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Water resource assessment for the Victoria catchment

A report from the CSIRO Victoria River Water Resource Assessment for the National Water Grid

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CSIRO Victoria River Water Resource Assessment acknowledgements

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The Assessment was guided by two committees:

i. The Assessment's 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 Assessment's joint Roper and Victoria River catchments Steering Committee: Amateur Fishermen's Association of the NT; Austrade; Centrefarm; CSIRO; National Water Grid (Department of Climate Change, Energy, the Environment and Water); Northern Land Council; NT Cattlemen's Association; NT Department of Environment, Parks and Water Security; NT Department of Industry, Tourism and Trade; NT Farmers; NT Seafood Council; Office of Northern Australia; Parks Australia; Regional Development Australia; Roper Gulf Regional Council Shire; Watertrust

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 Dr Brian Keating (Independent consultant). Individual chapters were reviewed by Dr Rebecca Doble, CSIRO (Chapter 2); Dr Chris Pavey, CSIRO (Chapter 3); Dr Heather Pasley, CSIRO (Chapter 4); Mr Chris Turnadge, CSIRO (Chapter 5); Dr Nikki Dumbrell, CSIRO (Chapter 6); Dr Adam Liedloff, 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 xxv.

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

The Victoria River is the longest singularly named river in the NT with permanent water. Photo: CSIRO – Nathan Dyer

5 Opportunities for water resource development in the Victoria catchment

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Chapter 5 examines the opportunities, risks and costs for water resource development in the catchment of the Victoria River. 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.

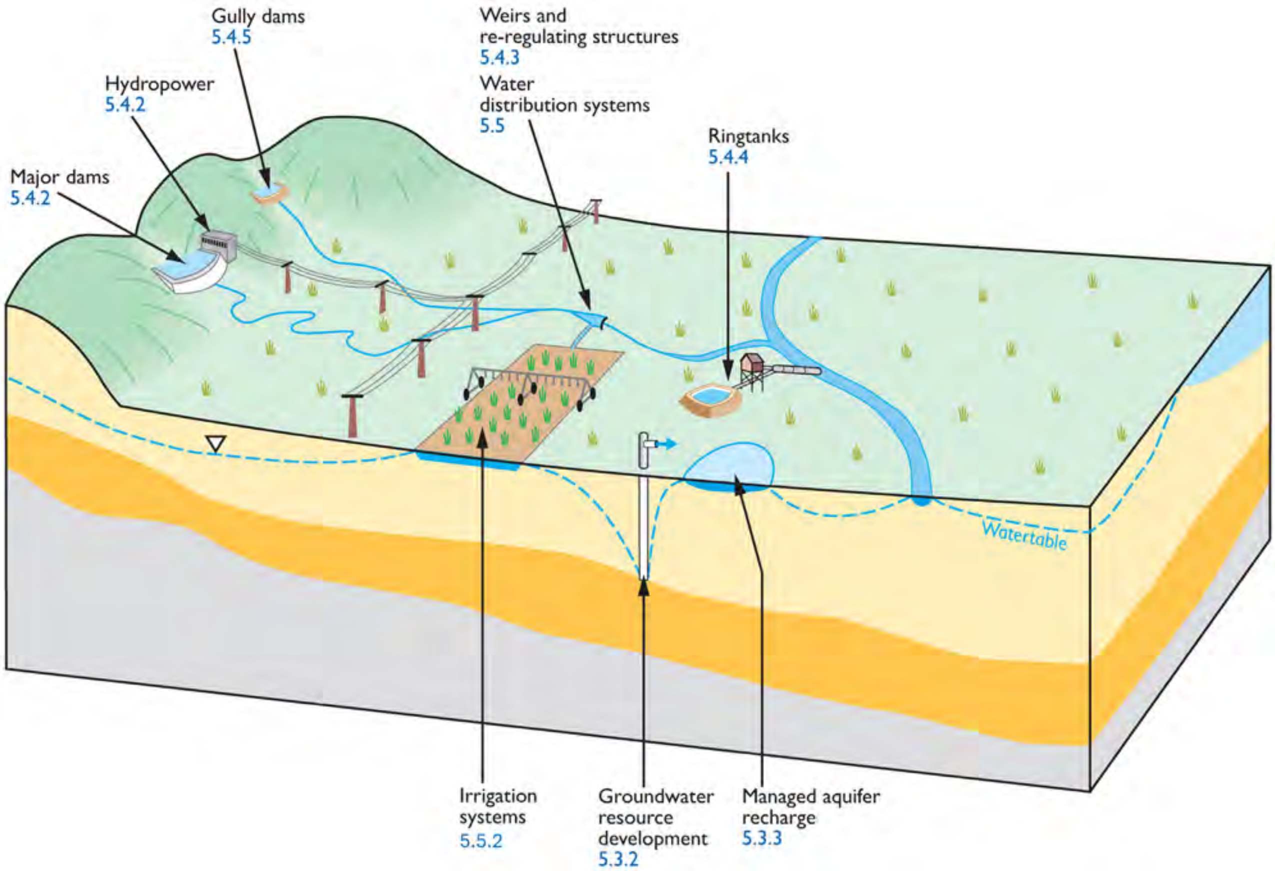

Figure 5-1 Schematic of key engineering and agricultural components to be considered in the establishment of a water resource and greenfield irrigation development

Numbers in blue refer to sections in this report.

5.1 Summary

This chapter provides information on a variety of potential options to supply water, primarily for irrigated agriculture. The methods used to generate these results included a mixture of field surveys and desktop analysis. The potential water yields reported in this chapter are based largely on physically plausible volumes. They do not consider economic, social, environmental, legislative or regulatory factors, which will inevitably constrain many developments. In some instances, the water yields are combined with land suitability information from Chapter 4 so as to provide estimates of areas of land that could potentially be irrigated close to the water source or storage.

5.1.1 Key findings

Water can be sourced and stored for irrigation in the Victoria catchment in a variety of ways. If the water resources of the Victoria catchment are further developed for consumptive purposes, it is likely that a number of the options below may have a role to play in maximising the cost-effectiveness of water supply in different parts of the catchment.

Groundwater extraction

Groundwater is already widely used in parts of the Victoria catchment for a variety of purposes (community water supplies, and stock and domestic uses) and offers some year-round niche opportunities that are geographically distinct from surface water development opportunities. The two most productive groundwater systems in the Victoria catchment are the regional-scale Cambrian Limestone Aquifer (CLA) in the east of the catchment and the local- to intermediate-scale Proterozoic dolostone aquifers (PDAs) in the centre and south of the catchment. There are currently no licensed groundwater entitlements from the CLA in the Victoria catchment. However, three licensed entitlements totalling 7.4 GL/year from the CLA are available for use in agriculture about 150 km to the north-east of the Victoria catchment, in the proposed Flora Tindall Water Allocation Plan area. However, actual groundwater use is less. There is currently very little development of groundwater from the PDAs other than stock and domestic bores, and the community water supply at Timber Creek, and no water allocation plan exists.

With appropriately sited borefields, up to 10 GL/year could potentially be extracted from the CLA to the south of Top Springs (i.e. groundwater extraction occurring between 20 and 80 km to the south toward Cattle Creek). Due to the time lags associated with groundwater flow, the additional hypothetical extraction will result in between an 11% and 14% reduction in modelled groundwater discharge to spring complexes and groundwater-fed vegetation near Top Springs. The modelled reduction in groundwater levels ranges from about 15 m at the centre of the hypothetical developments to 0.5 m up to 20 km away by about 2060.

Under a projected dry future climate (10% reduction in rainfall) and no future hypothetical groundwater development (Scenario Cdry), groundwater recharge to the CLA near Top Springs was projected to reduce by 32%. The equivalent reduction in modelled discharge to the spring complexes nearby was estimated to be 33%. The modelled changes in the water balance from a projected drier future climate are larger than for the modelled future hypothetical groundwater development. This highlights the sensitivity of groundwater storage in and discharge from the CLA near Top Springs to natural variations in climate.

Based on conservative annual recharge fluxes to the PDAs there may be potential to extract up to about 20 GL/year from the outcropping and subcropping parts of the aquifers in the centre and south of the catchment. However, these aquifers, while prospective, are data sparse, and understanding how water balance of these aquifers may change under future hypothetical groundwater development or projected future climates would require more detailed hydrogeological investigations. The actual scale of potential future groundwater development will depend upon community and government acceptance of potential impacts to groundwater-dependent ecosystems (GDEs) and existing groundwater users.

Opportunities for potential future groundwater development from aquifers hosted in other hydrogeological units (Cambrian basalt, Devonian–Carboniferous sandstone and Proterozoic sandstone) are most likely to be limited to use for stock and domestic purposes, and occasional community water supply. The Quaternary alluvium may offer some potential opportunities, but this requires further investigation.

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. This has particular significance to the Victoria catchment.

Based on topography and hydrology, there is considerable physical potential for large instream dams in the Victoria catchment. However, their utility is low due to the absence of large areas of contiguous soils suitable for irrigated agriculture downstream and the lack of electrical transmission infrastructure that could transmit hydro-electric power to potential markets. In the Victoria catchment, potential dams upstream of the larger contiguous areas of soil suitable for irrigated agriculture, and in areas of favourable topography for reticulation infrastructure, yield modest quantities of water due to the limited size of their headwater catchments. A potential large instream dam, located on Leichhardt Creek 85 km from the Victoria Highway, could yield 64 GL in 85% of years and cost $396 million (−20% to +50%) to construct, assuming favourable geological conditions. This equates to a unit capital cost of $6188/ML, making it one of the more cost-effective potential large instream dams in the Victoria catchment. A nominal 4000 ha reticulation scheme associated with the potential dam was estimated to cost an additional $12.67 million or $3168/ha (excluding farm development and infrastructure). The potential for large instream dams to mitigate flooding to very remote communities in the Victoria catchment is limited, and it would be more cost-effective to raise or relocate existing 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 of capturing and storing water from the Victoria River and its major tributaries. Approximately 8% of the catchment (540,000 ha) was modelled as being likely to be suitable or possibly suitable for ringtanks. However, unlike many large catchments in northern Australia, contiguous areas of soil suitable for irrigation within 5 km of the river are more limiting than surface water along the Victoria River and its major tributaries, except the West Baines River, for which irrigation is water limited. Along the West Baines River, the soils are most suitable for irrigated agriculture upstream of the Victoria Highway. Upstream of the highway it is physically possible to extract 100 GL in 75% of years by pumping or diverting water from the river to offstream storages such as ringtanks for irrigating dry-season crops. Downstream of the highway the soils become increasingly less versatile due to wetness and flooding. This would make irrigation establishment and operation costs higher due to the need for drainage and ensuring infrastructure has sufficient flood immunity. These problems would ultimately make potential water-harvesting enterprises less viable. Nonetheless, it would be possible to physically extract an additional 300 GL in 75% of years downstream of the highway for irrigation of broadacre crops during the dry season.

Along the Victoria River and its other major tributaries apart from the West Baines, water harvesting is limited due to narrow floodplains, sandy levee soils and increasing elevation with distance from the river resulting in higher reticulation infrastructure costs (e.g. pumps and pipelines). Nonetheless, across the entire Victoria catchment it is physically possible to extract 690 GL per year in 75% of years. This volume could irrigate approximately 50,000 ha (0.6% of catchment area) of broadacre crops such as cotton on the clay alluvial soil during the dry season. In this situation, water from the Victoria River and its major tributaries would be pumped or diverted and stored in offstream storages such as ringtanks. This scenario results in a modelled reduction in the mean and median annual discharges from the Victoria catchment of about 9% and 12%, respectively.

Managed aquifer recharge

The Assessment indicates there are few opportunities for managed aquifer recharge (MAR) in the Victoria catchment. The basic requirements for a MAR scheme are the presence of a suitable aquifer with sufficient storage capacity, soils with moderate to high permeability, landscapes with low to moderate slope (i.e. 10% or less) and a source of water. In the majority of those parts of the catchment where the soils, slope and hydrogeology are potentially suitable for MAR (i.e. where the CLA occurs along the eastern margin of the catchment), the rivers and streams are highly intermittent, so there is no reliable source of water for MAR. Furthermore, the soils are unsuitable for the construction of offstream storages. Approximately 64,500 ha (0.8%) of the Victoria catchment was identified as having potential for aquifers, groundwater and landscape characteristics suitable for infiltration MAR techniques within 5 km of a river with a median annual flow of greater than 20 GL and from which water could potentially be sourced for recharge (though in the headwaters of these rivers the reliability of flow would need to be locally assessed). Within 1 km, the equivalent area was around 24,000 ha (0.3%) of the catchment. However, 60% of the area within 1 km of the river was Quaternary alluvium aquifers for which there was no water-level data, little bore log data and consequently considerable uncertainty regarding their potential suitability for MAR. Jointly considering the location of areas potentially suitable for MAR and the location of soils potentially suitable for irrigated agriculture, opportunities for MAR-based irrigated agriculture in the Victoria catchment are highly limited.

Gully dams and weirs

Suitably sited, large farm-scale gully dams are a relatively cost-effective method of supplying water. The topography of the Victoria catchment is highly suitable for large farm-scale gully dams, and opportunities are scattered throughout the catchment. The major limitation is that the soil in many places is rocky and shallow, meaning that access is required to a nearby clay borrow pit for the cut-off trench and core zone. These sites will be less economically viable than sites with more suitable soil. Nonetheless, numerous favourable gully dam locations occur across the catchment near soils that are suitable for irrigated agriculture. Furthermore, the quantity of water that could potentially be supplied by gully dams is likely to be commensurate to the (limited) extent of contiguous soils suitable for irrigated agriculture scattered throughout the Victoria catchment.

The other sources of water and storage options, namely weirs and natural water bodies, can reliably supply considerably smaller volumes of water than major instream dams. Sourcing water from natural water bodies, although the most cost-effective option, is highly contentious, and irrigated agriculture would be limited to small-scale operations (e.g. tens of hectares), such as trialling irrigation prior to scaling up.

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

Table 5-1 summarises 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 affect existing uses, including ecological systems, to varying degrees depending on the level of development. This is examined in Section 7.2. All of the water source options reported in Table 5-1 are considerably cheaper than the cost of desalinisation. The initial cost of constructing four large desalinisation plants (capacity of 90 to 150 GL/year) in Australia between 2010 and 2012 ranged from $19,000 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 megalitre of supply, including operation and maintenance (O&M)

Costs and yields are indicative. Values are rounded. Capital costs are the cost of construction of the water storage/source infrastructure. They do not include the cost of constructing associated infrastructure for conveying water or irrigation development. Water supply options are not independent of one another, and the maximum yields and areas of irrigation cannot be added together. Equivalent annual cost assumes a 7% discount rate over the service life of the infrastructure. Total yields and areas are 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)	3.9	1.1	396	5–40	2.95	1.65	0.02
O&M cost ($ million/y)*	0.1	0.07	1.0	0.05–0.8	0.125	0.045	~0
Assumed service life (y)	50	50	100	50	40	30	15
Potential yield of individual representative unit at water source							
Yield at source (GL)††	2	0.6	64	0.1–10	2.4	3	0.125–0.5
Unit cost ($/ML)‡‡	1,950	1,830	6,190	6,500	1,040	570	100
Levelised cost ($/ML)§§	190	250	460	600	130	60	10
Potential yield of individual representative unit at paddock							

WATER SOURCE/ STORAGE	GROUND-WATER†	MANAGED AQUIFER RECHARGE‡	MAJOR DAM	WEIR§	LARGE FARM-SCALE RINGTANK	LARGE FARM-SCALE GULLY DAM	NATURAL WATER BODY
Assumed conveyance efficiency to paddock (%)†††	95	90	63	80	90	90	90
Yield at paddock (GL)	1.9	0.54	40	0.8–12	2.16	2.7	0.11–0.45
Unit cost ($/ML)‡‡	2050	2,040	9,820	8,125	1,160	630	110
Levelised cost ($/ML)	200	280	730	750	145	65	12
Total potential yield and area (unconstrained)							
Total potential yield (GL/y) at source ≥75% reliability‡‡‡	20	<10	600	<100	415	<50	<25
Potential area that could be irrigated at ≥75% reliability (ha)§§§	3,000	<1,500	50,000	<10,000	50,000	<5,000	<2,500

†Value assumes extraction from the Cambrian Limestone Aquifer with a mean bore yield of 25 L/s to meet mean peak evaporative demand over a 3-day period for 500 ha. Assumes a mean depth of 60 m and a drilling failure rate of 50%.
‡Based on recharge weir.
§Sheet piling weir.
*Annual cost of operating and maintaining infrastructure. It includes the cost of pumping groundwater, assuming groundwater is 10 to 20 m below ground level, and the cost of pumping water into ringtank.
††Yield at dam wall (considering 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.
§§Assumes 7% discount rate.
†††Conveyance efficiency between dam wall or 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 or groundwater bore.
§§§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 ways by which water can be sourced and stored, as this can have long-lasting benefits and facilitate an open and transparent debate.

More detailed information can be found in the companion technical reports. Sections 5.3 and 5.4 examine the nature and scale of groundwater and surface water storage opportunities, respectively, in the Victoria catchment. 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 is 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 the opportunity-level assessment is to provide a general indication of the likely scale of opportunity and geographic location of better options.
  – 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, particularly in local- and intermediate-scale groundwater systems.
- Equivalent annual cost is the annual cost of owning, operating and maintaining an asset over its entire life. Equivalent annual cost allows a comparison of the cost-effectiveness of various assets that have unequal service lives/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

The Assessment undertook a catchment-wide reconnaissance assessment and, at selected locations, a pre-feasibility assessment of:

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

Groundwater, where the aquifer is relatively shallow and of sufficient yield to support irrigation, is often one of the cheapest sources of water available, particularly where pumping costs are reduced because groundwater levels are close to the land surface. 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 storage capacity is available, are often at uneconomically viable distances (i.e. 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.

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

5.3.2 Opportunities for groundwater development

Introduction

Planning future groundwater resource developments and authorising licensed groundwater entitlements require value judgments about acceptability of impacts 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 government regulators and communities.

Scientific information to help inform these decisions includes: (i) identifying aquifers that may be potentially suitable for future groundwater resource development; (ii) characterising their depth, spatial extent, saturated thickness, hydraulic properties and water quality; (iii) conceptualising the nature of their flow systems; (iv) estimating aquifer water balances; and (v) providing initial estimates of potential extractable volumes and associated drawdown in groundwater level over time and distance relative to existing water users and GDEs. The changes in groundwater levels over time at different locations provide information on the potential risks of changes in aquifer storage and therefore water availability to existing groundwater users or the environment. Unless stated otherwise, the material presented in Section 5.3.2 has been summarised from the companion technical report on groundwater characterisation (Taylor 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 Victoria catchment

The hydrogeological units of the Victoria catchment (Figure 5-2) contain a variety of local-, intermediate- and regional-scale aquifers that host localised to regional-scale groundwater flow systems. The intermediate- to regional-scale limestone and dolostone aquifers are present in the subsurface across moderate areas, collectively occurring beneath about 24% of the catchment. Given their moderate spatial extent, they underlie and partially coincide with areas of soil suitable for irrigated agriculture (Section 4.2). They contain mostly fresh water (<1000 mg/L total dissolved solids, TDS) and have potential to yield water at a sufficient rate to support irrigation development (>10 L/s) with appropriately constructed and sited bores. These aquifers contain larger volumes of groundwater in storage (tens to hundreds of gigalitres) 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 moderate 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 Victoria catchment, 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 stock and domestic use or in some instances as a conjunctive water resource (i.e. combined use of groundwater with surface water or rainwater).

The Assessment identified six hydrogeological units hosting aquifers that may have potential for future groundwater resource development in the Victoria catchment (Table 5-2):

- Cambrian limestone
- Proterozoic dolostone
- Cambrian basalt
- Devonian–Carboniferous sandstone
- Proterozoic sandstone
- Quaternary alluvium.

Table 5-2 Opportunity-level estimates of the potential scale of groundwater resource development in the Victoria catchment

For locations of the hydrogeological units see Figure 5-2. Indicative scale of the resource is based on a combination of numerical modelling, estimates of mean annual recharge, and conceptualisation of the aquifers hosted in different hydrogeological units. The actual scale will depend upon government and community acceptance of potential impacts to groundwater-dependent ecosystems (GDEs) and existing groundwater users.

HYDROGEOLOGICAL UNIT	LOCATION	LEVEL OF KNOWLEDGE	INDICATIVE SCALE OF RESOURCE (GL/y)†	COMMENTS
Cambrian limestone	Eastern part of the catchment	Medium	≤10	The most promising regional-scale aquifer, the Cambrian Limestone Aquifer (CLA), along the eastern margin of the catchment. Aquifer is typically tens of metres thick, has potential to achieve high bore yields (>10 L/s) with appropriately constructed bores and hosts fresh water (<1000 mg/L total dissolved solids, TDS). This aquifer has potential to support a few small- to intermediate-scale (1–3 GL/y) developments. Greatest opportunities exist in the Wiso Water Management Zone of the Georgina Wiso Water Allocation Plan south-east of Top Springs, where the CLA has a saturated thickness of >20 m. Opportunities are limited to the north-east of Top Springs where the CLA has a thin saturated thickness of <20 m or is unsaturated, and/or where the nature and cumulative scale of development will potentially affect the reliability of access to water by existing groundwater users (Top Springs community) and the spring complexes around Top Springs (Illawarra, Lonely, Old Top and Palm springs)
Proterozoic dolostone	Central part of the catchment	Low	≤20	Promising intermediate-scale dolostone aquifers in the central part of the catchment. Aquifers are typically tens of metres thick, have potential to achieve high bore yields (>20 L/s) and host fresh water (<500 mg/L TDS). Have potential to support

HYDROGEOLOGICAL UNIT	LOCATION	LEVEL OF KNOWLEDGE	INDICATIVE SCALE OF RESOURCE (GL/y)†	COMMENTS
				multiple small- to intermediate-scale (1–3 GL/y) developments where they coincide with suitable soil. Greatest opportunities exist where the aquifers outcrop and are unconfined around Timber Creek and Yarralin. Opportunities are limited near community water supplies for Timber Creek and also in the vicinity of spring complexes at the edge of the aquifer outcrops (e.g. Crawford Spring, Bulls Head Spring, and Kidman Springs). Potential opportunities also exist in the far south of the catchment to the south-east of Limbunya. However, given the sparse data for the dolostone aquifers, these opportunities need to be confirmed with further hydrogeological investigations (e.g. drilling, pump testing, hydrological modelling)
Cambrian basalt	Eastern part of the catchment	Low	<5	Local-scale fractured and weathered rock aquifers composed mostly of basalt. Variable bore yields, often <2 L/s but can be as high as 40 L/s where either fracturing is prominent or fractured basalt co-occurs with chert and/or sandstone. Water quality is variable, ranging from fresh (<1000 mg/L) to brackish (~6000 mg/L). Only likely to offer potential for very small-scale (<0.25 GL/y) localised developments (i.e. mostly suited to stock and domestic water supplies) or as a conjunctive water resource in the outcropping/subcropping areas where they are fractured and weathered and/or co-occur with chert and/or sandstone. Even though bore yields can be high (>10 L/s) in places, aquifers are storage limited due to the amount and interconnectivity of fracturing
Devonian–Carboniferous sandstone	Far north of the catchment	Low	<5	Local-scale fractured and weathered sandstone aquifers in the far north of the catchment. Variable bore yields, often between 2 and 5 L/s, and variable water quality (fresh to brackish). Only likely to offer potential for very small-scale (<0.25 GL/y) localised developments (i.e. mostly suited to stock and domestic water supplies) or as a conjunctive water resource in the outcropping area where fracturing and weathering are high. Opportunities are limited in close vicinity to the coast where the freshwater–saltwater interface occurs
Proterozoic sandstone	North and west of the catchment	Low	<5	Local-scale sandstone aquifers in the north and west of the catchment. Variable bore yields, often <2 L/s but can be as high as 30 L/s. Variable water quality (fresh to brackish). Only likely to offer potential for small-scale (<0.5 GL/y) localised developments (i.e. mostly suited to stock and domestic water supplies) or as a conjunctive water resource where fracturing is prominent
Quaternary alluvium	Patches associated with major streams and their tributaries	Low	<5	Local-scale aquifers occurring in patches associated with the streambed, stream channel and floodplain of major streams and their tributaries. The largest occurrences of the alluvium are in the north of the catchment along the lower reaches of the Angalarri, Victoria and West Baines rivers. Variable bore yields, often <3 L/s but as high as 11 L/s. Variable water quality (fresh to brackish). Only likely to offer potential for small-scale (<1.0 GL/y) localised developments (i.e. mostly suited to stock and domestic water supplies) 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) mostly fine-textured sediments (clay lenses), (iii) regularly flooded and (iv) highly connected to perennial reaches of streams and development may limit water availability to GDEs

†Actual scale will depend upon government and community acceptance of impacts to GDEs and existing water users.

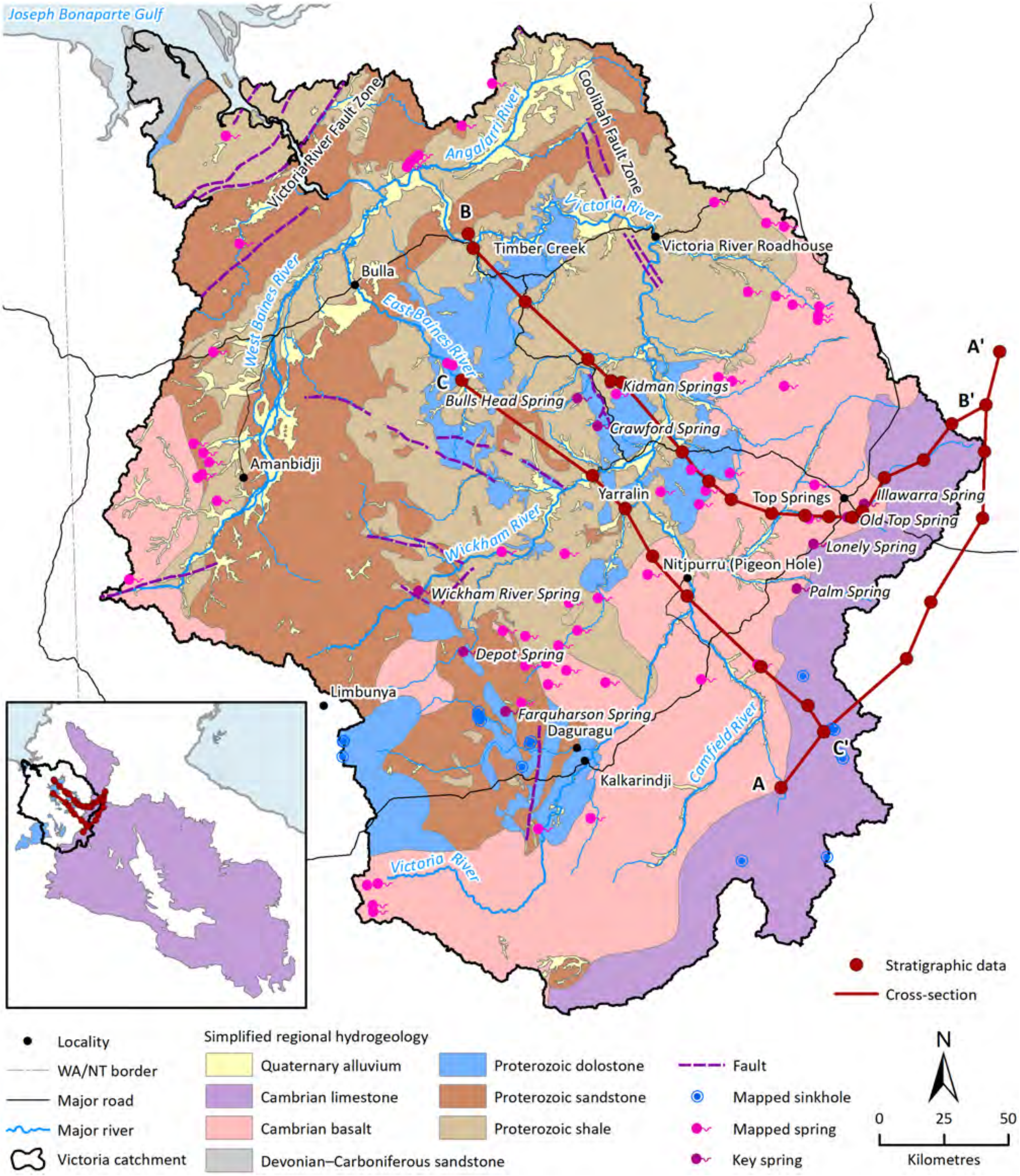

Figure 5-2 Key hydrogeological units of the Victoria catchment

The spatial extent of the outcropping and subcropping component of each hydrogeological unit is presented with the majority of overlying Cretaceous and Cenozoic cover removed (except the alluvium). Right inset shows the spatial extent of the Cambrian limestone and Proterozoic dolostone that extend outside the Victoria catchment.

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: (i) the depth to groundwater-bearing rock/and or sediments in the subsurface (hydrogeological unit), which influences the cost of drilling; and (ii) the depth to groundwater, which influences the cost of pumping. For example, in unconfined aquifers, the depth to groundwater can be greater than the depth to the top of the aquifer and will change over time due to groundwater recharge and/or groundwater pumping. Information on the spatial extent of changes in groundwater levels is also presented. This is relevant to the potential hydraulic impact of future groundwater development on receptors such as existing licensed groundwater 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 to grant an authorisation to extract groundwater. Key considerations for an individual proponent include:

- determining the locations to drill production bores
- testing the production bores
- 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 a mean bore yield of 25 L/s and that 16 production bores are required to meet peak evaporative demands of an area of 250 ha. Does not include operating and maintenance costs.

DRILLING, CONSTRUCTION, INSTALLATION AND TESTING OF BORES	ESTIMATED COST ($)
Production bores	2,044,500†
Monitoring bores	226,500‡
Submersible pumps	1,360,000§
Mobilisation/demobilisation	15,000§§
Aquifer testing	168,000*
Hydrogeological assessment	100,000††

†Value assumes 16 production bores drilled and constructed at a mean depth of 80 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 of two drill-holes needed for every cased production bore to account for the variability in the nature of the aquifer at each location.
‡Value assumes six monitoring bores drilled and constructed at a mean depth of 80 m at a cost of $500/m, constructed with 150 mm PVC and machine-slotted 5 m 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/second and from depths of up to 50 m below ground level (mBGL). Value based on 16 pumps.
§§Value assumes a mobilisation/demobilisation rate of $10/km from Darwin to south of Top Springs and return (approximately 1500 km round trip).
*Value assumes six 72-hour constant-rate discharge 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 groundwater users and GDEs. Assumes the regulator has already characterised the aquifers at an intermediate to regional scale to better understand the resource potential under cumulative extraction scenarios and under current and future constraints to development.

Pre-feasibility-level assessment of groundwater resource development opportunities and risks associated with the Cambrian Limestone Aquifer

The Assessment identified the CLA along the east of the catchment to be the most promising regional-scale aquifer with potential for future groundwater resource development.

The CLA is hosted mostly in the Montejinni Limestone and is almost exclusively unconfined in the Victoria catchment. This means the CLA outcrops at the land surface or is within tens of metres of the land surface and is directly recharged via outcrop areas or via overlying variably permeable Cretaceous claystone, siltstone and sandstone, and Cenozoic sand, silt and clay, across its extent in the Victoria catchment (see Figure 2-25 in Section 2.2.5). The thickness of the CLA varies spatially beneath the eastern part of the Victoria catchment. It is influenced by historical weathering of the limestone in places and by changes in the topography of the underlying volcanic rocks (Figure 5-3). The CLA is generally about 50 to 120 m thick beneath the eastern part of the Victoria catchment and over 120 m thick in the Wiso Basin to the north-west of the catchment boundary. The saturated thickness (amount of saturated rock) also varies spatially and is an important characteristic, along with aquifer hydraulic properties, in relation to groundwater storage and flow. In some parts of the western Wiso Basin beneath the eastern part of the Victoria catchment, the saturated thickness can be thin (<20 m), or unsaturated, as shown by the mixed success of historical drilling (dry holes or bores with little water). Along the eastern margin of the Victoria catchment, the saturated thickness is variable, ranging between about 10 and 100 m (Figure 5-3). See Figure 2-4 in Section 2.2.3 for an overview of the spatial extent of the different geological basins in the Victoria catchment.

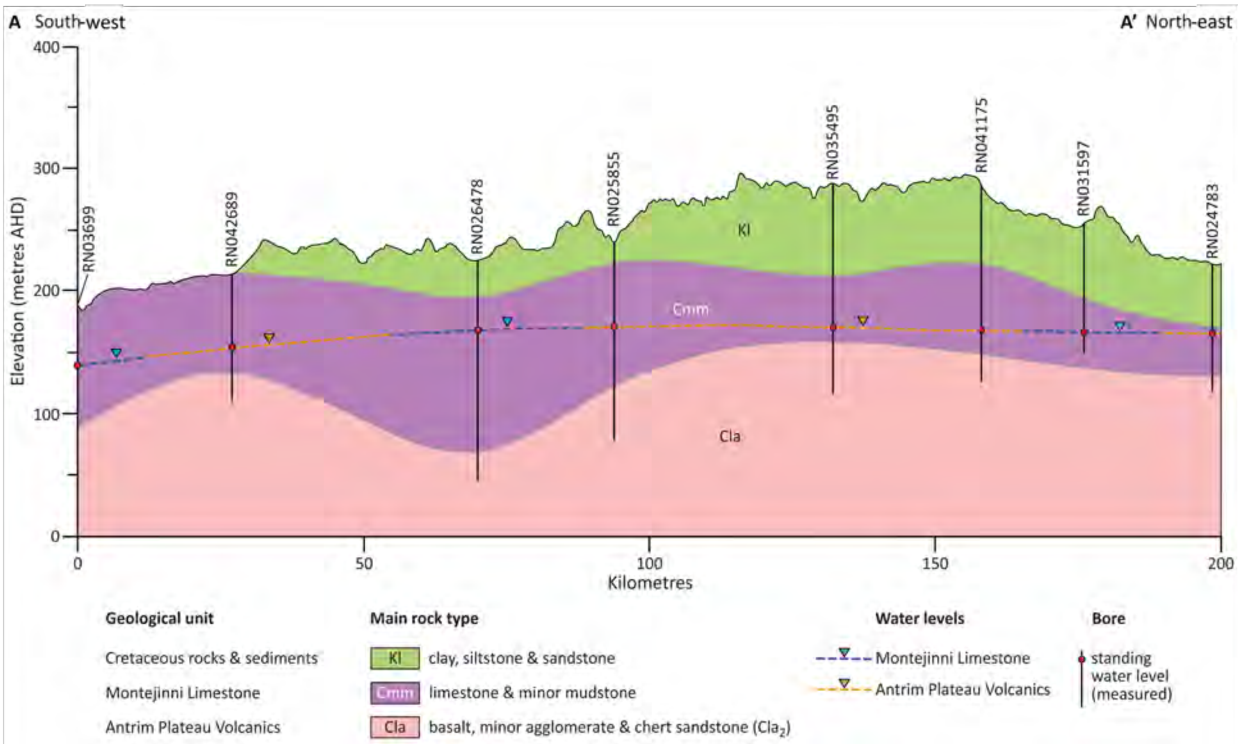

Figure 5-3 Hydrogeological cross-section through the Cambrian Limestone Aquifer in the east of the Victoria catchment

See Figure 5-2 for the spatial location of the cross-section.

The CLA beneath the Victoria catchment is generally flat. Depth to the top of the CLA in the subsurface along the eastern margin of the Victoria catchment is generally shallow (<50 mBGL) as the aquifer outcrops across large areas (Figure 5-5). To the north-east of Top Springs, depth to the top of CLA increases to about 120 mBGL where overlying Cretaceous rocks are more extensive (Figure 5-3 and Figure 5-5). Depth to the top of the CLA generally increases (>150 mBGL) east of the catchment boundary out into the central Wiso Basin where the overlying Cretaceous rocks are thicker. Depth to the CLA also increases (>150 mBGL) where the aquifer dips below mean sea level in the Daly Basin in the far north (Figure 5-5). See Figure 2-25 in Section 2.5.2 for information on the spatial occurrence and extent of the geological basins.

Changes in the depth to groundwater across the CLA, also referred to as depth to standing water level (SWL), exhibit similar spatial patterns to the depth to the top of the aquifer. For example, groundwater is shallow (<10 mBGL) along the western margin of the aquifer around and to the south of Top Springs (Figure 5-6) where groundwater discharges by: (i) intermittent lateral outflow to streams (Armstrong River, and Bullock, Cattle and Montejinni creeks), where they are incised into the aquifer outcrop; (ii) perennial localised spring discharge at spring complexes (Old Top, Lonely, Palm and Horse springs); and (iii) evapotranspiration from groundwater-dependent vegetation in nearby groundwater-fed streams and springs. For this reason, GDEs associated with the CLA in the Victoria catchment are largely limited to the western margin of the aquifer around Top Springs (see conceptual model in Figure 5-7). Depth to groundwater then increases subtly to depths ranging from 40 to 50 mBGL in a somewhat radial pattern north-east, east and south-east from the western aquifer boundary towards the eastern margin of the Victoria catchment. Beyond the eastern margin of the catchment, the depth to groundwater often exceeds 70 mBGL (Figure 5-6).

Figure 5-4 Groundwater pumps powered by the wind provide water points for cattle

Photo: CSIRO – Nathan Dyer

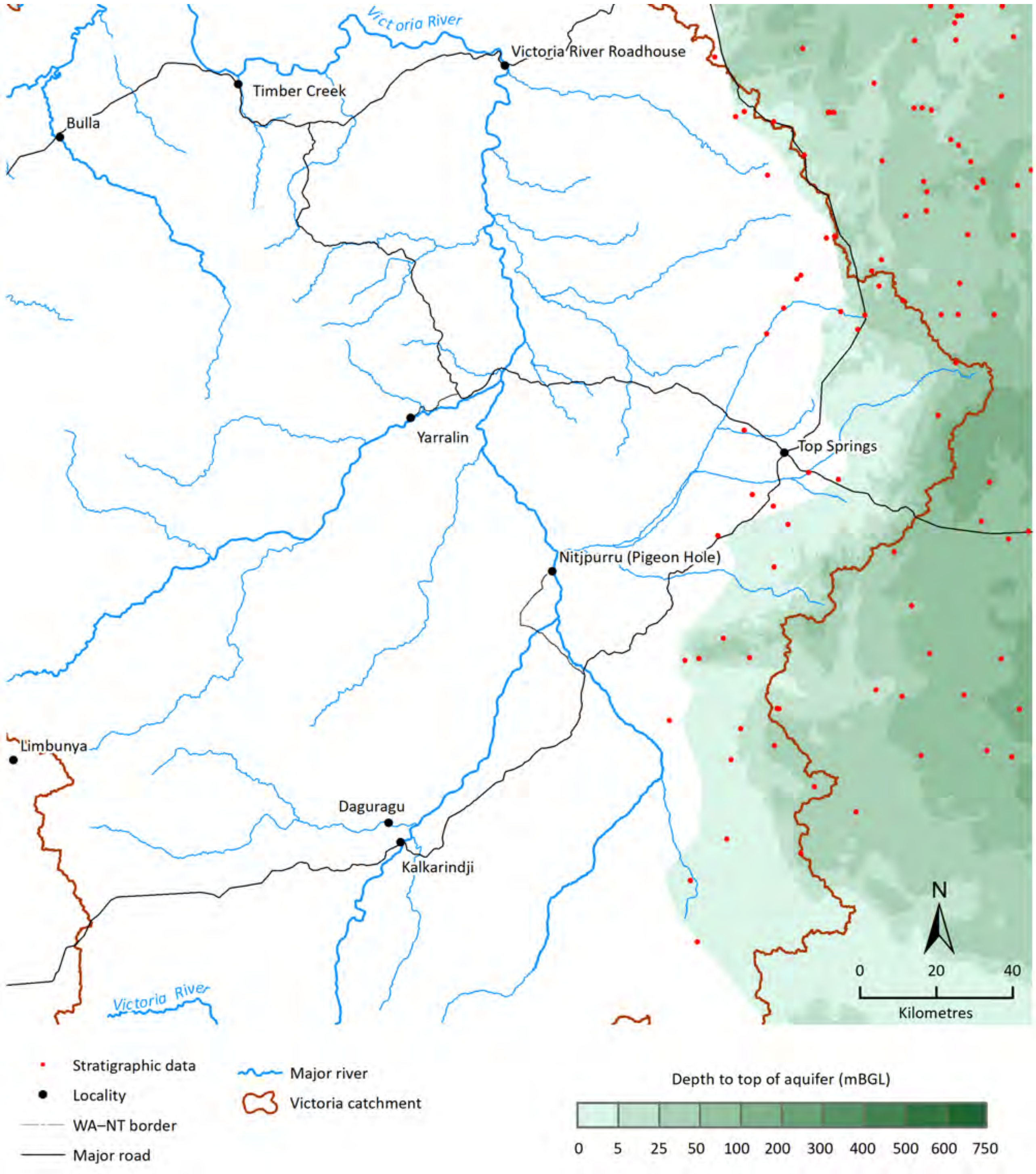

Figure 5-5 Depth to the top of the Cambrian Limestone Aquifer

Only a partial spatial extent of the CLA is shown beyond the Victoria catchment boundary. Depths are in metres below ground level (mBGL). Stratigraphic data points represent a bore with stratigraphic data that provides information about changes in geology with depth.

Aquifer extent data source: Knapton (2020)

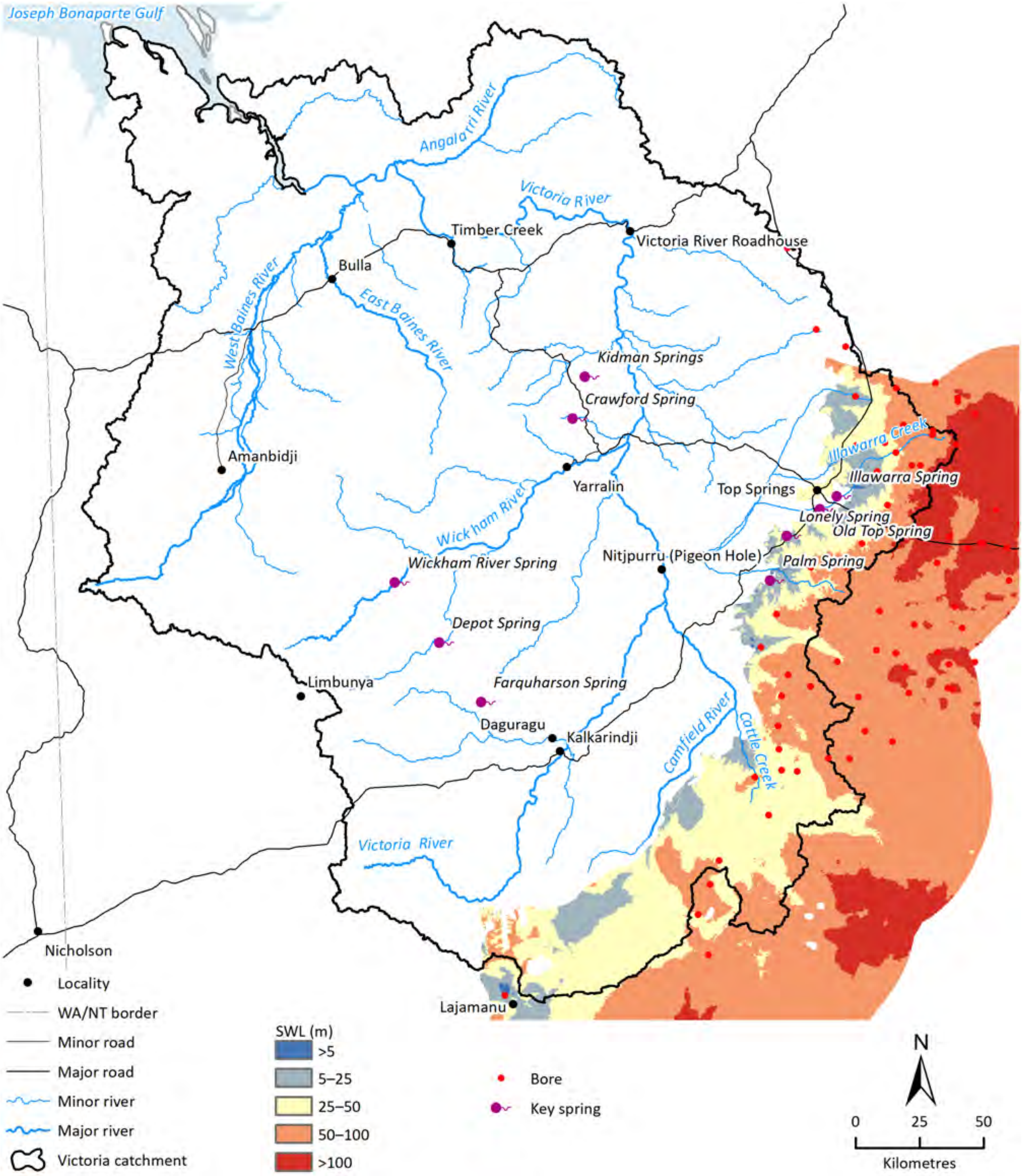

Figure 5-6 Depth to standing water level (SWL) of the Cambrian Limestone Aquifer

Only a partial spatial extent of the CLA is shown beyond the Victoria catchment boundary. Depths are in metres below the land surface.

Aquifer extent data sources: Knapton (2020)

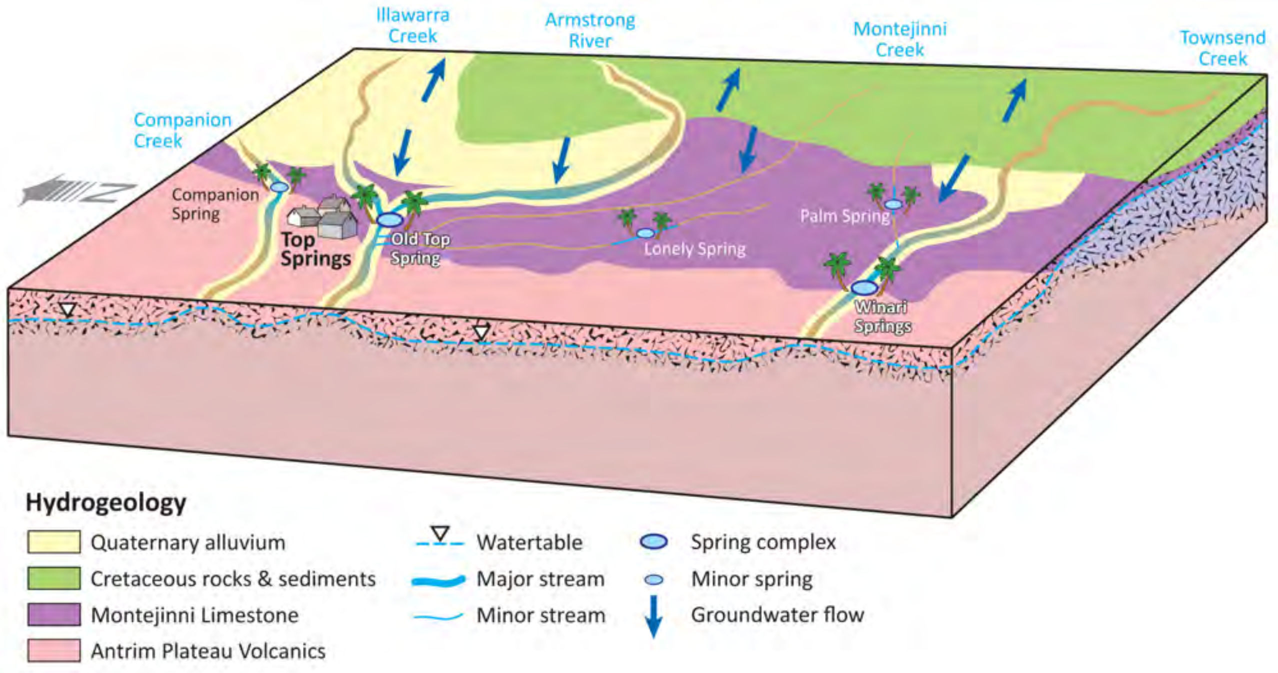

Figure 5-7 Conceptual block model of part of the Cambrian Limestone Aquifer near Top Springs along the eastern margin of the Victoria catchment

Large blue arrows represent groundwater flow directions. Larger blue sections associated with streams represent perennial reaches where groundwater discharge supports surface water flow. Texture in the hydrogeological units represent fractured and/or karstic rocks.

Impacts of extracting groundwater from the Cambrian Limestone Aquifer to groundwater-dependent ecosystems and existing groundwater users

The Assessment used a groundwater model which covers part of the CLA in the Victoria catchment (see companion technical report on groundwater modelling in the Victoria catchment, Knapton et al., 2024), based on the revised conceptual model (e.g. Figure 5-7), to evaluate the impacts of incrementally larger groundwater extractions on localised perennial groundwater discharge to the spring complexes around Top Springs and existing groundwater users under historical and future climates. The results, detailed in the report by Knapton et al. (2024), are summarised in Table 5-4 and Table 5-5.

The potential impacts, in terms of groundwater drawdown, of three hypothetical annual groundwater extraction quantities (3, 4 and 5 GL) at three hypothetical locations within the CLA are reported at ten stock and domestic bores (each with a registered number, RN) installed in a range of different hydrogeological settings and proximities to existing users. The three hypothetical extraction locations, located to the south of Top Springs, were selected considering the location of existing groundwater users, suitability of soil for irrigated agriculture, suitable hydrogeological properties for groundwater extraction and distance from ecologically and culturally important GDEs (see Knapton et al. (2024) for more detail). The locations of the hypothetical groundwater extractions and the reporting sites are shown in Figure 5-8, along with the location of numerous spring complexes along the western margin of the CLA. A picture of Old Top Spring is shown in Figure 5-9.

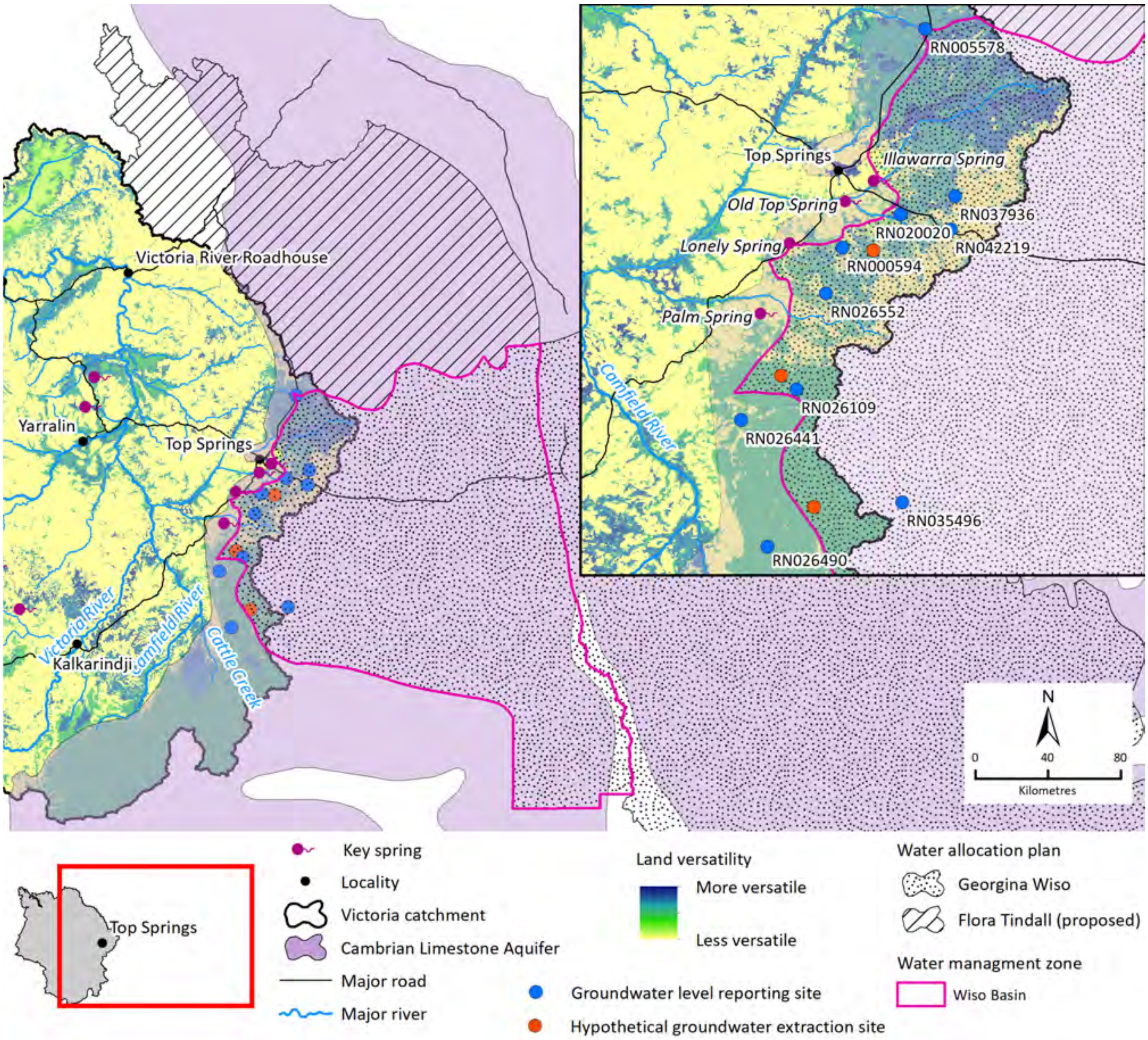

Figure 5-8 Location of hypothetical groundwater extraction sites in relation to modelled groundwater level reporting sites and modelled discharge at key springs for the Cambrian Limestone Aquifer

Figure 5-9 Perennial localised discharge from the Cambrian Limestone Aquifer to Old Top Spring

Photo: CSIRO

The CLA is a regional-scale groundwater system, which means that changes in climate and increases in groundwater extraction can take many hundreds of years to fully propagate through the system. Consequently, the results are sensitive to the reporting time period. All model results are reported at 2060 (~40 years). This is considered a pragmatic time period over which to consider the impacts of changes in climate and groundwater extraction because it is: (i) equivalent to more than twice the length of the investment period of a typical agricultural enterprise, (ii) roughly equivalent to the service life of a commissioned groundwater borefield and (iii) consistent with the time period over which future climate projections have been evaluated. Note that this time period is about four times the length of the current period over which NT water licences are assigned.

Importantly, in reporting the results of the hypothetical groundwater development scenarios, no judgment is made about acceptability of the impact of the modelled groundwater-level drawdown to receptors such as groundwater-dependent environmental assets or existing users.

Drawdown in groundwater levels in the CLA under the three hypothetical annual extraction scenarios – B9 (3 × 3 GL extraction), B12 (3 × 4 GL extraction) and B15 (3 × 5 GL extraction) – is concentric around the three hypothetical groundwater extraction sites (Figure 5-10). At the smallest cumulative hypothetical extraction rate (9 GL/year, Scenario B9) the maximum modelled drawdown in groundwater level after the 40-year period (~2060) is about 14 m in the centre of each of the three hypothetical extraction sites (Figure 5-10). At RN026109, which is about 6 km from the epi-centre of the three hypothetical extraction sites (Figure 5-8), the maximum modelled drawdown in groundwater level is about 4 m under Scenario B9 after 40 years (Table 5-4). At the largest cumulative extraction rate (15 GL/year, Scenario B15), the modelled drawdown in groundwater level at the centre of each of the three hypothetical extraction sites after the 40-year period (~2060) was 26 m (Figure 5-10). At RN026109, (Figure 5-8), the maximum modelled drawdown in groundwater level is about 7 m under Scenario B9 after 40 years (Table 5-4). Drawdown of about 1 m in groundwater level – a value that can be considered measurable – is modelled to extend >20 km radially from the centre of the three hypothetical development sites (Table 5-4 and Figure 5-10). At RN026109, the modelled groundwater drawdown under scenarios B9, B12 and B15 exceeds the groundwater drawdown under Scenario Cdry (Table 5-4). However, at five of the ten groundwater level reporting sites (RN000594, RN005578, RN020020, RN26552 and RN037936), modelled groundwater drawdown under Scenario Cdry exceeds the drawdown under scenarios B9, B12 and B15 (Table 5-4). This highlights the spatial and temporal influence climate variability may have on the aquifer's water balance. Under a dry future climate (Scenario Ddry), the modelled groundwater drawdown arising from the three hypothetical groundwater developments is further exacerbated relative to under Scenario B.

Table 5-4 Mean modelled groundwater levels at ten locations within the Cambrian Limestone Aquifer under extraction scenarios A, B, C and D Locations are shown in Figure 5-8

All results are reported for approximately 2060. Values shown are the differences in modelled groundwater level relative to Scenario A (a negative value is a decrease; a positive value is an increase). Additional maps of groundwater drawdown are provided in the companion technical report on groundwater modelling (Knapton et al., 2024).

SCENARIO	MODELLED GROUNDWATER LEVEL (m)									
	RN000594 (~13 km east of Lonely Spring)	RN005578 (~45 km north-east of Old Top Spring)	RN020020 (~15 km east of Old Top Spring)	RN026109 (~20 km south-east of Palm Spring)	RN026490 (~56 km south of Palm Spring)	RN035496 (~58 km south-east of Palm Spring)	RN026441 (~26 km south of Palm Spring)	RN026552 (~15 km south-east of Lonely Spring)	RN037936 (~26 km east of Old Top Spring)	RN042219 (~27 km south-east of Old Top Spring)
A	0	0	0	0	0	0	0	0	0	0
B9	−2.2	–	−0.2	−4.3	−1.3	−0.8	−0.5	−1.9	−0.2	−0.9
B12	−2.9	–	−0.3	−5.7	−1.7	−1.1	−0.7	−2.5	−0.3	−1.2
B15	−3.6	–	−0.3	−7.1	−2.1	−1.4	−0.8	−3.2	−0.4	−1.5
Cdry	−5.7	−2.3	−0.5	−1.6	–	–	−0.1	−4.0	−1.3	−0.7
Cmid	−1.3	−1.0	−0.1	−0.4	–	–	–	−0.9	−0.4	−0.2
Cwet	+7.6	+2.2	+0.6	+2.2	–	–	+0.2	+5.3	+1.7	+1.0
Ddry9	−7.9	−2.3	−0.7	−5.7	−1.2	−0.8	−0.6	−5.9	−1.5	−1.6
Dmid9	−3.5	−1.0	−0.4	−4.6	−1.2	−0.8	−0.5	−2.8	−0.6	−1.1
Dwet9	+5.4	+2.2	+0.4	−2.0	−1.2	−0.8	−0.3	+3.4	+1.5	+0.1
Ddry12	−8.7	−2.3	−0.8	−7.1	−1.7	−1.1	−0.8	−6.5	−1.6	−1.9
Dmid12	−4.2	−1.0	−0.4	−6.0	−1.7	−1.1	−0.7	−3.5	−0.6	−1.4
Dwet12	+4.8	+2.2	+0.3	−3.5	−1.7	−1.1	−0.5	+2.8	+1.4	−0.2
Ddry15	−9.4	−2.3	−0.8	−8.5	−2.1	−1.4	−0.9	−7.2	−1.7	−2.2
Dmid15	−4.9	−1.0	−0.5	−7.3	−2.1	−1.4	−0.8	−4.1	−0.7	−1.7
Dwet15	+4.1	+2.2	+0.3	−4.9	−2.1	−1.4	−0.6	+2.2	+1.3	−0.5

Scenario A baseline is 0 m. – represents no modelled change. A negative value represents a decrease in groundwater level relative to Scenario A. A positive value represents an increase relative to Scenario A.

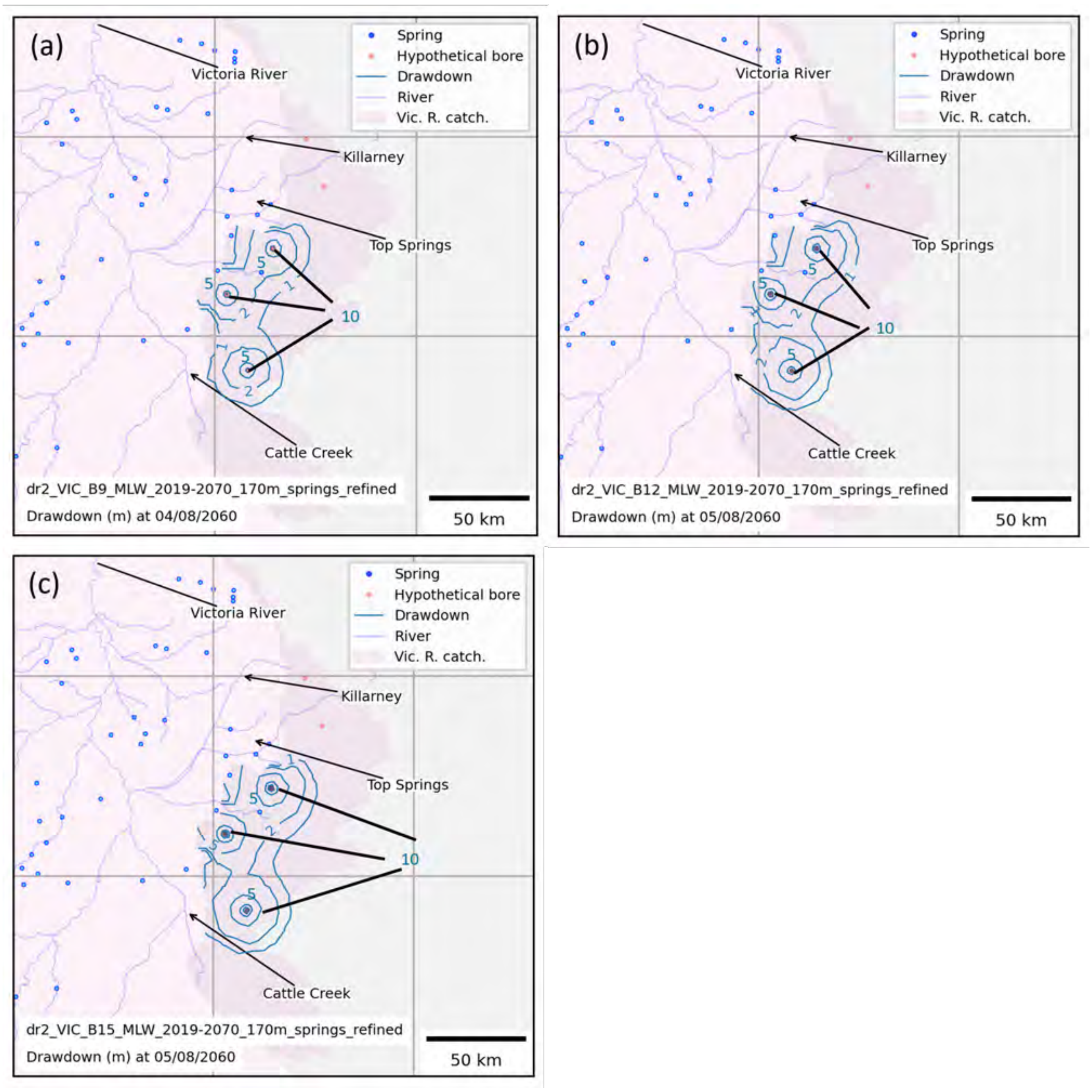

Figure 5-10 Modelled drawdown in groundwater level in the Cambrian Limestone Aquifer (CLA) under scenarios (a) B9, (b) B12 and (c) B15 in approximately 2060

Drawdown contours relate to drawdown in groundwater level. The darker shade of pink represents the extent of the CLA. For more detail see companion technical report on groundwater modelling (Knapton et al., 2024).

Under Scenario B9, the modelled mean groundwater discharge (i.e. total of evapotranspiration) and localised spring discharge) from the CLA is 9.9 GL/year, a reduction in modelled discharge of 11% compared to under Scenario A (11.1 GL/year) (Table 5-5). Under Scenario B15, the modelled mean groundwater discharge from the CLA is 9.1 GL/year (Table 5-5). This is 2.0 GL/year less (18% reduction) than the mean modelled groundwater discharge under Scenario A (Table 5-5). The reductions in mean modelled groundwater discharge under groundwater extraction scenarios B9, B12 and B15 are due to the small spatial extent of the CLA in the Victoria catchment (12,000 km^2) and the short distance (about 15 km) between the closest hypothetical groundwater extraction site relative to the spring complexes around Top Springs (Figure 5-8). The three hypothetical extraction sites are between about 15 and 80 km from the discharge areas of the aquifer. This highlights that changes in the CLA's water balance depend on a range of factors, including the location, magnitude and duration of extraction, and the nature of the aquifer's hydrogeological properties (saturated aquifer thickness, aquifer hydraulic properties, hydrogeological conceptual model) on spatial and temporal changes in groundwater flow in an aquifer.

Table 5-5 Mean modelled groundwater discharge by evapotranspiration and localised spring discharge from the Cambrian Limestone Aquifer at spring complexes along its western margin near Top Springs

SCENARIO	DISCHARGE (SPRINGS AND ET)	
	VOLUME (GL/y)	CHANGE FROM SCENARIO A (%)†
A	11.1	–
B9 (3 × 3 GL)	9.9	−11
B12 (3 × 4 GL)	9.5	−14
B15 (3 × 5 GL)	9.1	−18
Cdry	7.3	−34
Cmid	9.8	−12
Cwet	15.8	+42
Ddry9	6.2	−44
Dmid9	8.6	−22
Dwet9	14.5	30
Ddry12	5.8	−48
Dmid12	8.3	−26
Dwet12	14.1	+26
Ddry15	5.5	−51
Dmid15	7.9	−29
Dwet15	13.6	+23

†A negative value represents a decrease in groundwater discharge relative to Scenario A. A positive value represents an increase relative to Scenario A.

The mean modelled groundwater discharge from the CLA at spring complexes along the western margin of the CLA (Figure 5-8) in the Victoria catchment under projected future climate scenarios C and D are summarised in Table 5-5. Under Scenario Cdry (projected future dry climate with no groundwater development), the reduction in groundwater recharge to the aquifer will result in a larger reduction in groundwater discharge via evapotranspiration and localised spring discharge than groundwater extraction. This is because the CLA outcrops near Top Springs, where it receives localised recharge, and the groundwater system has relatively short groundwater flow paths to the spring complexes. Consequently, inter-annual variations in climate are evident in inter-annual variations in discharge. Based on these findings, with appropriately sited borefields up to 10 GL/year could potentially be extracted from the CLA to the south of Top Springs (i.e. groundwater extraction occurring between 20 and 80 km to the south toward Cattle Creek) (Table 5-2). However, this would depend upon government and community acceptance of potential impacts to GDEs and existing groundwater users, as well as approval of licenses to extract groundwater.

Groundwater resource development opportunities and risks associated with the Proterozoic dolostone aquifers

The Assessment also identified the PDAs in the centre and south of the catchment that host intermediate-scale aquifers as having potential for future groundwater resource development.

The PDAs, despite being data sparse, appear to offer some opportunities for potential future groundwater resource development but require further investigation. The aquifers outcrop, subcrop and are unconfined in the centre and south of the Victoria catchment (Figure 5-11). This means they outcrop at the surface or close to the surface (within tens of metres of it) and are directly recharged by outcrop areas or vertical leakage through a thin (<20 m) and patchy veneer of overlying, variably permeable Cenozoic sediments and rocks (black soil plains, laterite, silcrete, sand, gravel and clay).

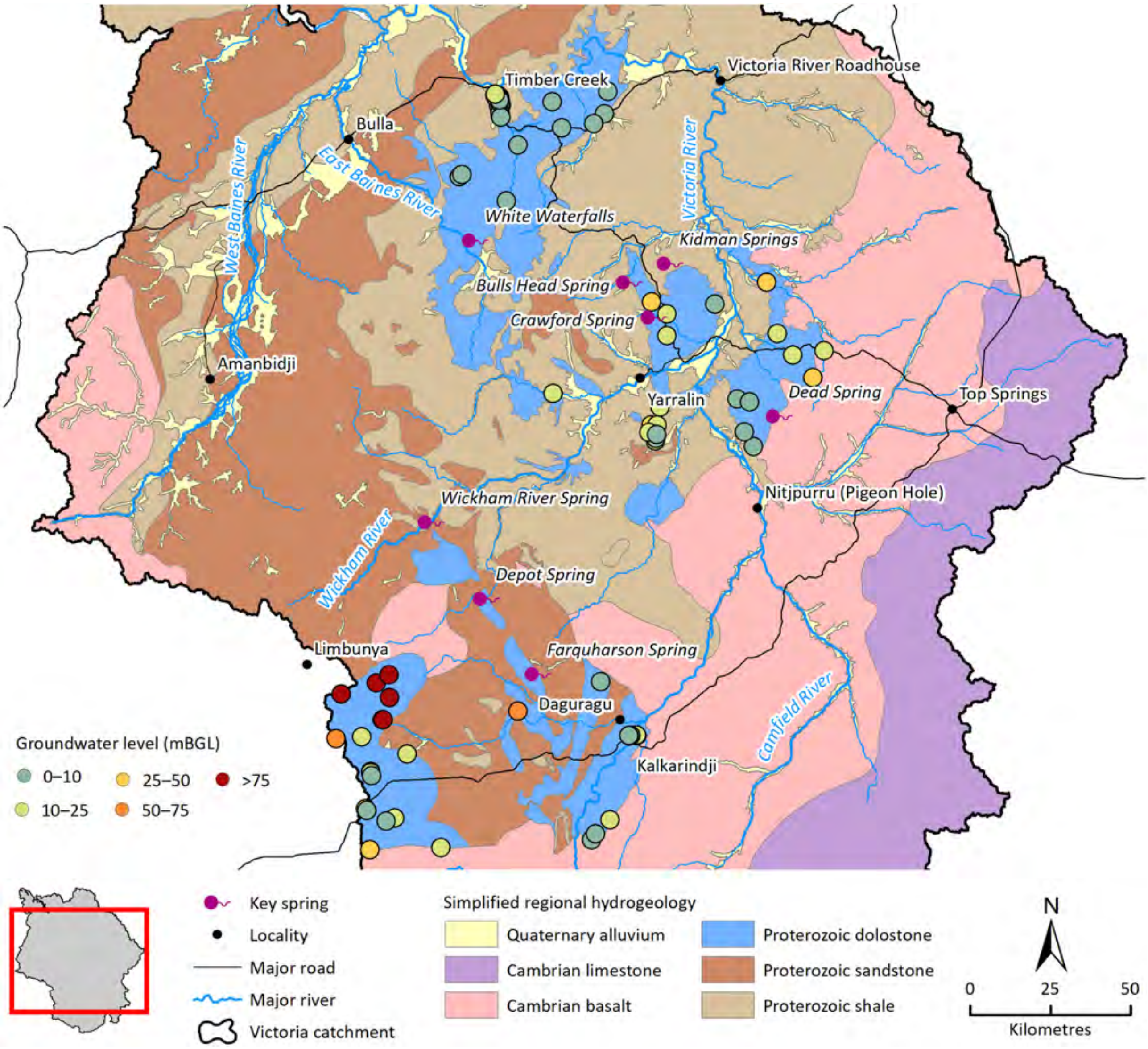

Figure 5-11 Outcropping and subcropping areas of the Proterozoic dolostone aquifers in the Victoria catchment
The spatial extent of the outcropping and subcropping component of the Proterozoic dolostone is presented with the majority of overlying Cretaceous and Cenozoic cover removed (except the alluvium). mBGL = metres below ground level.

While pre-feasibility information about the dolostone aquifers is limited, the following factors indicate they offer potential for future development:

- The spatial extent to which their outcropping/subcropping area (7000 km^2, Figure 5-11) coincides with cracking clay soils and red loamy soils potentially suitable for agricultural intensification (Section 2.3.2) is moderate.
- The aquifers can be intersected by drilling at relatively shallow depths in the outcropping and subcropping areas (mostly <100 mBGL, Figure 5-12).
- Their potential to achieve high bore yields (>20 L/s) indicates that they have potential to yield water at a sufficient rate for groundwater-based irrigation.
- The depth to pump groundwater to the surface is less than 50 mBGL across most areas except for in the far south, west of Kalkarindji (>75 mBGL, Figure 5-11).
- They host fresh water suitable for a variety of irrigated crops (mostly <500 mg/L TDS).

Insufficient information exists to develop geological models and water balance models for the PDAs. However, an indicative scale of the resource can be derived by applying the estimated recharge rates for the aquifers (Section 2.5.3) to the outcropping and subcropping areas of these aquifers to assess the potential recharge component of the water balance for these aquifers. Given the likelihood that the water balance for the PDAs will be sensitive to climate variability similar to that of the CLA, a conservative approach of using the 95th percentile exceedance of the estimated range in annual recharge rates to the outcropping and subcropping areas of the PDAs (see Section 2.5.3) results in a conservative estimate for the annual recharge flux of 105 GL/year. Assuming 20% of the conservative recharge flux may potentially be available for future groundwater resource development, an indicative scale of the groundwater resource in the PDAs was estimated to be less than or equal to 20 GL/year (Table 5-2). However, this requires further hydrogeological investigations (drilling and pump testing), and hydrological risk assessment modelling is needed to evaluate groundwater extraction and climate variability impacts to existing groundwater users and GDEs. If and how much groundwater is licensed will ultimately depend upon government and community acceptance of impacts to GDEs and existing groundwater users.

Recharge rates are challenging to estimate, especially in karstic aquifers, and despite applying only the 5th percentile recharge rate (95^{th} percentile exceedance) in this Assessment these initial estimates of annual recharge and the indicative scale of the resource require further investigation. In addition, as is the case for the CLA, climate variability is likely to influence the magnitude of annual recharge fluxes to the aquifers. Furthermore, temporal water level information for the aquifers is sparse, and it is unclear if the aquifers can accept this magnitude of annual recharge flux. The aquifers dip steeply in the subsurface, indicating they shift across different areas from unconfined to confined conditions, which influences the nature and timescale of groundwater flow (Figure 5-12). The aquifers host numerous ecologically and culturally important springs (Figure 5-13), and support Timber Creek’s water supply.

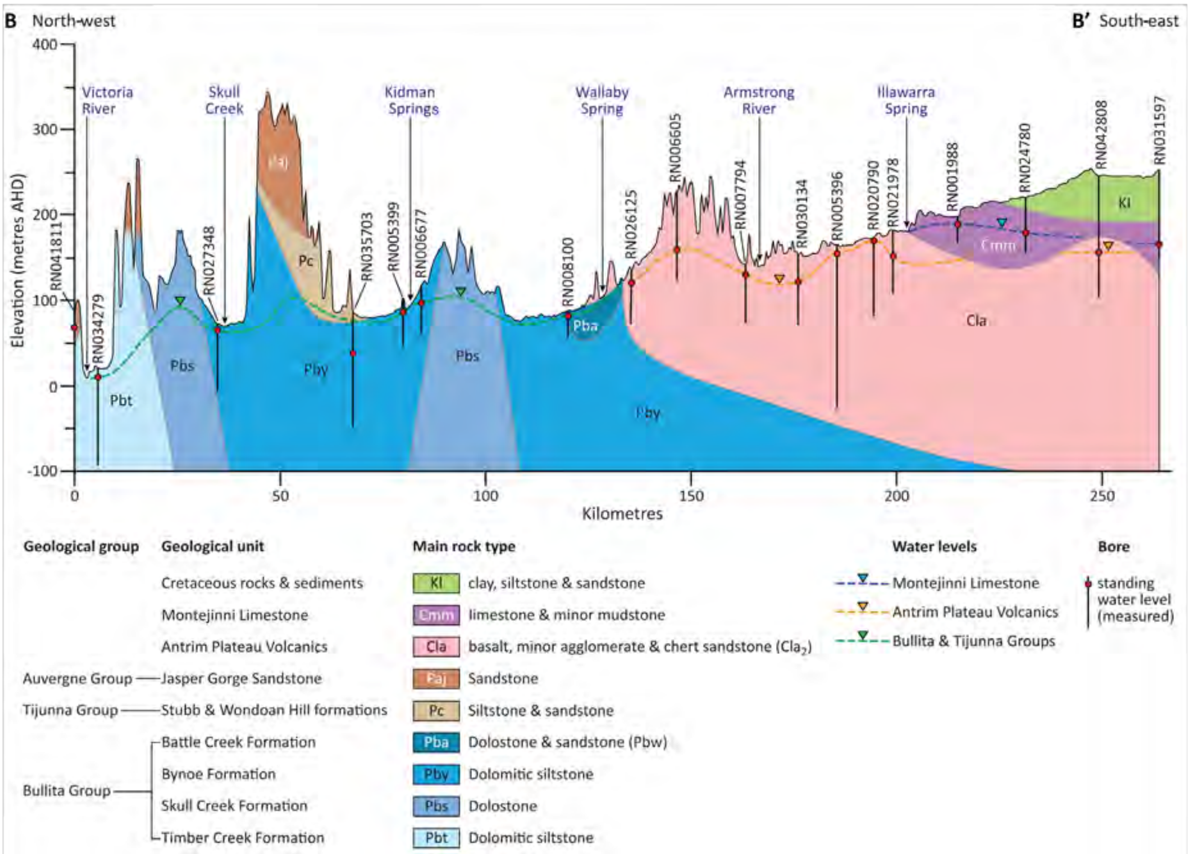

Figure 5-12 North-west to south-east cross-section traversing the dolostone aquifers hosted in the Bullita Group

Vertical axis is exaggerated. See Figure 5-2 for the spatial location of the cross-section B–B′. AHD = Australian Height Datum.

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

Opportunities for potential future groundwater resource development from aquifers hosted in other hydrogeological units (Cambrian basalt, Devonian–Carboniferous sandstone and Proterozoic sandstone) across the Victoria catchment are most likely to be limited to use for stock and domestic purposes and occasional community water supply. Productive local-scale aquifers hosted in the Quaternary alluvium occurring in patches associated with the streambed, stream channel and floodplain of major streams and their tributaries may offer some opportunities; these will require local investigation. The largest occurrences of the alluvium are in the north of the catchment along the lower reaches of the Angalarri, Victoria and West Baines rivers (Figure 5-2). Indicative bore yield data indicate bore yields can be as high as 11 L/s, but the aquifer is currently sparsely tested. Water quality can vary from fresh to brackish, but it is also sparsely tested. However, in places the aquifers may offer potential for small-scale (<1.0 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) made up mostly of fine-textured sediments (clay lenses), (iii) regularly flooded and (iv) highly connected to perennial reaches of streams such that development may limit water availability to GDEs.

Figure 5-13 Water sampling at Kidman Springs

Photo: CSIRO

5.3.3 Opportunities for 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, but they also operate in the agricultural sector. This scale of operation can sustain rural 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 hydrogeological assessment (Taylor et al., 2024)). Source water availability is considered in terms of presence or absence rather than volumes with respect to any existing water management plans.

Pre-feasibility assessment was based on MAR scheme entry-level assessment in the *Australian guidelines for water recycling: managed aquifer recharge* (NRMMC-EPCH-NHMRC, 2009) – referred to as the MAR guidelines. The MAR guidelines provide a framework to assess feasibility of

MAR, incorporating four stages of assessment and scheme development: (i) entry-level assessment (pre-feasibility), (ii) investigations and risk assessment, (iii) MAR scheme construction and commissioning, and (iv) operation of the scheme.

There are numerous types of MAR (Figure 5-15), and the selection of MAR type is influenced by the characteristics of the aquifer, the thickness and depth of low-permeability layers, land availability and proximity to the recharge source. Infiltration techniques can be used to recharge unconfined aquifers, with water infiltrating through permeable sediments beneath a dam, river or basin. If infiltration is restricted by superficial clay, the recharge method may involve a pond or sump that penetrates the low-permeability layer. Bores are used to divert water into deep or confined aquifers. Infiltration techniques are typically lower cost than bore injection (Dillon et al., 2009; Ross and Hasnain, 2018) and are generally favoured in this Assessment. The challenge in northern Australia is to identify a suitable unconfined aquifer with capacity to store more water when water is available for recharge.

Unless stated otherwise, the material presented in this section has been summarised from the Northern Australia Water Resource Assessment technical report on MAR (Vanderzalm et al., 2018).

Figure 5-14 The Ord River Irrigation Area 290 km west of Timber Creek has a similar climate and some similar soils and climate setting to the Victoria catchment

Photo: CSIRO – Nathan Dyer

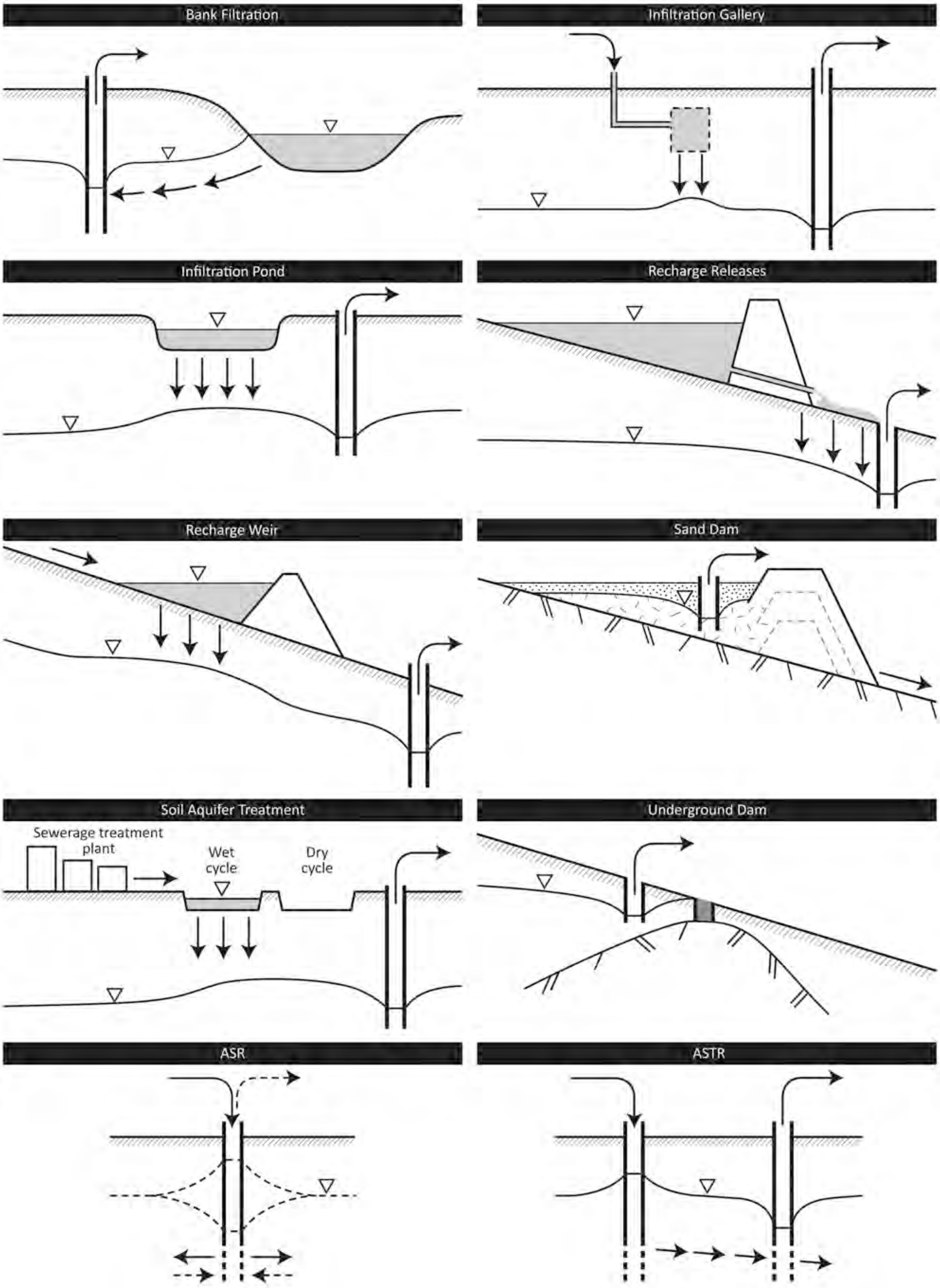

Figure 5-15 Types of managed aquifer recharge

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

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

Opportunity-level assessment of infiltration-based managed aquifer recharge in the Victoria catchment

The most promising aquifers for infiltration-based MAR in the Victoria catchment are within limestones and dolostones because these formations host the major aquifer systems in the Victoria catchment: the CLA and PDAs respectively (Figure 5-2). Available geological mapping indicates that some of the major drainage lines of the Victoria catchment are accompanied by narrow strips of Quaternary alluvium. In some instances, these could be used for MAR provided there is sufficient depth of alluvium and available storage capacity. Groundwater-level data are currently very sparse within the Quaternary alluvium.

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

Water-level data for stock and domestic bores across the Victoria catchment 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 to have no storage space at any time of year. Only sparse water-level information is available for aquifers hosted in the Quaternary alluvium. While water-level data for the CLA and PDAs indicate that sufficient storage capacity is available (Figure 5-16), there is no source water over most of the CLA along the eastern margin of the Victoria catchment, as the drainage lines in this part of the catchment are highly intermittent, and the soils are unlikely to be suitable for the construction of offstream storages (Section 5.4.4).

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 managed aquifer recharge (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 5-16 shows the suitability map for MAR in the Victoria catchment, with classes 1 and 2 considered potentially suitable for MAR and classes 3 and 4 considered to be poorly suitable. Figure 5-17 shows areas of classes 1 to 4 that occur within 5 km of a drainage line with a median annual flow greater than 20 GL.

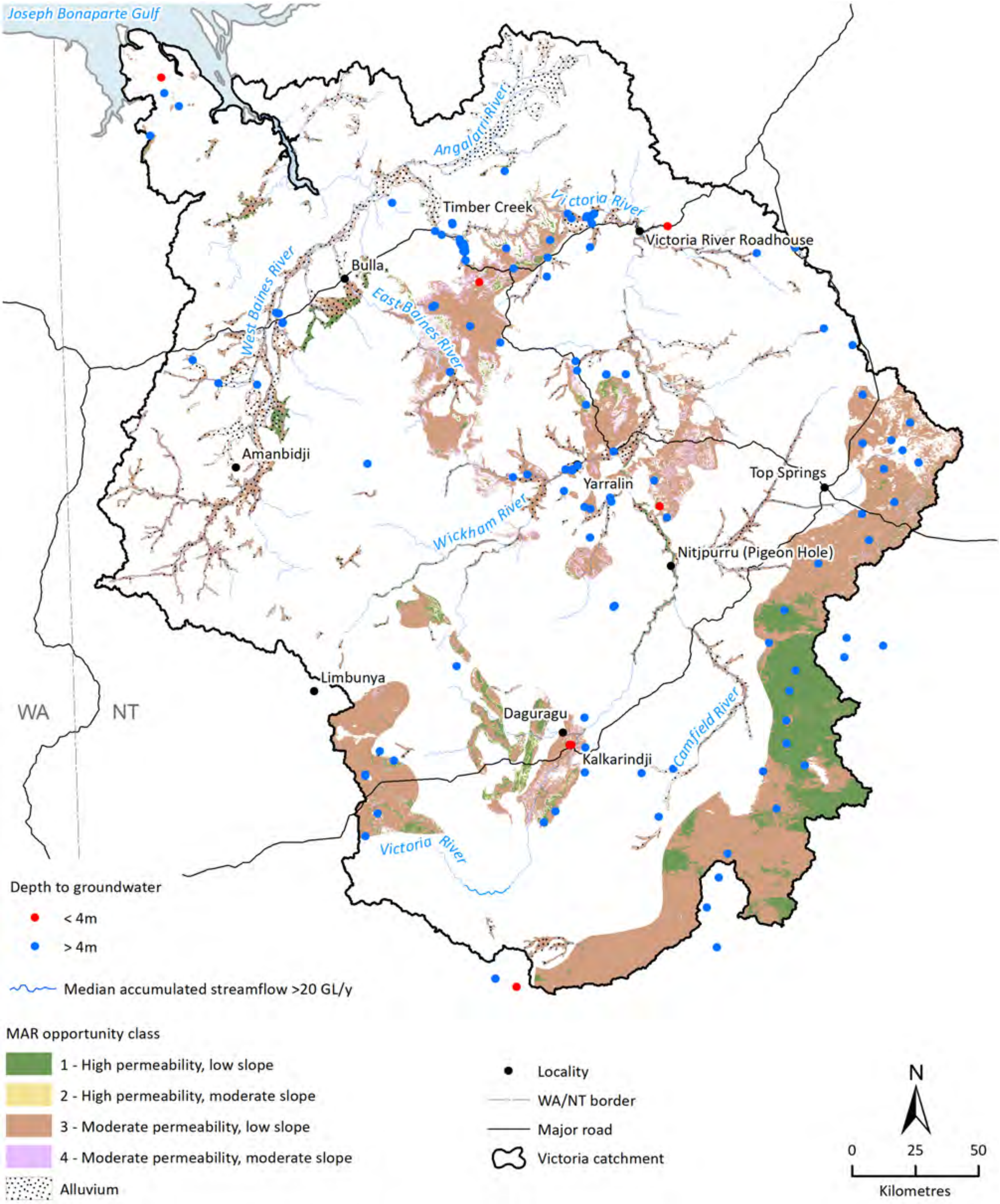

Figure 5-16 Managed aquifer recharge opportunities for the Victoria catchment, independent of distance from a water source for recharge

Analysis based on soil permeability (Thomas et al., 2024) and terrain slope (Gallant et al., 2011) datasets and limited to the following aquifer formations: Cambrian limestone, Proterozoic dolostone and Quaternary alluvium (Figure 5-2).

The opportunity assessment (Figure 5-17) indicates approximately 64,500 ha (0.8%) of the Victoria catchment may have aquifers (including areas of Quaternary alluvium) with potential for MAR within 5 km of drainage lines with a median annual flow greater than 20 GL. Approximately 24,000 ha (~0.3%) of the catchment is considered Class 1 or Class 2 and is within 1 km of drainage lines with a median annual flow greater than 20 GL. However, 60% of this area is underlain by Quaternary alluvium aquifers for which the storage capacity and water level are unknown. Opportunities for MAR that coincide with soils that may be suitable for irrigated agriculture appear to be limited to small parts of the West Baines River catchment. However, Quaternary alluvium is a potential aquifer for MAR although considerable additional investigations would be required.

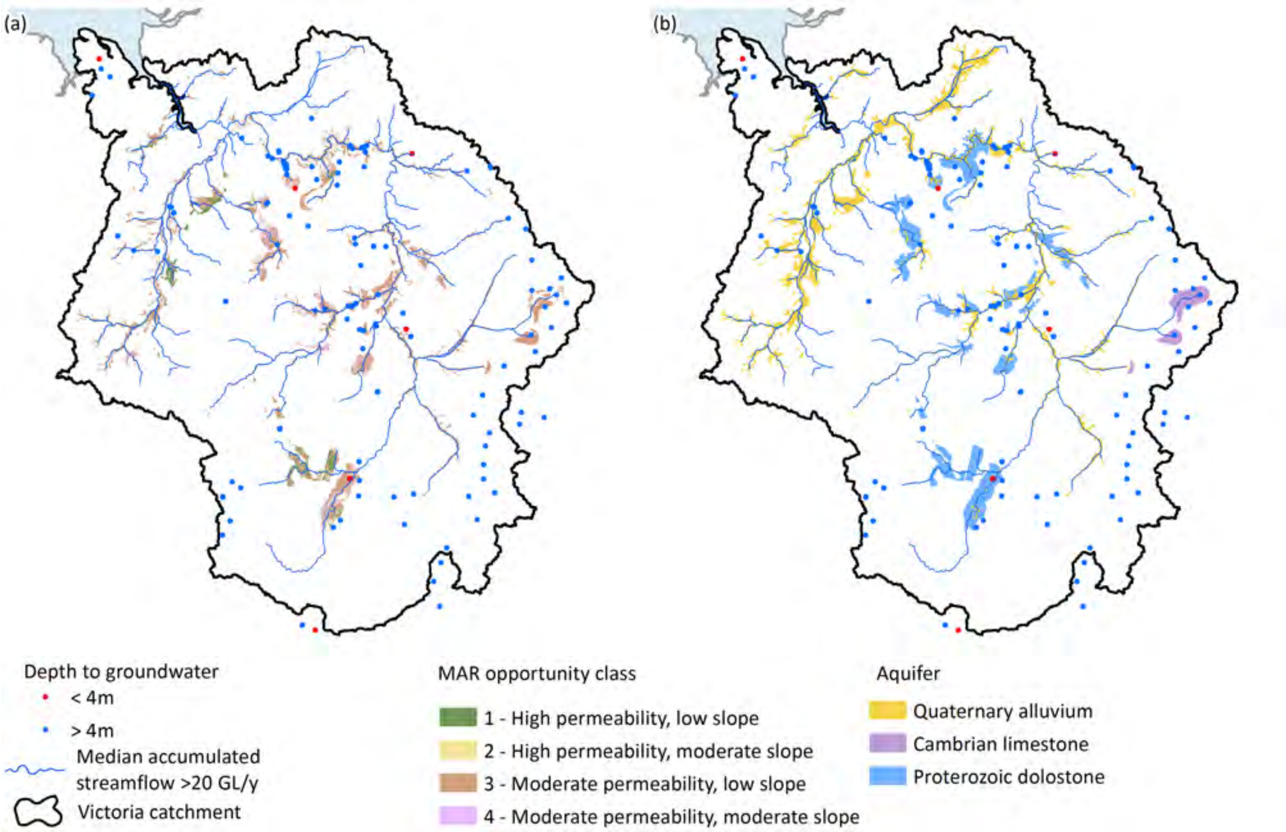

Figure 5-17 Managed aquifer recharge (MAR) opportunities in the Victoria catchment (a) within 5 km of major rivers
Analysis based on the permeability (Thomas et al., 2024) and terrain slope (Gallant et al., 2011) datasets and limited to the following aquifer formations (b): Cambrian limestone, Proterozoic dolostone and Quaternary alluvium (Figure 5-2).

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.

5.4 Surface water storage opportunities

5.4.1 Introduction

In a highly seasonal climate, such as that of the Victoria catchment, 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 another larger drainage line. Ringtanks and turkey nest tanks are examples of offstream storages with a continuous embankment; the former are 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 and reservoir capacity, 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 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 1984 in Australia, however, roller compacted concrete (RCC) has been used, where low-cement concrete is placed in continuous thin layers from bank to bank and compacted with vibrating rollers. This approach allows large dams to be constructed in a far shorter time frame than required for conventional concrete construction, often with large savings in cost (Doherty, 1999). RCC is best used for high dams where a larger-scale plant can provide significant economies of scale. This is now the favoured type of construction in Australia whenever foundation rock is available within reasonable depth, and where a larger-capacity spillway is required. In those parts of the Victoria catchment 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 Victoria catchment

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. The only study identified in the literature that looked at surface water storage in the Victoria catchment was undertaken in 1995 by the NT Government (Tickell and Rajaratnam, 1995) who undertook a water resource survey of Legune Station in the Victoria catchment. This study evaluated small gully dams, excavated tanks and modified waterholes on Legune Station. No studies of large dams in the Victoria catchment have been identified. Consequently an opportunity-level assessment of potential major dams in the Victoria catchment was undertaken using a bespoke computer model, the DamSite model (Petheram et al., 2017a, Petheram et al., 2017b), to assess over 50 million sites in the study area for their potential as major offstream or instream dams.

Broad-scale geological considerations

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

Potentially, feasible dam sites occur where resistant ridges of rock that have been incised by the river systems outcrop on both sides of river valleys. The rocks are generally weathered to varying degrees, and the depth of weathering, the amount of outcrop on the valley slopes, the occurrence of dolomitic rocks (which may contain solution features), and the width and depth of alluvium in the base of the valley are fundamental controls on the suitability of the potential dam sites.

Where the rocks are relatively unweathered and outcrop on the abutments of the potential dam site, less stripping (removal of material) will be required 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, siltstones, mudstones and conglomerates will form a reasonably watertight dam foundation, requiring conventional grout curtains and foundation preparation. However, because dolostones are soluble over a geological timescale, it is possible that, where they occur within the Proterozoic sequences, potentially leaky dam abutments and reservoir rims may be present, which would require specialised and costly foundation treatment such as extensive grouting. The extent and depth of the Cenozoic or Quaternary alluvial sands and gravels in the floor of the valley are also important geological controls on dam feasibility, as these materials will have to be removed to achieve a satisfactory founding level for the dam.

Where rivers are tidal (e.g. lower Victoria River), 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 5-18 displays the most promising sites across the Victoria catchment in terms of topography, assessed in terms of approximate cost of construction per unit of storage volume. Favourable locations with a small catchment area and adjacent to a large river may be suitable as major offstream storages.

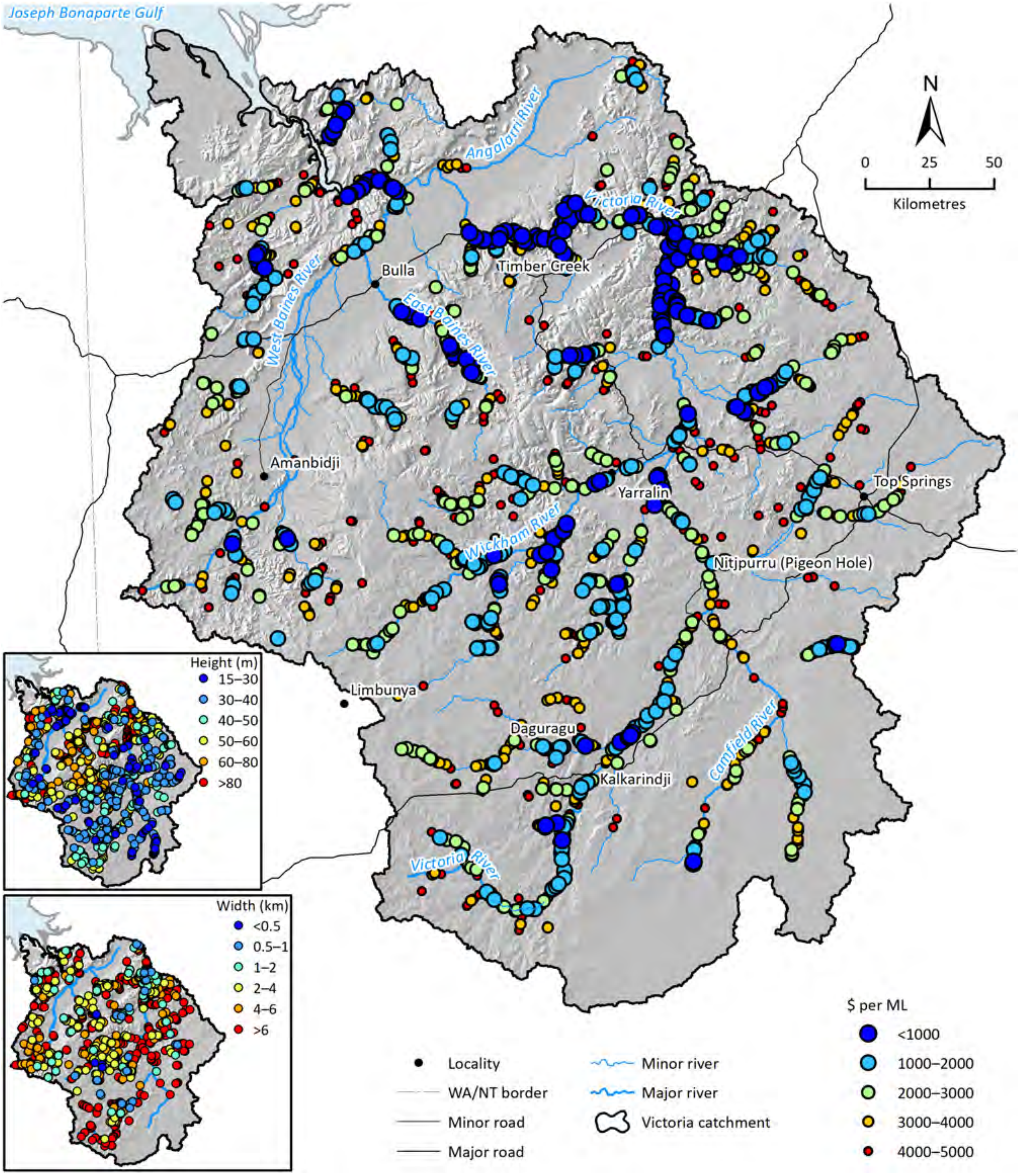

Figure 5-18 Topographically more favourable potential storage sites in the Victoria catchment based on minimum cost per megalitre storage capacity

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 provided a source of water was nearby. 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. Insets display height and width of dam wall at full supply level at the minimum cost per megalitre storage capacity. For more detail see companion technical report on surface water storage (Yang et al., 2024).

In Figure 5-18, only those locations with a ratio of cost to storage of less than $5000/ML are shown. This is a simple way to display those locations in the Victoria catchment 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 help 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 open water evaporation, hydrology or geological suitability for dam construction.

Figure 5-18 shows that the parts of the Victoria catchment with the most favourable topography for storing water are predominantly along the lower Victoria, East Baines and Wickham rivers. The topography of the West Baines River is less suitable for large instream dams. There is little favourable topography for large instream dams on the Sturt Plateau in the east of the catchment or the deeply weathered landscapes to the south of Kalkarindji.

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 5-19. No values greater than $10,000/ML are shown.

The most cost-effective potential dam sites are along the lower reaches of the Victoria River. However, as shown by the versatile land map in Figure 5-19, very little land is suitable for irrigated agriculture below these potential dam sites. The results presented in Figure 5-19 do not consider the geological suitability of a site for dam construction.

Based on this analysis and a broad-scale desktop geological evaluation, four 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 Victoria catchment. The locations of these pre-feasibility potential dam sites are denoted in Figure 5-19 by black circles and the letters ‘A’, ‘B’, ‘C’ and ‘E’. Two additional sites were short-listed for pre-feasibility analysis – one to provide a commentary on the potential for large dams to generate hydro-electric power in the Victoria catchment (denoted by a black circle and the letter ‘D’) and the second to explore the potential for large dams in the Victoria catchment to mitigate the impacts of flooding on very remote communities downstream (denoted by a black circle and the letter ‘F’).

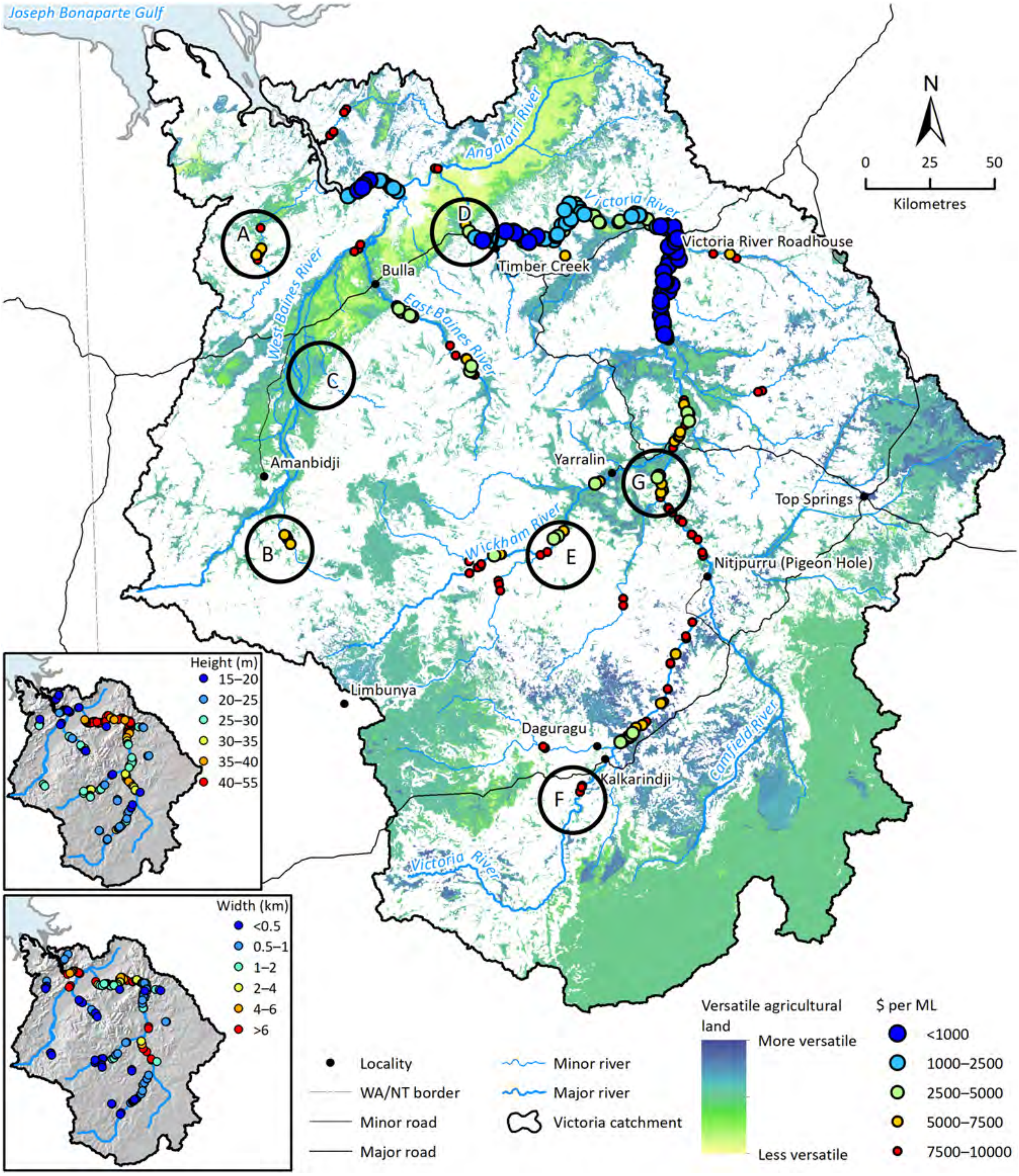

Figure 5-19 Topographically and hydrologically more favourable potential storage sites in the Victoria catchment based on minimum cost per megalitre yield at the dam wall

This figure indicates those sites more suitable for major dams in terms of cost per ML 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 megalitre yield and left inset displays width of FSL at the minimum cost per megalitre yield. Letters indicate potential dams listed in Table 5-6 and Table 5-7: A – Bullo River adopted middle thread distance (AMTD) 57 km; B – Leichhardt Creek AMTD 26 km; C – Gipsy Creek AMTD 56 km; D – Victoria River AMTD 97 km; E – Wickham River AMTD 63 km; F –Victoria River AMTD 283 km; G – Victoria River AMTD 320 km. For more detail see companion technical report on surface water storage (Yang et al., 2024).

Along the Victoria River downstream of the junction with the Wickham River is a relatively large area of soil potentially suitable for irrigated agriculture that could potentially be supplied water from a large instream dam denoted by the letter 'G' in Figure 5-19. However, irrigated agriculture would be expensive to establish at this location as the landscape (soils and topography) is complex and an extensive network of pumps and pipelines would be required to distribute water across the area. Consequently this site was not short-listed.

Key parameters and performance metrics are summarised in Table 5-6 and an overall summary comment is recorded in Table 5-7. More detailed analysis of the six pre-feasibility sites is provided in the companion technical report on surface water storage (Yang et al., 2024).

Hydro-electric power generation potential in the Victoria catchment

The potential for major instream dams to generate hydro-electric power is presented in Figure 5-20, following an assessment of more than 50 million potential dam sites in the Victoria catchment (Yang et al., 2024). This figure provides indicative estimates of hydro-electric power generation potential but does not consider the existence of supporting infrastructure (e.g. transmission lines) or geological suitability for dam construction. No values greater than $20,000/ML are shown.

The only sites that meet this criteria in the Victoria catchment are on the lower reaches of the Victoria River near Timber Creek and upstream of Victoria River Roadhouse, where high dam walls could potentially be constructed to provide the necessary elevation head. As discussed in Section 3.3.4, however, the Victoria catchment is in a very remote part of the NT that does not have access to major electricity networks, and the small communities rely on diesel generators or hybrid diesel – solar systems provided by Power and Water Corporation. Due to the high cost of electrical infrastructure to support hydro-electric power generation in the Victoria catchment, investigations into hydro-electric power generation were not progressed further. For more details on the hydro-electric power generation capacity of one of the more favourable potential sites on the Victoria River see the companion technical report on river modelling simulation (Hughes et al., 2024b).

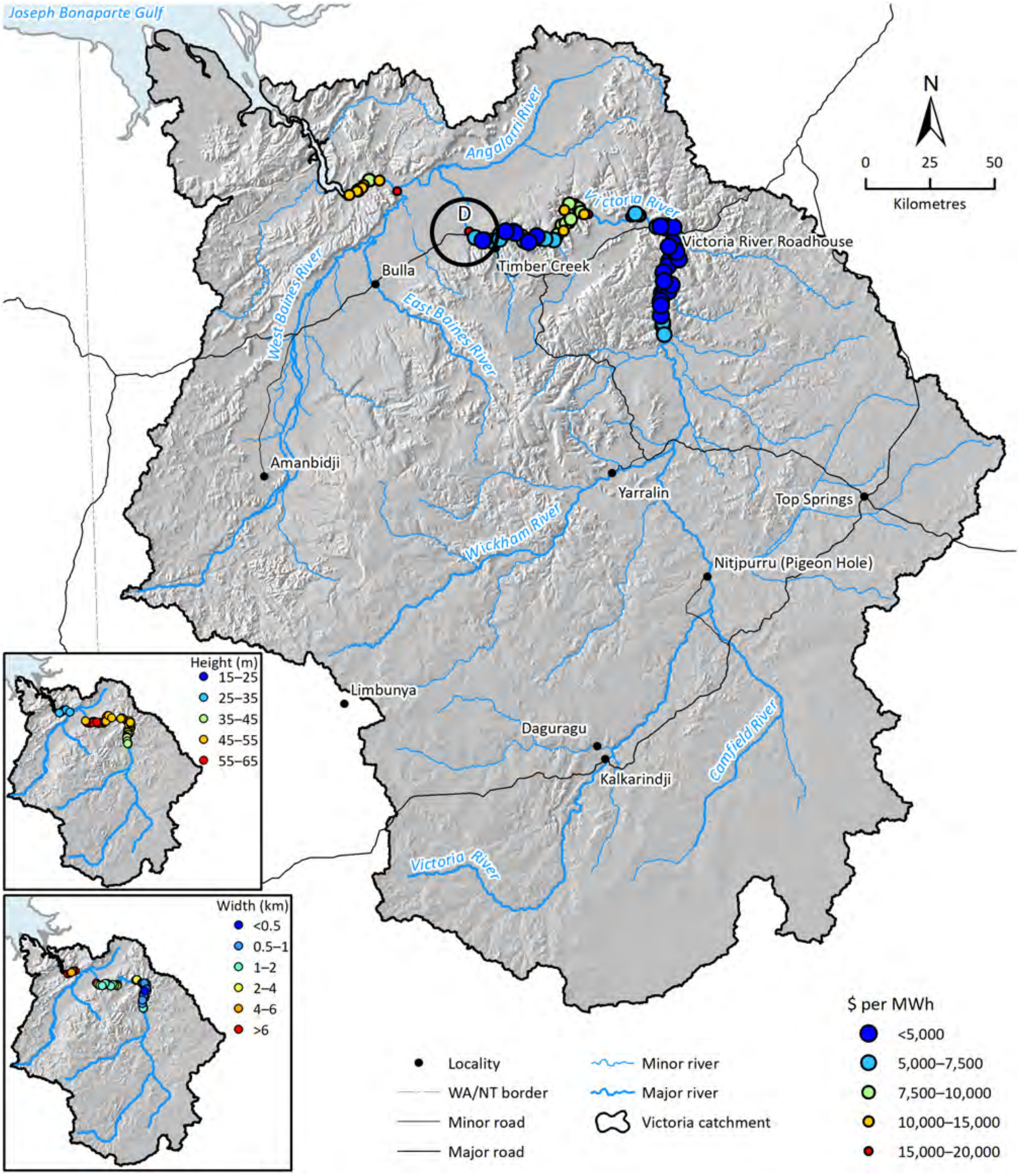

Figure 5-20 Victoria catchment hydro-electric power generation opportunity map

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. Data are underlain by a shaded topographic relief map. 'D' indicates location of hypothetical hydro-electric power development on the Victoria River. Right inset displays height of full supply level (FSL) at the optimal cost per megawatt hour and left inset displays width of FSL at the optimal cost per megawatt hour. For more detail see companion technical report on surface water storage (Yang et al., 2024).

Pre-feasibility-level assessment of potential major dams in the Victoria catchment

Six potential dam sites in the Victoria catchment were examined as part of this pre-feasibility assessment. They are summarised Table 5-6 and Table 5-7. More detailed descriptions of the six potential dam sites, including impacts on migratory species and ecological impacts of reservoir inundation, are provided in the companion technical report on surface water storage (Yang et al., 2024).

Table 5-6 Potential dam sites in the Victoria catchment examined as part of the Assessment

All numbers have been rounded. Locations of potential dams are shown in Figure 5-19. AMTD = adopted middle thread distance; EB = embankment dam; FSL = full supply level; RCC = roller compacted concrete.

SITE NAME	MAP ID	DAM TYPE	SPILLWAY HEIGHT ABOVE BED* (m)	CAPACITY AT FSL (GL)	CATCHMENT AREA (km²)	ANNUAL WATER YIELD** (GL)	CAPITAL COST# ($ million)	UNIT COST## ($/ML)	LEVELISED COST### ($/ML)
Bullo River AMTD 57 km	A	RCC	34	127	605	55	232☐	4,218	312
Leichhardt Creek AMTD 26 km	B	RCC	33	193	1,120	64	396◘	6,188	458
Gipsy Creek AMTD 56 km	C	RCC	29	56	645	43	384☐	8,930	662
Victoria River AMTD 97 km§	D	RCC	46	10,426	54,605	2590	4137☐&	1,597	118
Wickham River AMTD 63 km	E	RCC	28	547	5,431	209	1593☐	7,622	565
Victoria River AMTD 283 km§§	F	EB	9	17	4,413	17	740◘	43,529	3051

*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 A. This is yield at the dam wall (i.e. does not take into account distribution losses or downstream transmission losses). These yield values do not take into account downstream existing entitlement holders or environmental considerations.

◘Indicates manually derived preliminary manual 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. If site geotechnical investigations reveal unknown unfavourable geological conditions, costs could be substantially higher.

##This is the unit cost of annual water supply and is calculated as the capital cost of the dam divided by the water yield at 85% annual time reliability.

###Assumes a 7% real discount rate and a dam service life of 100 years. Includes operation and maintenance costs, assuming these costs are 0.4% of the total capital cost.

§This site was evaluated to investigate the potential for hydro-electric power in the Victoria catchment. The yield at this site greatly exceeds the quantity of water required to irrigate the limited area of soil suitable for irrigated agriculture immediately downstream of this potential dam site.

§§This potential dam site was evaluated to investigate the potential for dams to mitigate the impacts of flooding to remote communities in the Victoria catchment. For this potential dam the spillway height is actually 23 m, however, the storage capacity is only 10 m.

&Includes cost of power station. Does not include cost of other energy infrastructure such as transmission lines or substations.

Table 5-7 Summary comments for potential dams in the Victoria catchment

Locations of potential dams are shown in Figure 5-19. AMTD = adopted middle thread distance.

SITE NAME	MAP ID	SUMMARY COMMENTS
Bullo River AMTD 57 km	A	Although commanding the smallest catchment area of the short-listed potential dam sites, the yield of this site is comparable with that of other sites with larger catchment areas due to the higher rainfall in the catchment of the Bullo River. With the lowest capital cost, this site also has the lowest cost per megalitre released from the dam wall. However, the site is very remote, and considerable additional capital expenditure would be required to develop this location. There is a high likelihood of unrecorded sites of cultural significance in the inundation area.
Leichhardt Creek AMTD 26 km	B	The hypothetical instream dam in the upper West Baines catchment is relatively low yielding and has a moderately high cost per megalitre released from the dam wall. The foundations appeared to be suitable for a roller compacted concrete (RCC) dam. Despite being one of the closer sites to large contiguous areas of soil suitable for irrigated agriculture in the Victoria catchment, the site is still located approximately 15 km upstream from the potential target location. An advantage of this potential dam site is its proximity to the Victoria Highway and Kununurra. Because the site is in a small headwater catchment, the impacts of a dam on migratory species are small relative to those at other locations, and the relatively small yield from the dam means that impacts associated with changes in flow are largely localised. There is a high likelihood of unrecorded sites of cultural significance in the inundation area.
Gipsy Creek AMTD 56 km	C	This potential dam site commands a relatively small catchment. Consequently, it is relatively low yielding and has one of the higher costs per megalitre yield released from the dam wall of the short-listed sites in the Victoria catchment. The dam site has potential to provide irrigation supplies downstream along the creek to land adjacent to the upper West Baines River. The foundations appear to be suitable for an RCC dam. Although the site is located on a small headwater catchment, this catchment has the highest area of suitable habitat of the modelled water-dependent species expressed as a percentage of the catchment area (99%). There is a high likelihood of unrecorded sites of cultural significance in the inundation area.
Victoria River AMTD 97 km	D	This potential instream dam site, approximately 10 km upstream of Timber Creek and the Victoria Highway, has a large catchment area and consequently has a large yield. The foundations of the sites appeared possibly to be suitable for an RCC dam. The site was evaluated primarily for its potential to generate hydro-electric power, though it could also potentially mitigate flooding at Timber Creek. The hydro-electric generation potential of this site is reported in the companion technical report on river system simulations in the Victoria catchment (Hughes et al., 2024b). Although the highest-yielding potential dam site, and the lowest in terms of cost per megalitre released from the dam wall, there is very little soil suitable for irrigated agriculture downstream of this site, and a smaller dam constructed to match the quantity of suitable soil downstream would still be one of the more expensive water storages in the catchment. Given the site is situated low on the main river channel in the Victoria catchment, a potential dam would have a large impact on migratory species. In addition, there is a high likelihood of unrecorded sites of cultural significance in the inundation area.
Wickham River AMTD 63 km	E	A hypothetical instream dam at this site has the potential to provide irrigation supplies downstream to riparian areas adjacent to the Wickham River. The foundations appeared possibly to be suitable for an RCC dam. Although one of the higher-yielding potential dam sites in the Victoria catchment, the site is also one of the more expensive and is very remote. The headwaters of the catchment of this site include part of the Judbarra National Park. In addition, there is a high likelihood of unrecorded sites of cultural significance in the inundation area.
Victoria River AMTD 283 km	F	This potential dam site on the upper Victoria River is an instream development investigated for its potential to provide flood mitigation benefit to the Kalkarindji, Nitjpurru (Pigeon Hole) and other Indigenous communities downstream. A dam for flood mitigation at this site could also provide a limited water supply to meet local needs. The flood mitigation potential is reported in the companion technical report on river system simulations in the Victoria catchment (Hughes et al., 2024b). The foundations at this site may not be stiff enough for an RCC dam, and a rockfill embankment dam was considered instead, with a separate lined chute spillway on either abutment. The catchment of the site has the lowest area of suitable habitat of the modelled water-dependent species expressed as a percentage of the catchment area (25%). 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 years or more. 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 in this report to advance to construction, far more comprehensive studies would be needed, including not just bio-physical studies such as geotechnical investigations, field measurements of sediment yield, archaeological surveys and ground-based vegetation and fauna surveys, but also extensive consultations with Traditional Owners (e.g. see companion technical report on Indigenous aspirations, interests and water values (Barber et al., 2024)) and other stakeholders. Studies at that level of 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 the catchment can be found in the companion technical report on Indigenous aspirations, interests and water values (Barber 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 Victoria catchment 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 (Stratford 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 7.2.

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) predicted 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 for water supply in the Victoria catchment were estimated to have about 2% or less sediment infilling after 30 years and less than 7% sediment infilling after 100 years.

Exploration of two potential dam sites in the Victoria catchment

Two potential dam sites on different rivers are summarised here. These sites are described because they are among the most cost-effective sites in close proximity to relatively large continuous areas of land suitable for irrigated agriculture in the Victoria catchment. More detailed descriptions of the six sites selected for pre-feasibility assessment are provided in the companion technical report on surface water storage (Yang et al., 2024).

Potential dam on Leichhardt Creek AMTD 26 km for water supply

This potential dam site is 15 km upstream of a floodplain above the junction with the West Baines River. An advantage of this potential dam site over other sites in the Victoria catchment is its proximity to the Victoria Highway and the regional service centre Kununurra. Access to the potential dam would partly be along an 85 km road constructed for the potential dam branching from Highway 1 east of the West Baines River crossing. The total distance from the site to Kununurra would be some 375 km. Although data from the NT cultural heritage sites register were not made available to the Assessment, it is likely that the site and parts of the potential inundation area would contain cultural heritage sites of significance.

Given the potential for significant flooding during construction and the spillway capacity required, an RCC gravity dam could have a 70 m wide central uncontrolled spillway. The FSL is nominally at an elevation of 122 mEGM96 (Earth Gravitational Model 1996), (i.e. approximately 45 m above the river bed). A 50 m wide 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 of the dam.

Based on geological mapping and satellite imagery, the potential dam site is located on Proterozoic rocks of the Jasper Gorge Sandstone, which consists of medium quartz sandstone with minor siltstone. There appear to be gently dipping outcrops on both of the abutments. The river bed is approximately 30 m wide, with ponded water approximately 20 m wide. In the river bed are possible rock bars, and the alluvium appears to be shallow. The foundations appear to be suitable for an RCC dam and the estimated depth of alluvium is approximately 5 m. It is estimated that 5 m of stripping would be required on the dam abutments. The storage area appears stable and watertight.

The floodplain downstream of the potential dam is dominated by red loamy soils (soil generic group (SGG) 4.1; see Section 2.3) and friable non-cracking clay loam to clay soils (SGG 2). These soils are suitable, with minor limitations (suitability Class 2, see Section 5.3.3), for dry-season, trickle-irrigated intensive horticulture such as cucurbits and dry-season, spray-irrigated root crops such as sweet potato (*Ipomoea batatas*) and peanut (*Arachis hypogaea*). The red loamy soils are also suitable, with minor limitations (Class 2), for spray-irrigated perennial grasses such as Rhodes grass (*Chloris gayana*) and pulse crops such as mungbean (*Vigna radiata*), soybean (*Glycine max*) and chickpea (*Cicer arietinum*). The friable non-cracking clay loam to clay soils are also suitable, with moderate limitations (Class 3), for spray-irrigated perennial grasses and pulse crops.

Approximately 4% of the catchment upstream of this potential dam site (5372 ha) is modelled as having suitable habitat for at least 40% of the 11 mobile or migratory species modelled (Figure 5-21). Some of these species are also found in neighbouring streams. However, the modelled suitable habitat for these water-dependent species upstream of the potential dam site is small; depending on the species, it ranges from zero % to 1.5% of its total modelled suitable habitat in the Victoria catchment. The potential for ecological change as a result of changes to the downstream flow regime is examined in Section 7.2.

Modelled yield and cost versus dam FSL are shown in Figure 5-22. At a nominal FSL 122 mEGM96 (23 m above river bed), the reservoir of the dam would inundate 2024 ha at full supply and have a capacity of 193 GL (Figure 5-22). At this FSL the reservoir could yield 64 GL of water in 85% of years at the dam wall. A manual cost estimate undertaken as part of the Assessment for an RCC dam on Leichhardt Creek with FSL 122 mEGM96 found the dam would cost approximately $396 million. Setting an (environmental) transparent flow threshold of 20% or 40% of mean daily inflows (i.e. daily inflows up to 20% (or 40%) of mean daily flow are allowed to pass through the dam) reduces the yield of the reservoir to 61 or 59 GL in 85% of years, respectively.

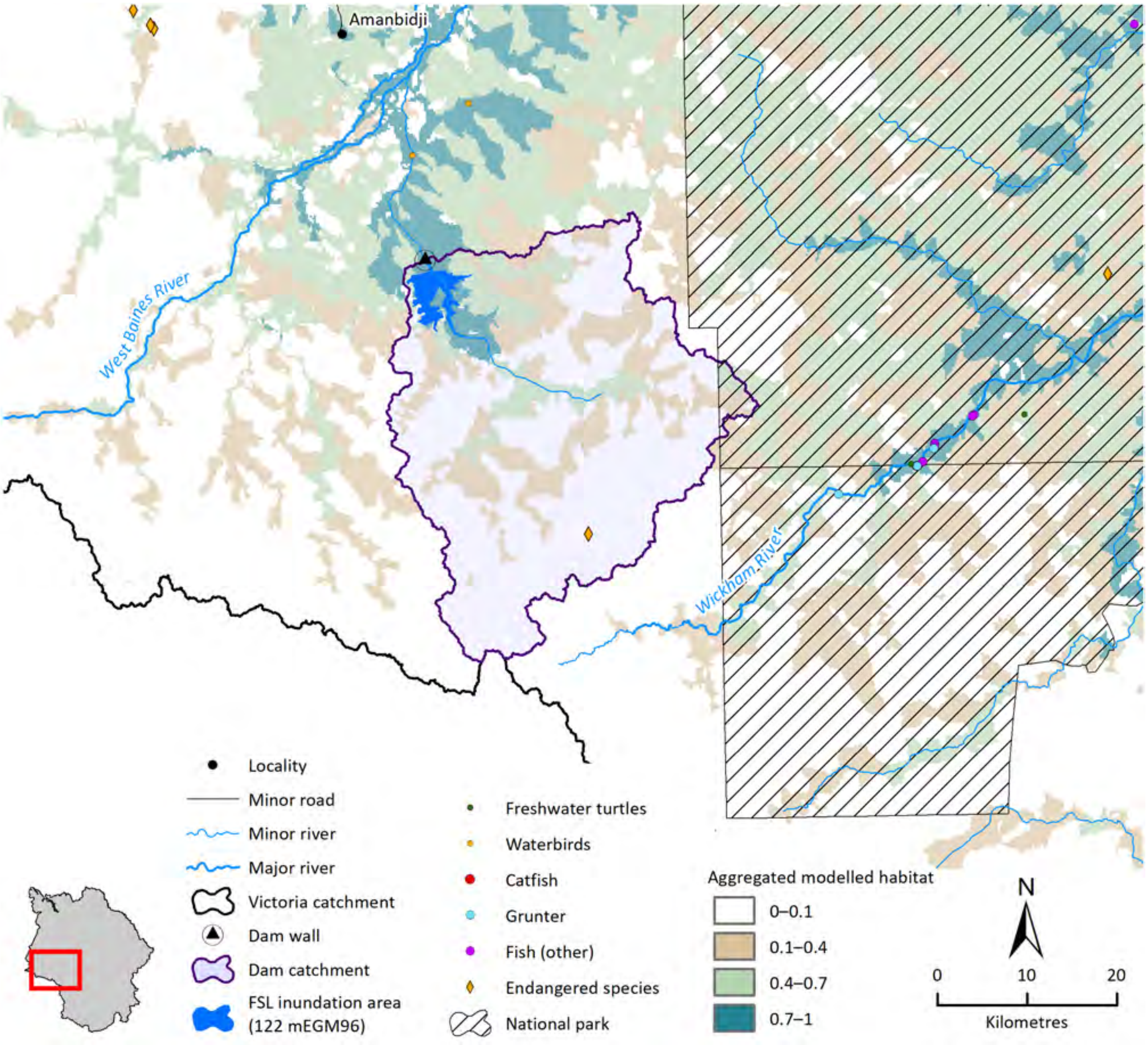

Figure 5-21 EPBC and NT listed species, water-dependent assets and aggregated modelled habitat in the vicinity of the potential dam site on Leichhardt Creek AMTD 26 km

AMTD = adopted middle thread distance; FSL = full supply level.

Under this hypothetical conceptual arrangement, water could be released from the storage into Leichhardt Creek where approximately 50 km downstream it could be impounded by a low concrete gravity weir of sufficient height (i.e. 0.75 m above river bed) to create submergence for pumping infrastructure. Water would then be pumped to an offstream storage of approximately 5 GL capacity. The offstream storage would form a buffer to releases from the dam and the actual irrigation demand. It is estimated that under this arrangement this potential dam could support an irrigated area of about 4000 ha, depending upon the cropping mix. The total cost of the reticulation infrastructure is estimated to be $12.67 million or $3168/ha (see companion technical report on irrigation scheme design and costs for the Victoria and Southern Gulf catchments (Devlin, 2024)).

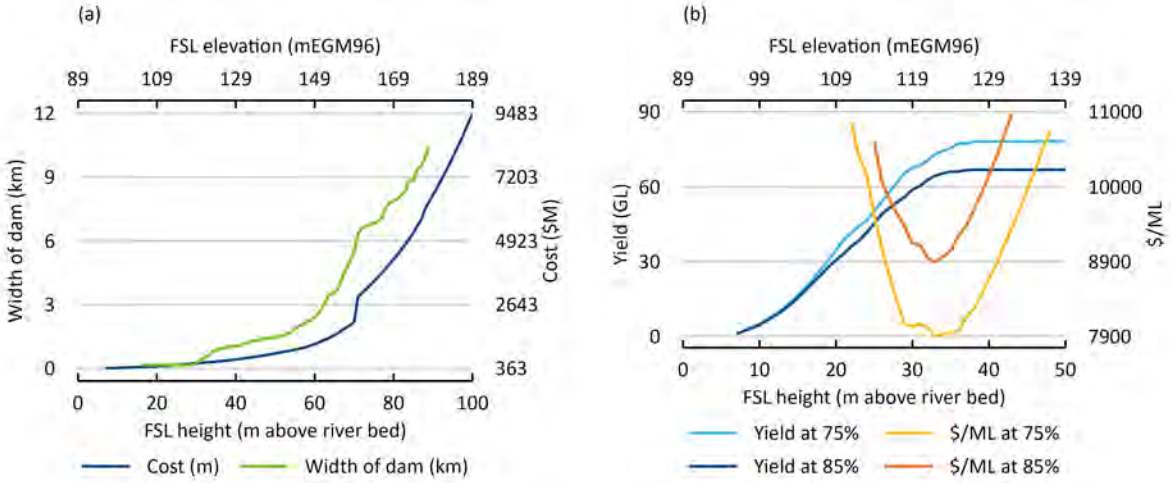

Figure 5-22 Potential dam site on Leichhardt Creek AMTD 26 km: cost and yield at the dam wall

(a) Dam width and modelled dam cost versus full supply level (FSL), and (b) dam yield and yield/$ million at 75% and 85% annual time reliability. Modelled cost estimates will differ from more detailed manual cost estimates presented in Table 5-6. AMTD = adopted middle thread distance.

Potential dam on Victoria River AMTD 283 km for flood mitigation

In 2023, flooding in the upper Victoria River resulted in the relocation of community members from Kalkarindji and Nitjpurru (Pigeon Hole) to Darwin. These events were modelled to have an annual exceedance probability (AEP) of 1.7% and 1.1% at Kalkarindji and Nitjpurru (Pigeon Hole), respectively, noting the paucity of stream gauge data in the upper reaches of the Victoria catchment (see companion technical report on river model calibration in the Victoria catchment (Hughes et al., 2024a)). Based on only the observed record (1953 to 2023), this event had AEP of 2.6% at Coolibah Homestead streamflow gauge, which is downstream of Kalkarindji and Nitjpurru (Pigeon Hole).

The potential Victoria River dam site is an instream development approximately 15 km upstream of Kalkarindji that was investigated for its potential to provide a flood mitigation benefit to Kalkarindji, Nitjpurru (Pigeon Hole) and other communities downstream. A flood mitigation dam at this site could also potentially provide a limited water supply to meet local needs at Kalkarindji (e.g. town water supply, market gardens). Access to the dam would be partly along a 5 km new road branching from the Buntine Highway 13 km south-west of Kalkarindji. The total distance from the site to Kununurra would be some 524 km. Alternatively, the distance to Katherine via Delamere would be 462 km.

No site-specific evaluation of cultural heritage considerations was possible at this site, 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.

Based only on geological maps and satellite imagery, the dam site is located on Cambrian rocks of the Antrim Plateau Volcanics, which consist of basalts with some minor sediments. There appears to be some outcrop on the abutments, but the basalts are likely to be deeply weathered. In the river bed is a 250 m wide area of pooled water and gravel bars. The foundations may not be stiff enough for an RCC dam and are thought to be more suitable for a concrete-faced rockfill dam or an embankment dam, with a separate lined chute spillway on either abutment. The depth of alluvium in the river bed is estimated to be 5 to 10 m, and it is estimated that 5 to 10 m of stripping on the abutments would be required. Storage appears stable and watertight.

Based on the anticipated foundation conditions, a concrete-faced rockfill embankment dam is assumed. Diversion of flows during construction would be through a tunnel constructed through the left abutment of the dam. Reinforced steel mesh protection on the downstream face of the embankment would be used as a protection against overtopping during construction. An uncontrolled, fully lined spillway channel would be excavated through the right abutment, with placement of the crest structure delayed until the embankment is raised to a safe height.

The potential for a dam on the Victoria River AMTD 283 km to mitigate flooding at Kalkarindji is moderate and negligible at Nitjpurru (Pigeon Hole).

Under this conceptual arrangement, the spillway is nominally at an elevation of 200 mEGM96 (i.e. approximately 23 m above the river bed), which would inundate an area of 4177 ha at full capacity (Figure 5-23). The dam could potentially store water to a level 10 m above bed level, with the storage to the spillway crest level serving as a temporary flood storage compartment. Under this configuration the reservoir could supply 17 GL of water in 85% of years. By way of context, if the potential dam were used for water supply purposes rather than for flood mitigation, the reservoir could yield 70 GL in 85% of years at the dam wall.

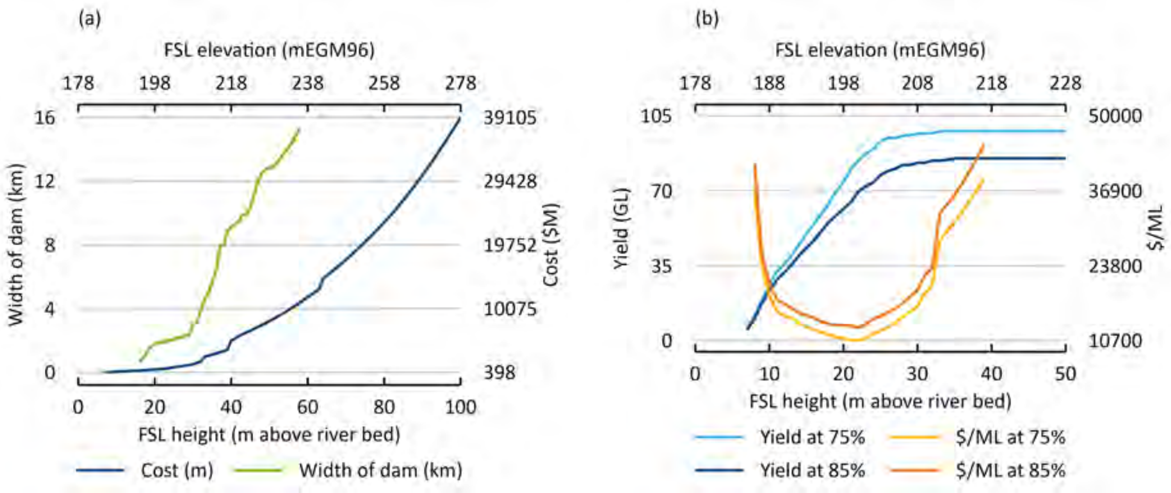

Figure 5-23 Potential dam site on Victoria River AMTD 283 km: cost and yield at the dam wall

(a) Dam width and modelled roller compacted concrete dam cost versus full supply level (FSL), and (b) dam yield and yield/$ million at 75% and 85% annual time reliability. Modelled cost estimates will differ from more detailed manual cost estimates presented in Table 5-6. AMTD = adopted middle thread distance

Approximately 20 km below the potential dam site, the Victoria River is deeply incised into a gently undulating basalt landscape. Moderately deep (0.5–1 m), slowly permeable neutral-to-alkaline cracking clay soils (SGG 9) with a high (100–250 mm) water-holding capacity (within 1 m of the surface) dominate the gently undulating plains. Soils have varying levels of surface and profile rock, limiting the extent suitable for agricultural development.

Approximately 2% of the catchment upstream of the potential dam (8137 ha) is modelled as having suitable habitat for at least 40% of the 11 'mobile' species modelled (Figure 5-24). The modelled suitable habitat for these water-dependent species upstream of the potential dam site is relatively small; depending on the species, it ranges from 0.04% to 6.8% of its total modelled suitable habitat in the Victoria catchment. The potential for ecological change as a result of changes to the downstream flow regime is examined in Section 7.2.

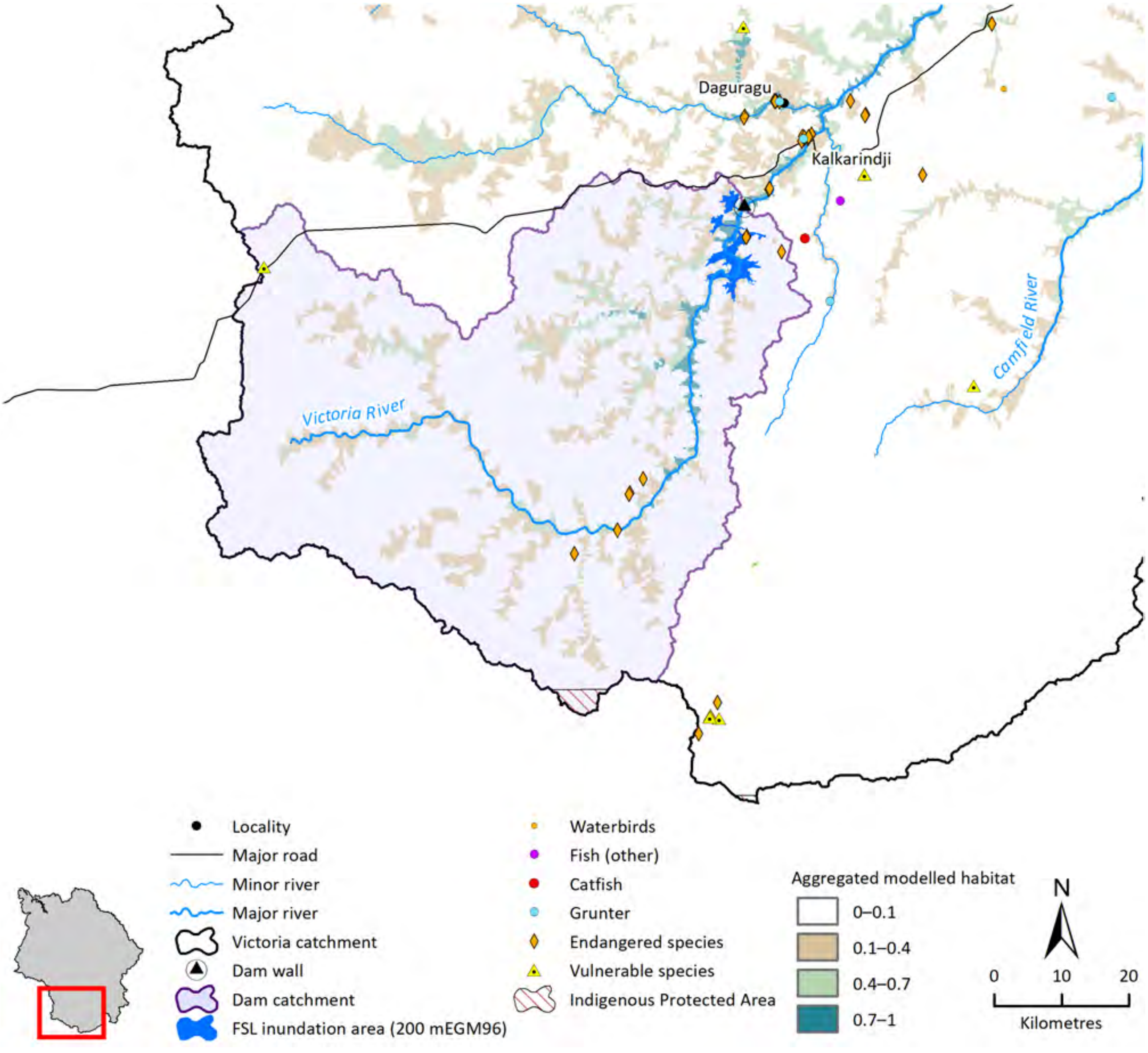

Figure 5-24 Listed species, water-dependent assets and aggregated modelled habitat in the vicinity of the potential dam site on the Victoria River AMTD 283 km

AMTD = adopted middle thread distance; FSL = full supply level.

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, 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.

Broadly speaking, there are two types of weir structure: concrete gravity type weirs and sheet piling weirs. These are discussed below. For each type of weir, rock-filled mattresses are often used on the stream banks, extending downstream of the weir to protect erodible areas from flood erosion. A brief discussion on sand dams is also provided.

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

Concrete gravity type weirs

Where rock bars are exposed at bed level across a stream, concrete gravity type weirs have been built on the rock at numerous locations across northern 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.

Sheet piling weirs

Where rock foundations are not available, stepped steel sheet piling weirs have been successfully used in many locations across Queensland. No sheet piling weirs have been constructed in the NT. 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 5-25). Indicative costs are provided in Table 5-8.

It should be noted, however, that in recent years Queensland Department of Agriculture and Fisheries have not approved stepped weirs in Queensland 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.

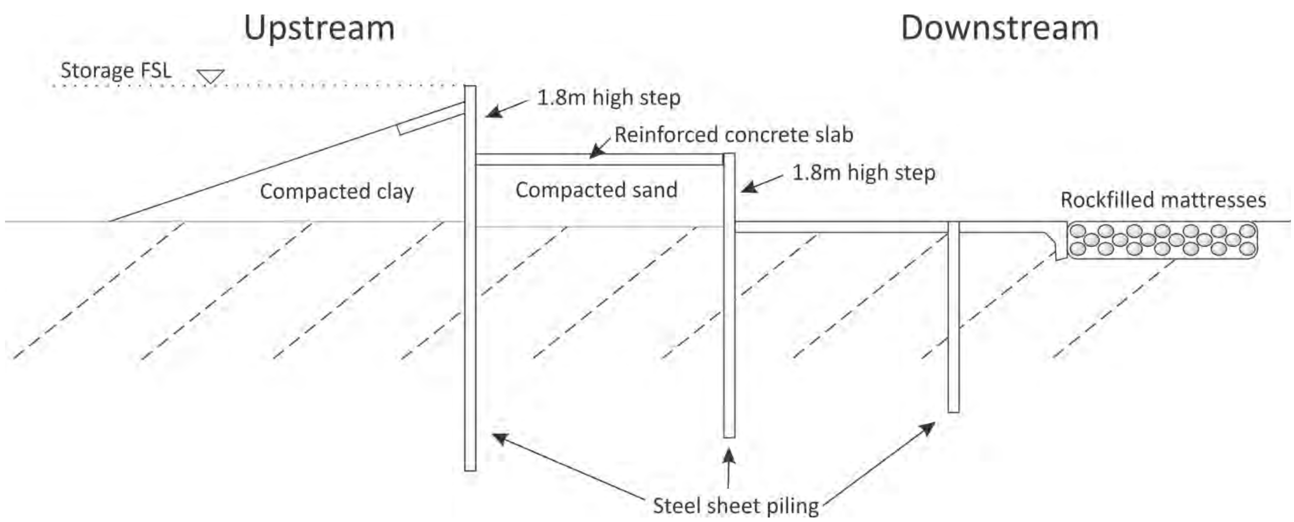

Figure 5-25 Schematic cross-section diagram of sheet piling weir
FSL = full supply level.
Source: Petheram et al. (2013)

Table 5-8 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

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

Typically, sand dams take three to four large excavators about 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 have greater access difficulties. Because sand dams only need to form a pool of sufficient size and depth from which to pump water, they usually only partially span a river and are typically constructed immediately downstream of large, naturally formed waterholes.

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

The application of sand dams in the Victoria catchment is likely to be limited.

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 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 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 Victoria catchment, refer to the companion technical reports on surface water storage (Yang et al., 2024). river modelling simulation (Hughes et al., 2024b) and pump stations (Devlin, 2023). Also of relevance is the Northern Australia Water Resource Assessment technical report on large farm-scale dams (Benjamin, 2018). A rectangular ringtank in the catchment of the Flinders River (Queensland) is pictured in Figure 5-26.

In this section, the following assessments of ringtanks in the Victoria catchment 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 5-26 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 background.
Photo: CSIRO

Suitability of land for ringtanks in the Victoria catchment

Figure 5-27 displays the broad-scale suitability of land for large farm-scale ringtanks in the Victoria catchment. Approximately 8% of the Victoria catchment (488,000 ha) is classed as being potentially suitable. Several land types are likely to be suitable for ringtanks. These include the poorly drained coastal marine clay plains, the cracking clay soils on the alluvial plains of the Victoria River and tributaries, the Cenozoic clay plains of the upper catchment and the black and red Vertosols on the Cambrian basalts.

Very poorly drained saline coastal marine clay plains

The very poorly drained saline coastal marine plains subject to tidal inundation have very deep, strongly mottled, grey non-cracking and cracking clay soils with potential acid-sulfate deposits in the profile. They are likely to be suitable for ringtanks but are subject to storm surge from cyclones.

Very deep alluvial clay plains

The very deep (>1.5 m) alluvial clay plains of the Victoria and upper Baines rivers are predominantly impermeable, imperfectly drained to moderately well-drained grey and brown, hard-setting, cracking clay soils, frequently with small (<0.3 m) normal gilgai depressions. These soils on the Baines River alluvial plains grade to seasonally wet soils along the lower reaches of the river and may be subject to regular flooding. Soils are usually strongly sodic at depth. The clay soils of the middle Victoria River alluvial plains are frequently dissected by severe gully erosion adjacent to the stream channels.

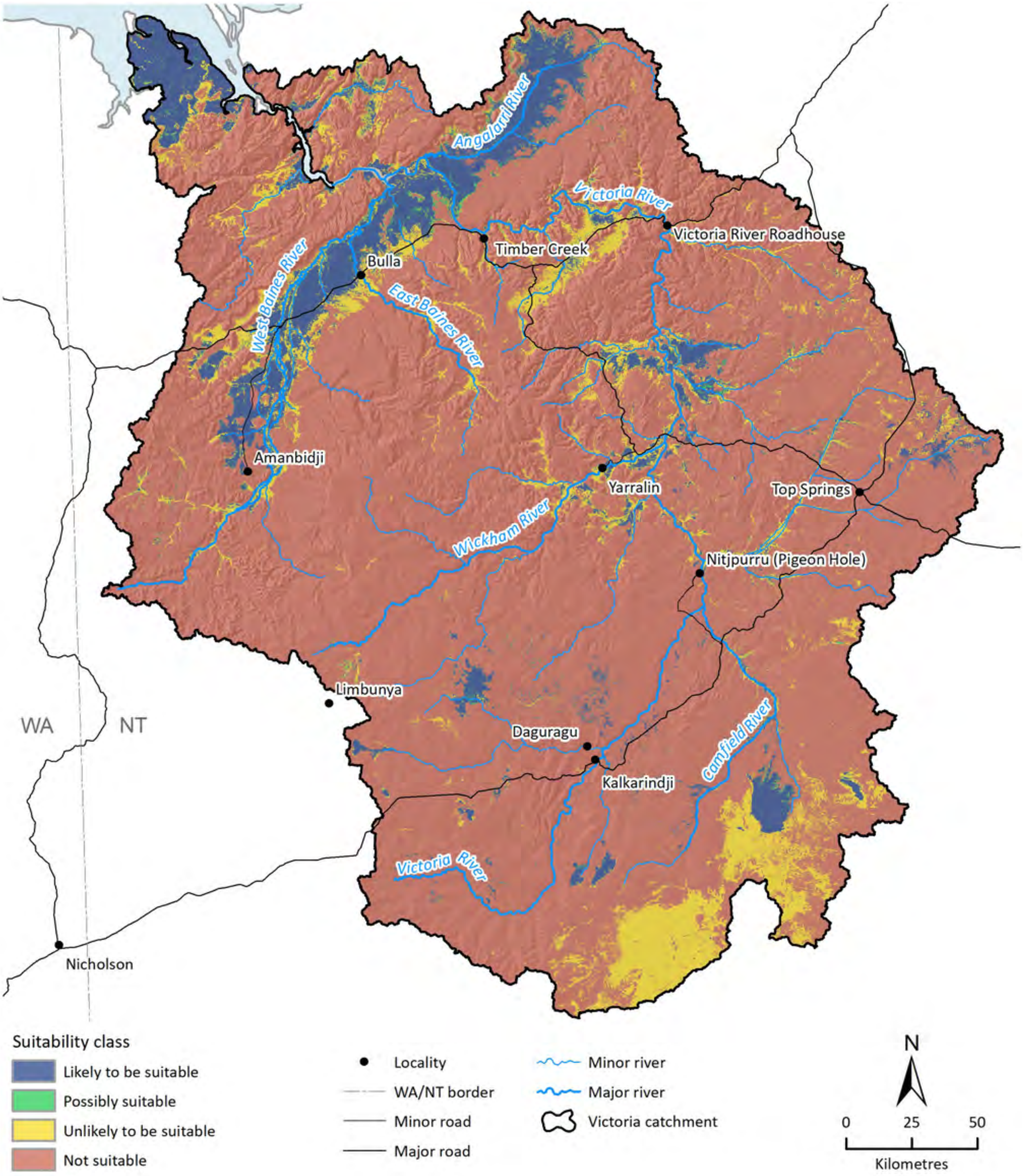

Figure 5-27 Suitability of land for large farm-scale ringtanks in the Victoria catchment

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.

Cenozoic clay plains of the upper catchment

The Cenozoic clay plains are dominated by strongly sodic, impermeable, imperfectly drained self-mulching, grey cracking clay soils grading to moderately well-drained grey-brown clay soils in the lower-rainfall southern parts of the catchment. This relict alluvium deposited over a diverse range of geologies frequently has shallow (0.1 to 0.2 m) normal to linear gilgai and surface gravels/stones of various lithology. It frequently occurs in drainage depressions, enabling collection and storage of overland flows.

Black and red Vertosols on Cambrian basalts

The moderately deep to deep (0.5 to <1.5 m), gilgaied, slowly permeable, non-sodic brown, black and red Vertosols on Cambrian basalts are predominantly gravelly/stony, with slopes greater than 2%, but small areas of 'less rocky' soils occasionally occur on level to very gently undulating plains (slopes <1%) and are likely to be suitable for ringtanks. These less rocky soils are moderately well-drained self-mulching, brown and black cracking clay soils in the north-eastern and far western parts of the catchment, grading to well-drained brown and red clay soils in the lower-rainfall southern part of the catchment. However, such areas are usually small and fragmented.

Reliability of water extraction

The reliability at which an allocation or volume of water can be extracted from a river depends upon a range of factors including the:

- quantity of discharge and the natural inter- and intra-variability 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)
  - a 'diversion commencement requirement', which is the minimum flow that must pass a specified node in the river model before pumping can commence each water year (1 September to 31 August). In the Victoria catchment, this is the point at which the Victoria River discharges into the Joseph Bonaparte Gulf, referred to hereafter as the 'end-of-system'.

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 perturbations 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 reliability of water extraction under different conditions and at different locations in the Victoria catchment is detailed in the companion technical report for river modelling (Hughes et al., 2024b). A selection of plots from that report are provided below to illustrate key concepts.

Figure 5-28 can be used to explore the reliability of extracting ('harvesting') or diverting increasing volumes of water at five locations in the Victoria catchment 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 whole catchment 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). This example assumes a 30-day pump capacity, that is, the system and reach target volumes (i.e. nominal entitlement volume) that can be pumped in 30 days (not necessarily consecutive). This means an irrigator with a 3 GL ringtank would need a pump capacity of 100 ML/day to fill their ringtank in 30 days. In this example there is no end-of-system flow requirement.

The impacts of pump start thresholds and end-of-system flow requirements on extraction reliability are explored because these environmental flow provisions are among the least complex to regulate and ensure compliance in very 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 the course of a single season) and more difficult for regulators to ensure compliance. Within each river reach, water could be harvested by one or more hypothetical water harvesters and the water nominally stored in ringtanks adjacent to the river reach. The locations of the hypothetical extractions are illustrated in the map in the bottom right corners of Figure 5-28 to Figure 5-34. Their relative proportions of the total system allocation (left vertical axis) were assigned based on joint consideration of area of crop versatility, broad-scale flooding, ringtank suitability and river discharge (see companion technical report on river modelling (Hughes et al., 2024b)).

At the smallest pump start threshold examined, 200 ML/day (nominally representative of a lower physical pumping limit), more than 800 GL of water can be extracted in the Victoria catchment in 75% of years. However, insufficient soil is suitable for irrigated agriculture in close proximity (~5 km) to the rivers to fully use this volume of water for irrigated agriculture. The hashed shading (diagonal white lines) in Figure 5-28 indicates where the system target volumes are in excess of that required to irrigate the area of land suitable for irrigated agriculture (assuming 10 ML is required to be extracted per hectare). This figure shows that, as the total system and reach targets increase, the extraction reliability for the full system and reach targets decreases. Similarly, as the pump start threshold increases, the extraction reliability for the full system and reach targets decreases.

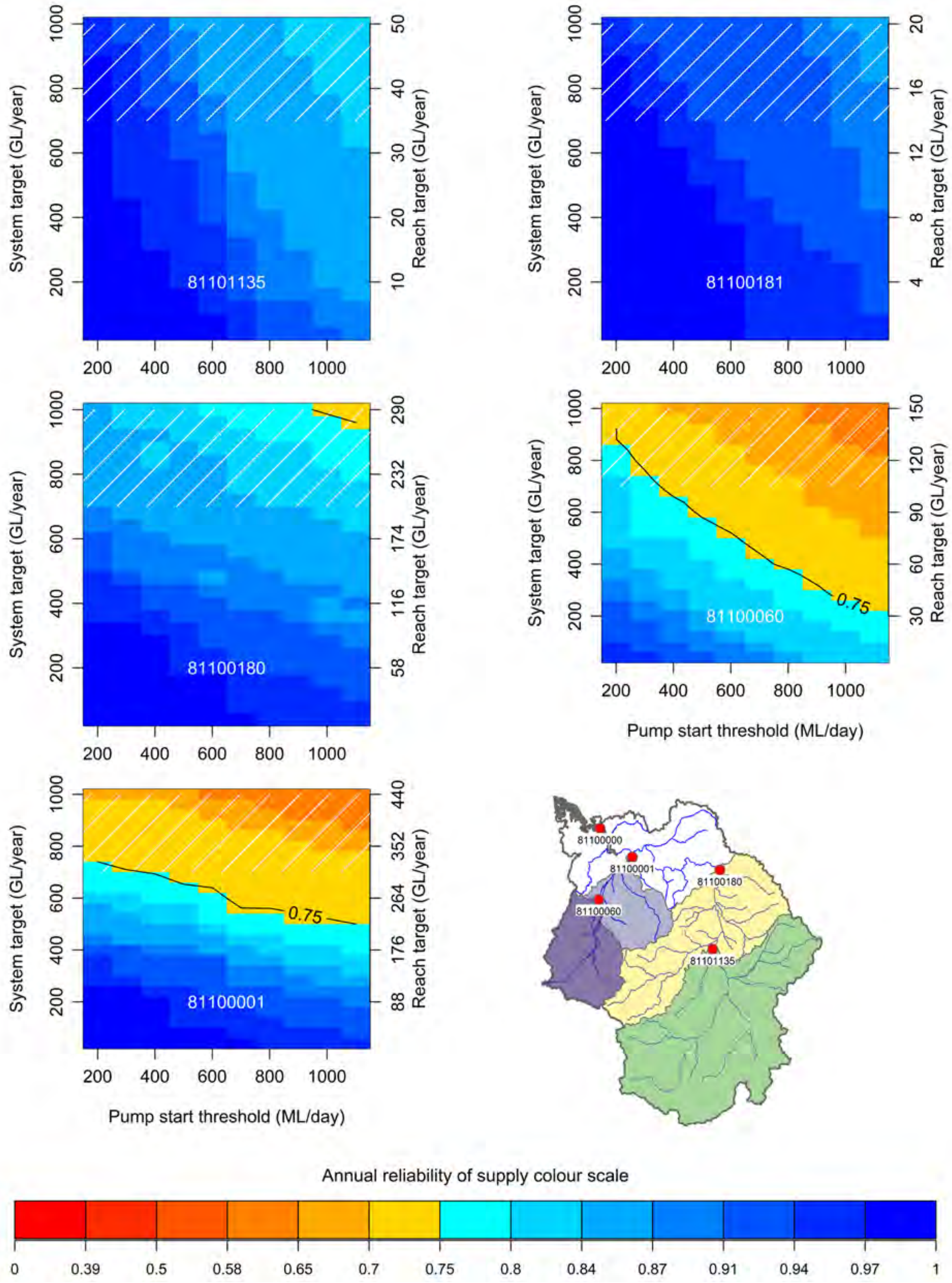

Figure 5-28 Annual reliability of diverting annual system and reach target volumes for varying pump start thresholds

No end-of-system flow requirement before pumping can commence. Cross-shading indicates volumes of water for which there is insufficient soil suitable for irrigated agriculture in close proximity to the river. Eight-digit numbers refer to model node locations. For more detail see companion technical report on river modelling (Hughes et al., 2024b).

The data presented in Figure 5-30 and Figure 5-31 are similar to those presented in Figure 5-28, but in Figure 5-30 and Figure 5-31 an additional extraction condition is imposed: 500 GL (Figure 5-30) and 700 GL (Figure 5-31), respectively, have to flow past the end of the system (node 81100000) each wet season before any water can be extracted. These figures show that increasing the end-of-system flow requirement reduces the extraction reliability for the system and reach targets.

Figure 5-32 and Figure 5-33 show how median (50% exceedance) annual streamflow and 80% exceedance annual streamflow vary under different levels of extraction and different end-of-system flow requirements. These plots show median annual flow is sensitive to irrigation target and insensitive to end-of-system requirements (Figure 5-32). However, 80% exceedance annual flows are sensitive to both irrigation target volumes and end-of-system requirements (Figure 5-33) illustrating that end-of-system requirements have some utility in ‘preserving’ flow in drier years.

Figure 5-34 shows the relationship between the reliability of achieving system and reach target volumes and pump capacity, expressed in days to pump target. With a pump start threshold of 1000 ML/day and an annual end-of-system flow requirement of 500 GL, large pump capacities (i.e. 10 days or less) are required to extract the system and reach targets in 75% of years or greater.

Figure 5-29 Victoria River has the second largest median annual streamflow of any river in the NT

Photo: CSIRO – Nathan Dyer

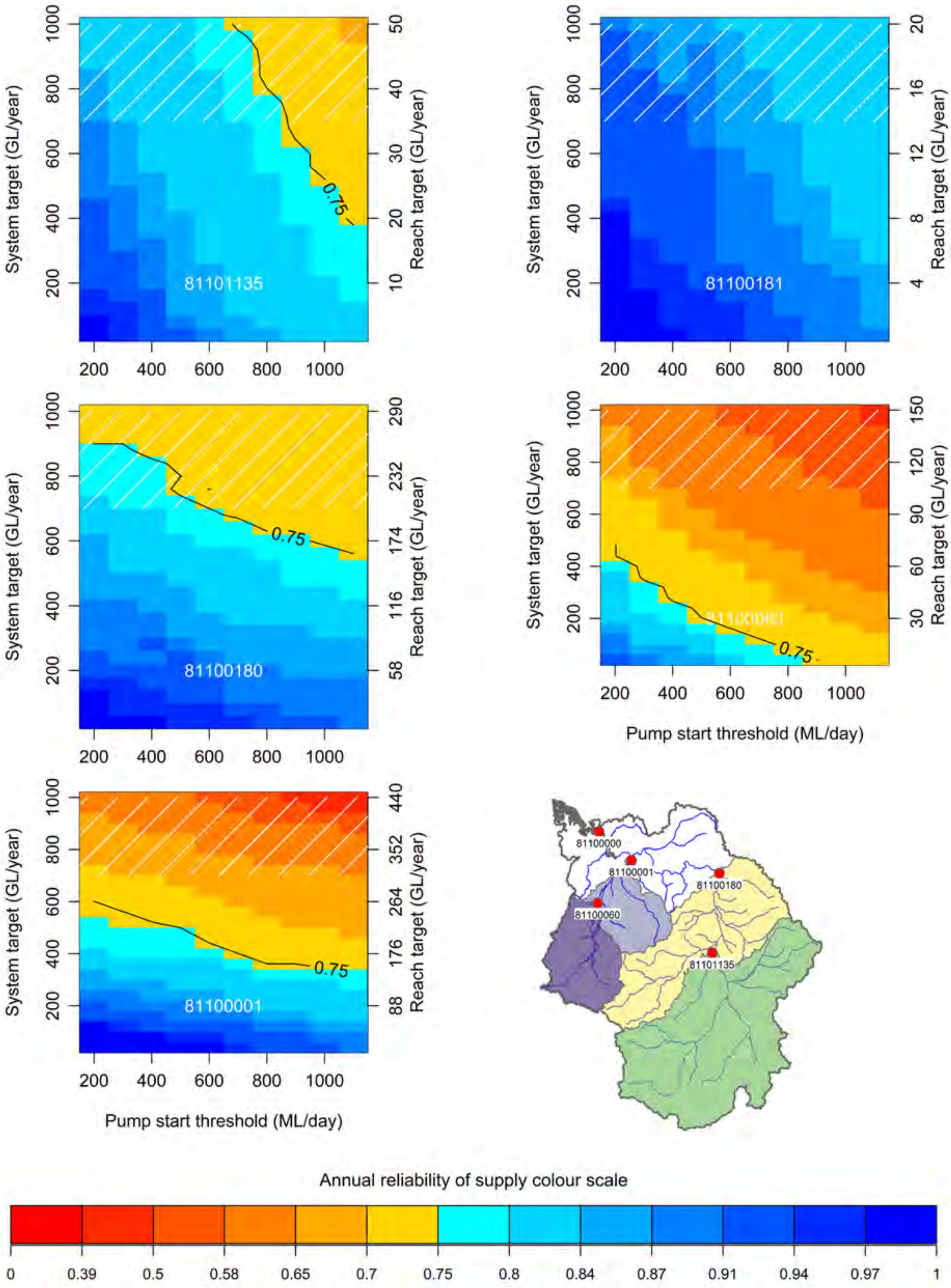

Figure 5-30 Annual reliability of diverting annual system and reach target volumes for varying pump start thresholds assuming end-of-system flow requirement before pumping can commence is 500 GL

Assumes pumping capacity of 30 days (i.e. system and reach targets can be pumped in 30 days). Diagonal white lines indicates volumes of water for which there is insufficient soil suitable for irrigated agriculture in close proximity to the river. Eight-digit numbers refer to model node locations. For more detail see companion technical report on river modelling (Hughes et al., 2024b).

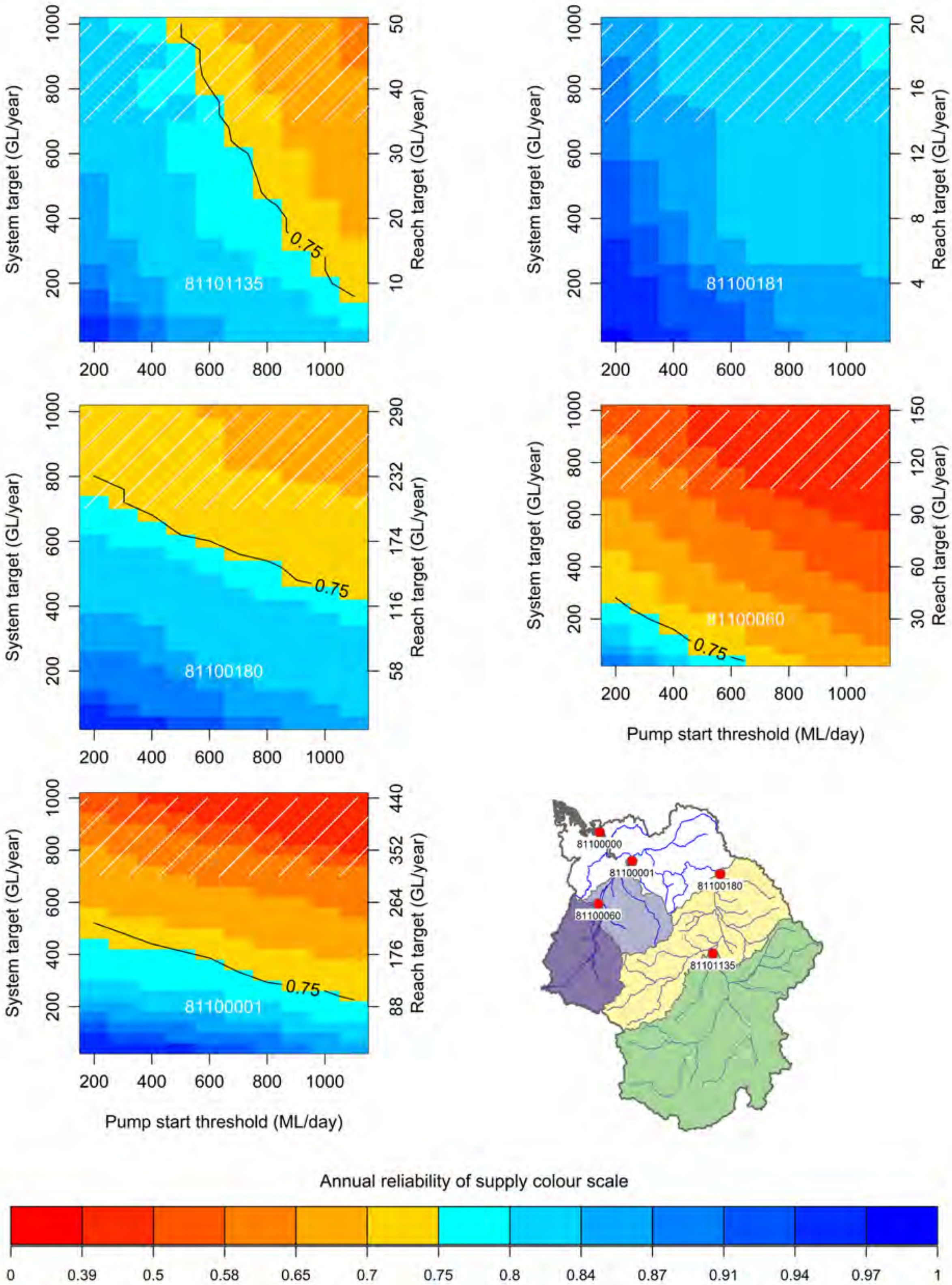

Figure 5-31 Annual reliability of diverting annual system and reach target volumes for varying pump start thresholds assuming end-of-system flow requirement before pumping can commence is 700 GL

Assumes pumping capacity of 30 days (i.e. system and reach targets can be pumped in 30 days). Diagonal white lines indicates volumes of water for which there is insufficient soil suitable for irrigated agriculture in close proximity to the river. Eight-digit numbers refer to model node locations. For more detail see companion technical report on river modelling (Hughes et al., 2024b).

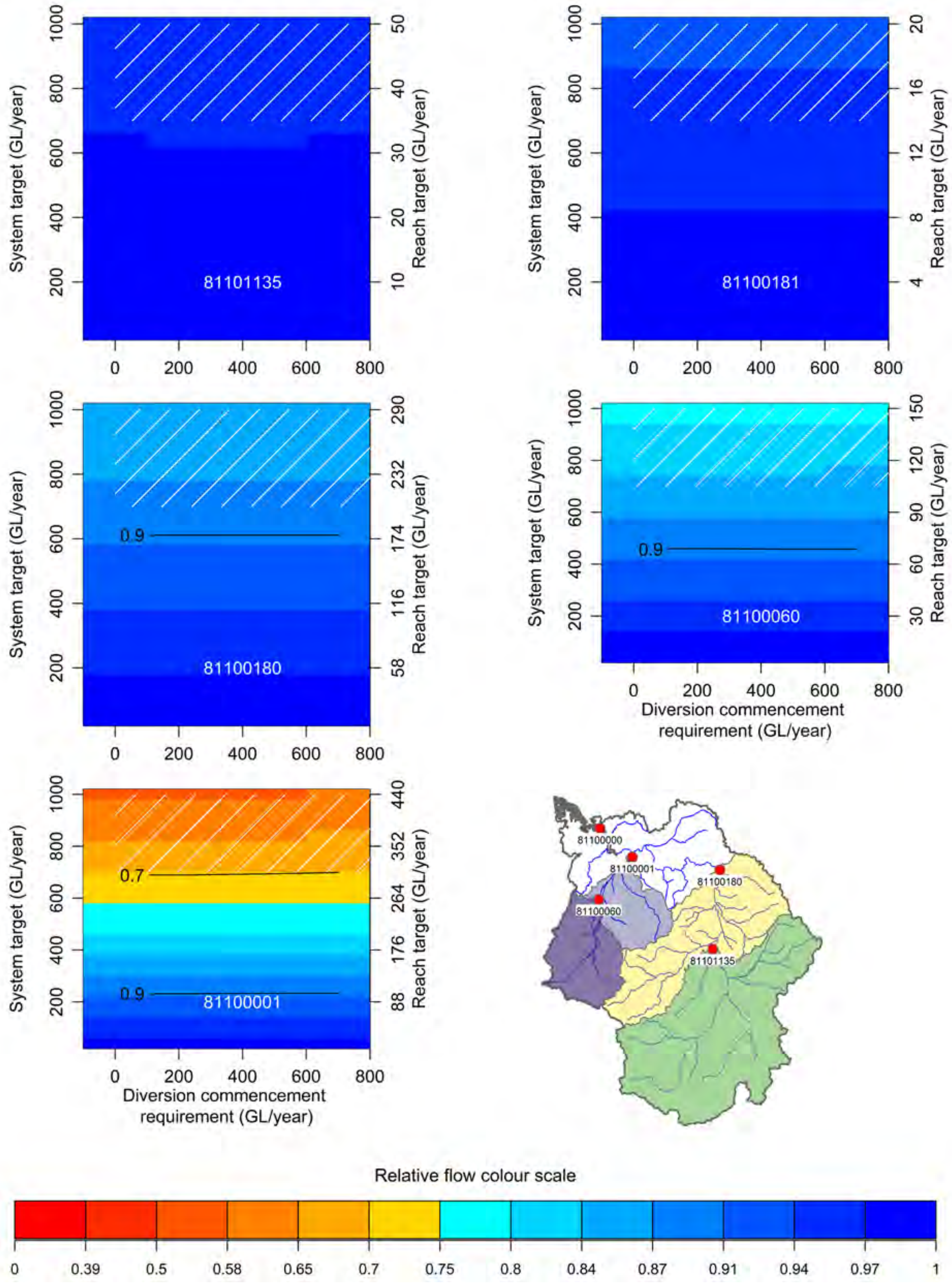

Figure 5-32 50% annual exceedance (median) streamflow relative to Scenario A in the Victoria catchment for varying end-of-system (EOS) requirements assuming a pump start threshold of 1000 ML/day and a pump capacity of 30 days

Diagonal white lines indicates volumes of water for which there is insufficient soil suitable for irrigated agriculture in close proximity to the river. Eight-digit numbers refer to model node locations. For more detail see companion technical report on river modelling (Hughes et al., 2024b).

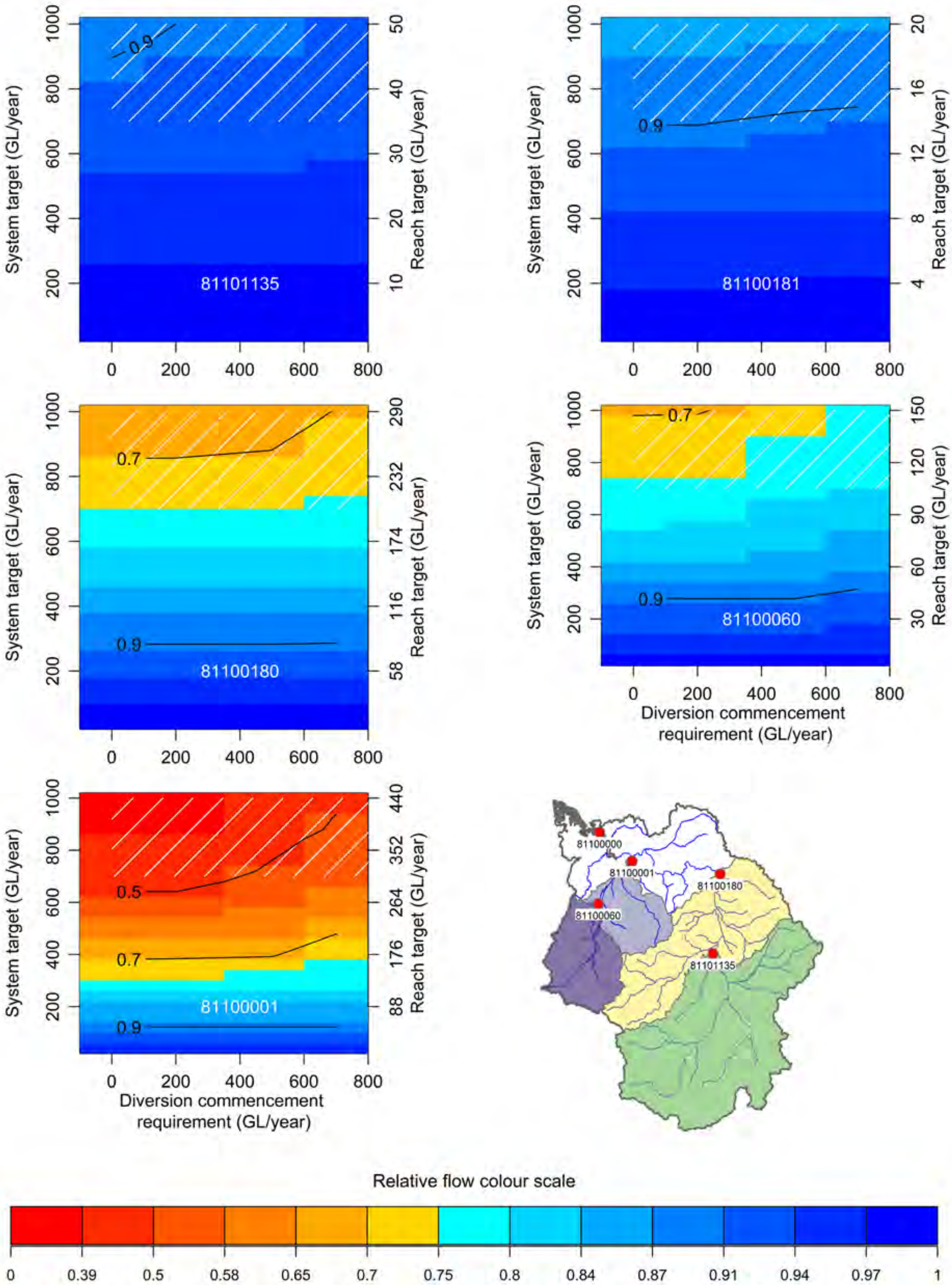

Figure 5-33 80% annual exceedance streamflow relative to Scenario A in the Victoria catchment for varying end-of-system (EOS) requirements assuming a pump start threshold of 1000 ML/day and a pump capacity of 30 days

Diagonal white lines indicates volumes of water for which there is insufficient soil suitable for irrigated agriculture in close proximity to the river. Eight-digit numbers refer to model node locations. For more detail see companion technical report on river modelling (Hughes et al., 2024b).

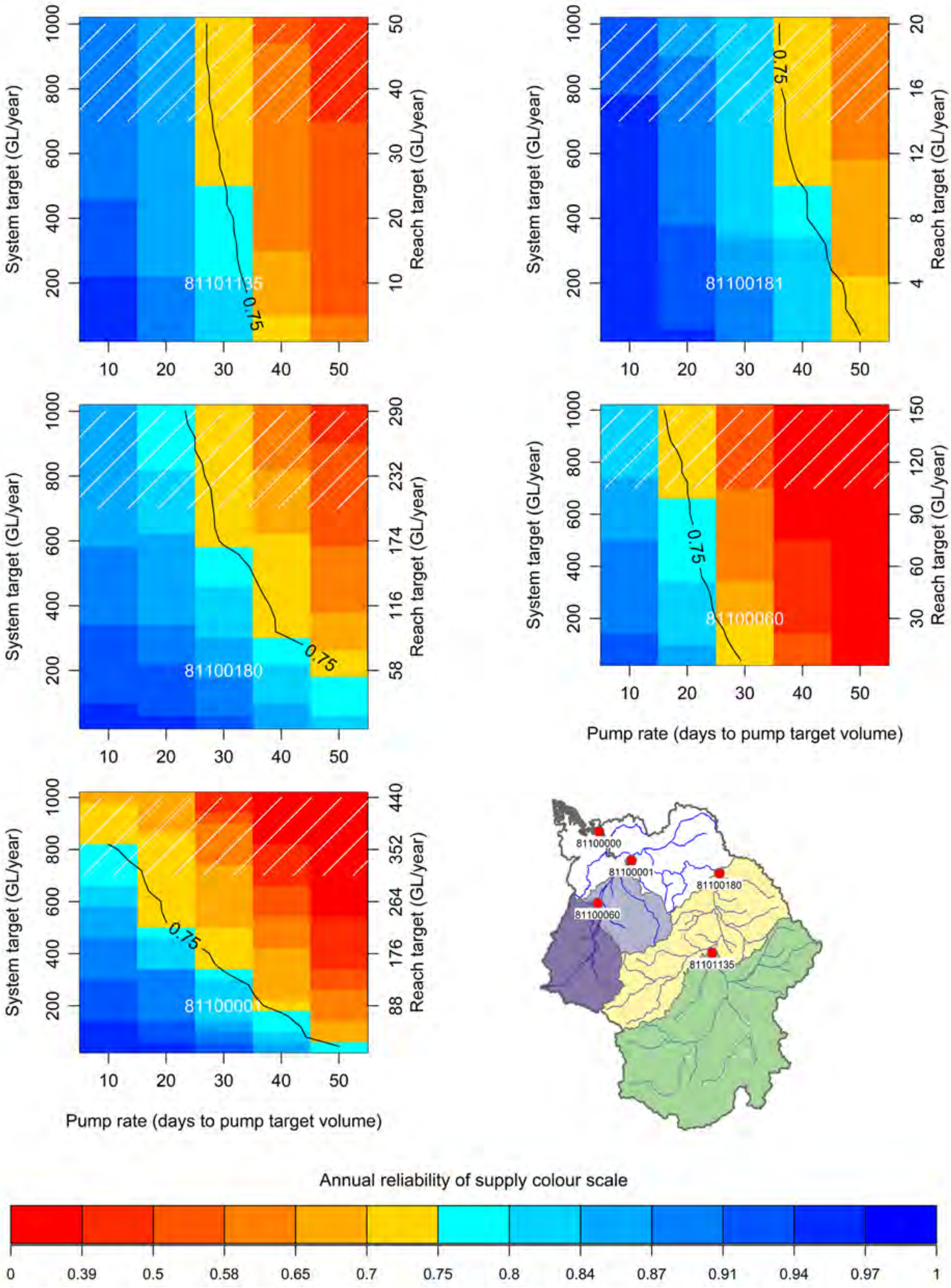

Figure 5-34 Annual reliability of diverting annual system and reach targets for varying pump rates assuming a pump start flow threshold of 1000 ML/day

End-of-system flow requirement before pumping can commence is 500 GL. Diagonal white lines indicates volumes of water for which there is insufficient soil suitable for irrigated agriculture in close proximity to the river. Eight-digit numbers refer to model node locations. For more detail see companion technical report on river modelling (Hughes et al., 2024b).

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 of 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 if 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 (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 5-9, 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, more than half the stored volume (56%) would be lost to evaporation and seepage. The example provided in Table 5-9 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 5-9 Effective volume after net evaporation and seepage for hypothetical ringtanks of three mean water depths, under three seepage rates, near the Victoria River Downs in the Victoria catchment

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	2923	73	2393	60	1777	44
	14:1	2	2756	69	2159	54	1441	36
	14:1	5	2254	56	1456	36	435	11
6	7.5:1	1	3359	84	3044	76	2676	67
	7.5:1	2	3260	82	2906	73	2478	62
	7.5:1	5	2964	74	2490	62	1883	47
8.5	5:1	1	3554	89	3335	83	3079	77
	5:1	2	3486	87	3239	81	2941	74
	5:1	5	3281	82	2952	74	2530	63

†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 5.4.5), it is also considerably more expensive to double the height of an embankment wall than double its length due to the low angle of the walls of the embankment (often at a 3:1 ratio, horizontal to vertical).

Table 5-10 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, and this may increase the construction costs presented in Table 5-10 and Table 5-11 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 and pumping infrastructure costs see the Northern Australia Water Resource Assessment technical report on large farm-scale dams (Benjamin, 2018) and the Victoria and Southern Gulf Water Resource Assessment technical report on pumping infrastructure (Devlin, 2023).

Table 5-10 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. Costs indexed to 2023. Pump station operation and maintenance (O&M) costs assume cost of diesel of \$1.49/L.

SITE DESCRIPTION/ CONFIGURATION	EARTHWORKS COSTS (\$)	GOVERNMENT PERMITS AND FEES (\$)	INVESTIGATION AND DESIGN FEES (\$)	PUMP STATION (\$)	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 lives to be compared. The total equivalent annual costs for the construction and operation of a 1000 ML ringtank with 4.25 m high embankments and 55 ML/day pumping infrastructure is about $143,600 (Table 5-11). For a 4000 ML ringtank with 4.25 m high embankments and 160 ML/day pumping infrastructure, the total equivalent annual cost is about $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 about $457,600.

Table 5-11 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 2023. 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 short 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 an mean water depth of 3.5 m (embankment height of 4.25 m) lose a higher percentage of their capacity to evaporation and seepage than ringtanks of equivalent capacity with mean water depth of 6 m (embankment height of 6.75 m) (Table 5-9); their annualised unit costs are lower (Table 5-12) due to the considerably lower cost of constructing embankments with lower walls (Table 5-11).

In Table 5-12 the levelised cost (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 5-12 Levelised costs for two hypothetical ringtanks of different capacities under three seepage rates near Victoria River Downs in the Victoria catchment

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 assuming earthfill and compacted clay costs of $\$5/m^3$ and $\$6.50/m^3$, respectively. Earthwork costs include vegetation clearing, mobilisation/demobilisation of machinery and contractor accommodation. 1000 ML ringtank reservoir has surface area of 27 ha and storage volume to excavation ratio of about 7:1. 4000 ML ringtank and 4.25 m embankment height reservoir has surface area of 110 ha and storage volume to excavation ratio of about 14:1. 4000 ML ringtank with 6.75 m embankment height reservoir has surface area of 64 ha and storage volume to excavation ratio of about 7.5:1. 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 ($/My)	LEVELISED COST ($/ML)
			5 months (April to August)	**7 months (April to October)**	**10 months (April to January)**
1000 ML and 4.25 m	143,580	1	196	240	323
	143,580	2	208	266	399
	143,580	5	255	394	1321
4000 ML and 4.25 m	301,550	1	359	396	451
	301,550	2	370	415	487
	301,550	5	407	484	641
4000 ML and 6.75 m	457,600	1	515	549	595
	457,600	2	525	565	622
	457,600	5	558	620	724

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. Dams with a crest height of over 10 or 12 m typically require some form of downstream batter drainage incorporated into embankments. Large farm-scale gully dams typically have a maximum catchment area of about 40 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 5-36 indicates those locations where it is more topographically and hydrologically favourable to construct large farm-scale gully dams in the Victoria catchment and the likely density of options. This analysis 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 5-37. 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 Victoria catchment 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, cement and imported clay soils, increasing the cost of their construction.

Figure 5-35 Julius Dam on the Leichhardt River

Photo: CSIRO

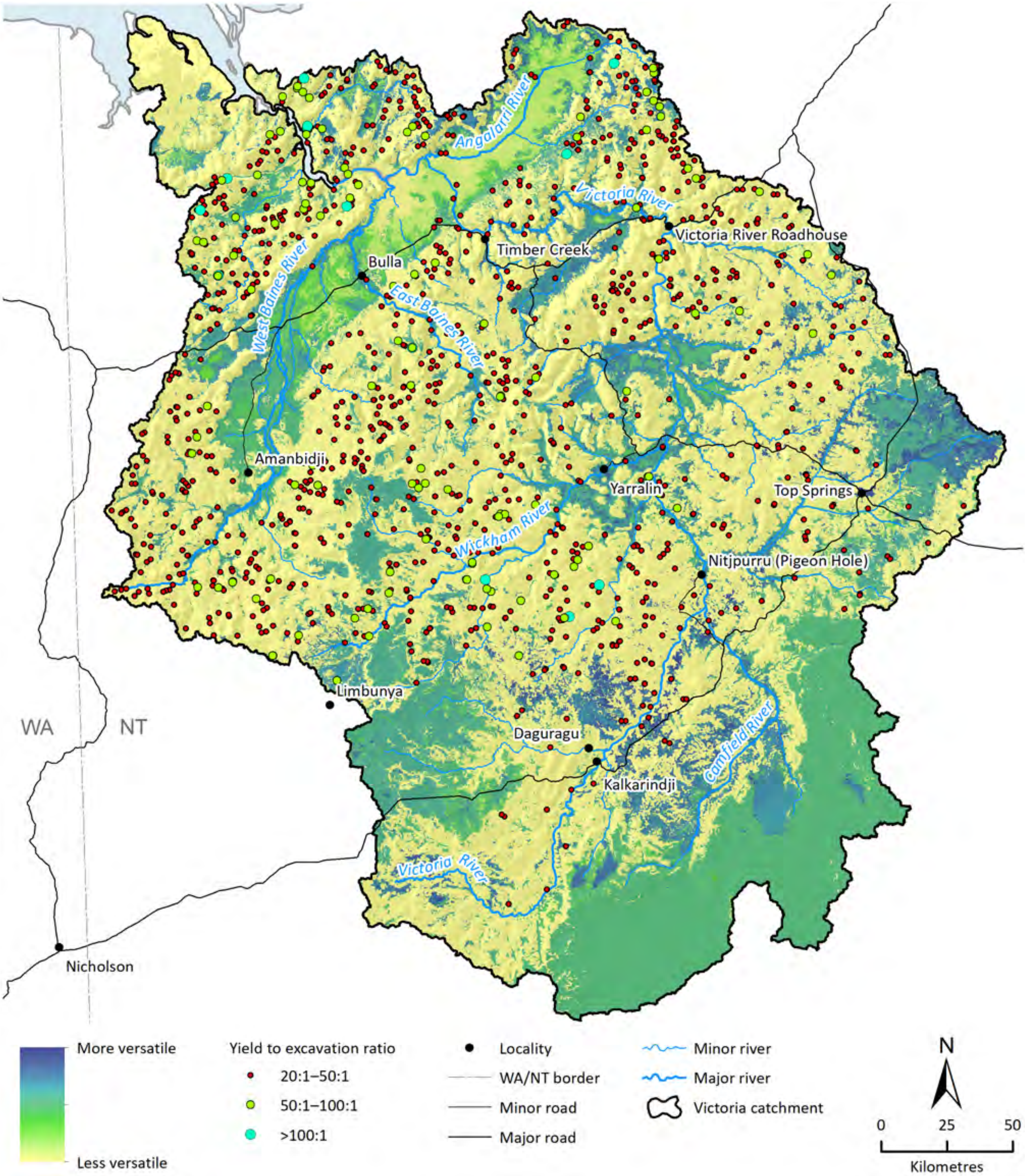

Figure 5-36 Most economically suitable locations for large farm-scale gully dams in the Victoria catchment

Gully dam data overlaid on agricultural versatility data (see Section 4.2.3). Agricultural versatility data indicate those parts of the catchment that are more or less versatile for irrigated agriculture. For the gully dam analysis, soil and subsurface data were only available to a depth of 1.5 m, hence this Assessment does not consider the suitability of subsurface material below this depth. Sites with catchment areas greater than 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. Site-specific investigations by a suitably qualified professional should always be undertaken prior to dam construction.

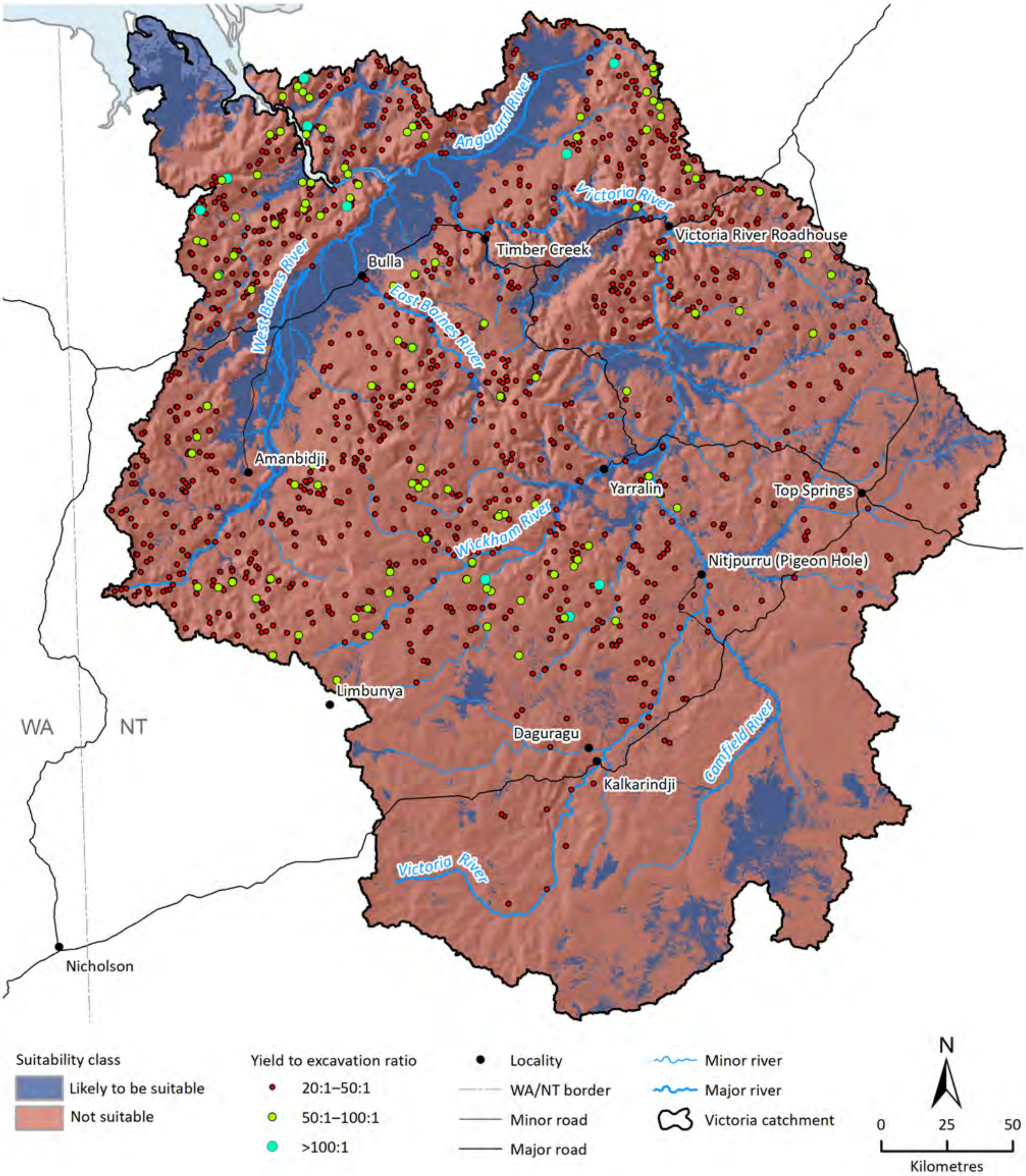

Figure 5-37 Suitability of soils for construction of gully dams in the Victoria catchment

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 5 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 5-13.

Table 5-13 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)	COMMENTS
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	2,323	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	Georgetown	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 (4000 ML) capacity farm-scale gully dam configurations is provided in Table 5-14 and a high-level breakdown of the major components of the capital costs for each of the three configurations is provided in Table 5-15. 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 5-14 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	CATCH-MENT 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 5-15 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)	1770,000	50,000	117,000	1,937,000

Table 5-16 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 Victoria catchment.

Table 5-16 Effective volumes and cost per megalitre for three 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

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	CONSTRUCTION COST ($)	COST ($/ML)	SEEPAGE LOSS (mm/d)	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 m and 133 ha	1,250,000	250	1	3087	77	2639	66	2113	53
	1,250,000	250	2	2946	74	2441	61	1830	46
	1,250,000	250	5	2522	63	1847	46	979	24
6 m and 66 ha	1,900,000	375	1	3545	89	3321	83	3057	76
	1,900,000	375	2	3475	87	3223	81	2917	73
	1,900,000	375	5	3265	82	2929	73	2496	62
9 m and 44 ha	2,500,000	500	1	3692	92	3540	88	3361	84
	2,500,000	500	2	3644	91	3474	87	3266	82
	2,500,000	500	5	3503	88	3276	82	2983	75

Based on the information presented in Table 5-14, 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 5-17 and Table 5-18).

Table 5-17 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. Costs indexed to 2023.

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	214,500	75,000	290,000

Table 5-18 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 5-17. 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	405	47	474	55	592	69
	144,800	2	424	49	512	59	683	79
	144,800	5	496	57	677	78	1277	148
6 m and 66 ha	220,000	1	536	62	572	66	622	72
	220,000	2	547	63	590	68	651	75
	220,000	5	582	67	649	75	761	88
9 m and 44 ha	290,000	1	677	78	706	82	744	86
	290,000	2	686	79	720	83	765	89
	290,000	5	714	83	763	88	838	97

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 a ringtank of equivalent capacity.

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 5-9 and assuming minimal leakage (i.e. 1 mm/day), approximately 74%, 61% and 50% 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. Costs of reticulation infrastructure are highly site specific. Examples for two locations in the Victoria catchment are provided in the companion technical report on irrigation scheme design and costs (Devlin, 2024).

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 Victoria catchment. 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 5-19 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 5-19. 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 5-19 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 5-20.

The conveyance efficiencies in Table 5-20 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 5-20 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† (%)	COMMENTS
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 Victoria catchment, 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 8000 ML was delivered to irrigators, then the conveyance efficiency was 80% and the conveyance losses were 20%.

Figure 5-38 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.

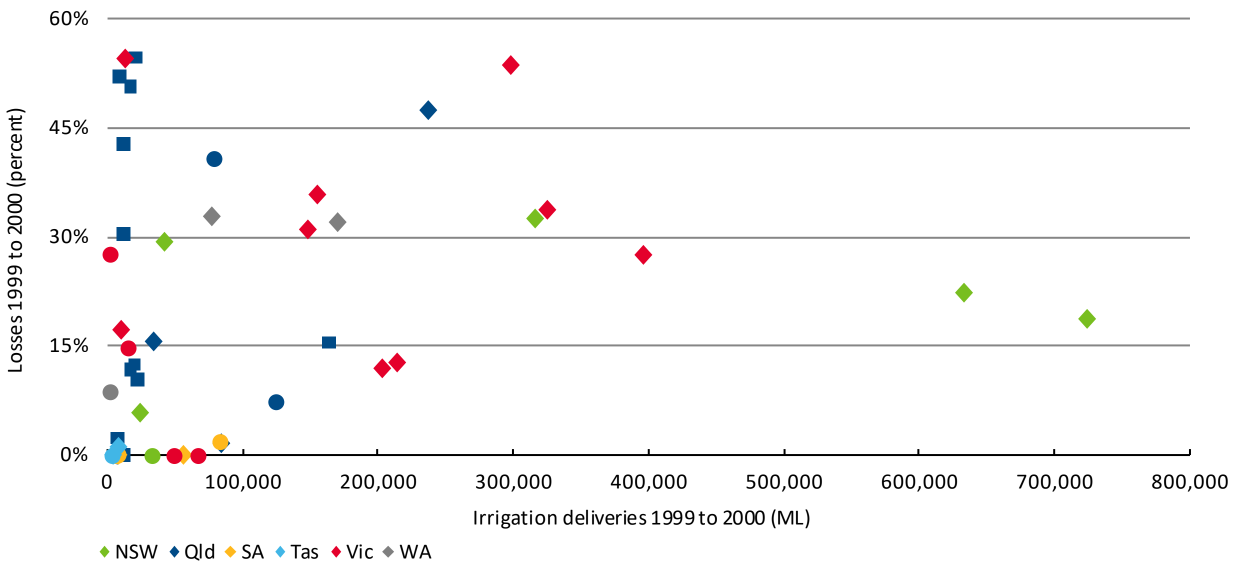

Figure 5-38 Reported conveyance losses from irrigation systems across Australia

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 Victoria catchment: surface irrigation, spray irrigation and micro irrigation (Figure 5-39). Irrigation systems applied in the Victoria catchment need to be tailored to the soil, climate and crops that may be grown in the catchment and matched to the availability of water for irrigation. This is taken into consideration in the land suitability assessment figures presented in Section 4.2. System design will also need to consider investment risk in irrigation systems as well as likely returns, degree of automation, labour availability and O&M costs (e.g. the cost of energy).

Irrigation systems have a trade-off between efficiency and cost. Table 5-21 summarises the different types of irrigation systems, 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 5-21) 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 systems follow Table 5-21.

(a) (b) (c)

Figure 5-39 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%.
Photos: CSIRO

Table 5-21 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/micro sprinklers	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 Victoria catchment 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 soils adjacent to the Victoria River and its 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 Victoria catchment, 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 5-21). 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 Victoria catchment. 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 Victoria catchment.

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 or micro sprinklers. 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 5-21). 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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