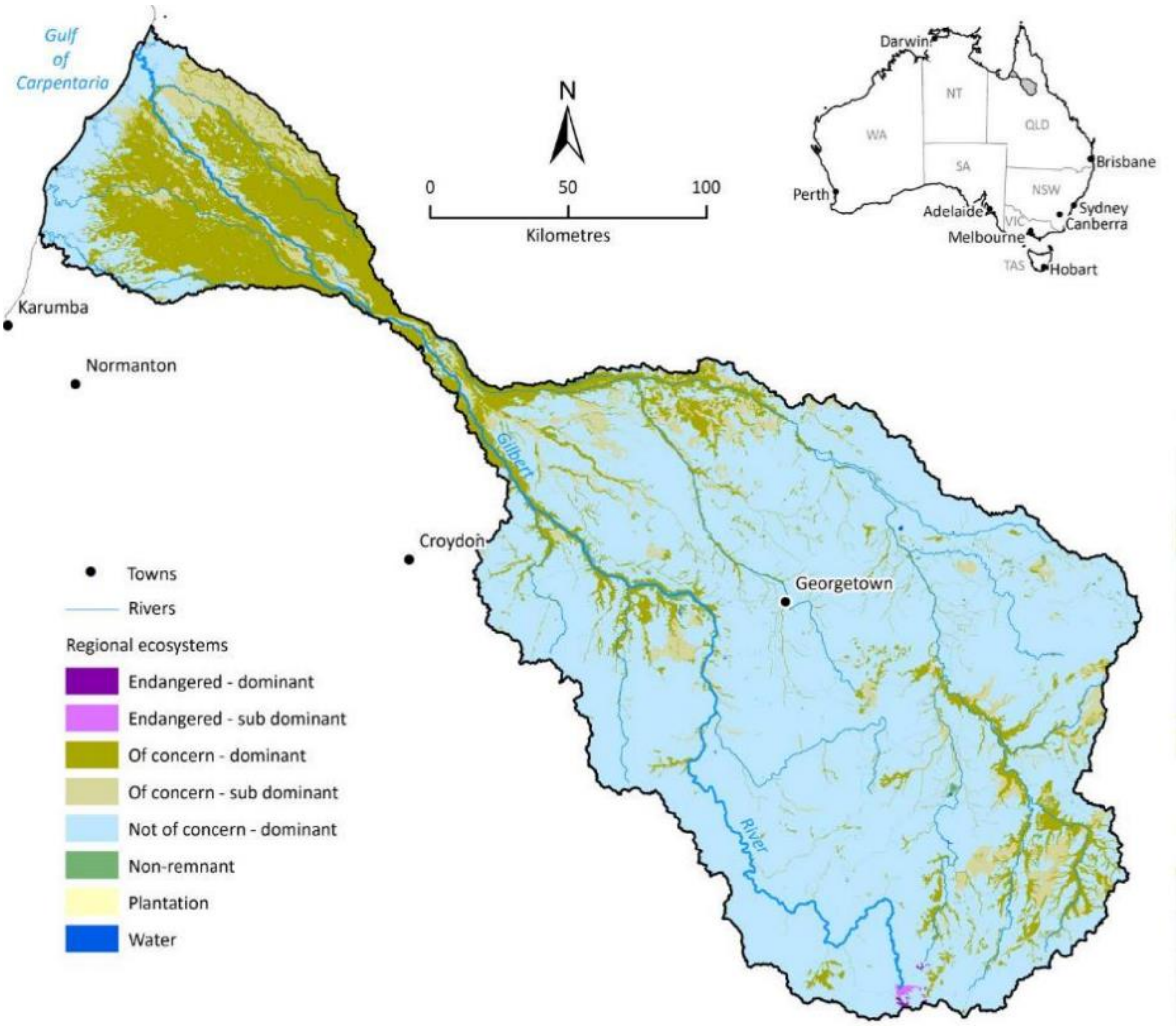

Figure 61 Status of regional ecosystem (vegetation) biodiversity for the Gilbert catchment (Source: Petheram et al., 2013).

Fauna

Impediments, such as instream dams, pose a risk to the movement of fish species. Species at particular risk in the Gilbert catchment included barramundi (*Lates calcarifer*), freshwater sawfish (*Pristis microdon*) and freshwater whipray (*Himantura dalyensis*) (Petheram et al., 2013). Other aquatic species in the catchment may be less impacted by the building of infrastructure, but instead possibly be affected by changes in flow regimes and waterholes. These species include freshwater turtles, frogs, crustaceans and crocodiles (Petheram et al., 2013).

Waterholes

The waterholes that persist into the dry season in the Gilbert catchment provide habitat for a wide range of aquatic species, especially during the dry season in intermittently flowing rivers (Waltham et al., 2013).

The water level in most waterholes in river reaches are in equilibrium with the water table of the river bed sands (Petheram et al., 2013). Pumping water from the bed sands has been suggested to cause the water level in nearby water holes to drop at a faster than usual rate (Petheram et al., 2013). Compared to the other major river in the catchment, the Einasleigh River, the Gilbert River has less persistent and smaller waterholes (see Figure 12). The waterholes that form in the Gilbert River once flow has stopped are mobile in nature, forming in different locations at the end of each wet season (Petheram et al., 2013).

Good water quality, with high clarity, is important to ensure efficient light penetration at all depths of waterholes (Petheram et al., 2013). Other quality characteristics, for example temperature and dissolved oxygen concentration, can cause stress on the flora and fauna that seek refuge in the waterholes throughout the dry season (Petheram et al., 2013).

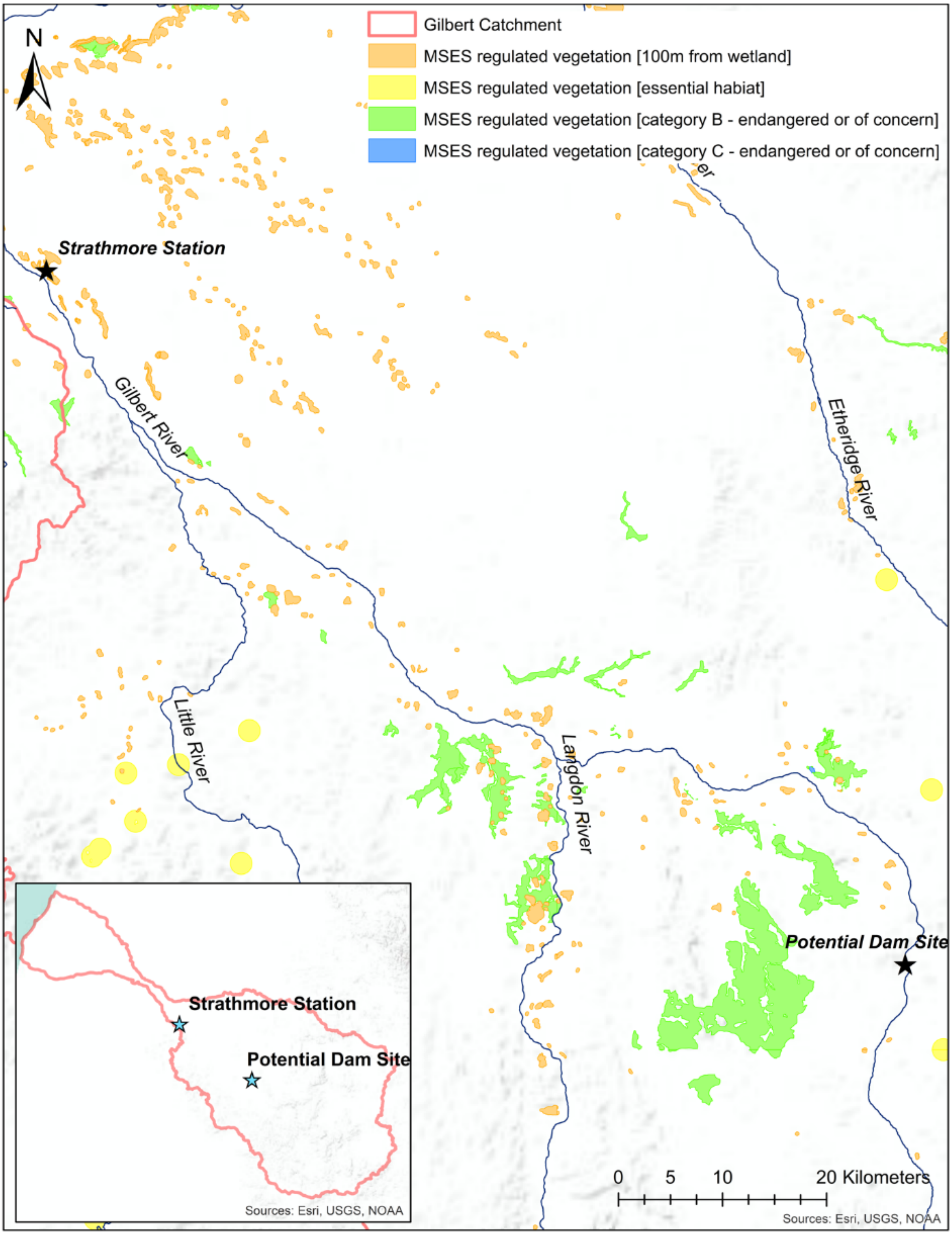

Figure 62 Regulated vegetation mapping based on QLD Matters of State Environmental Significance (MSES).

In terms of the impact of possible irrigated agriculture development on waterhole ecology, the major threats are (Waltham et al., 2013):

1. Large sediment loss, being further exacerbated when stubble retention and minimum tillage practices are not employed
2. Large nutrient (e.g., phosphorus and nitrogen) losses
3. Large herbicide losses

Large herbicide losses may be reduced when planting cotton, as GM cotton varieties do not require the same magnitude of herbicide and pesticide use compared to other crops. (Waltham et al., 2013).

Groundwater dependent ecosystems (GDEs)

Tea-tree (*Melaleuca* spp.) forests and woodland are thought to be the major groundwater dependent ecosystem (GDE) in Northern Australia (O'Grady et al., 2006, Eamus et al., 2006, Eamus et al., 2016), with occurrences noted in the Gilbert catchment (Ford, 2010). These ecosystems have been described as opportunistic users of groundwater and are not entirely reliant upon groundwater (Murray et al., 2003).

In the Gilbert catchment, Ford (2010) identified that a small tea-tree (*Melaleuca leucadendra*) community on creek alluvium was fed by an underlying semi-permanent sandstone spring. The springs of the Gilbert catchment are concentrated in the uplands/headwaters of the system (Figure 70), so it is plausible that GDEs are present there. How this relates to the middle reaches of the Gilbert River is less clear; however from the Australia wide maps produced by Doody et al. (2017), the Gilbert catchment has areas with high potential of being GDEs, both in terms of vegetation ecosystems (Figure 63, Figure 64) and ecosystems that require surface expression of groundwater (Figure 65). The mid lengths of the Gilbert River, the GRAP, are predicted to have a high potential of being a GDE based on national assessments (Figure 64, Figure 65). However, there are no ***known*** GDEs in the GRAP based on this assessment (Figure 65). Determining the degree of dependency of an ecosystem on groundwater is difficult, requiring years of site study (Eamus et al., 2006, Eamus et al., 2016) and this has not been done in the Gilbert catchment. If the ecosystem is an opportunistic user of groundwater it may require study during drought to determine dependency (Eamus et al., 2006, Eamus et al., 2016). However, there are ways to infer an ecosystems groundwater dependence, including studying river flows, wetlands, groundwater levels and remote sensing imagery (Eamus et al., 2006, Eamus et al., 2016). Such methods could be incorporated into a full impact assessment of the AOI.

Threats to GDEs include depleting groundwater reserves, altering groundwater regimes and degrading groundwater quality (Eamus et al., 2006, Eamus et al., 2016).

No monitoring data is available to assess the impact of water take on bed sand ecosystems. However, a risk assessment by the QLD Department of Science, Information Technology, Innovation and the Arts (DSITIA, 2014) looked at the impact of water extraction from the bed sands of the Gilbert River on riparian vegetation (DNRME, 2018a, DSITIA, 2014). This study suggested that under full utilisation of entitlements, drawdown in the bed sands would be below the root zone (2.5 m depth) for a small percentage (4.5%) of the simulation period (DNRME, 2018a, DSITIA, 2014). This estimated amount of drawdown was considered low risk to adult trees although establishment of *Melaleuca* seedlings may be negatively affected (DNRME, 2018a, DSITIA, 2014). However, full utilisation of bed sand entitlements has not occurred in the past several years (Section 5.2.1) (DNRME, 2018a).

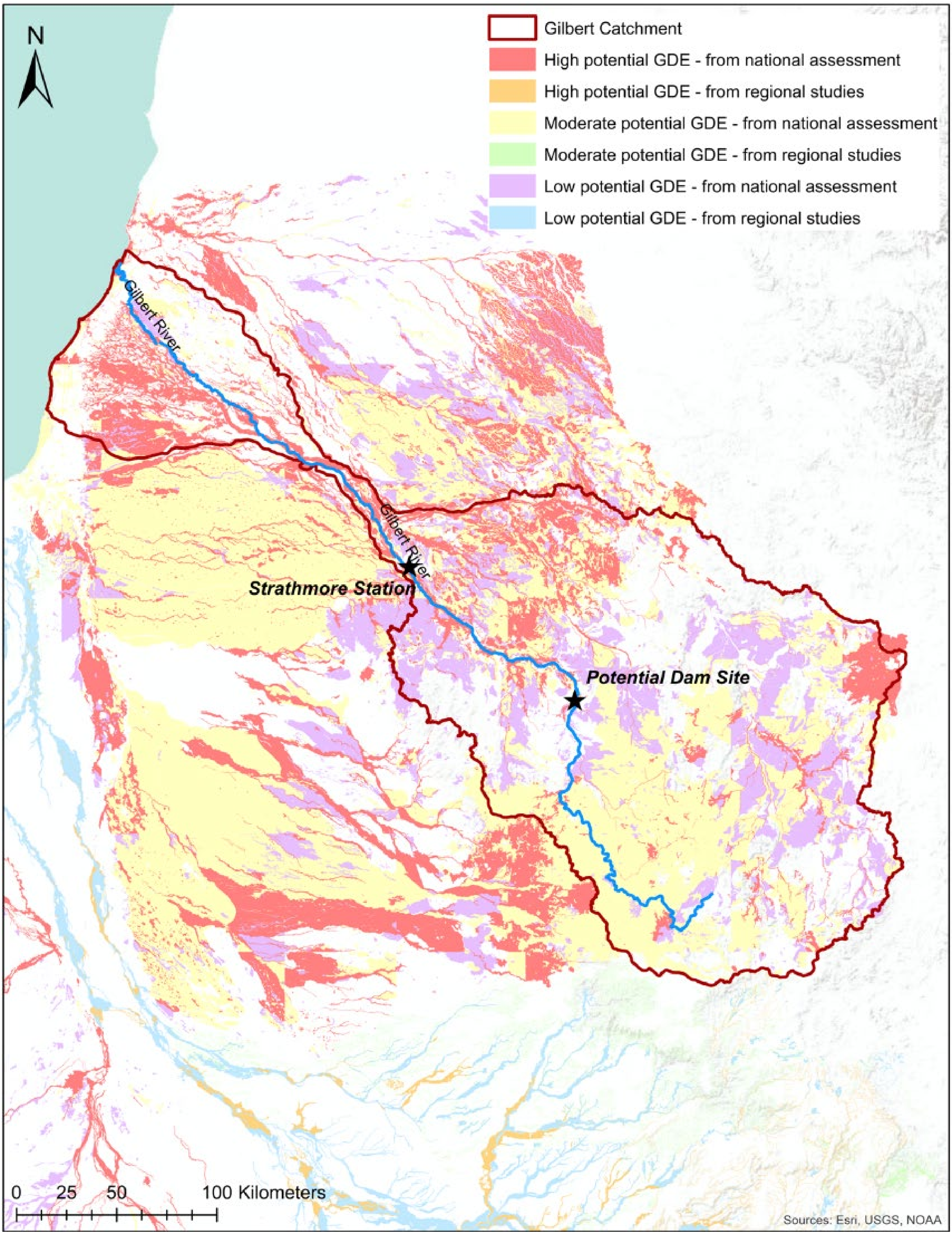

Figure 63 Potential groundwater dependent ecosystems of the Gilbert catchment and neighbouring areas that rely on the subsurface presence of groundwater (e.g., vegetation). Data from Bureau of Meteorology [81]. For methods see Doody et al. (2017).

[81] http://www.bom.gov.au/water/groundwater/gde/map.shtml, accessed 12 March 2021

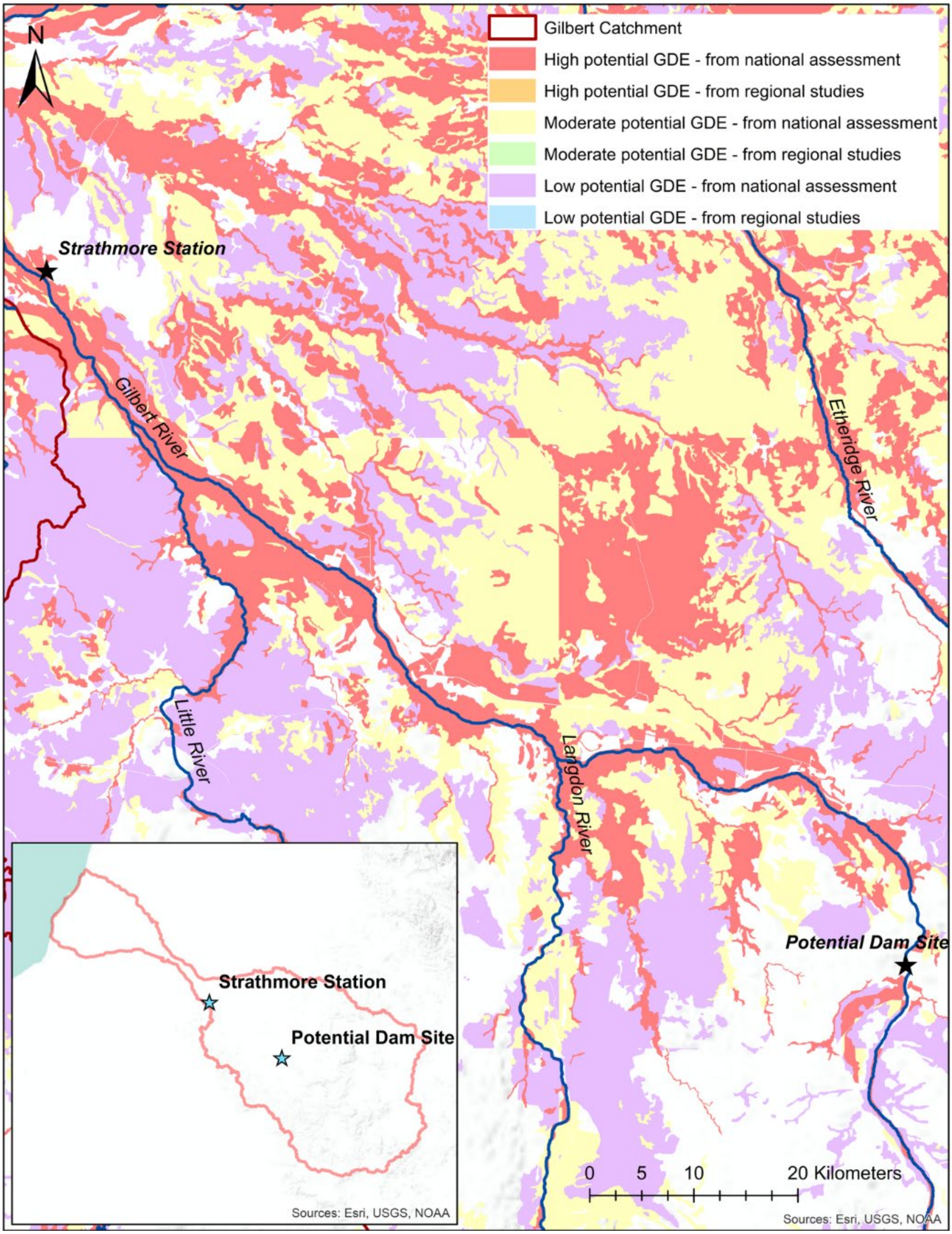

Figure 64 Potential groundwater dependent ecosystems of the area of interest that rely on the subsurface presence of groundwater (e.g., vegetation). Data from Bureau of Meteorology [82]. For methods see Doody et al. (2017).

[82] http://www.bom.gov.au/water/groundwater/gde/map.shtml, accessed 12 March 2021

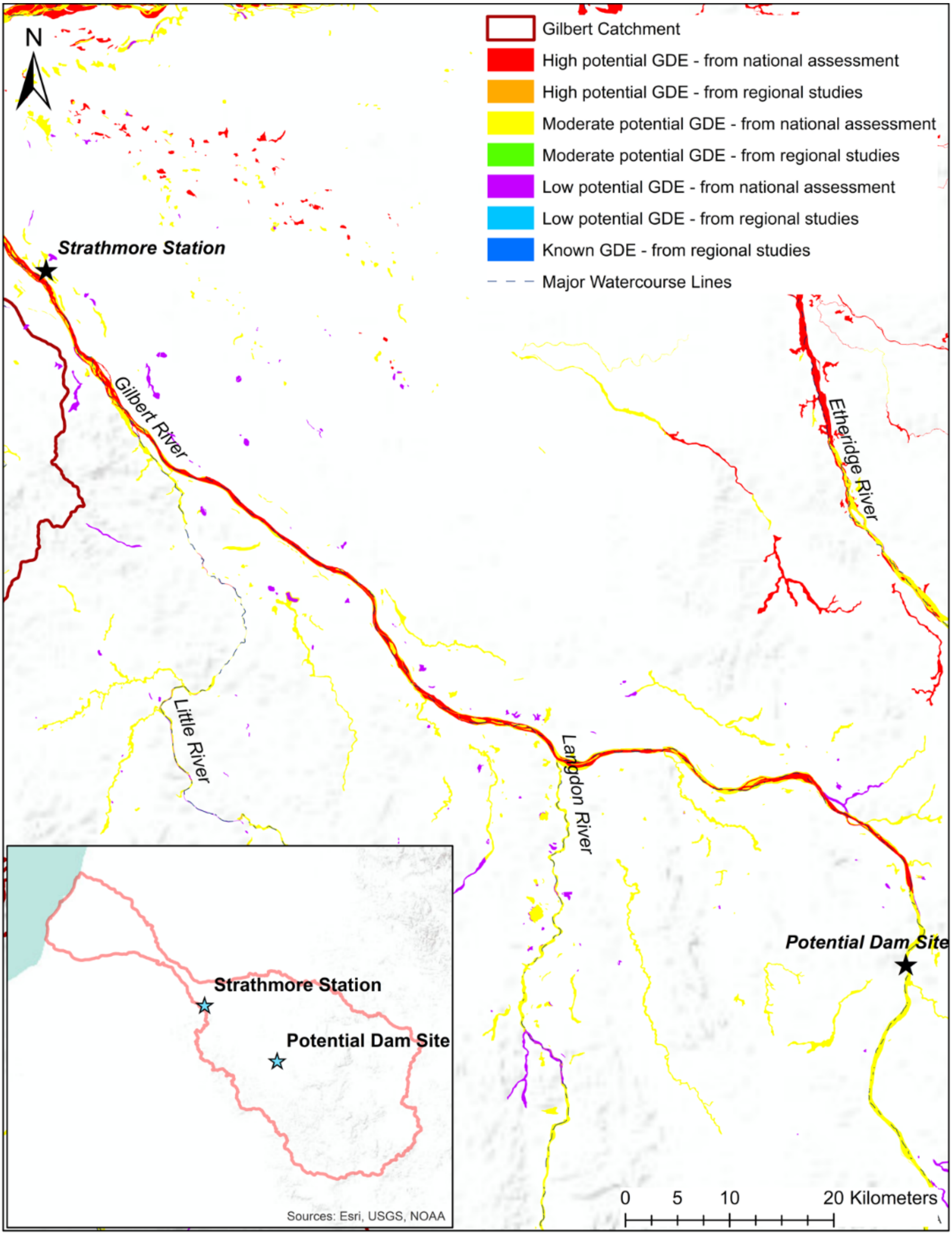

Figure 65 Potential groundwater dependent ecosystems of the area of interest that rely on the surface expression of groundwater (e.g., springs, wetlands and rivers). Data from Bureau of Meteorology [83]. For methods see Doody et al. (2017).

Hyporheic environments

Alluvial rivers are often associated with subsurface flows through the hyporheic zone – saturated sediments of the river bed (Figure 66) (Hancock et al., 2005, Stanford and Ward, 1993). Water can be supplied to the hyporheic zone from both the overlying river and the underlying aquifers (Stanford and Ward, 1993, Boulton et al., 1998). Water from both these sources frequently exchanges (Boulton, 2007). Hyporheic flows are able to provide water to nearby wetlands, as well as support an ecosystem themselves.

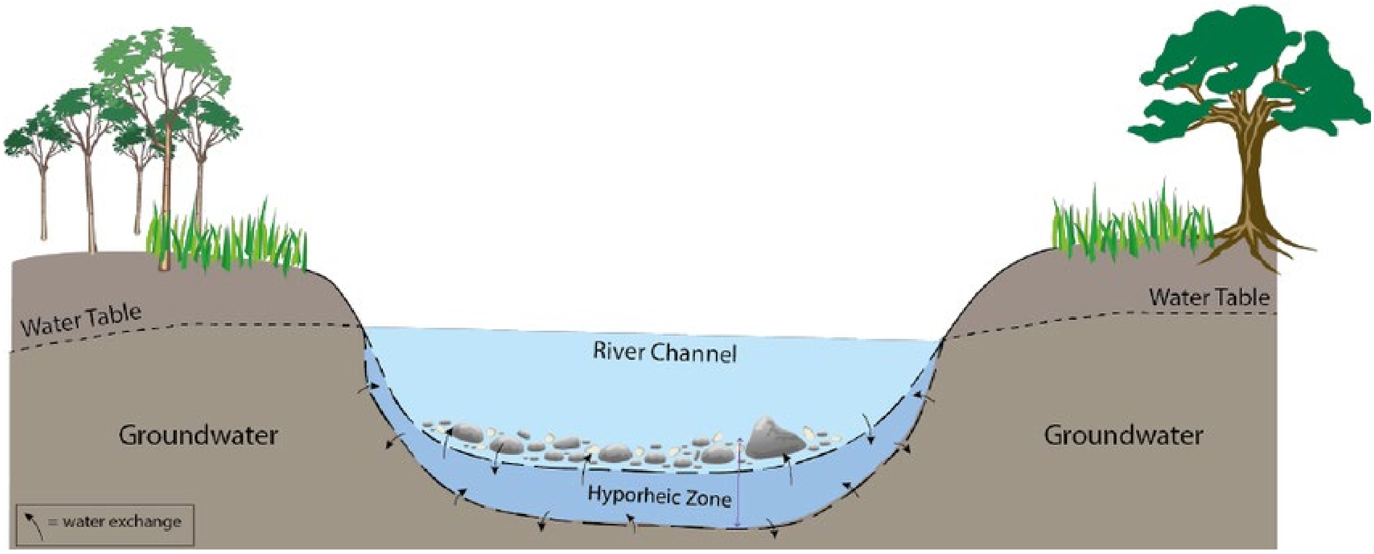

Figure 66 Depiction of the hyporheic zone (Source: Biddulph, 2015).

Although noted as an important ecosystem in many of the documents that inform water policy in the Gulf and the Gilbert River (see Section 5.7.1), little is known about the hyporheic zone of Gulf rivers (Close et al., 2012).

Subsurface hyporheic flows in the Gilbert River extend beyond the cease-to-flow period and into the dry season (Close et al., 2012). These flows are sustained by groundwater discharge (Kennard et al., 2011) from deep sand beds in the mid to low reaches of the river (Close et al., 2012). The bed sands of the Gilbert River are home to a diverse range of aquatic fauna (Greiner et al., 2009).

Presumed ecologically important subsurface flows in the hyporheic zone of Gulf rivers may be impacted by water development, both groundwater and surface water (Close et al., 2012). The water to meet the needs of agriculture activities, besides grazing, along the Gilbert River are predominantly sourced from the near-perennial hyporheic flows in the river bed sands (Close et al., 2012). There is concern that the current water licences from the bed sands may be close to or at the upper limit (Close et al., 2012). Because of this, there may already be current impacts of this extraction on the hyporheic zone (e.g., persistence, duration of surface pools for refugia, impacts on hyporheic fauna) but, if occurring, these impacts are not well known or documented (Close et al., 2012).

Wetlands and floodplains

There are wetlands in the Gilbert catchment (Figure 70) and the GRAP (Figure 67). These wetlands are commonly associated with the rivers and creeks of the area (Figure 67). Wetland inundation is an important ecological process in the catchment (see Section 5.5.2).

[83] http://www.bom.gov.au/water/groundwater/gde/map.shtml, accessed 12 March 2021

Other than the larger coastal floodplains, the seasonal nature of the catchment means that smaller floodplains occur throughout the Gilbert catchment, away from major watercourses (Figure 68). Many of these areas experience high recharge rates (Figure 68).

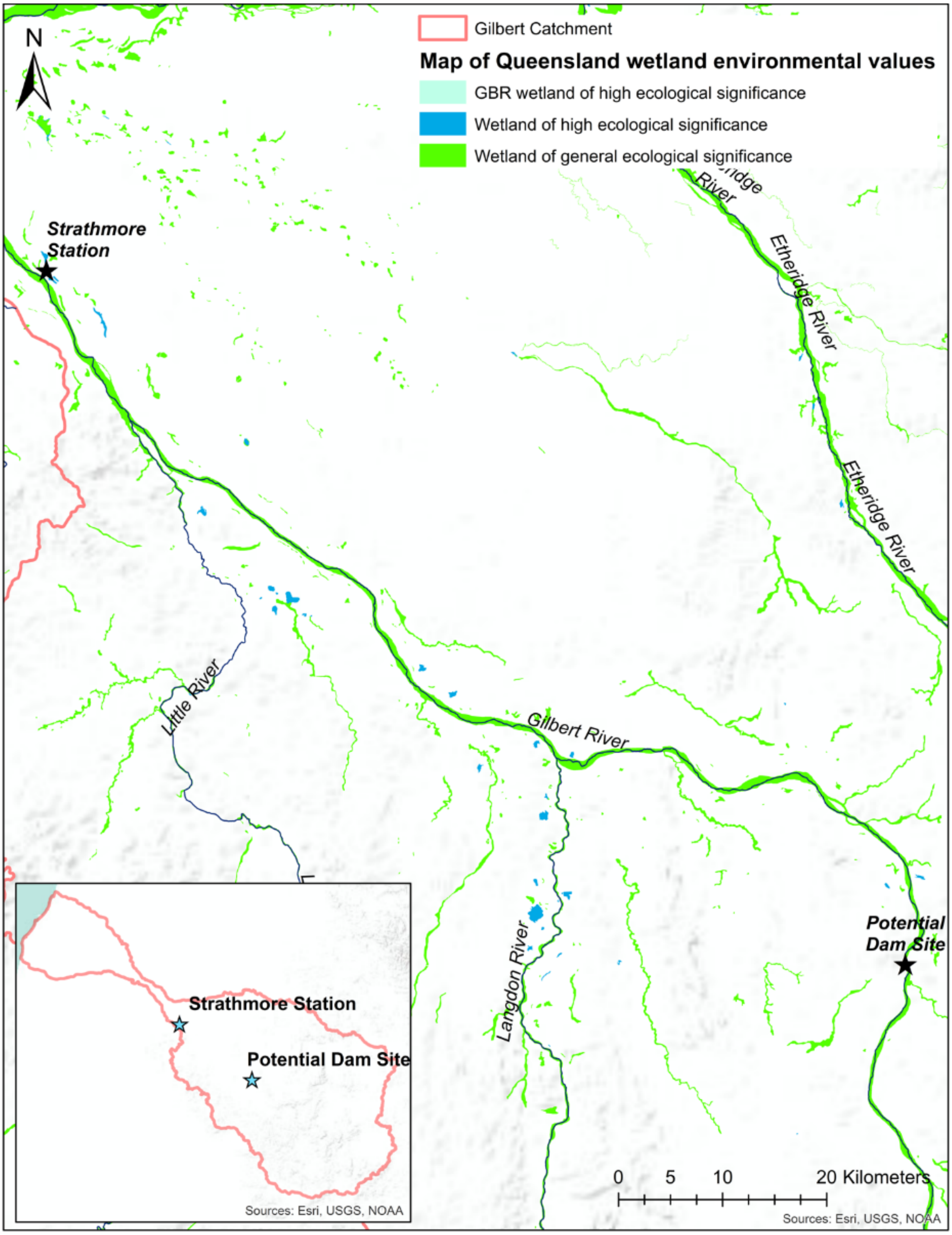

Figure 67 Wetlands in the GRAP. Data source: Wetland maps under the Environmental Protection Act 1994[84]

[84] https://environment.des.qld.gov.au/wildlife/wetlands/map-referrable-wetlands, accessed 18 March 2021

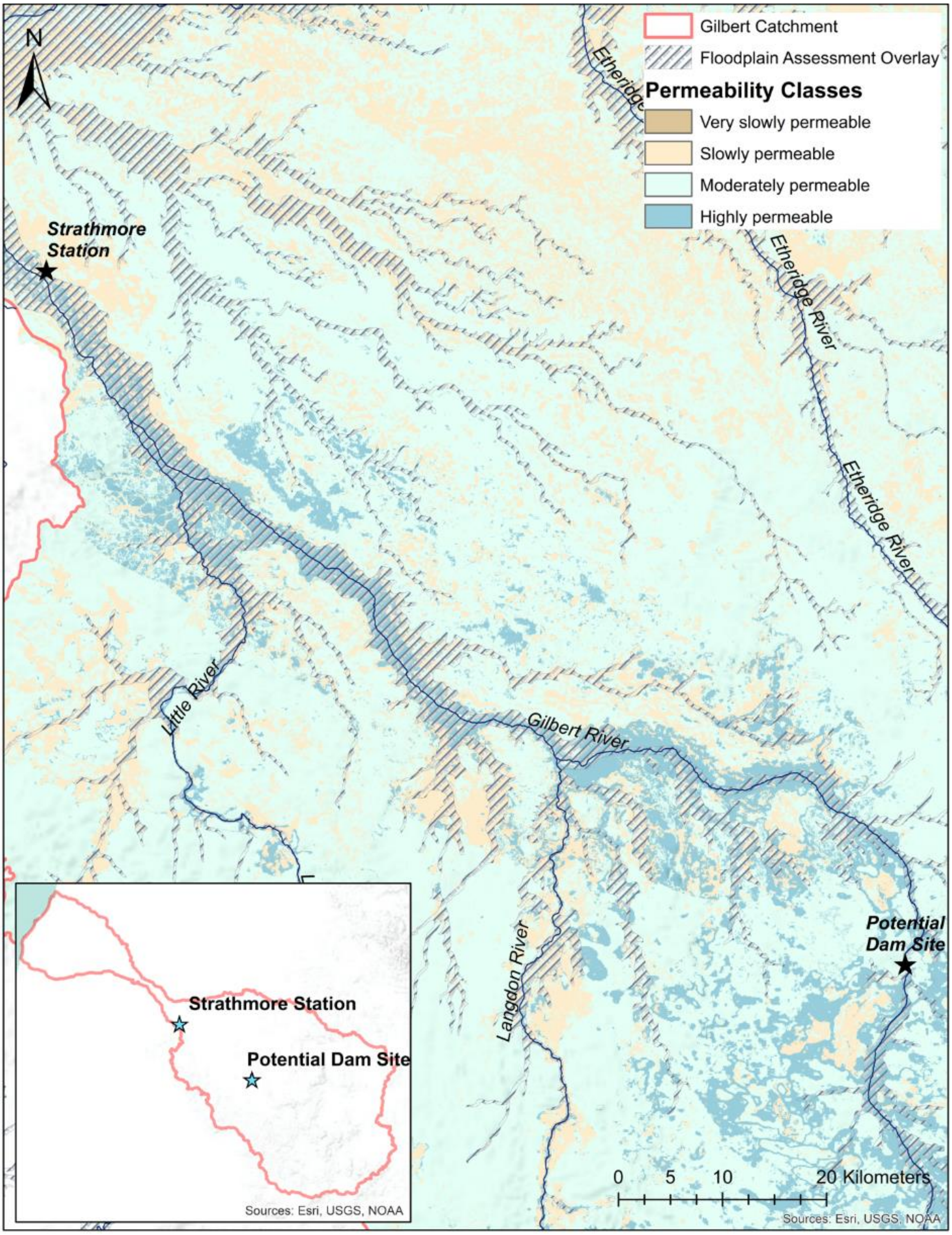

Figure 68 Floodplains in the GRAP. Data source: Queensland floodplain assessment overlay[85]

Prawn industry

Catchment flows into the estuaries of temperate and tropical Australia have a direct relationship to fishery catch (Petheram et al., 2013). Nutrients from the estuary stimulate primary production which provide food for fish, prawns and crabs (Petheram et al., 2013). Streamflow into the estuaries also promotes movement

[85] http://qldspatial.information.qld.gov.au/catalogue/custom/viewMetadataDetails.page?uuid=%7B0944E8CD-8618-4100-B7DC-8C87CC74736C%7D, accessed 18 March 2021

of species out of the estuaries for reproduction and increases catchability (Figure 69) (Petheram et al., 2013, Griffiths et al., 2014). This is true for the Gulf of Carpentaria prawn fishery, which experiences a strong positive relationship between streamflow and fishery production; i.e. higher number of prawn landings after an above average wet season (Petheram et al., 2013). The FGARA research concluded that the relationship between streamflow, estuaries and fisheries productivity should be considered from both an environmental and economic perspective when assessing suitability of an area to water resource development (Petheram et al., 2013). In the Gilbert catchment and surrounding catchments, a model-based study suggested that water extraction during low flow periods would have the greatest impact on fishery catch (Broadley et al., 2020). Protecting low flows, especially during dry years, should act to preserve the link between terrestrial and marine environments, a link that the fisheries industries in the Gulf rely on (Broadley et al., 2020). Both a fisheries industry and an agriculture industry in the Gilbert (and other Gulf catchments) are thought to be feasible if water extraction for agriculture occurs during periods of high flows (Broadley et al., 2020).

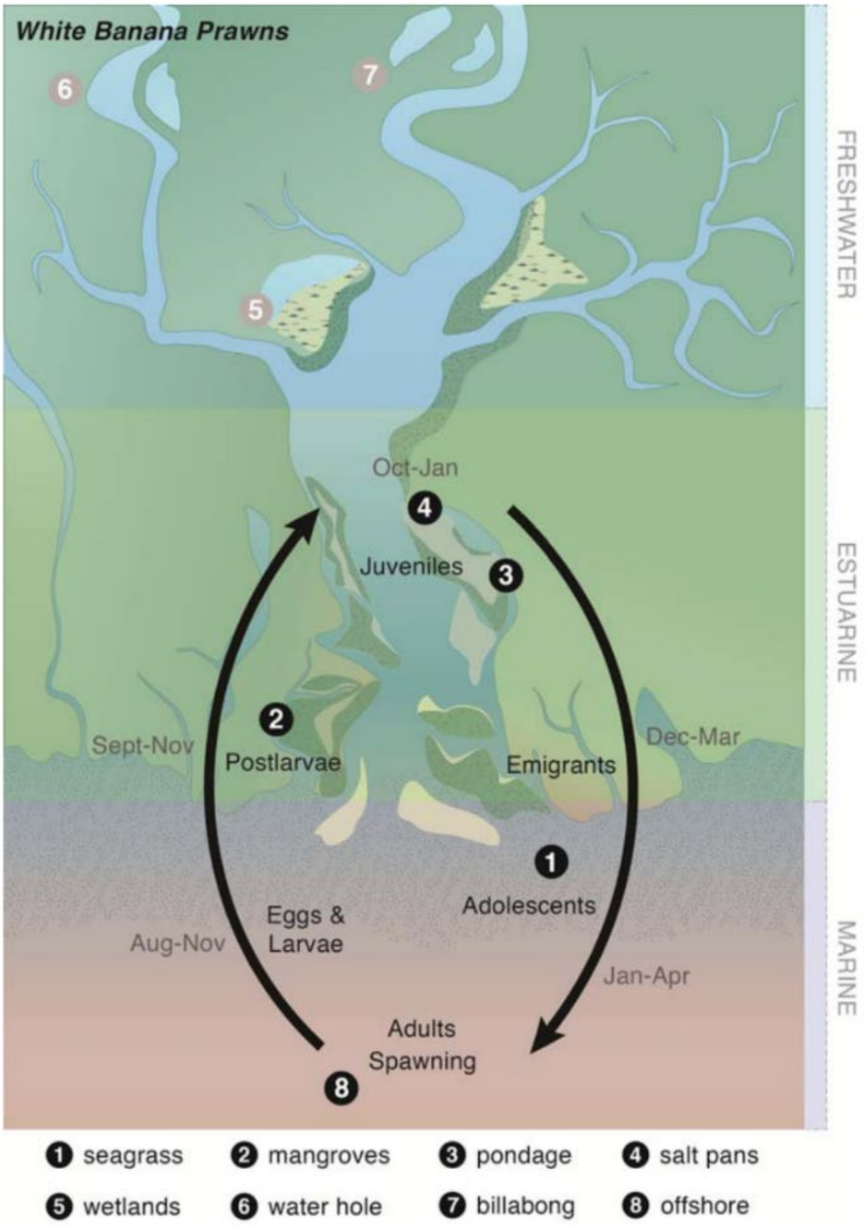

Figure 69 Conceptual model of the life history of the White Banana Prawn (Penaeus merguiensis) illustrating its use of marine and estuarine habitats in the Gulf of Carpentaria Source: Griffiths et al. (2014).

Important/protected areas

There are multiple recognised areas of ecological importance in the Gilbert catchment (Petheram et al., 2013, CSIRO, 2009, Karim et al., 2015) (Figure 70).

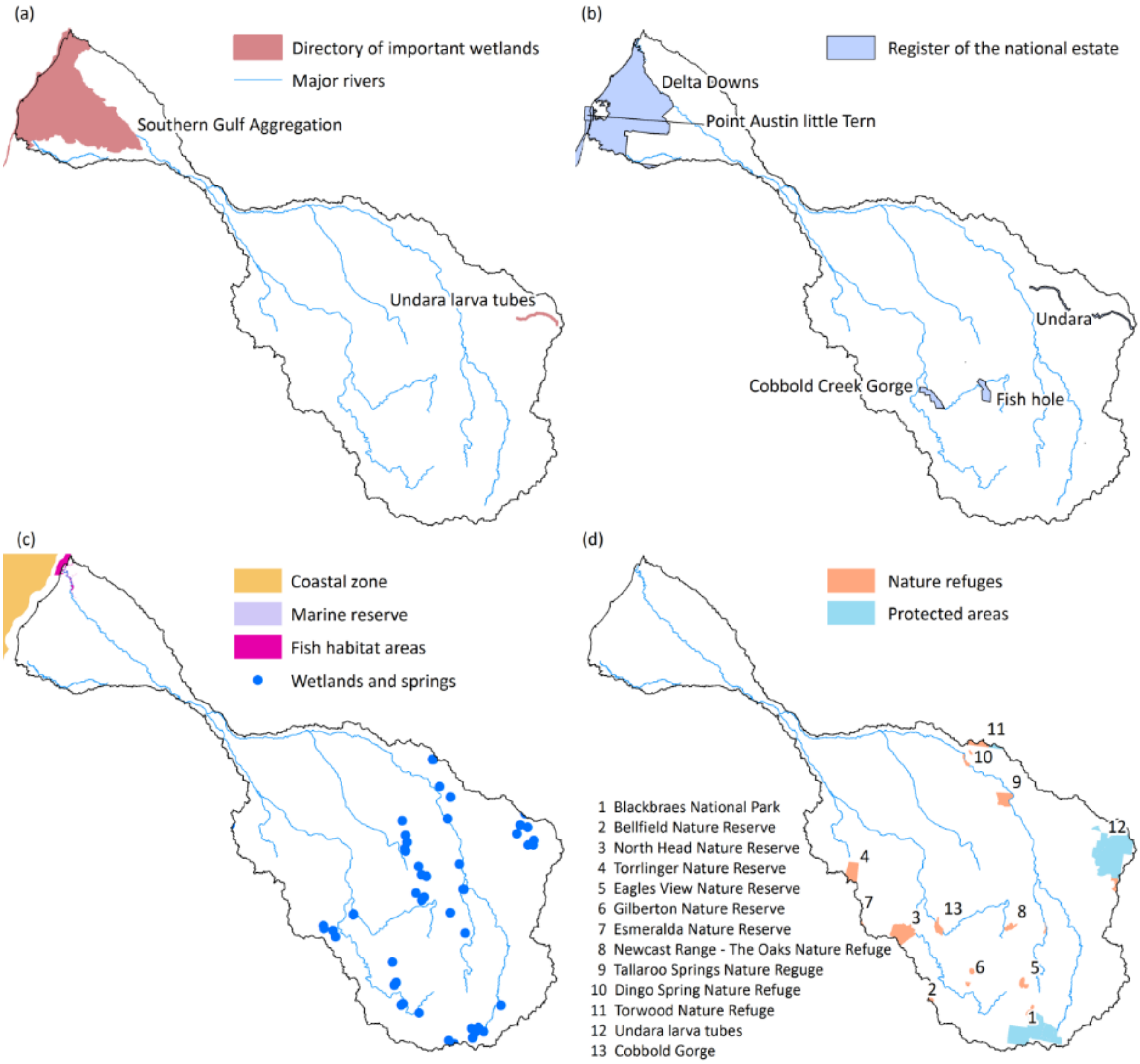

Figure 70 Important ecological assets and protected areas in the Gilbert catchment (Source: Petheram et al., 2013).

5.5.2 Wetland and floodplain processes

The connection of wetlands and floodplains in the Gilbert catchment to rivers during high flow periods allows for migration of species and nutrients exchanged between these systems that are disconnected for the dry season (Petheram et al., 2013, Karim et al., 2015). It follows that changes to the frequency and magnitude of high flows could disrupt these processes and have environmental consequences.

Wetlands in the Gilbert catchment are thought to be dependent on flood pulses to facilitate biophysical exchanges (Karim et al., 2015). Previous modelling work showed that the construction of large instream dams could reduce the duration of connectivity between the wetlands and rivers in the Gilbert and Flinders catchments by 2% (Karim et al., 2015). This reduction in connectivity is less than the modelled reduction resulting from a drier climate (Karim et al., 2015).

A recent report focused in both the Gilbert and neighbouring Flinders catchments investigated the main drivers of floodplain inundation (Ndehedehe, 2020). From this research it was suggested that local rainfall over the floodplain area (i.e., downstream of the convergence of the Gilbert and Einasleigh Rivers) was the main driver of floodplain inundation extent (Ndehedehe, 2020). However, the importance of river discharge should not be understated, in terms of both floodplain inundation extent and floodplain productivity (Ndehedehe, 2020). The larger rainfall volumes and large discharge volumes in the Gilbert catchment suggest that, compared to the Flinders, water extraction and infrastructure (e.g., dams) upstream of the floodplains will be less likely to disrupt floodplain processes (Ndehedehe, 2020). This is not to say that water development will have no effect on floodplain inundation processes in the Gilbert catchment, with possible consequences being changes to flow variability and discharge volumes (Ndehedehe, 2020). The riparian vegetation present in the catchment acts to filter the runoff before it reaches streams and rivers, while reducing erosion (Petheram et al., 2013).

Floodplain inundation also has a direct link to the formation of aquatic habitats including waterholes (Ndehedehe, 2020). Both the persistence of waterholes and the accumulation of biomass within them is linked to floodplains rivers exceeding their banks during extreme wet periods (Ndehedehe, 2020).

Identified threats to these areas include cattle grazing, feral pigs and infestation of rubber vine (*Cryptostegia grandiflora*) and other invasive flora species (Waltham et al., 2013).

5.5.3 Timing of water extraction to minimise environmental impacts

The impacts of surface water extractions from the river (or bed sands) in the Gilbert catchment, and within the GRAP, will vary depending on when water is extracted from the system. The Northern Gulf inland waters regional NRM assessment (NGRMG, 2015) summarised potential threats by flow class from proposed surface water development in the Gilbert Catchment – the proposed Greenhills and Dagworth dams – and mitigation strategies to address the threats (Table 25).

High flows

An event thought to have major environmental benefit in the North is the first flush event (Petheram et al., 2013). The first flush event renews streams and waterholes that haven't seen substantial rainfall since the end of the last wet season (Petheram et al., 2013). It has been suggested that extraction of water should occur after this first flush event (i.e., first large rainfall event of the season), however identifying what constitutes a first flush event is problematic; set rules on extraction that consider first flush avoidance are difficult to define (Petheram et al., 2013).

As long as water extractions avoid the first flush event, it has been proposed that environmental impacts can be minimized by only extracting water during periods of high flows (Petheram et al., 2013, Broadley et al., 2020). This is mirrored in the current surface water policy, where flow restrictions have been set for the currently unallocated water (Table 10, Figure 23, Figure 24).

Low flows

Like many other processes in the Gilbert catchment the lack of data complicates the identification of definite ecological impacts resulting from changes to the system (CSIRO, 2009). Site-specific flow metrics relating to ecology, the impacts on ecosystems to alterations in low or zero flows and the importance on inundation extent and duration are all significant unknowns (CSIRO, 2009).

Table 25 Potential impacts of proposed surface water resource development in the Gilbert River (by flow class) and strategies identified that would mitigate these impacts (Source: NGRMG, 2015).

Flow Class	Potential threats from water resource development	Related ecosystem components	Mitigation strategies proposed in the Gilbert*
No flow – low flow	Capture of low flows by storages and increase in the duration and number of no flow spells Pumping of waterholes and bed sands during spells without flow	Waterholes as refugia Stable flow spawning fish (Eastern rainbowfish)	Inflow-outflow rules proposed for both Dagworth and Green Hills Dams.
Low – medium flow	Capture of low and medium flows by storages Loss of seasonal migratory opportunities and cues Loss of ephemeral nature of system	Migratory fish (Hyrtl's tandan, Narrow-fronted catfish, Spangled perch and Largetooth sawfish)	As above
High flow (1 in 2-year flow events)	Capture of high flows by instream storages and water harvesting Loss of seasonal migratory opportunities and cues Reduced connectivity of system	Freshwater turtles (Northern snakenecked turtle, Cann's long-necked turtle) Fluvial geomorphology and river forming processes (including sediment load and nutrient export) Barramundi and Banana prawns	Jan – Mar first wet season flow (provide for fisheries migration) Water harvesting developments without instream storages have been recommended
Overbank flow (1 in 10 year flow events)	Capture of overbank flows by instream storages and water harvesting Loss of connectivity to floodplain	Floodplain energy subsidy to riverine food webs, Floodplain wetlands, Floodplain vegetation	The impacts to overbank flows were not able to be mitigated under the Greenhills and Dagworth Dam scenario, but are able to be mitigated under water harvesting development scenarios

5.5.4 Sustainable irrigation development

Established irrigation development schemes in river basins or catchments have often followed a similar trajectory of utilization of available resources leading to water scarcity and a shift in management focus towards managing demand to fit the available supply and redressing environmental and social damage from overexploitation (Lorenzen et al., 2006). Reflecting the troubled history of irrigation development in southern Australia, and globally (including tropical regions), calls for water resource development and expansion of agriculture in Northern Australia and the Gilbert River catchment are accompanied by pleas for any development to be sustainable (Petheram et al., 2013, Barber, 2018, Waltham et al., 2013, Crossman and Bark, 2013). Camkin et al. (2008) notes community expectations are now that developments will have acceptable environmental impacts as well as deliver social and economic benefits to the community. The authors argue that there is 'a unique and historic opportunity to ensure that management of Australia's northern water resources takes place within a strategic, ecologically, culturally and economically sustainable framework'.

This subsection introduces the underpinnings and principles of sustainable development. Drawing on literature both a developed and developing country perspective, an overview is then provided of frameworks and processes to support research into sustainable agricultural or water resource development in northern Australia.

Sustainable development

Sustainable development – comprised of economic development, environmental protection, and social development – ensures the needs of both present and future generations are met (McConville and Mihelcic, 2007). The intent is on development for common interest (society not individuals) now and into future (Plantey, 1999, McConville and Mihelcic, 2007), with an emphases on equity and transparency (Plantey, 1999), and an inclusive and integrated approach to the design, implementation and monitoring of projects (Camkin et al., 2008). Camkin et al. (2008) note that the success of development for irrigation in norther Australia "will require transparency and accountability to local communities, ongoing monitoring and early identification of emerging problems, and funding to deal with unexpected problems that invariably occur well after development". This emphasis on community is also noted by McConville and Mihelcic (2007) who conceptualise the social development dimension of sustainable development as being comprised of sociocultural respect, community participation, and political cohesion.

The above definition of sustainable development is consistent with the Gulf Water (2007) Plan requirement for social, economic and ecological outcomes from water development and use. The Etheridge Shire Council, similarly has expressed the importance of proceeding with caution and deliberation to build local community support to grow the GRAP sustainably. As mentioned in Section 5.1.3, local participants at the Gilbert River Agricultural Forum, expressed the desire that future agricultural development would retain the character of the catchment and support local development and jobs. With concern about the impacts of water development and extractions on the environment (Section 5.5.3), and the uncertainty around the impact of extractions from river bed sands on hyporheic zone and GDE, there is a clear need for integrative and reflective approaches that will support research and practice toward sustainable development in the Gilbert River catchment. The strong Indigenous history in the region should also be considered when evaluating developments, with participation from Indigenous groups (Petheram et al., 2013).

Impact assessment process of new water infrastructure for irrigation or flood mitigation

Impact assessment is an essential component of construction projects although the approach for impact assessment can vary considerably depending on the nature and scale of a project. In developing a checklist for assessing sustainability performance of construction projects, (Shen et al., 2007) take a project life cycle approach that outlines economic, environmental and social sustainability factors to consider against the inception, design, construction, operation and demolition phases of a project; some examples of factors included in their checklist are given in Table 26. For irrigation development and flood mitigation projects designed to positively impact regional communities and economies, a process that integrates across biophysical, social and economic dimensions, and which engages with communities and stakeholders is needed.

In an International Water Management Institute (IWMI) guidance manual on management of impacts of irrigation development on fisheries, Lorenzen et al. (2006) outlined an iterative process for impact assessment (Figure 71). This process can be generalised to other ecological (e.g. wetlands or waterholes), economic or sociocultural impacts. Important characteristics are that major stakeholders and community are represented and participate in the process, and that the process is flexible and responsive with due consideration given to monitoring and adaptive management. This allow the identification of specific approaches and methods in response to local priorities, capacity and knowledge and supports the effective integration and use of both local and scientific knowledge (Lorenzen et al., 2006).

Table 26 Life cycle approach to assess the sustainability of construction projects (Shen et al., 2007)

Sustainability dimension	Factors to be assessed
	Inception phase
Economic	Supply and demand, marketing forecast, scale and business scope, effects on local economy, life cycle profit analysis, capital budget, finance plan, investment plan
Social	Land use, conservation of cultural and natural heritage, employment, infrastructure capacity-building, community amenities, safety assessment
Environment	Eco-environmental sensitivity, ecological impacts, air, water, noise, waste
	Design phase
Economic	Consideration of life cycle cost, project layout, materials choice
Social	Safety design, security consideration
Environment	Energy savings and environmental issues, life cycle design, environmentally conscious design, modular and standardised design

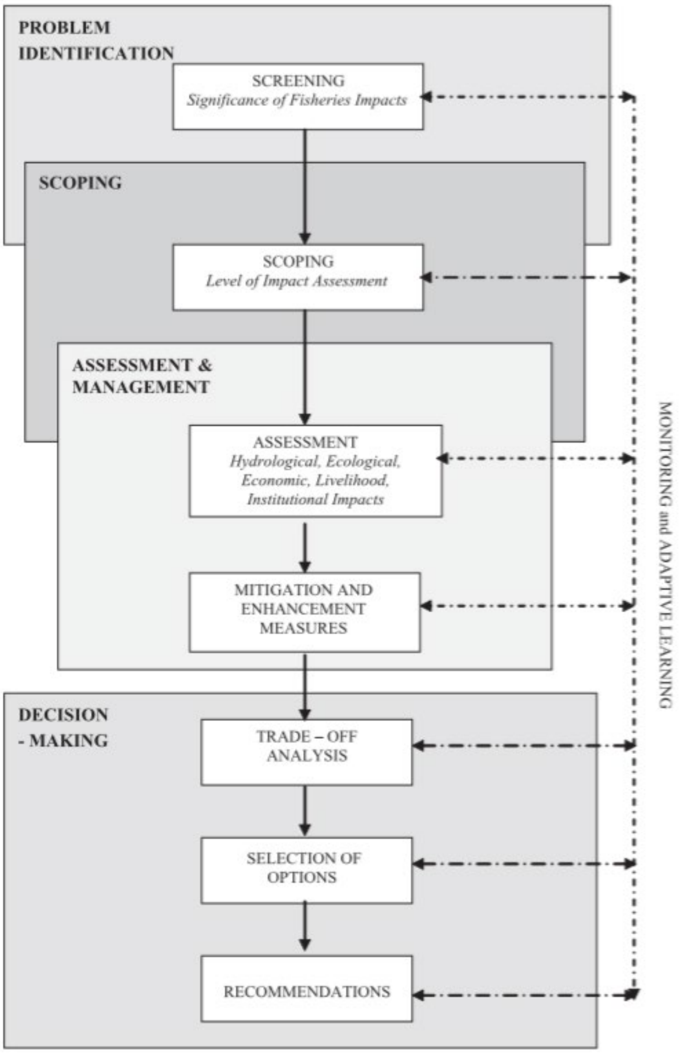

Figure 71 Assessment process for impacts of irrigation on fisheries (Lorenzen et al., 2006).

Recent developments in research or development innovations

Responsible Research and Innovation (RRI): RRI has gained attention over the last decade to guide 'socially and ethically acceptable innovation' that aims to anticipate the implications of innovations and proactively respond to societal concerns (Eastwood et al., 2019). It can be conceptualised in the anticipation-inclusion-reflexivity-responsiveness (AIRR) framework (Figure 72). The approach has been used in relation to emerging technologies where a broad range of public concerns can exist and there is an 'institutional void'. In these situations, collective stewardship of science and innovation is needed into ensure good outcomes in the future. Stilgoe et al. (2013) define RRI as *"a transparent, interactive process by which societal actors and innovators become mutually responsive to each other with a view to the (ethical) acceptability, sustainability and societal desirability of the innovation process and its marketable products (in order to allow a proper embedding of scientific and technological advances in our society)."*

Transitions research and management: transition research investigates the establishment of sustainable regimes through tracking how incumbent regimes are disrupted and replaced over time (Smith and Stirling, 2010). Transition management embeds this perspective within an iterative, four-stage *cyclical* governance framework (Table 27).

Table 27 Governance framework for transition management

Stage	Characteristics
Problem structuring and goal envisioning	- multi stakeholder, but usually overseen by government - development of a shared vision for sustainability and how to reach these goals - sustainability goals → practical visions **VIA** scenario-building techniques - visions shape subsequent activities
Transition pathways and experiments	- participants identify pathways towards visions - pathways influence the development of niche experiments - multiple niches created/tested - niche pre-development → take-off/acceleration → more sustainable regime
Learning and adaptation	- highlight links between long-term goals and the short-term actions in niche experiments - niche experiments improve understanding of institutional constraints and opportunities, not just instrumental outcomes
Institutionalization	- point at which serious commitments are needed - redirect institutional, economic and political commitments into promising niches + desired pathways

Anticipatory governance: Guston (2014) defines anticipatory governance as 'a broad-based capacity extended through society that can act on a variety of inputs to manage emerging knowledge-based technologies while such management is still possible'. The motivation behind the approach is to build capacities in *foresight, engagement,* and *integration* (Table 28) that support the reflection of scientists, engineers, policy makers, and others on their roles in new technologies. As in RRI, reflection means awareness of one's own position as participant, with a specific set of roles and responsibilities, in a field of other actors (Guston, 2014).

Precautionary principle for technology policy: Stirling (2007) notes that it is not possible to 'concurrently pursue all possible viable technological directions and so taking any one path will likely open up some choices whilst closing others down. In the context of technology policy, Stirling considers the precautionary principle to provide a 'guide to the social processes through which robust decisions may be formed' and giving greater 'attention to a broader range of issues, complexities, uncertainties, possibilities, options, benefits, knowledges, strategic qualities, values and perspectives' related to an innovation. That is, "precaution properly amounts to is the adoption of more rigorous, complete and inclusive processes for the deliberate social appraisal of contending technological choices". Whilst such processes may increase legitimacy in the final stages of technology choice, Stirling (2007) argues that stakeholder deliberation and citizen participation is essential for the initial 'framing' of procedures for scientific and technical assessment.

Responsible Research and Innovation (RRI)

Anticipation

- Aim is to increase resilience while revealing new opportunities for innovation using processes to identify and minimise unintended consequences of future innovation (e.g. what is known, what is likely, what is plausible and what is possible)
- Well-timed processes that are early enough to be constructive but late enough to be meaningful
- Use of foresight exercises, horizon scanning and scenario-building techniques
- Plausible positive *and* negative scenarios envisaged

Inclusion

- Inclusion of new voices in the governance of science and innovation using a variety of partnerships and engagement mechanisms
- Addition of public and stakeholder perspectives to improver trust in innovation process
- Assess the quality of dialogue (e.g. intensity, openness and quality)
- Openly and actively seeking critical input by providing room for public and stakeholder voices to question the framing assumptions around research and policy issues

Reflexivity

- Holding a mirror up to one's own activities, commitments and assumptions, being aware of the limits of knowledge and being mindful that a particular framing of an issue may not be universally held
- Ask scientists, in public, to blur the boundary between their role responsibilities and wider, moral responsibilities
- Encourage openness and leadership within cultures of science and innovation

Responsiveness

- Requires a capacity to change shape or direction of the innovation process in response to stakeholder and public values and changing circumstances
- Adjusting courses of action while recognising the insufficiency of knowledge and control
- Responding to new knowledge as this emerges and to emerging perspectives, views and norms.

Figure 72 Conceptualisation of RRI in the anticipation-inclusion-reflexivity-responsiveness (AIRR) framework. Adapted from Stilgoe et al. (2013) and Eastwood et al. (2019)

Table 28 Capacities that an anticipatory governance approach aims to develop in participants (Guston, 2014).

Capacity	Aim	Intended outcome
Foresight	Be more methodological about looking at plausible alternative futures; methods include scenario development	A more diverse (and normative) outlook compared to seeking a single, mostly likely future
Engagement	Encourage exchange of ideas among and between lay people, and those who traditionally frame/set the agenda for/conduct scientific research	Encourage public engagement and develop bottom-up research and policy tailored to affected communities
Integration	Create of opportunities to exchange ideas between lay people and experts	Increase long-term reflective capacity building

Implications for sustainable development of MAR schemes targeting river bed sands: an argument for active management

In the Gilbert River catchment, both surface water development and MAR innovations targeting the river bed sands are inherently uncertain and associated with a range of social, economic and environmental outcome (positive or negative). There is no magic bullet to improving water access and management in the catchment and there is much uncertainty in demonstrating effectiveness and return on investment. There is also a need to convincingly address environmental risk to ease existing rules and build the social license that is key to successful transformative change.

Despite the absence of perfect & complete information, there are ways forward to explore water innovations that would support sustainable water resource developments and associated irrigation precincts. We propose an active management paradigm that aims to

- Learn by doing to build understanding together over time
- Demonstrate understanding and continued stewardship of the water resource
- Avoid lock-in, but provide transparency and vision to attract investment

Active management of water resources would examine the potential for incremental change from existing use and explore the multiple possible options (and their combination). As development is constrained by concerns about risks, an active management approach would place high value of new information around the optimisation and impacts of existing pumping from the river bed sands, better articulating water needs and opportunities in the GRAP, and better identifying risks (and ways to mitigate them) that would support the relaxation of regulation that currently prohibits the use of new spear bore licences other than at high flows. The action-state-consequence framework outlined in Section 5.3.7 could form the basis of identification, assessment and mitigation of risks associated with incremental development of water resources in the catchment (be it MAR or surface water schemes).

5.6 Social acceptability

In Section 5.6.1, the key findings of previous engagement with community in the Gilbert catchment as part of the CSIRO FGARA project around surface water management and the DBC for the Gilbert River Irrigation Project (Jacobs Australia Pty Limited., 2020). An overview of the engagement undertaken for this MAR feasibility projects follows in Section 5.6.2.

5.6.1 Previous stakeholder engagement in the region

Detailed Base Case for the Gilbert River Irrigation Project

As part of the DBC for the Gilbert River Irrigation Project prepared by Jacobs Australia Pty Limited. (2020) stakeholder engagement was undertaken. Stakeholders included potential customers, impacted landholders, traditional owners and government. Stakeholder engagement was conducted through meetings in person, workshops, presentation, phone call and written communication. Engagement begun in 2017 and continued through to December 2019.

The proposed development, including the dam, has strong support from the local council, Etheridge Shire Council. Their hope is that such a development will support the growth of both population and industry in the region, bringing economic benefits.[86] After initial information sessions landowners who would be impacted and/or benefit from the dam endorsed the continuation of the project into the DBC phase and exhibited a desire to participate (Jacobs Australia Pty Limited., 2020).

Jacobs Australia Pty Limited. (2020) reported a mixed response from farmers and landholders to the proposed dam. Some people expressed demand for increased water availability and economic stimulus, while others were not interested in pursuing irrigated agriculture and/or were not going to benefit from the construction of the dam (as they were not part of the proposed irrigation area). Many landowners wanted to see a robust, fact-based, independent assessment that addressed social, economic and environmental aspects. As part of the DBC, an expression of interest was undertaken with stakeholders to gauge demand, based on the pricing outlined in Section 5.4.3. Based on this assessment likely water demand from local landholders and external investors was 79,000 ML and 58,000 ML, respectively.

The traditional owners of the land, the Ewamian and Tagalaka People were consulted and oversaw the geotechnical site investigations undertaken as part of the DBC. Their key concerns were that the proposed project, would enact proper management of cultural impacts and would provide employment opportunities to First Nations peoples.

Flinders and Gilbert Agricultural Resource Assessment

Past studies documenting attitudes to kinds of water development in the region summarised a general trend from most to least favourable as (Petheram et al., 2013):

1. Smaller, offstream storages supplied by flood harvesting
2. Groundwater extraction (e.g., from bores)
3. Small instream dams in tributaries that do not restrict all of the flow
4. Large instream dams in major rivers

The relatively positive attitudes to groundwater suggest MAR may be well received (although MAR was not specifically considered in the FGARA study).

5.6.2 Case study engagement for the MAR feasibility project

Preliminary phone interviews

Six phone interviews were conducted with local cotton growers [CG1, CG2] and external researchers [R1, R2] or government employees [QG1, QG2] with experience in the Gilbert River catchment between January 2019 to March 2019. Information from these interviews (and interviews from other candidate catchments) were used in selection of the project case studies and scoping the focus area (the Gilbert River above Strathmore, the GRAP) and target aquifer (the bed sands) of the Gilbert case study.

The interviews indicated that there is considerable interest in cotton production with farmers in the Gilbert catchment, with support provided through promising trials with DAF and other researchers on some farms in the catchment. Although the primary agricultural industry in the area is beef cattle, broadacre cropping is recognised as a growth opportunity in the catchment [QG2], subject to the constraints posed by 'patchy' soil suitability [R1], mosaics of irrigation suitability due to slope [CG2] and native vegetation clearing

[86] That said, the new council has deliberately stepped back from promoting only the dam and is taking a broader perspective of agricultural and water resource development in order to 'bring the community into the conversation' (see Section 5.1.3)

regulations [CG2]. One of the cotton growers had been growing dryland cotton for four years and at the time of interview was trialling some irrigation for the first time to 'finish off' their 4,500 ha planting [CG1]. their interest in cotton production was only increasing over time with promising yields and receiving a 'colour bonus' due to the whiteness of the harvested cotton. The other grower interviewed was producing cotton and guar, with the Queensland DAF conducting cotton irrigation trials on their property [CG2]. Cotton was desirable to them as it was not much impacted by pests, other than a little nibbling by wallabies. [CG2] aimed to get 10 bales/ha like they do down south, an increase from their current (as of 2019) dryland yields are 4 to 7 bales/ha (with small patches of 10 bales/ha noted while harvesting). The monsoonal rains are used to grow the crop but [CG1] noted that it would be good to have more water to finish off their cotton crop in July (an additional 1-2 ML was needed).

The interviewees noted the flashy nature of rainfall that, while it could be unreliable, provided plenty of flooding and an opportunity if that water could be stored [QG1, QG2, CG1]. Groundwater use in the area is from about 10-15m depth but these are mainly wind mills and solar bores for stock and domestic water [CG1]. Storing water is a critical constraint at present. On-farm dams will not be possible across much of the arable land as the soil is 'too light' for the construction of infrastructure such as 'ring tanks', although the proposed Greenhills dam would offer great potential for surface water storage in the region [CG2]. The DBC for this dam has been conducted but an EIS has not yet commenced and so in the short-term storage options will remain constrained.

Given the constraints to surface water storage, the idea of MAR held some promise to interviewees albeit they noted some challenges that would need to be overcome. MAR was not expected to be an approach that would work on a broad scale across the catchment but might work in particular locations [QG1, R1, R2]. [R2] noted there is limited hydrogeological information in the Gilbert region but felt that the basalts and GAB were not likely to support a MAR-based irrigation scheme. While the basalts had some high recharge areas, these were located far away from the best irrigation areas and so the costs of moving the water to the irrigation area would be problematic [R2]. The GAB is a mostly confined aquifer that underlies the alluvium and following rainfall at the recharge sites, [R2] said that the pressure can create baseflow into the river and 'reject recharge' into the GAB. The recharge zones tend to be in high rocky outcrops and are not suited to irrigated agriculture, and the depth to the GAB (in the Gilbert Formation) can drop to 100-200m below the surface within only 10's of km from the recharge zones [R2].

The bed sands were identified as potentially viable option for MAR [QG1, R2]. Both cotton growers interviewed currently pump from 'surface water' sources directly from the alluvial river bed. If the spear bores of [CG2] are running properly, then they think they can extract 30L/s (2.6 ML/day) from their license that allows up to 20 ML/day. Their water licenses allow them access to a lot of water early in the season but it peters out into the dry season (following the availability of surface water). This is when they need the water to boost cotton crops at the end of the wet season [CG2]. This 'tapping' out of the bed sands was noted by [QG1] who thought there might be "say 20 days of flow which is stored in on-farm storage in the sandy river bed". MAR targeting the bed sand might extend this 'storage capacity'. However, the Gilbert alluvium is also 'gaining' connected to the stream in places so any MAR scheme would also need to know that the groundwater can be extracted before it is 'lost' downstream as streamflow [R2].

Beyond the issue of water availability at the time of finishing cotton crops, the interviews highlighted the need for a local cotton gin to ensure the financial viability of a cotton industry in the Gilbert catchment. Currently, cotton harvests are trucked to the Gin in Emerald and the costs to transport impact financial viability [QG1], comprising between 20% and 25% of [CG1] production costs. CG2 is about 1000 km Emerald and noted that transporting/ cotton to Emerald to the gin was viable if cotton is collecting $450 - $500/bale. Researchers with experience in the regions [R1, R2] were unsure as to whether there was sufficient interest and available water to grow the area of cotton needed to support a local gin. [R2] also expressed doubt that enough cotton could be produced using water from the alluvium to support a gin. [R2].

Targeted case study engagement

Unlike the Coleambally case study, there are low numbers of landholders growing agricultural or horticultural crops in the Gilbert River catchment. This, along with recognition of the uncertainty in the nature and feasibility of MAR, meant that no further phone interviews were conducted with local landholders. Instead we conducted targeted engagement (summarised in Table 29) with researchers, government employees, local council and NRM agencies to inform the pre-feasibility assessment in this section, and test and revise MAR scenarios in Section 4. Engagement was focused on aspects around aspects of agronomic considerations (Section 5.3.2), the interest in MAR targeting the river bed sands (this subsection), and associated technical feasibility (Section 5.3), environmental risks (Section 5.5) and governance implications (see Section 5.7).

Table 29 Summary of targeted engagement to support the pre-feasibility assessment and development of MAR and alternative scenarios

Institution	Purpose of engagement	Discussion highlights
CSIRO (agronomist)	• Gain understanding of opportunities and challenges of agricultural production in northern Queensland • Identify agronomic considerations to include MAR pre-feasibility assessment • Discuss strategies to overcome low aquifer yields	• Outcome of this discussion (and following Steering Committee meeting) focused our attention on MAR targeting the river bed sands • Highlighted the need to consider cotton as part of the cropping system • A critical constraint to agricultural development is the availability of cleared land with suitable soils (getting permission to clear land is now difficult)
ESC	• Test the potential MAR scenarios and their surface water alternatives • Understand the perspective of current Council on development of water infrastructure and agriculture industry	• Gained an update on the proposed Greenhills dam post-DBC (see Section 5.1.3) • Open to the idea of MAR as a storage option • Stressed the need for the community to be brought along in any investment in water development in the GRAP
GSNRM	• Understand the role the GSNRM play in land and water stewardship in the Gilbert catchment • Test the potential MAR scenarios and their surface water alternatives • Seek input on the development of ANU interactive session for the Gilbert River Agricultural Forum	• Gut feel that sorghum would be more attractive (than cotton) to farmers in the region as it is a fodder crop • Exploring MAR in the river bed sands opens up the debate around water management (beyond sole focus on a big dam) • Understanding attitudes of local graziers and farmers will be key to water development in the region • Will be critical to develop governance capacity and social licence and to address environmental risks
RDMW	• Check our understanding of the Gulf Water (2007) Plan • Explore the governance issues around MAR targeting the Gilbert River bed sands	• Clarified the flow conditions around extraction of water from the bed sands in the Gilbert river zones (see Sections 5.2.1 and 5.7.1) • Link to historical documents used in the development and amendment of the Gulf Water Plan and ROP [87]

[87] Search - DES, DoR and DRDMW - Liberty (softlinkhosting.com.au), accessed 22 June 2021

Discussions with CSIRO, ESC and GSNRM confirmed that MAR had not been considered in previous water resource assessments. Although acknowledging the uncertainty around technical feasibility and environmental risks, the potential scalability of MAR schemes targeting the river bed sands was seen as potential advantage. Water storage is a key issue in the monsoonal Gilbert River system, where substantial volumes of water are typically available in the wet, but is of greater value in the dry. While large in-stream dams have historically been a preferred storage solution, more recent focus on full cost recovery and environmental impact has meant that, particularly in remote regions such as northern Australia, investment in large dams is dependent on political action or intervention from large corporate entities. MAR targeting the river bed was seen as a possible storage solution that could support incremental and sustainable development of irrigated cropping in the catchment.

Gilbert River Agricultural Forum (7-8 April 2021)

On 7-8 April 2021, the Etheridge Shire Council hosted the Gilbert River Agricultural Forum, with the main objective being to explore opportunities for economic diversification in the region. Whilst the Council recognises that the mainstay of the region is grazing, they believe that the *"introduction of a horticulture and rotational cropping industry in conjunction with additional water allocations will ensure the long term expanded future of the Shire"* [88]. Primary producers and key stakeholders were invited to attend the forum workshop on 7 April to hear from other producers, industry groups and researchers on a range of topics including *Leucena* production within grazing enterprises, cotton production, horticulture, researcher cropping trials, the North Queensland cotton gin feasibility study, and horticulture opportunities. On the following day, participants visited cropping trial sites, table grapes operations and a mango plantation to learn about these operations and the opportunities and challenges for expansion of cropping in the catchment.

As part of the Forum activities on April 7, we presented an overview of the MAR Feasibility project and our Gilbert River case study followed by a truncated interactive session that aimed to have participants reflect on local experiences with agricultural production and visions for future agricultural industry in the catchment and to explore what information is needed to build capacity and confidence to invest in water management and irrigation over time. The planned session was reduced from 1.5 hours to 45 minutes due to extended discussions in earlier sessions.

Visions of future agriculture industry: as an ice-breaker, forum participants broke into groups and brainstormed their vision for agriculture in the Gilbert River catchment and were asked to identify what characteristics the industry would have (e.g. enterprise mix, outcomes for communities, associated industries and services, etc). The discussions within the group highlighted the need for considered development of agriculture in the region to ensure that (a) the character of the region was retained (reflecting the strong pastoral identity of the catchment population) and (b) local economic and social outcomes were delivered (Table 30).

Water and information needs required to support agriculture: in the same groups, participants explored the following questions:

- Where is water needed now and in the future?
- What information is needed to change how water is used and managed? Who might be involved? How and why?

Water is mostly needed to extend the growing season through May and June but may also be needed some years in January to establish crops and hay. Multiple sources of water were seen to be useful, namely from the river, bed sands licenses and off stream sources.

[88] https://www.etheridge.qld.gov.au/gilbert-river-agricultural-forum-1/gilbert-river-agricultural-forum, accessed 23 June 2021

There is a need for greater awareness of where landholders can go for information about what water is currently available, whether it can be used and how it can be stored. Some aspects raised one group were around the possibilities to access water from both sides of the river, and the need for clear advice on whether landholders were able to access water from overland flow into current farm dams. Information on the latter is publicly available (see Section 5.7.1) but was not known by the group. The group thought that stakeholders, landholders, and community all needed to be involved in building knowledge and capacity around water availability and use in the catchment, but that there was a need for leader or advisor who individuals can ask questions of. Any development of water infrastructure such as the proposed Greenhills Dam, or regional-scale MAR, aimed at supporting agricultural expansion would need involvement of local government, community, and outside expertise to enhance positive and mitigate detrimental consequences of development on the environment, downstream industries, and social outcomes for community.

Table 30 Visions of future agriculture in the Gilbert catchment and requirements needed to progress towards this vision.

	Vision	Requirements
Group 1	Agricultural development that (a) provides stable employment opportunities and services to the local community, (b) sees collaboration across government, investors and locals, and (c) retains the character of the region.	• Strategic agricultural growth or change that retains the character of the region, employs local people and delivers on services to the town(s) and community • Strategic workforce development on-ground and pre-development • Current and future situational analysis that identifies the skilled/12-month jobs for locals (versus seasonal workforce options) • Collaboration and agreement across all levels of government • Long term strategy around agronomy / science (investors versus locals) • Outcomes delivered for town services (roads, schools, social, welfare, medical, etc)
Group 2	A vibrant, sustainable economic zone which positively impacts the economy and local communities and employment	• Strategy for utilisation of overland flows to deliver dryland and livestock activities with intensive irrigated cropping that supports the vision (e.g. Farmers capturing and using overland flows using small dams) • Innovative agricultural systems • Skilled workforce
Group 3	An industry that encompasses viable traditional agriculture (grazing) and supports innovation into cropping and farming. The regions $/ML of water used will be maximised with grazing remaining the major land user with high value agriculture [located] where resources exist.	• Start small / slow development / scaleable development • Support existing industries [as well as emerging ones] • Improved physical and natural capital: Farming infrastructure, access to water [when needed] • Improved human capital: capacity building around agricultural production and irrigation access and management • Regional outcomes: public facilities, sundry industries, improved road networks • Supportive land tenure (e.g. ability to subdivide) and land clearing arrangements

Another group specifically considered the information needs around the bed sands. They highlighted the limited understanding the bed sands system and the need for monitoring of the bed sands. This includes the physical dimensions and capacity of the system (e.g. bed sands depth) and the movement and availability of water within the system. One person thought that more water was pumped from the bed sands 20 years ago than now and that bed sands license use was now minimal; the reason for this change was not known.

Field visits: spear bores extracting water from the bed sands were being used to irrigate at three of the field visit properties. Research trial plots of cotton, mung beans and other crops were being supplied by furrow irrigation on one property, whilst drip irrigation was used on a table grape trial and an established mango orchard on other properties. Landholders or managers using these bores (on the field visit properties or elsewhere) noted the variation in water availability over time and space. Some bores from zones 3-5 (where entitlements have no attached flow conditions) showed little change in pumping rates over time whilst others typically run into water shortages as the dry season progresses. Anecdotally, the concept of MAR targeting the bed sands was of interest to some local landholders, Council and external individuals. However, local interest in on-farm storage and capture of overland flows was also expressed by some attending the field trip.

5.7 Governance arrangements

This section addresses the governance arrangements that would relate to any proposed MAR scheme targeting river bed sands. Although there is the opportunity to purchase new water entitlements in the Gilbert catchment (Section 5.2, Table 31), there is no MAR specific policy in Queensland (Section 5.7.1) and the flow conditions outlined in the current surface water policy limits MAR schemes that would target river bed sands in the Gilbert region (Section 5.2.2). There is additional policies and approvals that MAR, water infrastructure and any other development would be subject to (Section 5.7.3). The governance arrangements for the one agricultural MAR scheme in Queensland – the Burdekin River region is – outlined in Section 0. The section concludes with a discussion on how current water policy could shift to an approach based on rules and Resource Condition Limits (RCL; Section 0).

5.7.1 Water Policy in the Gilbert Catchment

Water plans are prepared under the Water Act 2000. Water policy in the Gilbert (and surrounding catchments) fall under two plans depending on the location of the water:

- Groundwater in a GAB or other regional aquifer is managed under the *Water Plan (Great Artesian Basin and Other Regional Aquifers) 2017* [89]
- Surface water (water in a watercourse is managed under the *Water Plan (Gulf) 2007* [90]. Surface water includes water in a watercourse or lake, water in non-GAB connected springs and overland flow [91]. Surface water also includes hydraulically connected groundwater in an aquifer under a prescribed watercourse or under land within 1km of a prescribed watercourse [92]. The Gilbert River is a prescribed watercourse [93].

Underground water that is not GAB water but is in the *Water Plan (Gulf) 2007* plan area is managed under the *Water Plan (Gulf) 2007* [94]. As this research is focused on the bed sands of the Gilbert River, and not the deeper aquifers of the GAB, the focus policy document is the *Water Plan (Gulf) 2007*.

Water Plan (Gulf) 2007

The *Water Plan (Gulf) 2007* (here-on-in referred as the Plan) and the *Gulf Resource Operations Plan* [95] (the Gulf ROP) work collectively to outline and manage water in the Gulf area. Sections that relevant to the Gilbert catchment, irrigated agriculture and/or MAR are highlighted in the following text.

[89] https://www.legislation.qld.gov.au/view/html/inforce/current/sl-2017-0164, accessed 13 April 2021
[90] https://www.legislation.qld.gov.au/view/html/inforce/current/sl-2007-0268, accessed 13 April 2021
[91] **s 11 Water to which plan applies** in Water Plan (Gulf) 2007
[92] **s 8 Declaration about watercourse—Act, s 1006(2)** in Water Plan (Gulf) 2007
[93] **s 8 Declaration about watercourse—Act, s 1006(2)** in Water Plan (Gulf) 2007
[94] **s 11 Water to which plan applies** in Water Plan (Gulf) 2007
[95] https://www.resources.qld.gov.au/__data/assets/pdf_file/0005/293927/gulf-rop-amendment-august-2015.pdf, accessed 28 April 2021

Unallocated water held under various reserves (Indigenous, strategic and general) are outlined in the Plan [96], as was summarised in Section 5.2.2. Any new general reserve entitlements in the Gilbert Catchment are required to include at least one pass flow condition [97]. This condition is seen in the fixed price terms of release in the catchment (see Table 10) [98]. This condition effectively stops any new allocations from the bed sands that would replicate the current bed sand licences. This is confirmed in the 2018 Minister's Performance Assessment Report Water Plan (Gulf) 2007 (DNRME, 2018a): 'No new entitlements can be granted from the within bed sands zones from general reserve unallocated water.' [99]. ***Without policy change this limits the feasibility of MAR from bed sands in the catchment as new entitlements under low flow/cease to flow conditions are prohibited.***

The Plan details ecological outcomes, including 'maintenance of water in the bed sands of the Gilbert River between AMTD 317km and AMTD 263km' [100]. This area comprises of Zones 3 – 5 (see Figure 19), coinciding with the GRAP. The actively used bed sand allocations are located in this stretch of the river. The stated purpose of maintaining water in the bed sands are to support riparian vegetation, provide habitat during the dry season and contribute to flows in the Gilbert River [101]. Another ecological outcome of the Plan is the provision of suitable habitat for banana prawn development via the maintenance of flow in the Gilbert River [102]. Discussion of the prawn industry in the Gilbert can be found in Section 5.5.1.

The intended economic outcomes of the Plan are to support the growth of irrigated agriculture in the Gilbert River catchment area by making water available [103]; this is demonstrated by the unallocated water releases that are available in the Gilbert River (Table 10). To assign unallocated water for an irrigation water licence, the potential land suitability must be demonstrated [104] and the ecological and cultural sustainability of the proposed irrigation development must be shown [105].

Overland Flow: As well as the general unallocated water available from the watercourse in the Gilbert catchment (Section 5.2.2), there is also the ability to take overland flow under the Water Plan (Gulf) 2007 [106]. Overland flow can be taken for stock and domestic purposes, in works that allow the taking of overland flow and have a capacity of not more than 250 ML or under a water license, among other reasons [107].

The Gulf ROP: The Gulf ROP outlines any conditions and requirements relating to licences, both existing and future, and ensures that local conditions and downstream requirements are considered when taking water (CSIRO, 2009). This document also outlines when changes are made to the Plan, for example, the

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[96] **Schedule 6A Total volumes for indigenous unallocated water, Schedule 7 Total volumes for strategic unallocated water and Schedule 8 Total volumes for general unallocated water** in Water Plan (Gulf) 2007

[97] **s 39A Condition for general unallocated water in Flinders and Gilbert River catchments** in Water Plan (Gulf) 2007

[98] https://www.rdmw.qld.gov.au/__data/assets/pdf_file/0007/1486600/gulf-water-release-terms.pdf, accessed 29 November 2021

[99] **Table 5** in Minister's Performance Assessment Report Water Plan (Gulf) 2007 May 2018

[100] **s 15 Ecological outcomes** in Water Plan (Gulf) 2007

[101] **s 15 Ecological outcomes** in Water Plan (Gulf) 2007

[102] **s 15 Ecological outcomes** in Water Plan (Gulf) 2007

[103] **s 13 Economic outcomes** in Water Plan (Gulf) 2007

[104] **s 31 Requirement for information about land suitability** in Gulf Resource Operations Plan June 2010 Amendment August 2015

[105] **s 31 Requirement for information about land suitability** in Gulf Resource Operations Plan June 2010 Amendment August 2015

[106] **s 78 Limitation on taking overland flow water—Act, s 20(2)** in Water Plan (Gulf) 2007

[107] **s 78 Limitation on taking overland flow water—Act, s 20(2)** in Water Plan (Gulf) 2007

addition of pass flow conditions on water entitlements granted from the general unallocated water reserve in the Gilbert River and Flinders catchment (Insertion of s39A in the Plan (Gulf)) [108].

There were multiple assessments that were compiled to inform the first iteration of the Plan (then known as the Water Resource (Gulf) Plan 2007).

- **Assessment of development options (DNRME, 2004):** Identification of soils suitable for agricultural production informed the potential demand for water resources in the region. In this assessment, this potential demand was compared with water availability to assess development options. In the Gilbert catchment, the area between Prestwood and Chadshunt stations showed the greatest potential for irrigated agriculture; this is a very similar area to the GRAP (see Figure 15). As of 2004, the remoteness and associated high transport costs were considered to compromise the economic viability of irrigated along the Gilbert River and the Gulf region generally.
- **Considerations of hyporheic ecosystem:** Two reports highlighted the possible environmental importance of the bed sands of the Gilbert River as a hyporheic ecosystem (DNRME, 2006b, DNRME, 2006a). It was suggested that further use of the bed sands in the middle reaches of the Gilbert River could adversely affect these ecosystems (DNRME, 2006b). This line of thinking would result in no further entitlements from the bed sands, which is reflected in the current Plan (see Section 5.7.1). Other reports suggest that current bed sand allocations require critical reassessment and any extension of current use needs to be assessed on a case-by-case basis (DNRME, 2006a). This suggestion is based on the lack of information on the hyporheic zone beyond its existence and that the impacts from current and historic extractions is yet to be assessed (DNRME, 2006a). Monitoring and management was advocated to accompany any development (DNRME, 2006b).
- **Community submissions on the draft Plan (DNRME, 2006d)**: Community submission(s) suggested that the trading of existing bed sand entitlements be allowed (DNRME, 2006d), and this was included in subsequent Resource Operation Plans [109]. Community consultation was also considered when setting the initial unallocated general water reserves (DNRME, 2006d).

These initial assessments all highlight the lack of data for the Gulf catchments (DNRME, 2006b, DNRME, 2006a, DNRME, 2006d, DNRME, 2006c), and triggered a precautionary approach to water resource development and associated policy (DNRME, 2006a).

Water policy, and the provision of unallocated water released, has changed since the Plan was first released, following periodic reviews and updates based on new information. This is can be observed in Table 31, where unallocated general reserves were increased substantially based on the published findings from the FGARA reports [110].

A continued knowledge gap is localised bed sand water levels in the Gilbert River alluvium (DNRME, 2018b). Interactions of the bed sands area with GDEs is also undetermined (DNRME, 2018b).

The next major review of the Water Plan (Gulf) 2007 is in 2027 [111].

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[108] https://www.resources.qld.gov.au/__data/assets/pdf_file/0010/293932/gulf-rop-wrp-explanatory-notes.pdf, accessed 21 April 2021
[109] https://cabinet.qld.gov.au/documents/2009/Oct/Gulf%20Resource%20Op%20Plan/Attachments/gulf-rop.pdf, accessed 29 April 2021 & https://www.resources.qld.gov.au/__data/assets/pdf_file/0005/293927/gulf-rop-amendment-august-2015.pdf, accessed 21 April 2021
[110] **7 Unallocated water** in Minister's Performance Assessment Report Water Plan (Gulf) 2007 May 2018
[111] Water Plan (Gulf) (Postponement of Expiry) Notice 2018, https://www.legislation.qld.gov.au/view/pdf/asmade/sl-2018-0121, accessed 20 April 2021

Table 31 Updates to unallocated water reserves and associated releases in the Gilbert catchment as per Water Plan (Gulf) 2007 and accompanying Gulf Resource Operations Plans. CSIRO = Commonwealth Scientific and Industrial Research Organisation, FGARA = Flinders and Gilbert Agricultural Resource Assessment, ML = megalitres

Progress of unallocated general reserve in the Gilbert catchment	
Plan commencement	• Unallocated general reserves: 15,000 ML [112] • 15,000 ML released (14,200 ML allocated [113])
2014	• Unallocated general reserves increased based on findings from CSIRO FGARA report [114,115] • Unallocated general reserves: 467,000 ML [116]
Current	• 85,000 ML released [117] (flow conditions included [118], 'must be free of vegetation management constraints' [119])

Water Plan (Great Artesian Basin and Other Regional Aquifers) 2017

Water use in the GAB and other regional aquifers is managed through the *Water Act 2000* and the *Water Plan (Great Artesian Basin and Other Regional Aquifers) 2017* [120]. The extent of the area covered under this water plan is shown in Figure 73. A bore is needed to access groundwater in the GAB. New bores usually require development approval and must be located further than specified distance from existing bores in the area to limit any effect on those bores. Artesian bores also require a flow control mechanism. Water licences, issued for long-term activities, are separated into three types (Table 32). The majority (86%) of water licenses are stock and domestic licences.

The extent of the GAB area (Figure 73) is further broken into groundwater units and sub-areas, often associated with a formation [121]. The units that are associated with the Gilbert Catchment are shown in Figure 74. Current bores in the Gilbert Catchment are placed within multiple GAB formations (Figure 75). Unallocated water is available from many of the groundwater units and for many difference purposes [122]; such water associated with units underlying the Gilbert catchment is outlined in Table 33.

To better position MAR as a viable water supply/management technique in Australia, policy detailing the direct transfers of entitlements to recover recharged water is required (Ward and Dillon, 2012). How this would look in situations when the target aquifer is fully allocated or overdrawn is not defined (Ward and Dillon, 2012). To encourage MAR projects it has also been suggested that there needs to be secure and financially viable source water for recharge, both pre-establishment of MAR infrastructure and for the lifetime of the scheme (Ward-Noonan, 2021). Ward-Noonan (2021) suggested that this could be achieved through legislative reform. It is also important for MAR policy to outline how and from whom to obtain source water rights depending on where the water is to be sourced (e.g., river, wastewater, stormwater) (Ward-Noonan, 2021). Another requirement for the approval of MAR schemes is capability building at the government level, highlighting the potential of and increasing confidence in MAR (Dillon et al., 2020).

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[112] **s 33 Unallocated water reserves** in Gulf Resource Operations Plan June 2010
[113] **Appendix 4: Plan and instruments amendments** in Minister's Performance Assessment Report Water Plan (Gulf) 2007 May 2018
[114] Gulf draft amended plans Overview report (December 2014)
[115] **7 Unallocated water** in Minister's Performance Assessment Report Water Plan (Gulf) 2007 May 2018
[116] **Schedule 8 Total volumes for general unallocated water** in Water Plan (Gulf) 2007
[117] **7 Unallocated water** in Minister's Performance Assessment Report Water Plan (Gulf) 2007 May 2018
[118] **39A Condition for general unallocated water in Flinders and Gilbert River catchments** in Water Plan (Gulf) 2007
[119] https://www.business.qld.gov.au/industries/mining-energy-water/water/catchments-planning/unallocated-water/gulf, accessed 28 April 2021
[120] https://www.business.qld.gov.au/industries/mining-energy-water/water/catchments-planning/water-plan-areas/great-artesian-basin/water-use-approval, accessed 12 April 2021
[121] **Schedule 2 Area of groundwater units and groundwater sub-areas** in Water Plan (Great Artesian Basin and Other Regional Aquifers) 2017
[122] **Schedule 4 Volume of unallocated water for water licences to be granted from reserves** in Water Plan (Great Artesian Basin and Other Regional Aquifers) 2017

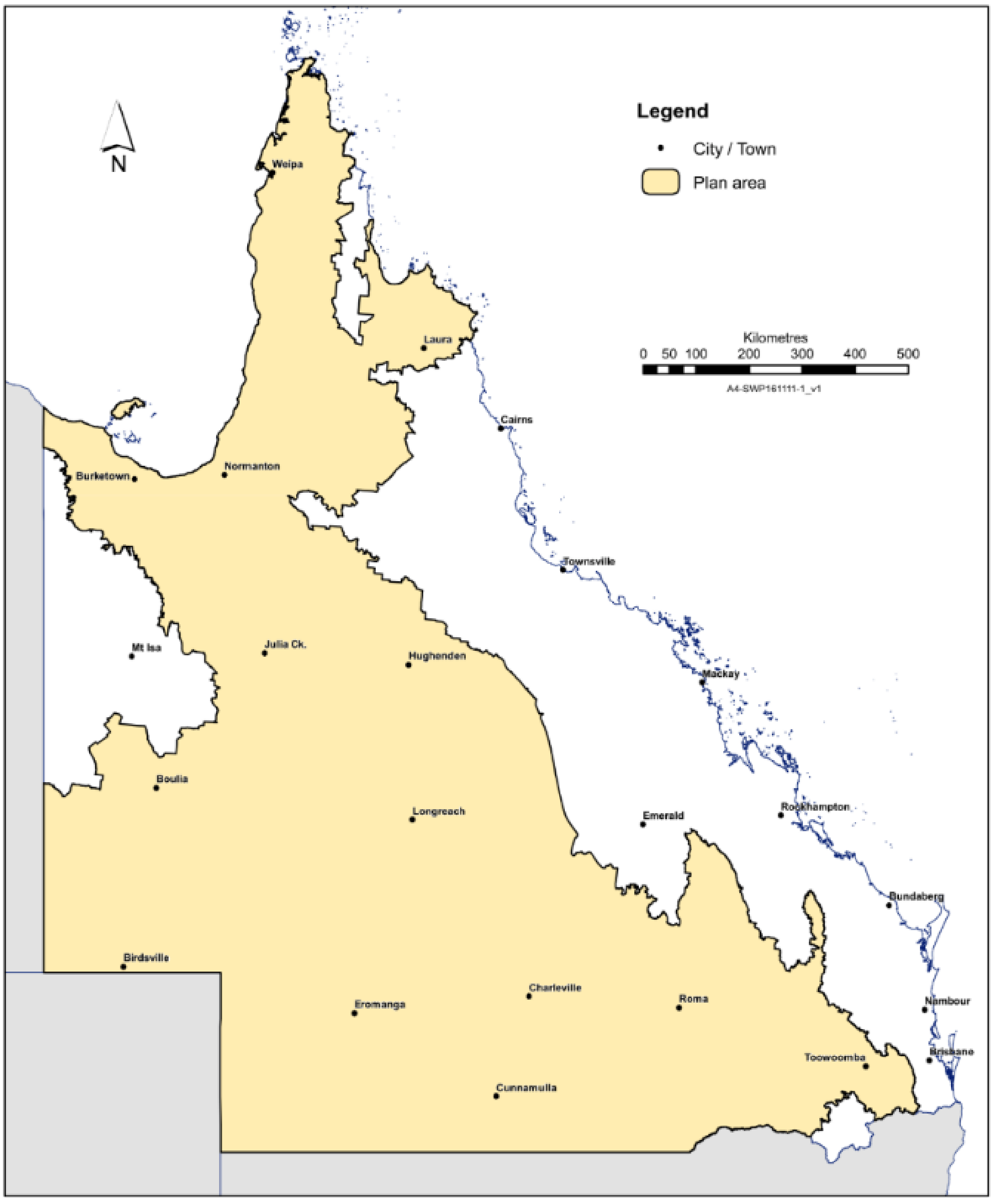

Figure 73 Water Plan (Great Artesian Basin and Other Regional Aquifers) 2017 Plan Area (from Schedule 1).

Table 32 Water licences to use water from the Great Artesian Basin (https://www.business.qld.gov.au/industries/mining-energy-water/water/catchments-planning/great-artesian-basin/water-use-approval)

Licences Type	Water Use/Water Uses	Notes
Stock and domestic	Stock and domestic purposes	Licences attach to specific land parcels and cannot be transferred to another holder, except when properties are sold or subdivided.
Volumetric water	Mines, businesses, local councils, feedlots and irrigators.	Licences can be relocated, i.e., traded, either permanently or seasonally, subject to rules in the water management protocol.
Area-based	Irrigators	Specify the area of land that can be irrigated, rather than the volume of water that can be used. No longer being issued and cannot be traded.

A effective starting point for the development of state level MAR policy are the national guidelines (Dillon et al., 2020); e.g., *Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2)–Managed Aquifer Recharge* (NRMMC et al., 2009). States that adopted the guidelines into policy have seen increases in MAR activity (Dillon et al., 2020).

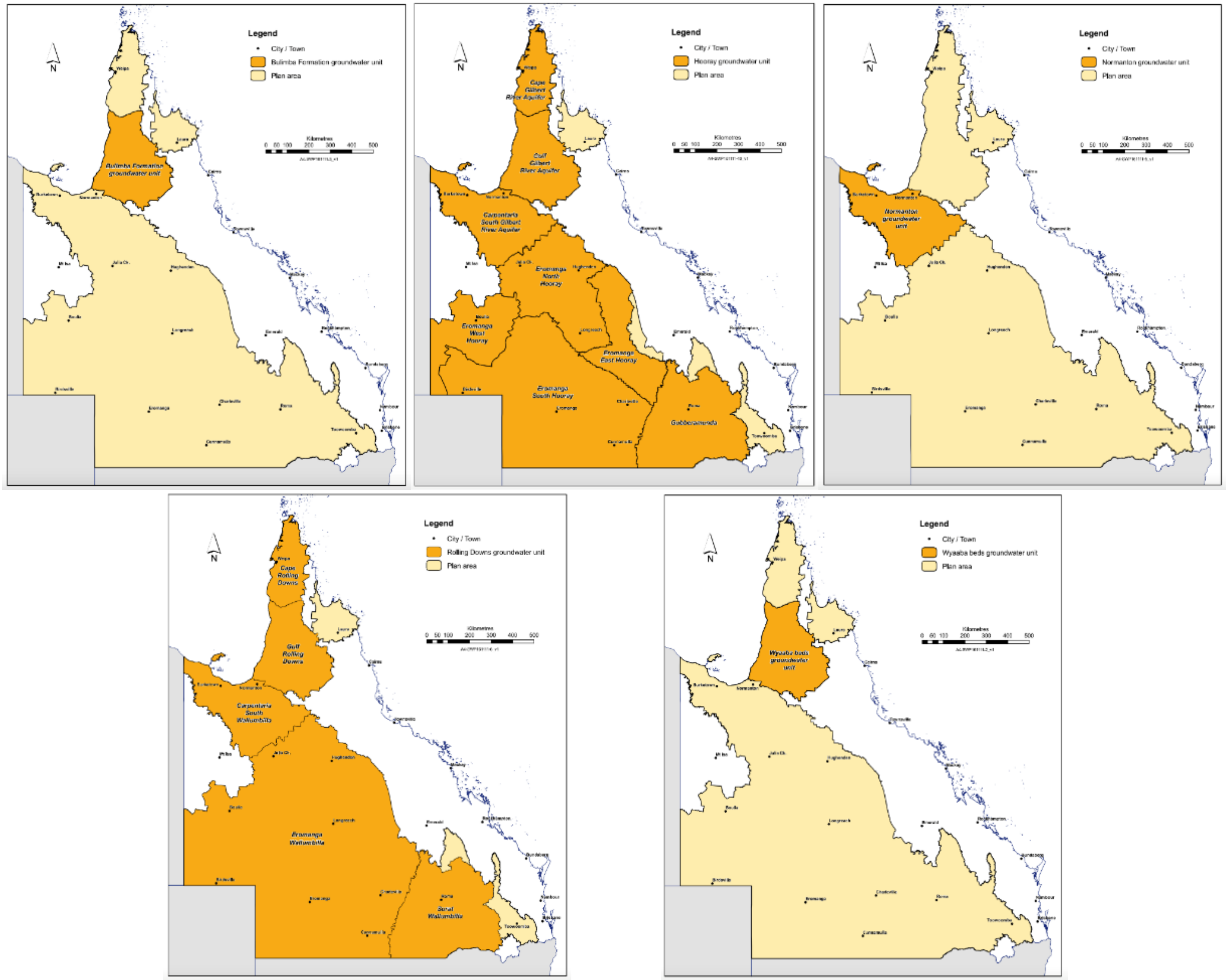

Figure 74 Great Artesian Basin groundwater units, as defined by the Water Plan (Great Artesian Basin and Other Regional Aquifers) 2017, within the Gilbert Catchment area

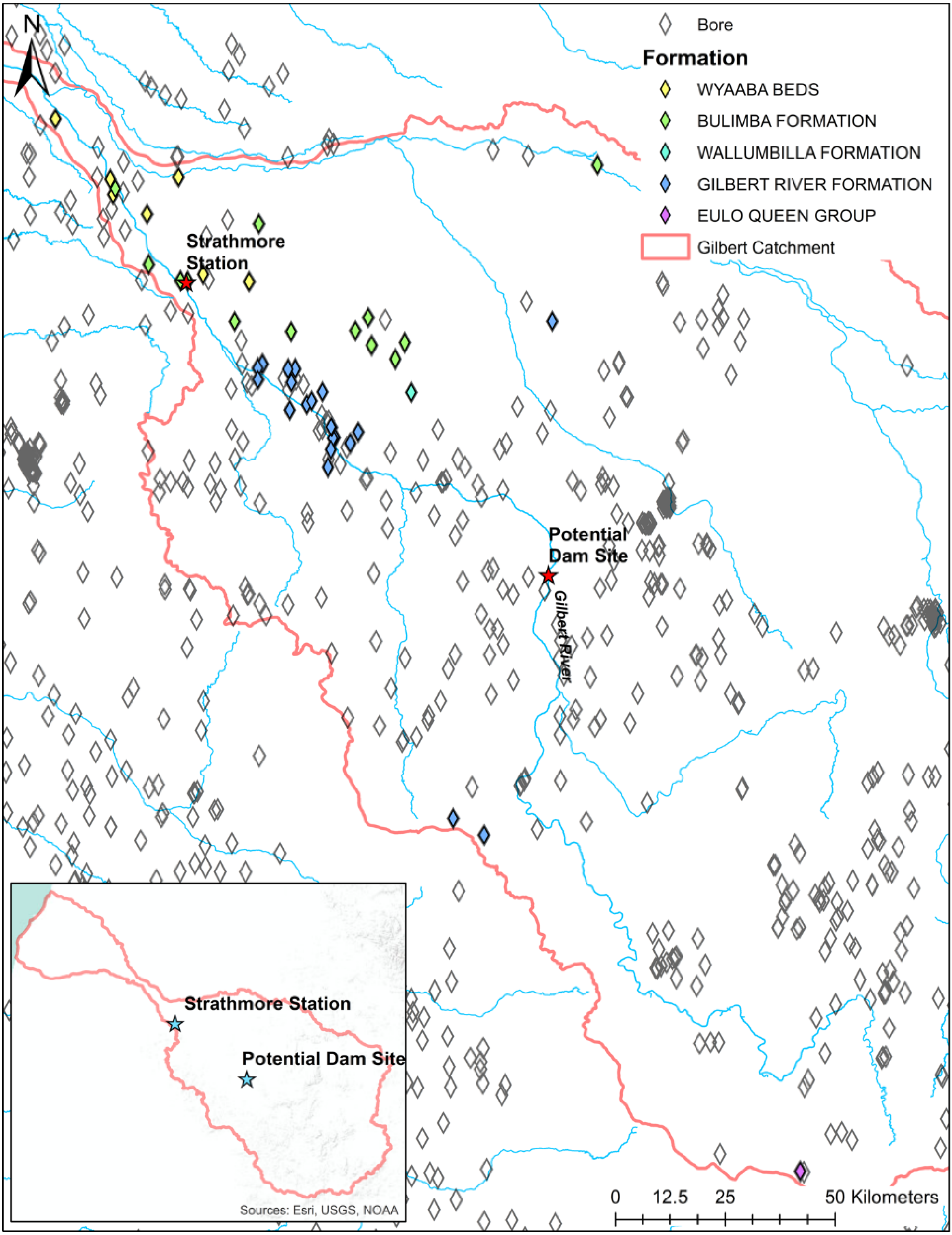

Figure 75 Registered bores in a portion of the Gilbert Catchment and surrounds, showing formation data where available.

Table 33 Unallocated water under the Water Plan (Great Artesian Basin and Other Regional Aquifers) 2017, focused in the Gilbert catchment

Groundwater Unit	Groundwater sub-areas in the Gilbert Catchment	Geological formations	Unallocated water – general reserve (ML)	Unallocated water – state reserve (ML)	Unallocated water - Aboriginal peoples and Torres Strait Islanders economic reserve (ML)
Bulimba Formation	-	- Bulimba Formation - Floraville Formation - Louisa Formation	1,440	10	50
Hooray	Gulf Gilbert River Aquifer	- Algebuckina Sandstone - Cadna-owie Formation (including the equivalent part of the Ronlow beds), other than in the Eromanga South Hooray and Gubberamunda groundwater sub-areas - Eulo Queen Group, only in the Carpentaria South Gilbert River Aquifer, Gulf Gilbert River Aquifer and Cape Gilbert River Aquifer groundwater sub-areas - Garraway Sandstone - Gilbert River Formation (including the equivalent part of the Ronlow beds) - Gubberamunda Sandstone (including the equivalent part of the Ronlow beds) Helby Beds - Hooray Sandstone (including the equivalent part of the Ronlow beds) - Longsight Sandstone - McKinlay Member - Murta Formation	1,440	500	115

	Carpentaria South Gilbert River Aquifer	- Namur Sandstone - Orallo Formation (including the equivalent parts of the Kumbarilla beds) - Southlands Formation - Wyandra Sandstone Member (including the equivalent part of the Ronlow beds), other than in the Eromanga South Hooray and Gubberamunda groundwater sub-areas	1,400	500	115
Normanton	-	- Allaru Mudstone - Normanton Formation	0	500	115
Rolling Downs	Gulf Rolling Downs	- Coreena Member - Doncaster Member - Jones Valley Member - Ranmoor Member - Rolling Downs Group, other than the Griman Creek Formation, Winton Formation, Mackunda Formation, Normanton Formation and Allaru Mudstone in the Carpentaria South Wallumbilla, Eromanga Wallumbilla and Surat Wallumbilla groundwater sub-areas - Surat Siltstone - Toolebuc Formation - Wallumbilla Formation	0	500	115
	Carpentaria South Wallumbilla		0	500	115
Wyaaba beds	-	- Carl Creek Limestone Falloch beds - Wyaaba beds - Yam Creek beds	0	10	50

5.7.2 Towards MAR policy for Queensland

Queensland as of yet does not have MAR specific policy (Dillon et al., 2020, Vanderzalm et al., 2018), although Ward and Dillon (2009) have compiled a list of Acts and legislation applying to MAR (Table 34). MAR schemes in Queensland are therefore assessed and approved on a case-by-case basis (Dillon et al., 2020).

The lack of MAR specific policy in many Australian states has resulted in MAR schemes being, at times, subject to un-coordinated and competing polices (Ward and Dillon, 2012). This has caused uncertainty around a MAR schemes entitlement to aquifer storage space and a schemes ownership over recharged water once it enters the target aquifer (Ward and Dillon, 2012). The surface water recharged under a MAR scheme is often redefined as groundwater post-recharge and, therefore, subject to regulation in the same way as native groundwater (Ward and Dillon, 2012).

Table 34 Queensland Acts and legislation applying to MAR (Source: Ward and Dillon, 2009)

	Policy	Comment
1 Capture Zone	x) LG Act 1993 and iii) SER Act 2007 i) W Act 2000 and WA and E Act 2008	Management and hence entitlement of stormwater and infrastructure remains with Local councils. Recycled water managed for Purified Recycled Water for reservoir augmentation rather than MAR All rights to water remain vested with State.
2 Pre-treatment	vi), vii), viii), ix), xi) and xii)	
3 Recharge		
4 Subsurface storage	i) W Act 2000	Applies to storage: limited aquifer suitability
5 Recovery	i) W Act 2000	Recharge and native waters not differentiated: Generally aquifers fully allocated. MAR will require licence to recover
7 End use	vi), vii), viii), ix), xi) and xii)	

i) Water Act 2000
ii) Water Availability and Entitlements Act 2008
iii) South East Water Restructuring Act 2007
iv) Native Title Act 1993
v) Integrated Planning Act 1997
vi) Public Health Act 2005 (Section 57)
vii) Environmental Protection Act 1994
viii) Environmental Protection (Water) Policy 2000
ix) Model Urban Stormwater Quality Management Plans and Guidelines (EPA 2007).
x) Local Government Act 1993
xi) The Australian Guidelines for water recycling: managing health and environmental risks: Stormwater harvesting and reuse (EPHC Draft May 2008)
xii) The Australian Guidelines for water recycling: managing health and environmental risks: Managed aquifer recharge
Note: The draft Australian guidelines for water recycling have now been published (NRMMC et al., 2009)

The Australian Guidelines for Water Recycling: Managed Aquifer Recharge

An effective starting point for the development of state level MAR policy are the national guidelines (Dillon et al., 2020): the Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2)–Managed Aquifer Recharge (NRMMC et al., 2009). States that adopted the guidelines into policy have seen increases in MAR activity (Dillon et al., 2020).

The Australian Guidelines for Water Recycling: Managed Aquifer Recharge (NRMMC et al., 2009) provide recommendations to minimise the effect on *water quality, human and environmental health* as a result of a new MAR project. The guidelines detail entry-level assessments that should be undertaken to prior to a MAR project being undertaken, namely a viability assessment (Figure 76) and an assessment of the degree of difficulty associated with the project. How this report addresses the components of the viability assessment is outlined in Table 35.

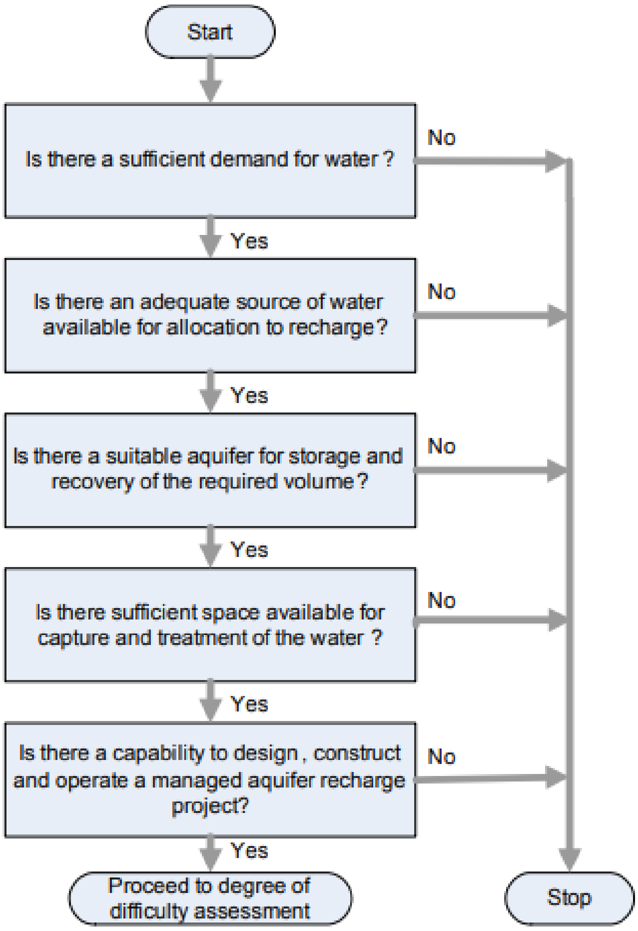

Figure 76 A flowchart of the entry-level viability assessment (Source: NRMMC, EPHC & NHMRC, 2009).

The NSW Aquifer Interference Policy

The NSW Aquifer Interference Policy could be drawn upon to develop policy in Queensland. NSW does have a specific Aquifer Interference Policy (AIP). While the focus of the policy is primarily on mining activities, the policy specifically mentions injection works used to transmit water into an aquifer. It appears that MAR through infiltration is not explicitly discussed in the policy (Box E). Approved aquifer interference activities including MAR require an aquifer access licence and a groundwater use licence for a share of the consumptive pool. In water sources where water sharing plans do not yet apply, an aquifer interference activity is required to hold a water licence under Part 5 of the Water Act 1912.

Table 35 Mapping the content of this report against the viability assessment components recommended by the Australian Guidelines for Water Recycling: Managed Aquifer Recharge entry-level viability assessment and this report (NRMMC, EPHC & NHMRC, 2009).

Attribute from the Guidelines	Notes from Guidelines	Assessed in this report	Comments
Is there a sufficient demand for water?	The ongoing volumetric demand for recovered water should be sufficient to warrant investment in the proposed project; if this is not the case, there needs to be a clearly defined environmental benefit. Either one of these criteria is essential for managed aquifer recharge. Projects involving recharge of partially treated water where recovery is incidental do not qualify as managed aquifer recharge	Yes in 5.1.2 and 5.1.3	
Is there an adequate source of water available for allocation to recharge?	Entitlement to water to be used for recharge needs to be secured. Mean annual volume of recharge should exceed mean annual demand, with sufficient excess to build up a buffer storage to meet reliability and quality requirements. In an already over allocated catchment, an entitlement to surface water is unlikely to be available.	Yes in 5.2.1 to 5.2.5	
Is there a suitable aquifer for storage and recovery of the required volume?	Presence of a suitable aquifer is critical for managed aquifer recharge. Such an aquifer needs to have an adequate rate of recharge and sufficient storage capacity; it also needs to be capable of retaining the water where it can be recovered. Low salinity and marginally brackish aquifers are preferred, to maximise the volume of recovered water that is fit for use after fresh recharge water mixes with ambient groundwater. Regional maps showing the potential of aquifers as storages for managed aquifer recharge have been developed for some urban and rural areas, and are available from water resources managers in the local jurisdiction. In over allocated aquifers, water managers may have additional constraints on the proportion of recharge that may be recovered.	Yes in 5.3.2 and 5.3.3	
Is there sufficient space available for capture and treatment of the water?	For stormwater recharge systems (either open space or dams), wetlands, ponds or basins are needed to detain sufficient water to achieve the target volume of recharge. Similarly, space needs to be available for whatever treatment process, if any, is subsequently determined to be required. For recycled water from a sewage treatment plant, generally no additional detention storage will be required at the recharge facility.	Yes in 5.3.1 and 5.3.5	
Is there a capability to design, construct and operate a MAR project?	Knowledge of hydrogeology and water-quality management is vital for the successful design, construction and operation of managed aquifer recharge projects. Also necessary for some projects are geotechnical know-how, and expertise in water storage and treatment design, water sensitive urban design, hydrology, monitoring and reporting. ***Proponents who do not have these skills are encouraged to gain access to them before proceeding with Stage 2 investigations.*** The number of consultants experienced in investigations and design of managed aquifer recharge projects is growing.		Development of capacity and skills is a key component of the proposed scenarios, as is the incremental development of local and subregional hydrogeology and groundwater response to recharge. Expertise from across Australia would need to be accessed and leveraged with the aim of building local expertise.

Table 36 The Australian Guidelines for Water Recycling: Managed Aquifer Recharge entry-level degree of difficulty assessment: attributes to consider.

Attribute from the guidelines
Does source water meet the water-quality requirements for the environmental value of ambient groundwater?
Does source water meet the water-quality requirements for the environmental values of the intended end uses of the water on recovery?
Does source water have low quality; for example: total suspended solids >10 mg/L, total organic carbon >10 mg/L, total nitrogen >10 mg/L? Also, is the soil or aquifer free of macropores?
Does ambient groundwater meet the water- quality requirements for the environmental values of intended end uses of water on recovery?
Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?
Does the salinity of native groundwater exceed either of the following: (a) 10 000 mg/L, (b) the salinity criterion for uses of recovered water?
Is redox status, pH, temperature, nutrient status and ionic strength of groundwater similar to that of source water?
Are there other groundwater users, groundwater-connected ecosystems or a property boundary within 100–1000 m of the MAR site?
Is the aquifer: (a) confined and not artesian?, (b) unconfined, with a water table deeper than 4 m in rural areas or 8 m in urban areas?
Is the aquifer unconfined, with an intended use of recovered water that includes drinking water supplies?
Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?
Has another project in the same aquifer with similar source water been operating successfully for at least 12 months?
Does the proponent have experience with operating managed aquifer recharge sites with the same or higher degree of difficult, or with water treatment or water supply operations involving a structured approach to water-quality risk management?
Does the proposed project require development approval? Is it in a built-up area; built on public, flood-prone or steep land; or close to a property boundary? Does it contain open water storages or engineering structures; or is it likely to cause public health or safety issues (e.g. falling or drowning), nuisance from noise, dust, odour or insects (during construction or operation), or adverse environmental impacts (e.g. from waste products of treatment processes)?

Under the NSW AIP proponents of aquifer interference activities including MAR are required to demonstrate that they can obtain the necessary licences, and ensure that minimal impact considerations can be met or propose remedial actions. Minimal impact considerations include impacts on water table levels, water pressure and water quality in different types of groundwater systems, and impacts on connected alluvial aquifers and surface water systems and other water dependent assets. These include impacts on water supply bores, GDEs and culturally significant sites that are groundwater dependent and take account of uncertainty. Thresholds are set so that the impacts of both an individual activity and the cumulative impacts of activities within each water source can be considered.

The NSW AIP requires proponents to take a risk management approach to assess the potential impacts of aquifer interference activities, with the level of detail proportion to a combination of the likelihood of impacts occurring on water resources uses and dependent ecosystems, and potential consequences of these impacts. The minimal impact assessment provides a rigorous and independent assessment of potential impacts of the projects on agricultural land and water resources before a development application can be lodged. Part 4 of the Environmental Planning and Assessment Act 1979 provides a streamlined approval process for the assessment.

Governance in the Burdekin

The system governing the Burdekin River region is quite unique. In the mid-1960s, to stop the intrusion of sea water under the already established farming district, farmers and government came together to establish Water Boards [123] (Dillon et al., 2009a, Evans et al., 2016, Bristow et al., 2000). The Water Boards

[123] http://lowerburdekinwater.com.au/about-us-2/about-us/, accessed 29 March 2021

were assigned to manage infiltration based MAR schemes that could limit and reverse sea water intrusion without restricting irrigation (Dillon et al., 2009a). The Boards have since amalgamated into one QLD Water Service Provider (Water Supply Act)/Public Utility Provider (Land Title Act 1994) - Lower Burdekin Water - functioning as a Category 2 Water Authority under the Queensland Water Act 2000 [124]. The day-to-day management of the scheme is controlled by the a board of directors, largely made up of local water users or individuals from associated industries (e.g. sugar mills) [125] (Evans et al., 2016). The policy framework for the scheme is set by the Queensland government [126]. The schemes success has been attributed to this two-pronged approach: clear local 'ownership' and on the ground control, combined with technical and policy support from government (Evans et al., 2016).

A current water licence type in the Burdekin Groundwater Management Area has the purpose of 'water harvesting' [127]. These licences work in a way that is approaching active management. A nominal volume of water is still assigned to the licence, but the availability of the water is subject to water levels in representative monitoring bores (i.e., water can be taken only when water levels in the monitoring bore associated with the licence are above a threshold level). This kind of water management required telemetry on the identified representative monitoring bores. This telemetry was installed by the Department of Natural Resources Mines and Energy.

Alternative approaches in setting groundwater policy

As summarised in Section 5.2.2, flow conditions are applied to extractions of surface water, including from spear bores in the bed sands (except historic spear bores in Zones 3-5). Water can only be extracted when flows are above a given threshold.

There are other management areas in Queensland that use innovative groundwater policies, for example trigger levels based on aquifer water levels and water quality (GHD, 2014). This type of approach to sustainably manage groundwater is through the implementation of rules that can then be associated with a resource condition limit (RCL), above which the impact on the groundwater system is unacceptable and the rules are triggered (GHD, 2014). To gauge when an RCL has been breached requires a resource condition indictor (RCI). Examples of RCIs include groundwater levels as measured by a piezometer or groundwater salinity measurements.

To set an RCL requires knowledge of the (groundwater) system to be managed (GHD, 2014). Knowledge is also required to establish RCI sites that are representative of the RCL to be implemented (GHD, 2014). There are many properties of a system that may have an associated RCL, including GDEs, aquifer water quality, aquifer integrity and surface-groundwater connectivity.

Table 37 outlines key datasets, reports and approaches that can help identify and implement RCLs/RCIs in a groundwater management setting. Types of rules and associated example RCLs are categorized and outlined in Table 38.

More general ways proposed to improve (water) planning and management in the Gilbert catchment include a cohesive vision for the area with associated policies from a federal, state and local perspective to build trust in locals, the incorporation of local knowledge and a focus on monitoring (Dale et al., 2014).

[124] http://lowerburdekinwater.com.au/about-us-2/governance/, accessed 29 March 2021
[125] http://lowerburdekinwater.com.au/about-us-2/board-management/, accessed 29 March 2021
[126] http://lowerburdekinwater.com.au/about-us-2/board-management/, accessed 29 March 2021
[127] **6 WATER HARVESTING – WATER LICENCE RULES** in Burdekin Groundwater Management, Area Water sharing rules, Seasonal water assignment rules Version 6.02

Table 37 Datasets, reports and approaches that can assist in the establishment of rules and resource condition limit (RCL), from the identification to implementation stage. How the resources relate to key parts/properties of groundwater systems (including groundwater dependent ecosystems (GDEs), aquifer water quality, aquifer integrity and surface-groundwater connectivity) are outlined. BOM = Bureau of Meteorology

Dataset/Report/Approach	Description	Possible uses and outcomes	Source
Atlas of Groundwater Dependent Ecosystems	Dataset of GDE locations and characteristics	• Identify GDEs • Determine level of groundwater dependence • Target RCLs spatially to focus on identified GDEs • Improved understanding of where to deploy RCI sites	BOM
National Groundwater Information System	Dataset of groundwater information, including bore information and water quality data	• Understand groundwater dynamics and current groundwater use • Assess current resource condition (including water quality)	BOM
Mapping Approaches to Recharge and Discharge Estimation and Associated Input Datasets	Approach to map recharge and discharge zones	• Identify GDEs and areas of surface-groundwater connection • Improved understanding of where to deploy RCI sites	Pain et al. (2011)
The Australian Groundwater Dependent Ecosystems Tool Box Part 1	Approach to determine the groundwater dependence of a GDE	• Identify the effect of altering the groundwater environment on a GDE • Establish RCLs that give more weight to more groundwater dependent GDEs	(SKM, 2011a)
The Australian Groundwater Dependent Ecosystems toolbox: Part 2 Assessment Tools	Tools to determine the environmental water requirement of a GDE	• Establish RCLs that meet the needs of GDEs within the management area	(SKM, 2011b)
Ecological water requirements of groundwater systems: a knowledge and policy review	Recommends approaches to determine ecological water needs	• Establish RCLs that meet ecological water needs and minimise impacts on GDEs	(Tomlinson, 2011)
A Framework for Assessing Environmental Water Requirements of GDEs	Framework that steps through from the identification of GDEs to assessing GDE water requirements and dividing resources	• Establish RCLs that meet water needs of GDEs • Improved understanding of where to deploy RCI sites	(SKM et al., 2007)
A National Approach for Investigating and Managing Poorly Understood Groundwater Systems	Framework that uses a precautionary approach to undertake a preliminary assessment based on aquifer characteristics and risks to inform management	• Identify groundwater-surface water connected systems • Assess effects of groundwater extraction on groundwater-surface water connected systems • Establish RCLs that maintain an adequate level of groundwater-surface water connection • Deploy RCI sites at key groundwater-surface water connected areas • Highlight where further investigations are needed	(RPS Aquaterra, 2012)
Impact of Groundwater Extraction on Streamflows on Selected Catchments throughout Australia	Presents two methods to understand connectivity issues. Assess groundwater pumping impacts on streamflow	• Define RCIs for managing groundwater pumping on connected systems	(SKM, 2012)

The Impact of Groundwater Use on Australia's Rivers: Exploring the Technical, Management and Policy Challenges	Discusses triggers for managing groundwater extraction.	• Establish suitable RCLs for a groundwater system	(Evans, 2007)
National Framework for Integrated Management for Connected Groundwater and Surface Water Systems	Framework to manage extraction impacts on groundwater-surface water connected systems	• Classify connectivity of a system • Establish RCLs that maintain an adequate level of connectivity • Deploy RCI sites in required areas	(SKM, 2011c)
Assessment of the Impacts of Future Climate Change and Groundwater Development on the Great Artesian Basin	Review of RCLs throughout Australia	• Provide inspiration for RCLs in management area under consideration	(Miles et al., 2012)
Groundwater Flow System Framework – Essential Tools for Planning Salinity Management	Assortment of components to help managers to understand salinity management	• Establish RCLs regarding water quality, specifically salinity	(Walker et al., 2003)
National Aquifer Framework	Dataset of aquifer characteristics	• Understand aquifers in management area • Set RCLs informed by aquifer(s) in area	BOM

Table 38 Groundwater rules, description and associated example Resource Condition Limits (RCLs). Adapted from GHD (2014). GDE = groundwater dependent ecosystems.

Type of Rule	Description	Example RCL(s)
Trigger levels	Monitor a groundwater response (e.g., levels and salinity) and implement immediate intervention when a pre-defined trigger level is reached. Modelling could be used to predict trigger levels when in-situ monitoring is unavailable.	• When groundwater levels fall to within 10% of historical minimum water levels the licensee must implement water efficiency measures. • When electrical conductivity exceeds 1500 μS/cm seasonal water assignment is not allowed
Drawdown limits	Prevent/manage the dewatering of confined aquifers by monitoring and responding to groundwater level declines.	• When drawdown exceeds 0.5 m of the surface of the aquifer, local rules will be implemented to minimise excessive drawdown (precautionary).
Temporary reductions to entitlements and allocations	Restrict entitlements/allocations in a staged level depending on conditions. Cease to pump rules may be initiated if required.	• When there is a decline in groundwater levels over 3 years access licences restrict usage to reinstate water levels. If further drawdowns occur further restrictions would be applied.
Water quality indicators	Restrict or cease current water allocations or stop the granting of new allocations based on water quality.	• When salinity increases by >2% above the baseline for five consecutive years investigative action will be started
Water trading in the groundwater management area	Limit water trading between aquifer systems to prevent increased drawdown in any aquifer system.	• Although not between groundwater management areas only, there are current water trading rules based on Zones in the Gilbert River catchment as per the Water Plan (Gulf) 2007
Distance rules for bores	Protect environmental assets (e.g., GDEs), current users and aquifer integrity by specifying a minimum offset for new bores.	• Groundwater extraction bores must be further then 100 m from high priority GDEs
Zonal limits and entitlement	Rules that set allocation limits for different zones in a management area.	• There are maximum annual limits for the zones in the Gilbert River bed sands (and other zone) in the Gilbert catchment
Technical investigations	Similar to trigger levels but allow extraction to continue alongside investigations that assess the impact as it occurs. Common when there is a limited knowledge of the system and potential impacts.	• When there is >10% drawdown of the water table the abstraction proponent must demonstrate that this (and further drawdown) will not impact nearby GDEs etc.

5.7.3 Related Policy

Beyond water specific policy, there are additional policies or approval processes that MAR, water infrastructure and any other development would be subject to (Ash and Watson, 2018). The number and complexity of approvals can add considerable cost and time to developments as well as frustrate proponents (Ash and Watson, 2018). The relevance (to MAR) of legislation beyond the water sphere is also noted in the US, a leader in MAR adoption (Ulibarri et al., 2021).

In the Gulf and Mitchell Agricultural Land and Water Resource Assessment Report (DNRME, 2004), a list was provided for 'legislation that is likely to impact on the assessment of future water-related development'. This is summarised in Table 39, where updates and additional policies highlighted by Lyons et al. (2018) are also included.

Table 39 Summary of legislation that is likely to impact on the assessment of future water-related development, based on the list provided in DNRME (2004) and Lyons et al. (2018). Legislation is highlighted as state (Queensland [QLD]) or federal.

Act	Details
State Development and Public Works Organisation Act, 1971 [QLD]	State planning and development is coordinated through departments and local governments, aiding in employment in the states and accounting for environmental effects. Functions alongside the Planning Act 2016.
Vegetation Management Act, 1999 [QLD]	No further broadscale clearing of land post December 2006. Clearing of vegetation still possible under some circumstances (e.g., thinning, for building of infrastructure).
Environmental Protection Act, 1994 [QLD]	Allow development that improves quality of life while protecting the environment, especially natural assets (e.g., rare/endangered species and communities). Outlines the processes proponents are required to follow to mitigate potentially adverse environmental impacts.
Coastal Protection and Management Act, 1995 [QLD]	Provides direction on coastal management policy. A proponent should ensure that the downstream impacts of a development are considered and manage impacts to avoid negative environmental outcomes (e.g., in relation to nutrients, sediments, other contaminants). Protects coastal tourism, recreation and fishing industry.
Fisheries Act, 1994 [QLD]	Protects fish habitat, particularly those that act as important nurseries (e.g., floodplain swamps, lagoons, billabongs). Provide migration pathways for fish.
Queensland Heritage Act, 1992 [QLD]	To conserve Queensland's cultural heritage, development proponents must engage traditional owners to identify (and avoid) significant sites and/or develop strategies to manage these sites.
Native Title (Queensland) Act, 1993 [QLD]	To manage native title interests and negotiating an Indigenous Land Use Agreement, proponents must engage with traditional owners. This is to ensure that traditional owners and the land benefit from participating in the proposed project.
Environment Protection and Biodiversity Conservation Act, 1999 [federal]	The Commonwealth has power to assess proposed developments (and actions more generally) that are likely to have impacts on matters of national environmental significance. Areas of significance include World Heritage areas, Ramsar listed wetlands, threatened species, communities of national significance and migratory species protected either internationally or by the Commonwealth.
Planning Act, 2016 [QLD] (previously Integrated Planning Act, 1997 and Sustainable Planning Bill, 2009)	Coordinating and integrating planning across local, regional and state levels to achieve ecological sustainability, both during the time the development occurs and the on-going effects of the development. Resource entitlement is required prior to application for development approval. Resource entitlement would be authorised under the Water Act 2000 and associated Water Plans.
Aboriginal and Torres Strait Islander Heritage Protection Act, 1984 [federal]	Protects significant Aboriginal areas and objects
Aboriginal Cultural Heritage Act, 2003 [QLD]	Recognises, protects and conserves Indigenous cultural heritage in Queensland. Protects heritage sites regardless of land tenure and physical evidence.
Regional Planning Interests Act, 2014 [QLD]	Manages the impact of activities on regional areas of the state that currently contribute or in the future may contribute to economic, social and environmental prosperity.

Many water-related developments involve the establishment of infrastructure in a waterway. Waterway barrier works are regulated under the Planning Act 2016 (or compliance with the Accepted Development Requirements) and Fisheries Act 1994. Waterway barriers include weirs and dams, among other structures, both permanent and temporary [128]. Queensland waterways have been coded based on the risk of in-stream barriers having adverse impacts on fish movement. The code also relates to the level of development approval required for a potential barrier in the waterway. The Gilbert River is coded as 'Major' impact (Figure 77), meaning that new dams and weirs are *assessable developments* requiring development approval under the Planning Act [129]. Temporary waterway barrier works within major impact waterways are self-assessable [130] and must commence and finish within 180 days [131].

The Planning Regulation 2017 supports the Planning Act 2016 by outlining the mechanisms of the Act. The fee for the development application to impound water or construct a barrier in a major risk waterway (e.g., Gilbert River, Figure 77) is $13,468.00 [132].

Projects that have economic, social and/or environmental significance to the state can be declared as coordinated projects and can be planned, assessed and approved as such (Lyons et al., 2018). This declaration would be made by Queensland's Coordinator-General, under the Planning Act 2016 and associated State Development and Public Works Organisation Act 1971. Coordinated projects must undergo an Environmental Impact Statement (EIS) or Impact Assessment Report (IAR) (Lyons et al., 2018). This declaration would also have implications for the assessment of a project under the Vegetation Management Act [133].

The majority of land tenure in the Gilbert is leasehold land, with only a small portion of freehold land (Dale et al., 2014). The dominance of Crown leasehold land is common in this region of Queensland (Lyons et al., 2018). Leasehold land is governed by the Land Act 1994 (Lyons et al., 2018). Leasehold land is can only be used for the purpose identified in the lease unless otherwise authorised (Lyons et al., 2018). A general duty of care is also required by holders of leases on Crown land (Lyons et al., 2018).

There is also substantial Indigenous land in the catchment, whether recognised and managed under native title, Indigenous land use agreements (ILUAS) or as Indigenous-owned pastoral leases (Figure 78, Figure 79) (Dale et al., 2014, Petheram et al., 2013). Water development in much of the catchment, where native title exists, will require engagement with Traditional Owners (Lyons et al., 2018). This engagement could take the form of revised ILUAS addressing changes to land and water use that would come from water development (Lyons et al., 2018).

[128] https://www.daf.qld.gov.au/business-priorities/fisheries/habitats/policies-guidelines/factsheets/what-is-a-waterway-barrier-work, accessed 25 April 2021

[129] **5.3 New dams and weirs** in Accepted development requirements for operational work that is constructing or raising waterway barrier works (Department of Agriculture and Fisheries, 2018), https://www.daf.qld.gov.au/__data/assets/pdf_file/0006/1476888/adr-operational-waterway-barrier-works.pdf, accessed 25 April 2021

[130] Guide for the determination of waterways using the spatial data layer Queensland waterways for waterway barrier works (Department of Agriculture, Fisheries and Forestry, 2013), https://www.ipwea.org/HigherLogic/System/DownloadDocumentFile.ashx?DocumentFileKey=fb39d2e0-82af-4c6b-aa35-94ad774e7ca3, access 25 April 2021

[131] **7 Temporary waterway barrier works** in Accepted development requirements for operational work that is constructing or raising waterway barrier works (Department of Agriculture and Fisheries, 2018)

[132] **Schedule 10, Part 6, Division 4, Subdivision 2, Table 1** in Planning Regulation 2017

[133] **Division 6, Subdivision 1, s 22A** in Vegetation Management Act 1999

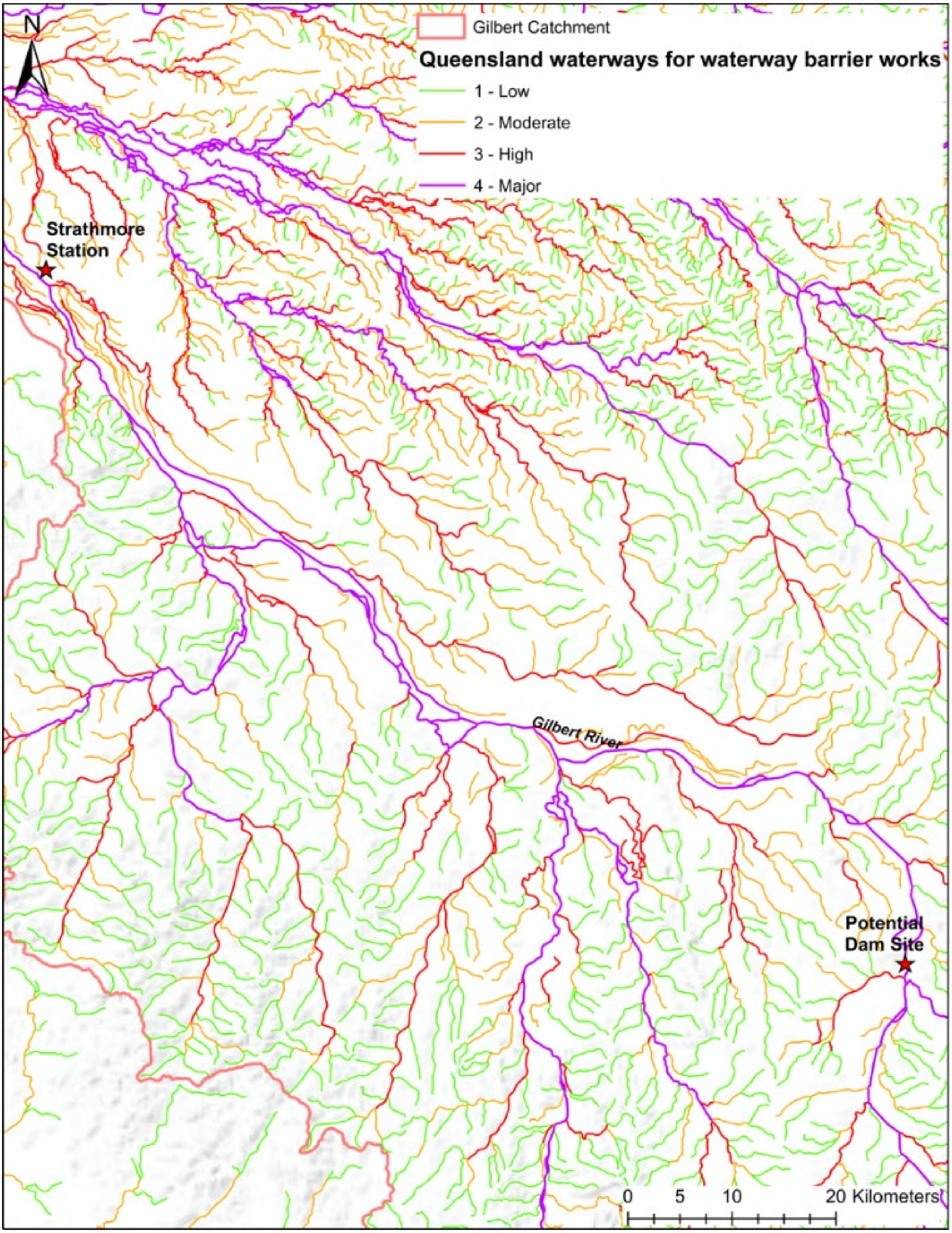

Figure 77 The waterways in the area of interest, coded based on the Queensland waterways for waterway barrier works dataset. Data source: http://qldspatial.information.qld.gov.au/catalogue/custom/search.page?q=%22Queensland waterways for waterway barrier works%22

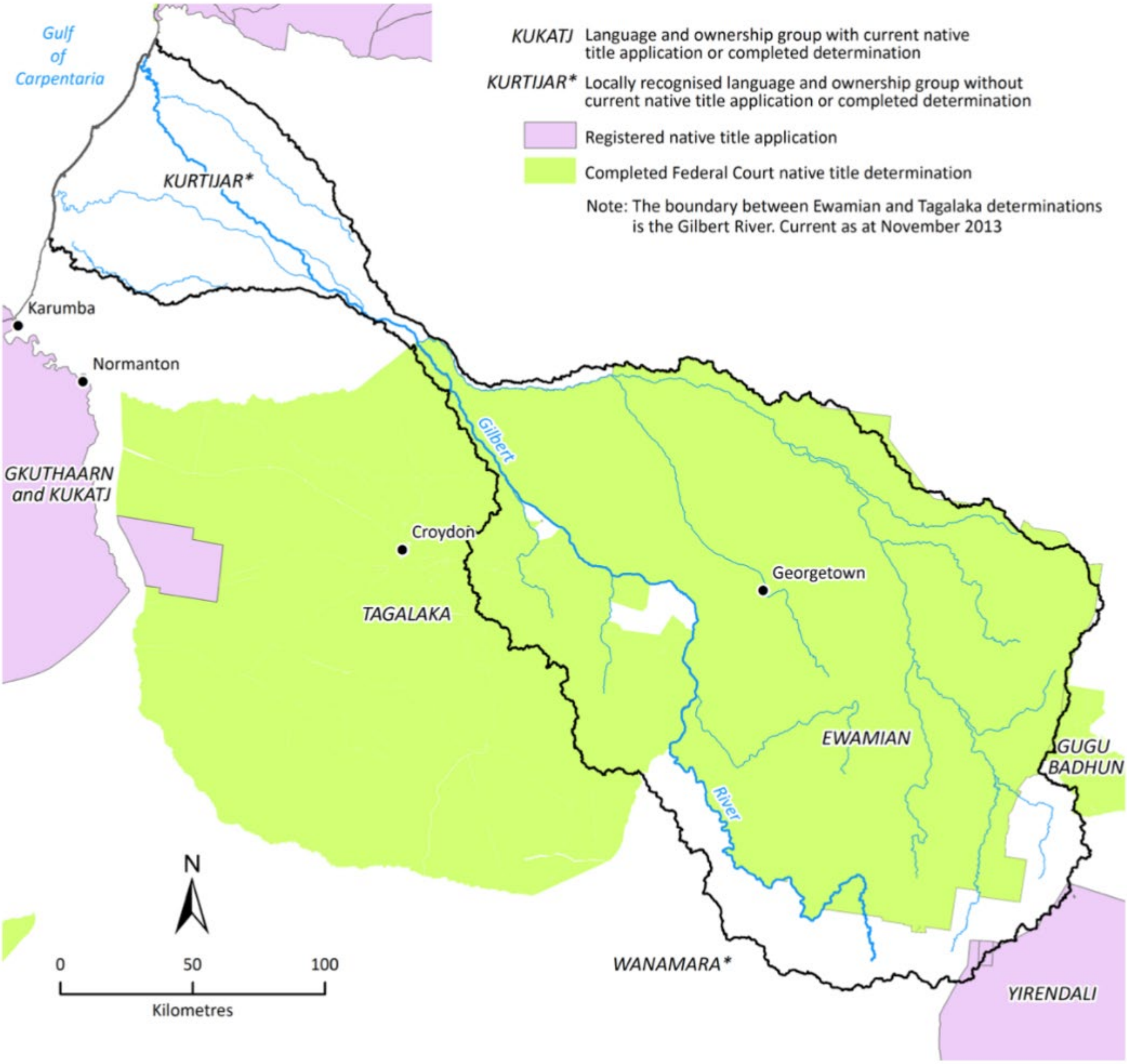

Figure 78 Native title status in the Gilbert catchment (Source: Petheram et al., 2013).

5.7.4 State Assessment and Referral Agency (SARA)

The Department of State Development, Infrastructure, Local Government and Planning's State Assessment and Referral Agency (SARA) is responsible for administrating the State's development assessment and planning framework through the *Planning Act 2016* and Planning Regulation 2017. The key role of SARA is the provision of a central point of call, responsible for coordinating and liaising across a multitude of State agencies to assist proponents in navigating planning approvals as they relate to state interests (e.g. native vegetation clearing, waterway barrier works) https://planning.statedevelopment.qld.gov.au/planning-framework/state-assessment-and-referral-agency, accessed 3 December 2021).

SARA are also responsible for ensuring that the state interests prescribed by the State Planning Policy (https://dsdmipprd.blob.core.windows.net/general/spp-july-2017.pdf, accessed 16 December 2021) are adequately reflected and protected in local government planning schemes. To assist, SARA maintain the State Planning Policy (SPP) Interactive Mapping System (IMS) and Development Assessment Mapping System (DAMS; https://planning.statedevelopment.qld.gov.au/planning-framework/mapping, accessed 3

December 2021). The latter provides mapping that can help proponents identify development assessment triggers that pertain to state interests and state planning matters. The DAMS can also assist proponents in addressing the assessment benchmarks prescribed by the State Development Assessment Provisions (SDAP). Mapping is also available from local councils which can help proponents identify development assessment triggers from a local government perspective under a council's planning scheme.

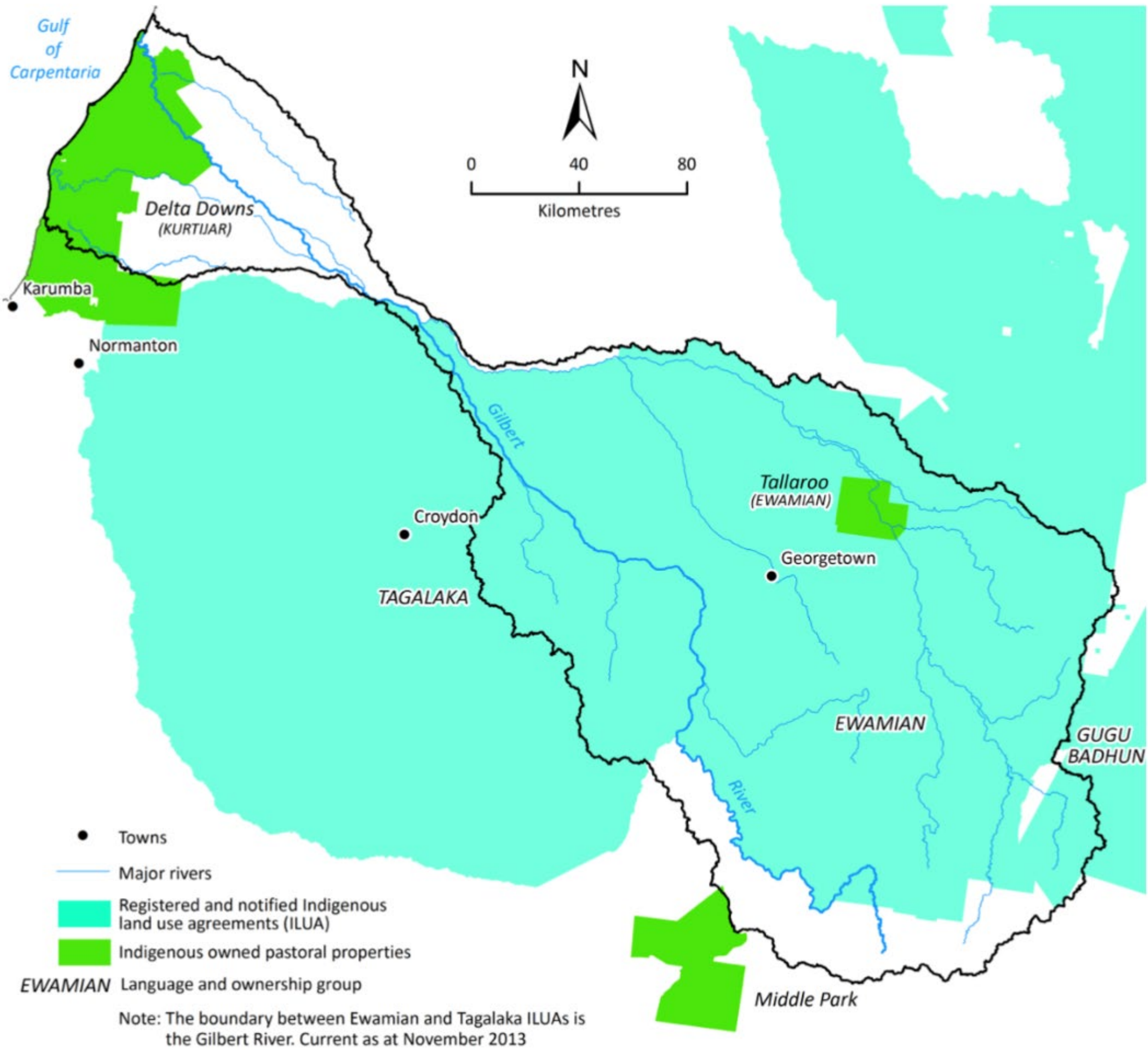

Figure 79 Indigenous land use agreements and Indigenous-controlled pastoral leases in the Gilbert catchment (Source: Petheram et al., 2013).

In the context of water related development, including MAR, SARA would provide a central point of contact for proponents requiring development approval for state interests and state planning matters. Before a development application is lodged, SARA is able to provide proponents with a pre-lodgement service that assists proponents in identifying what referrals are required. SARA will liaise with various state agencies who have a state interest impacted by the proposal. From there, the state agencies will provide technical advice back to SARA who then provide a single, consolidated response back to the proponent. For complex, multi-jurisdictional matters, engaging a planning consultant is encouraged.

If a water related development was considered assessable under a local government planning scheme, that local council would be classed as the assessment manager for that development application. In this instance, SARA would be the referral agency, and the various other state departments would provide technical advice, including recommended conditions, to SARA pertaining to their state interests. SARA then provide a single, consolidated response back to the local council with each state agencies conditions to be attached to any development approval. If the water related development did not require local government approval, SARA would be the assessment manager and the various other state departments would again provide the technical advice, including recommended conditions. SARA then provide the proponent with a decision, which could include not approved, approved, or approved with conditions (as recommended by the state departments).

For matters which sit outside the planning framework (i.e. water licences, land tenure) a project proponent would be directed to engage directly with the relevant state agency (i.e. the Department of Regional Development, Manufacturing and Water (DRDMW) to obtain these authorisations. Advice on water related matters can be obtained directly from DRDMW via their Water Management contacts (https://www.rdmw.qld.gov.au/about-us/contact; accessed 16 December 2021).

6. Towards an improved conceptualization of river bed sand aquifers in the Gilbert River catchment

6.1 Representation of the bed sands in the eWater Source model

Several iterations of eWater Source models have been developed during the CSIRO FGARA project and subsequently. Each of them focuses on exploring water resources development at the basin scale. This is achieved using empirical hydrological models focused on surface water (i.e., rainfall-runoff and routing models), where groundwater dynamics were not to be modelled explicitly. Purchasing access to the current model was out of scope of this project, so the discussion is based on our understanding of the final model developed in the FGARA project (Julien Lerat *pers comm*., 2021) and subsequent documentation (DSITIA, 2014). Based on that understanding, the bed sands are treated as a single storage node – node 043 (DSITIA, 2014)(Julien Lerat *pers comm*., 2021). This node represents the bed sands upstream of the Gilbert River at the Rockfields streamflow gauge (917001D) (Julien Lerat *pers comm*., 2021), having a storage volume of 19,480 ML () (DSITIA, 2014). The storage includes a 'valve' that can release discharge, even when the storage is not full (Julien Lerat *pers comm*., 2021). The release is assumed to be a linear function of the water level in the bed sands: 0 when the storage is empty up to 19,489 ML/day when the storage is full.

While the storage is only represented as a volume at a node, in order to estimate drawdown, the Queensland Government have subsequently interpreted the bed sands as a box of uniform depth (DSITIA, 2014), as shown in Figure 80. Parameter values associated with this representation of the bed sands are summarised in . To convert from maximum volume (m^3) to maximum saturated sand layer thickness (depth, m) the former was multiplied by specific yield of the aquifer then divided by the surface area in m^2 (all values shown in Table 40). This conversion is outlined in Figure 81. Multiplying the maximum volume by the specific yield accounts for the fact that water only occupies the pore space of the sand/gravel of the bed sands (i.e., with a specific yield of 0.2, a maximum of 20% of the total bed sand volume can be water).

The process used to calculate the volume of water in the bed sands and the depth-to-water table on a daily time step is as follows (DSITIA, 2014):

1. Calculate a conversion factor (Table 40) by dividing the maximum water volume in ML (Table 40) by the calculated maximum saturated sand thickness (Table 40)

2. Convert the daily Gilbert River bed sand volumes outputs from the eWater Source model node to thickness values using the conversion factor (Table 40) to create a daily time series of saturated sand layer thickness
    - Values range from 0 – 4.94 metres

3. Calculate daily depth-to-water table by subtracting the maximum saturated sand layer thickness (Table 40) from the daily modelled thickness

Reported difficulties with at least one iteration of the Gilbert eWater Source model include the tendency to overestimate both low flows and the frequency of cease-to-flow events (Lerat et al., 2013). As the bed sands may play a vital ecological role during low flow regimes, further work has been suggested to upgrade the model for both improved ecological understanding and water allocation assessment (DSITIA, 2014). However, the nature of the further work needed has not yet been identified.

Table 40 Reported and calculated characteristics of the bed sand aquifer in the eWater Source model

Characteristic	Value
Maximum Volume [134]	97,400,000 m^3
Specific Yield [135]	0.2
Surface Area [136]	19.676 x 10^6 m^2
Maximum Water Volume [137]	19,480 ML (= 19,480,000 m^3)
Maximum saturated sand layer thickness (depth) [138]	4.94 m
Length [139]	54 km = 54,000 m
Width [140]	364.4 m
Conversion factor [141]	3,943.32 ML m^{-1}

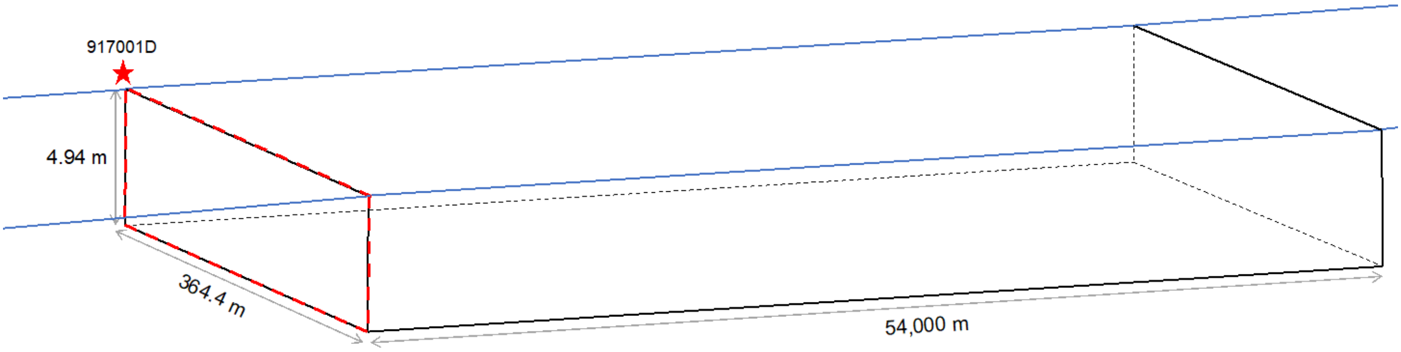

Figure 80 Representation of how the Gilbert River bed sands were modelled in DSITIA (2014), including the Rockfields gauge (917001D). The blue lines represent the river bed level, illustrating that the bed sands are subsurface.

6.2 Proposed extension of the river bed sands conceptualization

There are four key processes that are not included in the current model that we propose would improve simulation and might support changes to management and policy surrounding the bed sands. The four processes are groundwater flow, underflow under the gauge, infiltration, and surface flow hydraulics.

Currently, the water level in the bed sands is assumed to increase or decrease uniformly across the aquifer in response to pumping and recharge within a single timestep (a single day). In reality, and importantly from the managed aquifer recharge point of view, water is expected to flow within the aquifer, governed by groundwater flow equations. Depending on the transmissivity of the bed sands, we expect a slope in the hydraulic head that attenuates over time after pumping or recharge ceases. Put another way, this would improve the representation of local drawdown effects within the bed sands (Figure 82), rather than treating the bed sands as one unit where the hydraulic head is uniform. The length of the bed sands (Table

[134] Back calculated using the reported maximum water volume and specific yield. The reported values can be found in the Targeted review of Water Resource (Gulf) Plan 2007, Environmental Assessment.
[135] As reported in the Targeted review of Water Resource (Gulf) Plan 2007, Environmental Assessment
[136] Calculated using the reported depth and calculated total volume. The reported values can be found in the Targeted review of Water Resource (Gulf) Plan 2007, Environmental Assessment.
[137] As reported in the Targeted review of Water Resource (Gulf) Plan 2007, Environmental Assessment
[138] As reported in the Targeted review of Water Resource (Gulf) Plan 2007, Environmental Assessment
[139] Calculated based on the length of the bed sand zones (3, 4 and 5) reported in the Gulf Resource Operations Plan June 2010
[140] Back calculated using the reported length and calculated surface area. The reported values can be found in the Targeted review of Water Resource (Gulf) Plan 2007, Environmental Assessment.
[141] Calculated by dividing the reported maximum water volume in ML by the calculated maximum saturated sand thickness. The reported values can be found in the Targeted review of Water Resource (Gulf) Plan 2007, Environmental Assessment.

40) suggests that groundwater flow may be a significant factor depending on hydraulic properties. Section 6.3.2 provides a first assessment of the expected significance of this effect.

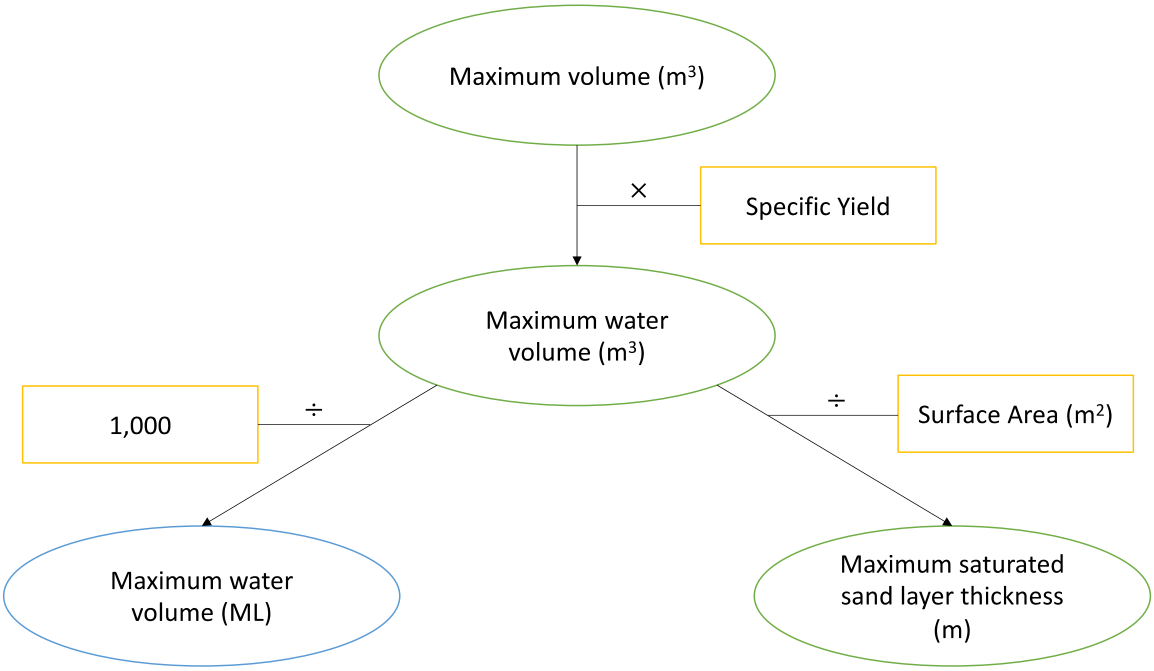

Figure 81 Converting from maximum thickness to maximum saturated sand layer thickness

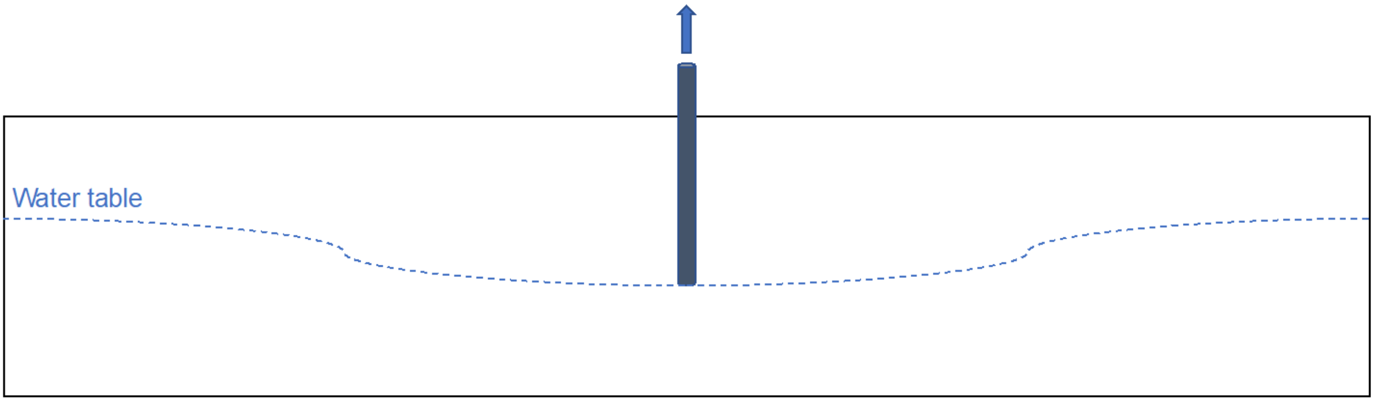

Figure 82 Simple depiction of local drawdown effects in response to extraction

Due to the sandy composition of the aquifer, it is hypothesised that underflow under the gauge could be an important process in the bed sands (Figure 83) [142]. The bed sands as modelled in eWater Source have clear spatial bounds within the Gilbert River, whereas in reality they would form part of the alluvial aquifer that extends both upstream and downstream of the modelled bed sand unit. Therefore, water would likely enter the modelled bed sand unit from upstream and be lost downstream, additionally to the water that infiltrates when there are surface flows. Underflow may also occur from the deeper sandstone aquifers though past reports have suggested little connectivity between the bed sands and the underlying aquifers (DNRME, 2006b, DNRME, 2018b). This is juxtaposed with the anecdotal suggestion that some spear bores never run dry because the section of bed sands is at an outcropping of the deeper sandstone aquifer. This provides a user with high yield throughout the entirety of the dry season. Another user's bore a little further downstream could not extract water throughout the whole dry season (typically yields declined by

[142] Underflow is the term for water entering into or exiting an aquifer system via subsurface flow. BARTOLINO, J. R. & COLE, J. C. 2002. *Ground-water resources of the middle Rio Grande basin, New Mexico*, US Department of the Interior, US Geological Survey.

October). Explicit representation of groundwater flow would be expected to tackle underflow also, though specific attention would need to be given to surface-groundwater connection and hyporheic exchange, between river channels and surrounding sediments.

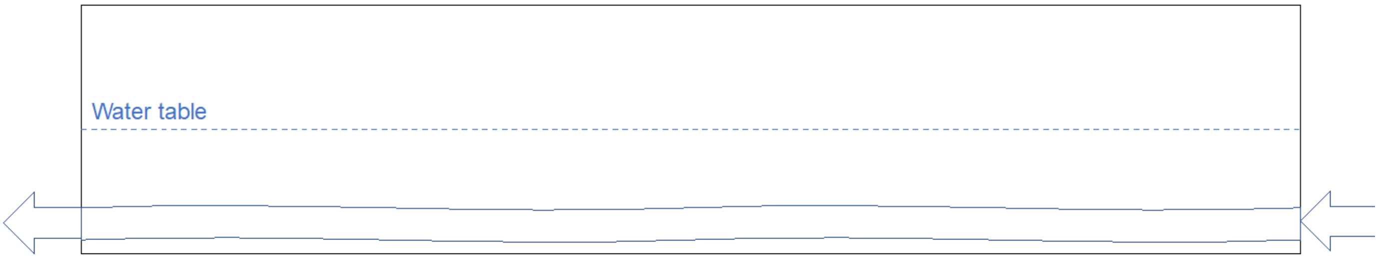

Figure 83 Simple depiction of underflow, where water is entering (and exiting) an alluvial aquifer system without infiltrating from above

Another process discounted in the current modelling of the bed sands is the infiltration time to fill. In the model, every drop of inflow immediately contributes to storage. Due to the flashiness of the flows in the area, there may be times when an event does not completely fill the bed sands (as depicted in Figure 84). This would be particularly true for smaller events at the start of the season. Only part of the flow event would contribute to recharge. The infiltration rate will depend on properties of the sands/gravels and presence of any preferential flow paths, as well as on the area inundated, recognising that flows frequently only occur on parts of the surface area of the Gilbert River and bed sands. Assuming an infiltration rate of 255 mm/day (DNRME, 2006b), the total infiltration volume (with the surface area in) would be 5012.38 ML/day (See Section 6.3.3).

A representation of hydraulics is the standard approach to quantify inundation (surface water) and surface water movement in the riverbed (Figure 85). Flow is affected by riverbed geometry (which may change over time in response through hydrogeomorphological processes) and surface roughness. This analysis would be at a finer spatial scale than a lumped hydrological model, which focuses on the overall water balance of a system. Hydraulics would also link to infiltration via a seepage parameter while keeping the processes distinct. In addition to inflow from (ungauged) tributaries, hydraulics of bed sands overlain by tributaries could also be explicitly modelled to account for their contribution to recharge. Dynamic conditions with sudden flow events, e.g. the effect of entrapped air, could also be an issue.

As shown in Figure 86, the division of the flows into distinct paths could be an important process at the end of the wet season (i.e., during low flow periods). Together with underflow, it would also dictate the formation of dry season waterholes, an important refuge for aquatic species during the dry season (Waltham et al., 2013).

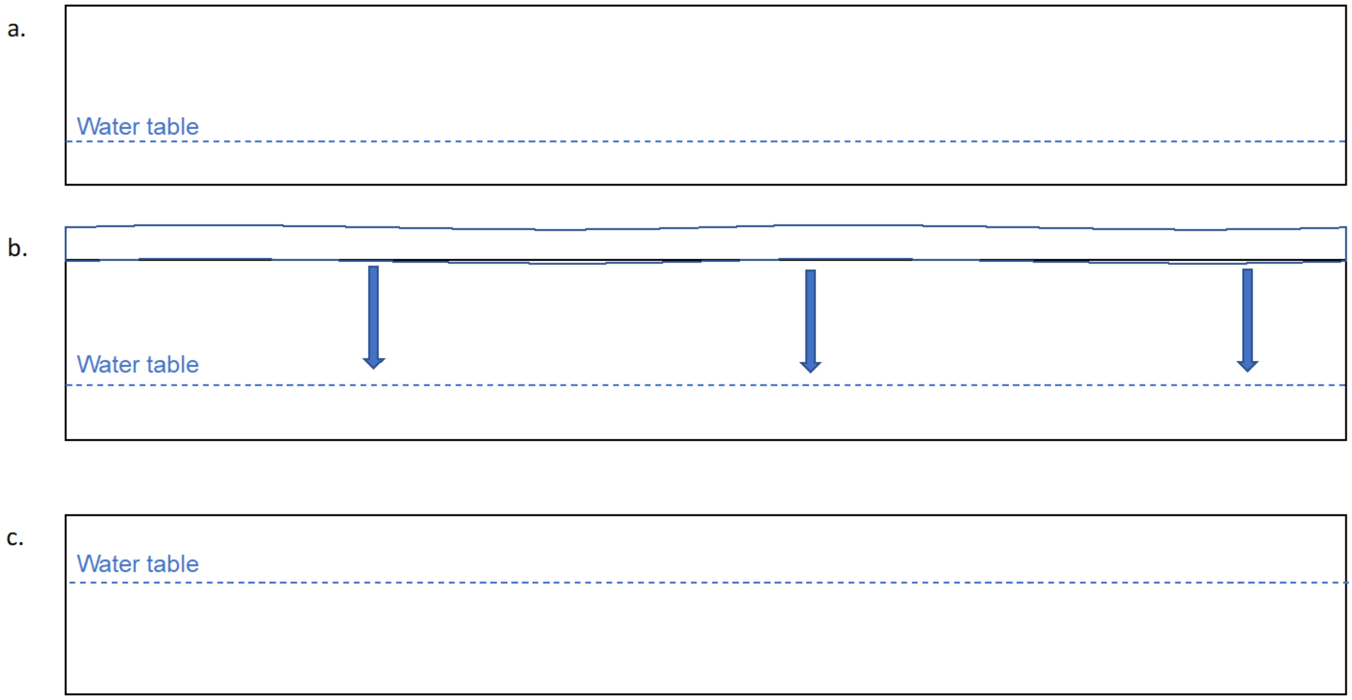

Figure 84 A simple depiction of a flash flow event. (a) Initially the water table in the bed sands is low. (b) A flash flood event occurs, which partially refills the bed sands via infiltration (blue arrows). (c) The water table increases in response.

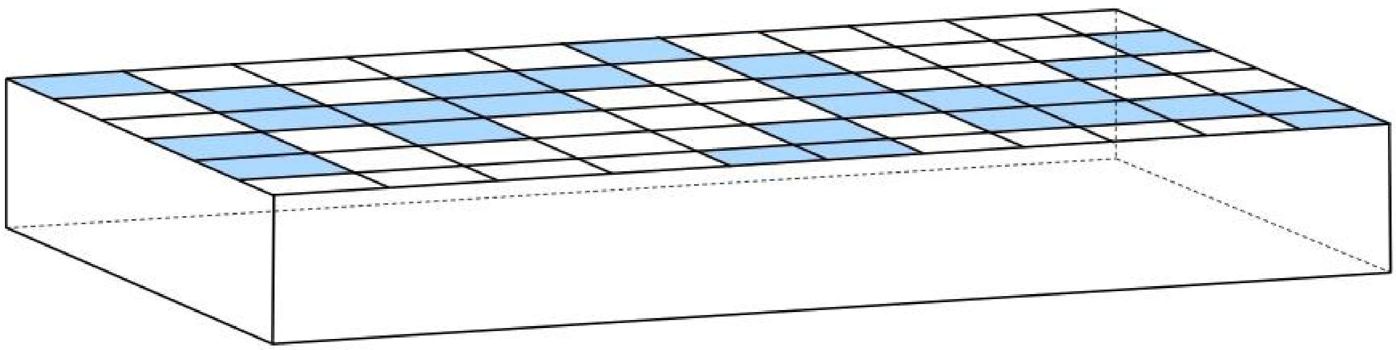

Figure 85 Simple depiction of how a hydraulic representation of surface water may look. The surface is gridded and the presence of water is assessed on a grid scale basis.

The hydrological properties of groundwater flow, underflow under the gauge, infiltration, and hydraulics are key to conceptualising the behaviour of the bed sands if they are to be actively managed as a water storage. By improving understanding of the key processes, modelled outputs could better simulate low flow and cease-to-flow events, allowing for more finely tuned management and supporting policy. It has been suggested that periods where the depth of water in the bed sands exceeds 2.5 m is a potential threat to GDEs (DSITIA, 2014). By simulating how drawdown fluctuates as a result of extraction at varying distances from the extraction point via groundwater flow equations, adequate depth to water levels can be maintained where required (i.e., to support GDEs) and increased where GDEs are absent. Knowledge of where GDEs are located along the stretch of the bed sands would be required to modify drawdown limits spatially. It should be noted that the threshold of 2.5m is not currently used as a trigger value to manage extraction from the bed sands in low flow conditions, which instead has an associated annual maximum extraction limit that equals the sum of current bed sand entitlements (Section 5.2.1, Figure 19, Table 9). Incorporating groundwater flow equations would also allow for the assessment of the impact of extraction from one bore on adjacent bores. This knowledge could be used to assess the impact of additional bores and associated water licences on current users. The filling phase of the bed sands is of particular importance to understand when the bed sands are full (i.e., completely saturated). Infiltration and hydraulic modelling could be used to understand the filling phase, with the intention of maximising filling via interventions (e.g., MAR) and prolonging when drawdown starts.

Figure 86 A period of low flow in the Gilbert River. This image was captured on the 8th of April 2021. The gauged flow on this day was 194.11 ML/day (Gilbert River at Rockfields gauge).

6.3 Preliminary analyses to support future model development

While the development of a new model for the bed sands is out of scope of this project, this section includes three preliminary analyses: an analysis of historical hydrographs, an analysis of the significance of aquifer properties for groundwater flow, and an analysis of possible infiltration volumes. Analysis of historical hydrographs can help identify the periods of time that are most relevant to active management of the bed sands, most affected by the changes to the conceptualisation, and which we expect have the greatest potential to improve model simulations. Preliminary analysis of groundwater flow can provide an indication of the magnitude of the effect of aquifer properties on spatial variation in drawdown. Possible infiltration volumes indicate the significance of infiltration processes at times of recharge.

6.3.1 Analysis of the hydrographs

This analysis provides a preliminary assessment of the periods we expect to be most relevant to active management of bed sands recharge and/or affected by changes to the conceptual model of the bed sands. Previous modelling efforts note the overestimation of low flow and frequency of cease-to-flow events (Lerat et al., 2013). An example of a time when a spatially explicit understanding of drawdowns may be important is into the dry season, when GDEs may rely on water stored in the bed sands until the onset of the next wet season. Infiltration processes would be important during the initial filling of the bed sands (onset of wet season) and also during late flow events in the dry season (e.g., mid-July to start of August 2016 in Figure 87 b)) once drawdown has begun. Inundation dynamics may be important into the dry season when streamflow ceases but waterholes are scattered along the river reach.

There is a stream gauge located immediately downstream of the modelled bed sand aquifer - Gilbert River at Rockfields (917001D[143]). The last several years of data from this gauge was plotted to understand observed streamflow over the bed sands for July to June, the water year (Figure 87 a–e).

[143] https://water-monitoring.information.qld.gov.au/, accessed 31 May 2021

This analysis highlights the interannual variability in flows. For example, peak flows in both the 2017/18 (Figure 87 c)) and 2018/19 (Figure 87 d)) wet seasons were substantially higher than those in the other years plotted, whilst the 2019/20 wet season was particularly dry (Figure 87 e)). Another phenomenon evident from the flow regime is that streamflow is highly event driven in response to rainfall in the catchment (Figure 87). For example, in the 2018/19 water year, the wet season streamflow was dominated by one large event, with minimal discharge otherwise (Figure 87 d)). In other years, however, there were multiple periods with considerable discharge past the gauge (Figure 87 a) – c) and e)).

Inspecting the hydrograph, coupled with anecdotal reports from bed sands water users, allows for estimation of the status of the bed sands. By mid-February, it could be assumed that the bed sands are full. This is supported by the already high flow volumes that have been recorded at the Rockfields gauge by this time in the wet season (Figure 87 a – e). The cross-section at the gauge indicates the full width of the river is inundated with a water level of ~4 m above the reference, which corresponds to a flow of ~120 cumecs (~10,000 ML/day) according to the rating curve. Given substantially higher flows and a maximum water volume of ~20,000 ML (Table 40), even relatively low rates of infiltration would likely fill the bed sands (see Section 6.3.3).

Surface flows decrease substantially around the start of April (Figure 87 a – e), and this is also the time after which surface water flows can no longer be extracted in accordance with the flow conditions applicable to new licenses in the Gilbert catchment [144]. From April to July or August (depending on the year), there are limited surface flows recorded at the gauge (Figure 87 a – e). However, it is possible that such flows would continuously top up the bed sands as drawdown occurs due to underflow and any pumping. This would be a period to ensure that the bed sands are completely full before the surface flows cease. Every year there are periods of no recorded surface flows throughout the dry season (Figure 87 a) – e)). The 2019 dry season experienced an especially long cease-to-flow period, lasting from mid-June to December (Figure 87 d – e). It is during the cease-to-flow period that drawdowns would not be refilled, except perhaps from limited underflow from upstream alluvial aquifers. Even in years where surface flows are almost continuously recorded at the gauge (Figure 87 c), surface water-bed sand connections are likely still relevant as recharge may not keep up with pumping, and continuous drawdown may in fact increase losses from surface flows and perennial pools. Anecdotal reports suggest that one spear bore downstream of the Rockfields gauge often runs dry towards the end of the dry season. The depth of this spear bore is 8 m. However, a bore licensee upstream of the gauge reported that their spear bore never ran dry, being high yielding year-round. This variation in the experience of water users provides an argument for a more dynamic modelling of the bed sands beyond the use of simple storages.

[144] https://www.business.qld.gov.au/industries/mining-energy-water/water/catchments-planning/unallocated-water/gulf, accessed 9 June 2021

Figure 87 Discharge (ML/day) as measured at the is Gilbert River at Rockfields (917001D) gauge for the past several years (July – June). The dashed grey line shows the 99th flow percentile (76,317 ML/day). Only when there is no flow is there no line, while (very) low flows appear as near-zero values.

6.3.2 Significance of aquifer properties for groundwater flow

While accurate modelling of groundwater flow requires detailed spatial information about aquifer characteristics, the importance of groundwater flow in the conceptual model can be evaluated using the aquifer characteristics, either reported above or based on literature values (Maidment, 1993, Jolly et al., 2013), to model the drawdown (also referred to as displacement) of an unconfined aquifer due to pumping using the Neuman solution (Neuman, 1974) in the AQTESOLV software [145]. The Neuman solution assumes uniform hydraulic conductivity and continuous pumping from a single well, with groundwater flowing radially inwards to the well. The bounds of the aquifer are not specified, so the credibility of the distance at which drawdown occurs needs to be considered when interpreting the results. The process of estimating water level is termed 'Forward Solution' in the AQTESOLV software. The data supplied to AQTESOLV, and its source if applicable, are outlined in Table 40 . Any values not outlined are kept at the default value, with the exception of the observation bore coordinates, which were updated multiple times to estimate displacement at varying distances from the pumping bore.

Table 41 Data required by AQTESOLV to estimate displacement as a result of pumping in an unconfined aquifer using the Neuman solution (Neuman, 1974).

Characteristic	Value
Maximum saturated sand layer thickness (depth) (b) [146]	4.94 m
Pumping rate [147]	1.8 m^3/min (= 30 L/sec)
Time since pumping started	Two time slices: 100 minutes; 161,280 minutes (16 weeks)
Hydraulic Conductivity Anisotropy Ratio (K_v/K_h) [148]	0.05
Transmissivity (T) [149]	3.29375 m^2/min (= 4743 m^2/day)
Storativity (S) [150]	0.2

As expected, drawdown decreases with increasing distance from the pumping location (Figure 88). Under the assumption that pumping was to occur for only 100 minutes, there would be a total of 0.18 ML extracted from aquifer. Drawdown would be seen close to the spear bore but is minor, if at all, at distances greater than 200 m from where the pumping occurs (Figure 88). After pumping ceases, local drawdown would be expected to attenuate with flows from elsewhere in the aquifer. Repeated short periods of pumping would therefore be expected to result in short periods of marginally more acute drawdown (~10 cm here). However, as the dry period progresses, pumping is likely to be continuous for long periods of time, as the irrigation water is rotated through a planted area. Using the same volume of water extraction (0.18 ML) drawdown was calculated using the box assumption as outlined in Section 6.1 (dashed blue line in Figure 88), yielding minimal drawdown (Figure 88).

[145] http://www.aqtesolv.com/#main-menu, access 15 Jun 2021
[146] As reported in the Targeted review of Water Resource (Gulf) Plan 2007, Environmental Assessment
[147] Based on yield estimates from the bed sands (See Section 5.3.6)
[148] Calculated based on the vertical and horizontal transmissivity determined from a pumping test in the Gilbert River alluvium, as reported in Jolly et al. (2013). Vertical transmissivity (K_v) was 237 m^2/day and horizontal transmissivity (K_h) was 4743 m^2/day. There is no need to convert from transmissivity from hydraulic conductivity because b is constant, and the ratio would remain the same regardless.
[149] As reported in Jolly et al. (2013).
[150] Calculated using the equation for storativity in an unconfined aquifer http://www.aqtesolv.com/aquifer-tests/aquifer_properties.htm. The S_s value reported for dense sandy gravel (1.5×10^{-5} ft^{-1} = 4.572×10^{-6} m^{-1}; http://www.aqtesolv.com/aquifer-tests/aquifer_properties.htm) was used based on the composition as reported by Department of Natural Resources (1998) (see Section 5.3.1). Depth (b) and specific yield (S_y) is as reported in Table 39.

Under the assumption that pumping from the single well was to occur for 16 weeks, there would be a total of 290.3 ML extracted from the aquifer. This is less than the maximum volumetric limit for the bed sands as a whole or any of the bed sand zones (Section 5.2.1) but is already sufficient to see a modelled whole of aquifer response horizontally. Once again drawdowns are larger closer to the spear bore but persist beyond the estimated bed sand width (~360 m, Figure 88). That is, beyond that distance, instead of the drawdown modelled here, one would expect that drawdown will extend further upstream and downstream. The full width of the aquifer is involved in supplying water, and effects are already propagating along the length of the aquifer to distances of over 1 km. Modelled drawdowns are limited beyond 8,500 m (data not shown), which is less than the full length of the aquifer (54,000 m; , Figure 80). Using the box assumption (Section 6.1) and the volume of water extracted here (290.3 ML), the modelled drawdown over the entire aquifer was less than 10 cm (green dashed line in Figure 88). Drawdowns modelled using the Neuman solution (Neuman, 1974) were substantially higher close to the pumping source but at ~ 900 m were less than what is estimated using the box assumption (Figure 88). This highlights the discounting of local drawdown effects when using the box assumption. The box assumption also does not account for the increased underflow or increased recharge from other points (Alley and Leake, 2004). With higher volumes of pumping which result in a whole aquifer response (both width and length), the box-aquifer approximation would become increasingly appropriate, though local heterogeneity in hydraulic properties may still have an impact. While the spatial variation in drawdown is relatively small (on the order of 10-50 cm for 290.3 ML), this difference may be significant in evaluating whether the threshold of 2.5 m drawdown is breached and may make a meaningful difference in allowing water to be taken later in the dry season.

These preliminary analyses show that the large surface water flows relative to the size of the bed sands storage mean that topping-up of the aquifer at the end of the season is likely more important than initial filling and that spatial effects of drawdown are expected to be subtle. Therefore, going beyond the current volumetric limit of 5082 ML/year requires relatively intensive understanding of bed sands recharge and drawdown behaviours and fine-tuned intervention, and existing data is not sufficient to identify whether any large gains might be possible for relatively small interventions. ***Managed aquifer recharge is therefore best approached through active management of existing water resources in a whole of systems perspective rather than through any single large recharge infrastructure development.***

6.3.3 Infiltration

Three infiltration rates (both measured and estimated) were used to assess maximum daily infiltration volumes (Table 42, Figure 89).

The infiltration volumes reported in Table 42 are estimates and do not account for preferential flow pathways (that would increase infiltration) and local barriers or areas of impermeability such as rock bars (DNRME, 2006b).

In Figure 89, recharge into the bed sands is infiltration-limited during events larger than the estimated threshold (dashed lines) and water-limited when the flow is smaller than the threshold. The infiltration threshold is rarely exceeded outside the peak of the wet season (Jan – April) (Figure 89), meaning that recharge into the system is water-limited throughout the majority of the year.

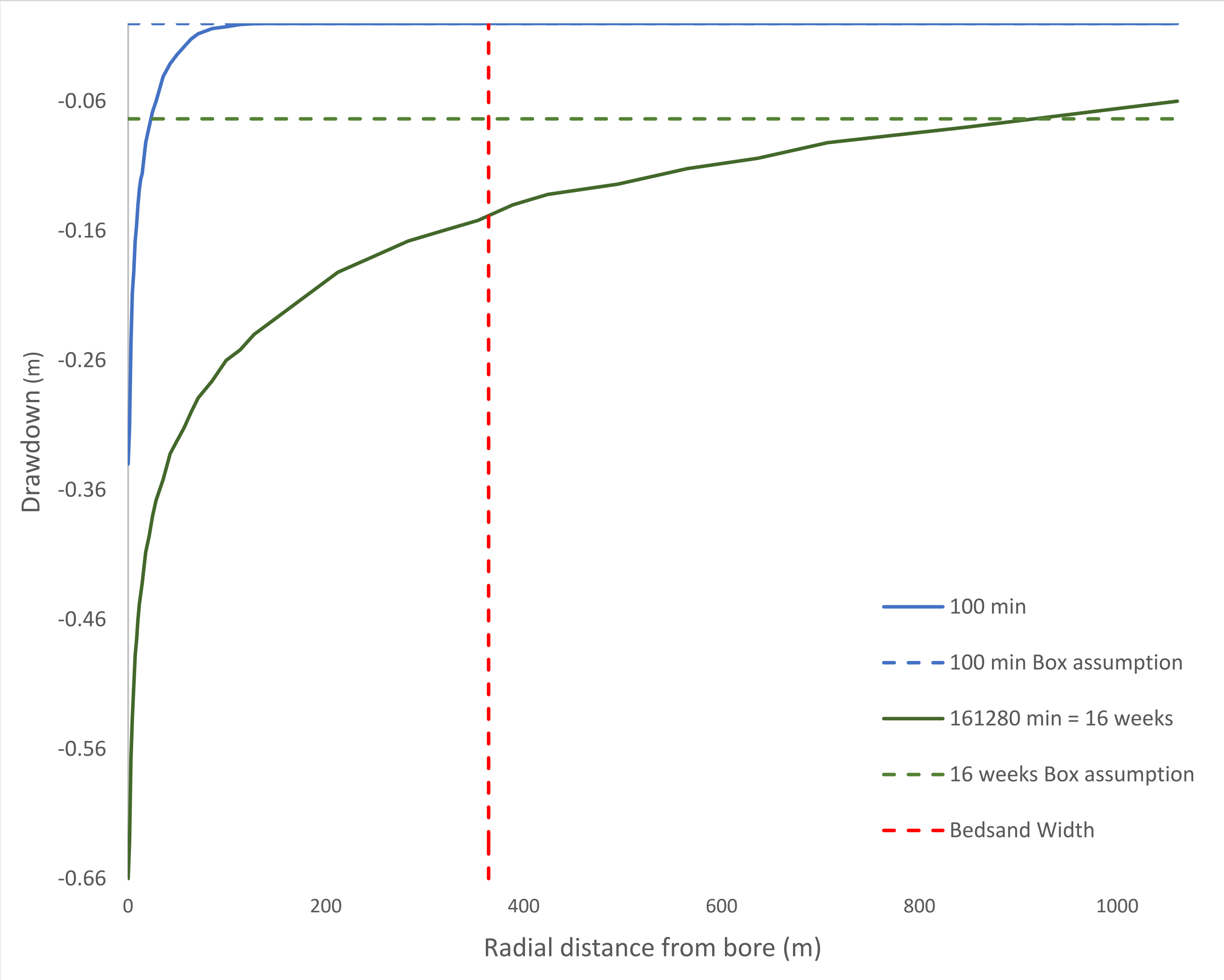

Figure 88 Drawdown (m) at different radial distances from a pumping bore (m), estimated using the Neuman solution (Neuman, 1974) in the AQTESOLV software and the data in Table 40. Two situations are modelled: one where pumping occurs for 100 minutes only and one where pumping occurs continuously for 16 weeks. The dashed orange line represents the estimated width of the bed sands (364.4 m in Table 40).

Table 42 Estimated infiltration based on multiple infiltration rates and the calculated surface area of the bed sands.

Infiltration rates (mm/day)	Source	Surface Area (m^2)	Infiltration (ML/day)
255	Measured (DNRME, 2006b)	19,676,767.68	5017.58
700	Estimated (DNRME, 2006b)	19,676,767.68	13773.74
1000	Estimated from particle size analysis (Jolly et al., 2013)	19,676,767.68	19676.77

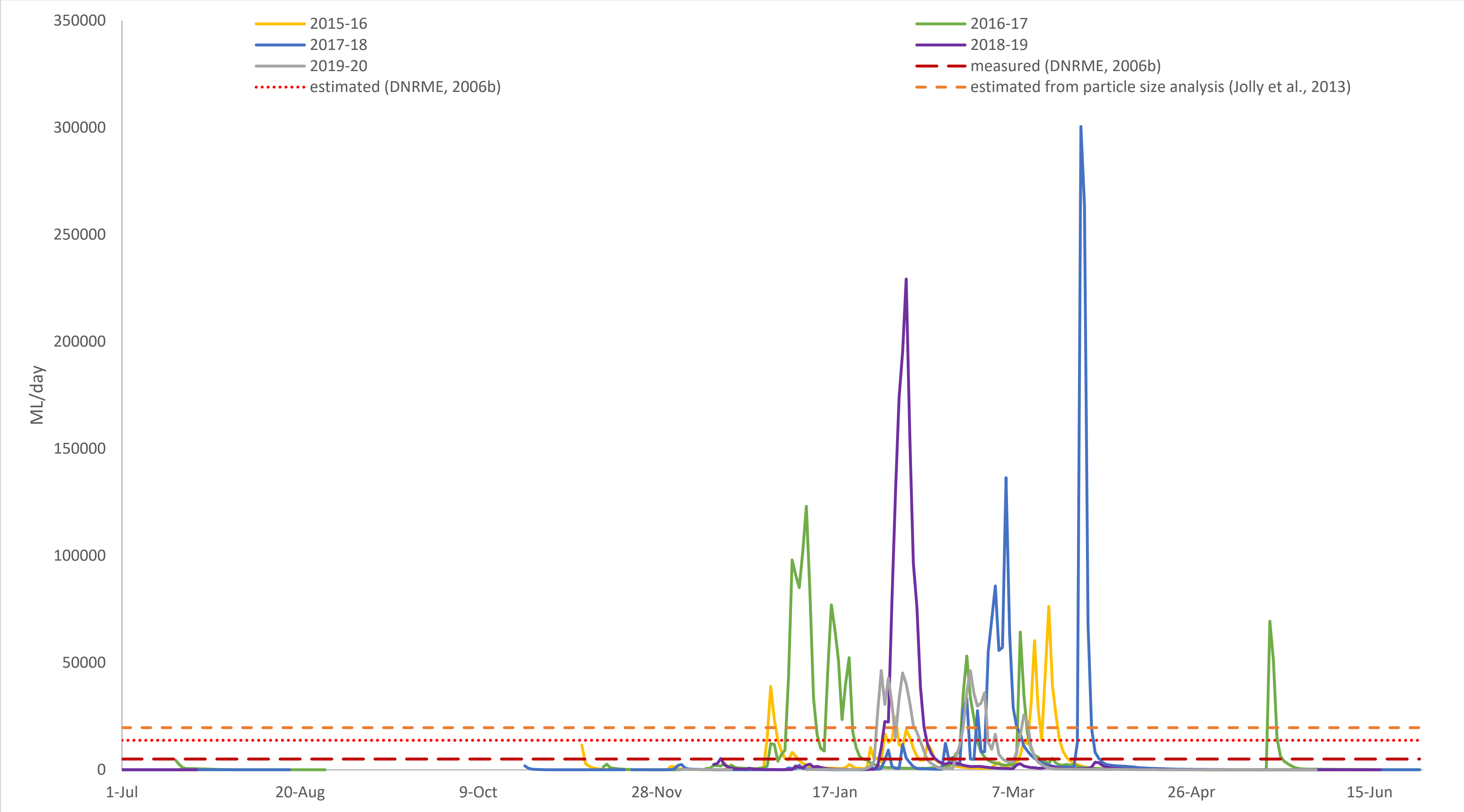

Figure 89 Discharge (ML/day) as measured at the is Gilbert River at Rockfields (917001D) gauge for the past several years (July – June) with estimated infiltration across the entire bed sands based on different infiltration rates shown

7. Synthesis

7.1 Key learnings

The comparatively 'greenfields' nature of irrigated agriculture and water resource development in the Gilbert catchment meant this case study was very different to the previous study in Coleambally (Guillaume et al., 2020). Key learnings from the pre-feasibility assessment follow.

Water availability: At first glance water availability does not seem like a major issue in this case study due to the large flow events observed in the catchment and the low uptake of new, and use of current, entitlements [151]. However, the entitlements currently available are associated with flow conditions meaning that water can only be taken when the flow conditions are met [152]; that is, during substantial flow events when the catchment has received rain. The water requirements for a cropping enterprise is low at this time compared to the end of the wet season and into the dry season. This could explain the low uptake of the water licences, compounded by the relatively limited adoption of water infrastructure such as farm dams to store the water between extraction from the river and use.

There are several current active licences where extraction of water from the bed sands occur, and usage from these licences is below the maximum allowed [153]. Purchases of new entitlements currently up for tender are not prevented from taking from the bed sands although any would be subject to the same flow conditions as extracting river flows.

Environment: Any water development is associated with environmental risks. In the Gilbert catchment, sustainable irrigation development is possible [154] but would have to be accompanied by the ramping up of monitoring with a focus on at risk ecosystems. There are suggestions of environmental assets that may be at risk if water use was to change [155], although this is based on limited information and negligible monitoring. Hyporheic ecosystems may be at risk from further extraction from the Gilbert River bed sands. Indeed, it has been suggested that current extraction could already be impacting the hyporheic ecosystems of the bed sands. The nature and extent of any impact is unknown and undocumented. Groundwater dependent ecosystems (GDEs) could also be impacted by increased water extraction from the bed sands. The current volumetric limits on extraction from the bed sands has been *modelled* to result in a very small impact on GDEs [156].

Technical feasibility: The bed sands are suggested as the most viable option for MAR given the good water quality (low risk of salinity [157]) of these waters, the low yields from the sandstone aquifers [158], and the high evaporative demand and high infiltration of surface storages [159]. This follows the findings of past MAR assessments in the region [160]. Multiple MAR interventions could be used in the Gilbert River, small off-streams and the alluvium adjacent to the river [161]. These include leaky weirs constructed across the small streams to rehydrate the land, recharge weirs to slow flows and infiltration basins that target the alluvial aquifer that extend beyond the river bed (if these are confirmed to exist). As a way to complement surface

[151] Section 5.2.2 and Table 8
[152] Table 10
[153] Section 5.2.1
[154] Section 5.5.4
[155] Section 5.5.1
[156] Page 86 Groundwater dependent ecosystems (GDEs)
[157] Page 53 Focus aquifer in the GRAP
[158] Figure 30, Section 5.3.1, Section 5.3.6
[159] Section 3.1, Section 5.3.2
[160] Section 5.3.4
[161] Section 5.3.5

water infrastructure, a recharge release strategy could be implemented. This would involve the recharge of bed sands by strategic releases from an upstream dam.

Governance arrangements: Current water policy in the catchment is focused on growing surface water use [162]. A review of the Water Plan (Gulf) 2007 is set for 2027 [163], so this would be an ideal time to catalyse policy change to update the rules around bed sand use and to develop policy to allow for intentional storage of river water in the bed sand aquifer. It is possible that governance arrangements in the Burdekin [164] could inform future policy development in the Gilbert. Beyond water policy, there are many other Acts and policies that water infrastructure would have to satisfy [165]. Major hurdles include the Vegetation Management Act and Fisheries Act.

Active management could be suitable approach were policy changed to allow further utilisation of the bed sands. This approach would adapting management (and water policy) based on new knowledge and understanding gained over time. Critically, it would involve collecting information on the bed sands – namely an increase in data and monitoring to support improved risk assessment of environmental and social impacts – to improve (over time) understanding of how the system works. The 'action-state-consequence' framework could provide a useful tool for active management [166], as could the preliminary efforts to develop an improved conceptualisation of the bed sands [167].

7.2 Recommendations

Based on the scenarios presented in Section 4, we conclude that MAR shows some promise in the GRAP, although would need to be part of a systems approach to sustainable water resource development. Investment in MAR has the potential to support incremental development of irrigated agriculture in the region, including cotton production by providing water at a time when it is needed to finish crops, and potentially sustain crops if there is a break in the rainfall post-germination.

To conclude, recommendations are provided in Table 43, drawing on the developed MAR scenarios and the pre-feasibility assessment. Recommendations are framed differently for each group:

- Landholders as a potential driver of farm-scale MAR
- Local organisations, including ESC as a prospective local driver of regional-scale MAR or facilitator of farm-scale MAR, and GSNRM as facilitators of a community supported active management approach to sustainable MAR
- State government as data and model custodian and regulator
- CRDC (or other research and development investors) as a potential facilitator or supporter who can influence or leverage other activities in this space.

These recommendations broadly relate to (a) improving knowledge systems relating to water resources and, specifically the alluvial riverbed sands, or (b) developing the management arrangements necessary for an active management approach to water development and use. While the recommendations were developed with a focus on the Gilbert River Agricultural Precinct, the recommendations also apply to other monsoonal areas with bed sands at a similar stage of agricultural development and scientific knowledge. The recommendations take a staged approach, targeting initial no-regret actions that minimize initial investment and provide value regardless of the extent to which active management and managed aquifer recharge are later pursued.

[162] Section 5.7.1
[163] Section 5.7.2
[164] Section 5.7.4
[165] Section 5.7.3
[166] Section 5.3.7
[167] Section 6

Table 43 Recommendations for initial steps for implementation of managed aquifer recharge and active management of the bed sands

	Landholders	Local organisations, including Etheridge Shire Council, Gulf Savannah Natural Resource Management Group	State government	R&D organisations (e.g., CRDC)
Improving knowledge systems	Evaluate current water use arrangements, especially spear bore use; plan monitoring to resolve gaps and identify improvements	Build capacity for site-specific assessment and planning of water storage management, including regional datasets	Partner to improve monitoring, conceptualisation and modelling of bed sands and associated impacts to inform assessment of active management arrangements	Build capacity for landholder groundwater use and status monitoring, and monsoonal water storage options assessment
Elaboration of management arrangements	Keep records of water levels and use of spear bores and consider opportunities to share information and collaborate on planning	Investigate possible business models and scope of a potential local water management organisation, considering possible partnerships and a systems view of storage options	Co-design requirements for MAR, including active management of bed sands, for consideration in 2027 review of the Gulf Water Plan (2007). This would include consideration of condition-based limits, MEL framework, and guidelines for approvals, water accounting and impact reporting	Support development of public-private information sharing arrangements and coordination mechanisms, to go beyond extraction limits and encourage active management and stewardship of resources

Improvement of knowledge systems includes landholder reflection on how water is currently accessed, particularly in the dry season, the information currently available about the resources being used, and identification of opportunities to complete this information in order to plan possible improvements. This can be supported by building capacity for this type of assessment regionally by local organisations, and more generally by R&D organisations in the sector. As reliance on groundwater increases and cotton production expands in monsoonal areas, it is particularly important for CRDC to support capacity of levy payers in these areas. As state government holds responsibilities as regulator and data and model custodian, they play an important role in improving understanding of bed sands, but in the context of assessment of active management arrangements would benefit from partnering in this task to address requirements beyond those tackled in previous water resource planning and leverage local knowledge. A learning-focused “digital twin” can help tackle this set of recommendations by providing a repository to bring together diverse knowledge sources. Combining computer models and a database of quantitative and qualitative data to describe water resources at multiple scales can help track conditions and facilitate discussion of information sharing and information collection needs of all stakeholders involved.

Active management firstly depends on change in the Gulf Water Plan (2007) to move towards condition-based limits that provide more freedom for experimentation with bed sands management while retaining sufficient confidence through a monitoring, evaluation, and learning (MEL) framework, and guidelines for approvals, water accounting of interception and recharge, and reporting of impacts, including arrangements for sharing of data and associated costs. This change is sufficiently demanding that it requires strong stakeholder buy-in and a collaborative co-creation process. The scheduled review in 2027 provides a realistic target for a first iteration of this type of arrangement. This will likely require support from R&D organisations to develop information sharing and coordination arrangements, and from local organisations to explore possible models for a local water management organisation that could lead active management of water resources. The facilitation role of these organisations is particularly critical given the historical focus on government-led setting of extraction limits and the radical departure that active management of the water resource therefore represents. Local monitoring and information sharing by landholders is expected to be a critical starting point, especially if a farm-scale rather than regional-scale approach is pursued. While local organisations, state government, and R&D organisations are critical to provide enablers and mitigate barriers, successful active management of bed sands and dry season water storage above all capitalises on bottom-up landholder initiative and involvement rather than disruptive outside change from any single large infrastructure development.

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