River model scenario analysis for the Victoria catchment

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

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Aspects of the Assessment have been undertaken in conjunction with the NT Government.

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. Jorge Pena-Arancibia (CSIRO) and Dr. Shaun Kim (CSIRO).

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

Timber Creek, NT. Source: CSIRO

Director’s foreword

Sustainable development and regional economic prosperity are priorities for the Australian and Northern Territory (NT) governments. However, more comprehensive information on land and water resources across northern Australia is required to complement local information held by Indigenous Peoples and other landholders.

Knowledge of the scale, nature, location and distribution of likely environmental, social, cultural and economic opportunities and the risks of any proposed developments is critical to sustainable development. Especially where resource use is contested, this knowledge informs the consultation and planning that underpin the resource security required to unlock investment, while at the same time protecting the environment and cultural values.

In 2021, the Australian Government commissioned CSIRO to complete the Victoria River Water Resource Assessment. In response, CSIRO accessed expertise and collaborations from across Australia to generate data and provide insight to support consideration of the use of land and water resources in the Victoria catchment. The Assessment focuses mainly on the potential for agricultural development, and the opportunities and constraints that development could experience. It also considers climate change impacts and a range of future development pathways without being prescriptive of what they might be. The detailed information provided on land and water resources, their potential uses and the consequences of those uses are carefully designed to be relevant to a wide range of regional-scale planning considerations by Indigenous Peoples, landholders, citizens, investors, local government, and the Australian and NT governments. By fostering shared understanding of the opportunities and the risks among this wide array of stakeholders and decision makers, better informed conversations about future options will be possible.

Importantly, the Assessment does not recommend one development over another, nor assume any particular development pathway, nor even assume that water resource development will occur. It provides a range of possibilities and the information required to interpret them (including risks that may attend any opportunities), consistent with regional values and aspirations.

All data and reports produced by the Assessment will be publicly available.

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Chris Chilcott

Project Director

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Shortened forms

SHORT FORM	FULL FORM
ALOS	Advanced Land Observing Satellite
APSIM	Agricultural Production Systems sIMulator
ARWA-L	Australian Water Resources Assessment Landscape
AWRA-R	Australian Water Resources Assessment River
AWRC	Australian Water Resources Council
CMIP	Coupled Model Intercomparison Project
DCFR	diversion commencement flow requirement
ET	evapotranspiration
FSL	full supply level
GCM	General circulation model
GRASP	Grass Production Model
IQQM	Integrated Water Quality and Quantity Model
NASY	Northern Australia Sustainable Yields
PS	pattern scaling
RR	rainfall-runoff
SILO	Scientific Information for Land Owners
SSP	Shared Socioeconomic Pathway
WAVES	Water and Vegetation, Energy and Solute model

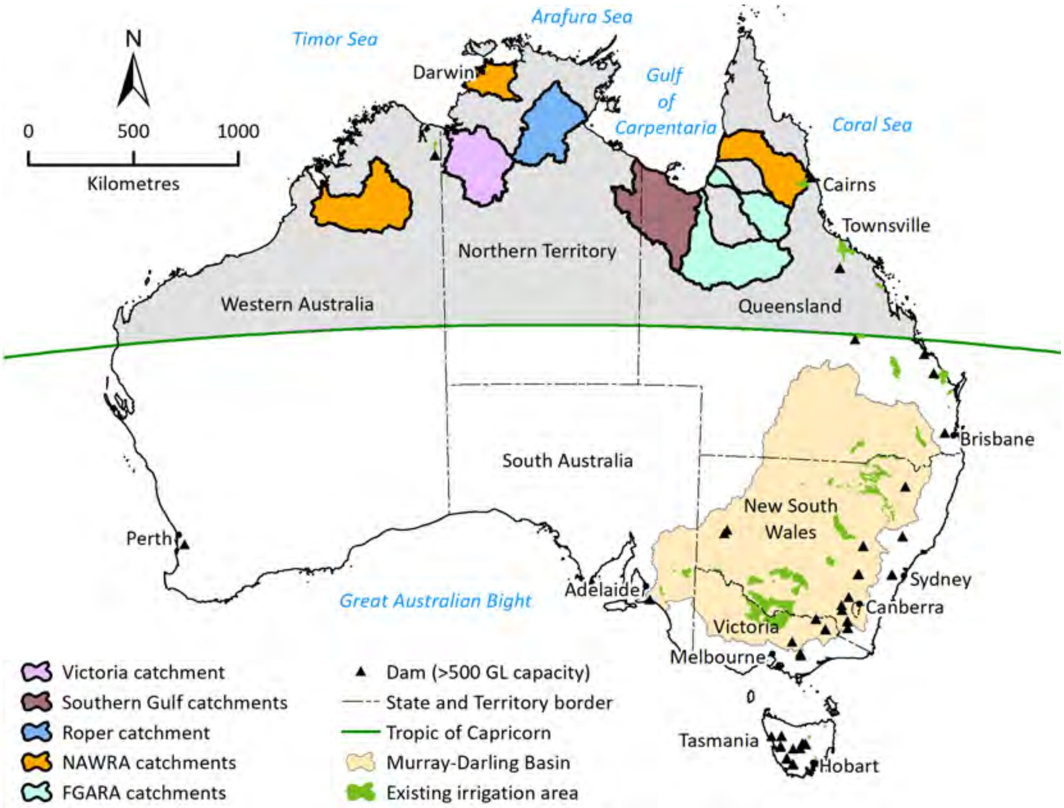
Units

UNIT	DESCRIPTION
d	day
GL	gigalitre
ha	hectare
km	kilometre
m	metre
mAHD	metres above Australian Height Datum
mEMG96	an elevation datum (metres)
ML	megalitre
mm	millimetre
y	year

Preface

Sustainable development and regional economic prosperity are priorities for the Australian and NT governments and science can play its role. Acknowledging the need for continued research, the NT Government (2023) announced a Territory Water Plan priority action to accelerate the existing water science program 'to support best practice water resource management and sustainable development.'

Governments are actively seeking to diversify regional economies, considering a range of factors. For very remote areas like the Victoria catchment (Preface Figure 1-1), the land, water and other environmental resources or assets will be key in determining how sustainable regional development might occur. Primary questions in any consideration of sustainable regional development relate to the nature and the scale of opportunities, and their risks.



Preface Figure 1-1 Map of Australia showing Assessment area (Victoria catchment and other recent CSIRO Assessments

FGARA = Flinders and Gilbert Agricultural Resource Assessment; NAWRA = Northern Australia Water Resource Assessment.

How people perceive those risks is critical, especially in the context of areas such as the Victoria catchment, where approximately 75% of the population is Indigenous (compared to 3.2% for Australia as a whole) and where many Indigenous Peoples still live on the same lands they have inhabited for tens of thousands of years. About 31% of the Victoria catchment is owned by Indigenous Peoples as inalienable freehold.

Access to reliable information about resources enables informed discussion and good decision making. Such information includes the amount and type of a resource or asset, where it is found (including in relation to complementary resources), what commercial uses it might have, how the resource changes within a year and across years, the underlying socio-economic context and the possible impacts of development.

Most of northern Australia's land and water resources have not been mapped in sufficient detail to provide the level of information required for reliable resource allocation, to mitigate investment or environmental risks, or to build policy settings that can support good judgments. The Victoria River Water Resource Assessment aims to partly address this gap by providing data to better inform decisions on private investment and government expenditure, to account for intersections between existing and potential resource users, and to ensure that net development benefits are maximised.

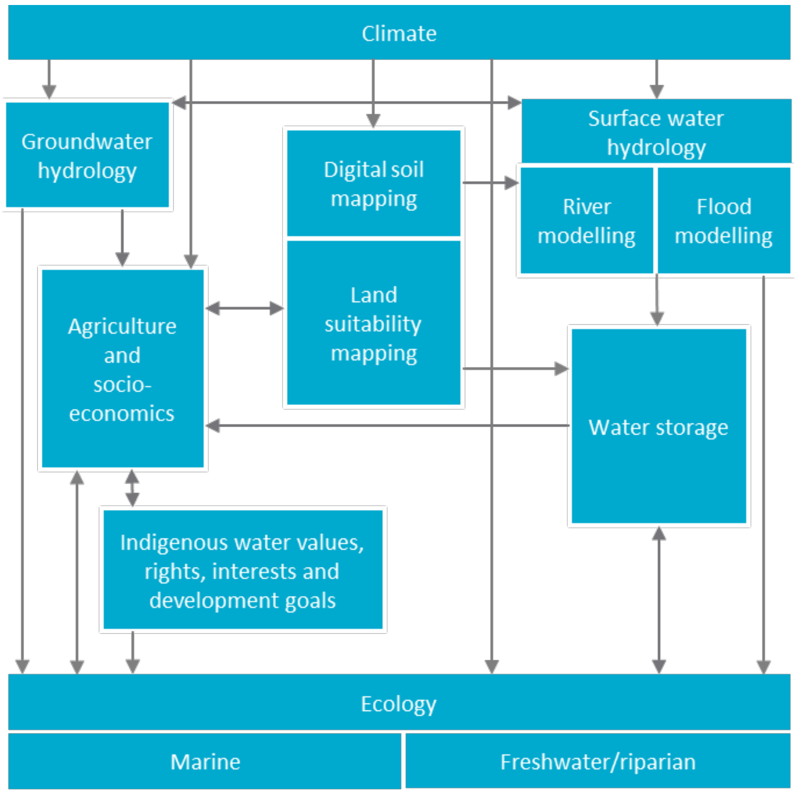
The Assessment differs somewhat from many resource assessments in that it considers a wide range of resources or assets, rather than being a single mapping exercise of, say, soils. It provides a lot of contextual information about the socio-economic profile of the catchment, and the economic possibilities and environmental impacts of development. Further, it considers many of the different resource and asset types in an integrated way, rather than separately. The Assessment has agricultural developments as its primary focus, but it also considers opportunities for and intersections between other types of water-dependent development.

The Assessment was designed to inform consideration of development, not to enable any particular development to occur. The outcome of no change in land use or water resource development is also valid. As such, the Assessment informs – but does not seek to replace – existing planning, regulatory or approval processes. Importantly, the Assessment does not assume a given policy or regulatory environment. Policy and regulations can change, so this flexibility enables the results to be applied to the widest range of uses for the longest possible time frame.

It was not the intention of – and nor was it possible for – the Assessment to generate new information on all topics related to water and irrigation development in northern Australia. Topics not directly examined in the Assessment are discussed with reference to and in the context of the existing literature.

CSIRO has strong organisational commitments to reconciliation with Australia's Indigenous Peoples and to conducting ethical research with the free, prior and informed consent of human participants. The Assessment consulted with Indigenous representative organisations and Traditional Owner groups from the catchment to aid their understanding and potential engagement with its fieldwork requirements. The Assessment conducted significant fieldwork in the catchment, including with Traditional Owners through the activity focused on Indigenous values, rights, interests and development goals. CSIRO created new scientific knowledge about the catchment through direct fieldwork, by synthesising new material from existing information, and by remotely sensed data and numerical modelling.

Functionally, the Assessment adopted an activities-based approach (reflected in the content and structure of the outputs and products), comprising activity groups, each contributing its part to create a cohesive picture of regional development opportunities, costs and benefits, but also risks. Preface Figure 1-2 illustrates the high-level links between the activities and the general flow of information in the Assessment.



Preface Figure 1-2 Schematic of the high-level linkages between the eight activity groups and the general flow of information in the Assessment

Assessment reporting structure

Development opportunities and their impacts are frequently highly interdependent and, consequently, so is the research undertaken through this Assessment. While each report may be read as a stand-alone document, the suite of reports for each Assessment most reliably informs discussion and decisions concerning regional development when read as a whole.

The Assessment has produced a series of cascading reports and information products:

- Technical reports present scientific work with sufficient detail for technical and scientific experts to reproduce the work. Each of the activities (Preface Figure 1-2) has one or more corresponding technical reports.
- A catchment report, which synthesises key material from the technical reports, providing well-informed (but not necessarily scientifically trained) users with the information required to inform decisions about the opportunities, costs and benefits, but also risks associated with irrigated agriculture and other development options.
- A summary report provides a shorter summary and narrative for a general public audience in plain English.
- A summary fact sheet provides key findings for a general public audience in the shortest possible format.

The Assessment has also developed online information products to enable users to better access information that is not readily available in print format. All of these reports, information tools and data products are available online at https://www.csiro.au/victoriariver. The webpages give users access to a communications suite including fact sheets, multimedia content, FAQs, reports and links to related sites, particularly about other research in northern Australia.

Executive summary

Surface water licence volumes within the Victoria River model domain are currently very low (~0.7 GL/year). This equates to less than 0.001% of mean annual end-of-system flow and substantially less than the estimated uncertainty in the surface water model used in this report (Hughes et al., 2024). Developing the surface water resources of this highly seasonal catchment to enable regional economic development, as has occurred in southern Australia, would in many instances require rivers to be regulated and water stored and/or diverted. Since development provides both opportunity and risks, it should only proceed when the size and nature of surface water resources and their coincidence with other bio-physical considerations, such as soil suitable for irrigation and ecological assets, are understood. This report details the key simulations undertaken using the Victoria River model.

The mean and median annual end-of-system flows for the Victoria River at node 81100000 for the reporting period (1890 to 2022) were simulated to be 6994 GL and 5734 GL, respectively. Uncertainty estimated using multiple realisations of acceptable parameters suggests a standard deviation of 10% for these values (Hughes et al., 2024). Note that various other sources of uncertainty, such as rainfall and streamflow observation uncertainty, were not or could not be readily estimated. It is therefore likely that overall uncertainty is higher than estimated here.

The availability of soils suitable for irrigation and ringtank construction in the Victoria catchment is limited, and when considered together with modelled streamflow, the maximum possible annual water harvest volume that could be physically extracted or diverted into offstream storages at a minimum of 75% annual reliability was 687 GL (i.e. ~10% of mean annual flow). However, this figure assumed a very low pump start threshold (200 ML/day) and did not consider any other restrictions due to economic, environmental, cultural or land tenure influences. The harvest volume of 687 GL is considered the physical limit (or upper bound) of the system in terms of water resource development. Water harvest analyses (which model water being extracted or diverted from a river into an offstream storage) indicated that uncertainty in water harvest estimates at a single site suggested higher uncertainty (standard deviation of 20%).

The effects of streamflow at three hypothetical dam sites in the Victoria catchment were evaluated to understand their cumulative water yield and cumulative perturbation to streamflow. These data are used in the companion technical report on ecological analysis to investigate the sensitivity of water-dependent ecosystems to large instream dams. Analyses also evaluated the reduction in dam yield as a result of transparent flow, where water is allowed to 'pass through' a dam to help mitigate potential ecological impacts. It was found that three potential dams operated concurrently could release 591 GL in 85% of years at the dam wall, which is modest relative to the potential to regulate water using potential dams elsewhere in northern Australia. In considering the likelihood of dam-based development in the Victoria catchment, it should also be noted that no large dams have been built in northern Australia west of the Great Dividing Range for the purpose of irrigation for more than 40 years.

Future climate analyses in the Victoria catchment show a large uncertainty in future rainfall projections. The general circulation model future rainfall projections for 32 (GCMs) range from a reduction of about 14% to an increase of 18%. Eight (25%) of the GCM projections indicate an increase in mean annual rainfall by more than 5%, eight (25%) indicate a decrease in mean annual rainfall by more than 5%, and 16 (50%) a change in future mean annual rainfall of less than 5% under a SSP2-4.5 at ~2060 scenario. Potential evaporation is projected to increase from 3% to 10%. Under a dry future climate (Scenario Cdry), the mean annual rainfall is projected to be 7% lower than the historical rainfall (1 September 1890 to 31 August 2022), and under a wet future climate (Scenario Cwet), it is assumed to be 9% higher. Propagating these long-term changes in rainfall (and potential evaporation) through the Victoria River model resulted in changes in mean annual streamflow of –25% and +24% under scenarios Cdry and Cwet, respectively. Under Scenario Cdry, the mean annual discharge at the end-of-system was simulated to be lower than any of the hypothetical water resource development scenarios examined, including those seeking to explore the maximum physically plausible water resource development.

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1 Introduction

Water supplied by regulated surface water resources in southern Australia meets about 70% of Australia's 25,000 GL mean annual water use (CSIRO, 2011). With the overallocation of water to diversion in southern states, the Millennium Drought, and projections of a drier future climate in southern Australia, there is interest in developing the water resources of northern Australia. However, extracting water from rivers, particularly for high water-using industries such as irrigation, can cause large perturbations to streamflow, which can affect existing industries and users and result in ecological change.

A variety of event-based and continuous hydrological modelling frameworks can be used to quantify the water resources of a catchment and examine the trade-offs associated with water regulation and extraction. However, different hydrological modelling frameworks have been developed for different purposes, and they have different data requirements and different levels of complexity.

At their simplest, hydrological models can be simple statistical relationships, typically with few input data requirements, but these simple models can also have a low predictive capacity. At the more complex end are fully distributed physically based models, for which every parameter has physical meaning and can be assigned a measurement. These include soil–vegetation–atmosphere transfer models, such as WAVES (Zhang and Dawes, 1988) and TOPOG (O'Loughlin, 1986), and some landscape models. These models can simulate a wide variety of processes and are useful for exploring scenarios that have not been previously observed in the historical record. However, a key challenge in using physically based models is that they have large data requirements, without which many parameters potentially need to be calibrated, which makes them difficult to apply with confidence, particularly across large areas. In between these two extremes are a wide variety of models of intermediate complexity, including those described in this report:

- lumped conceptual rainfall-runoff models (e.g. Sacramento, GR4J, RORB), which are particularly adept at modelling runoff
- river system models (e.g. Source, IQQM, AWRA-R), a genre of hydrological model well suited to modelling regulated systems and exploring trade-offs in water use, operation and management rules.

In selecting an appropriate model or suite of models, it is important to understand the modelling objectives and select a model that is commensurate with the level of data available and then to be cognisant of its predictive capacity and model limitations.

The Australian Water Resources Assessment River (AWRA-R) model was adopted for the Assessment. The rationale for using the AWRA-R model is discussed in the companion technical report on river model calibration in the catchment of the Victoria River (Hughes et al., 2024). Hughes et al. (2024) provides details on the AWRA-R model structure, calibration experiments and final calibrated model parameters, and on how runoff and streamflow vary spatially and temporally across the Assessment area. The calibrated AWRA-R river model was used for this report to answer the following questions:

- How much water is in the river at different locations and times under current and future climates?
- How much water can be extracted in different reaches and with what degree of reliability, and what is the timing of potential extractions?
- How may water regulation and extraction perturb downstream flow?
- How may mitigation options affect the degree of reliability of extraction?

To explore the relationship between the above variables, the report draws extensively on the use of scenarios. Importantly these scenarios are hypothetical and are not constrained by existing regulatory frameworks or what is likely to be politically palatable. Rather, hypothetical development scenarios are designed to explore the parameter space of what is physically possible. To this end, when evaluating the likelihood of hypothetical development scenarios arising in the Assessment area, it is instructive to consider that over the last 20 years the net mean increase in irrigated area across the NT has been less than 300 ha/year.

This report is structured as follows. Sections 1.1 and 1.2 outline previous surface water modelling studies in the Victoria catchment and key terminology used in this report. Section 2 provides a summary of the study area characteristics.

1.1 Previous surface water modelling studies in the Victoria catchment

In 1976 the Australian Water Resources Council (AWRC) oversaw an assessment of Australia's water resources. In that study, each jurisdiction across Australia provided estimates of mean annual flow and the percentage of mean annual flow that could be diverted in each AWRC river basin in Australia. No other information was provided, and the methods used to make these estimates varied from one jurisdiction to another and were not documented.

Thirty years after the AWRC continental assessment of Australia's water resources, the Australian Government commissioned CSIRO to undertake the Northern Australia Sustainable Yields (NASY) project, which was the first hydrological modelling study to examine the water resources of northern Australia (Timor Sea, Gulf of Carpentaria and northern north-east coast drainage divisions). The study included assessments of the three study areas using a consistent set of methods and models (CSIRO, 2009a, 2009b, 2009c). As part of the NASY project, lumped conceptual rainfall-runoff models were calibrated to streamflow data from 125 gauged catchments in northern Australia. Then model parameters were transposed to another 500 ungauged catchments using the nearest-neighbour regionalisation method extensively informed by expert knowledge (Petheram et al., 2009). The lumped conceptual rainfall-runoff models were calibrated to available observed data up to 31 August 2007. Due to time constraints, no new river system models were developed as part of NASY. At the time of the project, only four river system models (IQQM models) existed in the northern-draining drainage divisions. Within the Victoria catchment, rainfall-runoff models were calibrated to a single, reliable stream gauge. This model was then used to estimate streamflow within the Victoria River and simulate streamflow under historical and projected future climates.

Subsequent to the NASY study, CSIRO was commissioned to assess the opportunities for water resource development and associated risks in the catchments of the Flinders and Gilbert river (Queensland) between 2012 and 2013 (Petheram et al., 2013a, 2013b) in an assessment known as the Flinders and Gilbert Agricultural Resource Assessment, and then in the catchments of the Fitzroy (WA), Darwin (NT) and Mitchell (Queensland) rivers in 2016 to 2018 in an assessment known as the Northern Australia Water Resource Assessment. These Assessments employed river models, landscape models and hydrodynamic models to estimate the effects of development scenarios on water resources. Specific information with regard to river and landscape modelling in the Flinders and Gilbert Agricultural Resource Assessment is detailed by Lerat et al. (2013), and in the Northern Australia Water Resource Assessment it is detailed in Hughes et al. (2017) and Hughes et al. (2018). Subsequent to the Northern Australia Water Resource Assessment, CSIRO was commissioned to expand water resource assessment to the catchment of the Roper River in the NT (Hughes et al., 2023). The river model and methods used in this Assessment are largely an evolution of the methods used in the Northern Australia Water Resource Assessment and the Roper River Water Resource Assessment. Note that there is no jurisdictional or any legacy Victoria River model that can be referred to for this Assessment.

This report follows a companion report that details the construction, calibration and performance of the Victoria River model (Hughes et al., 2024a). Readers are directed to that manuscript for more information on the model and the site characteristics.

1.2 Key terminology used in this report

This document is largely concerned with reporting simulations of hypothetical development and/or future climate scenarios. The scenarios are configured to explore how different types and scales of water resource development, such as instream infrastructure (i.e. large dams) and water harvesting (i.e. pumping river water into offstream farm-scale storages), affect modelled flows across the catchment.

1.2.1 Wet-dry seasonal cycle: the water year

Northern Australia experiences a highly seasonal climate, with most rain falling during 4-month period from December to March. Unless specified otherwise, this Assessment defines the wet season as being the 6-month period from 1 November to 30 April and the dry season as the 6-month period from 1 May to 31 October. These definitions were chosen because they are the wettest and driest 6-month periods, respectively, for the study area. However, the transition from the dry to the wet season typically occurs in October or November, and meteorologists commonly define the northern wet season as 1 October to 30 April.

All results in the Assessment are reported over the water year, defined as the period from 1 September to 31 August, unless specified otherwise. This allows each individual wet season to be counted within a single 12-month period, rather than being split over two calendar years (and being counted as two separate seasons). The water year is more realistic for reporting climate statistics from a hydrological and agricultural assessment viewpoint.

1.2.2 Scenario terminology

The Assessment considered four scenarios, reflecting combinations of different levels of development and historical and future climates, much like those used in the Northern Australia Sustainable Yields projects (CSIRO, 2009a, 2009b, 2009c), the Flinders and Gilbert Agricultural Resource Assessment (Petheram et al., 2013a, 2013b) and the Northern Australia Water Resource Assessments (Petheram et al., 2018a, 2018b, 2018c):

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

Scenario A

Scenario A assumes a historical climate. The historical climate series is defined as the observed climate (rainfall, temperature and potential evaporation for the water years from 1 September 1890 to 31 August 2022). All results presented in this report are calculated over this period unless specified otherwise. Justification for use of this period is provided in the companion technical report on climate (McJannet et al., 2023).

Scenario A assumes no surface water or groundwater development. Scenario A was used as the baseline against which assessments of relative change were made. This will give the most conservative results. Historical tidal data were used to specify downstream boundary conditions for the flood modelling.

Scenario B

Scenario B is historical climate and future development. Scenario B used the same historical climate series as Scenario A. River inflow, groundwater recharge and flow, and agricultural productivity were modified to reflect potential future development. Potential development options were devised to assess responses of hydrological, ecological and economic systems. Modifications ranged from small incremental increases in surface water and groundwater extraction through to extraction volumes representative of the likely physical limits of the Victoria catchment (i.e. considering the co-location of suitable soil and water). All price and cost information was indexed to 2023 (i.e. reflective of pre-COVID-19 prices).

Scenario C

Scenario C is future climate and current levels of surface water and ground development assessed at approximately the year 2060. Future climate impacts on water resources were explored within a sensitivity analysis framework by applying percentage changes in rainfall and potential evaporation to modify the 132-year historical climate series (as in Scenario A). The percentage change values adopted were informed by projected changes in rainfall and potential evaporation under Shared Socioeconomic Pathways (SSPs) 2-4.5 and 5-8.5. SSP2-4.5 is broadly considered representative of a likely projection given current global commitments to reducing emissions and SSP5-8.5 is representative of an (unlikely) upper bound (IPCC, 2022)

Scenario D

Scenario D is future climate and future development. It used the same future climate series as Scenario C. River inflow, groundwater recharge and flow, and agricultural productivity were modified to reflect potential future development, as in Scenario B.

Therefore, in this report, the climate data for scenarios A and B are the same (historical observations from 1 September 1890 to 31 August 2022) and the climate data for scenarios C and D are the same (the above historical data scaled to reflect a plausible range of future climates).

1.2.3 Hypothetical development terminology

Water harvesting – an operation where water is pumped or diverted from a river into an offstream storage, assuming no instream structures.

Offstream storages – usually fully enclosed circular or rectangular earthfill embankment structures situated close to major watercourses or rivers so as to minimise the cost of pumping.

Large engineered instream dams – usually constructed from earth, rock or concrete materials as a barrier across a river to store water in the reservoir created. In the Victoria catchment most hypothetical dams were assumed to be concrete gravity dams with a central spillway (see companion technical report on water storage (Yang et al., 2024)).

Annual diversion commencement flow requirement (DCFR) – the cumulative flow that must pass the most downstream node (81100000) during a water year (1 September to 31 August) before pumping can commence. Usually implemented as a strategy to mitigate the ecological impact of water harvesting.

Pump start threshold – a daily flow rate threshold above which pumping or diversion of water can commence. Usually implemented as a strategy to mitigate the ecological impact of water harvesting.

Pump capacity – the capacity of the pumps expressed as the number of days it would take to pump the entire node irrigation target.

Reach irrigation volumetric target – the maximum volume of water extracted in a river reach over a water year. Note, the end use is not necessarily limited to irrigation. Users could also be involved in aquaculture, mining, urban or industrial activities.

System irrigation volumetric target – the maximum volume of water extracted across the entire study area over a water year. Note, the end use is not necessarily limited to irrigation. Users could also be involved in aquaculture, mining, urban or industrial activities.

Transparent flow – a strategy to mitigate the ecological impacts of large instream dams by allowing all reservoir inflows below a flow threshold to pass ‘through’ the dam.

Table 1-1 Scenario outlines and abbreviations

SCENARIO	DESCRIPTION	ASSUMES FULL USE OF EXISTING SURFACE WATER LICENCES	TRANSPARENT FLOW	TARGET EXTRACTION VOLUME (GL)	DCR FLOW REQUIREMENT (GL)	PUMP START THRESHOLD (ML/d)	PUMP CAPACITY (d)
Scenario A	**Historical climate and no hypothetical development**						
A	Historical/no development†	No	No	0†	0	NA‡	NA
Scenario B	**Historical climate and hypothetical future development**						
$B\text{-}D_3$ **(Dams 140, 341, 145)**	Three hypothetical dams, V-I, LC, V-F	No	No	591	NA	NA	NA
$B\text{-}D_F$	Single dam for flood mitigation only	No	NA	NA	NA	NA	NA
$B\text{-}D_{HE}$	Dams for hydro-electric energy generation	No	NA	45, 460, 1020, 1820, 2050	NA	NA	NA
$B\text{-}W_V, E_F, P_T, R_C$	Water harvesting with varying target extraction volume (V), DCR requirements (F), pump start threshold (T), and/or pump capacities (C)	No	NA	V = 40, 80, …, 960, 1000	F = 0, 200, 500, 700, 1000	T = 200, 300, …, 900, 1000	C = 10, 20, 30, 40, 50
Scenario C	**Future climate and current level of development**						
Cdry	Dry (10th percentile exceedance) GCM§ projection	No	No	NA†	0	NA	NA
Cmid	Mid (50th percentile exceedance) GCM projection	No	No	NA†	0	NA	NA
Cwet	Wet (90th percentile exceedance) GCM projection	No	No	NA†	0	NA	NA
Scenario D	**Future climate and hypothetical future development**						
$Dclim\text{-}D_3$	Three hypothetical dams (same as $B\text{-}D_3$), for each Scenario C climate (clim = dry)	No	No	591	NA	NA	NA
$Dclim\text{-}W_{150,F,600,c}$	Water harvesting with Scenario C climate (clim = dry)	No	NA	680	0	200	30

† Current surface water entitlement/licence in the model domain is 0.7 GL/year.

§ GCM = general circulation model.

2 Characteristics of the study area

This chapter provides an overview of physical characteristics of the catchment of the Victoria River relevant to river modelling.

The Victoria catchment has a hot and arid climate that is highly seasonal with an extended dry season. It receives a mean rainfall of 681 mm/year, 95% of which falls during the wet season. Mean daily temperatures and potential evaporation are high relative to other parts of Australia. On average, potential evaporation is approximately 1900 mm/year.

There is a distinct north–south rainfall gradient across the catchment. Mean annual rainfall is 1000 mm near the coast but less than 500 mm in the far south of the catchment. The area has experienced relatively higher rainfall since about 1970 (Figure 2-1).

The variation in rainfall from one year to the next is moderate compared to elsewhere in northern Australia but is high compared to other parts of the world with similar mean annual rainfall. The length of consecutive dry years in the Victoria catchment is not unusual when compared to other catchments in northern Australia, and the intensity of the dry years is similar to many areas in the Murray–Darling Basin and on the east coast of Australia. Since the 1969–1970 water year, the Victoria catchment has experienced one tropical cyclone in 21% of cyclone seasons and two tropical cyclones in 6% of seasons (McJannet et al., 2023).

The Victoria River and its tributaries, the most substantial being the Baines, Wickham, Armstrong, Camfield and Angalarri rivers, define a catchment area of 82,400 km^2 (Figure 2-2). The Victoria River itself has a length of approximately 500 km, from Entrance Island at its mouth to Kalkarindji in the far south of the catchment. Tidal variation at the mouth of the Victoria River is up to 8 m, and these tides propagate upstream to approximately 5 km downstream of Timber Creek (Power and Water Authority, 1987). The catchment is relatively flat with maximum elevations around 450 metres above Australian Height Datum (mAHD) in the far south-west. The mean annual flow at the catchment outlet is estimated to be around 7000 GL/year (Hughes et al., 2024).

At the time of writing there was only one surface water licence in the river model domain (730 ML/year). There are no substantial structures within the streams themselves across the catchment. The most obvious structure in the streams is the river ford at Dashwood Crossing on the Victoria River.

As described in the companion technical report on land suitability in the Victoria catchment (Thomas et al., 2024), the northern portion of the catchment area is dominated by escarpments, hills and ridges of sedimentary geology (Figure 2-3). Within this lies a north-east to south-west band of alluvial plain associated with the Baines and Angalarri rivers. Extensive areas of deep cracking clay soils are found on the broad alluvial plains of the major rivers, particularly along the Victoria and Baines rivers. Deep cracking clay soils are also found scattered throughout the eastern, southern and western parts of the upper catchment and are also subject to seasonal wetness. Areas of very friable loams are found along the Victoria and Wickham rivers mainly on narrow levees with broader areas scattered throughout the catchment. These soils are also susceptible to severe sheet and gully erosion and wind erosion. Tertiary level plains and plateaux in the southern catchment contain deep loamy soils that are suitable for a diverse range of irrigated horticulture and spray-irrigated grain, pulse and forage crops, timber crops, sugarcane and cotton. In the southern parts of the catchment where these more agriculturally versatile soils are located, surface water is relatively less available (Figure 2-4).

Nearly 60% of the catchment is dissected hills, outcrop, plateaux and scarps with rocky and/or shallow soils of little agricultural potential. These higher relief areas give way to lower relief, lower sloping land and alluvial plains. The coastal marine plains are seasonally or permanently wet saline soils with potential acid sulfate risks. These poorly drained soils are unsuitable for cropping but are prospective for aquaculture.

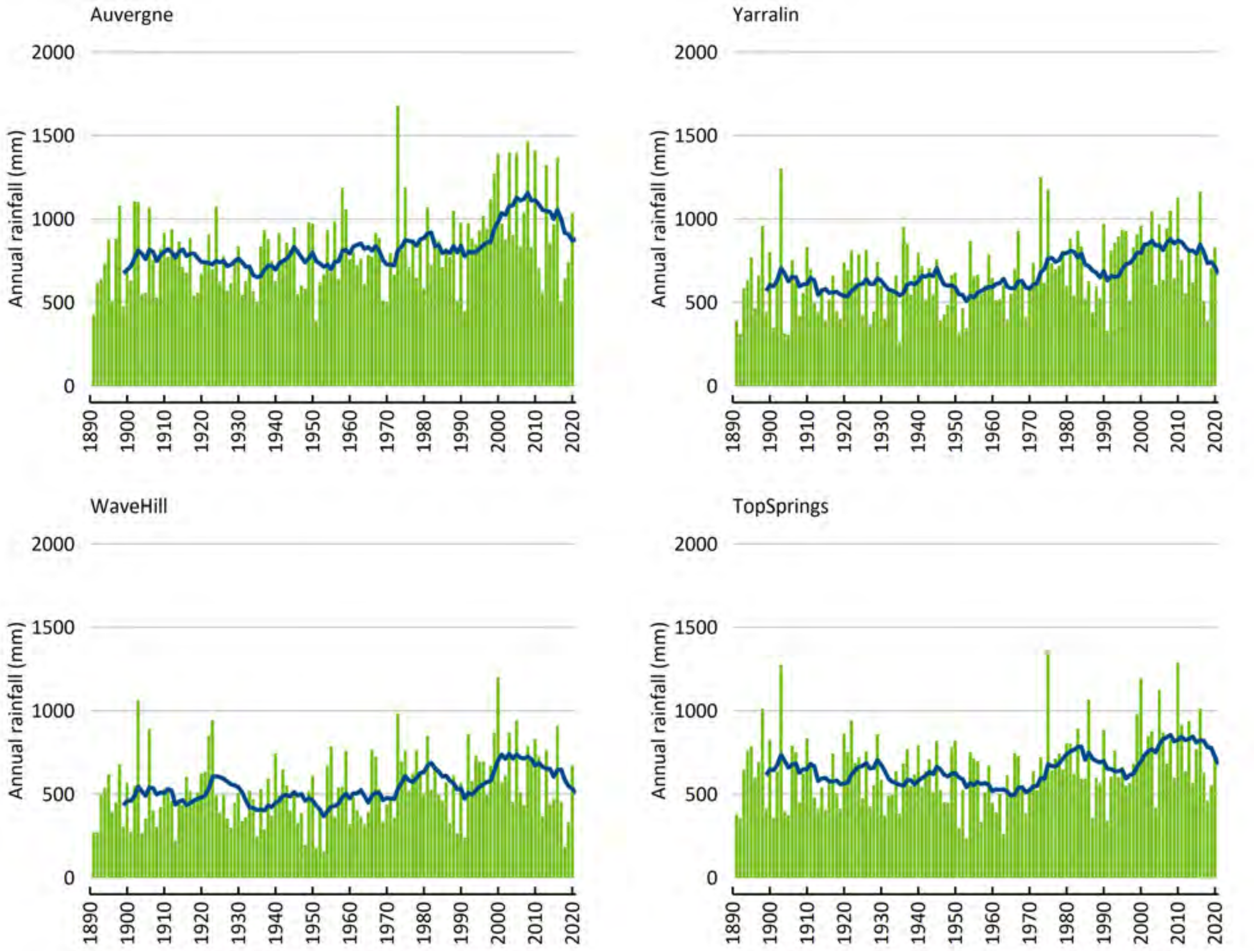

Figure 2-1 Annual rainfall at four locations in the Victoria catchment under Scenario A

Scenario A is the historical climate (1890 to 2021). The blue line represents the 10-year running mean.

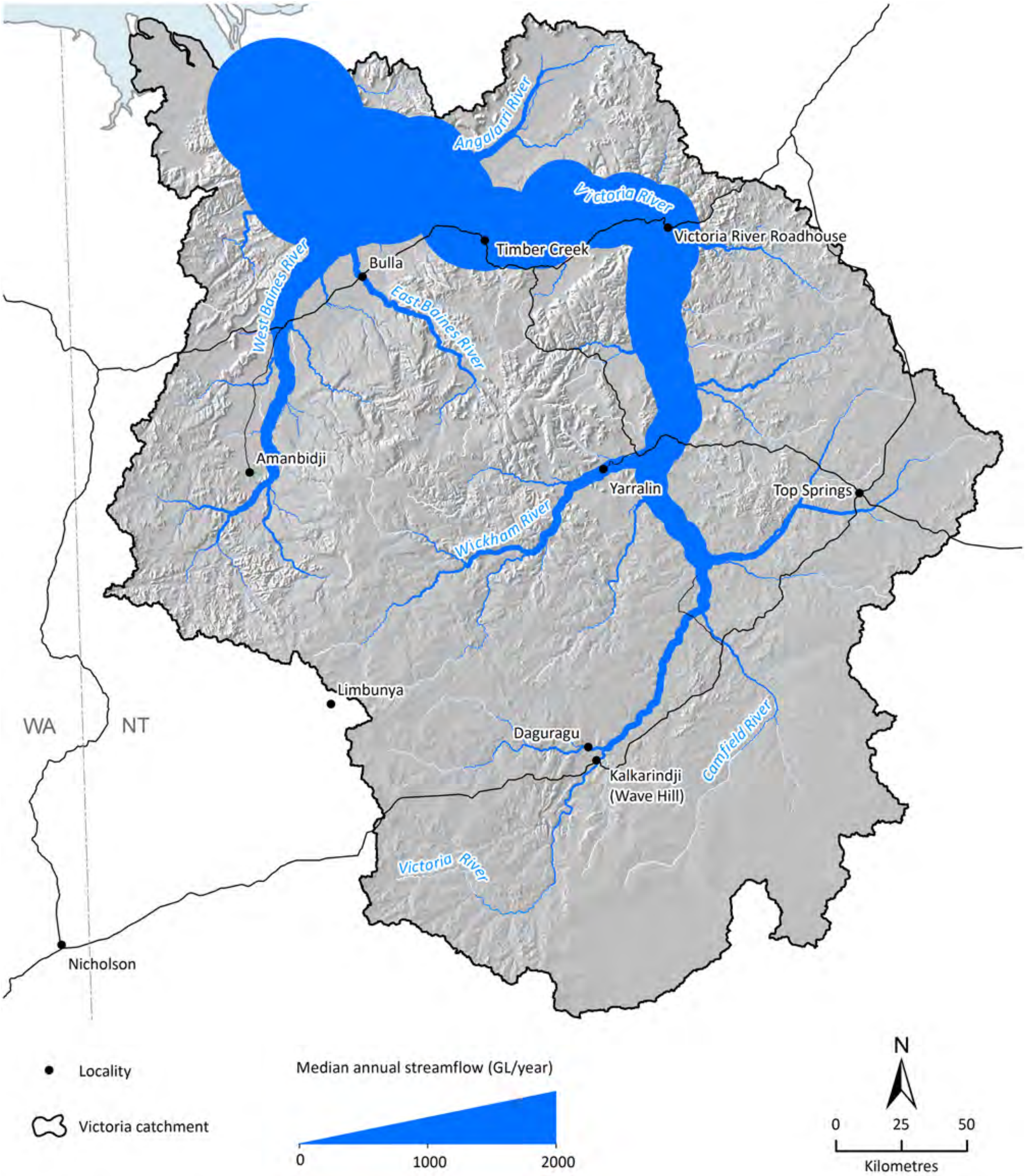

Figure 2-2 Median annual streamflow (50% exceedance) in the Victoria catchment under Scenario A

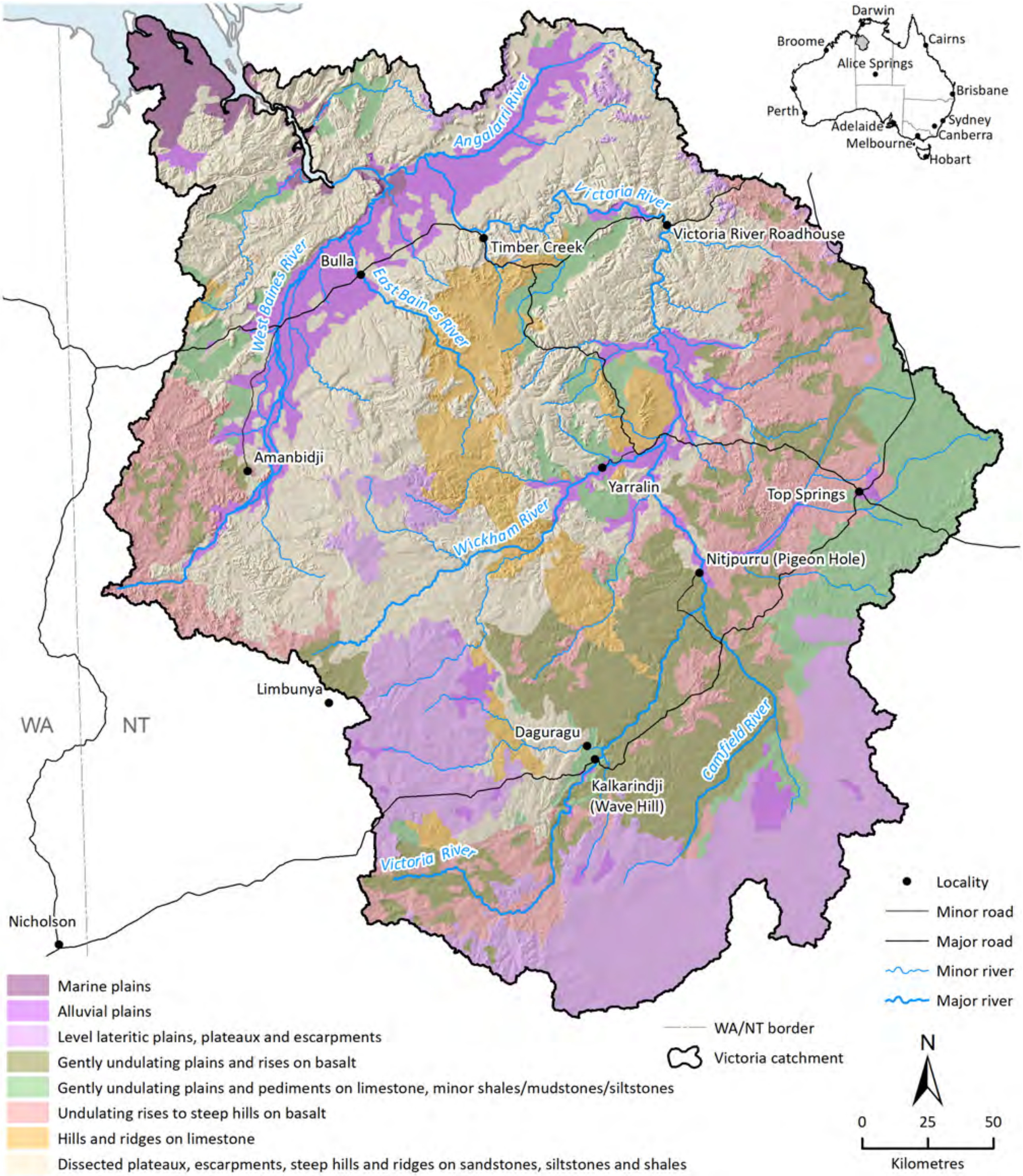

Figure 2-3 Physiographic units of the Victoria catchment

Physiographic provinces (after Sweet, 1977). Major tributaries, significant settlements and roads overlaid on hill shaded terrain relief.

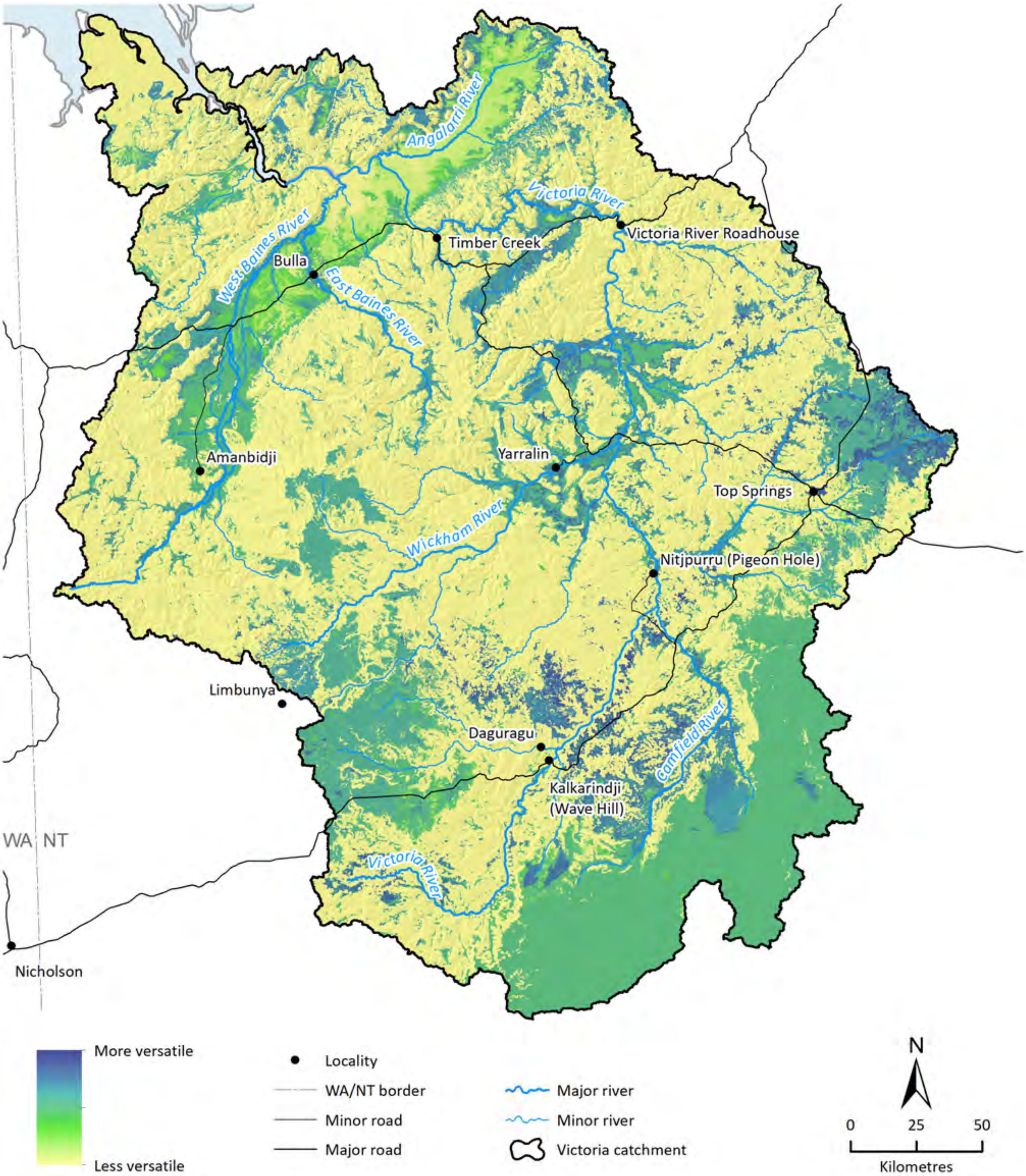

Figure 2-4 Agricultural versatility index map of the Victoria catchment (from Thomas et al., 2024)

3 Methods

The Victoria AWRA-R river model is composed of 41 nodes (Figure 3-3), and includes the following processes: rainfall, evaporation and runoff, routing of water across subcatchments, losses, irrigation extraction and reservoir behaviour. The Victoria River model structure, data availability and calibration methods are detailed in the companion technical report on river model calibration, Hughes et al. (2024. Methods specific to model simulation and scenario analysis are detailed in this report.

The Victoria River model was simulated using historical climate data for the period 1 January 1889 to 7 June 2023. After allowing for an 18-month model 'warm up', the results are presented over a 132-year period, from 1 September 1890 to 31 August 2022, as described in Section 1.2.2. As described in the companion technical report on climate (McJannet et al., 2023), this time period was adopted because it provides a wide range of possible environmental conditions across a range of temporal scales and, importantly, encompasses the extended dry periods that occurred in the first half of the 20th century.

The irrigation demand modelling was undertaken using the AWRA-R irrigation demand model (Hughes et al., 2013 2014. The AWRA-R irrigation model features a soil water store that represents the water balance for an entire irrigation development within individual reaches. Water is extracted from the virtual soil water store according to demand generated from a crop model. Crop demand is based on the FAO56 method (Allen et al., 1998), using crop factors for sown crops and climate data. As the soil water store becomes depleted, increasing volumes of irrigation demand are triggered. Irrigation demand is zero when the soil store is full. One-dimensional demand is converted to volumetric demands via sown crop area. Sown crop area is determined at a series of crop decision days within the irrigation season. Sown crop area can be adjusted depending upon the volume of available water from each of the three sources:

1. surface water licence (managed irrigation district)
2. on-farm storage
3. groundwater licence.

Crop demands for all irrigated crops grown in the reach are determined in the following way:

$$D = (Kc * ET_o * \rho - P * A_a) * A_c / L_t \quad (1)$$

where D is the total crop demand (m^3/second), Kc is the area-weighted crop factor (for one or more concurrently grown crops), ET_o is the time step potential evapotranspiration (ET) (m), ρ is the soil-dependent crop water stress (dimensionless, range 0–1), P is the time step rainfall (m), A_a is the proportion of the current irrigation area actively growing crops at the current time step, A_c is the current irrigation area, E is irrigation efficiency (dimensionless) and L_t is the time step length (s). Crop demand is supplied via the soil water store, which is in turn supplied via irrigation using the following relationships:

$$Irrigation = \begin{cases} I_{max} * A_a * A_c * E/L_t & if \quad \theta_t \leq 0 \\ I_{max} * e^{\left((-1*\theta_t^2) / 2\sigma^2 \right)} * A_a * A_c * E/L_t & if \quad \theta_t > 0 \end{cases} \tag{2}$$

and

$$I_{max} = \frac{\gamma}{\sigma\sqrt{2\pi}} \tag{3}$$

where γ and σ are user-defined parameters that are adjusted to suit the soil water-holding capacity of the area of interest, $I_{max}$is the highest possible rate of irrigation (m) per time step and θ_t is the first estimate of soil water storage for the current time step. When the soil water store is full (say, following rainfall, and $\theta_t = \text{soil capacity}$), no irrigation is triggered.

The model features an on-farm storage module that can extract water from a reach according to user-defined pump parameters, allocation or licence limits and reservoir volumes. Water can then be extracted from the storage as required. Additionally, water can be extracted for irrigation directly from the river, although this feature is more commonly used in larger managed irrigation districts where water is diverted and supplied to irrigators via a channel system. In this Assessment, however, only on-farm storage modules were used (as a part of water harvest analyses).

3.1 Reservoir and irrigation model

Large instream dams have the potential to ‘carry’ water across years and are, therefore, a means of mitigating the impacts of lower rainfall years on town water supply and irrigation developments. However, disruption to the hydrological characteristics of a stream can also be large, depending upon management, with consequences for ecosystems dependent on river flows (Pollino et al., 2018).

As an initial assessment, a large range of potential dam sites in the catchment of the Victoria River were identified using the DamSite model (Petheram at al., 2024). This model uses a series of algorithms automatically determining favourable locations in the landscape as sites for intermediate to large water storages (Read et al., 2012; Petheram et al., 2017, 2018c).

Two potential dam sites with higher yield per unit cost ratios than others in the catchment in distinctly different geographic regions were selected from the output produced by the DamSite model in the Victoria catchment (Yang et al., 2024). At a third site, a large potential dam was modelled in a topographically and hydrologically favourable location in the central catchment, upstream of the largest concentration of land suitable for irrigated agriculture along the Victoria River. A fourth potential dam site was selected in the south of the catchment for flood mitigation purposes, and a fifth potential dam site was selected for hydro-electric power generation. At all locations, the dam wall dimensions were recalculated using Advanced Land Observing Satellite (ALOS) data to refine the cost of the dam wall and associated infrastructure (Petheram et al., 2024). Subsequently, relationships were determined for the reservoir stage, reservoir volume and reservoir surface area for each analysed dam location. These relationships formed part of the dam sub-models within the river system model and allowed assessment of various full supply levels for potential yields and reliability of supply. The dam sub-model was configured so that reservoir size and diversion licence volume could be varied to calculate annual reliability of supply for a wide range of reservoir volumes and targets.

The reservoir model uses a water balance equation as follows:

$$V_t = V_{t-1} + Q_l + Q_{in} - D_t - S_t - T_t + (P_t - E_t) * A_t \quad (4)$$

where:

V_t is the reservoir volume at time t

V_{t-1} is the reservoir volume at the previous time step

Q_l is the estimate of local subcatchment streamflow, which is in part a function of the reservoir surface area

Q_{in} is the estimate of inflow from all other upstream subcatchments into the reservoir

D_t is the diversion out of the reservoir

S_t is the dam spill

T_t is transparent and/or translucent flow released from the reservoir for environmental purposes

P_t is the rainfall on the reservoir surface

E_t is the evaporation on the reservoir surface

A_t is the surface area of the reservoir at time t.

Similar to AWRA-R, the reservoir model was written using C code within an R wrapper.

Time series model inputs are:

- local climate (*P* and potential ET)
- reach inflow (from the river model)
- local runoff (from the river model)
- daily release pattern for irrigation requirement
- evaporation correction factor.

Additionally, various scalar inputs control such factors as reservoir evaporation adjustment, dam full supply level (and height, volume and area relationships for the site), spillway properties, irrigation licence volumes and environmental releases.

The evaporation inputs are calculated using the Morton's wet area algorithm (Morton, 1983). However, these and other commonly used evaporation algorithms have been shown to be different to measured lake evaporation in some instances (McJannet et al., 2013). Accordingly, Morton's wet area evaporation was modified using dynamic lake area (A_t) and monthly correction factors as outlined in Petheram et al. (2022). The calculation is as follows:

$$E_c = \alpha_{area} * A^{\beta} * K_m * E_m \quad (5)$$

where E_c is the corrected evaporation estimate (mm), α_{area} and β are locally calibrated conversion parameters, A is lake or reservoir area at a given time, K_m is a locally calibrated monthly conversion factor and E_m is Morton's wet area evaporation estimate for a given time.

The reservoir model features transparent and translucent flow facilities to release water from the reservoir for environmental purposes. Transparent releases are enabled by reservoir inflow thresholds below which 100% of dam inflows are released to the river downstream as if there was no dam present. Importantly, they seek to mimic the characteristics of low flows below the nominated threshold. Translucent flows occur at reservoir inflow rates above the transparent thresholds, where a proportion of inflows between the transparent threshold and a higher upper threshold is released. In the Assessment, the potential for transparent flow releases to mitigate impacts on water-dependent assets was examined and is reported in the companion technical report on ecological modelling (Stratford et al., 2024).

The Assessment used a release pattern that mimicked demands for a dry-season crop (sown on 1 April). Slightly higher annual reliabilities may be possible from crops sown in the wet season, but the dry-season crop release pattern is retained here since it allows for a more conservative estimate of irrigation reliability (Figure 3-1). This figure shows the pattern of daily water demand as a proportion of total annual demand.

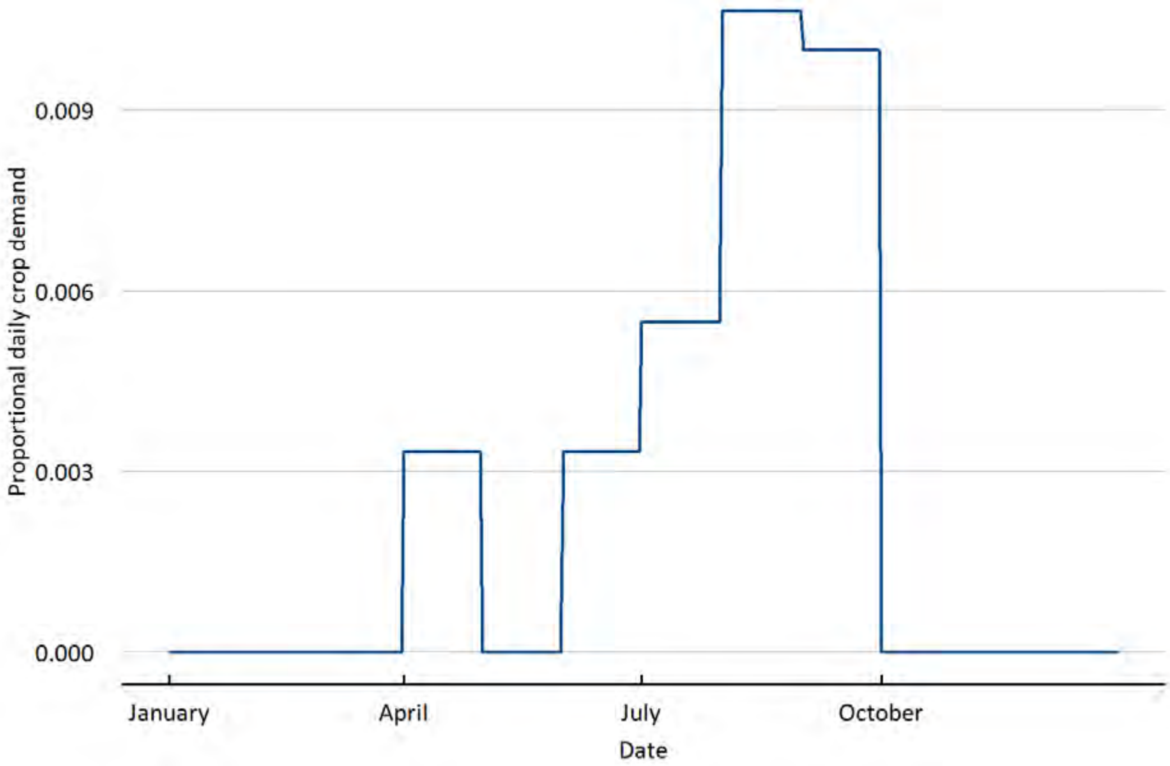

Figure 3-1 Dry-season crop water use pattern

3.1.1 Flood mitigation dam

An additional bespoke reservoir model was formulated, intended for flood mitigation only; that is, no diversion was implemented. This model was implemented in model node 81100160 upstream of the township of Kalkarindji (Figure 2-2), where flooding has created problems for residents in recent times. The most notable feature of the dam design was a large culvert sluice in the base of the dam that would be used to divert streamflow during construction and that, if constructed correctly, would allow for release of reservoir storage at a controlled rate once the dam is complete. Such a facility allows the reservoir to self-empty between runoff events, thereby more effectively dampening subsequent runoff events. The head flow relationship for the sluice is shown in Figure 3-2. The dam also featured a spillway at the full supply level, as did all dams in this Assessment.

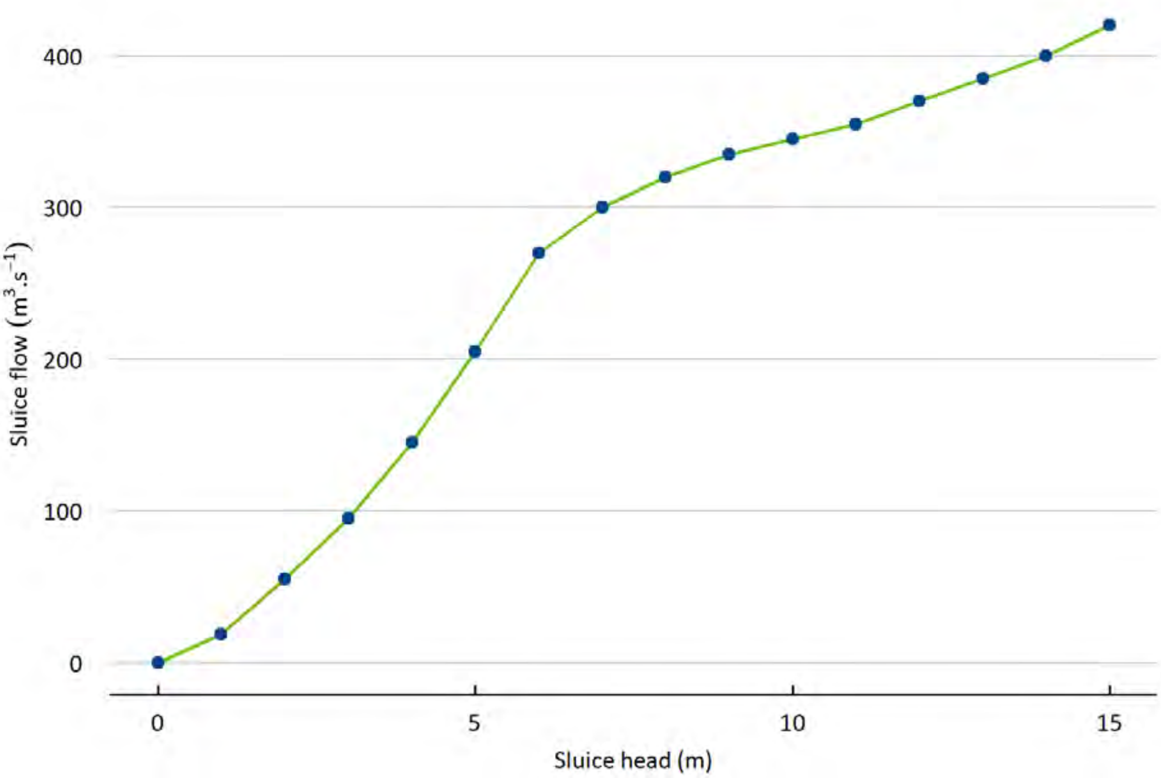

Figure 3-2 Head discharge relationship for the Kalkarindji flood mitigation dam

3.1.2 Hydropower dam

An investigation on the potential to generate hydroelectric power was undertaken at dam site 38 (Table 4-3). This dam used the same model as for irrigation potential dams (Section 3.1), however for these analyses, a constant daily release pattern was used. This follows from an assumption of base load power generation as the primary objective of these hypothetical dams. Power output for these dams were calculated daily as follows:

$$P = \eta * \rho * g * h * Q \quad (6)$$

where P is the power output in watts, η is the efficiency of the turbine (dimensionless), assumed here to be 0.85, g is the acceleration due to gravity, h is the dam head in metres and Q is the output flow of the dam (m^3/s).

3.2 Water harvest analyses

Water harvest analyses in the Assessment assume water is pumped from the river into on-farm (or at least offstream) reservoirs without any instream diversion structures. The analysis assumes that river water is extracted by groups or individual irrigators using pumps and on-farm storage as a means of supplying and regulating water to irrigate crops.

Water harvest scenarios were undertaken to explore trade-offs when water is extracted across a catchment. The goal is to understand with what degree of reliability different quantities of water can be extracted from the river system at locations where agricultural development is most likely and how the reliability of water extraction is affected by simple water extraction rules devised to mitigate ecological impact. The analysis is not intended to be prescriptive and is designed to test a wide range of water extraction scenarios (including the bio-physical extremes) to understand system dynamics.

Water harvest analyses were evaluated for concurrent extraction at six nodes within the Victoria River model (Table 3-1). Extraction locations were sited at locations where surface water and soil suitable for ringtanks and irrigated agriculture were modelled to be most abundant, that were near communities, and that took into consideration broad-scale flooding that may affect irrigated agriculture infrastructure.

Each water harvest node was assigned a proportional irrigation target (i.e. the proportion of the entire river system volumetric target that could be extracted at that particular node):

$$a_i = p_i * A \qquad (7)$$

where:

A is the annual system irrigation volumetric target (GL)

p_i is the proportional irrigation volumetric target of node i (dimensionless)

a_i is the annual irrigation volumetric target for node i, such that the sum of proportion node targets in the catchment will sum to 1:

$$\sum_{i=1}^{n} p_i = 1 \qquad (8)$$

where n is the number of water harvest nodes in the catchment.

Table 3-1 Median annual flow and proportional water harvest allocation for Victoria water harvest analyses

NODE ID	MEDIAN ANNUAL FLOW (GL)	PROPORTIONAL ALLOCATION
81101135	1083	0.05
81101131	473	0.05
81100181	1692	0.02
81100180	2500	0.29
81100060	264	0.15
81100001	1729	0.44

The reliability at which water can be extracted at each node will be influenced by node irrigation volumetric target, river flow and pump characteristics. In particular, the river flow rate above which the pumping can commence (pump start rate) and the pump capacity (conceptually this could be a physical limit of a pump or it could be a licence condition) will influence the ability to extract water from the river. To test the effects of system targets, pump start rates and pump capacities, combinations of these three variables were simulated in each subcatchment (Table 3-2).

Table 3-2 Water harvest parameters and values analysed for Roper water harvest analyses

WATER HARVEST PARAMETERS	VALUES ANALYSED	UNITS
River system irrigation target	40, 80,…, 960, 1000	GL/y
Pump start threshold	200, 300,…, 900, 1000	ML/day
Pump capacity	10, 20, 30, 40, 50	Days†
Annual diversion commencement requirement	0, 200, 500, 700	GL/y

† Pump capacity is the rate at which the pump(s) can operate to extract the reach annual irrigation target (a_i) in the given number of days. Hence the pump capacity used by the simulation (m^3/second) will be a function of a_i.

Note that these parameters are independent of other factors that may constrain extraction, such as availability of adequate areas of suitable soil to irrigate and other legal, social, economic and ecological considerations that may influence the extraction of surface water.

3.2.1 Unconstrained water harvest analyses

To test a range of water harvest possibilities, a range of system irrigation volumetric targets were used with a range of pump start thresholds and pump capacities. Rather than use an absolute pump capacity for each permutation of water harvest simulation, relative values were used. More specifically, the pump capacity was set using the rate by which it would be possible to pump the entire node irrigation volumetric target in a certain number of days. For example, a pump rate of 5 days would mean that the pump capacity would be high enough to extract the entire node volumetric target in 5 days (i.e. if the annual irrigation volumetric target for a reach was 10 GL, then conceptually a pump rate of 5 days means that all the pumps along that river reach could collectively pump a maximum of 2 GL/day). Minimum pump start thresholds were initially set at 200 ML/day, a nominal minimum physical threshold at which it was considered that pumping could potentially commence (and assuming the presence of suitable waterholes for pump stations).

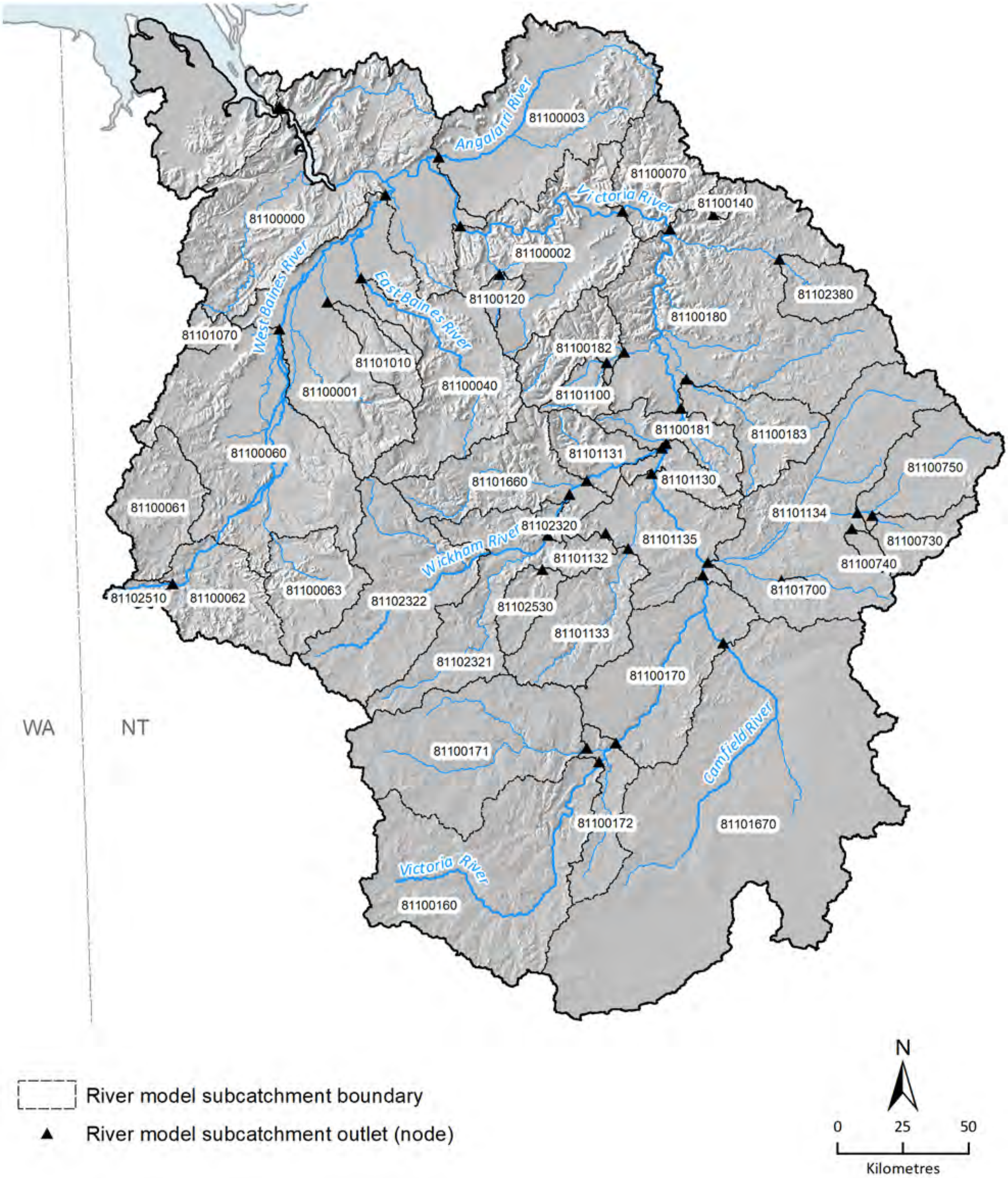

Figure 3-3 River model nodes and subcatchment areas

All nodes that end in a zero correspond to a streamflow gauging station.

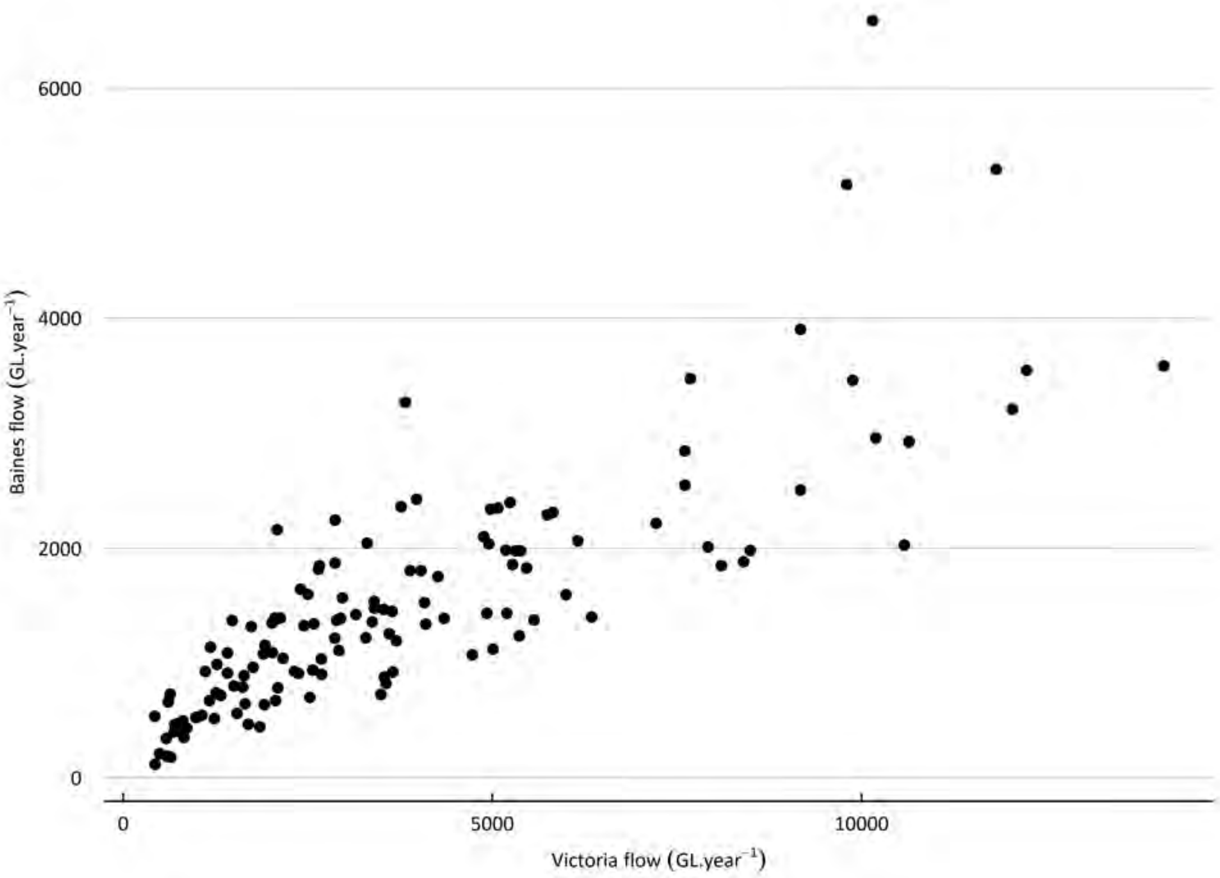

Figure 3-4 Simulated annual flow at model node 81100002 on the Victoria River upstream of the Baines River junction plotted against annual flow at model node 81100001 on the Baines River under Scenario A

Lastly, the effect of incrementally larger diversion commencement flow requirements (DCFRs) were tested. The DCFR restricts commencement of water harvesting across the entire Victoria catchment until a specified volume has passed the lowermost gauge. Accounting for the DCFR begins on 1 September each year (the start of the water year). Once the cumulative sum of flow exceeds the DCFR at the lowermost gauge, water harvest can begin for the water year across the entire catchment. For the Victoria catchment, the lowermost gauge for the purposes of these analyses was 81100000 (Figure 3-3, Victoria River at the end-of-system), which is about 67 km downstream of the junction of the Baines and Victoria Rivers. Examination of annual flow at nodes 81100002 on the Victoria River and 81100001 on the Baines River suggest that flow in these two rivers is only moderately correlated, with an R^2 value of 0.68 (Figure 3-4). Hence, operationally, implementing diversion commencement flow requirements may require separate accounting within the Victoria and Baines rivers in order to achieve the desired ecological outcomes. For the Assessment, the use of node 81100000 as the catchment-wide diversion commencement flow requirement was considered adequate to demonstrate the potential for this strategy to mitigate ecological impacts.

Computationally, each water harvest simulation at each node was enabled by the AWRA-R irrigation model (Hughes et al., 2014b). Typically, the AWRA-R irrigation model represents a crop or series of crops using a specific crop coefficient value (*Kc*) for each day. However, the aim of the water harvest analysis was to determine the annual time reliability at which a given annual irrigation volumetric target could be extracted for a given pump start threshold and pump capacity. Accordingly, for the purpose of this exploratory analysis, *Kc* values were set to 1 for every day in each node. Irrigated area was set to be high enough so that any water extracted would be used within the year of extraction from the river (i.e. water was not carried-over from one year to the next). On-farm storage was used within the model to store extracted water. The size of the on-farm storage was set to equal the node annual irrigation volumetric target volume so that on-farm storage would not limit extraction of water. The maximum annual extraction volume was set to equal the reach irrigation volumetric target for each node. All water harvest nodes were simultaneously run within the river model, so that any changes to the flow regime resulting from water extraction was propagated downstream to other nodes.

To illustrate the opportunity and risks for water harvesting, results focus on two aspects of the water harvest simulations: the reliability of extraction and the resulting perturbation to streamflow. In terms of calculating the reliability of supply to irrigation, annual irrigation volumetric extraction was compared to the annual irrigation volumetric target across 132 years of simulation. Reliability of supply in each water year was calculated as follows:

$$z_i = \begin{cases} 1, \sum_1^{\mathrm{m}} e_j = a_i \\ 0, \sum_1^{\mathrm{m}} e_j < a_i \end{cases} \tag{9}$$

where:

a_i is the annual irrigation volumetric target (GL) for each river node *i*

e_j is the extraction volume of river water for the node each day *j*

z_i is the extraction success statistic for the water year, with a value of 1 or 0, dependent on the full extraction of the node irrigation volumetric target

m is the number of days in the year.

This allows calculation of reliability for each node across the entire time series of simulation:

$$r_i = \sum_{y=1}^{t} z_{i,t}/t \tag{10}$$

where:

r_i is the reliability of irrigation supply at node *i*

t the number of water years of the simulation.

To quantify the effect of extracting water on river flow, the perturbed streamflow values at each node were compared to streamflow under Scenario A.

3.2.2 Soil-limited water harvest analyses

Within the Victoria catchment, the availability of soils suitable for irrigation within a reasonable distance of major drainage lines is relatively limited. For these reasons, the water harvest analysis outlined in Section 3.2.1 was extended in this section to account for soil and water limitation concurrently.

The soil-limited water harvest volume calculation took into consideration both the volume of surface water available at each model node and the volume of water required to irrigate a reference crop on all suitable soils within that model node subcatchment. The soil-limited water harvest volume (e_{sw}) for the node is taken as the minimum of these three values:

$$e_{sw} = min(e_{soil}, e_{water}, e_{rt}) \quad (11)$$

where:

e_{soil} is the soil-limited water harvest annual volume (GL)

e_{water} is the maximum annual irrigation volumetric target that has an annual reliability of supply of at least75% (see Section 3.2.1)

e_{rt} is the volume of water that can be stored on soils suitable for ringtanks within 5 km of the river assuming 33% of the dry-season-cotton-suitable soils (spray irrigation) area will need to be reserved for water storage if the ringtank-suitable soil and the cotton-suitable soil coincide.

$e_{soil}$is calculated for the following conditions:

- Soil area per reach is defined as the area of dry-season-cotton-suitable soils (spray irrigation) (Thomas et al., 2023) within 5 km of the main stream within each subcatchment. The available soil area was potentially further reduced when accounting for soil spatial continuity (i.e. some areas of suitable soils are isolated by areas of poor soil or topographic features such as larger streamlines) (Thomas et al., 2023).
- Soil area was further reduced (by 33%) due to the need to build ringtanks, and then a further 20% due to other infrastructure requirements (e.g. channels, roads, buildings).
- Assuming a dry-season crop requires 10 ML/ha on average (including transmission, storage and application losses), soil areas were converted to a 'mean annual water requirement' (i.e. volume of water required to irrigate the 'remaining' land suitable for irrigated agriculture).

The soil limitations (e_{soil}, e_{rt}) were calculated before the water harvest simulations were undertaken to make sure that irrigation volumetric targets did not exceed the calculated soil limitations in each reach. Additionally, irrigation volumetric targets were adjusted so that no reach had an annual time reliability of supply less than 75%.

3.3 Future climate analyses

Global climate models (GCMs) are an important tool for simulating global and regional climate. To simulate and assess the uncertainty of the range of future runoff projections, future climate projections from a large range of archived GCM simulations were downloaded from the Coupled Model Intercomparison Project 6 (CMIP6) website (https://pcmdi.llnl.gov/CMIP6/). Of the 92 available GCMs, 32 included the rainfall, temperature, solar radiation and humidity data required for the Australian Water Resource Assessment Landscape (AWRA-L) and River (AWRA-R) hydrological modelling, WAVES recharge modelling, Agricultural Production Systems sIMulator (APSIM) crop modelling and GRASP pasture modelling. For the purpose of the Assessment, the adopted the Shared Socioeconomic Pathway SSP2-4.5 from the Sixth Assessment Report (IPCC, 2022) was used to investigate the sensitivity of changes in rainfall and potential evaporation on streamflow at approximately the year 2060 (McJannet et al., 2023). Under SSP2-4.5, emissions rise slightly before declining after 2050, but do not reach net zero by 2100. At approximately 2060, SSP2-4.5 is representative of a 1.6 °C temperature rise relative to a time slice centred around 1990.

GCMs provide information at a resolution that is too coarse to be used directly in catchment-scale hydrological modelling. Hence, an intermediate step is generally performed: the broad-scale GCM outputs are transformed to catchment-scale variables. For these reasons, and due to the scale of the catchments being assessed, which makes it resource intensive to undertake dynamic or statistical downscaling, a simple scaling technique – the pattern scaling (PS) method (Chiew et al., 2009b) – was adopted.

The seasonal pattern scaling method employed used output from the 32 GCMs to scale the 132-year historical daily rainfall, temperature, radiation and humidity sequences (i.e. SILO (Scientific Information for Land Owners) climate data), to construct the 32 by 109-year sequences of future daily rainfall, temperature, radiation and humidity. The method is described in the companion technical report on climate (McJannet et al., 2023), and further detail can be found in Chiew et al. (2009b).

The percentage change in rainfall and potential evaporation spatially averaged across the Victoria catchment under SSP2-4.5 at approximately 2060 are shown in Figure 3-5. As outlined by McJannet et al. (2023), scenarios Cwet, Cmid and Cdry for the Victoria catchment were selected as the 10% (3rd), 50% (17th) and 90% (29th) percent exceedance of the 32 GCM-PS shown in Figure 3-5. Seasonal scaling factors from the selected GCMs (i.e. GFDL-ESM4, MIROC6 and INM-CM5-0) were then uniformly applied to each SILO climate grid cell sequence to transform the historical climate variables to the corresponding Cwet, Cmid and Cdry future climate projection (see McJannet et al. (2023) for more detail). Scaling factors for the three selected future climate scenarios are listed in Table 3-3. The climate projections were used for the Victoria River model to explore the sensitivity of streamflow to changes in rainfall and potential evaporation.

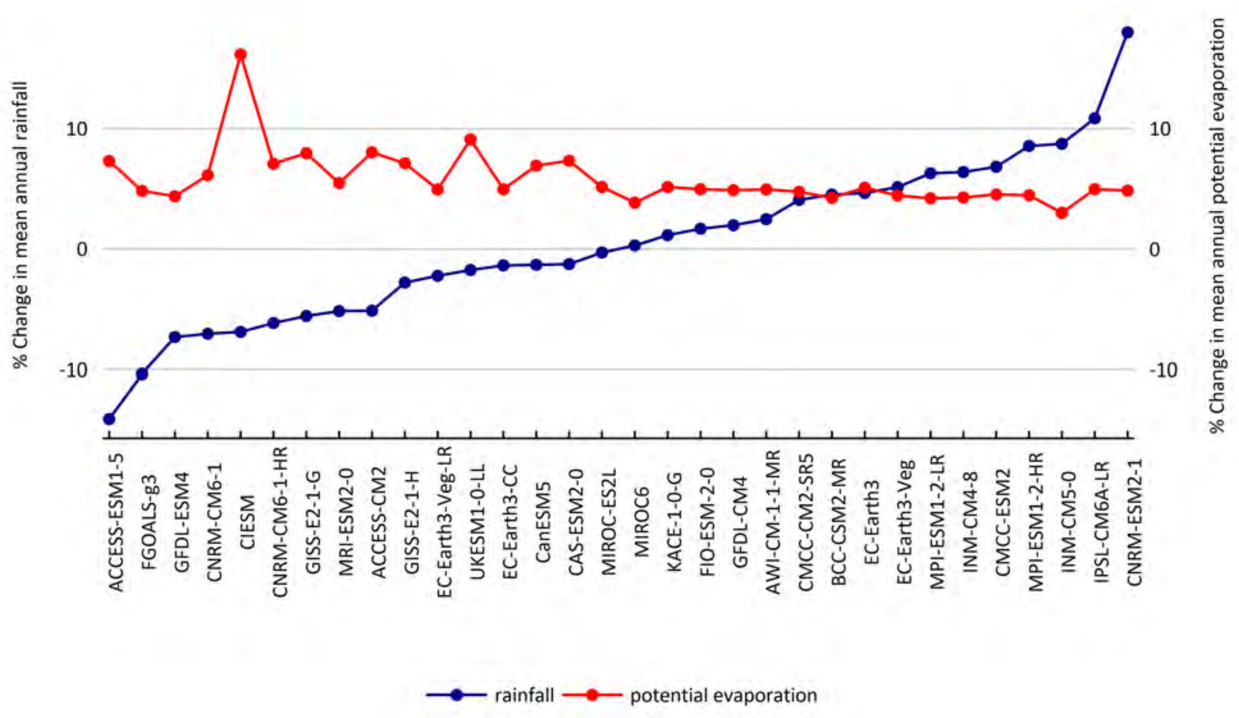

Figure 3-5 Percentage change in mean annual rainfall and potential evaporation under Scenario C relative to under Scenario A

Simple scaling of rainfall and potential evaporation have been applied to global climate model output (GCM-PS). GCM-PSs (SSP2–4.5) are ranked by increasing rainfall.

Table 3-3 Scaling factors for selected future climate scenarios

FUTURE CLIMATE SCENARIO	SELECTED GLOBAL CLIMATE MODEL	VARIABLE	ANNUAL SCALING FACTOR	DECEMBER. JANUARY AND FEBRUARY SCALING FACTOR	MARCH, APRIL AND MAY SCALING FACTOR	JUNE, JULY AND AUGUST SCALING FACTOR	SEPTEMBER, OCTOBER AND NOVEMBER SCALING FACTOR
Dry	GFDL-ESM4	P	0.927	0.933	0.693	1.122	1.257
		E	1.044	1.031	1.066	1.055	1.032
Mid	MIROC6	P	1.003	0.984	1.045	1.125	1.036
		E	1.039	1.038	1.044	1.040	1.034
Wet	INM-CM5-0	P	1.087	1.153	0.887	1.004	1.043
		E	1.030	1.023	1.032	1.042	1.028

4 Results

4.1 Scenario A

Flow statistics for the Victoria River model under Scenario A are shown in Table 4-1.

Table 4-1 Flow statistics for all model nodes in the Victoria River model under Scenario A

NODE ID	MEAN ANNUAL FLOW (GL)	80% ANNUAL EXCEEDANCE FLOW (GL)	MEDIAN ANNUAL FLOW (GL)	20% ANNUAL EXCEEDANCE FLOW (GL)	RUNOFF COEFFICIENT	MEAN ANNUAL RAINFALL (mm)
81100000	6994	3099	5734	10,071	0.130	672
81100001	1523	720	1365	2,061	0.141	713
81100002	3833	1425	2932	5,444	0.112	620
81100003	557	269	457	722	0.167	885
81100040	280	132	227	369	0.150	763
81100060	781	322	695	1,133	0.134	671
81100061	113	50	100	164	0.132	668
81100062	124	52	116	184	0.125	621
81100063	101	41	94	148	0.128	644
81100070	3415	1228	2621	5,017	0.107	609
81100120	23	10	19	32	0.174	805
81100140	19	6	15	26	0.156	776
81100160	214	36	84	307	0.092	509
81100170	860	147	469	1,376	0.073	524
81100171	188	33	112	289	0.097	564
81100172	442	77	244	638	0.094	531
81100180	3236	1151	2500	4,700	0.105	604
81100181	2289	766	1692	3,408	0.095	578
81100182	148	48	119	220	0.150	744
81100183	99	27	82	155	0.128	664
81100730	45	16	33	62	0.118	633
81100740	11	4	8	14	0.122	624
81100750	164	58	123	222	0.121	654
81101010	61	30	49	78	0.153	781
81101070	28	14	24	38	0.160	790
81101100	39	14	28	57	0.154	712
81101130	2215	752	1636	3,289	0.094	576
81101131	607	249	473	839	0.116	652
81101132	16	6	13	22	0.111	617

NODE ID	MEAN ANNUAL FLOW (GL)	80% ANNUAL EXCEEDANCE FLOW (GL)	MEDIAN ANNUAL FLOW (GL)	20% ANNUAL EXCEEDANCE FLOW (GL)	RUNOFF COEFFICIENT	MEAN ANNUAL RAINFALL (mm)
81101133	96	41	81	145	0.103	586
81101134	469	174	353	639	0.115	642
81101135	1571	447	1083	2,395	0.088	556
81101660	541	218	414	744	0.114	649
81101670	272	0	81	562	0.049	510
81101700	4	1	3	5	0.108	597
81102320	387	149	302	519	0.110	635
81102321	376	144	294	506	0.110	635
81102322	207	79	162	284	0.112	648
81102380	74	23	54	104	0.148	738
81102510	13	6	11	19	0.127	638
81102530	32	13	26	48	0.108	606

4.2 Scenario B

Irrespective of the physical resources that may support water and irrigated agricultural development in the Victoria catchment, if the future trajectory of irrigation development is similar to historical trends in the NT and Queensland, the scale of future irrigation development in the Victoria catchment is likely to be modest and unlikely to encompass large dam development. Patterns of development are more likely to be incremental, small-scale and based on off-stream storages, gully dams and groundwater. Nonetheless, large dams remain topical, and it is important that robust and independent analysis addresses the opportunities and the risks that large-scale developments present. Similarly, large scale water harvest operations in the Victoria catchment are unlikely, however, these scenarios are included to understand the opportunities and risks of development.

4.2.1 Water harvest (Scenario B-W)

Due to the infinite number of water harvest permutations, ‘heat map’ plots were used to distil the results and explore the sensitivity of the system to a range of water harvest strategies. The heat map plots display the annual reliability of extraction at each water harvest node given changes in annual irrigation volumetric target, pump start threshold, pump rate and end-of-system flow requirement. These plots are shown in the supplementary material. An example of annual reliability of extraction is shown for a single node in Figure 4-1. Additionally, colour ramps and contours are designed to indicate 75% annual reliability of extraction as a nominal benchmark. For relative residual streamflow plots, additional contour lines are also represented (Figure 4-3). It can be seen from Figure 4-1 that increasing pump start threshold decreases the annual reliability of extraction. Decreasing pump capacity (i.e. increasing the number of ‘pump days’), while all other parameters are held constant reduces the reliability of extraction. Varying water harvest parameters changes the quantity and pattern of modelled water extraction. For example, implementing annual diversion commencement requirements in the Victoria River model delays the start of extraction, where the larger the annual diversion commencement requirement the longer the delay. In the catchment of the Victoria River, an annual diversion commencement requirement of 200 GL resulted in a modelled median irrigation commencement day of 5 December under Scenario B. Annual diversion commencement requirements of 500 and 700 GL resulted in modelled median commencement days of 26 December and 6 January, respectively (Figure 4-2).

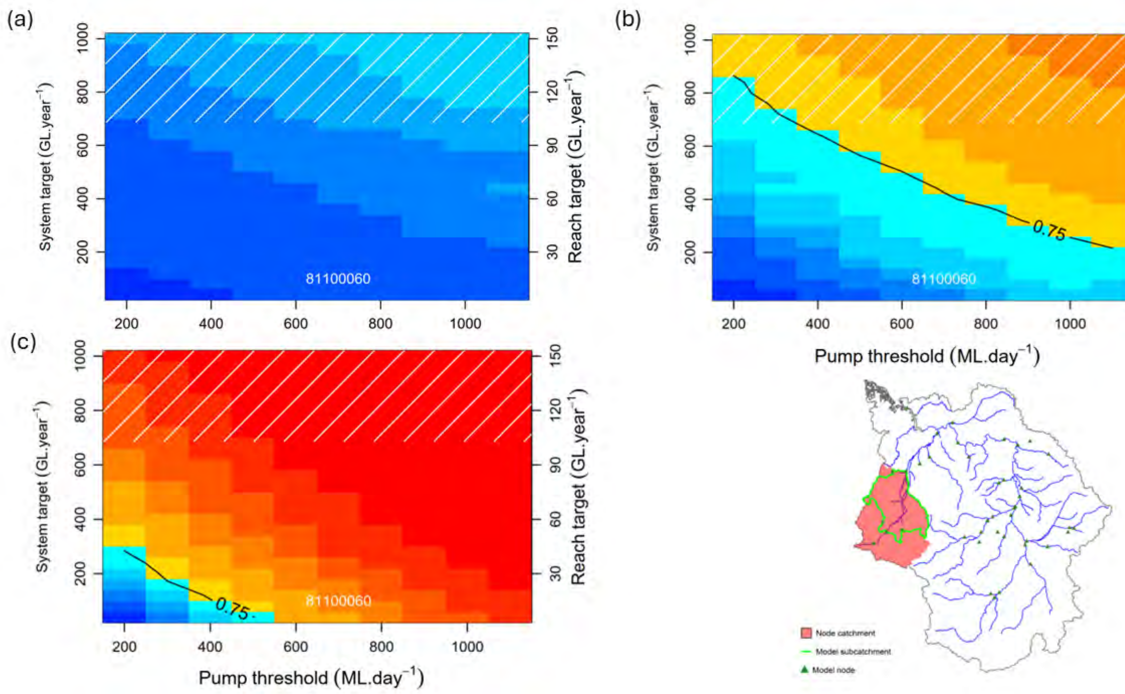

Figure 4-1 Annual reliability of irrigation supply under Scenario B for various pump start thresholds and irrigation volumetric targets at node 81100060 at pump rates of (a) 10 days, (b) 30 days and (c) 50 days.

No annual diversion commencement requirement. White hatched lines indicate annual volumes of water that exceed the amount required to irrigate the maximum area of soil suitable for irrigation in the catchment.

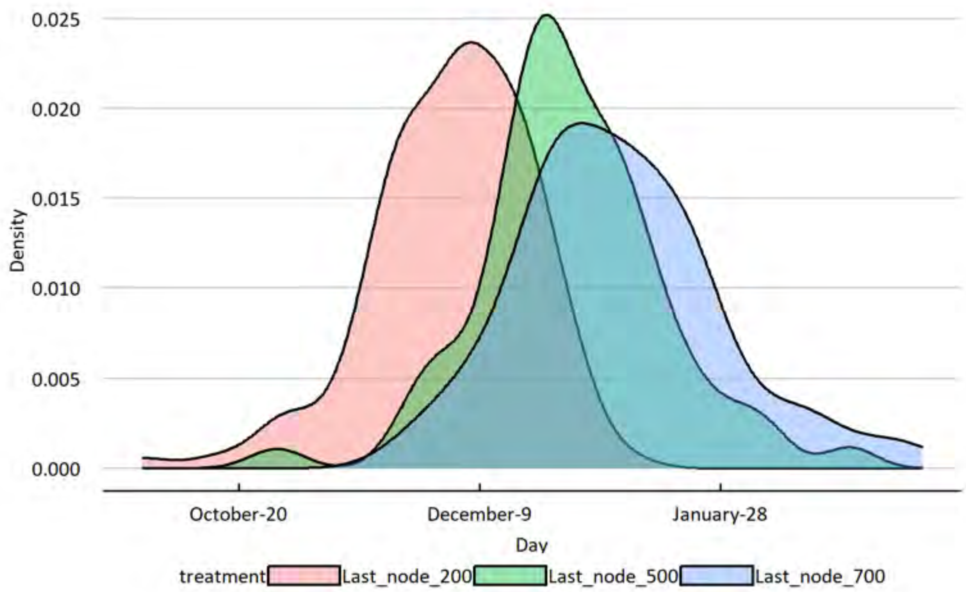

Figure 4-2 Sensitivity of the first day of pumping to annual diversion commencement requirement under Scenario B

Frequency density plot of three annual diversion commencement requirement volumes (200, 500 and 700 GL).

Water extraction reduces flow in the river. In dry years when the river flow is naturally lowest, the effects of extracting a given volume of water will be proportionally higher than in median and wetter years. In this regard it is useful to examine the effects of various water harvest strategies on streamflow relative to Scenario A downstream of the locations of extraction during drier years. A convenient statistic is the 80% exceedance annual flow relative to Scenario A. Figure 4-3 shows the effect of annual system irrigation target and annual diversion commencement requirement at node 81100000 on the 80% annual exceedance flow. This analysis shows that for system irrigation targets of greater than around 400 GL/year, reductions in the 80% annual exceedance flow are modest, although this effect is more marked at node 81100001 where reach irrigation volumetric targets are higher due to the relative abundance of soil suitable for dry-season cotton irrigation (Section 3.2.2). Additionally, the effects of water extraction will accumulate with distance downstream, and the extraction of water in headwater nodes is restricted at pump start thresholds of 1000 ML/day. More notably, it is apparent that annual diversion commencement requirements of at least 700 GL are required to considerably reduce the effects of water extraction on 80% annual exceedance flow. It is worth noting that sensitivity of 80% annual exceedance flow to water extraction in the Victoria catchment is lower than that modelled in the Roper catchment (Hughes et al., 2023). This is likely to be due to the arrangement of water harvest nodes in the Roper catchment in which many water harvest nodes were in series along the main river channel.

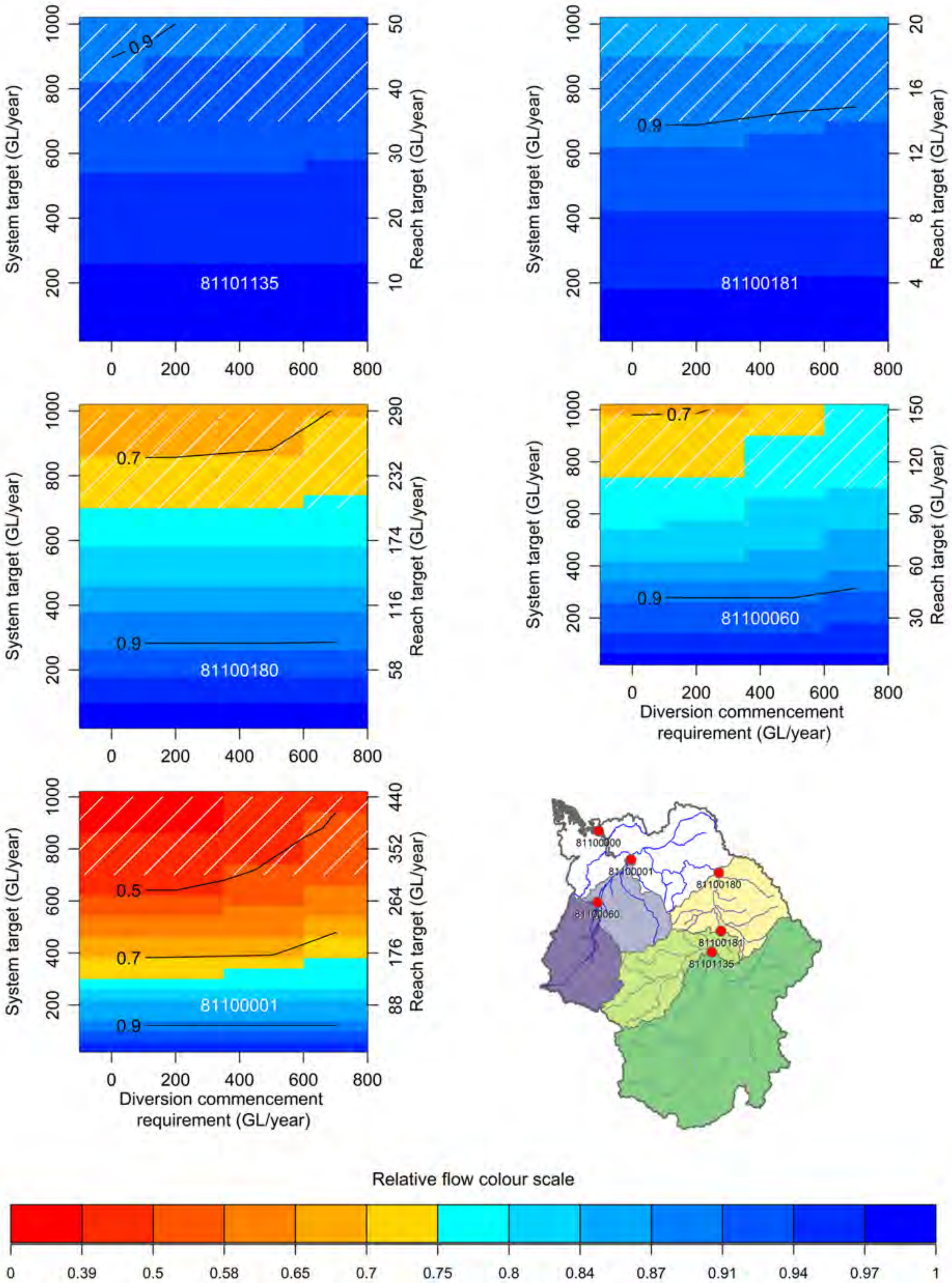

Figure 4-3 The 80% annual exceedance streamflow under Scenario B at five nodes relative to 80% annual exceedance streamflow under Scenario A at node 81100000

Based on a pump start threshold of 1000 ML/day and a pump capacity of 30 days. White hatched lines indicate the annual volumes of water that exceed the amount required to irrigate the maximum area of soil suitable for irrigation.

Soil-limited water harvest

Soil-limited water harvest volumes for the Victoria catchment were calculated according to the method outlined in Section3.2.2. The Victoria River model was used to calculate the volume of water that could be extracted at a minimum of 75% annual time reliability at all water harvest nodes. The calculated volumes are shown in Table 4-2, noting the volumes cannot exceed the minimum mean annual volume of water required to irrigate all soils suitable for irrigation in each reach (mean annual water requirement in Table 4-2). This analysis used a pump rate of 30 days and a pump start threshold of 200 ML/day at all water harvesting nodes.

Table 4-2 Mean annual water requirement and mean annual volume extracted at 75% annual time reliability

Assumes a pump rate of 30 days and a pump start threshold of 200 ML/day and no annual diversion commencement requirement. Mean annual volume extracted at a minimum of 75% annual time reliability cannot exceed mean annual water requirement in at each node. Mean annual water requirement is based on the mean volume of water required to irrigate soil suitable for irrigated agriculture within 5 km of the river, assuming 10 ML/ha.

NODE ID	MEAN ANNUAL WATER REQUIREMENT TO IRRIGATE AVAILBLE SUITABLE SOIL (GL)	MEAN ANNUAL VOLUME EXTRACTED AT 75% ANNUAL TIME RELIABLITY (GL/y)
81101131	33	33
81101130	37	37
81100181	17	17
81100180	246	200
81100060	427	100
81100001	384	300
Total	**1144**	**687**

The mean annual water requirement is higher than the mean annual volume of water that can be extracted at 75% annual time reliability, and it is clear that for many nodes where large areas of suitable soil are adjacent to the river reach (e.g. 81100060), water limits irrigated agriculture. At other nodes, where large volumes of water are apparent, soil limits to diversion apply (e.g. 81101130). With no annual diversion commencement requirement, a total of 687 GL could be diverted at 75% annual time reliability. Note that no consideration was given to the frequency or severity of flooding in the water harvest locations. These may further limit the viability or area of water harvest operations.

4.2.2 Instream dams (Scenario B-D)

Five potential dam sites across the Victoria catchment were modelled using the Victoria River model (Figure 4-4). Potential dam and reservoir information were obtained from the companion technical report on water storage (Yang et al., 2024), including height, volume and surface area relationships, dam capital cost of construction, optimum full supply level and water yield that can be supplied at an annual time reliability of 85%. These dam parameters were transposed into the Victoria River model for simulation for subsequent ecosystem analysis (Stratford et al., 2024). Three of the potential dams (Dam 140, Dam 341 and Dam 145) were simulated for the supply of water for irrigation. One potential dam (Dam 122), upstream of Kalkarindji, was simulated for its potential to mitigate flooding (i.e. the dam was designed with a tunnel and sluice at an elevation just above the streambed, which allows the dam to self-empty between flood or streamflow events). The final potential dam (Dam 39), which has limited soil downstream suitable for irrigated agriculture, was simulated to evaluate its potential as a hydro-electric dam, assuming the potential dam released water with a constant pattern (i.e. to provide baseload energy), given the lack of energy and transmission infrastructure in the Victoria catchment. Reservoirs impounded by the five potential dams are shown in Figure 4-4.

The three potential irrigation dams (Dam 140, Dam 341 and Dam 145) were simulated with and without transparent flow releases. Transparent flow thresholds were defined as:

$$t_t = \sum_{i=1}^{n} q_i/(n * 5) \quad (12)$$

where t_t is the transparent flow threshold, q_i is the streamflow on day i, and n is the number of simulation days. In other words, the threshold is the mean daily flow for the site divided by 5. This formula, although somewhat arbitrary, enables the threshold value to scale with flow rates at each potential dam site. Potential dam levels, yield, reliability and threshold flows are given in Table 4-3

Table 4-3 Potential dam full supply level, reservoir yield, and reliability of supply with and without transparent flow
Reservoir yield given at the dam wall.

	DAM 186†	DAM 131	DAM 230	DAM 134	DAM 38‡
Dam full supply level (mEMG96)	202	122	86	98	51
Dam volume at full supply level (GL)	302	195	56	1116	6003
Annual irrigation target (GL/y)	na§	60	31	500	1750
Annual reliability without transparent flow (%)	na	83	86	86	95
Transparent flow threshold (ML/day)	na	55	155	860	na
Annual reliability with transparent flow (%)	na	75	77	77	na

† Flood mitigation dam
‡ Hydro-electric power dam
§ na = not applicable

As shown in Table 4-3, transparent flow releases have a moderate impact on the reliability of water yield. The reductions in reliability are relatively consistent.

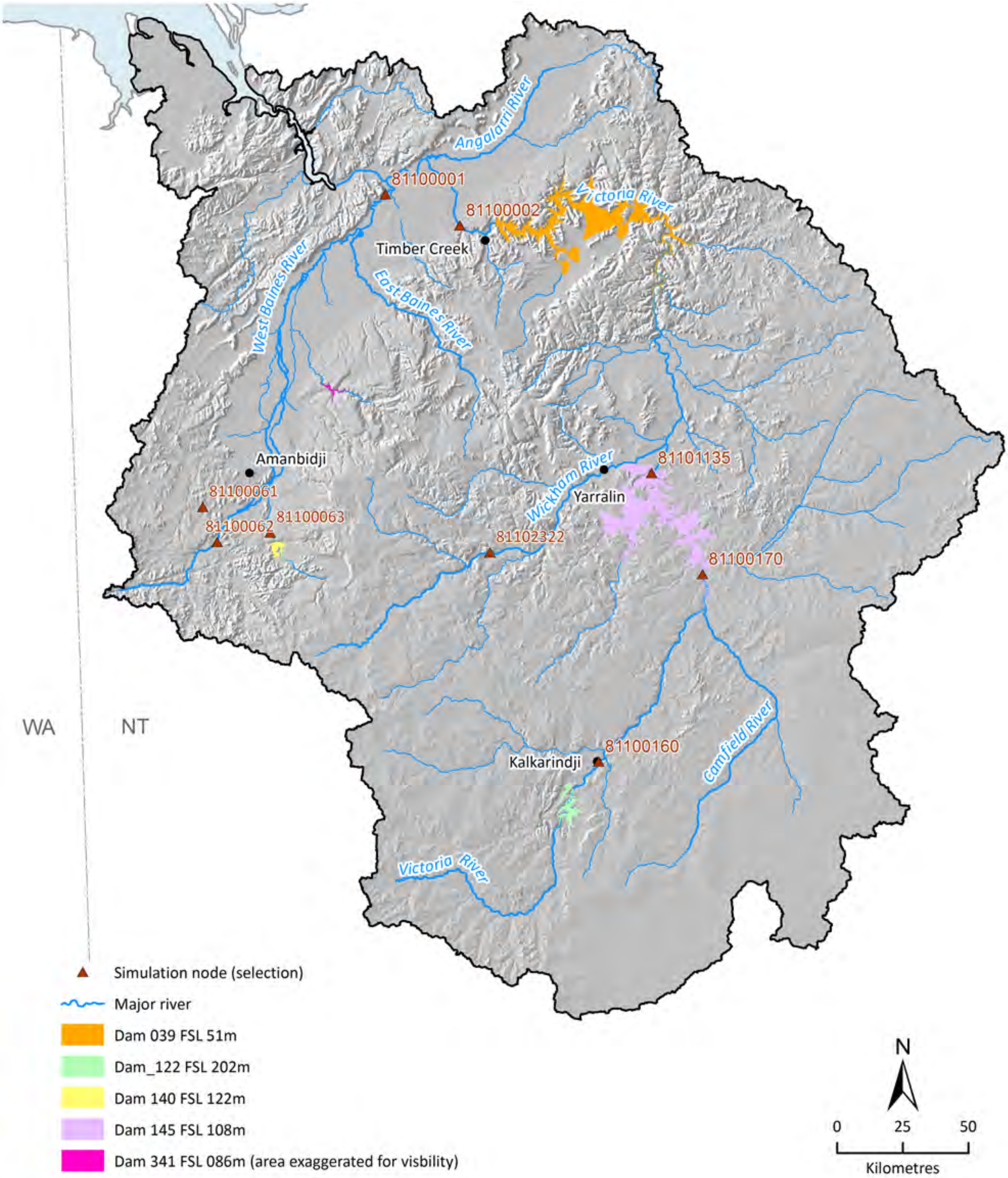

Figure 4-4 Reservoir areas impounded by potential dams at specified full supply level (FSL)

Only the river model simulation nodes relevant to each potential dam site are shown.

In addition to simulating each dam individually, the three irrigation dams were simulated operating concurrently to enable the maximum scale of irrigated agriculture in the Victoria catchment to be evaluated. Two simulations were undertaken, the first without transparent flows, referred to as Scenario B-D_3 and the second with transparent flows, referred to as Scenario B-D_3-T.

Flow quantiles under scenarios A, B-D_3 and B-D_3-T are shown in Table 4-4.

Table 4-4 Mean annual flow and daily exceedance flows for dam-affected gauges under scenarios A, B-D3 and B-D3-T Percentage change from Scenario A is given in parentheses.

	NODE ID	MEAN ANNUAL FLOW (GL/y)	90% EXCEEDANCE FLOW (ML/d)	80% EXCEEDANCE FLOW (ML/d)	50% EXCEEDANCE FLOW (ML/d)	20% EXCEEDANCE FLOW (ML/d)	10% EXCEEDANCE FLOW (ML/d)
Scenario A	81100000	6994	20	59	814	12,999	43,954
	81100001	1523	1	6	142	1,841	8,807
	81100002	3833	6	16	293	5,408	19,593
	81100060	781	0	0	3	490	3,434
	81100063	101	0	0	0	41	264
	81100070	3415	2	7	182	3,634	16,025
	81100180	3236	0	1	129	2,716	14,282
	81100181	2289	0	1	79	1,637	10,156
	81101130	2215	0	1	71	1,493	9,557
	81101135	1571	0	0	45	991	5,678
Scenario B-D3: three dams with no transparent flow	81100000	6207(89)	17(88)	50(86)	634(78)	11,444(88)	38,173(87)
	81100001	1408(92)	1(93)	5(97)	135(95)	1,722(94)	7,983(91)
	81100002	3163(83)	4(80)	12(72)	158(54)	4,303(80)	15,168(77)
	81100060	702(90)	0(†)	0(†)	3(81)	434(88)	3064(89)
	81100063	23(23)	0(†)	0(†)	0(†)	0(0)	0(0)
	81100070	2745(80)	2(75)	4(64)	71(39)	2,693(74)	11,830(74)
	81100180	2566(79)	0(50)	1(35)	35(27)	1,863(69)	10,192(71)
	81100181	1620(79)	0(†)	0(33)	16(21)	657(40)	6,273(62)
	81101130	1547(70)	0(†)	0(30)	13(18)	513(34)	5,826(61)
	81101135	903(57)	0(†)	0(†)	0(0)	0(0)	0(0)
Scenario B-D3-T: three dams with transparent flow	81100000	6235(89)	20(100)	59(100)	801(98)	11,883(91)	38,433(87)
	81100001	1411(93)	1(100)	6(100)	140(99)	1,785(97)	8,079(92)
	81100002	3188(83)	6(100)	16(100)	291(99)	4,712(87)	15,469(79)
	81100060	704(90)	0(†)	0(†)	3(100)	462(94)	3,082(90)
	81100063	25(25)	0(†)	0(†)	0(†)	41(100)	55(21)
	81100070	2770(81)	2(100)	7(100)	181(100)	3,126(86)	11,927(74)
	81100180	2591(80)	0(†)	1(100)	128(100)	2,306(85)	10,429(73)
	81100181	1645(72)	0(†)	1(100)	78(100)	1,214(74)	6,587(65)
	81101130	1572(71)	0(†)	1(100)	70(100)	1,109(74)	6,160(64)
	81101135	928(59)	0(†)	0(†)	45(99)	860(87)	860(15)

† Calculation of percentage change is not possible.

Flood mitigation dam in subcatchment 81100160 (Scenario B-D_F)

The flood mitigation dam upstream of node 81100160 (Dam 186) was simulated under Scenario B-D_F and compared with Scenario A flow. More specifically, the dam was analysed for its effectiveness in reducing peak flows. Figure 4-5 shows the distribution of annual peak flow under scenarios A and B-D_F (i.e. with the inclusion of a flood mitigation dam). The mean of the five highest peak daily flows at this node under Scenario A was 2834 m^3/second, and it was reduced to 1872 m^3/second under Scenario B-D_F. Note that the ability of the dam to reduce peak flows is a combination of the spillway and flood rise and the available dam storage prior to any event. For very large events, the available dam storage will be small relative to the volume of the event, lessening its ability to reduce peak flow. This is demonstrated in Figure 4-6, where peak outflow rates were recorded for a range of synthetically derived inflows. For peak inflows higher than around 2000 m^3/second, the dam is filled quickly and most inflow is return to the stream via the dam spillway.

The effect of the dam on flood peaks further downstream was also examined. It was found that, while the dam had a substantial effect at Kalkarindji, these effects did not persist downstream very far. For example, at node 81100170 (near the Pidgeon Hole community), the effects of the dam on flood peaks was negligible. This is partly since the dam does not reduce flood volume, only it's distribution across time, as well as the influence of other tributary inflows downstream of the dam.

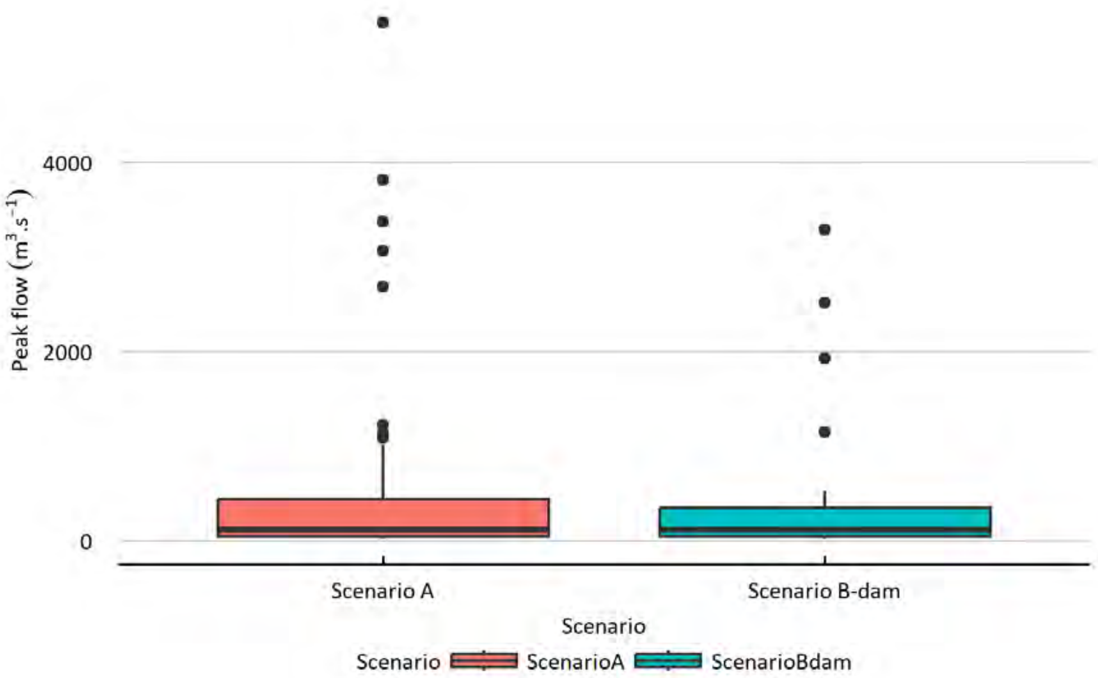

Figure 4-5 Annual maximum flow under scenarios A and B-D_F (flood mitigation dam) at node 81100160

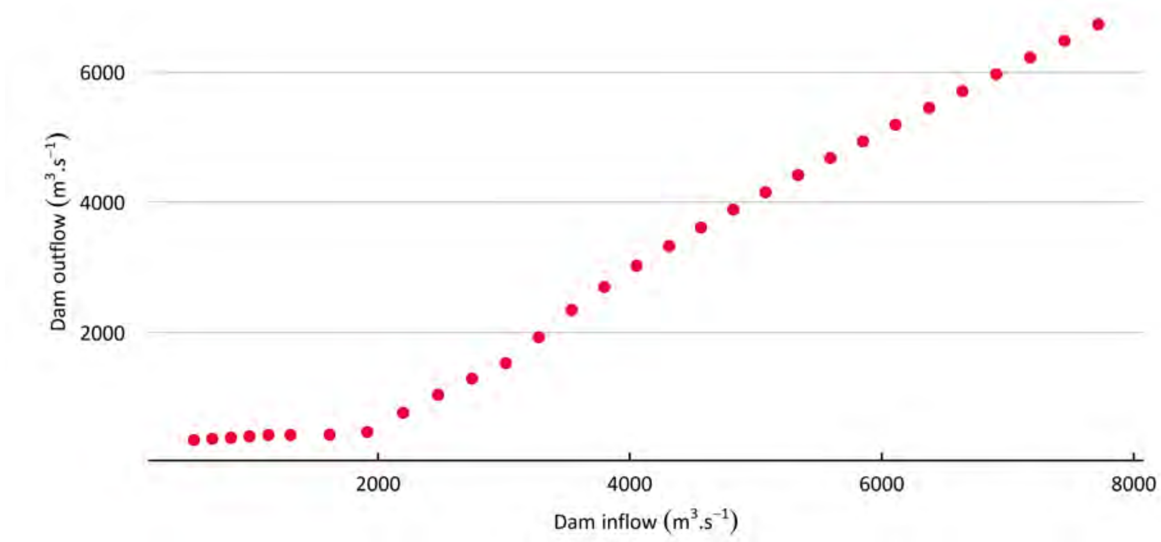

Figure 4-6 The relationship between peak inflow and peak outflow at Dam 186 in model node 81100160

Hydropower dams in subcatchment 81100002 (Scenario B-D_{HE})

Hydropower dams were simulated for a range of FSL values at dam site 39. Hydropower generation from an instream dam is largely dependent upon flow rates and head differences between the reservoir and river. For these reasons, larger dams will generate more power on average than smaller dams as can be seen in Figure 4-7.

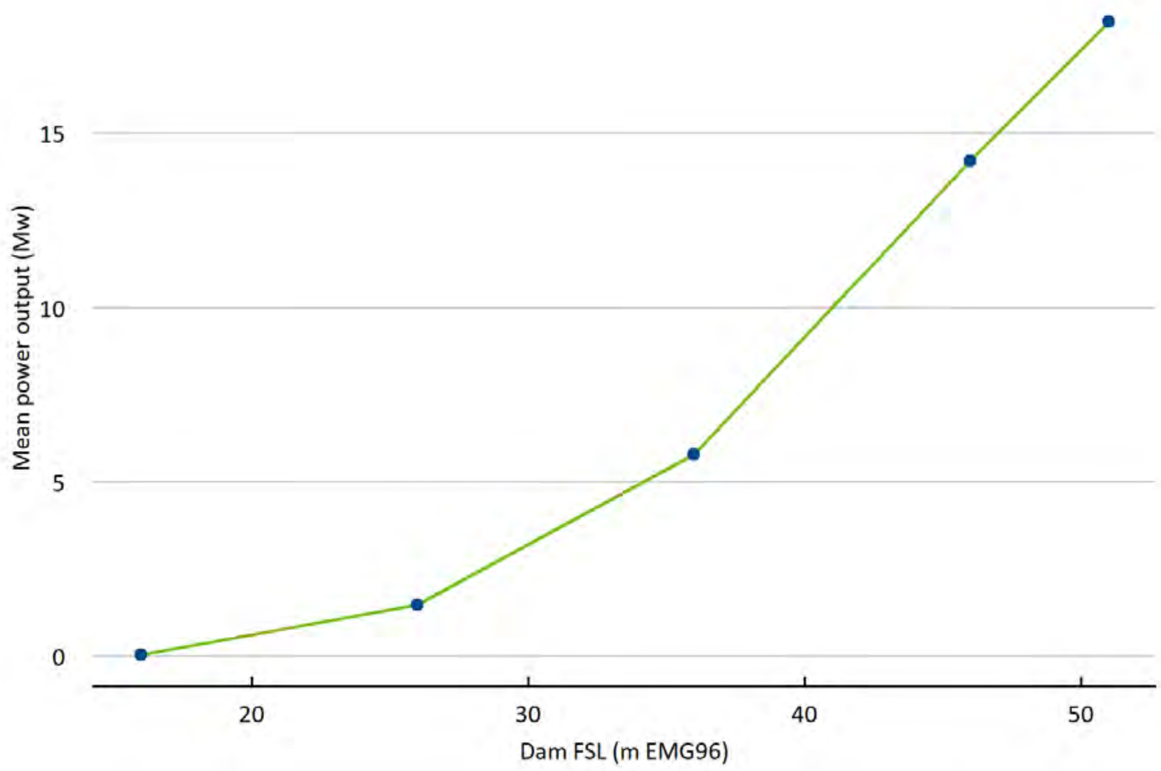

Figure 4-7 The relationship between dam full supply level and mean power output at dam site 38

While no water was diverted to irrigation for these dams, they can still have a large impact on stream hydrology. Using the largest simulate dam as an example (FSL 51 m), end of system flow was reduced by around 7% via dam evaporation. Also, the pattern of flow was substantially altered since much of the variability apparent in the scenario A flow is reduced due to a constant dam discharge Figure 4-8.

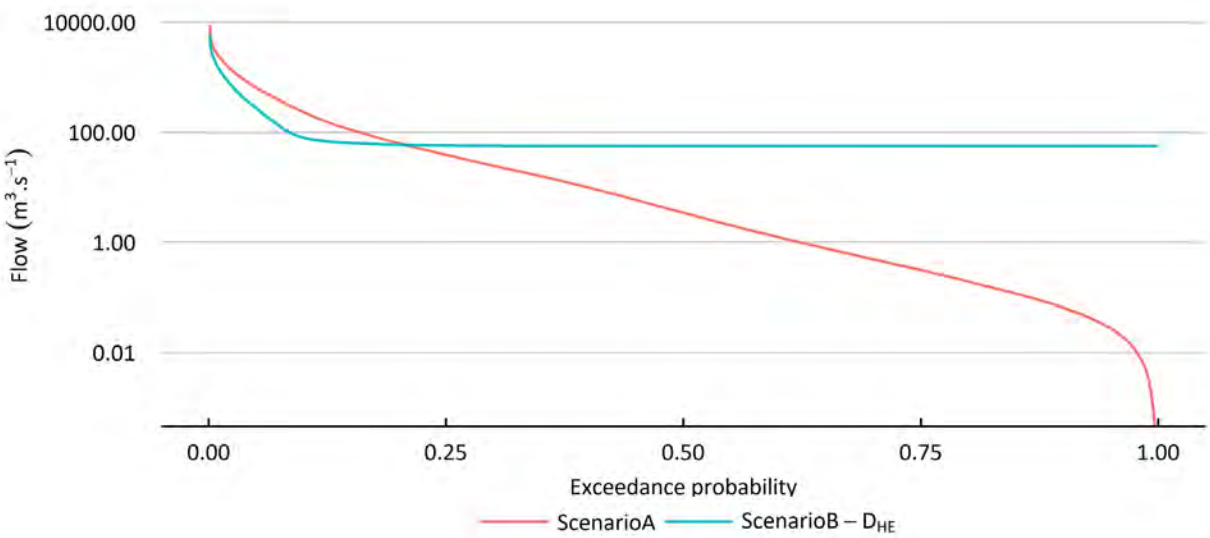

Figure 4-8 Flow duration curves at node 81100002 for scenario A and Scenario B–D_{HE} (FSL 51m)

4.3 Scenario C

Table 4-5 lists the mean annual flow and selected annual flow exceedance values at all nodes in the Victoria River model under scenarios Cdry, Cmid and Cwet.

Table 4-5 Annual flow exceedance values, mean runoff coefficients and mean annual flows at all model nodes under scenarios Cdry, Cmid and Cwet

SCENARIO	NODE ID	MEAN ANNUAL FLOW (GL)	90% ANNUAL EXCEEDANCE FLOW (GL)	80% ANNUAL EXCEEDANCE FLOW (GL)	50% ANNUAL EXCEEDANCE FLOW (GL)	20% ANNUAL EXCEEDANCE FLOW (GL)	10% ANNUAL EXCEEDANCE FLOW (GL)	RUNOFF COEFFICIENT
Cdry	81100000	5338	1593	2458	4305	7750	10,358	0.11
	81100001	1219	378	521	1074	1754	2,137	0.12
	81100002	2857	683	1057	2207	4267	6,229	0.09
	81100003	427	144	217	361	599	734	0.14
	81100040	224	81	111	187	306	370	0.13
	81100060	626	174	238	543	921	1,141	0.12
	81100061	91	25	39	84	133	178	0.11
	81100062	100	24	40	89	150	183	0.11
	81100063	81	19	31	77	120	155	0.11
	81100070	2535	519	856	1933	3770	5,517	0.09
	81100120	18	6	8	15	25	33	0.15
	81100140	14	2	4	11	20	25	0.12

SCENARIO	NODE ID	MEAN ANNUAL FLOW (GL)	90% ANNUAL EXCEEDANCE FLOW (GL)	80% ANNUAL EXCEEDANCE FLOW (GL)	50% ANNUAL EXCEEDANCE FLOW (GL)	20% ANNUAL EXCEEDANCE FLOW (GL)	10% ANNUAL EXCEEDANCE FLOW (GL)	RUNOFF COEFFICIENT
	81100160	154	29	34	57	211	412	0.07
	81100170	606	82	129	288	866	1,548	0.06
	81100171	135	25	31	67	189	340	0.08
	81100172	318	59	72	140	470	851	0.07
	81100180	2399	447	787	1820	3518	5,346	0.08
	81100181	1709	339	556	1228	2450	4,175	0.08
	81100182	111	19	32	91	173	216	0.12
	81100183	73	8	13	56	116	160	0.10
	81100730	35	9	12	27	49	64	0.10
	81100740	8	2	3	7	11	16	0.10
	81100750	128	31	45	96	180	229	0.10
	81101010	48	19	23	40	66	84	0.13
	81101070	23	9	11	20	32	40	0.14
	81101100	29	9	12	22	38	52	0.13
	81101130	1655	334	550	1193	2,297	4,128	0.08
	81101131	469	98	191	388	667	884	0.10
	81101132	12	3	5	11	17	23	0.09
	81101133	76	18	31	66	112	148	0.09
	81101134	363	92	134	273	523	674	0.10
	81101135	1157	230	335	768	1,589	2,947	0.07
	81101660	418	88	168	343	606	782	0.10
	81101670	172	0	0	0	309	600	0.03
	81101700	3	1	1	2	4	5	0.09
	81102320	300	66	120	251	439	547	0.09
	81102321	292	64	115	245	428	523	0.09
	81102322	161	39	54	135	243	298	0.09
	81102380	55	8	17	43	85	107	0.12
	81102510	11	3	5	9	17	20	0.11
	81102530	25	5	10	22	37	48	0.09
Cmid	81100000	6745	1939	3006	5608	9,616	13,124	0.12
	81100001	1477	485	699	1319	2,027	2,533	0.14
	81100002	3687	803	1395	2813	5,281	8,106	0.11
	81100003	541	190	264	439	699	935	0.16
	81100040	271	97	132	218	354	443	0.15
	81100060	760	229	320	681	1,085	1,392	0.13
	81100061	110	35	49	98	159	201	0.13
	81100062	121	34	50	111	177	217	0.12
	81100063	99	29	40	88	144	184	0.12
	81100070	3281	639	1196	2476	4,812	7,438	0.10

SCENARIO	NODE ID	MEAN ANNUAL FLOW (GL)	90% ANNUAL EXCEEDANCE FLOW (GL)	80% ANNUAL EXCEEDANCE FLOW (GL)	50% ANNUAL EXCEEDANCE FLOW (GL)	20% ANNUAL EXCEEDANCE FLOW (GL)	10% ANNUAL EXCEEDANCE FLOW (GL)	RUNOFF COEFFICIENT
	81100120	22	7	10	19	31	46	0.17
	81100140	18	3	5	14	25	40	0.15
	81100160	203	31	36	72	294	496	0.09
	81100170	815	99	146	430	1,313	2,134	0.07
	81100171	179	27	33	105	285	419	0.09
	81100172	421	64	76	214	609	992	0.09
	81100180	3107	560	1120	2347	4,617	6,989	0.10
	81100181	2197	423	753	1626	3,259	5,141	0.09
	81100182	142	22	46	113	211	279	0.14
	81100183	95	9	26	77	148	193	0.12
	81100730	43	11	15	32	60	77	0.11
	81100740	10	2	4	8	13	20	0.12
	81100750	158	36	54	121	218	286	0.12
	81101010	58	21	29	48	75	102	0.15
	81101070	27	10	14	23	37	47	0.16
	81101100	37	11	14	28	55	77	0.15
	81101130	2126	414	712	1582	3,139	4,969	0.09
	81101131	586	139	241	474	789	1,011	0.11
	81101132	15	3	6	13	22	28	0.11
	81101133	94	24	40	79	141	170	0.10
	81101134	453	102	175	341	638	800	0.11
	81101135	1503	271	436	1037	2,281	3,851	0.08
	81101660	522	117	209	420	716	918	0.11
	81101670	252	0	0	56	521	830	0.05
	81101700	4	1	1	3	5	7	0.10
	81102320	374	82	143	301	512	659	0.11
	81102321	363	80	138	293	494	644	0.11
	81102322	200	49	78	157	276	372	0.11
	81102380	72	15	24	51	101	142	0.14
	81102510	13	3	5	11	19	23	0.12
	81102530	31	7	13	25	46	58	0.10
Cwet	81100000	8679	2324	3724	6746	13,126	16,616	0.15
	81100001	1855	587	881	1537	2,594	3,268	0.16
	81100002	4804	1028	1743	3733	7,102	10,516	0.13
	81100003	673	226	315	534	951	1,349	0.19
	81100040	345	108	159	254	448	649	0.17
	81100060	943	291	391	793	1,336	1,630	0.15
	81100061	135	47	59	121	192	234	0.14
	81100062	148	44	65	129	219	268	0.14

SCENARIO	NODE ID	MEAN ANNUAL FLOW (GL)	90% ANNUAL EXCEEDANCE FLOW (GL)	80% ANNUAL EXCEEDANCE FLOW (GL)	50% ANNUAL EXCEEDANCE FLOW (GL)	20% ANNUAL EXCEEDANCE FLOW (GL)	10% ANNUAL EXCEEDANCE FLOW (GL)	RUNOFF COEFFICIENT
	81100063	121	34	50	112	173	215	0.14
	81100070	4294	851	1529	3280	6,426	9,522	0.12
	81100120	28	8	11	23	37	56	0.19
	81100140	23	4	7	17	34	50	0.17
	81100160	281	33	41	139	396	775	0.11
	81100170	1133	110	185	767	1,711	2,825	0.09
	81100171	246	29	40	147	348	610	0.12
	81100172	581	68	95	330	793	1,617	0.11
	81100180	4081	768	1432	3101	6,177	9,348	0.12
	81100181	2924	555	970	2160	4,311	6,996	0.11
	81100182	181	33	62	145	275	349	0.17
	81100183	121	17	33	101	185	242	0.14
	81100730	56	14	19	39	71	119	0.14
	81100740	13	3	5	10	17	29	0.14
	81100750	208	45	72	145	262	428	0.14
	81101010	76	26	33	56	107	152	0.18
	81101070	33	12	16	28	46	60	0.18
	81101100	48	12	17	33	75	100	0.18
	81101130	2834	540	912	2095	4,103	6,891	0.11
	81101131	764	174	289	559	1,061	1,562	0.13
	81101132	20	5	7	16	26	37	0.13
	81101133	119	30	49	98	168	245	0.12
	81101134	591	135	218	423	768	1,182	0.13
	81101135	2023	340	568	1494	2,948	5,095	0.10
	81101660	681	156	253	507	979	1,380	0.13
	81101670	375	0	0	224	716	1,089	0.06
	81101700	5	1	2	4	6	9	0.13
	81102320	486	112	184	370	654	972	0.13
	81102321	473	109	178	359	638	947	0.13
	81102322	262	59	96	199	353	529	0.13
	81102380	92	18	31	68	129	193	0.17
	81102510	16	5	7	13	23	27	0.14
	81102530	40	9	15	32	55	83	0.12

In Table 4-6 the change in streamflow under scenarios Cdry, Cmid and Cwet is expressed as a percentage of Scenario A at two nodes in the river model. A reduction in rainfall of 7.3% (Scenario Cdry) resulted in a modelled reduction of streamflow of around 25%, while an increase of rainfall of 8.7% (Scenario Cwet) resulted in a modelled streamflow increase across all nodes of 24% to 28%. Using these values, the simulated rainfall elasticity of streamflow can be calculated:

$$\varepsilon_P = {}^{\Delta \mathrm{Q}}/_{\Delta P} \quad (13)$$

where ε_P is the rainfall elasticity of streamflow, $\Delta \mathrm{Q}$ is the proportional change in streamflow (in this case from Scenario A to either Scenario Cdry or Scenario Cwet), and ΔP is the concurrent proportional change in precipitation. Values for these data were in the range 3.2 to 3.4, which are within the range of values calculated by Chiew (2006) for 219 Australian catchments (most of which were in southern Australia). Particular care was taken to ensure the future climate streamflow projections of the Victoria River model were robust. This included using novel model calibration methods that use streamflow, climate and regolith data from across northern Australia (Hughes et al., 2024a) and checking the hydrographic records for evidence of 'hydrological non-stationarity'.

Table 4-6 Mean annual flow under scenarios Cdry, Cmid and Cwet expressed as a percentage of Scenario A

SCENARIO	NODE 81101130	NODE 81100000
Dry	75%	76%
Mid	96%	96%
Wet	128%	124%

Analyses of the sensitivity of the Victoria River model to changes in rainfall and potential evaporation were undertaken in addition to the simulation of streamflow under scenarios Cdry, Cmid and Cwet. For the sensitivity analyses, a range of precipitation and potential evaporation pattern scaling factors were used that fully encompassed the values calculated for the 32 CMIP6, SSP2-4.5 GCMs at approximately 2060. Annual precipitation scaling factors ranged from 0.8 to 1.18, and potential evaporation scaling factors ranged from 1.0 to 1.18. In total, 210 combinations of rainfall and potential evaporation scaling values were used to create new river model climate inputs in order to simulate the mean annual end-of-system flow for each rainfall and potential evaporation combination. These data are presented in Figure 4-9, which clearly shows that the Victoria River model is much more sensitive to changes in precipitation than in potential evaporation. Mean annual end-of-system flow across the 32 GCMs ranges from around 4,500 GL to slightly greater than 10,000 GL.

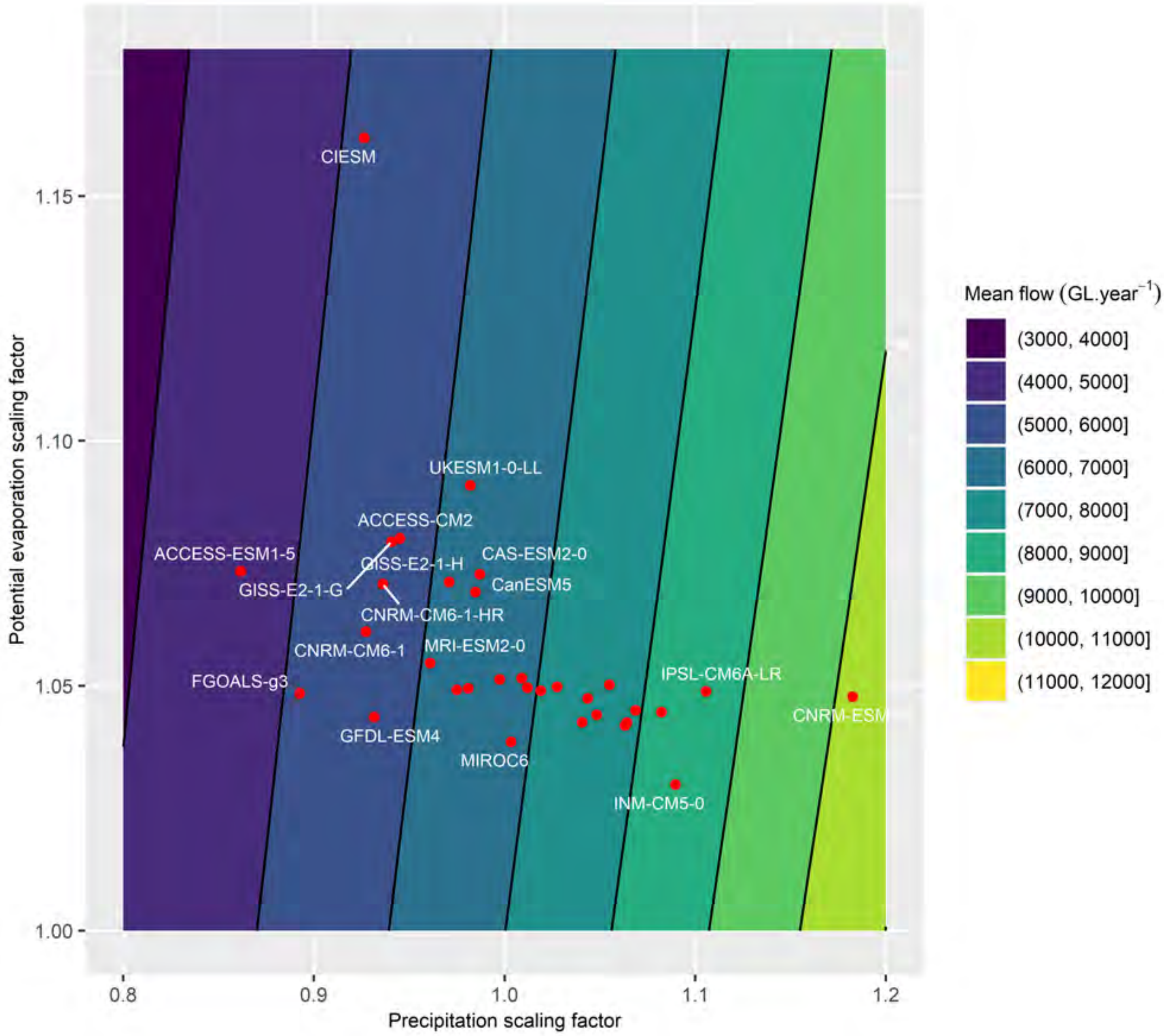

Figure 4-9 Sensitivity of the Victoria River model end-of-system flow to changes in rainfall and potential evaporation

Red circles represent annual scaling factors of the 32 CMIP6 GCMs.

4.4 Scenario D

Scenario D simulations are designed to explore the effects of water resource development in addition to long-term changes in climate. Of the three future projected climate scenarios, Scenario Ddry was the focus of the Assessment because it was the scenario under which competition for water would be the greatest between users and the environment. Reductions in streamflow due to long-term changes in climate compound reductions due to extractions, with consequences for streamflow-dependant ecosystems and/or reliability of supply.

4.4.1 Dry future climate and water harvest (Scenario Ddry-W)

The dry climate future in conjunction with water harvest analysis was conducted, and the streamflow results are given in Table 4-7. The water harvest parameters selected for future dry climate simulation were the same as those used for the calculating the soil-limited maximum Scenario B simulation, that is, a system irrigation target of 680 GL, a pump start threshold of 200 ML/day and a pump rate of 30 days. Under Scenario B, these parameters resulted in an annual reliability of at least 75% in all irrigation nodes. Due to some river reaches being soil limited, the reliability of extraction was higher in some reaches. The water harvest parameters under Scenario Ddry simulation remained the same as those used under Scenario B-W. Given the large reduction in modelled streamflow under Scenario Cdry relative to Scenario A, reliability of supply was modelled to be lower for some water harvest nodes (i.e. the minimum of 75% annual supply reliability was not enforced). However, in most cases the reduction in reliability was very small (0% to 10%). This was particularly the case for the nodes on the main Victoria River (81100180, 81100181, 81101131 and 81101135), where the low amount of suitable soil limited how much water needed to be extracted.

In terms of mean flow reductions relative to Scenario A, Scenario D-W_{680} (water harvest) is of similar magnitude to the addition of Scenario B water harvest (B-W_{680})and Scenario Cdry (Table 4-5), although Scenario Ddry-W_{680} (dry + water harvest) has large effects on annual flow for higher exceedance probabilities. For example, at the end-of-system (at node 81100000), 80% annual exceedance flow under Scenario A is 3099 GL. This falls to 2458 GL under Scenario C and to 1849 GL under Scenario D-W. See Table 4-8.

Table 4-7 Mean annual flow and annual flow exceedance values under Scenario Ddry-W_{680} (dry + water harvest 680 GL) and annual reliability of irrigation supply for scenarios B and Ddry

NODE ID	MEAN ANNUAL FLOW (GL/y)	80% ANNUAL EXCEEDANCE FLOW (GL/y)	50% ANNUAL EXCEEDANCE FLOW (GL/y)	20% ANNUAL EXCEEDANCE FLOW (GL/y)	NODE IRRIGATION TARGET (GL/y)	SCENARIO B ANNUAL RELIABILITY OF SUPPLY (%)	SCENARIO Ddry ANNUAL RELIABILITY OF SUPPLY (%)
81100000	4697	1849	3622	7061	NA†	NA	NA
81100001	848	153	672	1348	299.2	78	71
81100002	2587	795	1934	3991	NA	NA	NA
81100003	427	217	361	599	NA	NA	NA
81100060	531	137	440	819	102	80	70
81100070	2265	594	1660	3493	NA	NA	NA
81100180	2129	525	1547	3243	197.2	89	88
81100181	1630	485	1147	2369	13.6	99	99
81101130	1590	485	1126	2229	NA	NA	NA
81101131	437	163	354	633	34	81	81
81101135	1123	301	734	1555	34	98	96

Table 4-8 Mean annual flow and annual flow exceedance values for node 81100000 for scenarios A, B-W_{680}, Cdry and Ddry-W_{680}

SCENARIO	MEAN ANNUAL FLOW (GL)	80% ANNUAL EXCEEDANCE (GL)	50% ANNUAL EXCEEDANCE (GL)	20% ANNUAL EXCEEDANCE (GL)
Scenario A	6994	3099	5734	10,071
Scenario B-W_{680} (water harvest 680 GL)	6339	2435	5053	9,380
Scenario Cdry	5338	2458	4305	7,750
Scenario Ddry-W_{680} (dry + water harvest 680 GL)	4697	1849	3622	7,061

4.4.2 Dry future climate and three instream dams (Scenario Ddry-D_3)

The dry climate future was combined with three instream dams to assess the effect on streamflow. For this simulation, dam parameters, including full supply level and irrigation target volumes, were the same as under Scenario B (Section 4.2.2), and no transparent flow was implemented. For these reasons, reliability of supply was reduced relative to Scenario B simulations (where supply volumes at 85% annual reliability were optimised). For example, the largest dam (Dam 145 on node 81101135) reduced annual reliability of supply from 86% to 70%, but there were very large reductions in 80%, 50% and 20% annual exceedance flow at this location (Table 4-9).

Reduction in mean annual flow at the end-of-system under Scenario Ddry-D_3 relative to Scenario A was 35% (Table 4-9). This was of a similar magnitude to the reduction in mean annual flow under Scenario Ddry-W, and the reductions in 80%, 50% and 20% annual exceedance flows were also around 35%. Noted that Dam 145 impounds a very large reservoir of around 1116 GL at its full supply level, so the dam surface is also large as are losses to evaporation. However, a dam of any size is unlikely at this location (due to the marginal cost of water supplied), let alone a dam of this size.

Table 4-9 Mean annual flow and annual flow exceedance values under Scenario Ddry-D_3 (dry + three dams)

NODE ID†	MEAN ANNUAL FLOW (GL/y)	80% ANNUAL EXCEEDANCE FLOW (GL/y)	50% ANNUAL EXCEEDANCE FLOW (GL/y)	20% ANNUAL EXCEEDANCE FLOW (GL/y)
81100000	4597	1938	3526	6838
81100001	1110	447	948	1597
81100002	2225	692	1496	3578
81100060	554	207	471	786
81100063	10	0	0	0
81100070	1903	529	1234	2976
81100180	1768	474	1117	2811
81100181	1078	222	549	1602
81101130	1024	205	506	1494
81101135	527	0	0	832

† Only nodes affected by instream dams are listed.

5 Discussion and conclusions

The river model outlined in this report is the first of its kind to be attempted in the catchment of the Victoria River. Previous estimates have been made for streamflow at the catchment outlet (e.g. Petheram et al., 2009), and the mean annual end-of-system flow calculated here of 6990 GL was very similar to the Petheram et al. (2009) study. The calibration used streamflow data from across northern Australia to ensure the model was as robust as possible, particularly under extreme future climate projections (i.e. scenarios Cwet and Cdry) of streamflow, which can be difficult to simulate confidently since model behaviour will generally be outside the bounds of calibration conditions.

The magnitude of hypothetical developments explored using the river model was restricted by the availability of soils suitable for irrigated agriculture and the availability of potential dam sites in proximity to those locations. Under Scenario B, and considering soil restrictions, a physical maximum of 680 GL could be supplied at an annual time reliability of at least 75%, although even this assumed a very low pump start threshold (200 ML/day) and these scenarios, as well as dam scenarios did not consider any other restrictions that might arise from to economic, environmental, cultural or land tenure considerations.

The effects of dams for irrigation on streamflow at potential sites were considered at three locations within the catchment. These dams were selected from a more extensive assessment of water storage locations across the catchment (Yang et al., 2024) based on the unit cost of mean annual diversion and the geological suitability of the site. The dam parameters were then used to simulate the effect of all three dams concurrently. Using an 85% annual supply reliability benchmark, 591 GL/year could be diverted if no transparent flow is assumed. Again, these volumes and calculations do not consider other implications and restrictions due to environmental, cultural or land tenure considerations. As such, the modelled scenario is conservatively large, and was used subsequently for flood and ecosystem analyses.

These dams and simulated diversions caused a mean net reduction in streamflow at the catchment outlet of 787 GL/year (11% of Scenario A flow), noting that evaporation in the Assessment area is high. The release of transparent flows at these dam sites reduced this to 769 GL/year, although impacts of transparent flows on 90% and 80% daily exceedance flow values were substantial.

Future climate simulation used three selected future climates based on the 90%, 50% and 10% future climate rainfall from 32 GCMs from the CMIP6 collection. Additionally, a sensitivity analyses was conducted that used scaling factors for a range of future precipitation and evaporation values to examine the sensitivity of streamflow to future climate. Under the future wet scenario (Cwet), end-of-system flow increased by 24%, whereas it decreased by 24% under the future dry scenario (Cdry).

Scenario D simulations tested the effect of dry future climates plus either water harvest or instream dam scenarios. Using an annual irrigation target of 680 GL and a future dry climate, end-of-system streamflow was reduced by 33%. Similarly, using three instream dams with a combined annual irrigation target of 581 GL and a future dry climate, end-of-system streamflow was reduced by 34%.

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