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Water resource assessment for the Southern Gulf catchments

A report from the CSIRO Southern Gulf Water Resource Assessment for the National Water Grid

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Important disclaimer

CSIRO Southern Gulf Water Resource Assessment acknowledgements

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Aspects of the Assessment have been undertaken in conjunction with the Northern Territory (NT) and Queensland governments.

The Assessment was guided by two committees:

i. The Governance Committee: CRC for Northern Australia/James Cook University; CSIRO; National Water Grid (Department of Climate Change, Energy, the Environment and Water); Northern Land Council; NT Department of Environment, Parks and Water Security; NT Department of Industry, Tourism and Trade; Office of Northern Australia; Queensland Department of Agriculture and Fisheries; Queensland Department of Regional Development, Manufacturing and Water

ii. The Southern Gulf catchments Steering Committee: Amateur Fishermen's Association of the NT; Austral Fisheries; Burketown Shire; Carpentaria Land Council Aboriginal Corporation; Health and Wellbeing Queensland; National Water Grid (Department of Climate Change, Energy, the Environment and Water); Northern Prawn Fisheries; Queensland Department of Agriculture and Fisheries; NT Department of Environment, Parks and Water Security; NT Department of Industry, Tourism and Trade; Office of Northern Australia; Queensland Department of Regional Development, Manufacturing and Water; Southern Gulf NRM

Responsibility for the Assessment's content lies with CSIRO. The Assessment's committees did not have an opportunity to review the Assessment results or outputs prior to their release.

This report was reviewed by Mr Mike Grundy (Independent consultant). Individual chapters were reviewed by Dr Peter Wilson, CSIRO (Chapter 2); Dr Andrew Hoskins, CSIRO (Chapter 3); Dr Brendan Malone, CSIRO (Chapter 4); Dr James Bennett, CSIRO (Chapter 5); Dr Nikki Dumbrell, CSIRO (Chapter 6); Mr Darran King, CSIRO (Chapter 7). The material in this report draws largely from the companion technical reports, which were themselves internally and externally reviewed.

For further acknowledgements, see page xxviii.

Acknowledgement of Country

CSIRO acknowledges the Traditional Owners of the lands, seas and waters of the area that we live and work on across Australia. We acknowledge their continuing connection to their culture and pay our respects to their Elders past and present.

Photo

Saltwater Arm, a tributary of the Albert River. This view typifies the tidal rivers and estuaries along the southern coast of the Gulf of Carpentaria. Source: Shutterstock

5 Opportunities for water resource development in the Southern Gulf catchments

Authors: Matt Gibbs, Andrew R Taylor, Cuan Petheram, Ang Yang, Steve Marvanek, Lee Rogers, Fred Baynes, Geoff Hodgson, Justin Hughes, Anthony Knapton

Chapter 5 examines the opportunities, risks and costs for water resource development in the catchments of the Southern Gulf rivers, that is Settlement Creek, Gregory–Nicholson River and Leichhardt River, the Morning Inlet catchments and the Wellesley island groups[1]. Evaluating the possibilities for water resource development and irrigated agriculture requires an understanding of the development-related infrastructure requirements, how much water can be supplied and at what reliability, and the associated costs. The key components and concepts of Chapter 5 are shown in Figure 5-1.

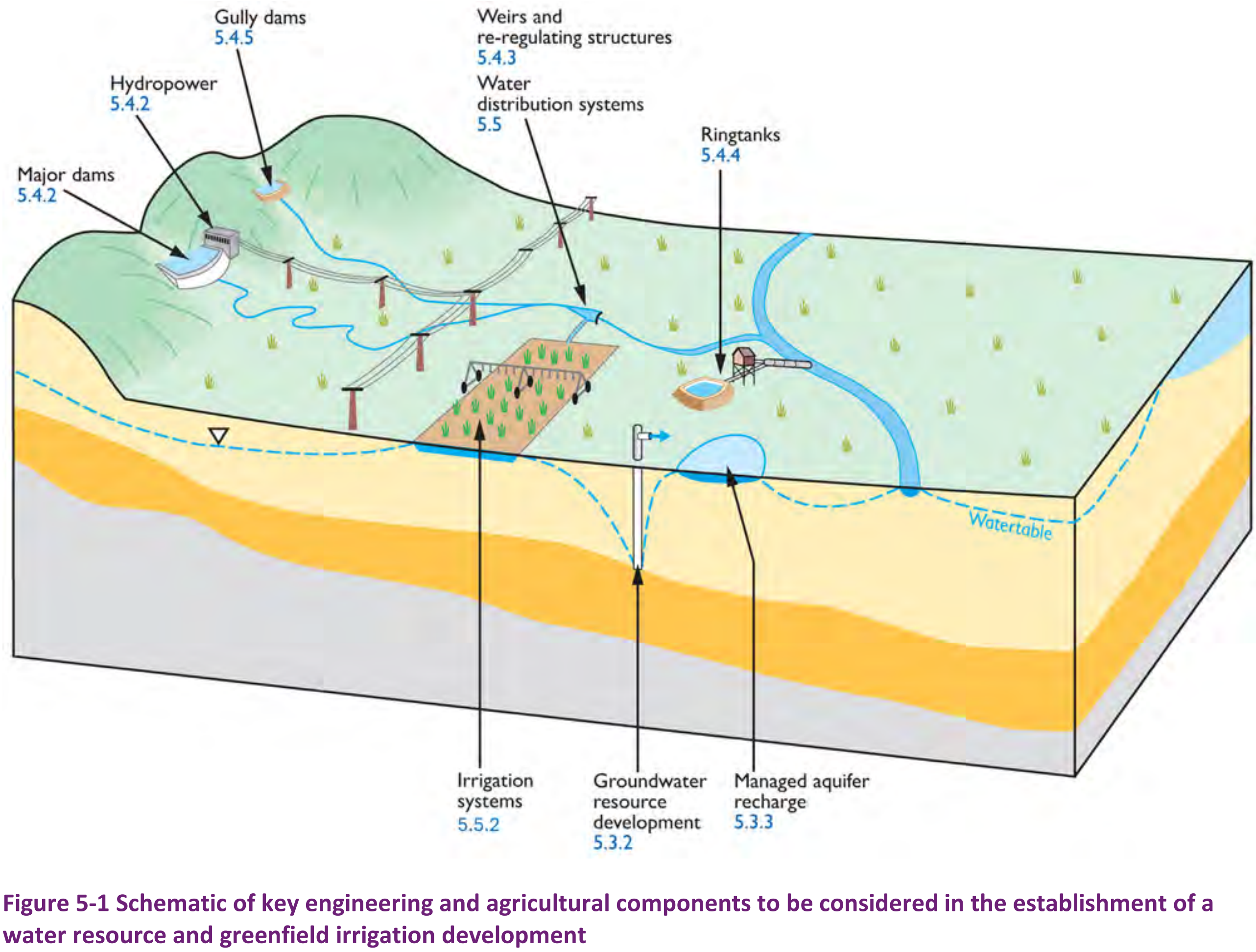

Figure 5-1 Schematic of key engineering and agricultural components to be considered in the establishment of a water resource and greenfield irrigation development

Numbers in blue refer to sections in this report.

[1] Only those islands greater than 1000 ha are mapped.

5.1 Summary

This chapter provides information on a variety of potential options to supply water, primarily for irrigated agriculture. The methods used to generate these involved collating and synthesising existing data. No fieldwork was undertaken as part of this Assessment. The potential water yields reported in this chapter are based largely on physically plausible volumes, and do not consider economic, social, environmental, legislative or regulatory factors, which will inevitably constrain many developments. In some instances, the water yields are combined with land suitability information from Chapter 4 to provide estimates of areas of land that could potentially be irrigated close to the water source or storage.

5.1.1 Key findings

Water can be sourced and stored for irrigation in the Southern Gulf catchments in a variety of ways. If the water resources of the Southern Gulf catchments are developed for consumptive purposes it is likely that some of the options below may help to maximise the cost effectiveness of water supply in different parts of the study area.

Groundwater extraction

Groundwater is already widely used in parts of the Southern Gulf catchments for a variety of purposes (stock, domestic activities, mining, irrigation, community water supplies) and offers year-round niche opportunities that are geographically distinct from surface water development opportunities. The two most productive groundwater systems in the catchments are the regional-scale Cambrian Limestone Aquifer (CLA) and Gilbert River Aquifer (GRA). Currently, existing annual licensed groundwater entitlements for both aquifers are small. These are 1.8 GL/year for the CLA and <0.25 GL/year for the GRA, neither aquifers are currently used for groundwater-based irrigation. Across different parts of the catchments small amounts of unlicensed groundwater use for stock and domestic purposes also occurs from both aquifers. Water plans exist for both aquifers in the Queensland portion of the study area. The Gulf Water Plan manages groundwater resources of the CLA, and the groundwater resources of the GRA are managed under the Great Artesian Basin and Other Regional Aquifers water plan. There are currently no water plans for the NT parts of the catchments, where (of the two regional-scale aquifers) only the CLA exists.

With appropriately sited borefields it may be possible to extract between 10 and 20 GL/year from the CLA in the south-west of the study area. This is where the aquifer outcrops to the west of where the reaches of Lawn Hill Creek and the Gregory and O'Shannassy rivers receive groundwater discharge from the CLA. This indicative scale of the resource is based on an initial estimate of the components of the water balance for the portion of the CLA underlying these catchments, as well as their potential sensitivity to climate variability. However, data for the CLA is sparse, and a more refined estimate of the scale of potential future groundwater resource development would require more detailed investigations of the water balance. Any potential development would also depend on potential impacts to groundwater-dependent ecosystems (GDEs), such as the prescribed reaches of Lawn Hill Creek and the Gregory River, to existing groundwater users (see Section 3.3.4), and community and government acceptance these changes.

The GRA may also offer some opportunities for future groundwater resource development, though the aquifer in the north-east of the catchment is deep (>500 metres below ground level (mBGL)) in places and exhibits variable water quality not always suitable for irrigation. It may be possible with appropriately sited borefields to extract about 5 GL/year near the south-western margin of the GRA in the north-east of the catchments, where the aquifer is less than 500 m deep, and in places hosts fresh water (<1000 mg/L total dissolved solids (TDS)). Similar to the CLA, the actual scale of potential future groundwater resource development would depend upon community and government acceptance of potential impacts to GDEs and existing groundwater users (e.g. active water licences for the communities of Burketown and Gununa).

Opportunities for potential groundwater resource development from aquifers hosted in other hydrogeological units (Proterozoic igneous, metasedimentary and metamorphic rocks) is most likely to be limited to use for stock and domestic purposes, and occasional community water supply. Aquifers within the Cenozoic alluvium may provide a source of water, though few data exists for these systems.

Major dams

Indigenous customary residential and economic sites are usually concentrated along major watercourses and drainage lines. Consequently, potential instream dams are more likely to have an impact on areas of high cultural significance than are most other infrastructure developments of comparable size.

Topographically and geologically, large parts of the Southern Gulf catchments have considerable potential for large instream dams, and there are already five large water supply dams in the Southern Gulf catchments with capacities of about 10 GL or greater. These dams are used to supply water for mining, industry and the city of Mount Isa. These users typically use considerably less water than the amounts required for irrigated agriculture. In the Southern Gulf catchments a limitation of large dams is the semi-arid climate and typically small catchment areas of those parts of the catchment with suitable topography. This means that most potential sites for dams in the Southern Gulf catchments have relatively low yields (typically less than 100 GL in 85% of years).

One of the most cost-effective potential large instream dam sites in the Southern Gulf catchments is on the Gregory River, immediately upstream of a large contiguous area (1.03 million ha) of soil suitable for irrigated agriculture. However, the site sits within the Thorntonia Aggregation wetland. A previous study found that residents at Mount Isa placed a particularly high value on the Gregory Rivers (Jackson et al., 2008). Considering existing consumptive users this potential dam could yield 133 GL in 85% of years and cost $683 million (−20% to +50%) to construct, assuming favourable geological conditions. With the land adjacent to the east bank of the Gregory River sloping away from the river, the land is highly suitable for the more cost-effective gravity channel reticulation infrastructure. A nominal reticulation scheme for 10,000 ha of irrigated land was estimated to cost an additional $31.8 million or $3180/ha (excluding farm development and infrastructure).

Water harvesting and offstream storage

Water harvesting, where water is pumped from a major river into an offstream storage such as a ringtank, is a cost-effective option for capturing and storing water from the Nicholson, Gregory and Leichhardt rivers. Approximately 21% of the study area (1,672,000 ha) was modelled as having soil and topography likely or possibly suitable for ringtanks, which is a large percentage relative to other catchments across northern Australia. The most favourable soil and topography for ringtanks in the study area is on the east bank of the Gregory River, where the extensive cracking clay soils of the Armraynald Plain gently slope away from the river, enabling the cost-effective conveyance of water using gravity. Water harvesting along the Nicholson is limited by the lack of soil suitable for the construction of off-stream storages. Downstream of Kajabbi the construction of ringtanks adjacent to the Leichhardt River is possible on heavier alluvial soils where the sandy levees are not so wide that the conveyance of water from the river to the ringtank would be prohibitively expensive. From the Nicholson and Leichhardt catchments it is physically possible to extract 150 GL in 75% of years and irrigate 12,000 ha of broadacre by pumping or diverting water from the Nicholson, Gregory and Leichhardt rivers and storing it in offstream storages such as ringtanks. This results in modelled reductions in mean and median annual discharge from the Gregory– Nicholson and Leichhardt rivers to the Gulf of Carpentaria of about 3% and 5%, respectively.

Managed aquifer recharge

The most promising aquifers for infiltration-based MAR in the Southern Gulf catchments are aquifers within the Cenozoic alluvium associated with many of the rivers in the study area. Visually the Cenozoic alluvium appears to be extensive relative to alluvium associated with many rivers elsewhere in northern Australia. However, bore logs and water-level information are not available for Cenozoic alluvium, and it is likely that the opportunity for MAR may vary between locations. Approximately 122,700 ha (1.1% of the study area) of the Southern Gulf catchments was identified as having potential for aquifers, groundwater and landscape characteristics suitable for infiltration MAR techniques within 5 km of a source of surface water – defined here as being a river with median annual flow greater than 20 GL. Approximately 37,100 ha (0.3% of the study area) within 1 km of such a river had similarly suitable characteristics; however, 94% of this area is underlain by Cenozoic alluvium.

There may be potential to use MAR in the CLA to offset the impacts of groundwater pumping on GDEs near Lawn Hill Creek and the Gregory River. However, this would be contingent on finding soils suitable for the construction of ringtanks (Section 5.4.4), to temporarily detain surface water, close to a location that is suitable for MAR (typically on highly permeable soils).

Gully dams and weirs

Suitably sited large farm-scale gully dams are a relatively cost-effective method of supplying water. Those areas that are more topographically suitable for large-scale gully dam sites generally do not coincide with areas that have soils suitable for their construction or suitable for irrigated agriculture. There are, however, some locations in the north-west of Doomadgee in the Settlement Creek catchment and Mornington Island where there is some topography suitable for gully dams, soil suitable for their construction and versatile agricultural land nearby. These areas are geographically distinct from those areas that are most suitable for water harvesting and ringtanks.

The remaining sources of water and storage options, namely weirs and natural water bodies, are estimated to be capable of reliably supplying considerably smaller volumes of water than major instream dams. Sourcing water from natural water bodies, although the most cost-effective option, is highly contentious.

Summary of investigation costs, capital, and operation and maintenance costs of different water supply options and potential scale of unconstrained development

Table 5-1 provides a summary of indicative investigative, capital, and operation and maintenance costs of different water supply options and estimates of the potential scale of unconstrained development. The development of any of these options will have an impact on existing uses, including ecological systems, to varying degrees, and will depend on the level of development. Ecological implications of altered flow regimes are examined in Section 7.3. All of the water source options reported in Table 5-1 are considerably cheaper than the cost of desalinisation. The initial cost of constructing four large desalinisation plants (capacity of 90 to 150 GL/year) in Australia between 2010 and 2012 ranged from $19,000/ML to $31,000/ML (AWA, 2018), indexed to 2023. This does not include the cost of ongoing operation (e.g. energy) and maintenance or the cost of conveying water to the demand.

Table 5-1 Summary of capital costs, yields and costs per ML supply, including operation and maintenance

Costs and yields are indicative. Values are rounded. Capital costs are the cost of construction of the water storage/source infrastructure. They do not include the cost of constructing associated infrastructure for conveying water or irrigation development. Water supply options are not independent of one another, and the maximum yields and areas of irrigation cannot be added together. Equivalent annual cost assumes a 7% discount rate over the service life of the infrastructure. Total yields and areas are indicative and based on physical plausibility unconstrained by economic, social, environmental, legislative or regulatory factors, which will inevitably constrain many developments.

WATER SOURCE/STORAGE	GROUND-WATER†	MANAGED AQUIFER RECHARGE‡	MAJOR DAM	WEIR§	LARGE FARM-SCALE RINGTANK	LARGE FARM-SCALE GULLY DAM	NATURAL WATER BODY
Cost and service life of individual representative unit							
Capital cost ($ million)	4.5	1.1	680	5–40	2.5	1.7	0.02
Operation and maintenance ($ million/y)*	0.1	0.07	2.7	0.1–0.8	0.125	0.045	~0
Assumed service life (y)	50	50	100	50	40	30	10
Potential yield of individual representative unit at water source							
Yield at source (GL)††	2	0.6	133	0.5–10	2.4	3	0.125–0.5
Unit cost ($/ML)‡‡	2,250	1,830	5,110	6,500	1,040	570	100
Levelised cost ($ million/ML) §§	215	250	380	600	130	60	10
Potential yield of individual representative unit at paddock							
Assumed conveyance efficiency to paddock (%)†††	95	90	75	80	90	90	90
Yield at paddock (GL)	1.9	0.54	100	0.4–8	2.2	2.7	0.11–0.45
Unit cost ($/ML)‡‡	2,370	2,040	8,115	8,125	1,160	630	110
Levelised cost ($ million/ML) †††	225	280	600	750	145	65	12

WATER SOURCE/STORAGE	GROUND-WATER†	MANAGED AQUIFER RECHARGE‡	MAJOR DAM	WEIR§	LARGE FARM-SCALE RINGTANK	LARGE FARM-SCALE GULLY DAM	NATURAL WATER BODY
Total potential yield and area (unconstrained)							
Total potential yield (GL/y) at source ≥75% reliability‡‡‡	30	<30	320	<100	90	<100	<20
Potential area that could be irrigated at ≥75% reliability (ha)§§§	4,500	<4,500	30,000	<10,000	12,000	<10,000	<2,000

†Value assumes extraction from Cambrian Limestone Aquifer assuming mean bore yield of 25 L/s irrigation of 250 ha to meet mean peak evaporative demand over a 3-day period. Assumes a mean depth of 80 m and a drilling failure rate of 50%.
‡Based on recharge weir.
§Sheet piling weir.
*Operation and maintenance (O&M) cost is the annual cost of operating and maintaining infrastructure and includes cost of pumping groundwater assuming groundwater is 10–20 m below ground level and the cost of pumping water into ringtank.
††Yield at dam wall (taking into consideration net evaporation from surface water storages prior to release) or at groundwater bore. Value assumes large farm-scale ringtanks do not store water past August.
‡‡Capital cost divided by the yield.
§§Equivalent annual cost of storage per bore per ML of yield of water. Includes capital cost and O&M costs. Assumes 7% discount rate.
†††Conveyance efficiency between dam wall/groundwater bore and edge of paddock (does not include field application losses).
‡‡‡Actual yield will depend upon government and community acceptance of impacts to water-dependent ecosystems and existing users. Yields are not additive. Likely maximum cumulative yield at the dam wall/groundwater bore. Potential yield of major dams based on yield of dams at Waterhouse River.
§§§Likely maximum area that could be irrigated (after conveyance and field application losses) in at least 75% of years. Assumes a single crop. Areas provided for each water source are not independent and hence are not additive. Actual area will depend upon government and community acceptance of impacts to water-dependent ecosystems and existing users.

5.2 Introduction

5.2.1 Contextual information

Irrigation during the dry season and other periods when soil water is insufficient for crop growth requires sourcing water from a suitable aquifer or from a surface water body. However, decisions regarding groundwater extraction, river regulation and water storage are complex, and the consequences of decisions can be inter-generational, where even relatively small inappropriate releases of water may preclude the development of other, more appropriate (and possibly larger) developments in the future. Consequently, governments and communities benefit by having a wide range of reliable information available prior to making decisions, including the manner of ways water can be sourced and stored, as this can have long-lasting benefits and facilitate an open and transparent debate.

Information is presented in a manner to easily enable the comparison of the variety of options. More detailed information can be found in the companion technical reports. Section 5.5 discusses the conveyance of water from the storage and its application to the crop. Transmission and field application efficiencies, and associated costs and considerations, are examined.

All costs presented in this chapter are indexed to December 2023.

Concepts

The following concepts are used in sections 5.3 and 5.4:

- Each of the water source and storage sections are structured around: (i) an opportunity- or reconnaissance-level assessment and (ii) a pre-feasibility-level assessment:
  - Opportunity-level assessments involved a review of the existing literature and a high-level desktop assessment using methods and datasets that could be consistently applied across the entire Assessment area. The purpose of an opportunity-level assessment is to provide a general indication of the likely scale of opportunity and geographic location of each option.
  - Pre-feasibility-level assessments involved a more detailed desktop assessment of sites/geographic locations that were considered more promising. This involved a broader and more detailed analysis including the development of bespoke numerical models, site-specific cost estimates and site visits. Considerable field investigations were undertaken for the assessment of groundwater development opportunities (Section 5.3.2).
- 'Yield' is a term used to report the performance of a water source or storage. It is the amount of water that can be supplied for consumptive use at a given reliability. For dams, an increase in water yield results in a decrease in reliability. For groundwater, an increase in water yield results in an increase in the 'zone of influence' and can result in a decrease in reliability over time, particularly in local- and intermediate-scale groundwater systems.
- Unit cost is the capital cost of the infrastructure divided by the amount of water that can be supplied at a specified reliability. It is commonly used to provide a comparison of the cost effectiveness of assets of similar life spans and operational costs.
- Equivalent annual cost is the annual cost of owning, operating and maintaining an asset over its entire life. Equivalent annual cost allows a comparison of the cost effectiveness of various assets that have unequal service lives/life spans.
- Levelised cost is the equivalent annual cost divided by the amount of water that can be supplied at a specified reliability. It allows a comparison of the cost effectiveness of various assets that have unequal service lives/life spans and water supply potential.

Other economic concepts reported in this chapter, such as discount rates, are outlined in Chapter 6.

5.3 Groundwater and subsurface water storage opportunities

5.3.1 Introduction

Groundwater, where an aquifer is relatively shallow (less than a couple of hundred metres) and of sufficient yield to support irrigation (typically greater than 10 L/s), is often one of the cheapest sources of water available, particularly where individual bore yields can be in the order of tens of litres per second thereby reducing the costs of groundwater infrastructure.

Even the cheapest forms of MAR, infiltration-based techniques, are usually considerably more expensive than developing a groundwater resource. Further to this, in northern Australia many unconfined aquifers, which are best suited to infiltration-based MAR, either have large areas with no 'free' storage capacity at the end of the wet season (because groundwater levels have risen to near the ground surface) or, where they do have the available storage capacity, are often not at economically viable distances (greater than 5 km) from a reliable source of water to recharge the aquifer. Therefore, MAR will inevitably only be developed following development of a groundwater system, where groundwater extraction may create additional storage capacity within the aquifer (by lowering groundwater levels) to allow additional recharge, and hydrogeological information is more readily available to evaluate the local potential of MAR. However, if developed, MAR can increase the quantity of water available for extraction and help mitigate impacts to the environment.

Where water uses have a higher value than irrigation (e.g. in mining, energy operations, town water supply), other more expensive but versatile forms of MAR, such as aquifer storage and recovery, can be economically viable and should be considered.

The Assessment involved a catchment-wide reconnaissance assessment of:

- the potential for groundwater resource development (Section 5.3.2)
- MAR (Section 5.3.3).

5.3.2 Opportunities for groundwater development

Introduction

Planning future groundwater resource developments and authorising licensed groundwater entitlements require value judgments of what is an acceptable impact to receptors such as environmental assets or existing users at a given location. These decisions can be complex, and they typically require considerable input from a wide range of stakeholders, particularly scientific information, to help inform these decisions, which include:

- identifying aquifers that may be potentially suitable for future groundwater resource development
- characterising their depth, spatial extent, saturated thickness, hydraulic properties and water quality
- conceptualising the nature of their flow systems
- estimating aquifer water balances
- identifying geographical opportunities within key aquifers and the associated risks for future groundwater development.

Opportunities include the identification and location of hydrogeological units and the aquifers they host. Risks include the potential to changes in aquifer storage and therefore reliability of access to water for existing users or the environment (groundwater-dependent ecosystems, GDEs). Unless stated otherwise, the material presented in Section 5.3.2 has been summarised from the companion technical report on groundwater characterisation (Raiber et al., 2024) and the companion technical report on groundwater modelling (Knapton et al., 2024).

Opportunity-level assessment of groundwater resource development opportunities in the Southern Gulf catchments

The hydrogeological units of the Southern Gulf catchments (Figure 5-2) contain a variety of local-, intermediate- and regional-scale aquifers that host localised to regional-scale groundwater flow systems. The regional-scale CLA and regional-scale GRA are present in the subsurface across large areas, collectively occurring beneath about 45% of the study area. Given their large spatial extent, they also underlie and frequently coincide with larger areas of soil suitable for irrigated agriculture (Section 4.2). They contain fresh water (<1000 mg/L TDS) in places and can yield water at a sufficient rate to support irrigation development (>10 L/s). These aquifers also contain larger volumes of groundwater in storage (gigalitres to teralitres) than local-scale aquifers and their storage and discharge characteristics are often less affected by short-term (yearly) variations in recharge rates caused by inter-annual variability in rainfall. Furthermore, their larger spatial extent provides greater opportunities for groundwater resource development away from existing water users and GDEs at the land surface such as springs, spring-fed vegetation and surface water, which can be ecologically and culturally significant. In contrast, local-scale aquifers in the Southern Gulf catchments, such as fractured and weathered rock and alluvial aquifers, host local-scale groundwater systems that are highly variable in composition, salinity and yield. They also have a small and variable spatial extent and less storage compared to the larger aquifers, limiting groundwater resource development to localised opportunities such as for stock and domestic use, or as a conjunctive water resource (i.e. combined use of surface water, groundwater or rainwater).

The Assessment identified five hydrogeological units hosting aquifers that may have potential for future groundwater resource development in the Southern Gulf catchments (Table 5-2):

- Cambrian limestone and dolostone
- Cretaceous rocks
- Cenozoic alluvium
- Proterozoic igneous rocks
- Proterozoic metasedimentary and metamorphic rocks.

Table 5-2 Opportunity-level estimates of the potential scale of groundwater resource development opportunities in the Southern Gulf catchments

For locations of the hydrogeological units see Figure 5-2. The indicative scale of the groundwater resource is based on the magnitude of the inputs and outputs of the groundwater balance. The actual scale will depend upon potential impacts to groundwater-dependent ecosystems and existing groundwater users, and government and community acceptance of these changes.

HYDROGEOLOGICAL UNIT	LOCATION	LEVEL OF KNOWLEDGE	INDICATIVE SCALE OF RESOURCE (GL/y)†	COMMENT
Cambrian limestone and dolostone	South-western part of the catchments	Low to medium	10–20	Most promising intermediate- to regional-scale aquifer. The Cambrian Limestone Aquifer (CLA) is typically tens of metres thick and mostly hosts fresh water (<1000 mg/L total dissolved solids, TDS). Indicative bore yields may be low (2–10 L/s) due to sparse aquifer testing, though, where appropriately constructed production bores have been installed in highly karstic parts (large, interconnected caves, caverns and fractures) of the aquifer outside the Southern Gulf catchments, pumping tests indicate bore yields of >20 L/s are achievable. Has potential to support a few small- (1–3 GL/y) to intermediate-scale (3–5 GL/y) developments. Greatest opportunities exist along the south-western part of the Southern Gulf catchments boundary in the aquifer outcrop. Opportunities are likely to be limited where the aquifer is adjacent to reaches of prescribed watercourses close to the north-eastern boundary of the CLA. This is where groundwater discharge from the CLA supports ecologically and

HYDROGEOLOGICAL UNIT	LOCATION	LEVEL OF KNOWLEDGE	INDICATIVE SCALE OF RESOURCE (GL/y)†	COMMENT
				culturally important springs and seeps that support streamflow in the Lawn Hill Creek, Gregory River and O'Shannassy River in the Nicholson Groundwater Management Area of the Gregory River subcatchment part of the Gulf Water Plan area.
Cretaceous rocks	North-eastern part of the catchments	Low	≤5	Promising regional-scale aquifer. The Gregory River Aquifer (GRA) is hosted in sandstone parts of the Cretaceous rocks and is typically tens of metres thick and can be artesian in places (groundwater is under pressure and naturally rises to the surface without pumping). Aquifer testing is sparse, but indicative bore yields range up to 20 L/s and in a few places have exceeded 20 L/s. The aquifer hosts water of a variable quality: some parts are fresh (<1000 mg/L TDS) but others can be brackish (>2000 mg/L). Has potential to support a several small-scale (1–2 GL/y) developments. Greatest opportunities exist along the south-western margin of the Cretaceous rocks where the GRA is less than 500 m deep, and groundwater is fresh. Opportunities may be limited near ecologically and culturally important springs and seeps, as well as near existing licensed water users such as the communities of Burketown and Gununa, also where the GRA is prohibitively deep (>500 mBGL) and/or where groundwater is brackish (>2000 mg/L TDS).
Cenozoic alluvium	Northern part of the catchments	Low	≤5	Local-scale alluvial (sand and gravel) aquifers occurring in association with stream channels, streambeds and floodplains of the middle to lower reaches of the Nicholson and Gregory rivers, and Settlement Creek, and their tributaries. Data for these aquifers are sparse, but indicative bore yields range from 2 to 5 L/s, and indicative water quality testing, though sparse, suggests they host good-quality water (<600 mg/L TDS) in places. Likely to offer potential for multiple small-scale (0.5–1.0 GL/y) localised developments or as a conjunctive water resource where surface water is available. Opportunities are likely to be limited where the saturated thickness of the aquifer is thin (<15 m), as well as areas within 1 km of the prescribed watercourses of the Leichhardt, Gregory and Nicholson rivers, whose streamflow is supported by groundwater discharge from the alluvium.
Proterozoic igneous rocks	Small patches in the north-west and south-east of the catchments	Low	<5	Local-scale fractured and weathered rock aquifers composed of a wide variety of volcanic rocks (basalt, breccia, rhyolite, tuff, agglomerate, dolerite). Variable bore yields, often <2 L/s, and variable water quality ranging from fresh (<500 mg/L TDS) to highly brackish (>7500 mg/L TDS). Only likely to offer potential for small-scale (<0.5 GL/y) localised developments (i.e. mostly suited to stock and domestic water supplies) where fracturing and weathering are high. Bore yields can exceed 20 L/s where the density and interconnectivity of secondary porosity features (fractures, faults and joints) are high, though in most cases aquifer storage is limited.
Proterozoic metasedimentary and metamorphic rocks	Central part of the catchments	Low	<5	Local-scale fractured and weathered rock aquifers composed of a wide variety of metasedimentary (sandstone, siltstone, shale, conglomerate) and metamorphic (gneiss and schist) rocks. Variable bore yields, often <2 L/s, and variable water quality from fresh (<500 mg/L TDS) to highly brackish (>7500 mg/L TDS). Only likely to offer potential for small-scale (<0.25 GL/y) localised developments (i.e. mostly suited to stock and domestic water supplies) in the outcropping area where fracturing and weathering are high.

†Actual scale will depend upon government and community acceptance of impacts to groundwater-dependent ecosystems and existing water users.

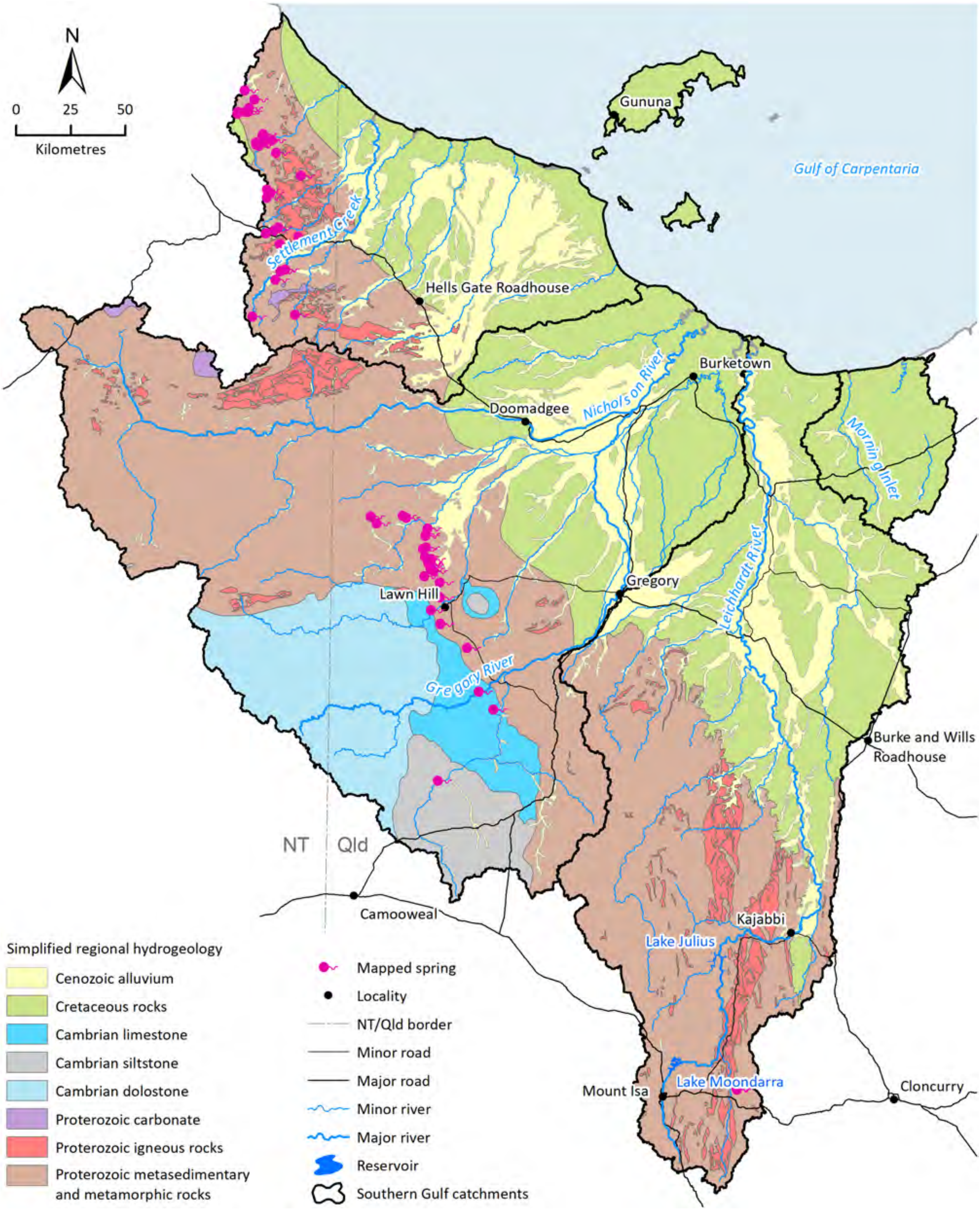

Figure 5-2 Hydrogeological units with potential for future groundwater resource development

Presents the spatial extent of the outcropping and subcropping component of each hydrogeological unit with the majority of the Cenozoic cover removed (except the alluvium). Entire spatial extent of the Cambrian limestone and dolostone, and Cretaceous rocks outside the Southern Gulf catchments is shown in Figure 2-28.

Groundwater development costs

The cost of groundwater development is the cost of the infrastructure plus the cost of the hydrogeological investigations required to understand the resource and risks associated with its development.

This section presents information relevant to the cost of further developing the groundwater resources of the CLA, including but not limited to the depth to water-bearing formation (control over cost of drilling) and the depth to groundwater (control over cost of pumping). Information on the spatial extent of drawdown of groundwater levels is also presented. This is relevant to the potential hydraulic impact of future development on receptors such as existing licensed water users and culturally and ecologically important GDEs. Aquifer yield information is presented in Section 2.5.2.

At a local development scale, individual proponents will need to undertake sufficient localised investigations to provide confidence around aquifer properties and bore performance. This information will also form part of an on-site hydrogeological assessment required by the regulator in order to grant an authorisation to extract groundwater. Key considerations for an individual proponent include:

- determining the location to drill a production bore
- testing the production bore
- determining the location and number of monitoring bores required
- conducting a hydrogeological assessment as part of applying for an authorisation to extract groundwater.

Estimates of costs associated with these local-scale investigations are summarised in Table 5-3.

Table 5-3 Summary of estimated costs for a 250 ha irrigation development using groundwater

Assumes mean bore yield of 25 L/s and with 16 production bores required to meet peak evaporative demands of 250 ha. Does not include operating and maintenance costs.

DRILLING, CONSTRUCTION, INSTALLATION AND TESTING OF BORES	ESTIMATED COST ($)
Production bore	2,550,000†
Monitoring bores	285,000‡
Submersible pumps	1,360,000§
Mobilisation/demobilisation	6,000§§
Aquifer testing	170,000*
Hydrogeological assessment	100,000††

†Value assumes 16 production bores drilled and constructed at a mean depth of 60 m at a cost per bore of $750/m, constructed with 200 mm steel casing at a cost of $82/m and 18 m stainless steel wire-wound screen at a cost of $150/m. Assumes on average two holes need to be drilled for every cased production bore.
‡Value assumes six PVC monitoring bores drilled and constructed at a mean depth of 60 m at a cost of $500/m, constructed with 150 mm PVC and 5 m machine-slotted screen at a cost of $50/m.
§Value assumes a pump that is rated to draw water at a rate of up to 60 L/s, as well as rated to draw water from depths of up to 50 mBGL. Value based on 16 pumps.
§§Value assumes a mobilisation/demobilisation rate of $10/km from Darwin to Daly Waters and return (approximately 1200 km round trip).
*Value assumes six 72-hour aquifer tests (48 hours pumping, 24 hours recovery) at a cost of $500/h and $4000 mobilisation/demobilisation.
††Indicative cost to proponent. Value assumes a small-scale development away from existing users and groundwater-dependent ecosystems. Assumes the regulator has already characterised the aquifers at the intermediate/regional scale to better understand the resource potential under cumulative extraction scenarios, as well as current and future constraints to development.

The Assessment identified the CLA to be the most promising intermediate- and regional-scale aquifer, with potential for future groundwater resource development in the Southern Gulf catchments. The CLA coincides with large, contiguous areas of cracking clay soils suitable for irrigated broadacre cropping (308,000 ha) along the south-western margin of the study area (Section 2.3). However, as discussed in Section 2.5.4, groundwater discharge from the CLA provides the dry-season flow in Lawn Hill Creek, and the Gregory and O'Shannassy rivers and some of their tributaries.

The parts of the CLA in the south-western part of the Southern Gulf catchments appear to offer some promising opportunities for potential future groundwater resource development but require further investigation. The aquifer outcrops, subcrops and is mostly unconfined in the south-west of the Southern Gulf catchments (Figure 5-2 and Figure 5-5). This means it outcrops at the surface, or is close to the surface (within tens of metres of it) and is directly recharged by outcrop areas or by infiltration of rainfall through either low-permeability black clay soils or by vertical leakage through the overlying Cambrian siltstone where it is present across the southern part of the aquifer (Figure 5-2).

The Georgina Basin, which hosts several hydrogeological units (Camooweal Dolostone, Thorntonia Limestone and Wonarah Formation) that collectively host the CLA, ranges in thickness from less than 100 m along the eastern/south-eastern basin margins to about 1000 m along the south-western boundary of the Southern Gulf catchments (Figure 5-4).

Figure 5-3 Groundwater dependent ecosystems along Lawn Hill Creek

Photo: Auscape/Universal Images Group via Getty Images

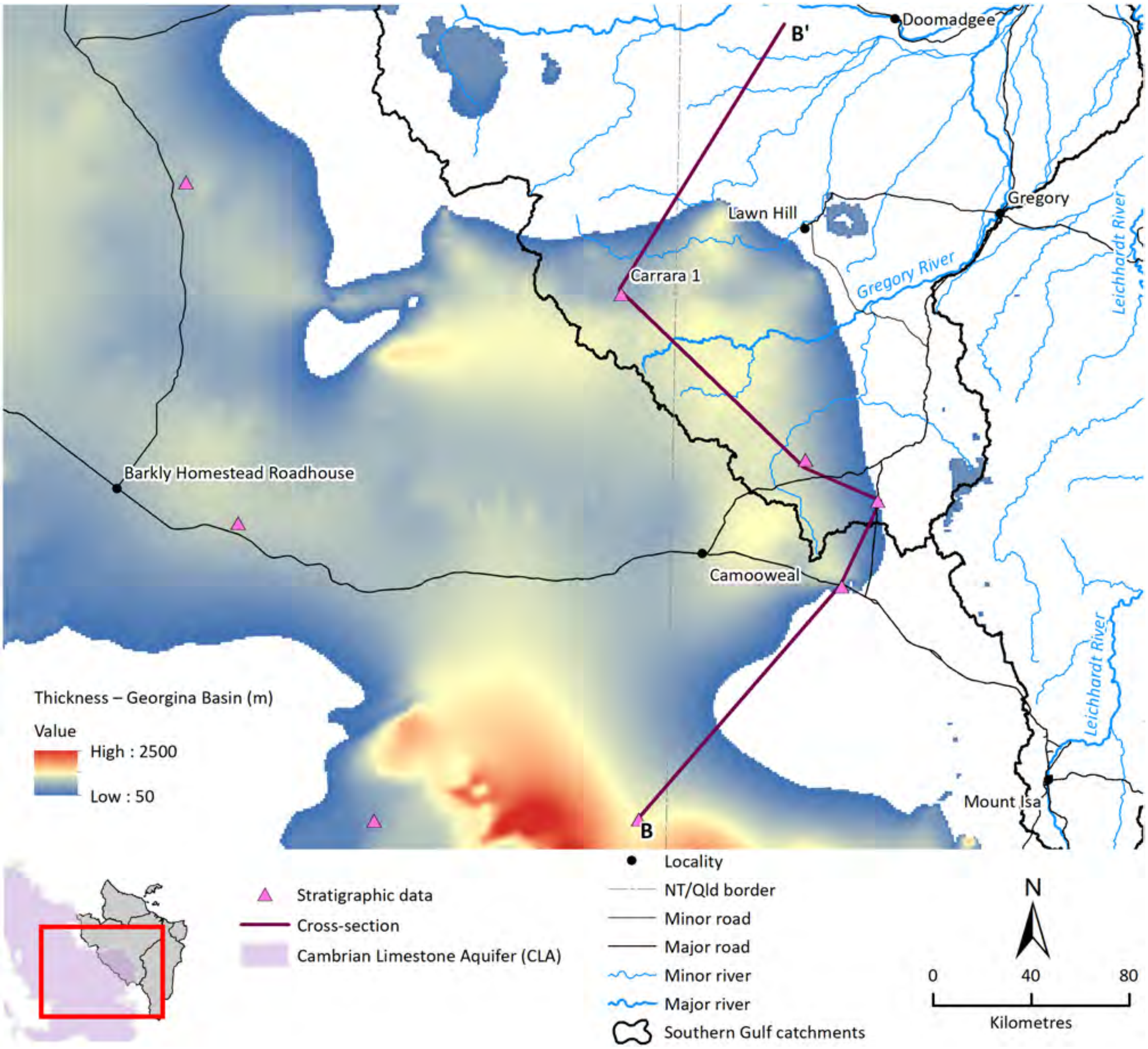

Figure 5-4 Thickness of the Georgina Basin in the Southern Gulf catchments

Only a partial spatial extent of the Georgina Basin is shown beyond the Southern Gulf catchments boundary. Depths are in metres.

Georgina Basin extent data source: Raymond (2018)

The CLA occurs within the top few hundred metres of the Georgina Basin and varies in thickness from about 50 m along the eastern margin to about 500 m towards the catchment’s boundary (Figure 5-4 and Figure 5-5). At Carrara 1 (deep stratigraphic drill-hole), the CLA is about 500 m thick (Figure 5-4 and Figure 5-5).

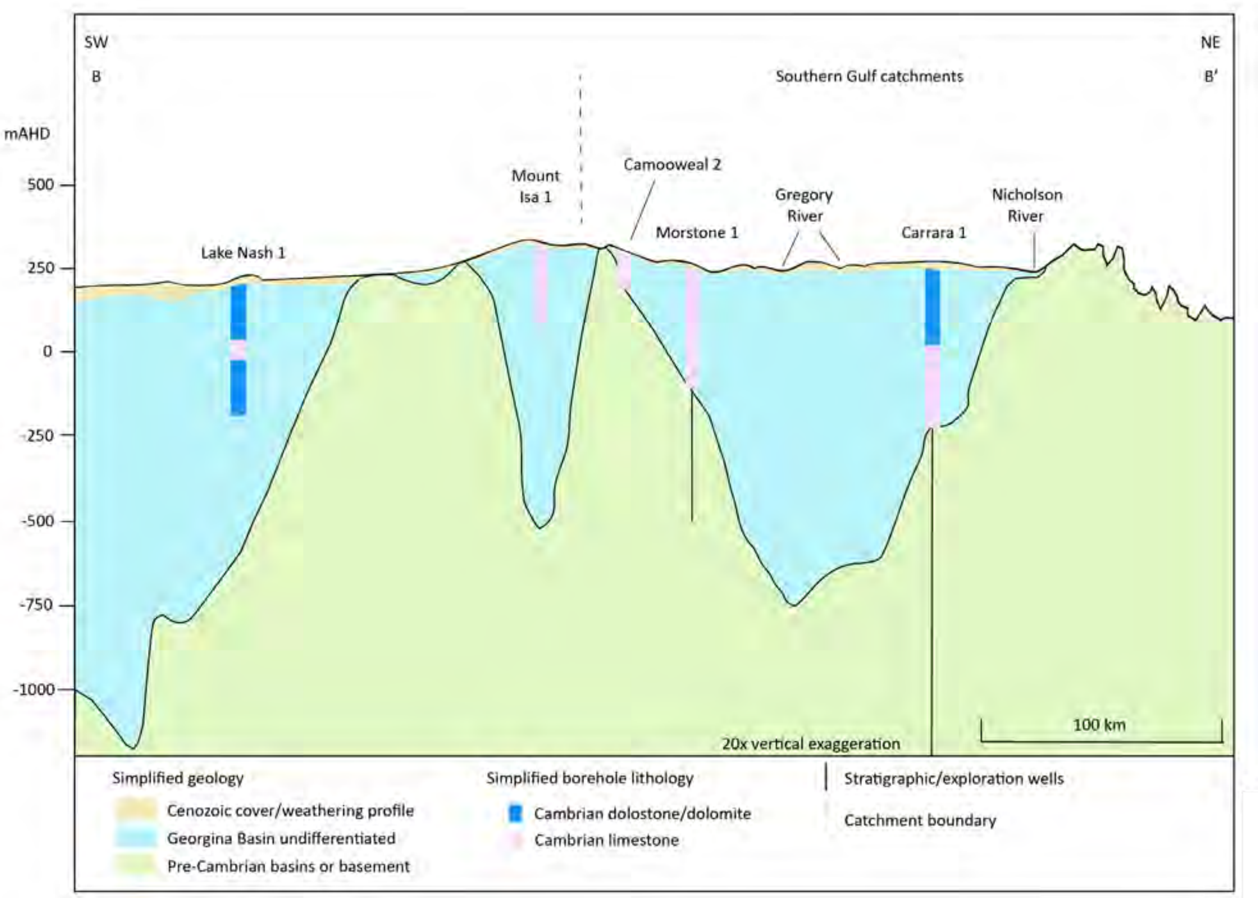

Figure 5-5 Hydrogeological cross-section through the Cambrian Limestone Aquifer in the Georgina Basin and south-west of the Southern Gulf catchments

See Figure 5-4 for the spatial location of the eastern part of the cross-section. AHD = Australian Height Datum.

While the current level of knowledge for the aquifer is considered low to medium, the following information indicates the aquifer offers potential for future development:

- The moderate spatial extent of the outcropping/subcropping area in the catchment (about 12,400 km^2, see Figure 5-2) coincides with areas of cracking clay soils potentially suitable for agricultural intensification (Section 2.3.2).
- The aquifer can be intersected by drilling at relatively shallow depths in the outcropping and subcropping areas (mostly <100 mBGL).
- Moderate bore yields (up to 20 L/s) indicate that the aquifer may have potential to yield water at a sufficient rate for groundwater-based irrigation.
- The depth to pump groundwater to the surface is less than 75 mBGL across most areas of the CLA, though groundwater-level data are sparse, and larger areas of shallow depths to groundwater (<10 mBGL) are likely to occur around the middle to lower reaches of the prescribed watercourses of Lawn Hill Creek, and the Gregory and O'Shannassy rivers, where the aquifer discharges (Figure 5-6).
- The aquifer host fresh water suitable for a variety of irrigated crops (mostly <1000 mg/L TDS).

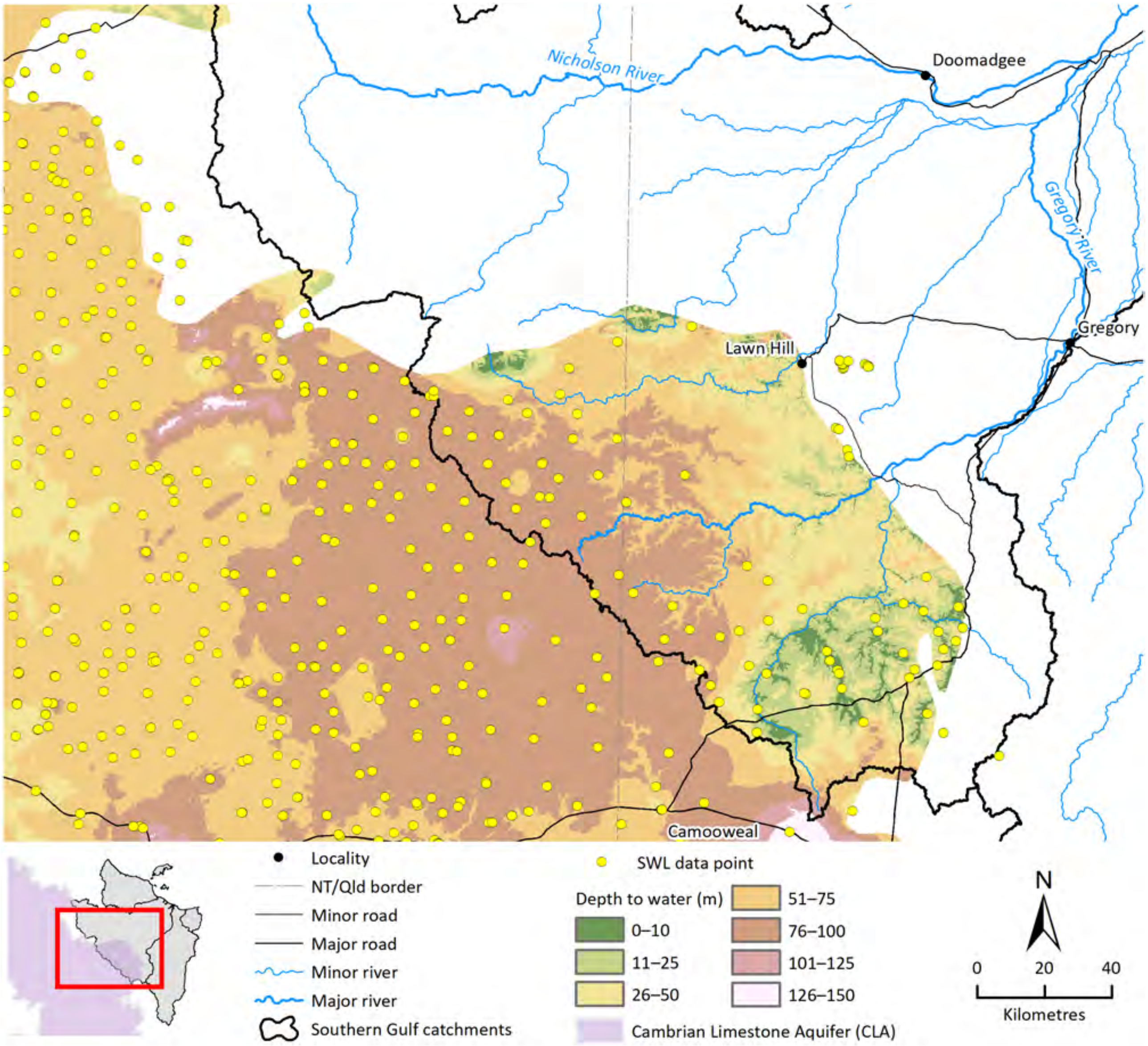

Figure 5-6 Depth to standing water level (SWL) of the Cambrian Limestone Aquifer (CLA)

Only a partial spatial extent of the CLA is shown beyond the Southern Gulf catchments boundary. Depths are in metres below the land surface. Lower left inset indicates the south-western part of the catchments where the mapped data are shown, as well as its location within the eastern part of the Georgina Basin (light purple).

The Assessment undertook an extensive review of the hydrogeological data and information to confirm the conceptual model of the CLA in the eastern Georgina Basin. This conceptual model was used to develop an initial two-dimensional groundwater flow model for the CLA in the south-western part of the Southern Gulf catchments (the Undilla Sub-basin in the eastern part of the Georgina Basin). The purpose of the model was to assess the nature and scale of the groundwater resources of the Undilla Sub-basin, which provides baseflow to parts of Lawn Hill Creek, and the Gregory and O'Shannassy rivers. Initial order of magnitude groundwater balance estimates were derived for the entire groundwater model domain, which extends south-west of the catchment boundaries, and also for the portions of the Lawn Hill Creek and Gregory River subcatchments, and Nicholson Groundwater Management Area (NGMA), that coincide with the CLA inside the Southern Gulf catchments (Figure 5-7).

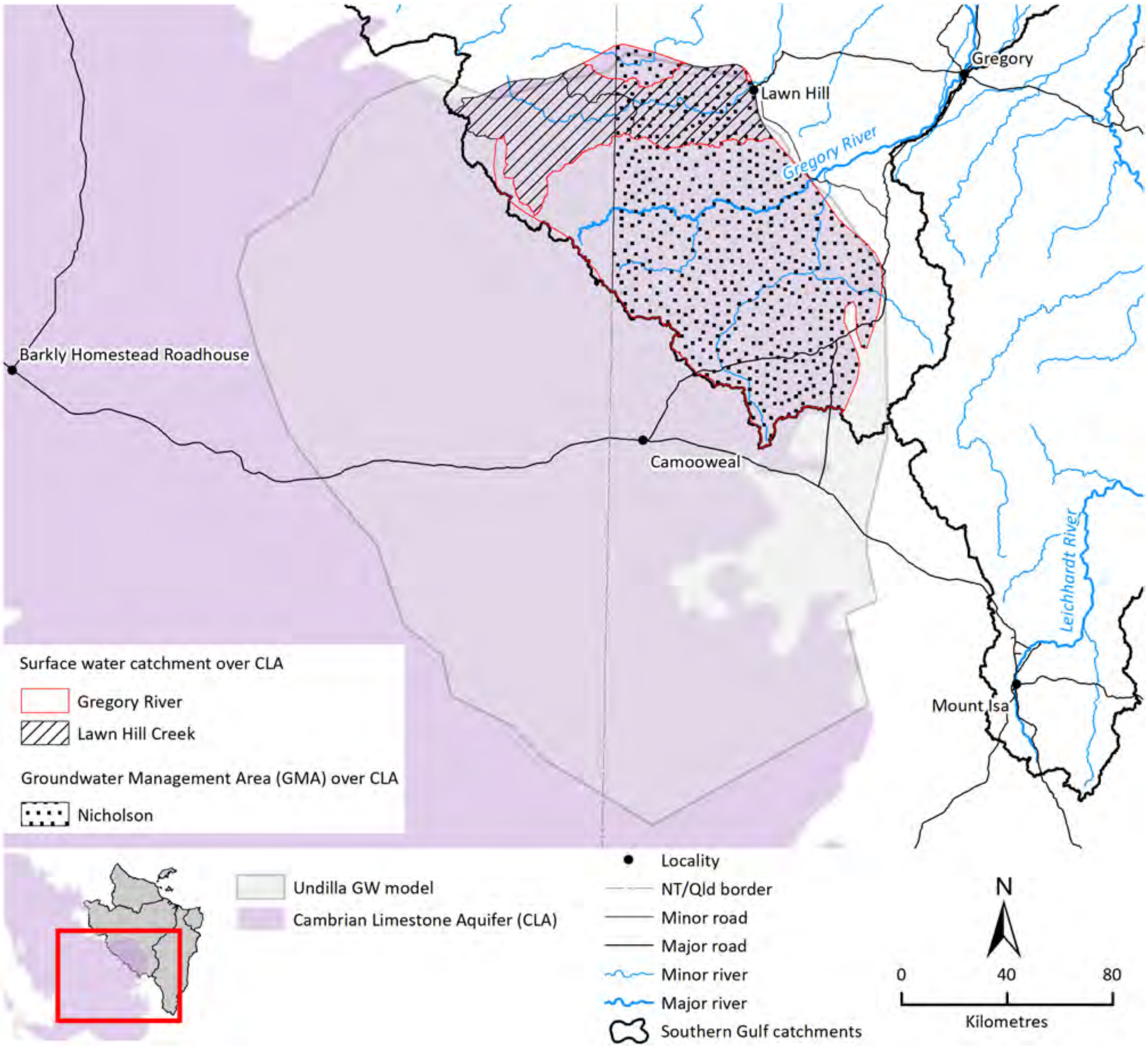

Figure 5-7 Location of the Undilla Sub-basin groundwater flow model in relation to the Southern Gulf catchments and portions of the model that coincide with the Lawn Hill Creek and Gregory subcatchments and Nicholson Groundwater Management Area

Lower left inset indicates the south-western part of the catchments where the mapped data are shown, as well as its location within the eastern part of the Georgina Basin (light purple). GW = groundwater.

Table 5-4 provides a summary of the mean annual groundwater balances for the 109-year climate sequence (1910–2019) presented for portions of the CLA that coincide with the Lawn Hill Creek and Gregory subcatchments, the NGMA and the entire model domain. Within the model domain the CLA coincides with 2344 km^2 of the Lawn Hill subcatchment and 9727 km^2 of the Gregory subcatchment. The CLA coincides with 10,266 km^2 of the NGMA, whereas the entire model domain for the CLA is 50,867 km^2, most of which extends to the south-west outside the catchments (Figure 5-7). When considering the magnitude in modelled recharge volumes by area, these equate to recharge rates of about 25 mm/year for the portion of the CLA in the Lawn Hill Creek subcatchment, 14 mm/year for the portion of the CLA in the Gregory subcatchment, 15 mm/year for the portion of the CLA in the NGMA and 7 mm/year for the entire model domain.

Table 5-4 Mean annual groundwater balance for the Cambrian Limestone Aquifer (CLA) in the Undilla Sub-basin of the Georgina Basin for a 109-year climate sequence (1910–2019) and areas of the CLA that coincide with the Lawn Hill Creek and Gregory subcatchments and Nicholson Groundwater Management Area (NGMA)

WATER BALANCE COMPONENT	LAWN HILL (GL/y)	GREGORY (GL/y)	NGMA (GL/y)	MODEL DOMAIN (GL/y)
Inflow (gains)				
Recharge (diffuse)	57.6	132.8	155.5	362.8
Release from storage	26.7	71.3	78.9	200.2
From river	0.0	0.0	0.0	0.0
Sub-total	**84.2**	**204.2**	**234.4**	**563.0**
Outflow (losses)				
Evapotranspiration	0.0	0.0	0.0	0.0
Extraction	0.0	0.0	0.0	0.0
Capture into storage	28.3	75.1	83.2	208.0
To rivers	36.1	83.8	119.9	355.0
Sub-total	**64.3**	**158.9**	**203.0**	**563.0**
Net flow In (+) / out (–)	–19.9	–45.3	–31.4	0.0

Initial modelling of the mean annual groundwater balance for the CLA in the south-western Southern Gulf catchments suggests the aquifer potentially offers opportunities for groundwater resource development based on the magnitude of groundwater flows. However, the initial model has limitations due to the data-sparse nature of the CLA in this area, including a lack of (i) spatial and temporal groundwater-level data, (ii) gauging of spring flow at discrete springs and (iii) estimates of mean annual recharge using a variety of independent methods. In addition, recent modelling of the CLA by Knapton et al. (2023) highlighted the potential sensitivity of the CLA groundwater balance to climate variables. Based on mean annual recharge summarised in Table 5-4, an indicate scale of the resource for the CLA in the Southern Gulf catchments is estimated to be between 10 and 20 GL. However, this required further investigation. In addition, the actual scale of development will depend upon government and community acceptance of potential impacts to groundwater-dependent ecosystems and existing groundwater users, as well as the approval of licenses to extract groundwater.

Groundwater resource development opportunities and risks associated with the Gilbert River Aquifer

The GRA within the Great Artesian Basin, despite being data sparse, appears to offer some opportunities for future groundwater resource development but requires further investigation. The GRA is a sandstone aquifer occurring beneath Cretaceous mudstone rocks in the north-west of the catchment and extends offshore out beneath the Gulf of Carpentaria (Figure 5-2). The depth to the top of the GRA beneath the mudstone rocks is shallowest (<150 mBGL) along the south-west margin of the GRA running in a north-west to south-east orientation, from north of Hells Gate Roadhouse to Burke and Wills Roadhouse (Figure 5-8). Depth to the top of the GRA increases in the subsurface in a north-easterly direction towards the coastline where depths are generally between 400 and 500 mBGL (Figure 5-8 and Figure 5-9). The deepest parts of the GRA near the coastline occur around Burketown, where depth to the top of the GRA is between 500 and 700 mBGL (Figure 5-8 and Figure 5-9). For example, the original Burketown community water supply bore intersected the top of the GRA at about 670 mBGL (Figure 5-8).

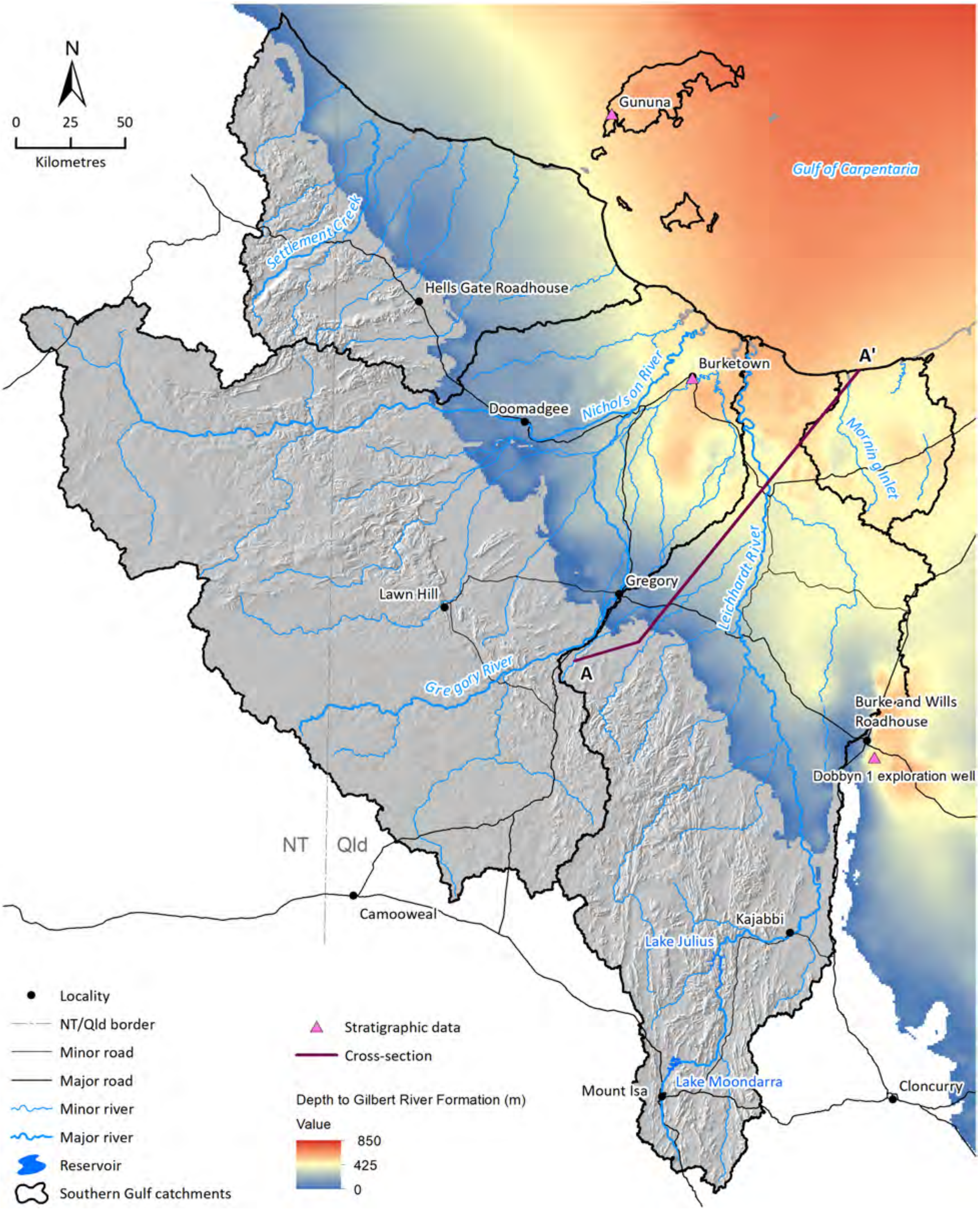

Figure 5-8 Depth to the top of the Gilbert River Aquifer (GRA)

This is a mapped spatial extent of the GRA both within and beyond the Southern Gulf catchments boundaries. Depths are in metres below the land surface. Stratigraphic data represent a bore with stratigraphic data to obtain information about changes in geology with depth. A to A′ represents the location of the cross-section in Figure 5-9.

Georgina Basin extent data source: Raymond (2018)

In the Gulf of Carpentaria beneath Gununa, the depth to the top of the GRA is similar to that around Burketown (~500 to 700 mBGL). The original Gununa community water supply bore intersected the top of the GRA at about 700 mBGL (Figure 5-8). The Cretaceous mudstone rocks that overlie the GRA are an aquitard (rocks of low permeability that store and transmit little groundwater), which confines the GRA (sealing it off from the atmosphere and pressurising the groundwater it stores and transmits) and prevents recharge from entering the aquifer. The GRA is recharged to the east of the Southern Gulf catchments, east of Karumba and Normanton. The GRA in the Southern Gulf catchments receives its inflows from groundwater in the GRA to the east of the Southern Gulf catchments, which flows into the catchment from west to north-west.

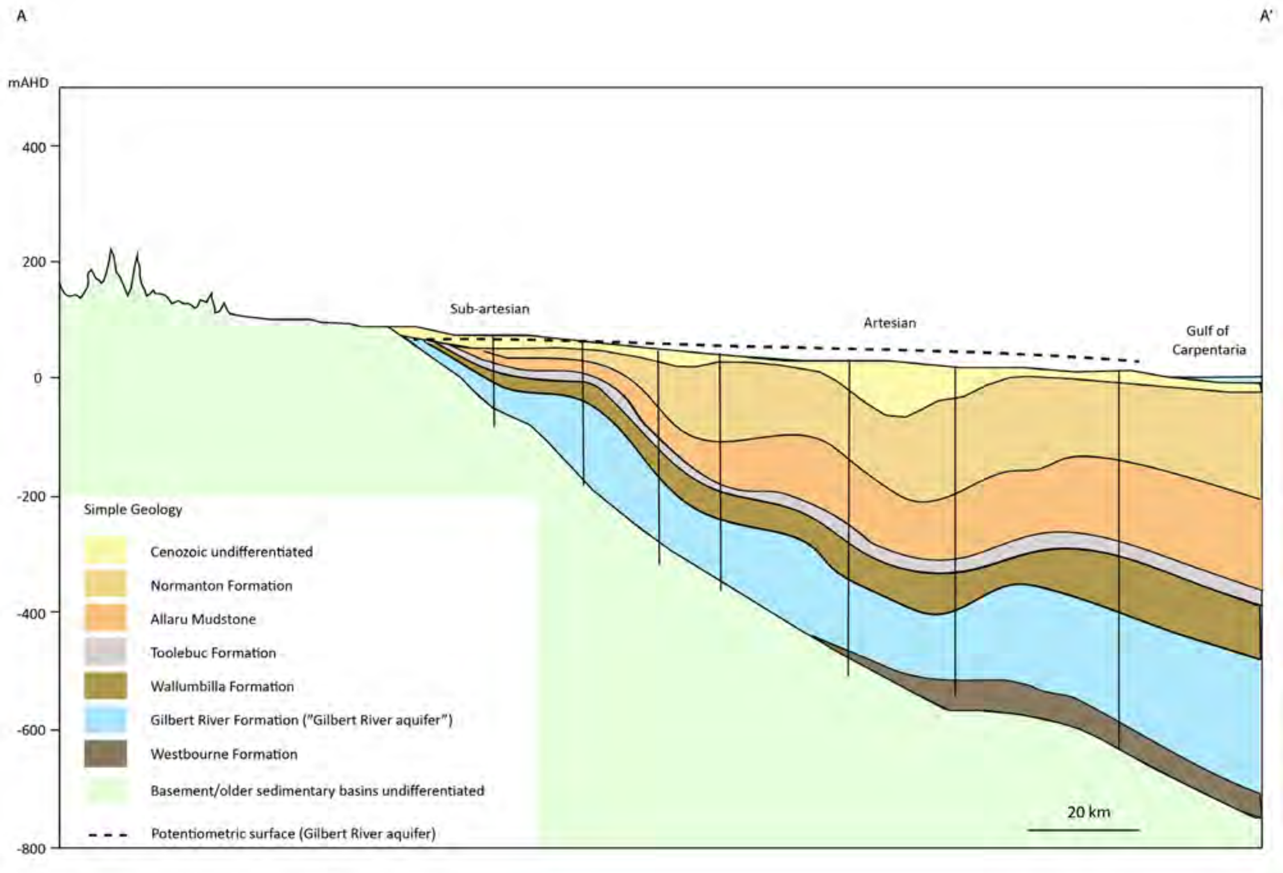

Figure 5-9 South-west to north-east cross-section traversing the Great Artesian Basin in the Southern Gulf catchments.

See Figure 5-8 for the spatial location of the cross-section. AHD = Australian Height Datum.

Changes in the depth to groundwater across the GRA vary from close to artesian (groundwater rises under natural pressure to the land surface) to artesian, though standing water level data for the aquifer are limited. The south-west margin of the GRA groundwater is close to artesian (<20 mBGL) (Figure 5-10). Further to the north-east, towards the coast, groundwater becomes artesian up to about 20 m above the land surface (Figure 5-10). The original Burketown water supply bore, drilled in the 1900s, had an artesian water level of about 40 m above the land surface and a flow rate of about 7 L/second.

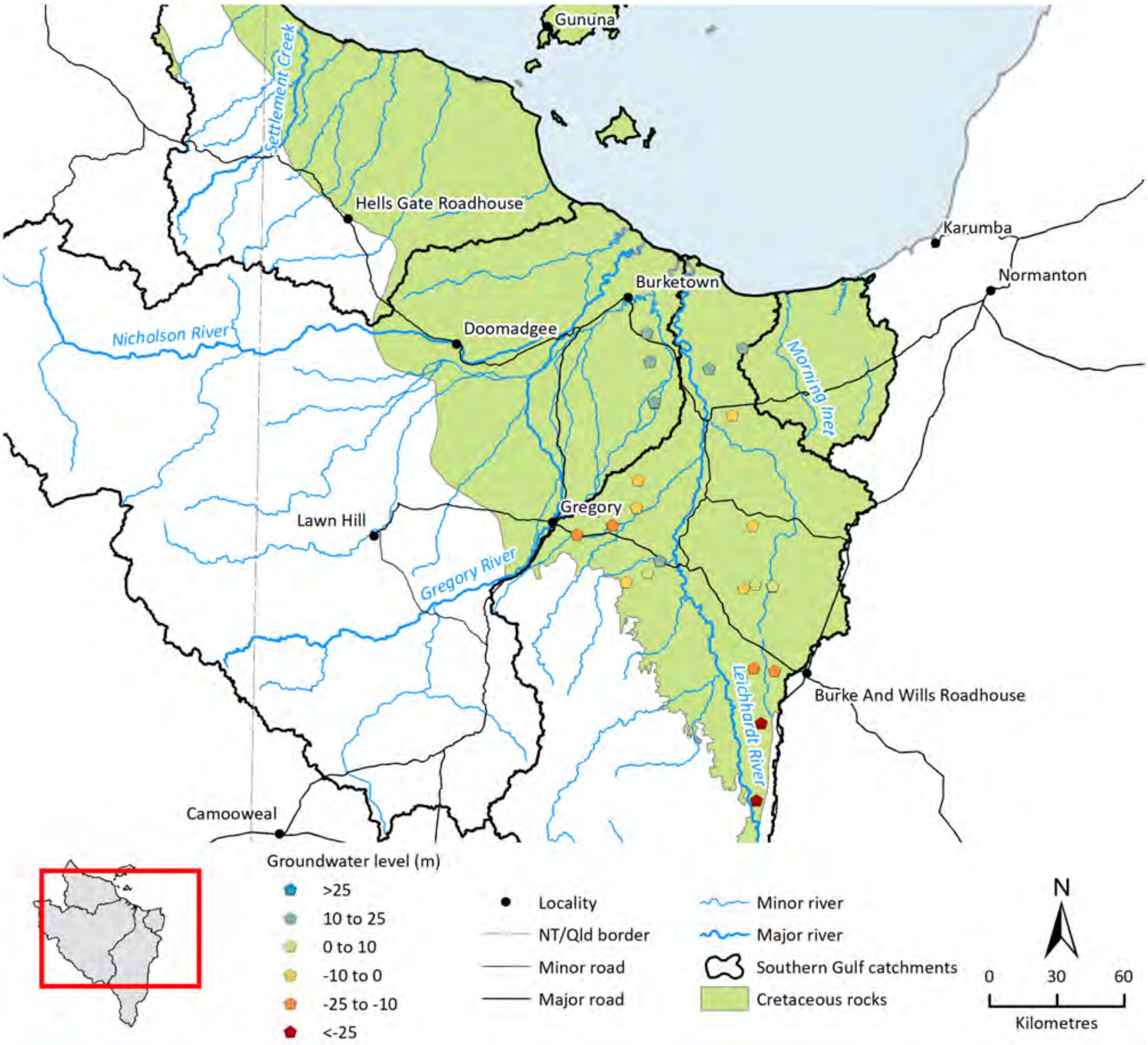

Figure 5-10 Depth to standing water level of the Gilbert River Aquifer (GRA)

Mapped spatial extent of the GRA both within and beyond the Southern Gulf catchments boundary. Positive values are depth above the land surface representing artesian conditions; negative values are depths below the land surface representing sub-artesian conditions.

Aquifer extent data source: Raymond (2018)

While the current level of knowledge for the GRA has limited pre-feasibility information, the following information indicates it offers potential for future development: (i) the large spatial extent of the aquifer in the subsurface (about 44,600 km^2, or about 40% of the study area; see Figure 5-2) that coincides with soils potentially suitable for agricultural intensification (Section 2.3.2); (ii) the aquifer can be intersected by drilling at depths of mostly less than <400 mBGL (Figure 5-8) along the south-western margin of the GRA in the north-east of the catchments, also an area where groundwater is mostly fresh (<1000 mg/L TDS); and (iii) the aquifer is either artesian or close to artesian, thereby reducing the costs of pumping the groundwater to the surface, though groundwater-level data are sparse (Figure 5-10).

Currently, insufficient information exists to quantify the water balance for the GRA in the Southern Gulf catchments. Furthermore, the aquifer: (i) has sparse temporal water-level information; (ii) dips steeply in the subsurface, indicating it shifts across different areas from semi-confined to confined conditions; and (iii) support active water licences for community water supplies at Burketown and Gununa, as well as potentially supporting ecologically and culturally important flora and fauna in the Gulf of Carpentaria's marine environment through coastal and submarine groundwater discharge. In the absence of further hydrogeological investigations (drilling and pump testing) and hydrological risk assessment modelling to evaluate groundwater extraction impacts to existing water users and GDEs, a conservative value of ≤5 GL/year has been assumed for the indicative scale of the resource for potential groundwater resource development (Table 5-2). However, this requires further investigation, and would depend upon government and community acceptance of potential impacts to groundwater-dependent ecosystems and existing groundwater users, as well as the approval of licenses to extract groundwater.

Groundwater resource development opportunities and risks associated with aquifers hosted in other hydrogeological units

Opportunities for potential groundwater resource development from aquifers hosted in other hydrogeological units (Proterozoic igneous, metasedimentary and metamorphic rocks) is most likely to be limited to use for stock and domestic purposes, and occasional community water supply. However, productive local-scale aquifers hosted in the Cenozoic alluvium occurring in patches associated with the streambed, stream channel and floodplain of parts of the Nicholson, Gregory and Leichhardt rivers and their tributaries may offer some opportunities but require further investigation. The largest occurrences of the alluvium occur in the north of the catchment along the middle to lower reaches of the Nicholson, Gregory and Leichhardt rivers (Figure 5-2). Indicative bore yield data indicate bore yields can be as high as 5 L/second, which is too low for commercial irrigated agriculture, but the aquifer is currently sparsely tested and yields are likely to be locally variable. Water quality can vary from fresh to brackish but also remains sparsely tested. However, in places the aquifers may offer potential for small-scale (<1 GL/y) localised developments or as a conjunctive water resource. Opportunities are likely to be limited where the alluvium is (i) storage-limited (thin saturated thickness <15 m), (ii) comprising mostly fine-textured sediments (clay lenses), (iii) regularly flooded and (iv) highly connected to perennial reaches of prescribed watercourses and development may impact water availability to GDEs.

5.3.3 Managed aquifer recharge

Introduction

MAR is the intentional recharge of water to aquifers for subsequent recovery or environmental benefit (NRMMC-EPHC-NHMRC, 2009). Importantly for northern Australia, which has high intra-annual variability in rainfall, MAR can contribute to planned conjunctive use, whereby excess surface water can be stored in an aquifer in the wet season for subsequent reuse in the dry season (Evans et al., 2013; Lennon et al., 2014).

Individual MAR schemes are typically small- to intermediate-scale storages with annual extractable volumes of up to 20 GL/year. In Australia, they currently operate predominantly within the urban and industrial sectors, and in the agricultural sector. This scale of operation can sustain rural to urban centres, contribute to diversified supply options in large urban centres and provide localised water management options, and it is suited to mosaic-type irrigation developments.

The basic requirements for a MAR scheme are the presence of a suitable aquifer for storage, availability of an excess water source for recharge and a demand for water. The presence of suitable aquifers is determined from previous regional-scale hydrogeological and surface geological mapping (see companion technical report on groundwater characterisation by Raiber et al., 2024)). Source water availability is considered in terms of presence/absence rather than volumes with respect to any existing water management plans.

Pre-feasibility assessment was based on MAR scheme entry-level assessment in the *Australian guidelines for water recycling: managed aquifer recharge* (NRMMC-EPHC-NHMRC, 2009; referred to as the 'MAR guidelines'). The MAR guidelines provide a framework to assess feasibility of MAR; they incorporate four stages of assessment and scheme development. The first stage is entry-level assessment (pre-feasibility), the second stage involves investigations and risk assessment, the third stage is MAR scheme construction and commissioning, and the fourth stage is operation of the scheme.

There are numerous types of MAR (Figure 5-12) and the selection of MAR type is influenced by the characteristics of the aquifer, the thickness and depth of low-permeability layers, land availability and proximity to the recharge source. Infiltration techniques can be used to recharge unconfined aquifers, with water infiltrating through permeable sediments beneath a dam, river or basin. If infiltration is restricted by superficial clay, the recharge method may involve a pond or sump that penetrates the low-permeability layer. Bores are used to divert water into deep or confined aquifers. Infiltration techniques typically have a lower cost than bore injection (Dillon et al., 2009; Ross and Hasnain, 2018) and are generally favoured in this Assessment. The challenge in northern Australia is to identify a suitable unconfined aquifer with capacity to store more water when water is available for recharge. In the Southern Gulf catchments, suitable unconfined aquifers are typically thought to rapidly recharge to full capacity during the wet season.

Figure 5-11 Uncontrolled artesian flow from the Gilbert River Aquifer at the Burketown groundwater bore

Photo: Shutterstock – Cam Laird

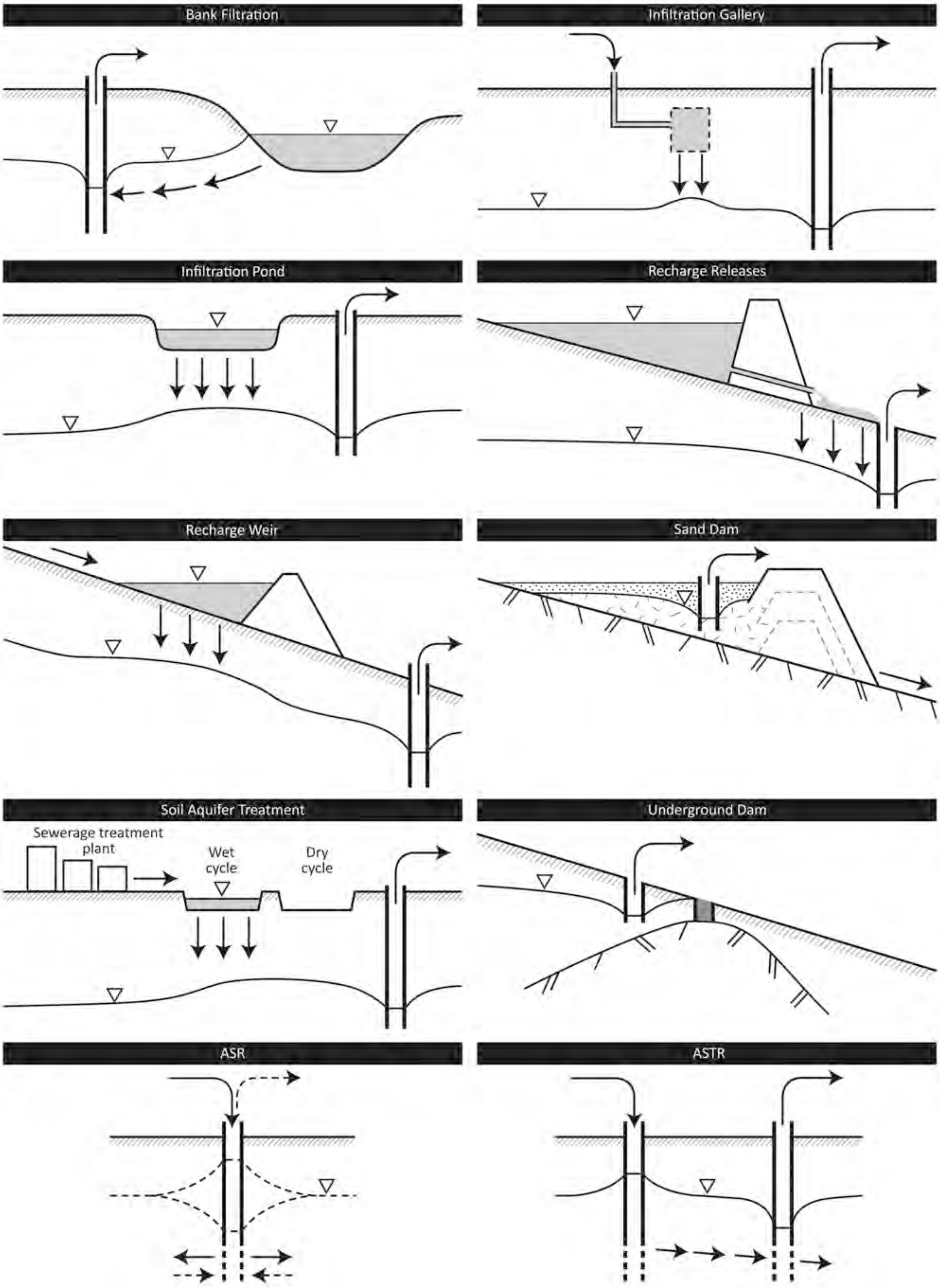

Figure 5-12 Types of managed aquifer recharge

ASR = aquifer storage and recovery; ASTR = aquifer storage, transfer and recovery. Groundwater level indicated by triangle. Arrows indicate nominal movement of water.

Source: Adapted from NRMMC-EPHC-NHMRC (2009)

Opportunity-level assessment of infiltration-based MAR in the Southern Gulf catchments

The most promising aquifers for infiltration-based MAR in the Southern Gulf catchments are aquifers within the Cenozoic alluvium associated with many of the rivers in the study area. Visually the Cenozoic alluvium appears to be extensive relative to alluvium associated with many rivers elsewhere in northern Australia. However, bore logs and water-level information are not available for Cenozoic alluvium, and it is likely the opportunity for MAR may vary between locations. There may be potential to use MAR in the CLA to offset the impacts of groundwater pumping on GDE near Lawn Hill Creek and the Gregory River. However, this would be contingent on finding soils suitable for the construction of ringtanks (Section 5.4.4), to temporarily detain surface water, close to a location that is suitable for MAR (typically on highly permeable soils).

Groundwater use lowers groundwater levels and therefore creates storage capacity in the aquifer, which is required for MAR. However, the challenge remains to target aquifers with storage capacity at the end of the wet season, or to identify an available recharge source near and when there is sufficient storage capacity (i.e. early in the dry season). Infiltration techniques recharging unconfined aquifers are generally favoured for producing cost-effective water supplies, hence the initial focus on recharge techniques and limitations for unconfined aquifers.

MAR opportunity maps were developed from the best available data at the catchment scale using the method outlined in the Northern Australia Water Resource Assessment technical report on MAR (Vanderzalm et al., 2018). This method uses four suitability classes for the more promising aquifers for MAR:

- Class 1 – highly permeable and low slope (<5%)
- Class 2 – highly permeable and moderate slope (5% to 10%)
- Class 3 – moderately permeable and low slope (<5%)
- Class 4 – moderately permeable and moderate slope (5% to 10%).

Class 1 is considered most suitable for MAR and Class 4 least suitable. All areas not classified into one of classes 1, 2, 3 and 4 are considered unsuitable. Figure 5-13 shows the suitability map for MAR in the Southern Gulf catchments, with classes 1 and 2 considered potentially suitable for MAR. The opportunity assessment (Figure 5-14) indicates approximately 480 km^2 (0.5%) of the Southern Gulf catchments may have aquifers with potential for MAR within 5 km of a major drainage line (excluding the highly intermittent drainage lines on the Sturt Plateau). Approximately 75 km^2 (~0.1%) of the study area is considered Class 1 or Class 2 and is within 1 km^2 of a major drainage line.

Water-level data for monitoring bores across the Southern Gulf catchments provide some insight into the potential for aquifers to store additional water. A watertable level deeper than 4 m is recommended in order to have sufficient storage capacity for MAR. Sufficient aquifer storage space is indicated where depth to water is either greater than 4 m at the end of the wet season (i.e. available for recharge year round) or greater than 4 m at the end of the dry season (i.e. available for seasonal recharge). Bores recording depth to water of less than 4 m at the end of the dry season could be considered as indicative that no storage space exists at any time of year. No water-level data are available for the Quaternary alluvium aquifers (Figure 5-14) and have been used for MAR elsewhere in Australia. However, the opportunity to use these aquifers for MAR in the Southern Gulf catchments is unknown and may vary between locations.

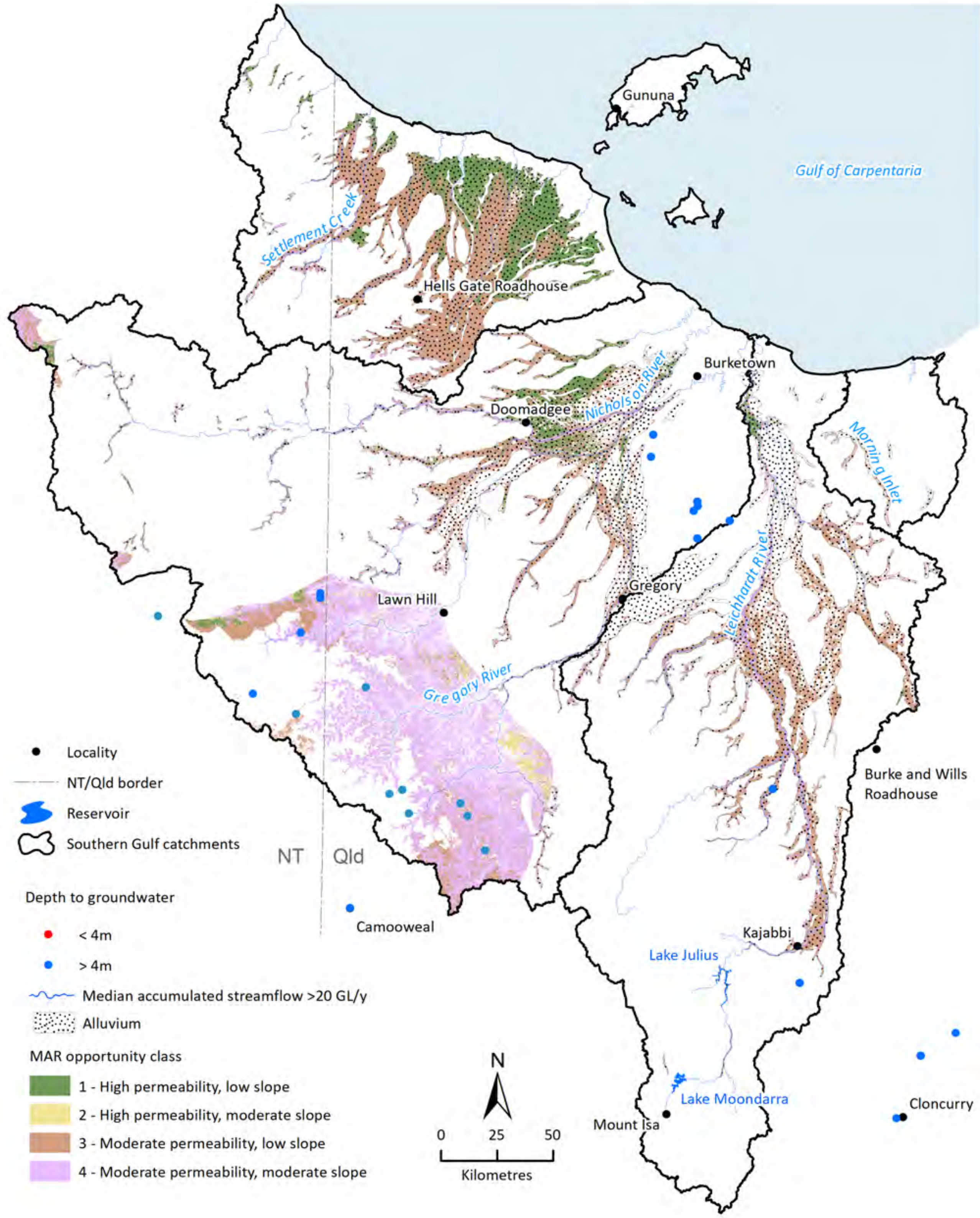

Figure 5-13 Managed aquifer recharge (MAR) opportunities for the Southern Gulf catchments independent of distance from a water source for recharge

Analysis based on the permeability (Thomas et al., 2024) and terrain slope (Gallant et al., 2011) datasets and limited to the Cambrian Limestone and Cenozoic alluvium aquifers.

The opportunity assessment (Figure 5-14) indicates approximately 122,700 ha (1.1%) of the Southern Gulf catchments may have aquifers (including areas of Quaternary alluvium) with potential for MAR within 5 km of drainage lines that have a median annual flow greater than 20 GL. Approximately 37,100 ha (~0.3%) of the study area is considered Class 1 or Class 2 and is within 1 km of drainage lines and with a median annual flow greater than 20 GL. However, 94% of this latter area is underlain by Quaternary alluvium aquifers for which the storage capacity and water level are unknown.

See the Northern Australia Water Resource Assessment technical report on MAR schemes in northern Australia (Vanderzalm et al., 2018) for detailed costings on ten hypothetical MAR schemes in northern Australia.

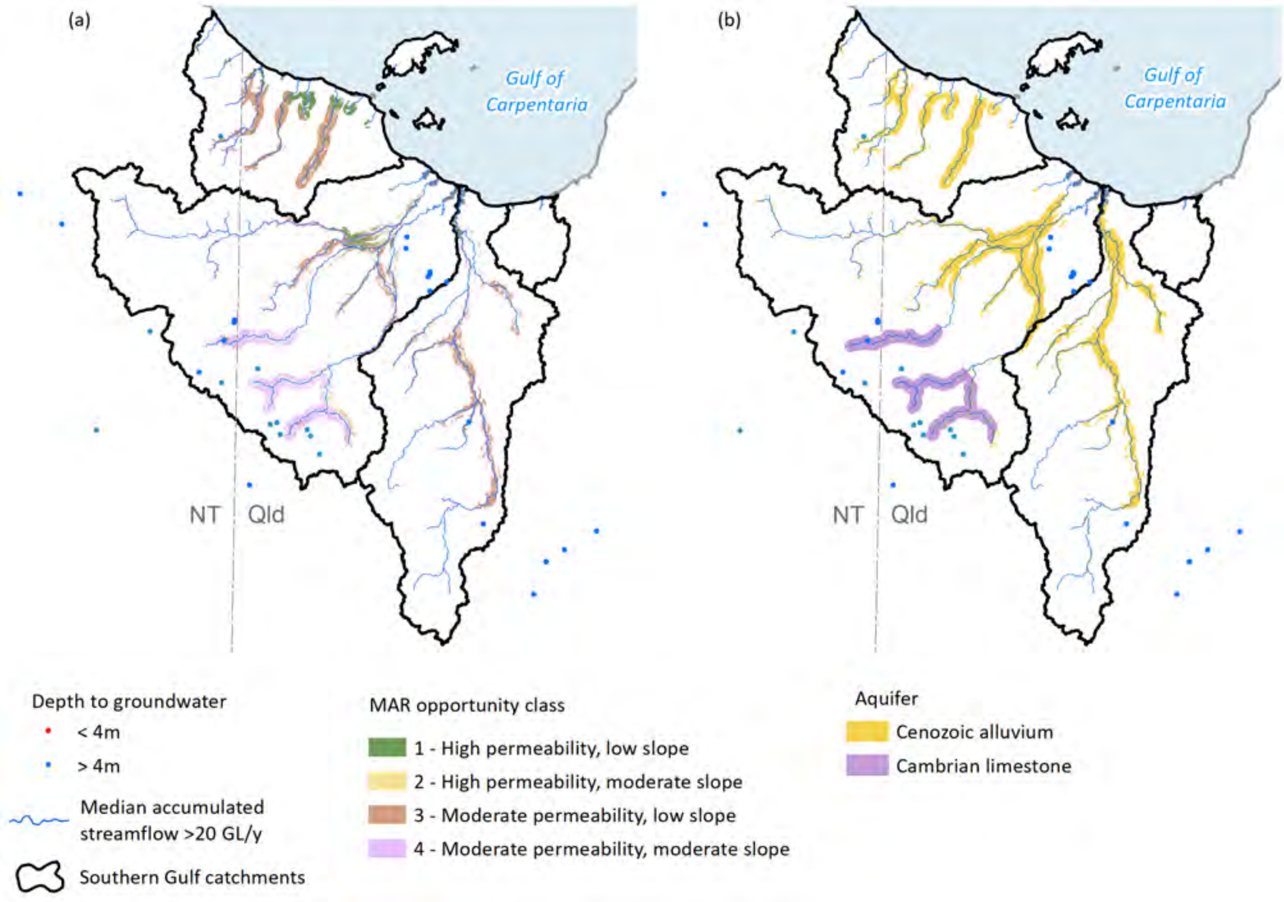

Figure 5-14 (a) Managed aquifer recharge (MAR) opportunities in the Southern Gulf catchments within 5 km of major rivers and (b) aquifer underlying the MAR opportunity classes

Analysis based on the permeability (Thomas et al., 2024) and terrain slope (Gallant et al., 2011) datasets and limited to the Cambrian Limestone and Cenozoic alluvium aquifers.

5.4 Surface water storage opportunities

5.4.1 Introduction

In a highly seasonal climate, such as that of the Southern Gulf catchments, and in the absence of suitable groundwater, surface water storages are essential to enable irrigation during the dry season and other periods when soil water is insufficient for crop growth.

The Assessment undertook a pre-feasibility-level assessment of three types of surface water storage options. These were:

- major dams that could potentially supply water to multiple properties (Section 5.4.2)
- re-regulating structures such as weirs (Section 5.4.3)
- large farm-scale or on-farm dams, which typically supply water to a single property (Section 5.4.4 and Section 5.4.5).

Both major dams and large farm-scale dams can be further classified as instream or offstream water storages. In the Assessment, instream water storages are defined as structures that intercept a drainage line (creek or river) and are not supplemented with water from another drainage line. Offstream water storages are defined as structures that (i) do not intercept a drainage line or (ii) intercept a small drainage line and are largely supplemented with water extracted from a nearby larger drainage line. Ringtanks and turkey nest tanks are examples of offstream storages with a continuous embankment; the former is the focus in the Assessment due to their higher storage-to-excavation ratios, relative to the latter.

The performance of a dam is often assessed in terms of water yield. This is the amount of water that can be supplied for consumptive use at a given reliability. For a given dam, an increase in water yield results in a decrease in reliability.

Importantly, the Assessment does not seek to provide instruction on the design and construction of farm-scale water storages. Numerous books and online tools provide detailed information on nearly all facets of farm-scale water storage (e.g. IAA, 2007; Lewis, 2002; QWRC, 1984). Siting, design and construction of weirs, large farm-scale ringtanks and gully dams are heavily regulated in most jurisdictions across Australia and should always be undertaken in conjunction with a suitably qualified professional and tailored to the nuances that occur at every site. Major dams are complicated structures and usually involve a consortium of organisations and individuals.

Unless otherwise stated, the material in Section 5.4 originates from the companion technical report on surface water storage (Yang et al., 2024).

5.4.2 Major dams

Introduction

Major dams are usually constructed from earth, rock and/or concrete materials, and typically act as a barrier wall across a river to store water in the reservoir created. They need to be able to safely discharge the largest flood flows likely to enter the reservoir, and the structure has to be designed so that the dam meets its purpose, generally for at least 100 years. Some dams, such as the Kofini Dam in Greece and the Anfengtang Dam in China, have been in continuous operation for over 2000 years, with Schnitter (1994) consequently coining dams as 'the useful pyramids'.

An attraction of major dams over farm-scale dams is that if the reservoir is large enough relative to the demands on the dam (i.e. water supplied for consumptive use and 'lost' through evaporation and seepage), when the reservoir is full, water can last 2 or more years. This has the advantage of mitigating against years with low inflows to the reservoir. For this reason, major dams are sometimes referred to as 'carry-over storages'.

Major instream versus offstream dams

Offstream water storages were among the first man-made water storages (Nace, 1972; Scarborough and Gallopin, 1991) because people initially lacked the capacity to build structures that could block rivers and withstand large flood events. One of the advantages of offstream storages is that, if properly designed, they can cause less disruption of the natural flow regime than large instream dams. Less disruption occurs if water is extracted from the river using pumps, or if there is a diversion structure with gates that can be raised, to allow water and aquatic species to pass through when not in use. In the very remote environments of northern Australia, the period in which these gates need to be operated is also the period in which it is difficult to move around wet roads and flooded waterways.

The primary advantage of large instream dams is that they provide a very efficient way of intercepting the flow in a river, effectively trapping all flow until the full supply level (FSL) is reached. For this reason, however, they also provide a very effective barrier to the movement of fish and other species within a river system, alter downstream flow patterns and can inundate large areas of land upstream of the dam.

Types of major dams

Two types of major dams are particularly suited to northern Australia: embankment dams and concrete gravity dams. Embankment dams are usually the most economic, provided suitable construction materials can be found locally, and are best suited to smaller catchment areas where the spillway capacity requirement is small. Concrete gravity dams with a central overflow spillway are generally more suitable where a large-capacity spillway is needed to discharge flood inflows, as is the case in most large catchments in northern Australia.

Traditionally, concrete gravity dams were constructed by placing conventional concrete in formed 'lifts'. Since construction of Kidston Dam (officially known as the Copperfield River Gorge Dam) in 1984 in Australia, however, roller compacted concrete (RCC) has been used, where low-cement concrete is placed in continuous thin layers from bank to bank and compacted with vibrating rollers. This approach allows large dams to be constructed in a far shorter time frame than required for conventional concrete construction, often with large cost savings (Doherty, 1999). RCC is best used for high dams where a larger-scale plant can provide significant economies of scale. This is now the favoured type of construction in Australia whenever foundation rock is available within reasonable depth, and where a larger-capacity spillway is required. In those parts of the Southern Gulf catchments with topography and hydrology most suited to large instream dams, RCC was deemed to be the most appropriate type of dam.

Opportunity-level assessment of potential major dams in the Southern Gulf catchments

A promising dam site requires inflows of sufficient volume and frequency, topography that provides a constriction of the river channel and, critically, favourable foundation geology. With few studies of large dams in the Southern Gulf catchments identified, the opportunity-level assessment of potential major dams in the Southern Gulf catchments was undertaken using a spatial analysis approach. To ensure no potential dam site had been overlooked, the Assessment used a bespoke computer model, the DamSite model (Petheram et al., 2017), to assess over 50 million sites in the Southern Gulf catchments for their potential as major offstream or instream dams.

Broad-scale geological considerations

The Southern Gulf catchments drain from the uplands in the south-west and south towards the north-east (referred to as the 'uplands'), where the river systems cross a broad depositional plain several tens of kilometres wide (referred to as the Armraynald Plain) before emptying into the Gulf of Carpentaria.

Favourable foundation conditions include a relatively shallow layer of unconsolidated materials, such as alluvium, and rock that is relatively strong, resistant to erosion, non-permeable or capable of being grouted. Geological features that make dam construction challenging include the presence of faults, weak geological units, landslides and deeply weathered zones.

Potentially feasible large dam sites in the Southern Gulf catchments occur where resistant ridges of Proterozoic sandstone beds that have been incised by the river systems outcrop on both sides of river valleys. The sandstones are generally weathered to varying degrees and the depth of weathering and the amount of sandstone outcrop on the valley slopes is a fundamental control on the suitability of the potential dam sites. Where the sandstones are relatively unweathered and outcrop on the abutments of the potential dam site, less stripping will be required to achieve a satisfactory founding level for the dam. The other fundamental control on the suitability of the dam is the extent and depth of the Quaternary alluvial sands and gravels in the floor of the valley, as these materials will have to be removed to achieve a satisfactory founding level for the dam.

In general, where stripping removes the more weathered rock, it is anticipated that the Proterozoic sandstones will form a reasonably watertight dam foundation requiring conventional grout curtains and foundation preparation.

Where potentially soluble dolomites occur within the Proterozoic sequences (soluble over a geological timescale) then it is possible that potentially leaky dam abutments and reservoir rims may be present, requiring specialised and costly foundation treatment such as extensive grouting.

Where rivers are tidal the presence of soft estuarine sediments has the potential to make dam design more challenging and construction more expensive, which may compromise the feasibility of a dam.

Sites potentially topographically suitable for large storages for water supply

Figure 5-15 displays the most promising sites across the Southern Gulf catchments in terms of topography, assessed in terms of approximate cost of construction per storage volume (ML). Favourable locations with a small catchment area and adjacent to a large river may be suitable as major offstream storages.

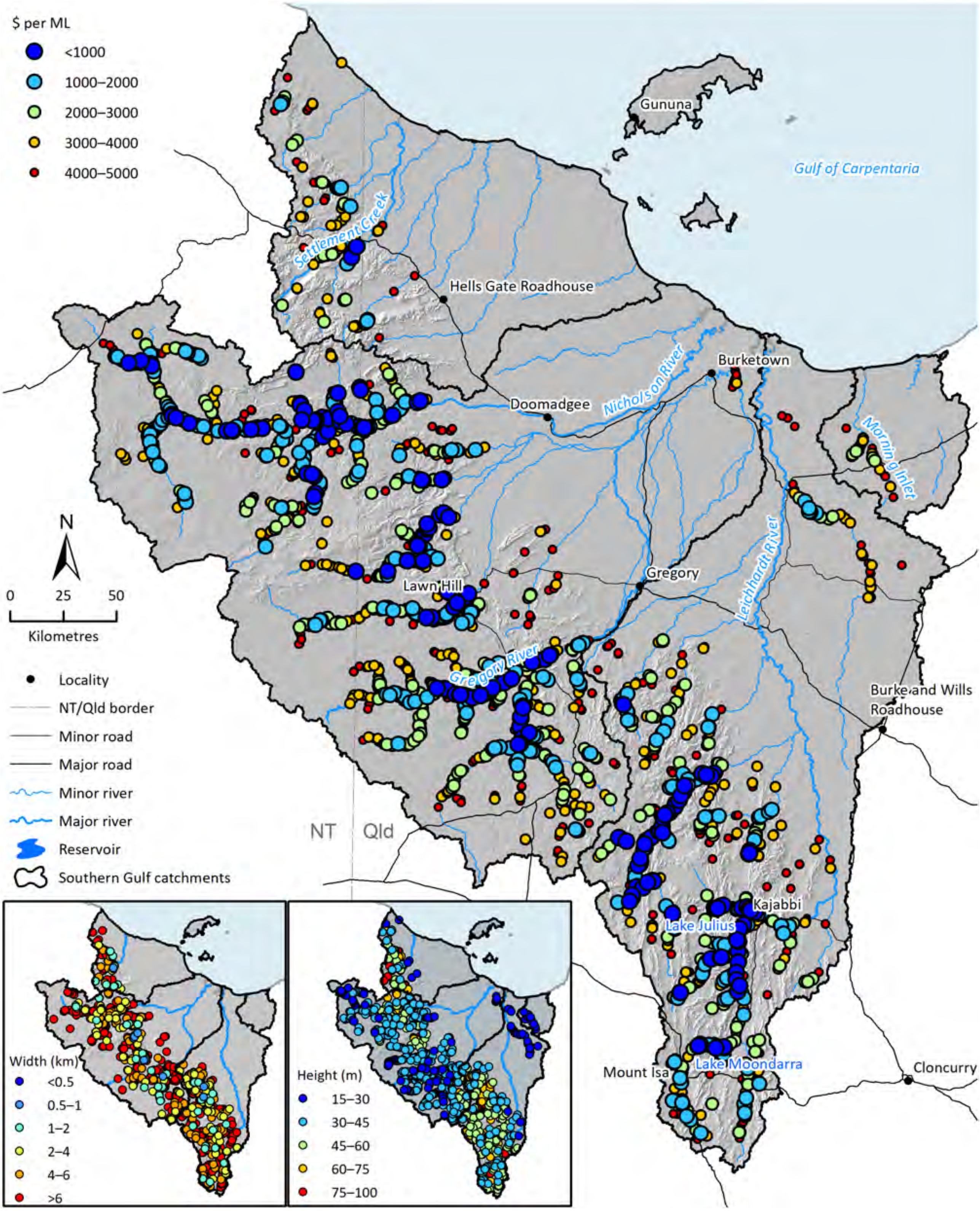

Figure 5-15 Potential storage sites in the Southern Gulf catchments based on minimum cost per megalitre storage capacity

This figure can be used to identify locations where topography is suitable for large offstream storages. At each location the minimum cost per megalitre storage capacity is displayed. The smaller the minimum cost per megalitre storage capacity ($/ML) the more suitable the site for a large offstream storage. Analysis does not take into account geological considerations, hydrology or proximity to water. Only sites with a minimum cost-to-storage-volume ratio of less than $5000/ML are shown. Costs are based on unit rates and quantity of material and site establishment for a roller compacted concrete dam. Inset displays height and width of dam wall at full supply level at the minimum cost per megalitre storage capacity.

In Figure 5-15, only those locations with a ratio of cost to storage less than $5000/ML are shown. This is a simple way to display those locations in the Southern Gulf catchments with the most favourable topography for a large reservoir relative to the size (i.e. cost) of the dam wall necessary to construct the reservoir. This figure can be used to identify more promising sites for offstream storage (i.e. where some or all of the water is pumped into the reservoir from an adjacent drainage line). The threshold value of $5000/ML is nominal and was used to minimise the amount of data displayed. This analysis does not consider evaporation, hydrology or geological suitability for dam construction.

Figure 5-15 shows that those parts of the Southern Gulf catchments with the most favourable topography for storing water are on the larger drainage lines on the uplands, in particular the Nicholson and Gregory rivers, Gunpowder Creek and the Leichhardt River.

Major instream dams for water and irrigation supply

In addition to suitable topography (and geology), instream dams require sufficient inflows to meet a potential demand. Potential dams that command smaller catchments with lower runoff have smaller yields. Results concerning this criterion are presented in terms of minimum cost per unit yield, where the smaller the cost per megalitre yield ($/ML) the more favourable the site for a large instream dam. The potential for major instream dams to cost-effectively supply water is presented in Figure 5-16. No values greater than $10,000/ML are shown.

The DamSite modelling results shown in Figure 5-16 indicate that the most cost-effective potential dam sites are on the Nicholson and Gregory rivers and Gunpowder Creek. The streamflow inputs to the DamSite modelling undertaken for the Southern Gulf catchments did not consider existing storages on the Leichhardt River, and hence the suitability of those sites shown on the Leichhardt River would be further diminished with reduced inflows. Also shown on this figure is the versatile agricultural land for the Southern Gulf catchments, with the most versatile agricultural land occurring on the Carpentaria Plain (Thomas et al., 2024).

Based on this analysis and a broad-scale desktop geological evaluation, seven of the more cost-effective larger-yielding sites in distinct geographical areas that are proximal to soils suitable for irrigated agriculture were selected for pre-feasibility analysis (see companion technical report on surface water storage, Yang et al., 2024) to explore the potential opportunities and risks of water supply dams in the Southern Gulf catchments. The locations of these pre-feasibility potential dam sites are denoted in Figure 5-16 by black circles and the letters ‘A’ to ‘G’. No potential sites upstream of Julius Dam on the Leichhardt River (Figure 5-17) were examined as part of the pre-feasibility analysis as a dam upstream of Julius Dam would reduce the inflows and yield of the latter.

Key parameters and performance metrics are summarised in Table 5-5 and an overall summary comment is recorded in Table 5-6. More detailed analysis of the seven pre-feasibility sites is provided in the companion technical report on surface water storage (Yang et al., 2024).

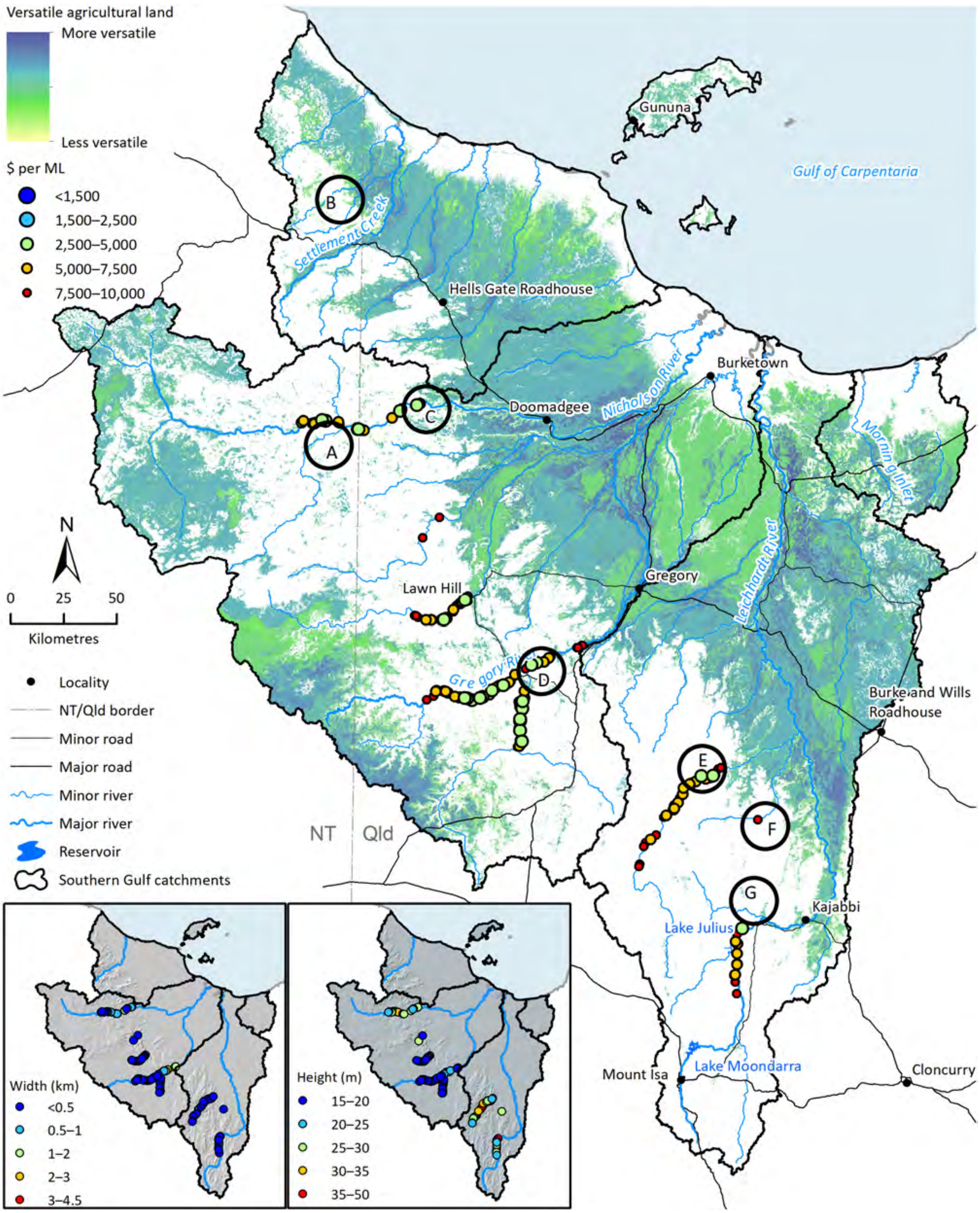

Figure 5-16 Potential storage sites in the Southern Gulf catchments based on minimum cost per megalitre yield at the dam wall

This figure indicates those sites more suitable for major dams in terms of cost per megalitre yield at the dam wall in 85% of years overlain on versatile land surface (see companion technical report on land suitability, Thomas et al., 2024). At each location the minimum cost per ML storage capacity is displayed. Only sites with a minimum cost to yield ratio less than $10,000/ML are shown. Costs are based on unit rates and quantity of material required for a roller compacted concrete dam with a flood design of 1 in 10,000. Right inset displays height of full supply level (FSL) at the minimum cost per ML yield and left inset displays width of FSL at the minimum cost per ML yield. Letters indicate potential dams listed in Table 5-5 and Table 5-6.

Figure 5-17 Julius Dam on the Leichhardt River

Photo: CSIRO

Hydro-electric power generation potential in the Southern Gulf catchments

The potential for major instream dams to generate hydro-electric power is presented in Figure 5-18 following an assessment of more than 50 million potential dam sites in the Southern Gulf catchments (Yang et al., 2024). This figure provides indicative estimates of hydro-electric power generation potential but does not consider the existence of supporting infrastructure or geological suitability for dam construction. No values greater than $45,000/MWh are shown.

Although the topography of the Southern Gulf catchments is moderately suitable for large water storage dams (i.e. narrow constrictions downstream of broad valleys), the topography appears to be less suitable for dams for hydro-electric power generation due to the lack of relief that is required to provide potential elevation head. Aside from a specific site on the Gregory River, Gunpowder Creek, a major tributary of the Leichhardt River, is the most favourable drainage line for dams for the purpose of hydro-electric power generation in the Southern Gulf catchments due to the more favourable topography and its proximity to Mount Isa, a major power demand centre. A companion technical report on hydro-electric power generation (Entura, 2024) undertakes a pre-feasibility analysis of a site on Gunpowder Creek to explore the potential for hydro-electric power in the Southern Gulf catchments.

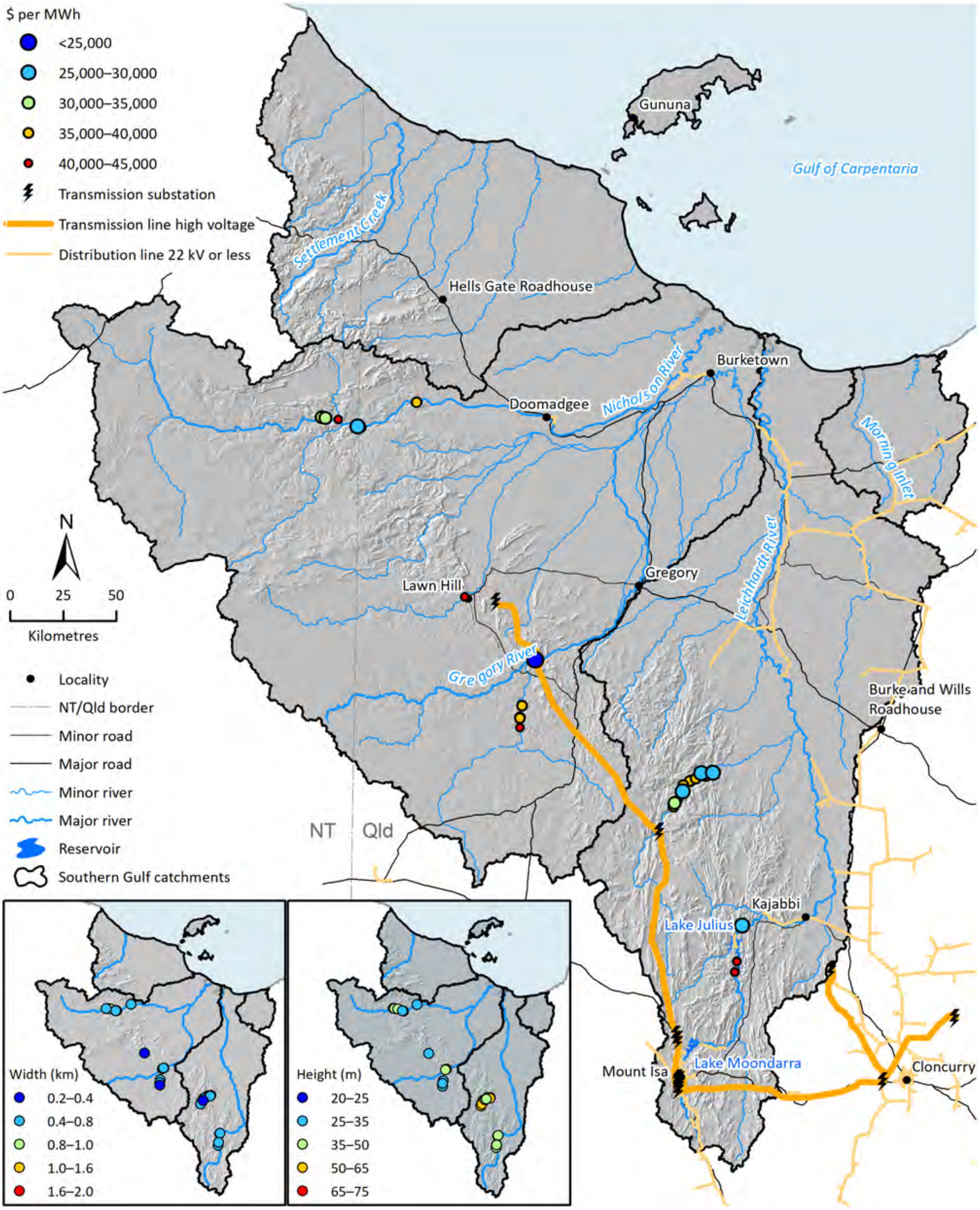

Figure 5-18 Southern Gulf catchments hydro-electric power generation opportunity map

Costs are based on unit rates and quantity of material required for a roller compacted concrete dam with a flood design of 1 in 10,000. Right inset displays height of full supply level (FSL) at the minimum cost per megalitre yield and left inset displays width of FSL at the minimum cost per megalitre yield.

Pre-feasibility-level assessment of potential major dams in the Southern Gulf catchments

Seven potential dam sites in the Southern Gulf catchments were examined as part of this pre-feasibility assessment. They are summarised in Table 5-5 and Table 5-6. More detailed descriptions of these seven potential dam sites, including impacts to migratory species and ecological impacts of reservoir inundation, are provided in the companion technical report on surface water storage (Yang et al., 2024).

Table 5-5 Potential dam sites in the Southern Gulf catchments examined as part of the Assessment

All hypothetical dams are assumed to be roller compacted concrete. Locations of potential dams are shown in Figure 5-16. Geology grade is an ordinal scale between 1 and 5 where grade 1 is best, grade 5 is worst. It is based on a holistic assessment based on whether bedrock is exposed at site, likely depth of weathering/stripping on abutments, likely depth of cut-off and presence of deep alluvium, and overall height-to-width assessment. AMTD = adopted middle thread distance; FSL = full supply level; O&M = operation and maintenance.

SITE NAME	MAP ID	GEOLOGY GRADE	SPILLWAY HEIGHT ABOVE BED * (m)	CAPACITY AT FSL (GL)	CATCHMENT AREA (km^2)	ANNUAL WATER YIELD ** (GL)	CAPITAL COST# ($ million)	UNIT COST## ($/ML)	LEVELISED COST### ($/ML)
South Nicholson River AMTD 9 km	A	1	37	382	3,113	42	1089☐	25,929	1921
Gold Creek AMTD 58 km	B	2	33	119	422	24	367☐	15,292	1133
Nicholson River AMTD 198 km	C	1	34	1403	13,870	289	3344☐	11,156	857
Gregory River AMTD 174 km	D	2	19	118	11,381	133	683◘	5,135	381
Gunpowder Creek AMTD 66 km	E	1	51	716	3,516	119	773◘	6,495	481
Mistake Creek AMTD 60 km	F	1	30	158	1,161	40	659☐	16,475	1220
Ewen Creek AMTD 6 km	G	1	30	245	706	29	466☐	16,069	1190

*The height of the dam abutments and saddle dams will be higher than the spillway height.
**Water yield is based on 85% annual time-based reliability using a perennial demand pattern for the baseline river model under Scenario AE. This is yield at the dam wall (i.e. does not take into account distribution losses or downstream transmission losses). With the exception of the Gregory River AMTD 174 km site and the Gunpowder Creek AMTD 66 km site, the yield values do not take into account downstream existing entitlement holders. At none of the sites do the yield estimates take into account of environmental considerations.
◘Indicates manually derived preliminary cost estimate, which is likely to be –10% to +50% of 'true cost'. ☐ Indicates modelled preliminary cost estimate, which is likely to be –25% to +100% of 'true' cost. Should site geotechnical investigations reveal unknown unfavourable geological conditions, costs could be substantially higher.
##The unit cost of annual water supply and is calculated as the capital cost of the dam divided by the water yield at 85% annual time reliability.
###Assumes a 7% real discount rate and a dam service life of 100 years. Includes operation and maintenance (O&M) costs, assuming operation and maintenance (O&M) costs are 0.4% of the total capital cost.

Table 5-6 Summary comments for potential dams in the Southern Gulf catchments

Locations of potential dams are shown in Figure 5-16. AMTD = adopted middle thread distance.

SITE NAME	MAP ID	SUMMARY COMMENT
South Nicholson River AMTD 9 km	A	This potential dam site is the most expensive of those on the short-list and is a considerable distance upstream of the soil potentially suitable for irrigated agriculture. Furthermore, the site is very remote and access would require considerable additional infrastructure. At the adopted full supply level (FSL), the inundation extent of this potential dam site overlaps with parts of the Ganalanga–Mindibirrina Indigenous Protected Area (IPA). There is a high likelihood of unrecorded sites of cultural significance in the inundation area. Asset models predicted that 46% of the catchment has habitat suitable for at least one of the ten modelled migratory species, which constitutes zero % to 6.4% of the total habitat modelled as suitable in the Southern Gulf catchments.
Gold Creek AMTD 58 km	B	This small potential instream dam site on a small catchment in the Settlement Creek Australian Water Resources Council river basin has a low yield and high cost per megalitre released from the dam wall. Downstream of the site, water could potentially be supplied to land with soils suitable for agriculture, with minor or moderate limitations, depending on the land use. Approximately 11% of the catchment was estimated as having habitat suitable for 40% or more of the (11) migratory species modelled. There is a high likelihood of unrecorded sites of cultural significance in the inundation area.
Nicholson River AMTD 198 km	C	This potential instream development has the potential to release water for irrigation along the Nicholson River to the Doomadgee and Armraynald plains and Doomadgee. The foundations appear to be suitable for a roller compacted concrete (RCC) dam. Nonetheless, the site is very remote and is one of the more expensive potential dam sites examined in the Southern Gulf catchments. At the adopted FSL, the inundation extent of this potential dam site overlaps with parts of the Ganalanga–Mindibirrina IPA. There is a high likelihood of unrecorded sites of cultural significance in the inundation area.
Gregory River AMTD 174 km	D	The potential Gregory River dam site is an instream development with potential to supply water to the large contiguous areas of black and grey cracking clay soils on the Armraynald Plain immediately downstream of the dam. Given the potential for significant flooding during construction and the spillway capacity required, an RCC gravity dam with a 400 m wide central uncontrolled spillway would be most suitable. The site is one of the largest-yielding and most cost-effective potential dam sites in the Southern Gulf catchments, and the foundations of this site appear to be suitable for an RCC dam. A major limitation of the site is its proximity to the Boodjamulla (Lawn Hill) National Park (upstream of the site), and the Thorntonia Aggregation wetland, which is up and downstream of the potential dam site. Despite being on a major river, the area of potentially suitable habitat for the four modelled migratory species was relatively small. There is a high likelihood of unrecorded sites of cultural significance in the inundation area. Limiting the FSL of the potential dam so that the area inundated would not extend into the Boodjamulla National Park resulted in a modelled yield of 180 GL in 85% of years at the dam wall. However, taking into consideration existing downstream users and assuming a dry-season crop resulted in a modelled yield of 133 GL in 85% of years.
Gunpowder Creek AMTD 66 km	E	This potential dam site is on Gunpowder Creek, a large tributary of the Leichhardt River, and it has the second-lowest cost per megalitre of the short-listed sites in the Southern Gulf catchments. The foundations appear to the suitable for an RCC dam. The site would nominally supply water to a large plain of recent alluvium at the junction of Gunpowder Creek and the Leichhardt River. There is a high likelihood of unrecorded sites of cultural significance in the inundation area. The area of potentially suitable habitat for modelled migratory species upstream of this dam site is relatively small. Previous studies of dams on Gunpowder Creek focused on areas further upstream, predominantly to supply water for mining.
Mistake Creek AMTD 60 km	F	This potential dam site would supply water to large areas of contiguous soils suitable for irrigated agriculture on the Carpentaria Plains. Being a relatively small tributary of the Leichhardt River, the site has a low yield, and it has the highest cost per megalitre released from the dam wall of all the short-listed sites examined in the Southern Gulf catchments. There is a high likelihood of unrecorded sites of cultural significance in the inundation area. For the migratory species modelled as part of the Assessment, the catchment of a dam at this potential site would constitute less than 1% of the total potentially suitable habitat modelled in the Southern Gulf catchments.
Ewen Creek AMTD 6 km	G	This low-yielding and relatively expensive potential dam site is located on the tributary that joins the Leichhardt River downstream of Lake Julius. The foundations appeared to be suitable for a RCC dam; however, the amount of dolomite rock in the foundation may represent a problem, due to cavities within dolomite strata. This would need to be investigated. Given the small catchment area and modest percentage of habitat suitable for migratory species upstream of the potential dam (22% for at least one species), a potential dam at this location would have an effect on zero % to 0.5% of the total potentially suitable habitat modelled in the Southern Gulf catchments. There is a high likelihood of unrecorded sites of cultural significance in the inundation area.

The investigation of a potential large dam site generally involves an iterative process of increasingly detailed studies over a period of years, occasionally over as few as 2 or 3 years but often over 10 or more years. It is not unusual for the cost of the geotechnical investigations for a potential dam site alone to exceed several million dollars. For any of the options listed in this report to advance to construction, far more comprehensive studies would be needed, including geotechnical investigations, field measurements of sediment yield, archaeological surveys and ground-based vegetation and fauna surveys, as well as extensive consultations with Traditional Owners and other stakeholders. Studies at that detail are beyond the scope of this regional-scale resource assessment. The companion technical report on surface water storage (Yang et al., 2024) outlines the key stages in investigation of design, costing and construction of large dams. More comprehensive descriptions are provided by Fell et al. (2005), while Indigenous Peoples' views on large-scale water development in north-eastern Queensland can be found in the companion technical report on Indigenous aspirations, interests and water values (Lyons et al., 2024).

Other important considerations

Cultural heritage considerations

Indigenous Peoples traditionally situated their campsites, and hunting and foraging activities, along major watercourses and drainage lines. Consequently, dams are more likely to affect areas of high cultural significance than are most other infrastructure developments (e.g. irrigation schemes, roads).

No field-based cultural heritage investigations of potential dam and reservoir locations were undertaken in the Southern Gulf catchments as part of the Assessment. However, based on existing records and statements from Indigenous participants in the Assessment, it is highly likely such locations will contain heritage sites of cultural, historical and wider scientific significance. Information relating to the cultural heritage values of the potential major dam sites is insufficient to allow full understanding or quantification of the likely impacts of water storages on Indigenous cultural heritage.

The cost of cultural heritage investigations associated with large instream dams that could potentially impound large areas is high relative to other development activities.

Ecological considerations of the dam wall and reservoir

The water impounded by a major dam inundates an area of land, drowning not only instream habitat but surrounding flora and fauna communities. Complex changes in habitat resulting from inundation could create new habitat to benefit some of these species, while other species would be affected by loss of habitat.

For instream ecology, the dam wall acts as a barrier to the movements of plants, animals and nutrients, potentially disrupting connectivity of populations and ecological processes. There are many studies linking water flow with nearly all the elements of instream ecology in freshwater systems (e.g. Robins et al., 2005). The impact of major dams on the movement and migration of aquatic species will depend upon the relative location of the dam walls in a catchment. For example, generally a dam wall in a small headwater catchment will have less of an impact on the movement and migration of species than a dam lower in the catchment.

A dam also creates a large, deep lake, a habitat that is in stark contrast to the usually shallow and often flowing, or ephemeral, habitats it replaces. This lake-like environment favours some species over others and will function completely differently to natural rivers and streams. The lake-like environment of an impoundment is often used by sports anglers to augment natural fish populations by artificial stocking. Whether fish stocking is a benefit of dam construction is a matter of debate and point of view. Stocked fisheries provide a welcome source of recreation and food for fishers, and no doubt an economic benefit to local businesses, but they have also created a variety of ecological challenges. Numerous reports of disruption of river ecosystems (e.g. Drinkwater and Frank, 1994; Gillanders and Kingsford, 2002) highlight the need for careful study and regulatory management. Impounded waters may be subject to unauthorised stocking of native fish and releases of exotic flora and fauna.

Further investigation of any of these potential dam sites would typically involve a thorough field investigation of vegetation and fauna communities. Ecological assets in the Victoria catchment are discussed in Section 3.2 and described in more detail in the companion technical reports on ecological assets (Merrin et al., 2024) and surface water storage (Yang et al., 2024).

Potential changes to instream, riparian and near-shore marine species arising from changes in flow are discussed in Section 7.3 .

Sedimentation

Rivers carry fine and coarse sediment eroded from hill slopes, gullies and banks, and sediment stored within the channel. The delivery of this sediment into a reservoir can be a problem because it can progressively reduce the volume available for active water storage. The deposition of coarser-grained sediments in backwater (upstream) areas of reservoirs can also cause back-flooding beyond the flood limit originally determined for the reservoir.

Although infilling of the storage capacity of smaller dams has occurred in Australia (Chanson, 1998), these dams had small storage capacities, and infilling of a reservoir is generally only a potential problem where the volume of the reservoir is small relative to the catchment area. Sediment yield is strongly correlated to catchment area (Tomkins, 2013; Wasson, 1994). Sediment yield to catchment area relationships developed for northern Australia (Tomkins, 2013) were found to predict lower sediment yield values than global relationships. This is not unexpected given the antiquity of the Australian landscape (i.e. it is flat and slowly eroding under 'natural' conditions).

Using the relationships developed by Tomkins (2013), potential major dams in the Southern Gulf catchments were estimated to have about 2% or less sediment infilling after 30 years and less than 5% sediment infilling after 100 years. The exception is the potential dam at Gregory River AMTD 174 km with an FSL of 138 mEGM96 to avoid incursion of the reservoir into the Boodjamulla National Park upstream. At this FSL the reservoir capacity is small (118 GL) relative to the catchment area of the potential dam (11,381 km^2), and consequently it was estimated sediment could potentially infill about 15% and 50% of the reservoir's capacity after 30 years and 100 years, respectively.

Cumulative yield of multiple hypothetical dams in the Southern Gulf catchments

This analysis examined the combined or cumulative yield of multiple dams in the Southern Gulf catchments and the resulting impact to end-of-system (EOS) flows. To undertake this analysis, the most promising hypothetical dam sites (in terms of lowest cost per megalitre at the dam wall) were incrementally included in each river model simulation. Cumulative yields are reported at the dam wall and do not include transmission and conveyance losses. Figure 5-19 shows the cumulative yield (left *y*-axis) from sequential dams as triangles, and the percentage change in median annual EOS volume is represented as circles on the right *y*-axis. The total yield at the dam wall at an annual time reliability of 85% while also maintaining supply to existing entitlement holders downstream of six of the seven instream dams analysed is 733 GL, with the majority of this yield provided by the first three dams (641 GL). The seventh dam, South Nicholson River AMTD 9 km, is not included in this analysis as it is upstream of the Nicholson River AMTD 198 km dam, resulting in reduced cumulative yield. The results from this analysis were used to investigate the cumulative impacts of multiple dams in the Southern Gulf catchments (Section 7.3).

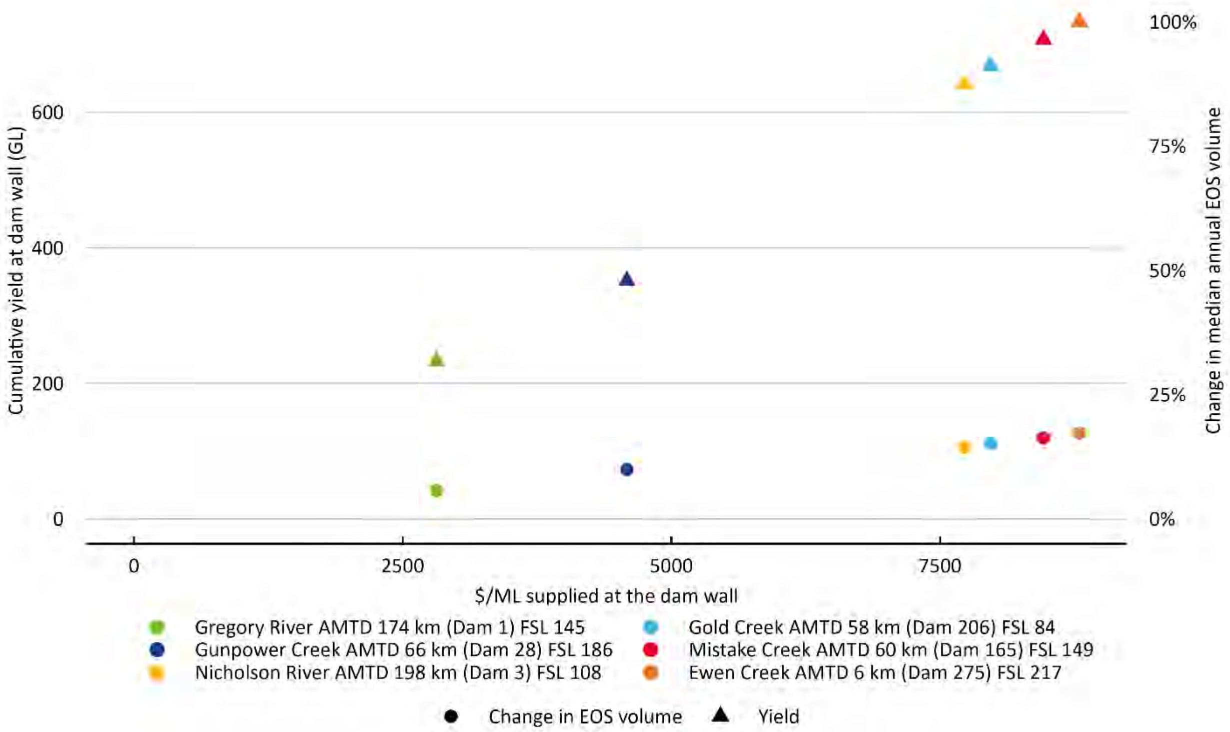

Figure 5-19 Cumulative yield at 85% annual time reliability versus cumulative cost of water in $/ML and change in the end-of-system (EOS) volume in the Southern Gulf catchments

Yield is reported at the dam wall under Scenario A. Triangles indicate combined water yield at 85% annual time reliability of one or more dams, and the colour of the dot indicates the most recently included dam in the cumulative yield calculation. Circles indicate change in median annual streamflow at the EOS for all mainland catchments compared to under Scenario A.

Exploration of two potential dam sites in the Southern Gulf catchments

Two potential dam sites on different rivers are summarised here. These sites are described because they are among the more cost-effective sites near relatively large continuous areas of land suitable for irrigated agriculture in the Southern Gulf catchments, and not too remote relative to other potential dam sites in the study area. More detailed descriptions of the seven sites selected for pre-feasibility assessment are provided in the companion technical report on surface water storage (Yang et al., 2024).

Potential dam on Gunpowder Creek AMTD 66 km and FSL 186 mEGM96 for water supply

The potential Gunpowder Creek dam site is an instream development with the potential to provide irrigation supplies downstream near the junction of Gunpowder Creek and the Leichhardt River. Previous investigations commissioned by the then Queensland Irrigation and Water Supply Commission (QWIS, 1960, 1974) in the 1970s examined a number of potential dam sites along Gunpowder Creek for their potential to supply proposed mining developments. The potential sites investigated by the Queensland Irrigation and Water Supply Commission are upstream of the potential dam site examined in this section. There have been no recent publicly funded investigations. The foundations at the nominated site appear suitable for an RCC dam and it is estimated that both the depth of alluvium and stripping on the abutments would be about 3 to 5 m. However, the extent of any dolomite in the sequence at the potential dam site should be checked in case there are strata with cavities, although the previous investigations at nearby sites did not note any problems. Given the potential for significant flooding during construction and the spillway capacity required, an RCC dam with a 140 m wide central uncontrolled spillway would be most suitable. Releases of water downstream of the dam could be made through two conduits installed in the right abutment of the dam, and would be regulated by two 900 mm diameter fixed-cone regulating valves. A fish-lift transfer facility would be installed in the right abutment of the potential dam.

No site-specific evaluation of cultural heritage considerations was possible, as pre-existing Indigenous cultural heritage site records were not made available to the Assessment. Land tenure and native title information were derived from regional land councils and the National Native Title Tribunal. There is a high likelihood of unrecorded sites of cultural significance in the inundation area. Habitat species distribution models developed for the study area estimate that approximately 5% of the potential dam catchment (18,028 ha) has suitable habitat for at least 40% of the ten species modelled (Figure 5-20). The estimated area of suitable habitat for these water-dependent species upstream of the potential dam site is small relative to the total estimated suitable habitat in the Southern Gulf catchments, ranging from zero% to 3% of the study area depending on the species. These species may have their habitat fragmented, and/or their movement may be impeded by a dam.

A manual cost estimate undertaken as part of the Assessment for a hypothetical RCC dam on the Gunpowder Creek AMTD 66 km site at an FSL of 186 mEGM96 was approximately $773 million. Access to the site could be along a 75 km long extension of the existing Mount Isa to Gunpowder Road, although this extension would require further investigation should this proposal be considered further. The total distance from Mount Isa to the dam site would be 205 km. Assuming full use of existing licence entitlement holders in the Leichhardt catchment and a dry-season demand pattern, the yield at 85% annual time reliability and FSL of 186 mEGM96 was modelled to be 119 GL at the dam wall (Gibbs et al., 2024). Figure 5-21 shows the modelled dam cost and yield at the dam wall without consideration of existing entitlement holders.

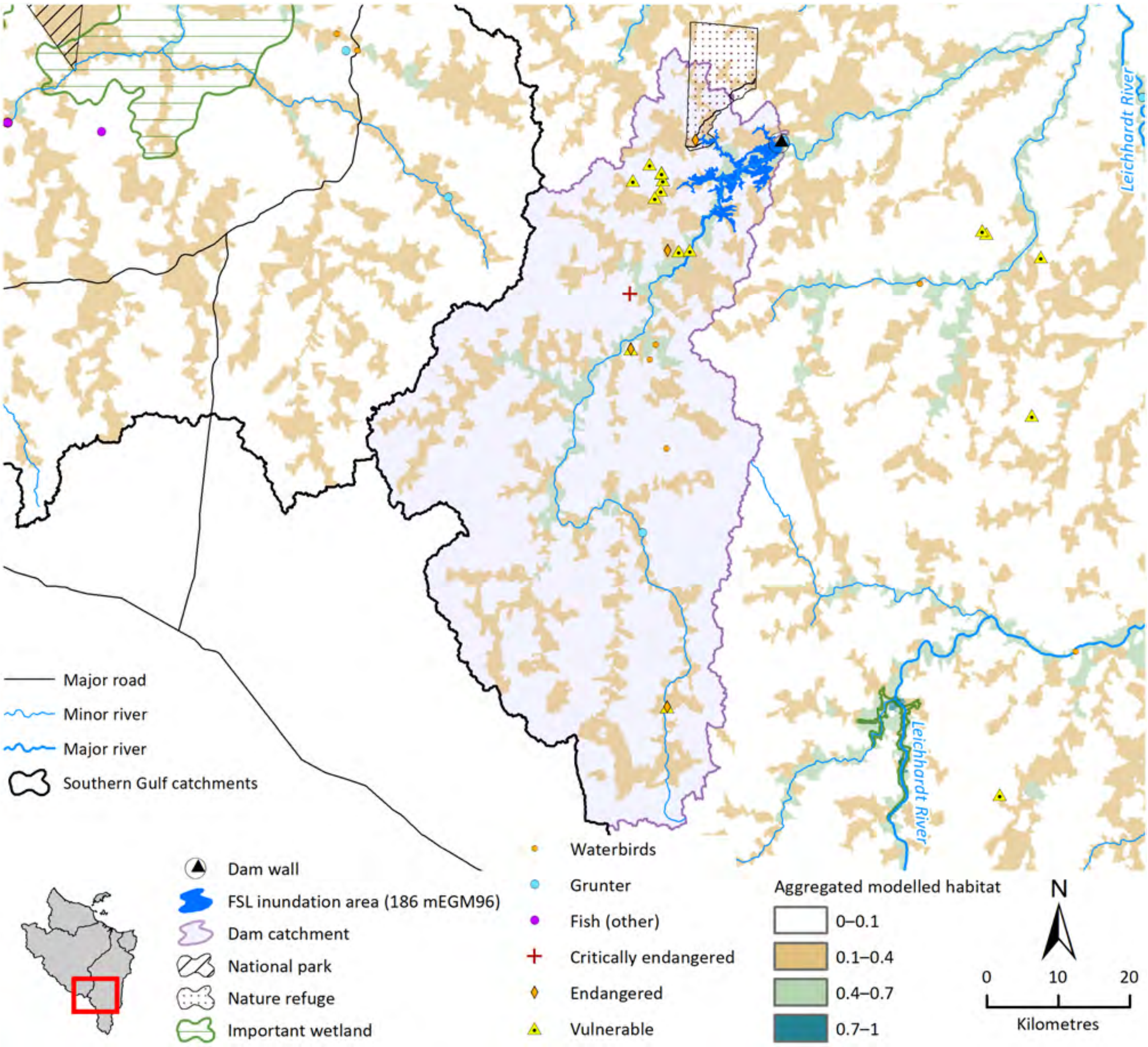

Figure 5-20 Location of listed species, water-dependent assets and aggregated modelled habitat in the vicinity of the potential dam site on Gunpowder Creek dam AMTD 66 km and reservoir extent

Near the junction of Gunpowder Creek and the Leichhardt River, approximately 35 km downstream of the potential dam site, a large plain of recent alluvium has formed. The nearest location for a potential re-regulating structure appears to be about 5 km upstream of the hypothetical target area. Friable non-cracking clay or clay loam soils (soil generic group (SGG) 2) and sand to loam over relatively friable red clay subsoils (SGG 1.1) have formed on the recent alluvium of the floodplain. Brown cracking clay soils (SGG 9) occur on the older Cloncurry Plain.

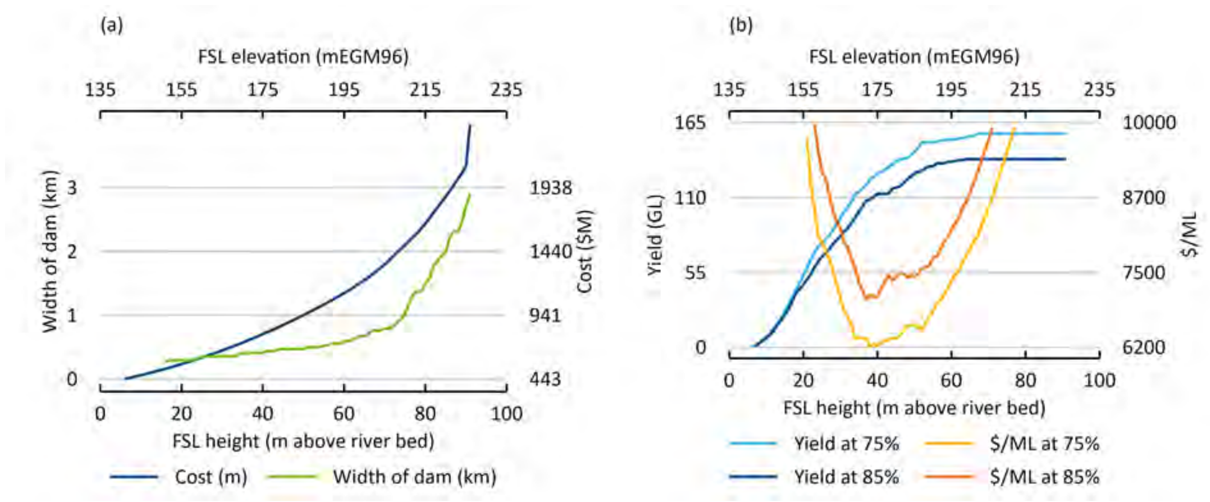

Figure 5-21 Potential dam site on Gunpowder Creek AMTD 66 km: cost and yield at the dam wall

Dam length and dam cost versus full supply level (FSL), and (b) dam yield and yield/$ million at 75% and 85% annual time reliability.

Due to the relatively steep slope of the land adjacent to the re-regulating weir and due to the texture of the soils, the likely irrigation application methods being spray or trickle, piped reticulation from the weir pump station would be likely. It is possible that this potential dam site could service about 11,000 ha, depending on crop type, irrigation method and reticulation arrangement (see companion technical report on irrigation systems in the Victoria and Southern Gulf catchments, Devlin, 2024). Based on a notional layout of pipeline infrastructure outlined by Devlin (2024), the cost of reticulation infrastructure to irrigate this area would be about $320 million or about $29,100 per irrigated hectare.

Potential dam on Gregory River AMTD 174 km and FSL 138 mEGM96 for water supply

The potential dam site on the Gregory River AMTD 174 km was first identified by the then Queensland Irrigation and Water Supply Commission in the late 1960s (QIWS, 1969) and subsequently identified by the Assessment as one of the largest-yielding and most cost-effective potential dam sites in the Southern Gulf catchments. There has been no recent consideration of this site for a potential water storage development. A major limitation of the site is its proximity to the Boodjamulla (Lawn Hill) National Park (upstream of the site), and parts of the Thorntonia Aggregation wetland, a *Directory of Important Wetlands in Australia* nationally important wetland, overlaps the potential reservoir and extends downstream from the potential dam wall. This hypothetical instream development has potential to supply water to the Armraynald Plain downstream of the dam.

The hypothetical dam site is located on Proterozoic rocks of the Shady Bore Quartzite, which consists of white medium orthoquartzite, siltstone and dolomitic fine sandstone, which appear to be gently folded and dipping upstream. The foundations appear suitable for an RCC dam and the depth of alluvium is estimated to be 7 to 10 m; 5 to 7 m of stripping would be required on the potential dam abutments.

Given the potential for significant flooding during construction, and the spillway capacity required, the RCC dam would have a 400 m wide central uncontrolled spillway. A hydraulic jump type spillway basin would be provided to protect the river bed against erosion during spillway overflows. Releases downstream of the dam would be made through pipework installed in a diversion conduit located in the right abutment of the dam. A fish-lift transfer facility would also be installed in the right abutment. Access to the site would be along 27 km of new road built to serve the potential dam branching from the Camooweal–Gregory Road some 58 km south-west of Gregory. The total distance of the site from Mount Isa via Camooweal is 371 km.

No site-specific evaluation of cultural heritage considerations was possible, as pre-existing Indigenous cultural heritage site records were not made available to the Assessment. Land tenure and native title information were derived from regional land councils and the National Native Title Tribunal. There is a high likelihood of unrecorded sites of cultural significance in the inundation area.

Despite being on a major river, the potentially suitable habitat for the four modelled migratory species was relatively small. It was estimated that approximately 3% of the potential dam catchment (35,144 ha) has suitable habitat for at least 40% of the ten species modelled (Figure 5-22). However, the estimated area of suitable habitat for these water-dependent species upstream of the potential dam site is small relative to the total estimated suitable habitat in the Southern Gulf catchments, ranging from 0.04% to 6.8% of the study area, depending on the species. These species may have fragmented habitat and/or their movement may be impeded by a dam.

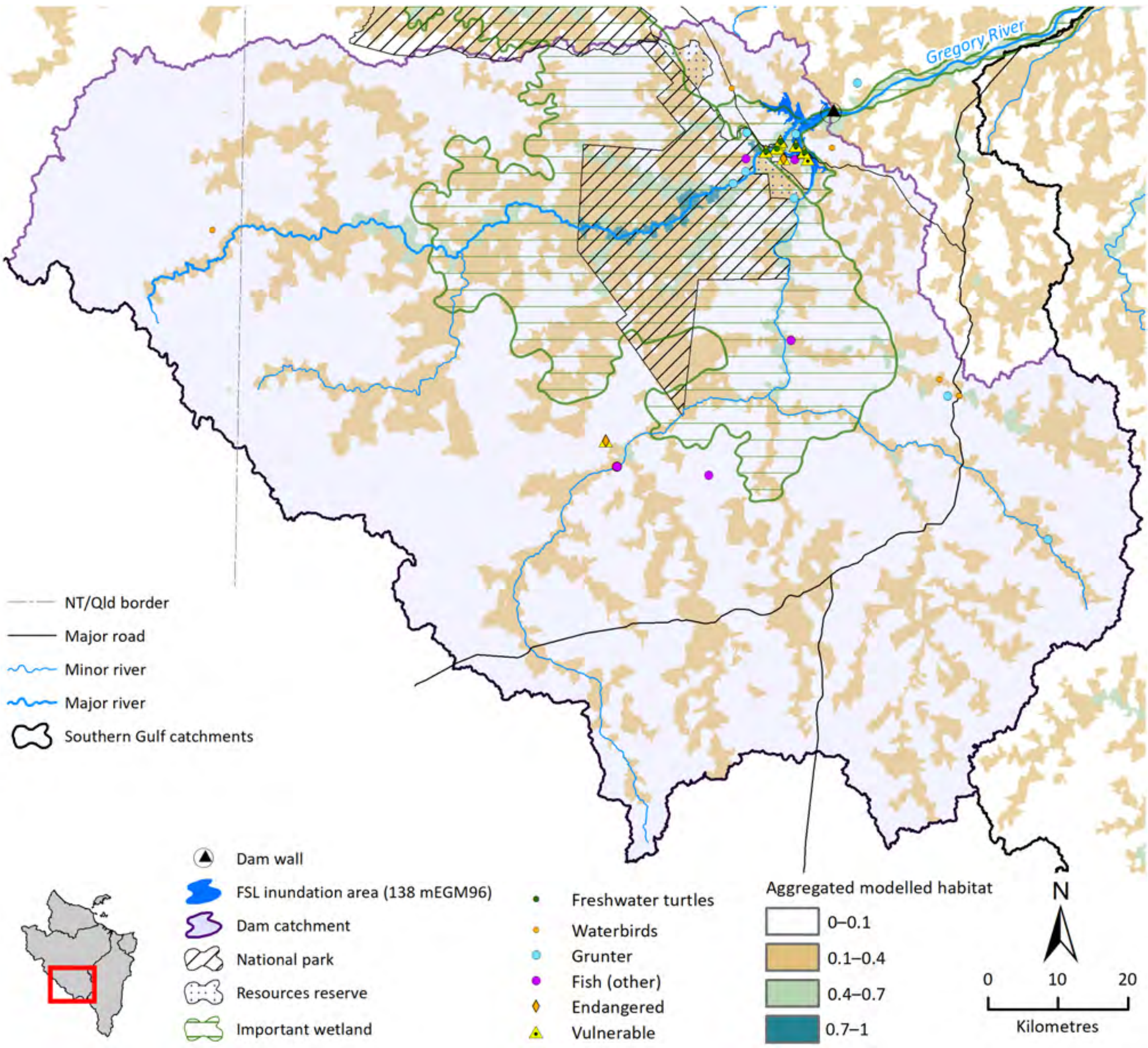

Figure 5-22 Location of listed species, water-dependent assets and aggregated modelled habitat in the vicinity of the potential dam site on the Gregory River AMTD 174 km

The FSL 138 m EGM96 was selected such that the reservoir did not encroach into the Boodjamulla (Lawn Hill) National Park and Lawn Hill Resources Reserve, which are located about 9 km upstream of the potential dam wall. At this reduced FSL the yield is considerably reduced and the reservoir, which is small relative to its catchment area, has an elevated risk of having its capacity notably reduced by sediment infill (Yang et al., 2024). For example, taking into consideration existing licence entitlement holders and assuming a dry-season demand pattern, the yields at 85% annual time reliability at FSLs of 138 mEGM96 and 145 mEGM96 were modelled to be 133 GL and 233 GL at the dam wall, respectively (see companion technical report on river model simulation in the Southern Gulf catchments, Gibbs et al., 2024). Figure 5-23 shows the modelled dam cost and yield at the dam wall without consideration of existing entitlement holders.

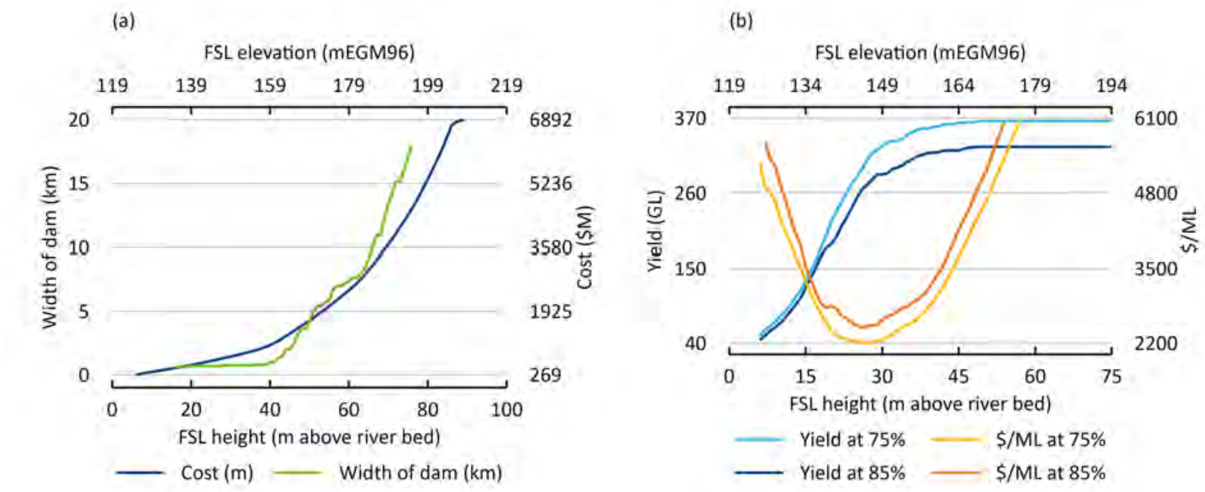

Figure 5-23 Potential dam site on Gregory River AMTD 174 km: cost and yield at the dam wall
(a) Dam length and dam cost versus full supply level (FSL), and (b) dam yield and yield/$ million at 75% and 85% annual time reliability.

A manual cost estimate undertaken as part of the Assessment for a hypothetical RCC dam on the Gregory River at AMTD 174 km at an FSL of 138 mEGM96 found the dam would cost approximately $683 million.

Although the nearby Boodjamulla (Lawn Hill) National Park (upstream of the site) and Thorntonia Aggregation wetland are major limitations of this potential dam site, a major benefit is its proximity to the Armraynald Plain (approximately 35 km downstream of the potential dam site), which is a large contiguous area of Pleistocene sediments that formed black and grey cracking clay soils (SGG 9) suitable for a range of dry-season crops. Due to the slope of the Gregory River near the potential dam site, water would be released from the dam down the river to a potential re-regulating weir on a natural bar with a 2.5 km long pool upstream. One of the favourable features of the site is that the river levees adjacent to the potential re-lift pump point mean the land naturally slopes away from the river at a gradient favourable for cost-effective open channels. Notionally the hypothetical scheme would be based around using two main channel alignments and constructed from the in-situ cracking clay soils. Under the nominal irrigation scheme outlined by Devlin (2024), a hypothetical dam on the Gregory River at AMTD 174 km and FSL 138 mEMG96 could potentially supply sufficient water to irrigate approximately 10,000 ha at a reticulation scheme cost of $31.8 million or $3180/ha (excluding farm development and infrastructure; Devlin 2024).

5.4.3 Weirs and re-regulating structures

Re-regulating structures, such as weirs, are typically located downstream of large dams. They allow for more efficient releases from the storages and for some additional yield from the weir storage itself, thereby reducing the transmission losses normally involved in supplemented river systems.

As a rule of thumb, however, weirs are constructed to one-half to two-thirds of the river bank height. This height allows the weirs to achieve maximum capacity, while ensuring the change in downstream hydraulic conditions does not result in excessive erosion of the toe of the structure. It also ensures that large flow events can still be passed without causing excessive flooding upstream.

Two types of weir structures have been constructed in Queensland: concrete gravity weirs and sheet piling weirs. These are discussed below. For each type of weir, rock-filled mattresses are often used on the stream banks, extending downstream of the weir to protect erodible areas from flood erosion. A brief discussion on sand dams is also provided.

Weirs, sand dams and diversion structures obstruct the movement of fish in a similar way to dams during the dry season.

Concrete gravity type weirs

Where rock bars are exposed at bed level across a stream, concrete gravity type weirs have been built on the rock at numerous locations across Queensland. This type of construction is less vulnerable to flood erosion damage, both during construction and in service. Indicative costs are provided for a small weir structure with only sufficient height (e.g. 0.75 m above river bed) to submerge pumping infrastructure. Assuming exposed bedrock across the river bed, and rock for aggregates and mattresses, are available locally, the cost of a low reinforced concrete slab with upstand (i.e. 0.75 m above river bed, nominally 150 m width along crest) for the purpose of providing pump station submergence is estimated to cost about $13 million. Nominal allowances were made for site access, services and construction camp costs on the basis that more substantial site establishment costs would be incurred by the nearby irrigation development (Yang et al., 2024).

Sheet piling weirs

Where rock foundations are not available, stepped steel sheet piling weirs have been successfully used in many locations across Queensland. These weirs consist of parallel rows of steel sheet piling, generally about 6 m apart, with a step of about 1.5 to 1.8 m high between each row. Reinforced concrete slabs placed between each row of piling absorb much of the energy as flood flows cascade over each step. The upstream row of piling is the longest, driven to a sufficient depth to cut off the flow of water through the most permeable material (Figure 5-24). Indicative costs are provided in Table 5-7.

In recent years the Queensland Department of Agriculture and Fisheries has not approved stepped weirs on the basis that the steps result in fish mortalities. Sheet piling weirs would therefore have to have a sloping face with a more extensive dissipator at bed level.

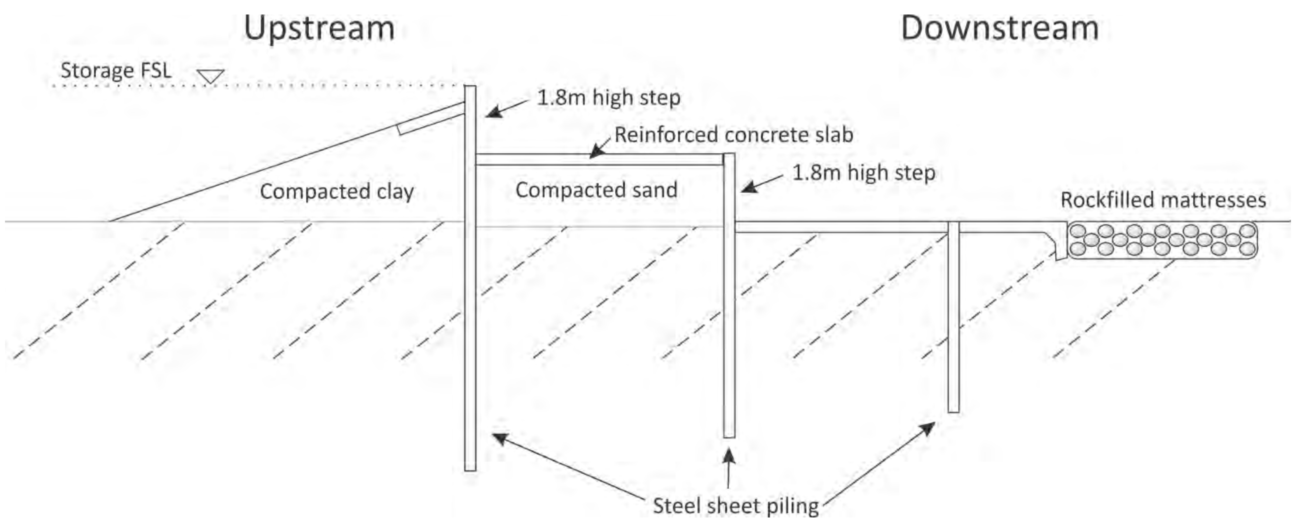

Figure 5-24 Schematic cross-section of sheet piling weir

Source: Petheram et al. (2013)

Table 5-7 Estimated construction cost of 3 m high sheet piling weir

Cost indexed to 2023.

WEIR CREST LENGTH (m)	ESTIMATED CAPITAL COST ($ million)
100	32
150	42
200	50

Sand dams

As many of the large rivers in northern Australia are very wide (e.g. >300 m), weirs are likely to be impractical and expensive at many locations. An alternative structure is a sand dam, which consists of low embankments built of sand and constructed at the start of each dry season during periods of low or no flow, when heavy earth-moving machinery can access the bed of the river. A sand dam is constructed to form a pool of sufficient depth to enable pumping (i.e. typically greater than 4 m depth) and this type of dam is widely used in the Burdekin River near Ayr in Queensland, where the river is too wide to construct a weir.

Typically, sand dams take three to four large excavators approximately 2 to 3 weeks to construct, and no further maintenance is required until they need to be reconstructed again after the wet season. Bulldozers can construct a sand dam more quickly than can a team of excavators, but they have greater access difficulties. Because a sand dam only needs to form a pool of sufficient size and depth from which to pump water, it usually only partially spans a river and is typically constructed immediately downstream of large, naturally formed waterholes.

The cost of 12 weeks of hire for a 20 t excavator and float (i.e. for transportation) is approximately $100,000. Although sand dams are cheap to construct relative to a concrete or sheet piling weir, they require annual rebuilding and have much larger seepage losses beneath and through the dam wall. No studies are known to have quantified losses from sand dams.

5.4.4 Large farm-scale ringtanks

Large farm-scale ringtanks are usually fully enclosed circular earthfill embankment structures constructed close to major watercourses/rivers to minimise the cost of pumping infrastructure by ensuring long 'water harvesting' windows. For this reason, they are often subject to reasonably frequent inundation, usually by slow-moving flood waters. In some exceptions embankments may not be circular; rather, they may be used to enhance the storage potential of natural features in the landscape such as horseshoe lagoons or cut-off meanders adjacent to a river (see Section 5.4.6 for discussion on extracting water from persistent waterholes).

An advantage of ringtanks over gully dams is that the catchment area of the former is usually limited to the land that it impounds, so costs associated with spillways, failure impact assessments and constructing embankments to withstand flood surges are considerably less than those for large farm-scale gully dams. Another advantage of ringtanks is that unless a diversion structure is utilised in a watercourse to help 'harvest' water from a river, a ringtank and its pumping station do not impede the movement of aquatic species or transport of sediment in the river. Ringtanks also have to be sited adjacent to major watercourses to ensure there are sufficient days available for pumping. While this limits where they can be sited, it means that because they can be sited adjacent to major watercourses (on which gully dams would be damaged during flooding – large farm-scale gully dams are typically sited in catchments of areas less than 40 km^2), they often have a higher reliability of being filled each year than gully dams. However, operational costs of ringtanks are usually higher than those of gully dams because water must be pumped into the structure each year from an adjacent watercourse, typically using diesel-powered pumps (solar and wind energy do not generate sufficient power to operate high-volume axial flow or centrifugal flow pumps). Even where diversion structures are utilised to minimise pumping costs, the annual cost of excavating sediment and debris accumulated in the diversion channel can be in the order of tens of thousands of dollars.

For more information on ringtanks in the Southern Gulf catchments, refer to the companion technical reports on surface water storage (Yang et al., 2024) and river model simulation (Gibbs et al., 2024). Also of relevance is the Northern Australia Water Resource Assessment technical report on large farm-scale dams (Benjamin, 2018) and companion technical report on pumping stations in northern Australia (Devlin, 2024). A rectangular ringtank in the catchment of the Flinders River (Queensland) is pictured in Figure 5-25.

In this section, the following assessments of ringtanks in the Southern Gulf catchments are reported:

- suitability of land for large farm-scale ringtanks
- reliability with which water can be extracted from different reaches
- indicative evaporative and seepage losses from large farm-scale ringtanks
- indicative capital, operation and maintenance costs of large farm-scale ringtanks.

Figure 5-25 Rectangular ringtank and 500 ha of cotton in the Flinders catchment (Queensland)
The channel along which water is diverted from the Flinders River to the ringtank can be seen in the foreground.
Photo: CSIRO

Suitability of land for ringtanks in the Southern Gulf catchments

Figure 5-26 displays the broad-scale suitability of land for large farm-scale ringtanks in the Southern Gulf catchments. Approximately 21% of the Southern Gulf catchments is classed as being likely suitable. Those areas of the Southern Gulf catchments with soil and topography suitable for ringtanks are mainly restricted to the level, slowly permeable, rock-free cracking clay soils (SGG 9) of the Armraynald Plain, Barkly Tableland and northern parts of Donors Plateau (Figure 5-26). The very poorly drained saline coastal marine plains (Karumba Plain), which are subject to tidal inundation and have very deep, strongly mottled, grey non-cracking and cracking clay soils with potential acid-sulfate deposits in the profile, are likely to be suitable for ringtanks but are subject to storm surge from cyclones. The soils of the Armraynald Plain are very deep (>1.5 m), imperfectly drained, slowly permeable, medium to heavy clays that crack when dry and swell when wet, reducing the rate of deep drainage. Soils have a self-mulching clay surface with gilgai common. On the Barkly Tableland, the cracking clays are deep (1.2 to 1.5 m) and underlain by limestone and dolomite karst, and hence are often moderately well drained and with gravel common. On Donors Plateau, the cracking clay soils are shallower (<0.5 m).

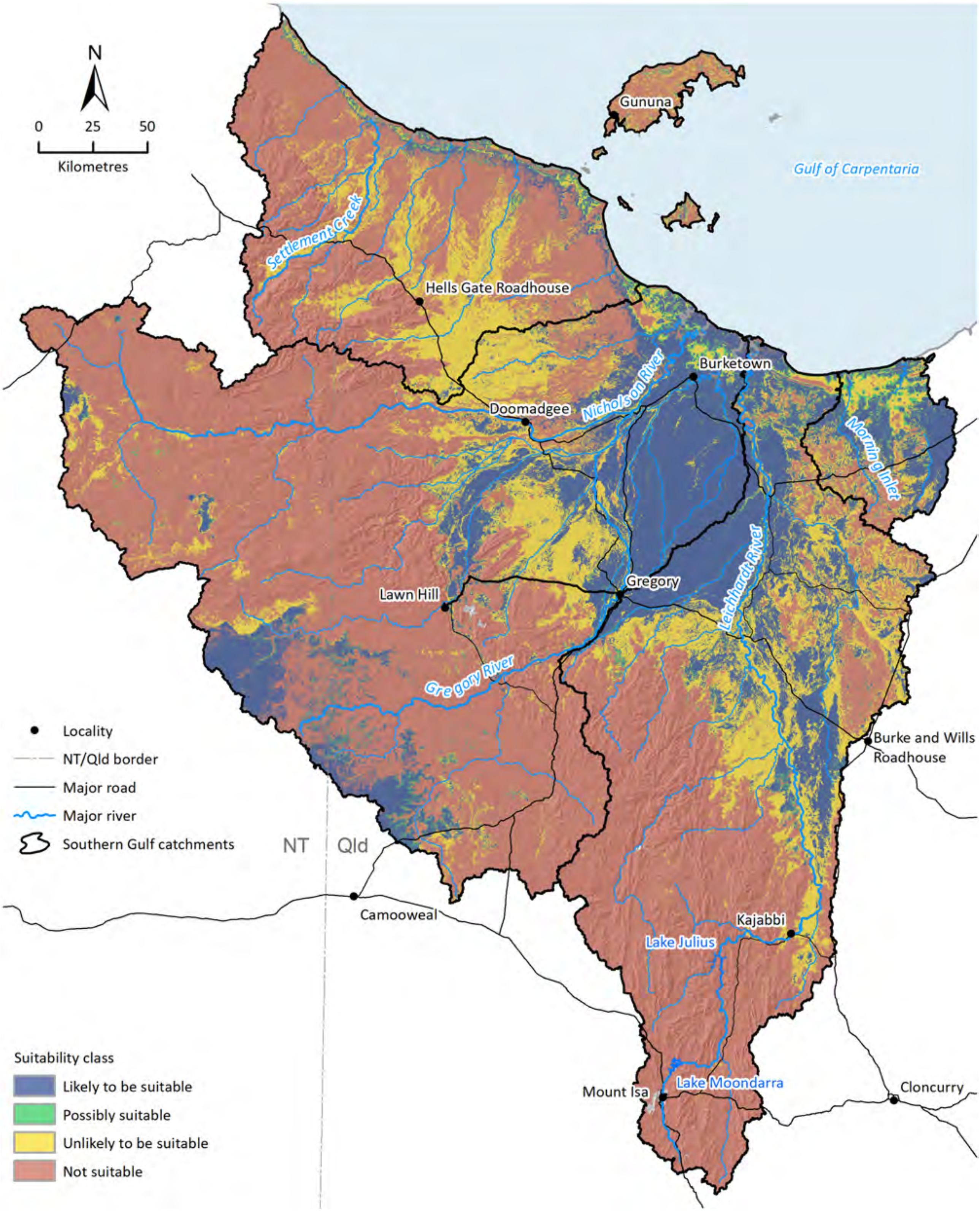

Figure 5-26 Suitability of land for large farm-scale ringtanks in the Southern Gulf catchments

Soil and subsurface data were only available to a depth of 1.5 m, hence the Assessment does not consider the suitability of subsurface material below this depth. This figure does not consider the availability of water. Data are overlaid on a shaded relief map. The results presented in this figure are only indicative of suitable locations for siting a ringtank; site-specific investigations by a suitably qualified professional should always be undertaken prior to ringtank construction.

Reliability of water extraction

The existence of a water entitlement does not mean the full volume will be available in all years. The reliability for extraction of an allocation or volume of water from a river depends upon a range of factors including the:

- quantity of discharge and the natural inter- and intra-variability of a river system (Section 2.5.5)
- capacity of the pumps or diversion structure (expressed here as the number of days taken to pump an allocation)
- quantity of water being extracted by other users, and their locations
- conditions associated with a licence to extract water, such as:
  - a minimum threshold (i.e. water height level/discharge) at which pumping can commence (pump start threshold)
  - an annual diversion commencement flow requirement (ADCFR), the volume that must pass through the system before pumping can commence each water year (1 September to 31 August). The ADCFR was assumed to be the combined outflow from rivers that included hypothetical extractions, the Gregory–Nicholson and Leichhardt River basins.

Licence conditions can be imposed on a potential water user to ensure downstream entitlement holders are not affected by new water extractions and to minimise environmental change that may arise from changes to streamflow. In some cases a pump start threshold may be a physical threshold below which it is difficult to pump water from a natural pumping pool, but it can also be a regulatory requirement imposed to minimise impacts to existing downstream users and mitigate changes to existing water-dependent ecosystems.

The impact of pump start thresholds and ADCFR flow requirements on extraction reliability are explored because they are the least complex environmental flow provision to regulate and ensure compliance in remote areas. Although more targeted environmental flow provisions may be possible, these are inevitably more complicated for irrigators to adhere to (usually requiring many dozens of pump operations during a season) and more difficult for regulators to enforce. Within each river reach, water could be harvested by one or more hypothetical water harvesters and the water nominally stored in ringtanks adjacent to the river reach.

The reliability of water extraction under different conditions and at different locations in the Southern Gulf catchments is detailed in the companion technical report for river model simulation (Gibbs et al., 2024). A selection of plots from that report are provided in Figure 5-27 to Figure 5-31 to illustrate key concepts. The locations of the hypothetical extractions are illustrated in the maps in the bottom right corners, and their relative proportions of the total system allocation (left vertical axis) were assigned based on joint consideration of crop versatility, broad-scale flooding, ringtank suitability and river discharge (see companion technical report on river modelling, Gibbs et al., 2024).

Figure 5-27 can be used to explore the reliability of extracting (‘harvesting’) or diverting increasing volumes of water at five locations in the Southern Gulf catchments under varying pump start thresholds. The left vertical axis (*y*1-axis) indicates the system target volume, which is the maximum volume of water extracted across the Southern Gulf catchments each season (nominal catchment-wide entitlement volume). The right vertical axis (*y*2-axis) is the maximum volume of water extracted in that reach each season (nominal reach entitlement volume).

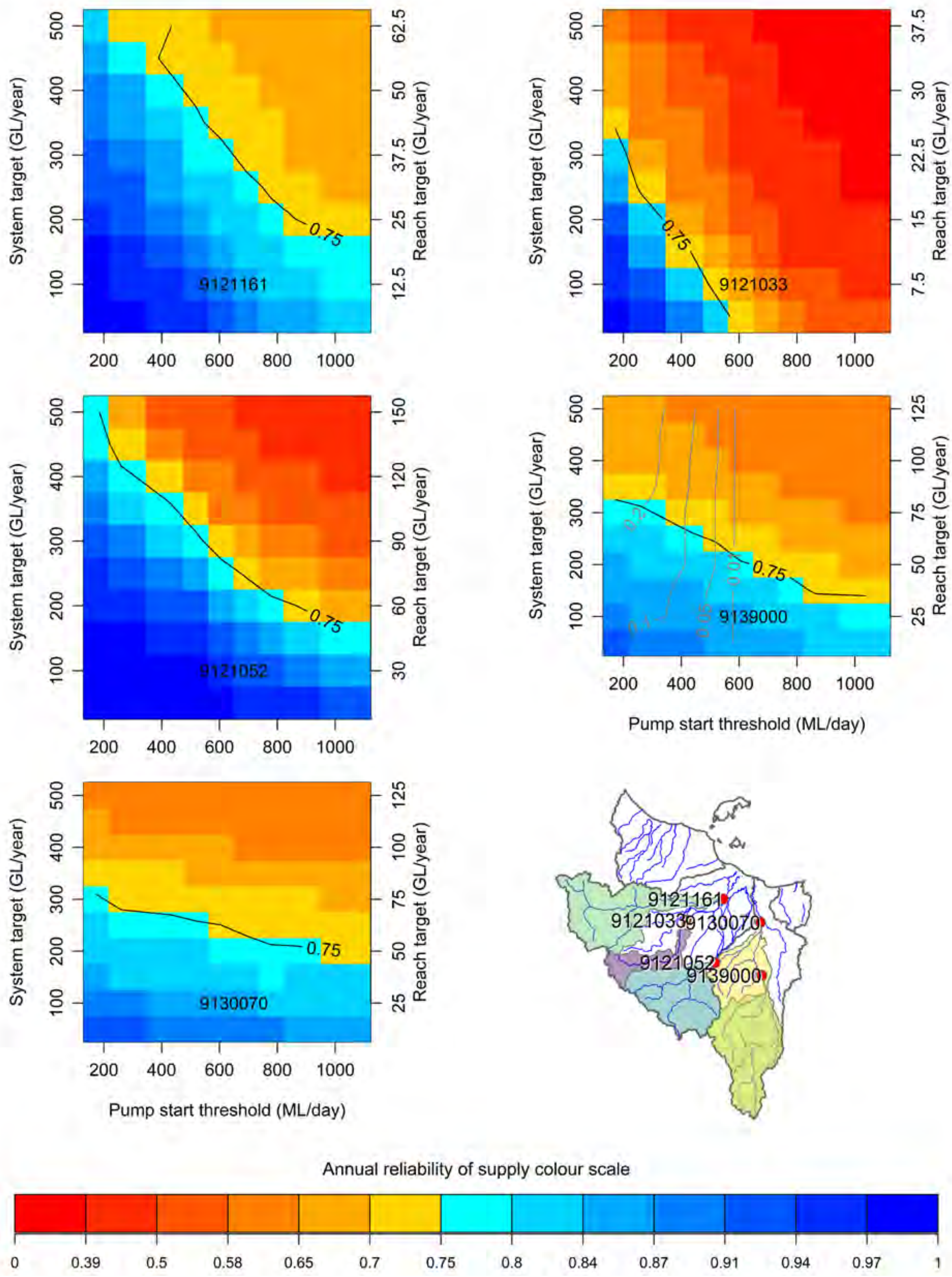

Figure 5-27 Annual reliability of diverting annual system and reach target volumes for varying pump start thresholds

The results assume no annual diversion commencement flow requirement before pumping can commence. Pump capacity is such that system and reach target volumes can be pumped in 20 days. Seven-digit numbers refer to model node locations. Black contour lines indicate conditions that meet a 75% annual reliability of supply, and grey contour lines on node 9139000 indicate proportion of years with a reduction in supply to existing users compared to Scenario A. For more detail see companion technical report on river modelling (Gibbs et al., 2024).

This example assumes a 20-day pump capacity – that is, pump capacities are set to enable the system and reach target volumes to be pumped in 20 days (not necessarily consecutively). This means an irrigator with a 4 GL ringtank has a pump capacity of 200 ML/day to fill their ringtank in 20 days. In this example there is no annual diversion commencement flow requirement based on the volume at the end of the system.

At the smallest pump start threshold examined, 200 ML/day (nominally representative of a lower physical pumping limit), approximately 300 GL of water can be extracted in the Southern Gulf catchments in 75% of years; however, this relatively low pump start threshold results in some impacts on existing downstream licence holders along the Leichhardt River (grey contour lines on node 9139000 in Figure 5-27). This figure shows that as the total system and reach targets increase, the extraction reliability for that volume decreases. Similarly, as the pump start threshold increases, reducing the opportunities to extract water, the extraction reliability for the full system and reach targets decreases. At a pump start threshold of 600 ML/day, which does not affect existing users downstream, approximately 150 GL of water can be extracted in the Southern Gulf catchments in 75% of years.

The data presented in Figure 5-28 are similar to that presented in Figure 5-27 except in Figure 5-28 an additional extraction condition is imposed: a combined total of 150 GL has to flow past the outlets of the Gregory–Nicholson and Leichhardt rivers each wet season before any water can be extracted. Figure 5-28 shows that increasing the EOS flow requirement reduces the extraction reliability for the system and reach targets for different pump start thresholds. Figure 5-29 models increasing the pumping capacity by modifying the conditions such that the target volume can be extracted in 10 days instead of 20 days, with the result being that reliability of supply increases for a given target and pump start threshold. This relationship is shown in more detail in Figure 5-30, this time with pump rate in days on the *x*-axis instead of pump start threshold, which has been fixed to 600 ML/day. With a pump start threshold of 600 ML/day and an annual EOS flow requirement of 150 GL, large pump capacities (i.e. to enable pumping in 20 days or less) are required to extract the system and reach target volumes in 75% of years or greater.

Figure 5-31 and Figure 5-32 indicate, respectively, the post-extraction 50% and 80% annual flow exceedance combined across the outlets with water harvest extractions upstream as a proportion of change relative to Scenario A. The median annual flow is relatively insensitive to the ADCFR flow requirement (Figure 5-31). However, in drier years (represented by the 80% annual flow exceedance data in Figure 5-32) the ADCFR flow requirement has the effect of ‘protecting’ streamflow, with a higher relative proportion of the Scenario A EOS flow maintained.

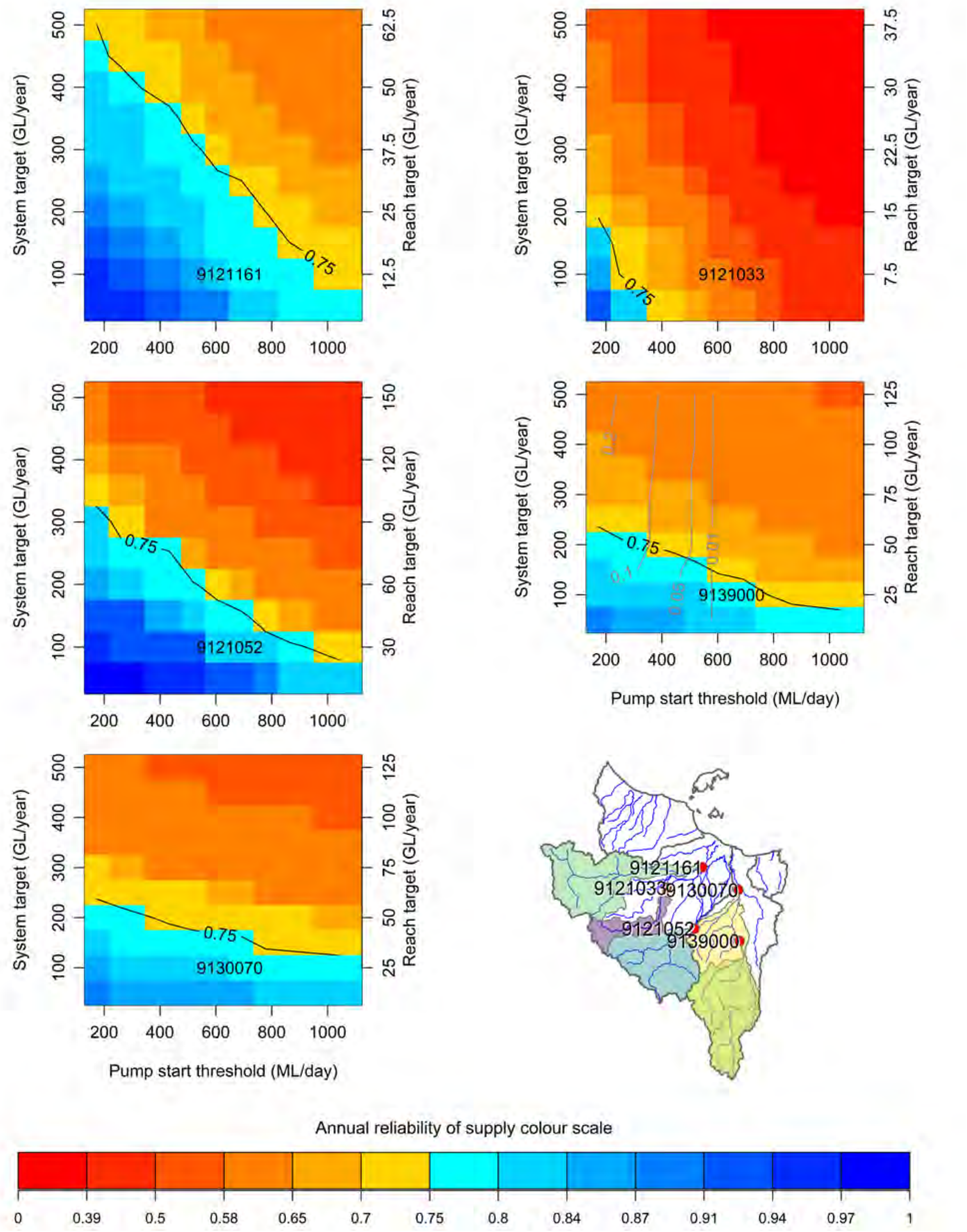

Figure 5-28 Annual reliability of diverting annual system and reach target volumes for varying pump start thresholds with annual diversion commencement flow requirement of 150 GL

Assumes pumping capacity of 20 days (i.e. system and reach target volumes can be pumped in 20 days). Seven-digit numbers refer to model node locations. Black contour lines indicate conditions that meet a 75% annual reliability of supply, and grey contour lines on node 9139000 indicate proportion of years with a reduction in supply to existing users compared to Scenario A. For more detail see companion technical report on river modelling (Gibbs et al., 2024).

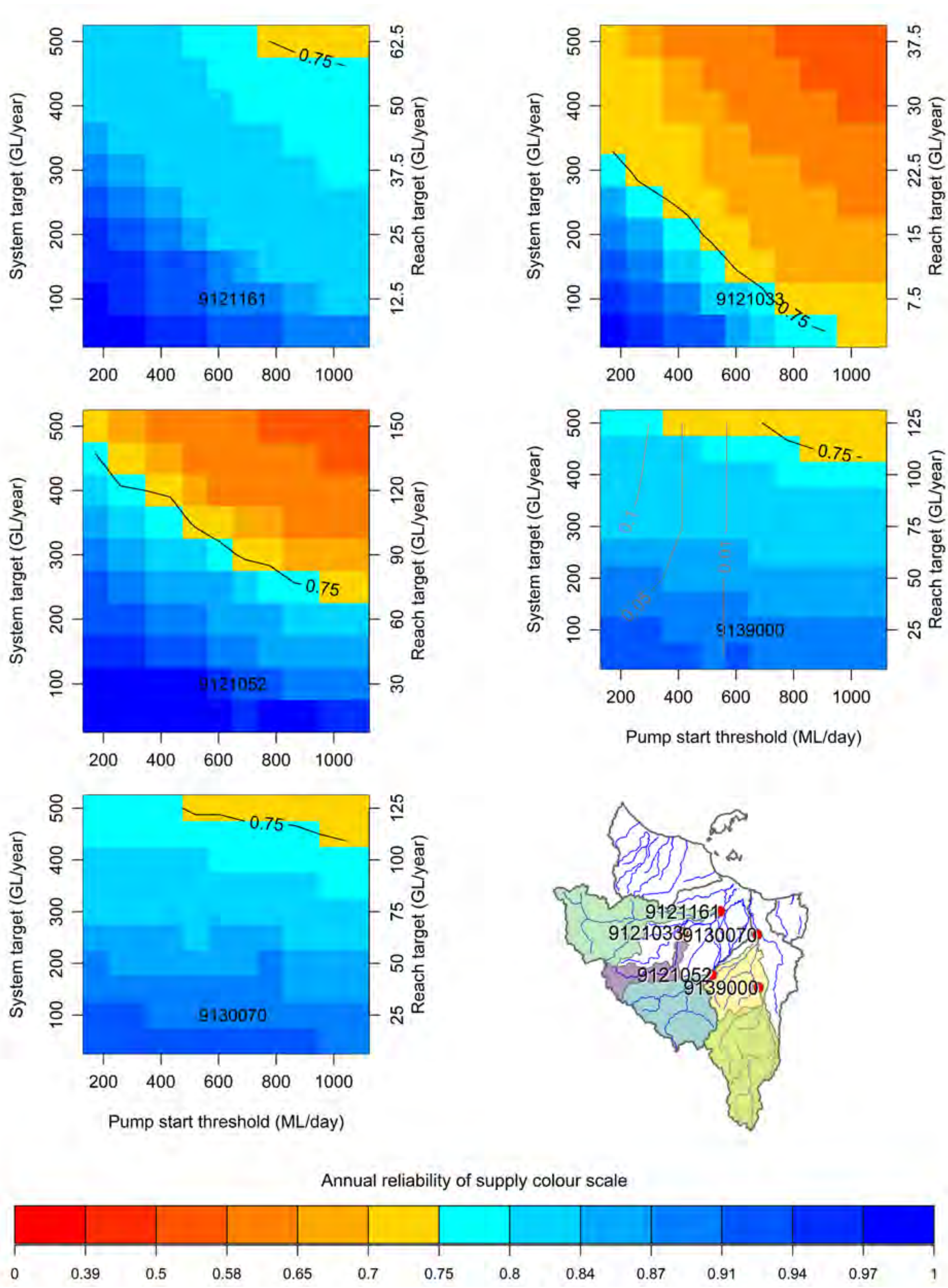

Figure 5-29 Annual reliability of diverting annual system and reach target volumes for varying pump start thresholds assuming pumping capacity of 10 days

Annual diversion commencement flow requirement of 150 GL before pumping can commence and pumping capacity such that system and reach target volumes can be pumped in 10 days. Seven-digit numbers refer to model node locations. Black contour lines indicate conditions that meet a 75% annual reliability of supply, and grey contour lines on node 9139000 indicate proportion of years with a reduction in supply to existing users compared to Scenario A. For more detail see companion technical report on river modelling (Gibbs et al., 2024).

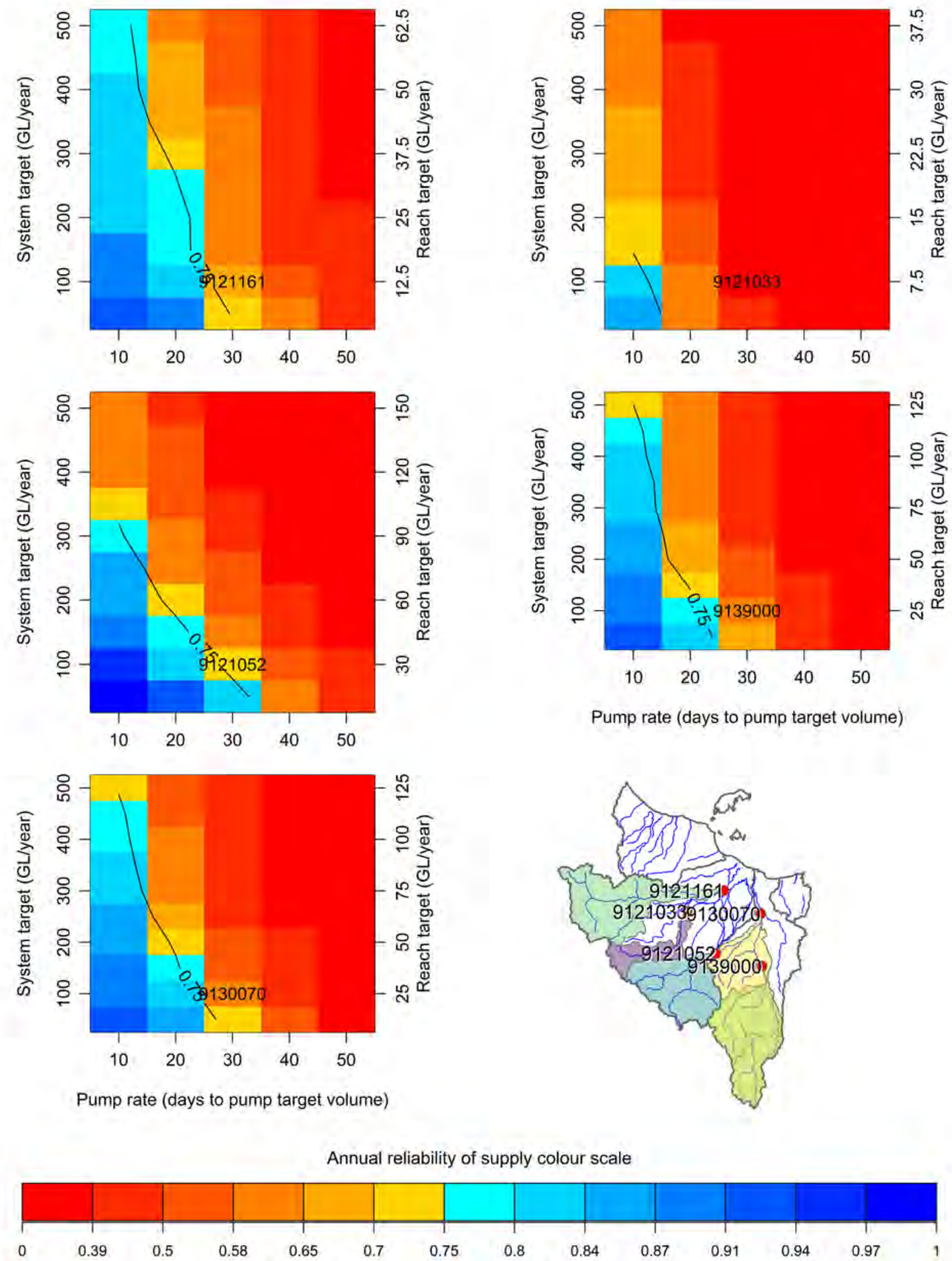

Figure 5-30 Annual reliability of diverting annual system and reach target volumes for varying pump rates assuming a pump start threshold of 600 ML/day

Annual diversion commencement flow requirement of 150 GL before pumping can commence. Seven-digit numbers refer to model node locations. Black contour lines indicate conditions that meet a 75% annual reliability of supply, and no grey contour lines on node 9139000 indicate no impact on reliability of supply to existing users (e.g. Figure 5-29) compared to Scenario A with a pump start threshold of 600 ML/day. For more detail see companion technical report on river modelling (Gibbs et al., 2024).

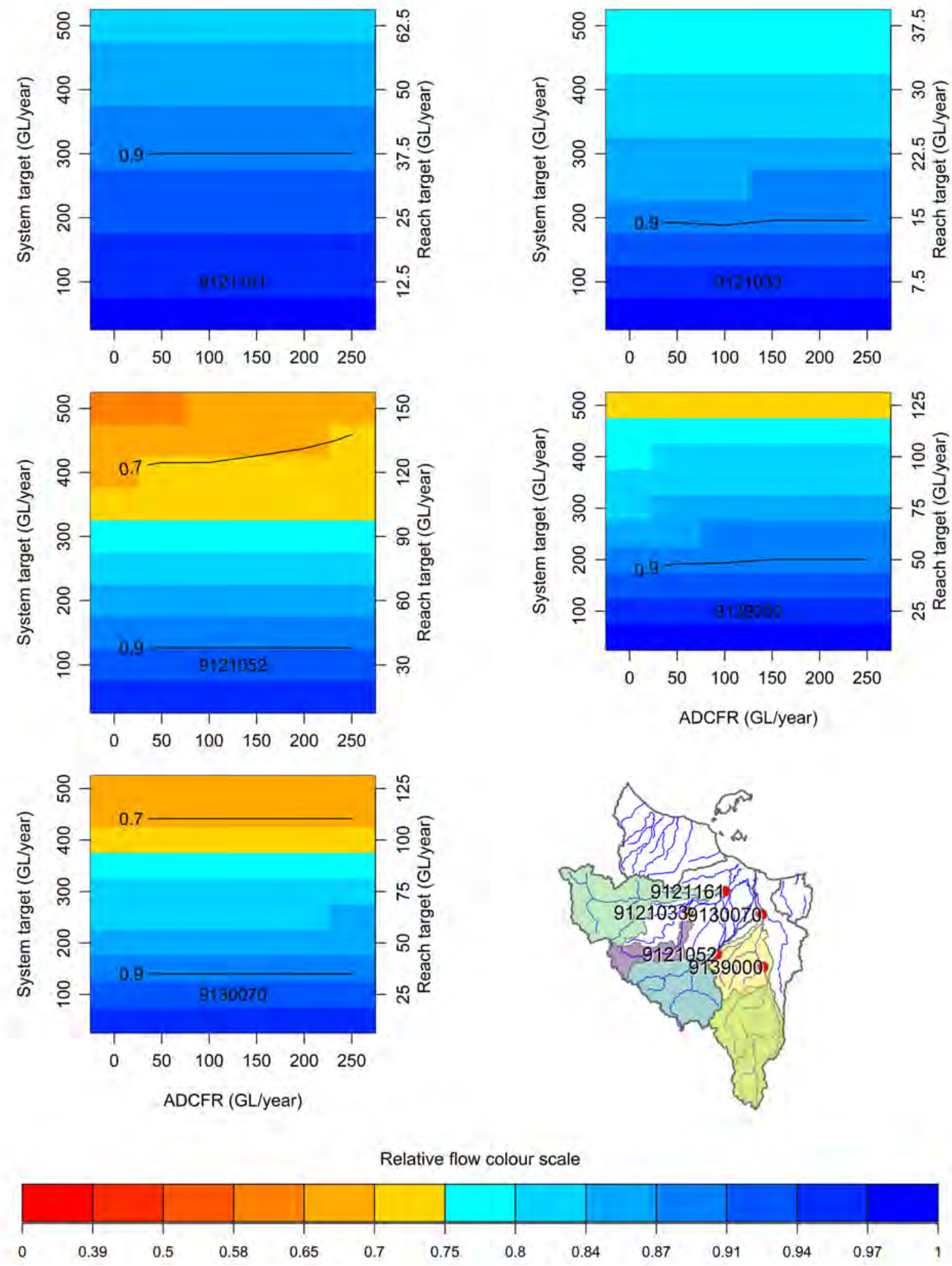

Figure 5-31 50% annual exceedance (median) streamflow relative to Scenario A in the Southern Gulf catchments for a pump start threshold of 600 ML/day and a pump capacity of 20 days

Seven-digit numbers refer to model node locations. For more detail see companion technical report on river modelling (Gibbs et al., 2024). ADCFR = Annual diversion commencement flow requirement, the volume flowing past the end of the system before pumping can commence.

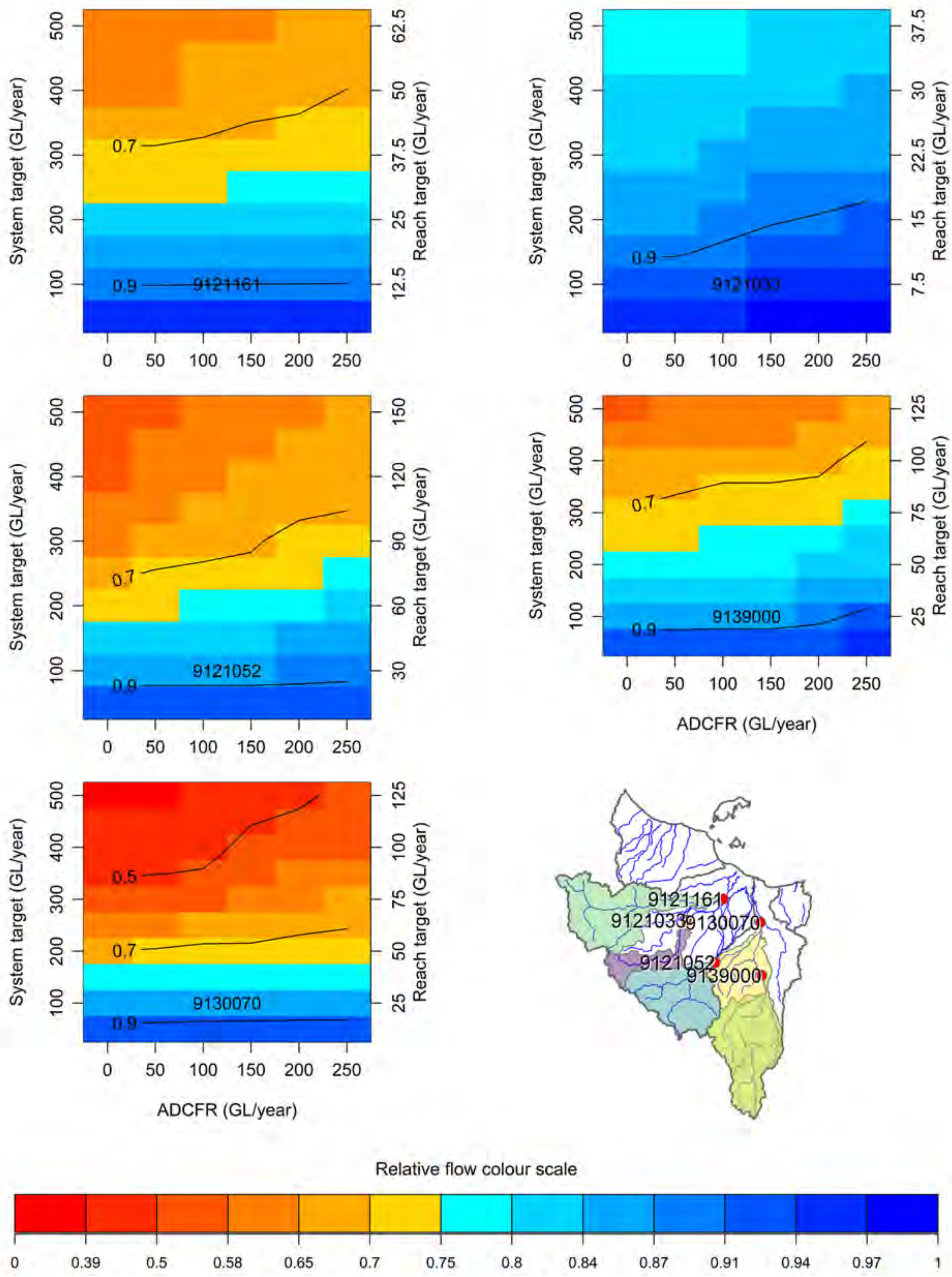

Figure 5-32 80% annual exceedance streamflow relative to Scenario A in the Southern Gulf catchments for a pump start threshold of 600 ML/day and a pump capacity of 20 days

Seven-digit numbers refer to model node locations. For more detail see companion technical report on river modelling (Gibbs et al., 2024). ADCFR = Annual diversion commencement flow requirement, the volume flowing past the end of the system before pumping can commence.

Evaporation and seepage losses

Losses from a farm-scale dam occur through seepage and evaporation.

A study of 138 farm dams ranging in capacity from 75 to 14,000 ML from southern NSW to central Queensland by the Cotton Catchment Communities CRC (2011) found mean seepage and evaporation rates of 2.3 and 4.2 mm/day, respectively. Of the 138 dams examined, 88% had seepage values of less than 4 mm/day and 64% had seepage values less than 2 mm/day. These results largely concur with those of the Irrigation Association of Australia (IAA, 2007), which states that reservoirs will have seepage losses equal to or less than 1 to 2 mm/day when constructed on suitable soils and greater than 5 mm/day if sited on less suitable (i.e. permeable) soils.

When calculating evaporative losses from farm dams it is important to calculate net evaporation (i.e. evaporation minus rainfall) rather than just evaporation. Ringtanks with greater mean water depths lose a lower percentage of their total storage capacity to evaporation and seepage; however, they have a smaller ratio of storage capacity to excavation. In Table 5-8, effective volume refers to the actual volume of water that could be used for consumptive purposes after losses due to evaporation and seepage. For example, if water is stored in a ringtank with mean water depth of 3.5 m from April until January and the mean seepage loss is 2 mm/day, nearly three-quarters of the stored volume (i.e. 70%) would be lost to evaporation and seepage. The example provided in Table 5-8 is for a 4000 ML storage but the effective volume expressed as a percentage of the ringtank capacity is applicable to any storage (e.g. ringtanks or gully dams) of any capacity for mean water depths of 3.5, 6.0 and 8.5 m.

Table 5-8 Effective volume after net evaporation and seepage for ringtanks of three mean water depths, under three seepage rates, near Century Mine in the Southern Gulf catchments

Effective volume refers to the actual volume of water that could be used for consumptive purposes as a result of losses due to net evaporation and seepage, assuming the storage capacity is 4000 ML. For storages of 4000 ML capacity and mean water depths of 3.5, 6.0 and 8.5 m, reservoir surface areas are 110, 65 and 45 ha, respectively. Effective volumes are calculated based on the 20% exceedance net evaporation. For more detail see companion technical report on surface water storage (Yang et al., 2024). S:E ratio = storage capacity to excavation ratio.

MEAN WATER DEPTH† (m)	S:E RATIO	SEEPAGE LOSS (mm/day)	EFFECTIVE VOLUME (ML)	EFFECTIVE VOLUME AS PERCENTAGE OF CAPACITY (%)	EFFECTIVE VOLUME (ML)	EFFECTIVE VOLUME AS PERCENTAGE OF CAPACITY (%)	EFFECTIVE VOLUME (ML)	EFFECTIVE VOLUME AS PERCENTAGE OF CAPACITY (%)
			5 months (April to August)		**7 months (April to October)**		**10 months (April to January)**	
3.5	14:1	1	2879	72	2327	58	1545	39
	14:1	2	2711	68	2093	52	1210	30
	14:1	5	2210	55	1390	35	203	5
6	7.5:1	1	3332	83	3004	75	2537	63
	7.5:1	2	3233	81	2865	72	2338	58
	7.5:1	5	2937	73	2450	61	1744	44
8.5	5:1	1	3535	88	3306	83	2981	75
	5:1	2	3467	87	3210	80	2843	71
	5:1	5	3262	82	2923	73	2432	61

†Mean water depth above ground surface.

Strategies to minimise evaporation include liquid and solid barriers, but these are typically expensive per unit of inundated area (e.g. \$12 to \$40 per m^2). In non-laboratory settings, liquid barriers such as oils are susceptible to being dispersed by wind and have not been shown to reduce evaporation from a water body (Barnes, 2008). Solid barriers can be effective in reducing evaporation but are expensive, at approximately two to four times the cost of constructing a ringtank. Evaporation losses from a ringtank can also be reduced slightly by subdividing the storage into multiple cells and extracting water from each cell in turn to minimise the total surface water area. However, constructing a ringtank with multiple cells requires more earthworks and incurs higher construction costs than outlined in this section.

Capital, operation and maintenance costs of ringtanks

Construction costs of a ringtank may vary considerably, depending on its size and the way the storage is built. For example, circular storages have a higher ratio of storage volume to excavation cost than rectangular or square storages. As discussed in the section on large farm-scale gully dams (Section 3.5.6), it is also considerably more expensive to double the height of an embankment wall than double its length due to the low angle of the walls of the embankment (often at a 3:1 ratio, horizontal to vertical).

Table 5-9 provides a high-level breakdown of the capital and operation and maintenance (O&M) costs of a large farm-scale ringtank, including the cost of the water storage, pumping infrastructure, up to 100 m of pipes, and O&M costs of the scheme. In this example it is assumed that the ringtank is within 100 m of the river and pumping infrastructure. The cost of pumping infrastructure and conveying water from the river to the storage is particularly site specific.

In flood-prone areas where flood waters move at moderate to high velocities, riprap (rocky material) protection may be required. The addition of riprap protection may increase the construction costs presented in Table 5-9 and Table 5-10 by 10% to 20% depending upon the volume of rock required and proximity to a quarry with suitable rock.

For a more detailed breakdown of ringtank costs see the Northern Australia Water Resource Assessment technical report on large farm-scale dams (Benjamin, 2018), and for more information on pumping infrastructure see the companion technical report on pump stations for flood harvesting and irrigation downstream of storages (Devlin, 2024).

Table 5-9 Indicative costs for a 4000 ML ringtank

Assumes a 4.25 m wall height, 0.75 m freeboard, 3:1 ratio on upstream slope, 3:1 ratio on downstream slope and crest width of 3.1 m, approximately 60% of material can be excavated from within storage, and costs of earthfill and compacted clay are $5.40/m^3 and $7/m^3, respectively. Earthworks costs include vegetation clearing, mobilisation/demobilisation of machinery and contractor accommodation. For a more detailed costing, see the Northern Australia Water Resource Assessment technical report on large farm-scale dams (Benjamin, 2018). Pump station costs were derived from the companion technical report on pump stations in northern Australia (Devlin, 2023). Costs indexed to 2023. Pump station operation and maintenance (O&M) costs are based on a diesel cost of $1.49/L.

SITE DESCRIPTION/ CONFIGURATION	EARTHWORKS COSTS ($)	GOVERNMENT PERMITS AND FEES ($)	INVESTIGATION AND DESIGN FEES ($)	PUMP STATION COSTS ($)	TOTAL CAPITAL COST ($)	O&M COSTS OF RINGTANK ($/y)	O&M COSTS OF PUMP STATION ($/y)	TOTAL O&M COSTS ($/y)
4000 ML ringtank	2,000,000	43,000	92,000	380,000	2,515,000	21,000	92,000	113,000

The capital costs can be expressed over the service life of the infrastructure (assuming a 7% discount rate) and combined with O&M costs to give an equivalent annual cost for construction and operation. This enables infrastructure with differing capital and O&M costs and service life to be compared. The total equivalent annual costs for the construction and operation of a 1000 ML ringtank with 4.25 m high embankments and 55 ML/day pumping infrastructure are approximately $143,600 (Table 5-10). For a 4000 ML ringtank with 4.25 m high embankments and 160 ML/day pumping infrastructure, the total equivalent annual cost is approximately $301,550. For a 4000 ML ringtank with 6.75 m high embankments and 160 ML/day pumping infrastructure, the total equivalent annual cost is approximately $457,600.

Table 5-10 Annualised cost for the construction and operation of three ringtank configurations

Assumes freeboard of 0.75 m, pumping infrastructure can fill ringtank in 25 days and assumes a 7% discount rate. Costs based on those provided for 4000 ML provided in Northern Australia Water Resource Assessment technical report on large farm-scale dams (Benjamin, 2018). Costs indexed to 2021. Pump station operation and maintenance (O&M) costs assume cost of diesel of $1.49/L.

CAPACITY AND EMBANKMENT HEIGHT	ITEM	CAPITAL COST ($)	LIFE SPAN (y)	ANNUALISED CAPITAL COST ($)	ANNUAL O&M COST ($)
1000 ML and 4.25 m	Ringtank	1,075,000	40	80,480	10,700
	Pumping infrastructure†	245,000	15	26,900	4,500
	Pumping cost (diesel)	NA	NA	NA	21,000
4000 ML and 4.25 m	Ringtank	2,000,000	40	150,000	17,250
	Pumping infrastructure†	380,000	15	41,700	7,600
	Pumping cost (diesel)	NA	NA	NA	85,000
4000 ML and 6.75 m	Ringtank	3,863,000	40	290,000	33,300
	Pumping infrastructure†	380,000	15	41,700	7,600
	Pumping cost (diesel)	NA	NA	NA	85,000

NA = data not available.
†Costs include rising main, large-diameter concrete or multiple strings of high-density polypipe, control valves and fittings, concrete thrust blocks and headwalls, dissipator, civil works and installation.

Although ringtanks with a mean water depth of 3.5 m (embankment height of 4.25 m) lose a higher percentage of their capacity to evaporative and seepage losses than ringtanks of equivalent capacity with mean water depth of 6 m (embankment height of 6.75 m) (Table 5-8), their annualised unit costs are lower (Table 5-11) due to the considerably lower cost of constructing embankments with lower walls (Table 5-10).

In Table 5-11 the levelised cost, or the equivalent annual cost per unit of water supplied from the ringtank, takes into consideration net evaporation and seepage from the storage, which increase with the length of time water is stored (i.e. crops with longer growing seasons will require water to be stored longer). In this table, the results are presented for the equivalent annual cost of water yield from a ringtank of different seepage rates and lengths of time for storing water.

Table 5-11 Equivalent annual cost per megalitre for two different capacity ringtanks under three seepage rates based on a climate station near the Century Zinc Mine in the Southern Gulf catchments

Assumes a 0.75 m freeboard, 3:1 ratio on upstream slope, 3:1 ratio on downstream slope. Crest widths are 3.1 and 3.6 m for embankments with heights of 4.25 and 6.75 m, respectively, and assumes earthfill and compacted clay costs of $5.40/m^3 and $7/m^3, respectively. Earthworks costs include vegetation clearing, mobilisation/demobilisation of machinery and contractor accommodation. 1000 ML ringtank reservoir has surface area of 27 ha and storage volume to excavation ratio of about 7:1. 4000 ML ringtank and 4.25 m embankment height reservoir has surface area of 110 ha and storage volume to excavation ratio of about 14:1. 4000 ML ringtank with 6.75 m embankment height reservoir has surface area of 64 ha and storage volume to excavation ratio of about 7.5:1. Annualised cost indexed to 2023 and assumes a 7% discount rate.

CAPACITY AND EMBANKMENT HEIGHT	ANNUALISED COST ($)	SEEPAGE (mm/day)	LEVELISED COST ($/ML)	LEVELISED COST ($/ML)	LEVELISED COST ($/ML)
			5 months (April to August)	**7 months (April to October)**	**10 months (April to January)**
1000 ML and 4.25 m	148,955	1	200	247	372
	148,955	2	212	274	475
	148,955	5	260	413	2828
4000 ML and 4.25 m	374,415	1	362	402	476
	374,415	2	373	421	516
	374,415	5	411	492	692
4000 ML and 6.75 m	457,600	1	518	554	614
	457,600	2	528	570	644
	457,600	5	561	626	753

5.4.5 Large farm-scale gully dams

Large farm-scale gully dams are generally constructed of earth, or earth and rockfill embankments with compacted clay cores, and usually to a maximum height of about 20 m, though most gully dams are homogenous fill embankments and their height is typically 8 m or less. Large farm-scale gully dams typically have a maximum catchment area of about 30 km^2 due to the challenges in passing peak floods from large catchments (large farm-scale gully dams are generally designed to pass an event with an annual exceedance probability of 1%), unless a site has an exceptionally good spillway option.

Like ringtanks, large farm-scale gully dams are a compromise between best-practice engineering and affordability. Designers need to follow accepted engineering principles relating to important aspects of materials classification, compaction of the clay core and selection of an appropriate embankment cross-section. However, costs are often minimised where possible; for example, by employing earth bywashes and grass protection for erosion control rather than more expensive concrete spillways and rock protection as found on major dams. This can compromise the integrity of the structure during extreme events, and the longevity of the structure, as well as increase the ongoing maintenance costs, but can considerably reduce the upfront capital costs.

In this section the following assessments are reported:

- suitability of the land for large farm-scale gully dams
- indicative capital and O&M costs of large farm-scale gully dams.

Net evaporation and seepage losses also occur from large farm-scale gully dams. The analysis presented in Section 5.4.4 is also applicable to gully dams.

Suitability of land for large farm-scale gully dams

Figure 5-33 indicates those locations where it is more topographically and hydrologically favourable to construct large farm-scale gully dams in the Southern Gulf catchments and the likely density of options. This analysis takes considers those sites likely to have more favourable topography. It does not explicitly consider those sites that are underlain by soil suitable for the construction of the embankment and to minimise seepage from the reservoir base. This is shown in Figure 5-34. In reality, dams can be constructed on eroded or skeletal soils provided there is access to a clay borrow pit nearby for the cut-off trench and core zone. However, these sites are likely to be less economically viable.

These figures indicate that those parts of the Southern Gulf catchments that are more topographically suitable as large-scale gully dam sites generally do not coincide with areas with soils that are moderately suitable for irrigated agriculture. Furthermore, in many areas topographically suitable for gully dams, dam walls would need to be constructed from rockfill and imported clay soils, increasing the cost of their construction. There are, however, some locations in the north-west of Doomadgee in the Settlement Creek catchment and Mornington Island where there is some topography suitable for gully dams, soil suitable for their construction and versatile agricultural land nearby.

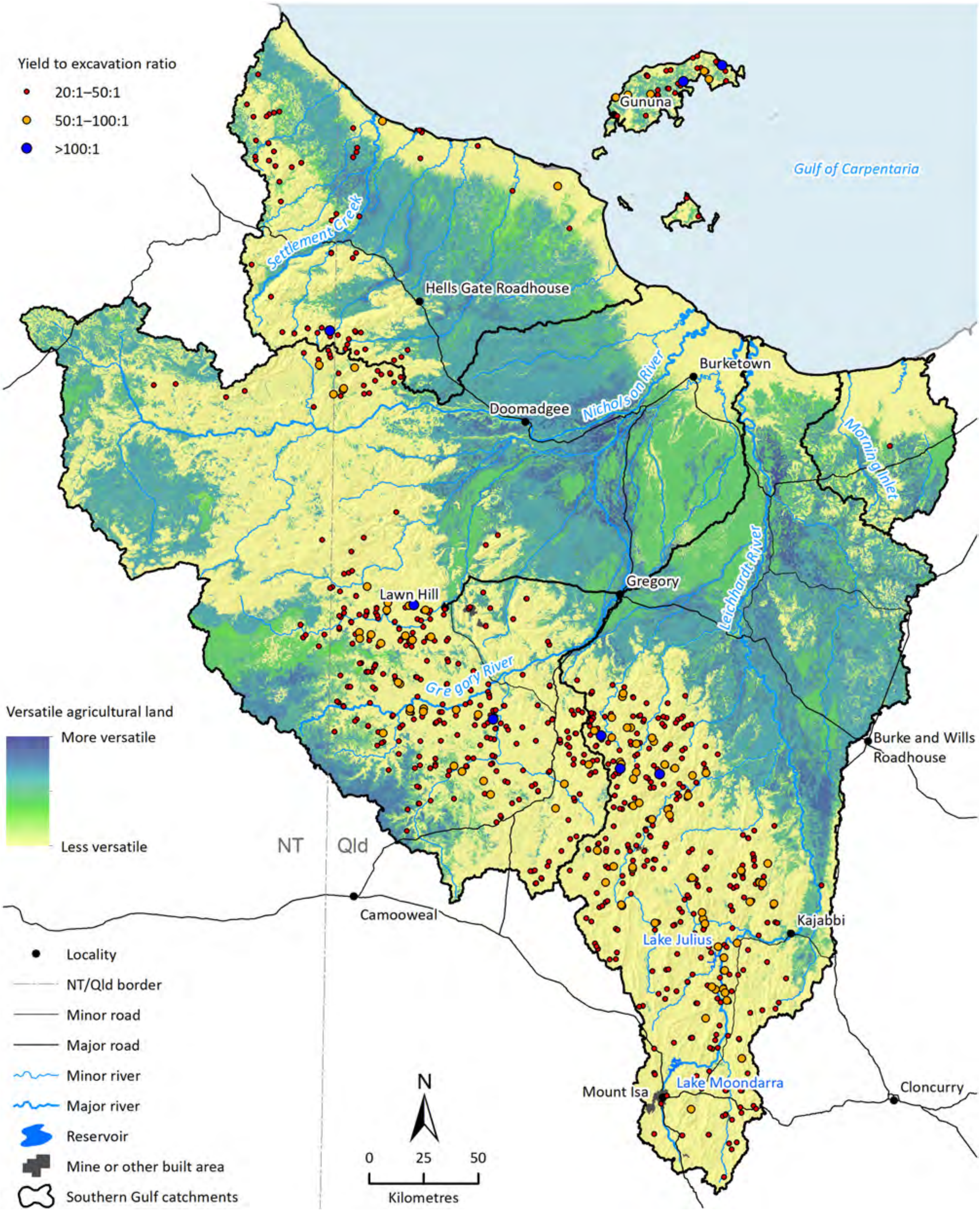

Figure 5-33 Most economically suitable locations for large farm-scale gully dams in the Southern Gulf catchments

Agricultural versatility data (see Section 4.3) indicate those parts of the catchment that are more or less versatile for irrigated agriculture. For the gully dam analysis, soil and subsurface data were only available to a depth of 1.5 m, hence this Assessment does not consider the suitability of subsurface material below this depth. Sites with catchment areas greater than 40 km^2 or yield to excavation ratio less than 10 are not displayed. The results presented in this figure are modelled and consequently only indicative of the general locations where siting a gully dam may be most economically suitable. This analysis may be subject to errors in the underlying digital elevation model, such as effects due to the vegetation removal process. An important factor not considered in this analysis was the availability of a natural spillway.

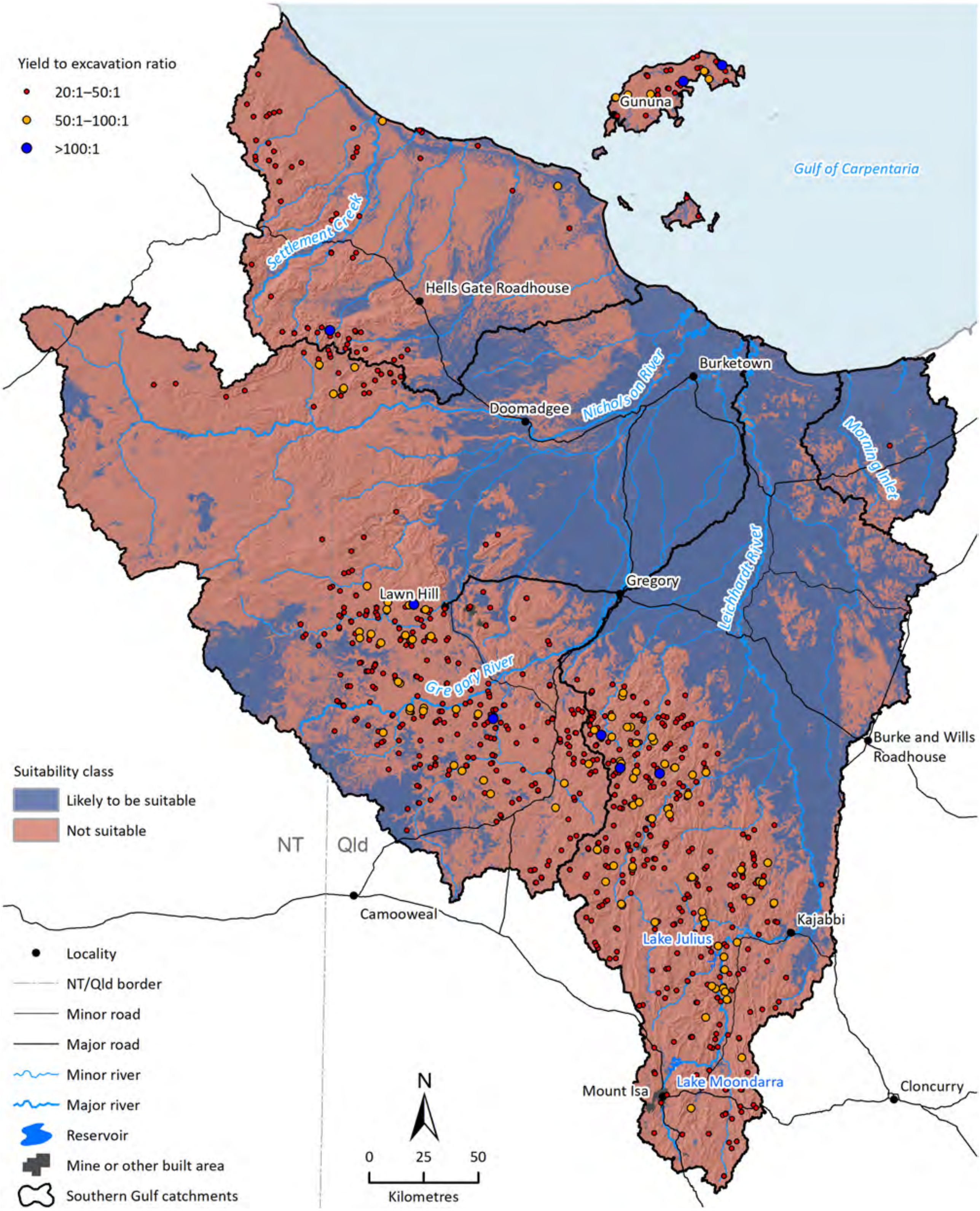

Figure 5-34 Suitability of soils for construction of gully dams in the Southern Gulf catchments

Capital, operation and maintenance costs of large farm-scale gully dams

The cost of a large farm-scale gully dam will vary depending upon a range of factors, including the suitability of the topography of the site, the size of the catchment area, quantity of runoff, proximity of site to good-quality clay, availability of durable rock in the upper bank for a spillway and the size of the embankment. The height of the embankment, in particular, has a strong influence on cost. An earth dam to a height of 8 m is about 3.3 times more expensive to construct than a 4 m high dam, and a dam to a height of 16 m will require 3.6 times more material than the 8 m high dam, but the cost may be more than five times greater, due to design and construction complexity.

As an example of the variability in unit costs of gully dams, actual costs for four large farm-scale gully dams in northern Queensland are presented in Table 5-12.

Table 5-12 Actual costs of four gully dams in northern Queensland

Sourced from Northern Australia Water Resource Assessment technical report on farm-scale design and costs, (Benjamin, 2018). Costs indexed to 2023.

DAM NAME	LOCATION	CAPACITY (ML)	YIELD (ML/y)	COST ($)	UNIT COST ($/ML)	COMMENT
Sharp Rock Dam	Lakelands	3300	1070	400,700	374	Chimney filter and drainage under-blanket. Two-stage concrete sill spillway. No fishway. Pump station not included
Dump Gully Dam	Lakelands	1450	420	975,600	2323	Deep and wet cut-off. Chimney filter and downstream under drainage. No fishway. Pump station was $91,000
Spring Dam #2	Lakelands	2540	1377	1,111,600	807	Chimney filter and drainage under-blanket. Two-stage rock excavation. Spillway with fishway. Fishway was $36,500. Pump station not included
Ronny's Dam	George-town	9975	1700	555,900	327	Very favourable site. Low embankment and 450 ha ponded area. Natural spillway. No pump station, gravity supply by pipe

Performance and cost of three hypothetical farm-scale gully dams in northern Australia

A summary of the key parameters for three hypothetical 4 GL (i.e. 4000 ML) capacity farm-scale gully dam configurations is provided in Table 5-13 and a high-level breakdown of the major components of the capital costs for each of the three configurations is provided in Table 5-14. Detailed costs for the three hypothetical sites are provided in the Northern Australia Water Resource Assessment technical report on large farm-scale dams (Benjamin, 2018).

Table 5-15 presents calculations of the effective volume for three configurations of 4 GL capacity gully dams (varying mean water depth/embankment height) for combinations of three seepage losses and water storage capacities over three time periods in the Southern Gulf catchments.

Based on the information presented in Table 5-13, an equivalent annual unit cost including annual O&M cost for a 4 GL gully dam with a mean depth of about 6 m is about $220,000 (Table 5-16 and Table 5-17).

Where the topography is suitable for large farm-scale gully dams and a natural spillway is present, large farm-scale gully dams are typically cheaper to construct than ringtanks.

Table 5-13 Cost of three hypothetical large farm-scale gully dams of capacity 4 GL

Costs include government permits and fees, investigation and design and fish passage. For a complete list of costs and assumptions see the Northern Australia Water Resource Assessment technical report on farm-scale dams (Benjamin, 2018). Costs indexed to 2023. O&M = operation and maintenance; S:E ratio = storage capacity to excavation ratio.

SITE DESCRIPTION/ CONFIGURATION	CATCHMENT AREA (km^2)	EMBANK-MENT HEIGHT (m)	EMBANK-MENT LENGTH (m)	S:E RATIO	MEAN DEPTH (m)	RESERVOIR SURFACE AREA (ha)	TOTAL CAPITAL COST ($)	O&M COST ($)
Favourable site with large catchment, suitable topography and simple spillway (e.g. natural saddle)	30	9.5	1100	29:1	5.0	80	1,600,000	70,000
Less favourable site with small catchment, challenging topography and limited spillway options (e.g. steep gully banks, no natural saddle)	15	14	750	21:1	6.3	63	1,844,000	44,000
Less favourable site with moderate catchment, challenging topography and limited spillway options (e.g. steep gully banks, no natural saddle)	20	14	750	21:1	6.3	63	1,937,000	50,000

Table 5-14 High-level breakdown of capital costs for three hypothetical large farm-scale gully dams of capacity 4 GL

Earthworks include vegetation clearing, mobilisation/demobilisation of equipment and contractor accommodation. Investigation and design fees include design and investigation of fish passage device and failure impact assessment (i.e. investigation of possible existence of population at risk downstream of site). Costs indexed to 2023.

SITE DESCRIPTION/CONFIGURATION	EARTHWORKS COST ($)	GOVERNMENT PERMITS AND FEES ($)	INVESTIGATION AND DESIGN FEES ($)	TOTAL CAPITAL COST ($)
Favourable site with large catchment, suitable topography and simple spillway (e.g. natural saddle)	1,447,000	46,000	107,000	1,600,000
Less favourable site with small catchment, challenging topography and limited spillway options (e.g. steep gully banks, no natural saddle)	1,677,000	50,000	117,000	1,844,000
Less favourable site with moderate catchment, challenging topography and limited spillway options (e.g. steep gully banks, no natural saddle)	1,770,000	50,000	117,000	1,937,000

Table 5-15 Effective volumes and cost per megalitre for a 4 GL storage with different mean depths and seepage loss rates based on a climate station at the Century Zinc Mine in the Southern Gulf catchments

Time periods of 4, 6 and 9 months refer to length of time water is stored or required for irrigation.

MEAN DEPTH AND MAXIMUM RESERVOIR SURFACE AREA	CON-STRUCTION COST ($)	COST ($/ML)	SEEPAGE LOSS (mm/d)	EFFECTIVE VOLUME (ML)	EFFECTIVE VOLUME AS PERCENT-AGE OF CAPACITY (%)	EFFECTIVE VOLUME (ML)	EFFECTIVE VOLUME AS PERCENT-AGE OF CAPACITY (%)	EFFECTIVE VOLUME (ML)	EFFECTIVE VOLUME AS PERCENT-AGE OF CAPACITY (%)
				5 months (April to August)		**7 months (April to October)**		**10 months (April to January)**	
3 m and 133 ha	1,250,000	250	1	3049	76	2582	65	1918	48
	1,250,000	250	2	2908	73	2384	60	1634	41
	1,250,000	250	5	2484	62	1790	45	783	20
6 m and 66 ha	1,900,000	375	1	3525	88	3291	82	2958	74
	1,900,000	375	2	3455	86	3193	80	2818	70
	1,900,000	375	5	3245	81	2899	72	2397	60
9 m and 44 ha	2,500,000	500	1	3678	92	3519	88	3293	82
	2,500,000	500	2	3631	91	3453	86	3199	80
	2,500,000	500	5	3489	87	3255	81	2915	73

Table 5-16 Cost of construction and operation of three hypothetical 4 GL gully dams

Assumes operation and maintenance (O&M) cost of 3% of capital cost and a 7% discount rate. Figures have been rounded.

MEAN DEPTH AND MAXIMUM RESERVOIR SURFACE AREA	ITEM	CAPITAL COST ($)	ANNUALISED CAPITAL COST ($)	ANNUAL O&M COST ($)	EQUIVALENT ANNUAL COST ($/y)
3 m and 133 ha	Low embankment, wide gully dam	1,250,000	107,000	37,500	144,800
6 m and 66 ha	Moderate embankment, gully dam	1,900,000	163,000	57,000	220,000
9 m and 44 ha	High embankment, narrow gully dam	2,500,000	214500	75,000	290,000

Table 5-17 Equivalent annualised cost and effective volume for three hypothetical 4 GL gully dams with various mean depths and seepage loss rates based on climate data at Victoria River Downs Station in the Victoria catchment

Dam details are in Table 5-16. Annual cost assumes a 7% discount rate. Time periods of 4, 6 and 9 months refer to length of time water is stored or required for irrigation.

MEAN DEPTH AND MAXIMUM RESERVOIR SURFACE AREA	EQUIVALENT ANNUAL COST ($/y)	SEEPAGE LOSS (mm/d)	UNIT COST ($/ML)	LEVELISED COST ($/ML)	UNIT COST ($/ML)	LEVELISED COST ($/ML)	UNIT COST ($/ML)	LEVELISED COST ($/ML)
			5 months (April to August)		**7 months (April to October)**		**10 months (April to January)**	
3 m and 133 ha	144,800	1	410	47	484	56	652	75
	144,800	2	430	50	524	61	765	89
	144,800	5	503	58	698	81	1596	185
6 m and 66 ha	220,000	1	539	62	577	67	642	74
	220,000	2	550	64	595	69	674	78
	220,000	5	585	68	655	76	793	92
9 m and 44 ha	290,000	1	680	79	710	82	759	88
	290,000	2	689	80	724	84	782	91
	290,000	5	716	83	768	89	858	99

5.4.6 Natural water bodies

Wetland systems and waterholes that persist throughout the dry season are natural water bodies characteristic of large parts of the northerly draining catchments of northern Australia. Many property homesteads in northern Australia use natural waterholes for stock and domestic purposes. However, the quantities of water required for stock and domestic supply are orders of magnitude less than those required for irrigated cropping, and it is partly for this reason that naturally occurring persistent water bodies in northern Australia are not used to source water for irrigation.

For example, a moderately sized (5 ha) rectangular water body of mean depth 3.5 m may contain about 175 ML of water. Based on the data presented in Table 5-8 and assuming minimal leakage (i.e. 1 mm/day), approximately 72%, 58% and 39% of the volume would be available if a crop were to be irrigated until August, October and January, respectively. Assuming a crop or fodder with a 6-month growing season requires 5 ML/ha of water before losses, and assuming an overall efficiency of 80% (i.e. the waterhole is adjacent to land suitable for irrigation, 95% conveyance efficiency and 85% field application efficiency), a 175 ML waterhole could potentially be used to irrigate about 20 ha of land for half a year if all the water was able to be used for this purpose. A large natural water body of 20 ha and mean depth of 3.5 m could potentially be used to irrigate about 80 ha of land if all the water was able to be used for this purpose.

Although the areas of land that could be watered using natural water bodies are likely to be small, the costs associated with storing water are minimal. Consequently, where these waterholes occur at sufficient size and adjacent to land suitable for irrigated agriculture, they can be a very cost-effective source of water. It would appear that where natural water bodies of sufficient size and suitable land for irrigation coincide, natural water bodies may be effective in staging a development (Section 6.3), where several hectares could potentially be developed, enabling lessons learned and mistakes made on a small-scale area before more significant capital investments are undertaken (noting that staging and learning are best to occur over multiple scales).

In a few instances it may be possible to enhance the storage potential of natural features in the landscape such as horseshoe lagoons or cut-off meanders adjacent to a river.

The main limitation to the use of wetlands and persistent waterholes for the consumptive use of water is that they have considerable ecological significance (e.g. Kingsford, 2000; Waltham et al., 2013), and in many cases there is a limited quantity of water contained within the water bodies. In particular, water bodies that persist throughout the dry season are considered key ecological refugia (Waltham et al., 2013).

For a water body situated in a sandy river, a waterhole is likely to be connected to water within the bedsands of the river. Hence, during and following pumping water within the bedsands of a river, the bedsands may in part replenish the waterhole and vice versa. While water within the bedsands of the river may in part replenish a depleted waterhole, in these circumstances it also means that pumping from a waterhole will have a wider environmental impact than just on the waterhole from which water is being pumped.

5.5 Water distribution systems – conveyance of water from storage to crop

5.5.1 Introduction

In all irrigation systems, water needs to be conveyed from the water source through artificial and/or natural water distribution systems before ultimately being used on-field for irrigation. This section discusses water losses during conveyance and application of water to a crop, and the associated costs.

5.5.2 Conveyance and application efficiencies

Some water diverted for irrigation is lost during conveyance to the field before it can be used by a crop. These losses need to be taken into account when planning irrigation systems and developing likely irrigated areas. The amount of water lost during conveyance depends on the:

- river conveyance efficiency, from the water storage to the re-regulating structure or point of extraction
- channel distribution efficiency, from the river offtake to the farm gate
- on-farm distribution efficiency, in storing (using balancing storages) and conveying water from the farm gate to the field
- field application efficiency, in delivering water from the edge of the field and applying it to the crop.

The overall or system efficiency is the product of these four components.

Little research on irrigation systems has been undertaken in the Southern Gulf catchments. The time frame of the Assessment did not permit on-ground research into irrigation systems. Consequently, a brief discussion on the components listed above is provided based on relevant literature from elsewhere in Australia and overseas. Table 5-18 summarises the broad range of efficiencies associated with these components.

The total conveyance and application efficiency of the delivery of water from the water storage to the crop (i.e. the overall or system efficiency) depends on the product of the four components in Table 5-18. For example, if an irrigation development has a river conveyance efficiency of 80%, a channel distribution efficiency of 90%, an on-farm distribution efficiency of 90% and a field application efficiency of 85%, the overall efficiency is 55% (80% × 90% × 90% × 85%). This means only 55% of all water released from the dam can be used by the crop.

Table 5-18 Summary of conveyance and application efficiencies

COMPONENT	TYPICAL EFFICIENCY (%)
River conveyance efficiency	50–90†
Channel distribution efficiency	50–95
On-farm distribution efficiency	80–95
Field application efficiency	60–90

†River conveyance efficiency varies with a range of factors (including distance) and may be lower than the range quoted here. Under such circumstances, it is unlikely that irrigation would proceed. It is also possible for efficiency to be 100% in gaining rivers. Achieving higher efficiencies requires a re-regulating structure (Section 5.4.3).

River conveyance efficiency

The conveyance efficiency of rivers is difficult to measure and even more difficult to predict. Although there are many methods for estimating groundwater discharge to surface water, there are few suitable methods for estimating the loss of surface water to groundwater. In the absence of existing studies for northern Australia, conveyance efficiencies as nominated in water resource plans and resource operation plans for four irrigation water supply schemes in Queensland were examined collectively. The results are summarised in Table 5-19.

The conveyance efficiencies in Table 5-19 are from the water storage to the farm gate and are nominated efficiencies based on experience delivering water in these supply schemes. These data can be used to estimate conveyance efficiency of similar rivers elsewhere.

Table 5-19 Water distribution and operational efficiency as nominated in water resource plans for four irrigation water supply schemes in Queensland

WATER SUPPLY SCHEME IN QUEENSLAND	TOTAL ALLOCATION VOLUME (ML)	RIVER AND CHANNEL CONVEYANCE EFFICIENCY† (%)	COMMENT
Burdekin Haughton	928,579	78	The primary storage is the Burdekin Falls Dam (1860 GL), approximately 100 km upstream of Clare Weir, the major extraction point. The Bowen River, a major unregulated tributary of the Burdekin River, joins the Burdekin River downstream of Burdekin Falls Dam. This may assist in reducing transmission losses between the dam and Clare Weir.
Lower Mary	34,462	94‡	The Lower Mary Irrigation Area is supplied from two storages: a barrage on the Mary River and a barrage on Tinana Creek. Water is drawn directly from the barrage storages to irrigate land riparian to the streams. Water distribution is predominantly through pipelines.
Proserpine River	87,040	72	The scheme has a single source of supply: Peter Faust Dam (491 GL). At various distances downstream of the dam, water is extracted from the river bedsands and is distributed to urban communities, several irrigation water supply boards and individual irrigators.
Upper Burnett	26,870	68	The Upper Burnett is a long run of river scheme with one major storage (Wuruma Dam, 165 GL) and four weir storages. The total river length supplied by the scheme is 165 km.

†Ignores differences in efficiency between high- and medium-priority users and variations across the scheme zone areas.
‡Channel conveyance efficiency only.

Channel distribution efficiency

Across Australia, the mean water conveyance efficiency from the river to the farm gate has been estimated to be 71% (Marsden Jacob Associates, 2003). For heavier-textured soils and well-designed irrigation distribution systems, conveyance efficiencies are likely to be higher.

In the absence of larger scheme-scale irrigation systems in the Southern Gulf catchments, it is useful to look at the conveyance efficiency of existing irrigation developments to estimate the conveyance efficiency of irrigation developments in the study area. Australian conveyance efficiencies are generally higher than those found in similarly sized overseas irrigation schemes (Bos and Nugteren, 1990; Cotton Catchment Communities CRC, 2011).

The most extensive review of conveyance efficiency in Australia was undertaken by the Australian National Commission on Irrigation and Drainage, which tabulated system efficiencies across irrigation developments in Australia (ANCID, 2001). Conveyance losses were reported as the difference between the volume of water supplied to irrigation customers and the water delivered to the irrigation system. For example, if 10,000 ML of water was diverted to an irrigation district and 8,000 ML was delivered to irrigators, then the conveyance efficiency was 80% and the conveyance losses were 20%.

Figure 5-35 shows reported conveyance losses across irrigation areas of Australia between 1999 and 2000, along with the supply method used for conveying irrigation water and associated irrigation deliveries. There is a wide spread of conveyance losses both between years and across the various irrigation schemes. Factors identified by Marsden Jacob Associates (2003) that affect the variation include delivery infrastructure, soil types, distance that water is conveyed, type of agriculture, operating practices, infrastructure age, maintenance standards, operating systems, in-line storage, type of metering used, and third-party impacts such as recreational, amenity and environmental demands. Differences across irrigation seasons are due to variations in water availability, operational methods, climate and customer demands.

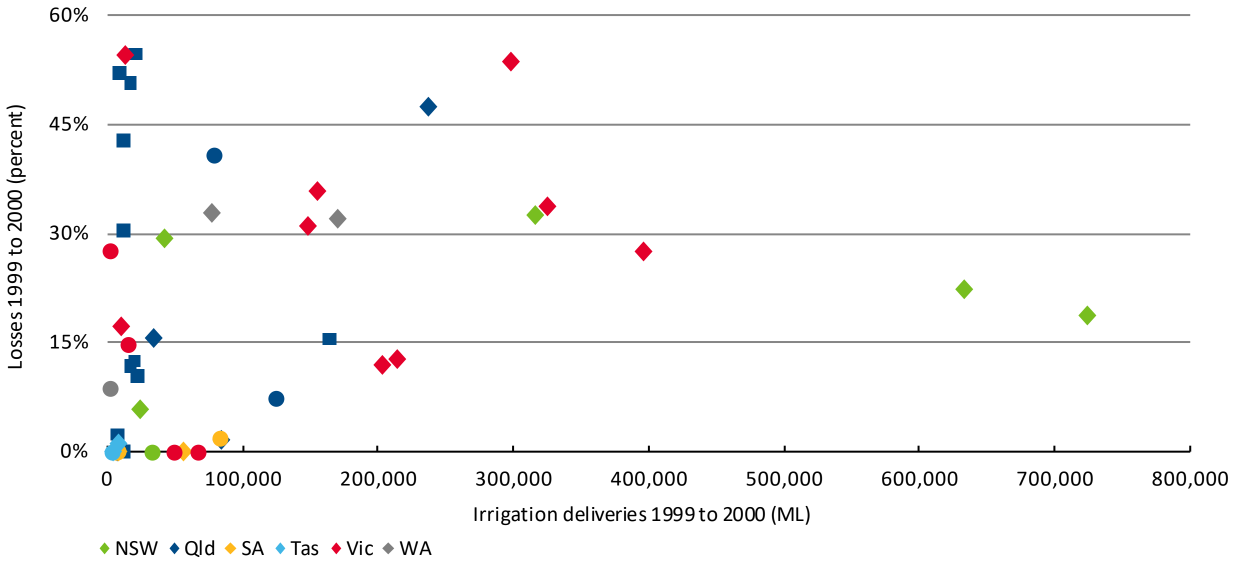

Figure 5-35 Reported conveyance losses from irrigation systems across Australia

The shape of the marker indicates the supply method for the irrigation scheme: square (▪) indicates natural carrier, circle (•) indicates pipe and diamond (♦) indicates channel. The colour of the marker indicates the location of the irrigation system (by state), as shown in the legend.

Source: ANCID (2001)

Based on these industry data, Marsden Jacob Associates (2003) concluded that, on average, 29% of water diverted into irrigation schemes is lost in conveyance to the farm gate. However, some of this 'perceived' conveyance loss may be due to meter underestimation (about 5% of water delivered to provider (Marsden Jacob Associates, 2003)). Other losses were from leakage, seepage, evaporation, outfalls, unrecorded usage and system filling.

On-farm distribution efficiency

On-farm losses are losses that occur between the farm gate and delivery to the field. These losses usually take the form of evaporation and seepage from on-farm storages and delivery systems. Even in irrigation developments where water is delivered to the farm gate via a channel, many farms have small on-farm storages (i.e. less than 250 ML for a 500 ha farm). These on-farm storages enable the farmer to have a reliable supply of irrigation water with a higher flow rate, and also enable recycling of tailwater. Several studies have been undertaken in Australia for on-farm distribution losses. Meyer (2005) estimated an on-farm distribution efficiency of 78% in the Murray and Murrumbidgee regions, while Pratt Water (2004) estimated on-farm efficiencies to be 94% and 88% in the Coleambally Irrigation and Murrumbidgee Irrigation areas, respectively. For nine farms in these two irrigation areas, however, Akbar et al. (2000) measured channel seepage to be less than 5%.

Field application efficiency

After water is delivered to a field, it needs to be applied to the crop using an irrigation system. The application efficiency of irrigation systems typically varies between 60% and 90%, with more expensive systems usually resulting in higher efficiency.

Three types of irrigation system can potentially be applied in the Southern Gulf catchments: surface irrigation, spray irrigation and micro irrigation (Figure 5-36). Irrigation systems applied in the Southern Gulf catchments need to be tailored to the soil, climate and crops that may be grown in the catchments and matched to the availability of water for irrigation. This is considered in the land suitability assessment figures presented in Section 4.2. System design will also need to consider investment risk in irrigation systems as well as likely returns, degree of automation, labour availability and O&M costs (e.g. the cost of energy).

Irrigation systems have a trade-off between efficiency and cost. Table 5-20 summarises the different types of irrigation system, including their application efficiency, indicative cost and limitations. Across Australia the ratio of areas irrigated using surface, spray and micro irrigation is 83:10:7, respectively. Irrigation systems that allow water to be applied with greater control, such as micro irrigation, cost more (Table 5-20) and as a result are typically used for irrigating higher-value crops such as perennial horticulture and vegetables. For example, although only 7% of Australia's irrigated area uses micro irrigation, it generates about 40% of the total value of produce grown using irrigation (Meyer, 2005). Further details on the three types of irrigation system follow Table 5-20.

(a) (b) (c)

Figure 5-36 Efficiency of different types of irrigation system

(a) For bankless channel surface irrigation systems, application efficiencies range from 60% to 85%. (b) For spray irrigation systems, application efficiencies range from 75% to 90%. (c) For pressurised micro irrigation systems on polymer-covered beds, application efficiencies range from 80% to 90%.

Photo: CSIRO

Table 5-20 Application efficiencies for surface, spray and micro irrigation systems

Application efficiency is the efficiency with which water can be delivered from the edge of the field to the crop. Costs indexed to 2023.

IRRIGATION SYSTEM	TYPE	APPLICATION EFFICIENCY (%)	CAPITAL COST ($/ha)†	LIMITATIONS
Surface	Basin	60–85	4,900	Suitable for most crops; topography and surface-levelling costs may be limiting factor
	Border	60–85	4,900	Suitable for most crops; topography and surface-levelling costs may be limiting factor
	Furrow	60–85	4,900	Suitable for most crops; topography and surface-levelling costs may be limiting factor
Spray	Centre pivot	75–90	3,600–7,850	Not suitable for tree crops; high energy requirements for operation
	Lateral move	75–90	3,600–7,150	Not suitable for tree crops; high energy requirements for operation
Micro	Drip	80–90	8,600–12,900	High energy requirement for operation; high level of skills needed for successful operation

Adapted from Hoffman et al. (2007), Raine and Bakker (1996) and Wood et al. (2007).
†Sources: DEEDI (2011a, 2011b, 2011c).

Surface irrigation systems

Surface irrigation encompasses basin, border strip and furrow irrigation, as well as variations such as bankless channel systems. In surface irrigation, water is applied directly to the soil surface, with check structures (banks or furrows) used to direct water across a field. Control of applied water is dictated by the soil properties, soil uniformity and the design characteristics of the surface system. Generally, fields are prepared by laser levelling to increase the uniformity of applied water and allow ease of management of water and adequate surface drainage from the field. The uniformity and efficiency of surface systems are highly dependent on the system design and soil properties, timing of the irrigation water and the skill of the individual irrigator in operating the system. Mismanagement can severely degrade system performance and lead to systems that operate at poor efficiencies.

Surface irrigation has the benefit that it can generally be adapted to almost any crop and usually has a lower capital cost compared with alternative systems. Surface irrigation systems perform better when soils are of uniform texture as infiltration characteristics of the soil play an important part in the efficiency of these systems. Therefore, surface irrigation systems should be designed into homogenous soil management units and layouts (run lengths, basin sizes) tailored to match soil characteristics and water supply volumes.

High application efficiencies are possible with surface irrigation systems, provided soil characteristic limitations, system layout, water flow volumes and high levels of management are applied. On ideal soil types and with systems capable of high flow rates, efficiencies can be greater than 85%. On poorly designed and managed systems on soil types with high variability, efficiencies can be less than 60%.

Generally, the major cost in setting up a surface irrigation system is land grading and levelling, with costs directly associated with the volume of soil that must be moved. Typical earth-moving volumes are in the order of 800 m^3/ha but can exceed 2500 m^3/ha. Volumes greater than 1500 m^3/ha are generally considered excessive due to costs (Hoffman et al., 2007).

Surface irrigation systems are the dominant form of irrigation type used throughout the world. Their potential suitability in the Southern Gulf catchments would be due to their generally lower set-up costs and adaptability to a wide range of irrigated cropping activities. They are particularly suited to the heavier-textured soils on the alluvial plains adjacent to the Gregory and Leichhardt rivers and major tributaries, which reduce set-up or establishment costs of these systems. With surface irrigation, little or no energy is required to distribute water throughout the field, and this 'gravity-fed' approach reduces energy requirements of these systems.

Surface irrigation systems generally have lower applied irrigation water efficiency than spray or micro systems when compared across an industry and offer less control of applied water; however, well-designed and well-managed systems can approach efficiencies of alternative irrigation systems in ideal conditions.

Spray irrigation systems

In the context of the Southern Gulf catchments, spray irrigation refers specifically to lateral move and centre pivot irrigation systems. Centre pivot systems consist of a single sprinkler, laterally supported by a series of towers. The towers are self-propelled and rotate around a central pivot point, forming an irrigation circle. Time taken for the pivot to complete a full circle can range from as little as half a day to several days depending on crop water demands and application rate of the system.

Lateral or linear move systems are similar to centre pivot systems in construction, but rather than move around a pivot point the entire line moves down a field perpendicular to the lateral direction. Water is supplied by a lateral channel running the length of the field. Lateral lengths are generally in the range of 800 to 1000 m. Their advantage over surface irrigation systems is they can be utilised on rolling topography and generally require less land forming.

Both centre pivot and lateral move irrigation systems have been extensively used for irrigating a range of annual broadacre crops and are capable of irrigating most field crops. They are generally not suitable for tree crops or vine crops, or for saline irrigation water applications in arid environments, which can cause foliage damage. Centre pivot and lateral move systems usually have higher capital costs but are capable of very high efficiencies of water application. Generally, application efficiencies for these systems range from 75% to 90% (Table 5-20). They are used extensively for broadacre irrigated cropping situations in high evaporative environments in northern NSW and South West Queensland. These irrigation developments have high irrigation crop water demand requirements, which are similar to those found in the Southern Gulf catchments. A key factor in the suitable use of spray systems is sourcing the energy needed to operate these systems, which are usually powered by electricity or diesel depending on available costs and infrastructure. Where available, electricity is considerably cheaper than diesel for powering spray systems.

For pressurised systems such as spray or micro irrigation systems, water can be more easily controlled, and potential benefits of the system through fertigation (application of crop nutrients through the irrigation system (i.e. liquid fertiliser)) are also available to the irrigator.

Micro irrigation systems

For high-value crops, such as horticultural crops where yield and quality parameters dictate profitability, micro irrigation systems should be considered suitable across the range of soil types and climate conditions in the Southern Gulf catchments.

Micro irrigation systems use thin-walled polyethylene pipe to apply water to the root zone of plants through small emitters spaced along the drip tube. These systems are capable of precisely applying water to the plant root zone, thereby maintaining a high level of irrigation control and applied irrigation water efficiency. Historically, micro irrigation systems have been extensively used in tree, vine and row crops, with limited applications in complete-cover crops such as grains and pastures due to the expense of these systems. Micro irrigation is suitable for most soil types and can be practised on steep slopes. Micro irrigation systems are generally of two varieties: above-ground and below-ground (where the drip tape is buried beneath the soil surface). Below-ground micro irrigation systems offer advantages in reducing evaporative losses and improving trafficability. However, below-ground systems are more expensive and require higher levels of expertise to manage.

Properly designed and operated micro irrigation systems are capable of very high application efficiencies, with field efficiencies of 80% to 90% (Table 5-20). In some situations, micro irrigation systems offer water and labour savings and improved crop quality (i.e. more marketable fruit through better water control). Management of micro irrigation systems, however, is critical. To achieve these benefits requires a much greater level of expertise than for other traditional systems such as surface irrigation systems, which generally have higher margins of error associated with irrigation decisions. Micro irrigation systems also have high energy requirements, with most systems operating at pressure ranges from 135 to 400 kPa, with diesel or electric pumps most often used.

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