Estimated effects of climate change and groundwater development scenarios on the Cambrian Limestone Aquifer in the eastern Victoria River catchment

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

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Important disclaimer

CSIRO Victoria River Water Resource Assessment acknowledgements

This report was funded through the National Water Grid's Science Program, which sits within the Australian Government's Department of Climate Change, Energy, the Environment and Water.

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 Cuan Petheram (CSIRO) and Mr Chris Turnadge (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

Old Top Spring. 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.

C. Chilcott

Chris Chilcott

Project Director

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Shortened forms

SHORT FORM	FULL FORM
AHD	Australian Height Datum
BC	boundary condition
CLA	Cambrian Limestone Aquifer
CMB	chloride mass balance
DRBWCD	Daly Roper Beetaloo Water Control District
FTWMZ	Flora Tindall Water Management Zone
GCM	global climate model
NT	Northern Territory
PET	potential evapotranspiration
SILO	Scientific Information for Land Owners
WCD	water control district
WWMZ	Wiso Water Management Zone

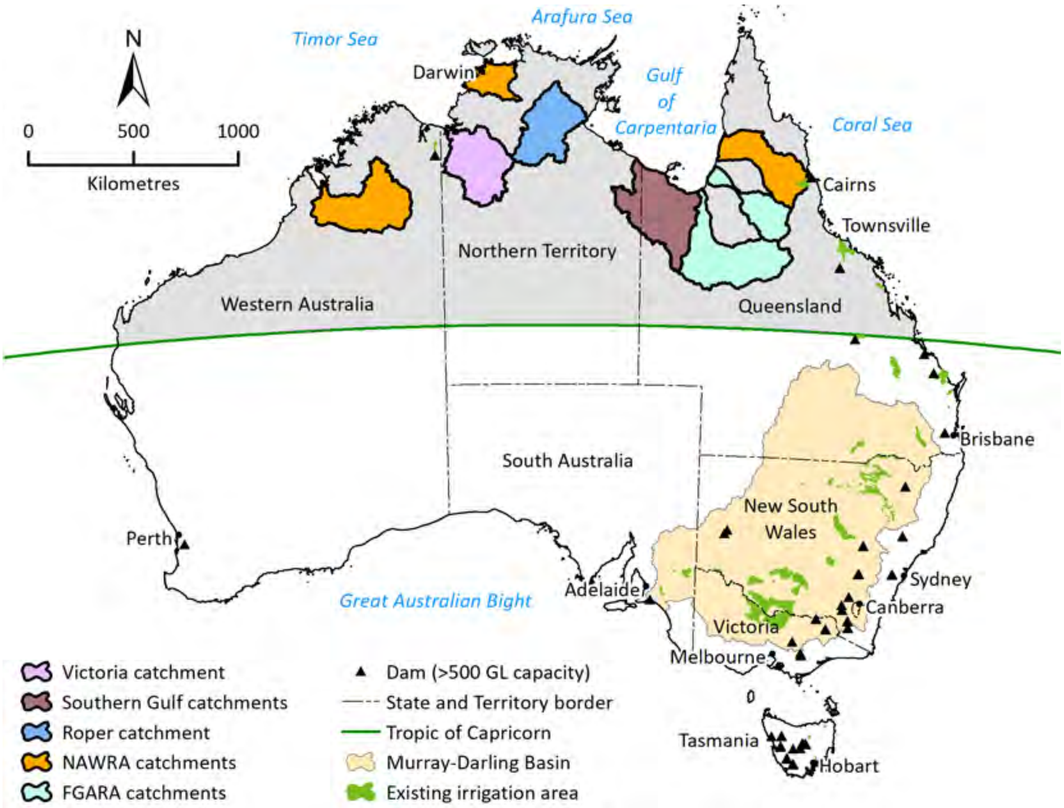
Units

UNIT	DESCRIPTION
GL	gigalitre
km	kilometre
L	litre
m	metre
mAHD	metres above Australian Height Datum
y	year
kL	kilolitres

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.

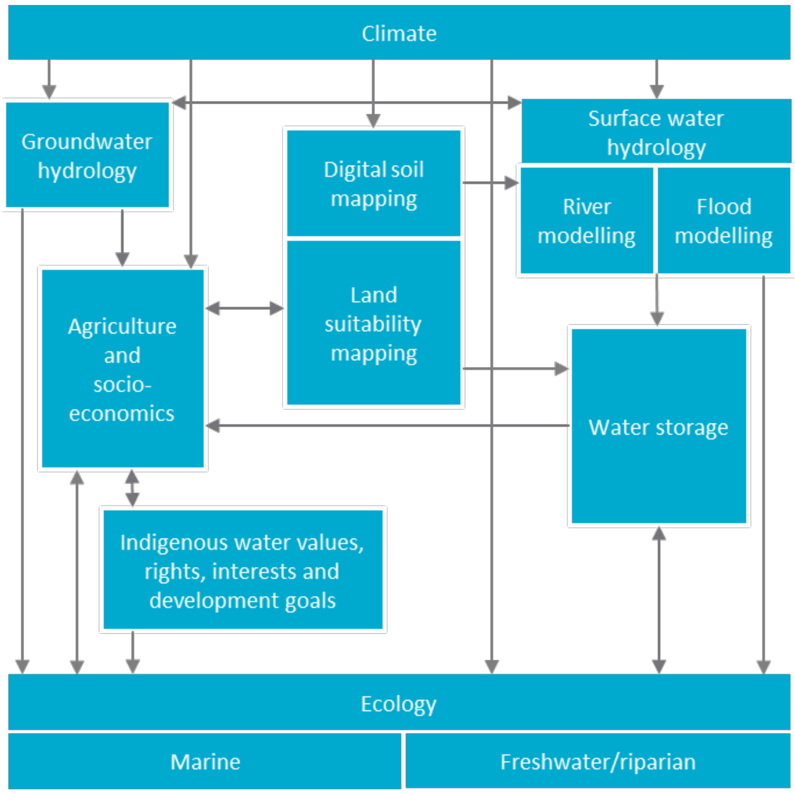
The Assessment differs somewhat from many resource assessments in that it considers a wide range of resources or assets, rather than being a single mapping exercise of, say, soils. It provides a lot of contextual information about the socio-economic profile of the catchment, and the economic possibilities 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

Background

The Victoria catchment has an area of approximately 82,400 km^2 and lies in the wet-dry tropics of northern Australia. Its rainfall and runoff are characterised by a 4-month wet season with significant runoff and an 8-month dry season with negligible surface runoff. During this period, aquifers within the south of the Victoria River catchment supply approximately 4 m^3/second of baseflow to the Victoria River through the riverbed and springs. The Victoria River has continuous inflows along the headwaters from the Cambrian Limestone Aquifer (CLA). Discharge also occurs from discrete points in the landscape at springs (e.g. Top Spring), some diffuse discharge also occurs along portions of the rivers.

The potential for increased groundwater extraction from this aquifer within the Victoria catchment for irrigation or other land use has the potential to adversely impact existing groundwater users or groundwater dependent ecosystems. Additional groundwater extraction can result in the lowering of groundwater levels and thereby reduce the dry season discharge to springs and baseflow to rivers. This study sought to assess the potential for future groundwater developments to impact existing groundwater users or groundwater dependent ecosystems in the Victoria catchment. An existing numerical model of the CLA was used to estimate changes in groundwater balances and hydraulic impacts on dry-season spring flows for a range climate and development scenarios.

This study forms part of the CSIRO-led Victoria River Water Resource Assessment, which was commissioned by the Australian Government.

Objectives and scope

The objectives of this modelling investigation were to assess the impacts of changes in rainfall and potential evaporation and/or potential increased water resource development on the streamflow of the upper Victoria River and some of its eastern tributaries, including existing groundwater users and environmental receptors. To do this, eight scenarios were simulated using the CLA groundwater model.

To examine representative 2060 conditions in the CLA, 109 years of historical climate data were used to prime the CLA groundwater model to 2019 and thereafter:

- Scenario A – 1 × 50-year climate sequence (based on a 50-year window over the period 1910 to 1960 historical climate) – nominally representative of conditions centred on 2060 (2055 to 2065) and using current development
- Scenario B – 1 × 50-year climate sequence – nominally representative of conditions centred on 2060 (2055 to 2065) and using current and hypothetical future groundwater development listed below:
  - B9 – current development + 3 × 3 GL/year hypothetical future enterprises (i.e. total hypothetical future extraction sums to an additional 9 GL/year)

- B12 – current development + 3 × 4 GL/year hypothetical future enterprises (i.e. total hypothetical future extraction sums to an additional 12 GL/year)
- B15 – current development + 3 × 5 GL/year hypothetical future enterprises (i.e. total hypothetical future extraction sums to an additional 15 GL/year)

- Scenario C – 1 × 50-year future climate sequence (based on a 50-year window over the period 1910 to 1960 Scenario C climate) — nominally representative of conditions centred on 2060 (2055 to 2065) and using current groundwater development:
  - Cdry corresponding to a 10% reduction in mean annual rainfall and 10% increase in potential evaporation relative to the historical climate (1910 to 2019)
  - Cmid corresponding to a 2% reduction in mean annual rainfall and 7.5% increase in potential evaporation relative to the historical climate (1910 to 2019)
  - Cwet corresponding to a 10% increase in mean annual rainfall and a 5% increase in potential evaporation relative to the historical climate (1910 to 2019)
- Scenario D – 1 × 50-year future climate sequence (based on the 50-year Scenario C climate sequences) — nominally representative of conditions centred on 2060 (2055 to 2065) and using current and hypothetical future groundwater development:
  - Ddry9 – current development + 3 × 3 GL/year hypothetical future enterprises (i.e. total hypothetical future extraction sums to an additional 9 GL/year)
  - Ddry12 – current development + 3 × 4 GL/year hypothetical future enterprises (i.e. total hypothetical future extraction sums to an additional 12 GL/year)
  - Ddry15 – current development + 3 × 5 GL/year hypothetical future enterprises (i.e. total hypothetical future extraction sums to an additional 15 GL/year).

Model description

A numerical model of the CLA was first developed in 2009 and was subsequently updated in 2018 (Knapton, 2009; Knapton, 2020). The model, known as the DR2 model, encompasses an area of approximately 159,000 km^2 and includes the entire extent of the CLA in the Daly, northern Wiso, and northern Georgina basins. The DR2 model was developed with all available river geometry and aquifer data. The DR2 groundwater model was calibrated with all available rainfall, river flow, river level and groundwater level data (Knapton, 2020).

The recharge inputs to the FEFLOW model under the eight scenarios were generated using the MIKE SHE recharge model (Knapton, 2020) with future precipitation and evapotranspiration input data scaled using factors derived from various GCMs.

Water management zones

Two declared and proposed water management zones (WMZs) were considered: the Wiso Water Management Zone (WWMZ) and the Flora Tindall Water Management Zone (FTWMZ).

Reported metrics

Four metrics were considered:

- Time series of groundwater levels at 10 groundwater-level sites corresponding to bores located in the east of the Victoria River catchment.
- Changes in groundwater levels (i.e., drawdown values) relative to scenario A (i.e., current climate and current extraction)
- Groundwater discharge from springs along the margin of the DR2 model domain.
- Groundwater balances for three areas within the model domain: the Victoria River catchment within the DR2 model domain, the Flora Tindall Water Management Zone and the Wiso Water Management Zone.

Conclusions

The DR2 groundwater flow model was used to examine the effects of four scenarios, encompassing climate change and groundwater development, on the water resources of the CLA in the Victoria catchment. From this analysis, the following key findings have emerged:

- For predicted future climate scenarios that are wetter than historical conditions, groundwater development is anticipated to negatively affect spring discharge.
- It is estimated that current levels of groundwater extraction from the CLA in the Victoria catchment (stock and domestic use and community water supply at Top Springs) will not reduce groundwater discharge from the CLA to the Flora River.
- Similarly, it is estimated that hypothetical future groundwater extraction (as simulated) will not reduce discharge from the CLA to the Flora River before the year 2060. This was attributed to the considerable distance between the simulated locations of extraction and the Flora River. However, reductions in discharge to the Flora River may occur over larger timescales; i.e., greater than 50 years.
- The extensive spatial coverage, thickness and variable hydraulic properties of the karstic groundwater systems also significantly influences the time lags for hydrological impacts of both climate variability and groundwater extraction to propagate through each system.
- Estimated decreases in groundwater discharge to springs were not linearly proportional to increases in hypothetical groundwater extraction. This was attributed to a large proportion of groundwater extraction being sourced from aquifer storage, as well as from the capture of groundwater throughflows that would otherwise flow beyond the boundaries of the Victoria catchment and the WWMZ.
- The relative impact of changes in future climate was estimated to be greater than that of future hypothetical groundwater extraction (as simulated) on conditions in the CLA in the east of the Victoria River catchment. This was attributed to changes in relatively larger magnitude of changes in recharge resulting from changes in future climate.

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1 Introduction

1.1 Background

The Cambrian Limestone Aquifer (CLA) is the largest, most productive, and potentially most promising aquifer within and beneath the Victoria catchment for future groundwater-based development (CSIRO, 2009; Taylor et al., 2024; Tickell and Rajaratnam, 1998). Parts of this aquifer coincide with land recently identified as potentially suitable for agricultural intensification (Thomas et al., 2024). Water resource modelling was undertaken to better understand the potential opportunities and risks associated with future development of groundwater resources. This new information could potentially help inform future water resource planning, investment and management across parts of the CLA considered potentially suitable for groundwater-based irrigation. CSIRO engaged CloudGMS Pty Ltd to run, process and evaluate the results of multiple future hypothetical groundwater development and climate scenarios using an existing finite element groundwater model of the CLA. This study is part of the Victoria River Water Resource Assessment, which was commissioned by the Australian Government.

The specific objectives of this modelling investigation were to assess the possible effects of changes in rainfall and potential evaporation and hypothetical development of groundwater resources on the availability of groundwater for environmental requirements of surface water resources and existing licensed water users in key parts of the Victoria catchment. The climate data used as input to the groundwater models were sourced from climate analyses undertaken in a companion technical report on the climate of the Victoria catchment (McJannet et al., 2023). The locations for future hypothetical groundwater development were identified from analyses undertaken in a companion technical report on a groundwater characterisation of the CLA (Taylor et al., 2024).

The focus of this report is on the dynamics of groundwater and does not include modelling of river flows. However, companion technical reports on river model calibration (Hughes et al., 2024a) and simulation (Hughes et al., 2024b) detail the model build and calibration process of a river model for the Victoria catchment and report the results of model simulation runs.

A companion technical report on ecological assets in the Victoria catchment (Stratford et al., 2022) identified potential ecological assets in the Victoria catchment that may be susceptible to changes in streamflow and groundwater levels.

The report is structured as follows. Chapter 2 provides an overview of the Victoria catchment relevant to the groundwater modelling of the CLA. Chapter 3 describes the numerical groundwater models used to represent groundwater flow in the CLA. Chapter 4 outlines the scenario-modelling approach, and Chapter 5 presents the results of the scenario modelling for the CLA projected up to 2055 to 2065. Finally, Chapter 6 presents a summarised overview of the key findings and conclusions drawn from the entire scenario-modelling process.

2 Catchment overview

2.1 Location of the Victoria catchment

The catchment of the Victoria River is in the wet-dry tropics of northern Australia approximately 300 to 400 km south-east of Darwin, the capital of the Northern Territory (NT) (Figure 2-1).

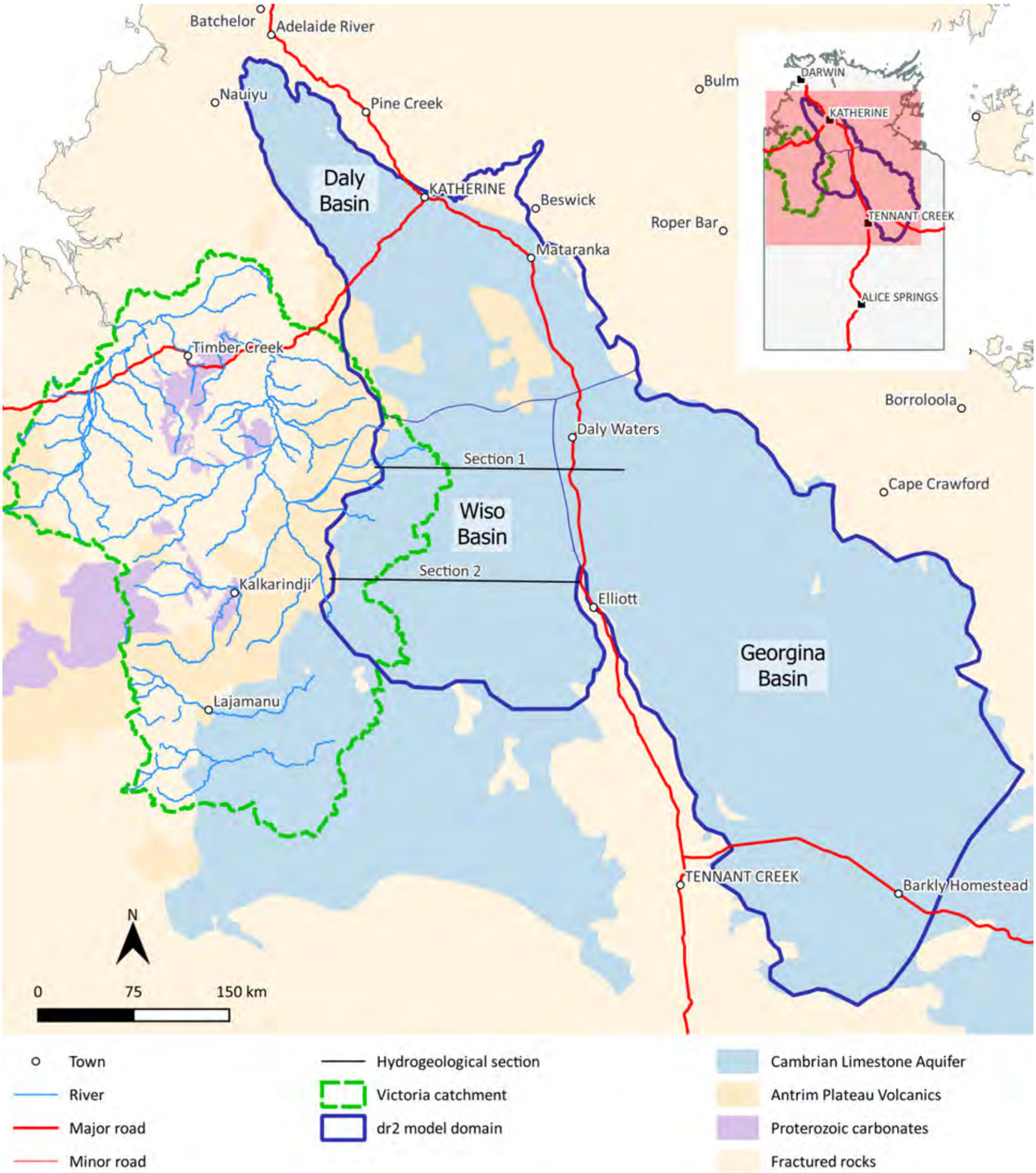

Figure 2-1 Location of the Victoria catchment and its relationship to the groundwater systems of the Cambrian Limestone Aquifer in the Daly, Wiso and Georgina basins represented in the DR2 groundwater flow model

Victoria River Catchment boundary shown only for context.

Victoria River catchment source: HydroBasins v1.0 Level 6 (Lehner and Grill, 2013)

The Victoria River is in the north-western part of the NT, flowing through the Victoria River District. The river begins at Riveren Station and travels around 720 km through a diverse landscape of grassy plains, rolling savannas, rocky spinifex country, mesas and plateaux. The river eventually drains into the Joseph Bonaparte Gulf and from there into the Timor Sea to the north. Most of the river's catchment area is less than 450 m above sea level. The Victoria River is generally shallow with numerous sandbars and rock bars.

Major tributaries join the river along its course, having sources in the Gregory National Park and the Sturt Plateau, which form the south-eastern and south-western boundaries, respectively, of the catchment (Kirby and Faulks, 2004). The river's mouth, more than 10 km wide, is characterised by mudflats and extensive mangrove stands. Tidal influence extends approximately 500 km upstream, reaching a series of rapids about 20 km above Timber Creek.

2.2 Climate

The climate in the Victoria River catchment area is classified as hot and semi-arid, characterised by distinct wet and dry seasons. During the wet season, temperatures are typically high (daytime temperatures often exceed 30°C) and humidity levels can be quite high. The wet season brings heavy rainfall, which replenishes water sources and supports lush vegetation growth. In contrast, the dry season is characterised by lower temperatures and lower humidity levels, clear skies and little to no rainfall. Daytime temperatures during the dry season are generally milder, ranging from 25 to 35 °C. Annual potential evapotranspiration (PET) is annually greater than rainfall, so the region may be considered water limited. The region has years when it is water limited throughout the entire year with annual PET exceeding rainfall even through the wet season (CSIRO, 2009).

2.3 Victoria River hydrology

2.3.1 Flow regime

The Victoria River is characterised by seasonal flow dynamics typical of many Australian rivers. During the wet season, which generally occurs from November to April, the river experiences high flows because of monsoonal rains and tropical cyclones. These high flows can lead to significant flooding in the river's catchment area. In contrast, during the dry season, which typically occurs from May to October, the river experiences low flows, and some sections may even dry up entirely, especially in its upper reaches.

The Victoria River is a mostly ephemeral river with a catchment area of approximately 87,900 km^2. The river has a distinct seasonal flow regime of high water levels and discharges during the wet season (November through April) and much lower water levels and discharges towards the end of the dry season. The river's flow diminishes considerably over the dry season, and in some sections the river bed may become a series of disconnected pools or dry out entirely, as only a small proportion of the total annual runoff in the Victoria catchment is baseflow.

The dry-season discharges along the margins of the Cambrian Limestone Aquifer (CLA) into the Victoria catchment are sourced from the regional carbonate aquifers of the Daly and Wiso basins.

The headwaters of the Victoria River are incised into the Tindall Limestone and Montejinni Limestones.

2.3.2 Springs

Spring flows depend on short-term rainfall patterns, and they gradually decrease in discharge as the dry season progresses, often not being able to maintain permanent flows (Tickell and Rajaratnam, 1998).

Springs in the Victoria catchment have flows ranging from seeps to 170 m^3/day (Tickell and Rajaratnam, 1998). Spring flows and seepages mostly occur low in the landscape, mainly in the headwaters of the Victoria River between Mount Sanford and Top Springs, where the watertable is generally shallow (Tickell and Rajaratnam, 1998). Their occurrence is determined by a combination of the properties of the aquifer, landscape and aquifer location, and geological features such as faults or contacts with impermeable units (Tickell and Rajaratnam, 1998). Most springs in the Victoria catchment are ephemeral. Small springs occur in some parts of the region after years of average to above-average rainfall. Some have a small flow (<10 L/second) throughout the year. Most cease to flow early in the dry season.

2.4 Geology

The south-east margin of the Victoria catchment is underlain by the Wiso Basin. The Wiso Basin is a large (160,000 km^2) intracratonic sedimentary basin located in central north-western NT. To the north, the Wiso Basin connects with the Daly Basin, and to the east, it links with the Georgina Basin. These neighbouring basins contain stratigraphic successions of similar age to those in the Wiso Basin and form distinct depocentres. These depocentres are separated from the Wiso Basin by basement ridges formed by basaltic rocks from the Kalkarindji Province (Tickell, 2005).

The Palaeozoic succession is generally less than 300 m thick in the Wiso Basin. It is deposited on a tectonically stable platform. It contains the middle Cambrian rocks, the Montejinni Limestone and the Hooker Creek Formation (a lateral correlative of Tindall Limestone in the Daly Basin and Gum Ridge Formation in the Georgina Basin). The Montejinni Limestone rests disconformably on the lower Cambrian Antrim Plateau Volcanics and is the most prominent unit present in the Daly Basin beneath the Victoria catchment. In the northern part of the Wiso Basin, nearly flat-lying rocks of the early Cambrian Antrim Plateau Volcanics (Kalkarindji Province) provide the basement for the Palaeozoic succession. The central portion of the northern Wiso Basin is largely concealed beneath Cretaceous sediments of the Carpentaria Basin (CSIRO, 2009).

2.5 Hydrogeology

Three major aquifer types are present in the Victoria catchment: fractured rocks (including the Antrim Plateau Volcanics), karstic carbonate rocks (including the Montejinni Limestone and Proterozoic dolostones) and Cretaceous sediments. These aquifer types are briefly described below, and their areal extent is shown in Figure 2-2.

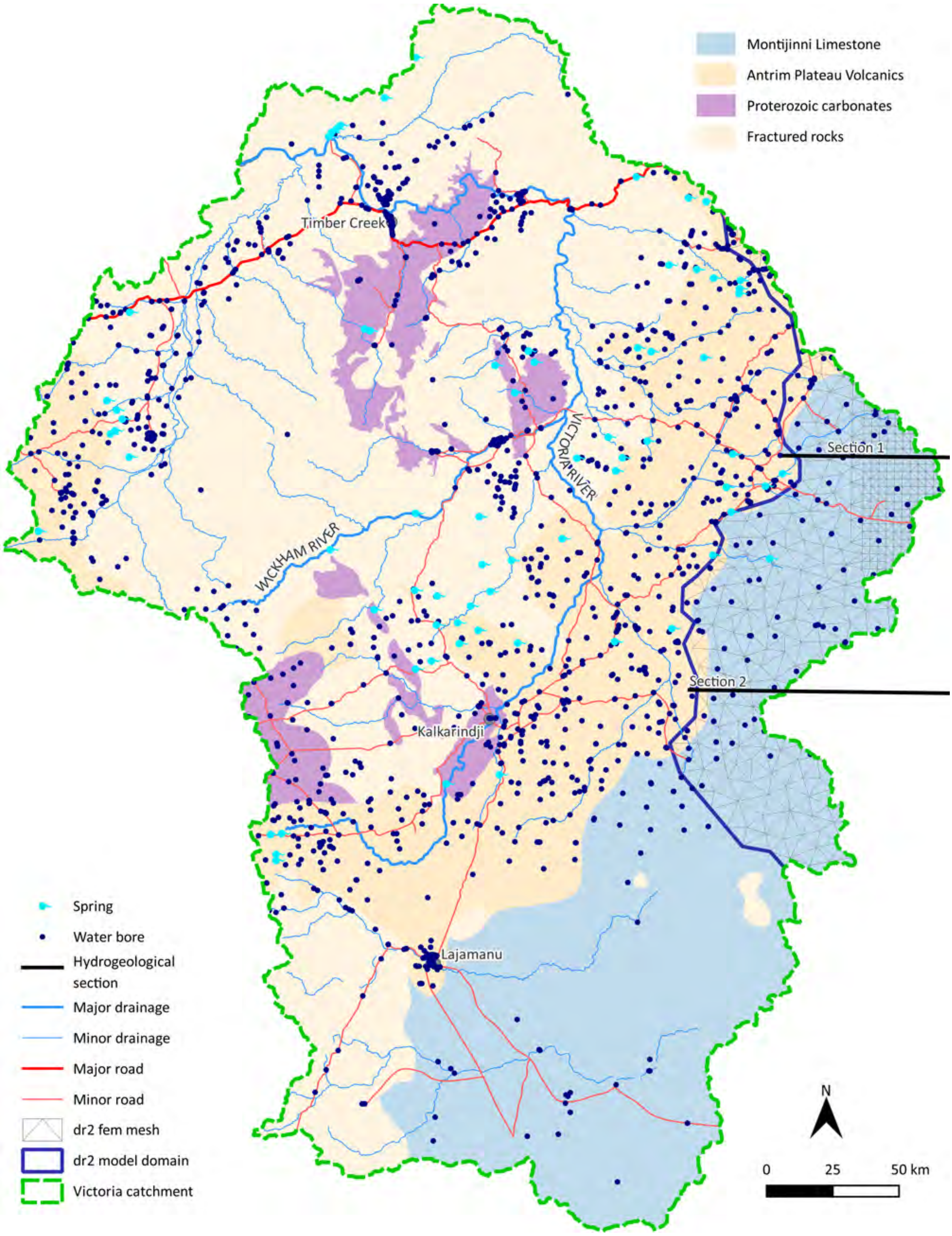

Figure 2-2 Hydrogeology of the Victoria catchment and areas with surface water-groundwater connectivity indicated by locations of springs

The locations of the hydrogeological cross-sections are included for reference. Victoria River Catchment boundary shown only for context.

Victoria River catchment source: HydroBasins v1.0 Level 6 (Lehner and Grill, 2013).

The major hydrogeological features in the south-east of the Victoria catchment include the Cambrian–Ordovician southern Daly Basin, the northern Wiso Basin and the northern Georgina Basin. These basins host the Cambrian Limestone Aquifer, which comprises the Tindall Limestone (Daly), Gum Ridge Formation (Georgina), Montejinni Limestone (Wiso) and the Jinduckin Formation / Anthony Lagoon Beds (Daly/Georgina). Early Cretaceous rocks overlie much of the Cambrian rocks (refer to Figure 2-2). Hydrogeological mapping of the Daly Basin and the northern Georgina and northern Wiso basins is presented by Tickell (2005) and Bruwer and Tickell (2015). Table 2-1 summarises the important hydrogeological units or hydrostratigraphy relevant to the Victoria catchment.

Table 2-1 Key aquifer of the Victoria catchment

FORMATION	DISCHARGE RECEPTOR	FORMATION CHARACTER	TRANSMISSIVITY RANGE (M^2/DAY)	STORAGE COEFFICIENT
Proterozoic carbonates	Victoria River	Karstic	100–1000	0.01–0.04
Antrim Plateau Volcanics	Springs and evapotranspiration	Fractured rocks – minor localised aquifers	<100	<0.01
Cambrian Limestone Aquifer	Roper, Katherine, Flora, Douglas and Daly rivers	Karstic limestone	2000–5000	0.01–0.04

2.5.1 Fractured rocks

A variety of Precambrian (older than 540 million years) rocks form the bedrock of the area. These are mainly sedimentary but also include granite and volcanic rocks. Sandstone, siltstone and greywacke are the main sedimentary rock types. In some areas they are flat lying while in other areas they have been folded and faulted and show low-grade metamorphism.

In the early Cambrian (540 million years ago), volcanic eruptions produced an extensive sheet of basalt flows, now known as the Antrim Plateau Volcanics. These underlie the Daly, Wiso and Georgina basins.

Water is usually intersected in weathered fractured zones within the fractured rocks, typically less than 100m below the top of the formation. Groundwater yields are controlled by the degree of fracturing of these units and are likely to be greater in areas located along large-scale joints and fault zones.

2.5.2 Karstic carbonate rock – Montejinni Limestone and Limbunya Group and Bullita Group carbonate rocks

The major aquifers in the region occur within the carbonate rocks of the Wiso, Daly and Georgina basins. These carbonate rocks extend across a large part of the NT and into Queensland. The Montejinni Limestone and its equivalents (the Tindall Limestone in the Daly Basin and the Gum Ridge Formation in the northern part of the Georgina Basin) host widespread karstic aquifers. These aquifers have very high permeabilities due to an extensive network of interconnected solution cavities and are referred to collectively as the Cambrian Limestone Aquifer (CLA).

The aquifers of the CLA are typical of karstic aquifers where dissolution by chemical weathering has produced widespread secondary porosity and permeability in the carbonates. The carbonate aquifers are expected to have greatest permeability within the weathered zone, up to a maximum of 150 m depth below the top of the formation. The karstic nature of the aquifers means that, on a local scale, groundwater flow occurs via preferential pathways; however, at a basin-wide scale the aquifers are considered to behave as an equivalent porous medium with very high transmissivities and a relatively low storage coefficient.

Lauritzen and Karp (1993) concluded that the karst aquifers developed before the Cretaceous period. The permeability of the karst aquifer was further increased by the movement of acidic groundwater from the aquifer developed in the overlying Cretaceous sandstone.

The CLA in the Wiso Basin contributes to dry-season flow in the Flora River. The CLA is the aquifer of most interest to irrigators as it occurs beneath land suitable for irrigation and can yield high flow rates (>50 L per second per bore) from relatively shallow depths.

The saturated thickness of the CLA is relatively thin toward the western margin of the Wiso Basin (refer to Figure 2-3 and Figure 2-4). Therefore, bore yields in this area are expected to be lower than those to the east in the centre of the Wiso Basin. The median airlift yield for limestone bores is 2.1 L/second, which is relatively low because most stock bores only penetrate the top of the aquifer. Yields of 5 to 15 L/second should be obtainable if bores were drilled deeper. Standing water levels are less than 30 m in the northern part of the map and deepen to between 30 and 90 m in the south around Cattle Creek Station.

2.5.3 Cretaceous sediments

The Cretaceous sediments form a mantle of lateritised claystone and sandstone covering much of the area. In Figure 2-2, the sediments have only been mapped where it is expected that they form the major aquifer at that locality. However, they overlay the karstic rock aquifers over much of the region. The beds are sub-horizontal and may be divided into an upper claystone and siltstone unit and a basal sandstone unit. Outcrop is generally sparse due to the soft nature of the rock, but in places silicification has altered them to porcellanite and quartzite.

In the Wiso Basin the formation may be up to 100 m thick with the upper claystone unit comprising 60 m of its thickness. The thickness of the lower sandstone unit is variable, ranging from less than 5 m up to 25 m. Where the upper claystone unit is thin and eroded, the potential recharge to the underlying limestone aquifer is increased. In most places within the basins, the sediments lie above the regional water level.

The main influence of the Cretaceous sediments is to reduce the recharge to the CLA. The effect of reduced recharge is based on the lithology of the unit, which is predominantly clay and/or clayey sand, and the subdued response of groundwater hydrographs for the bores located in areas where Cretaceous rocks cover the underlying carbonate aquifer.

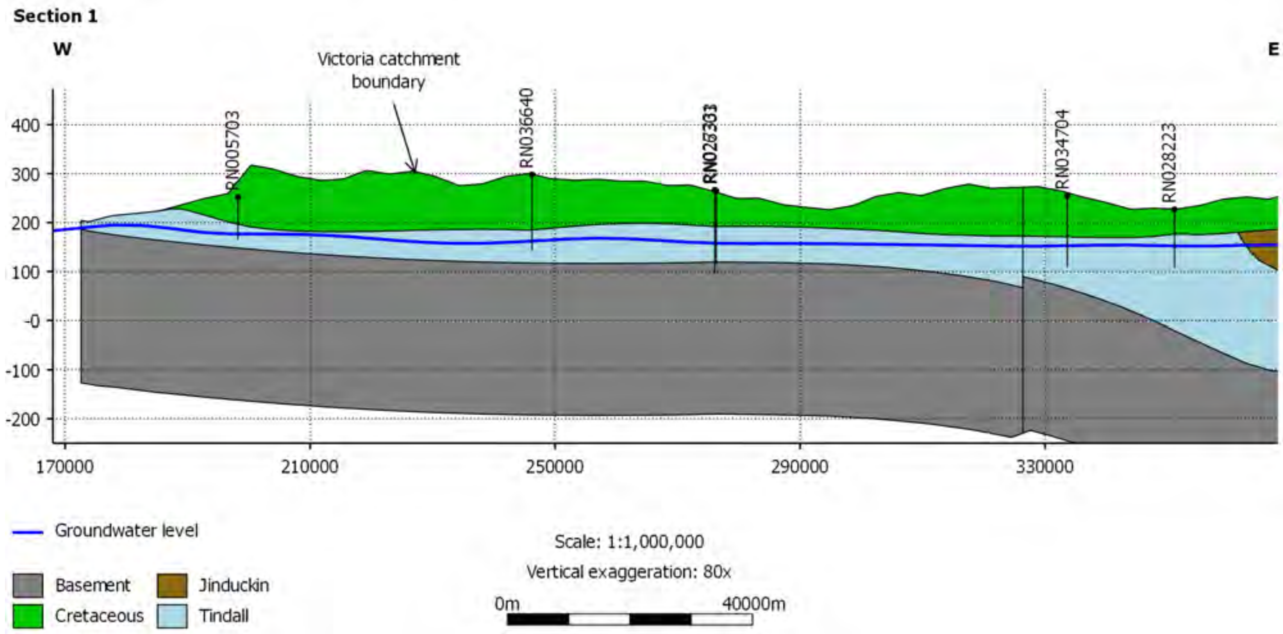

Figure 2-3 Leapfrog hydrogeological section across the northern section of the Victoria catchment

The location of Section 1 is shown in Figure 2-1.

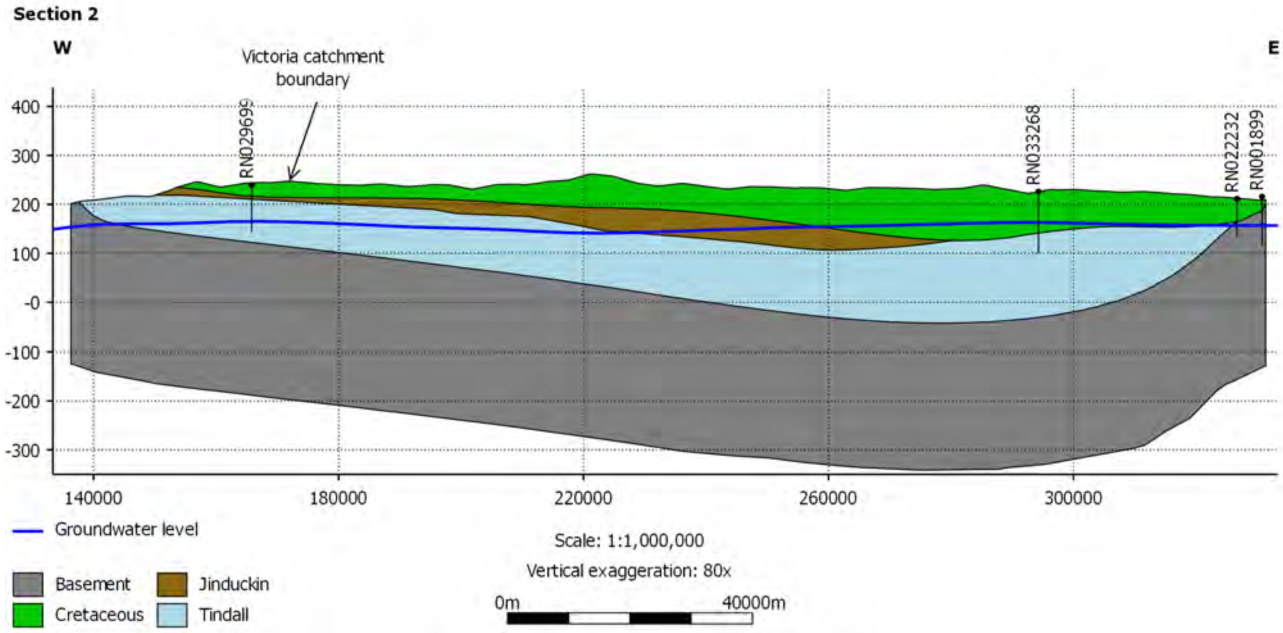

Figure 2-4 Leapfrog hydrogeological section across the southern section of the Victoria catchment

The location of Section 2 is presented in Figure 2-1.

2.5.4 Groundwater contribution to surface flow in the Victoria catchment

The Victoria River and some of its tributaries rely on groundwater contributions to maintain flow, particularly during the dry season when surface water flow diminishes. Baseflow surveys conducted at the end of the dry season indicate that the lower Victoria River's flow is maintained by fresh groundwater sources (Power and Water Authority, 1987). The Wickham River, a tributary of the Victoria River, benefits from persistent streamflow or baseflow due to groundwater discharge from regional aquifers. However, as the dry season progresses, groundwater levels generally fall below the river bed, resulting in intermittent river flows and semi-permanent pools (Tickell and Rajaratnam, 1998).

Baseflow to the Wickham River is observed along a 7.5 km stretch where groundwater seeps from Proterozoic carbonates of the Limbunya Group into the river bed. A single large spring is reputed to issue from a fissure in the rock in the bed of a large waterhole (Jackson and Jolly, 2004).

In the eastern part of the Victoria catchment, the river cuts back into the Sturt Plateau, an area characterised by flat to gently undulating terrain developed on the CLA. Drainage on the plateau is poorly defined, especially towards the south, where sand dunes dominate the landscape. Ground elevations average around 250 m above sea level. Dry season discharge occurs along the margins of the Victoria catchment where the headwaters of the Victoria River are incised into the CLA and the underlying fractured rocks of the Antrim Plateau Volcanics.

2.5.5 Surface water – groundwater connectivity

Surface water - groundwater connectivity is strongly controlled by the prevailing geological conditions such as basement outcrop or subcrop, or the presence of faults or dykes. Regions of the Victoria catchment where the carbonate sediments outcrop exhibit high connectivity with the rivers. Connectivity occurs via features associated with the karstic carbonate rocks of the Montejinni Limestone. However, the connectivity between the rivers and the aquifers is reduced in areas where Cretaceous sediments overlie the CLA. Perennial streamflow in the Flora River headwaters about 230 km to the north is fed in part by groundwater recharged to the CLA from within the Victoria catchment (Bruwer and Tickell, 2015; Karp, 2008; Knapton, 2020; Tickell and Bruwer, 2018; Knapton, 2009; 2020).

In the Victoria catchment, groundwater discharge occurs where the watertable has sufficient elevation to discharge at the surface. The locations of areas where surface water and groundwater are connected are presented in Figure 2-2 as discrete springs.

Evapotranspiration is also thought to be a major discharge mechanism (Tickell and Rajaratnam, 1998).

2.6 Water management zones

In 2024, two water management zones within the Victoria catchment are proposed under the NT Government's Daly Roper Beetaloo Water Control District (DRB WCD) (see https://depws.nt.gov.au/water/water-management/water-allocation-plans).

The first is the Wiso Water Management Zone (WWMZ), which will be established to oversee the management of the water resources in the unconfined Montejinni Limestone portion of the CLA where major groundwater resources occur in the Wiso Basin. Currently no groundwater extraction licences are held within the WWMZ (NT Department of Environment Parks and Water Security, 2018).

The second is the Flora Tindall Water Management Zone (FTWMZ), which will be established to oversee the management of water resources of the CLA in the Daly Basin to the north of the WWMZ. The water allocation plan for the FTWMZ is currently under development.

The spatial extents of the two water management zones used to calculate groundwater balance information are presented in Figure 2-5. Within the FTWMZ there are currently three licences totalling 7.4 GL/year (Department of Environment Parks and Water Security, 2018).

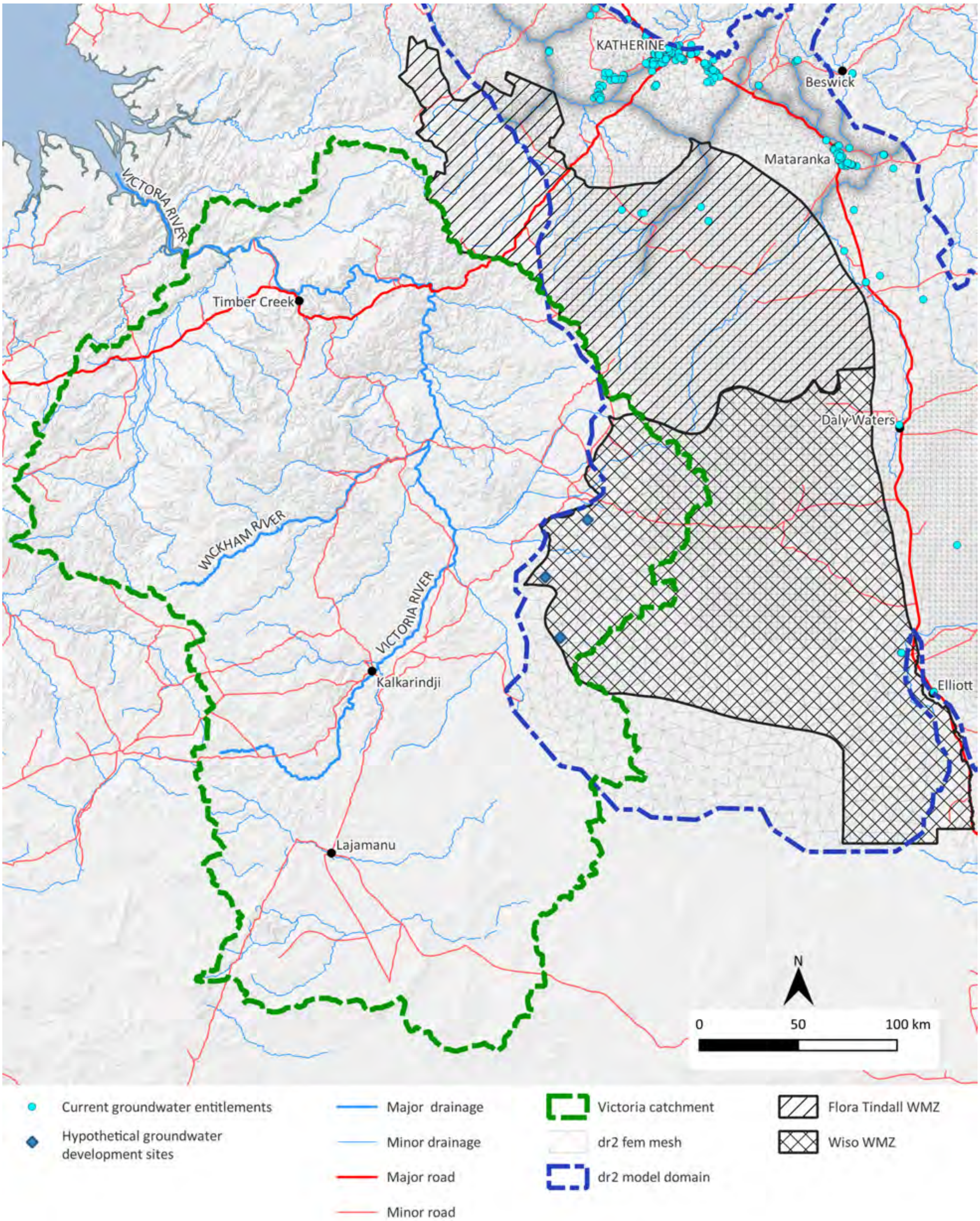

Figure 2-5 Water allocation plan water management zones (WMZs) within the Victoria catchment, indicating position of existing entitlements and future hypothetical groundwater developments

Victoria River Catchment boundary shown only for context.

Victoria River catchment source: HydroBasins v1.0 Level 6 (Lehner and Grill, 2013).

3 Groundwater flow model description

3.1 Introduction

Groundwater flow in the CLA was modelled using the DR2 groundwater flow model, which was described by Knapton (2020). The groundwater flow model is summarised in the following subsections.

3.2 Previous modelling

Previous studies of groundwater modelling of the aquifers of the Roper River include groundwater modelling of the Tindall Limestone in the area of the Katherine River (Puhalovich, 2005; Water Studies, 2001) and groundwater modelling of the CLA of the Daly, Georgina and Wiso basins, referred to as 'DR1' (Knapton, 2006). Knapton (2009) documented the details of the recalibration of the DR1 coupled Daly River catchment model and investigated the effects of future climate predictions and groundwater extraction development scenarios on groundwater levels and river flows as part of the Northern Australia Sustainable Yields Project (CSIRO, 2009). The DR1 model was updated to facilitate the coupling of the Roper River (Knapton, 2009). This updated model is referred to as 'DR2'. Knapton (2020) documented the details of the recalibration of the DR2 groundwater flow model.

3.3 Conceptual model

The major aquifers in the CLA are karstic and dominated by secondary porosity and permeability due to chemical weathering. The carbonate aquifers are expected to have greatest permeability within the weathered zone, up to a maximum of 100 to 150 m below the surface. The karstic nature of the aquifers means that, on a local scale, groundwater flow is via preferential pathways. However, previous modelling has demonstrated that at a basin-wide scale the aquifers are considered to behave as an equivalent porous medium (Abusaada and Sauter, 2013; Ghasemizadeh et al., 2012; Ghasemizadeh et al., 2015; Scanlon et al., 2003) with very high transmissivities (5000 m^2/day for the Cambrian limestone) and relatively low storage coefficient/specific yield, with estimates ranging from 0.01 to 0.06 (i.e., 1% to 6%). Increased permeability is associated with areas where sinkhole development has occurred.

Recharge and discharge processes within the unconfined portions are expected to dominate the water balance of the CLA groundwater system.

3.3.1 Recharge

The CLA underlies such a large area that its recharge rate can vary significantly due both to the areal variability in rainfall and the presence or absence of Cretaceous sediments overlying it. Currently there is insufficient groundwater level data to assess recharge events, as there is only one groundwater monitoring bore (RN042219) with about 2-years of record present in the Victoria catchment.

Recharge is thought to occur via the following mechanisms:

- diffuse direct recharge where water is added to the groundwater, in excess of soil water deficits and evapotranspiration, by direct vertical percolation of precipitation through the unsaturated zone; this is thought to be the dominant mechanism in areas with Cretaceous cover
- macropores where precipitation is preferentially 'channelled' through the unsaturated zone and has a limited interaction with the unsaturated zone
- localised indirect recharge where surface water can be channelled into karstic features such as dolines (sinkholes); this is a poorly understood component of recharge
- river recharge when the stage height of the river exceeds the adjacent groundwater level in the aquifer; this is thought to be a minor component of the overall water budget.

Recharge to the groundwater of the outcropping carbonates is thought to be dominated by macropore and local indirect recharge. Water balance and hydrograph analysis have estimated that recharge to the CLA is about 0 to 25 mm/year in the Wiso Water Management Zone (WWMZ) (Knapton, 2020).

Recharge beneath native vegetation is dominated by bypass flow rather than diffuse movement through soil horizons (Tickell, 2016). This is most likely to occur via stream sinks, sinkholes and/or macropores such as cracks and root holes in the soil. Sinkholes and stream sinks have been located over the CLA, such as in the Sturt Plateau to the north-east of the Victoria catchment (Deslandes et al., 2019).

The dominant recharge mechanism in the areas of outcropping CLA is via preferential pathways, but this mechanism is not well understood and is poorly represented numerically. The recharge was therefore estimated as diffuse recharge using a simple soil water deficit model using rainfall and estimated evapotranspiration (Jolly et al., 2004). It was found that this method did not quantify the increase in recharge during wetter periods in the rainfall record, when compared to groundwater-level hydrographs and gauged flows, because sinkhole processes become active in the wet periods. It has been assumed that preferential flows at local scales can be represented adequately as diffuse recharge when they are integrated over large spatial scales and that increased recharge during wet periods can be simulated using bypass flow available in codes such as MIKESHE and LUMPREM. Recharge is also expected during periods when the river stage height is greater than the groundwater level adjacent to the river where the river overlies the aquifers, and the model simulates this process.

Recharge rates estimated by history matching DR2 model outputs to measured groundwater levels and pressures were consistent with values estimated using the chloride mass balance method and environmental tracers in Taylor et al. (2024). This was consistent with expectation, because the latter two methods also typically provide recharge estimates that are integrated across large spatial scales.

3.3.2 Regional groundwater flow

The direction of groundwater flow within the CLA is predominantly northward from the Georgina and Wiso basins to the Daly Basin. In the Roper River catchment discharge from the CLA occurs to the lower section of Elsey Creek and the upper Roper River and its major tributaries, Roper Creek and Waterhouse River. In the Katherine River, Flora River, and Douglas River catchments CLA discharge occurs through riverbeds and at discrete springs. Considerable discharge from the CLA occurs along the Roper River and Flora River, which intercept relatively larger groundwater flows from the Georgina and Wiso basins respectively (Figure 3-1).

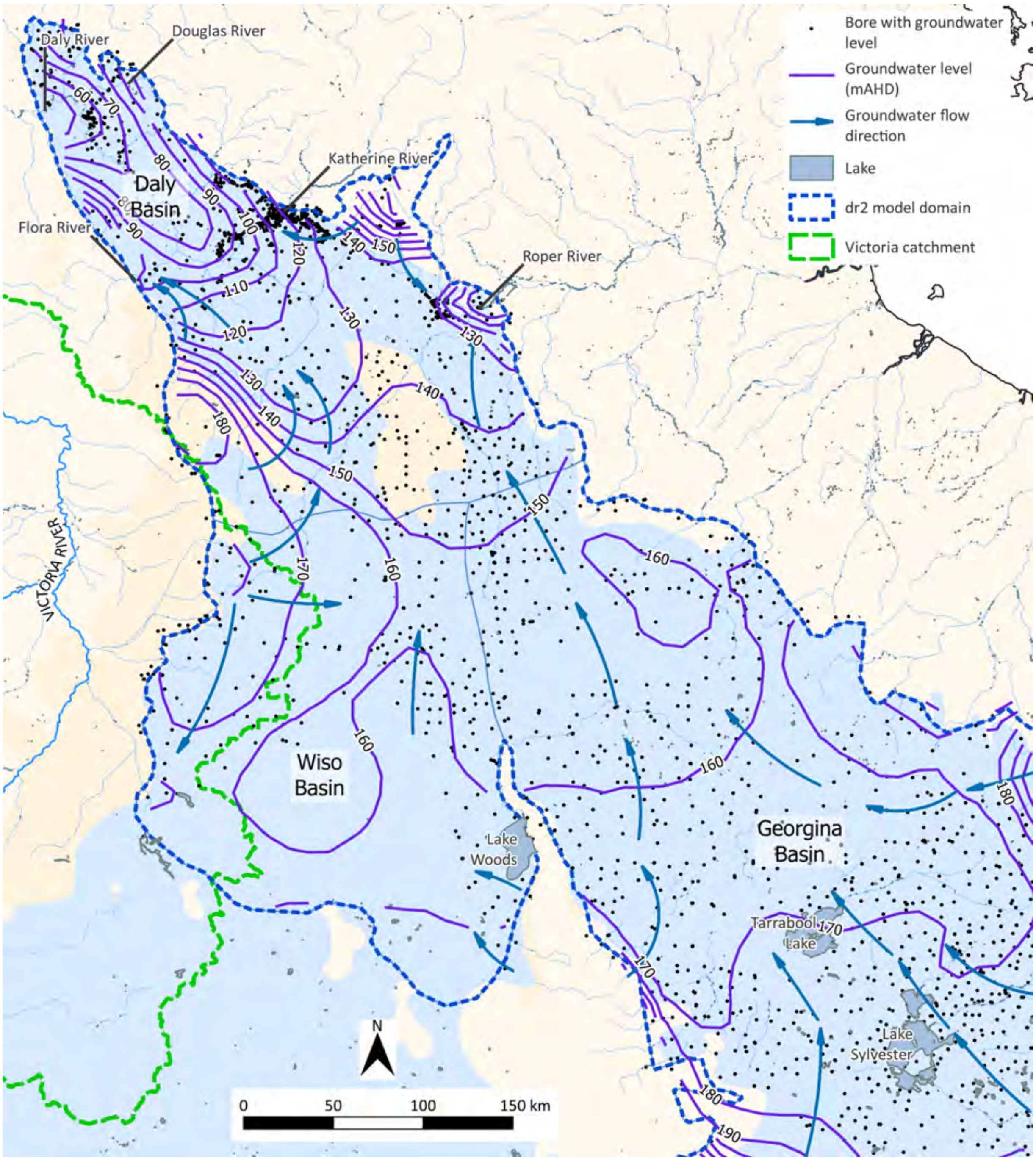

Figure 3-1 Regional CLA watertable surface contours and interpreted flow path directions (after Knapton, 2020) using groundwater levels from 14605 bore records spanning the period from 1945 to 2014

Victoria River Catchment boundary shown only for context.

Victoria catchment source: HydroBasins v1.0 Level 6 (Lehner and Grill, 2013)

The direction of flow within the Wiso Basin is also from south to north, flowing from Lake Woods towards the Daly Basin; however, there are also elevated groundwater levels along the western margin where there is relatively thin saturated thickness of CLA (see Figure 2-3 and Figure 2-4). The elevated groundwater levels form a divide where a portion of the flow discharges to the margin of the CLA in the Victoria catchment.

3.3.3 Local groundwater flow

A watertable map for CLA aquifers present on the western margin of the Wiso Basin was generated using recorded water levels from the DEPWS bore database from 14605 bore records spanning the period from 1945 to 2014 (https://data.nt.gov.au/dataset/nt-bore-locations-water-quality-and-groundwater-levels) and online bore statements (http://www.ntlis.nt.gov.au) and is presented in Figure 3-2. A groundwater divide occurs along the western margin of the Wiso Basin, roughly coincident with the boundary of the DR2 model domain. To the east of the divide groundwater flows eastward toward both the Wiso and Daly basins and the Victoria River catchment. Here, groundwater discharges at either discrete springs or over broad areas via diffuse evapotranspiration.

The contours are consistent with contours from Randal (1973), and they suggest some flow in the CLA to the south following topography into the area between Lake Woods and the Victoria River catchment.

3.3.4 Groundwater discharge

Groundwater outflows from the WWMZ consist of throughflow to the adjacent Daly Basin to the Flora River. Groundwater is also discharged to the Victoria catchment from the CLA along the western margin of the Wiso Basin (refer to Figure 3-2). Discharge is via a succession of separate springs, such as at Top Springs, or via diffuse or discrete areas of evapotranspiration where vegetation uses groundwater or watertables are shallow (Tickell and Rajaratnam, 1998; NT Department of Environment, Parks and Water Security, 2023).

The CLA is also the primary source of dry-season (May to October) flow in the perennial rivers of the Flora and Roper catchments to the north and north-east, respectively (Kerle and Cruickshank, 2014; Wagenaar and Tickell, 2013; Waugh and Kerle, 2014).

3.3.5 Summary of Cambrian Limestone Aquifer water budget components

NT Department of Environment, Parks and Water Security (2023) provides a first-pass estimate of the groundwater budget components:

- Groundwater inflows consist of throughflow into the WWMZ as zero GL/year. The exposed Proterozoic rocks along the margins of the WWMZ and a groundwater divide in the south-east restricts groundwater inflow from other areas. Mean annual recharge for the period 1970 to 2022 is estimated at approximately 46 GL/year into the Wiso Basin.
- Groundwater outflows, consisting of throughflow out from the WWMZ to the north into the adjacent Daly Basin (Flora River system), is estimated to be about 0.3 GL/year for the period 1970-2022. Evapotranspiration losses from groundwater are estimated to typically be a

negligible as the depth to the watertable is generally beyond the reach of vegetation (i.e. > 15 mBGL).

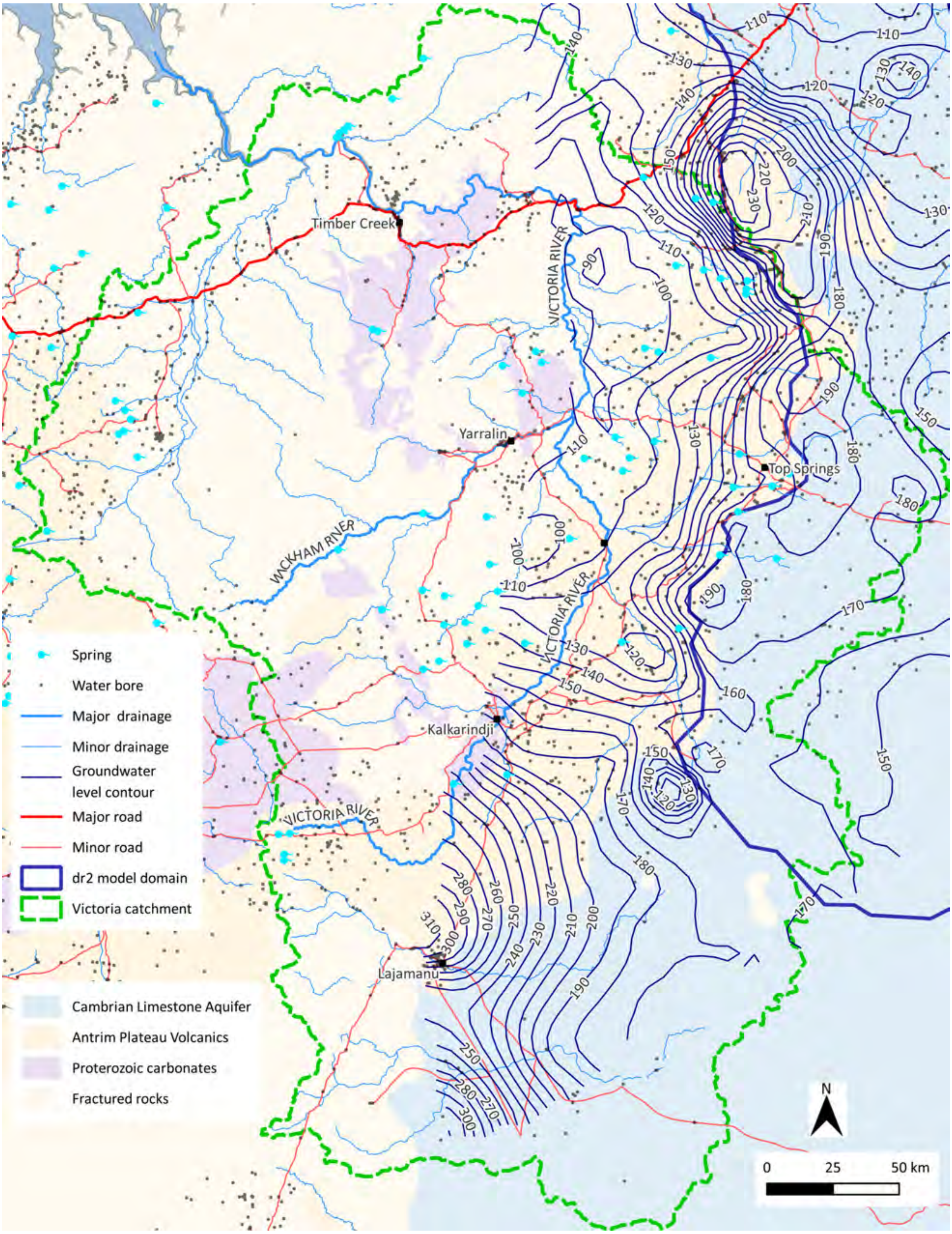

Figure 3-2 Groundwater contours along the western margin of the Wiso Basin indicating the inferred groundwater divide separating flow to the east into the Daly and Wiso basins and to the west into the Victoria catchment
Victoria River Catchment boundary only shown for context.

Victoria catchment source: HydroBasins v1.0 Level 6 (Lehner and Grill, 2013)

3.4 DR2 (Cambrian Limestone Aquifer) model description

The groundwater flow model of the CLA in the Victoria catchment is based on a calibrated three-dimensional finite element groundwater model referred to as DR2 (Knapton, 2020).

The DR2 groundwater model covers an area of 159,000 km^2 and represents the unconfined and confined areas of the CLA in the Daly Basin, the Wiso Basin to the south and the Georgina Basin to the south-east (Figure 2-1).

The groundwater model was developed using finite element methods in the FEFLOW simulation code (Diersch, 2008) and consists of three layers. The CLA groundwater system is conceptually characterised as an equivalent porous medium (EPM). This simplification allows for the development of a more manageable and computationally efficient model while still capturing the essential characteristics of the groundwater system using calibrated regional aquifer parameters to reproduce the observed groundwater levels and discharge to the rivers. This assumption means that the actual flow paths cannot be modelled and that there is no intention for this model to be used for contaminant-transport problems.

Recharge is applied to the top slice of the groundwater model according to recharge zones based primarily on the mapped surface geology (Knapton, 2005; Knapton, 2006). The time series recharge flux estimates of recharge have been determined either using the MIKE SHE code (DHI, 2008) or, more recently due to its efficient run times and integration with PEST using Python, the LUMPREM utility (Doherty, 2020); these models also include an estimate of preferential or bypass flow. Where there are insufficient transient observations, steady-state estimates of recharge are used (i.e. portions of the Wiso Basin). The recharge applied to the areas within the Victoria catchment use steady-state estimates from the CMB recharge (Crosbie and Rachakonda, 2021). The scaling factors used to estimate future recharge rates were taken from the Roper River Water Resource Assessment study (Knapton et al., 2023).

The groundwater model includes boundary conditions (BCs) that define the interaction between the rivers and the groundwater system. Discharge from the rivers is implemented using Cauchy (i.e., third type) BCs. The groundwater model assumes that recharge/discharge to the rivers, where they are in connection with the aquifer, is relatively uniform between adjacent nodes. The transfer in/out rates vary spatially across the model domain and areas of preferential recharge/discharge along the rivers are simulated by adjusting the transfer in/out parameters. Springs are not included in the model as discrete pathways as they are too poorly understood and at a scale too small to be adequately represented. The inferred discharge areas along the western margin of the Wiso Basin into the Victoria catchment are represented as seepage faces using flux constrained Dirichlet (i.e. first type) BCs. The BC elevations were set at the ground surface values for the discharge areas outside the DR2 model domain (nominally 170 m above Australian Height Datum (mAHD)) and the inflow flux set to zero m^3/day. Extraction for stock and domestic and horticultural use is simulated from the model domain via well BCs (i.e., Neumann second type) at model nodes. Pumping rates were applied as a steady-state value equal to the annual pumped volume for the bore converted to m^3/day. The extent of the saturated CLA forms the boundary of the model domain and is implemented as a zero-flux Neumann or no-flow BC.

The method used to calibrate the DR2 groundwater model is documented in detail by Knapton (2020). The calibration process used a combination of pilot points (Doherty, 2003) and PEST, an automated nonlinear parameter estimation code (Doherty, 2004). Pilot points were strategically placed throughout the model domain to allow for flexible spatial parameterisation, capturing the spatial variability of hydraulic properties (i.e. hydraulic conductivity, storage coefficient and transfer in/out). PEST was then used to iteratively calibrate the model by adjusting the pilot point parameters and recharge parameters to minimise the objective function (i.e. discrepancies between observed and simulated data). The observed data used to define the objective function included available historical groundwater levels (9151 head observations) in the CLA and discharge measurements for the Roper, Flora, Katherine and Douglas rivers. The results of the calibration process are detailed in Knapton (2020).

The upper layer of the DR2 groundwater model is also capable of coupling to a MIKE11 river model of the Roper River. Groundwater–surface water interaction along the rivers occurs where the MIKE11 model is joined to the FEFLOW model at the Cauchy BCs.

3.5 Limitations

Current assumptions and limitations of the DR2 model are as follows:

- An equivalent porous media (EPM) approach was used to represent groundwater flow in the karstic CLA. The regional scale DR2 groundwater flow model only assumes approximate homogeneous isotropic conditions at element scales and is not suited to analysis of local karstic terrains (e.g. for tracking of local scale pollutant flow).
- Recharge is assumed to be diffuse; however, bypass flow via features such as sinkholes is known to be a dominant recharge mechanism. Although the codes used to calculate recharge include estimates of bypass flow, it is expected that, for the years with above-average rainfall, the MIKE SHE and LUMPREM recharge will underestimate actual recharge.
- There is no consideration of deep drainage from recycled irrigation associated with the future hypothetical groundwater developments.
- Individual springs are not considered in the DR2 model as the distributions of the discrete pathways are too poorly understood and at a scale too small to be adequately represented.
- The areas of spring and/or diffuse evapotranspiration discharge along the western margin of the Wiso Basin are represented as specified head BCs to obtain an order of magnitude estimate of the effects of extraction in the area.

4 Scenario modelling

This section discusses the inputs to the eight scenarios input `to the DR2 groundwater flow model.

The Cambrian Limestone Aquifer (CLA) is a regional-scale scale groundwater flow system, which means it may take several hundreds of years after a change in model state (such as climate or development) before the system re-establishes a quasi-equilibrium state in which the groundwater flow patterns stabilise. Consequently, the impacts of development or future climate will in part depend on the timescale over which the modelling results are reported. For the purposes of this report, the modelling results are reported for future conditions representing the projected 2060 model state, nominally representative of the range in conditions between 2055 and 2065.

The projected 2060 model state is consistent with the time frames over which projected future climate scenarios were evaluated in the companion technical report on climate (McJannet et al., 2023) and time frames over which water planning and investment decisions are made.

For each of these evaluation timescales, four scenarios were assessed:

- Scenario A – historical climate (1910 to 2019) and current levels of development
- Scenario B – historical climate (1910 to 2019) and hypothetical development
- Scenario C – future climate (dry, mid and wet) and current levels of development
- Scenario D – future climate (dry, mid and wet) and hypothetical levels of development.

It should be noted that the 1910 to 2019 period was used as the climate baseline to be consistent with the historical climate sequence used for the Roper River Water Resource Assessment (see the Roper River Water Resource Assessment technical report on groundwater modelling (Knapton et al., 2023)).

The method by which future climate sequences were generated is outlined in Section 4.1. The method of establishing hypothetical developments is outlined in Section 4.2, and the adopted model scenarios and naming conventions are outlined in Section 4.3. The reporting metrics for each of the scenarios are presented in Section 4.4.

4.1 Generation of future climate sequences

The potential impacts of future climate change were evaluated within a sensitivity analysis framework. Future climate sequences were evaluated using seasonal scaling factors from selected global climate models (GCMs), as described below, to scale the historical climate data. The entire climate sequence was then re-scaled using an annual scaling factor representative of a percentage change from the long-term annual rainfall and potential evaporation (PET), as detailed below.

Scenario Cdry used the seasonal scaling factors from the ACCESS1-0 model (the GCM with the 10th percent exceedance annual rainfall – see McJannet et al. (2023)) but had an annual scaling factor that reduced the long-term mean annual rainfall by 10% and increased the long-term mean annual PET by 10%.

Scenario Cmid used the seasonal scaling factors from the MRI-CGCM3 model but had an annual scaling factor that reduced the long-term mean annual rainfall by 2% and increased the long-term mean annual PET by 7.5%.

Scenario Cwet used the seasonal scaling factors from the FIO-ESM model but had an annual scaling factor that increased the long-term mean annual rainfall by 10% and increased the long-term mean annual PET by 5%.

Percentage change in long-term annual rainfall and PET were based on the 10%, 50% and 90% exceedance values shown in McJannet et al. (2023).

The climate change scenarios (C and D) are based on sensitivity to climate change (±10% rainfall and PET). Under Scenario Cwet, results from a 10% increase in rainfall and PET are used. Under Scenario Cdry, results from the reduction in mean annual recharge associated with a 10% decrease in rainfall and PET are used. Under Scenario Cmid, the mean annual recharge results from the medium global warming scenario are used.

Scenario D results all include the extreme 'dry' variant of the climate change scenarios with the addition of proposed future development (i.e. Ddry). In considering changes to the hydrological regime under different scenarios, all results were assessed relative to current conditions (i.e. Scenario A, which is based on historical climate and current development).

A comparison of the scenario Cwet, Cmid and Cdry rainfall and potential evaporation data at the six climate locations used in the DR2 groundwater model is provided in

Figure 4-1 and Figure 4-2, respectively.

4.1.1 Rainfall

Historical rainfall data for the six representative climate sites were downloaded from the Scientific Information for Land Owners (SILO) database (https://www.longpaddock.qld.gov.au/silo/), which is maintained and hosted by the Science and Technology Division of the Queensland Government's Department of Environment and Science. SILO is a comprehensive database and platform that provides climate data and related information for Australia (Jeffrey et al., 2001).

The cumulative historical (Scenario A) rainfall and the three scaled rainfall sequences (Cdry, Cmid, and Cwet) at the six representative sites, used in the recharge models, are presented in Figure 4-1.

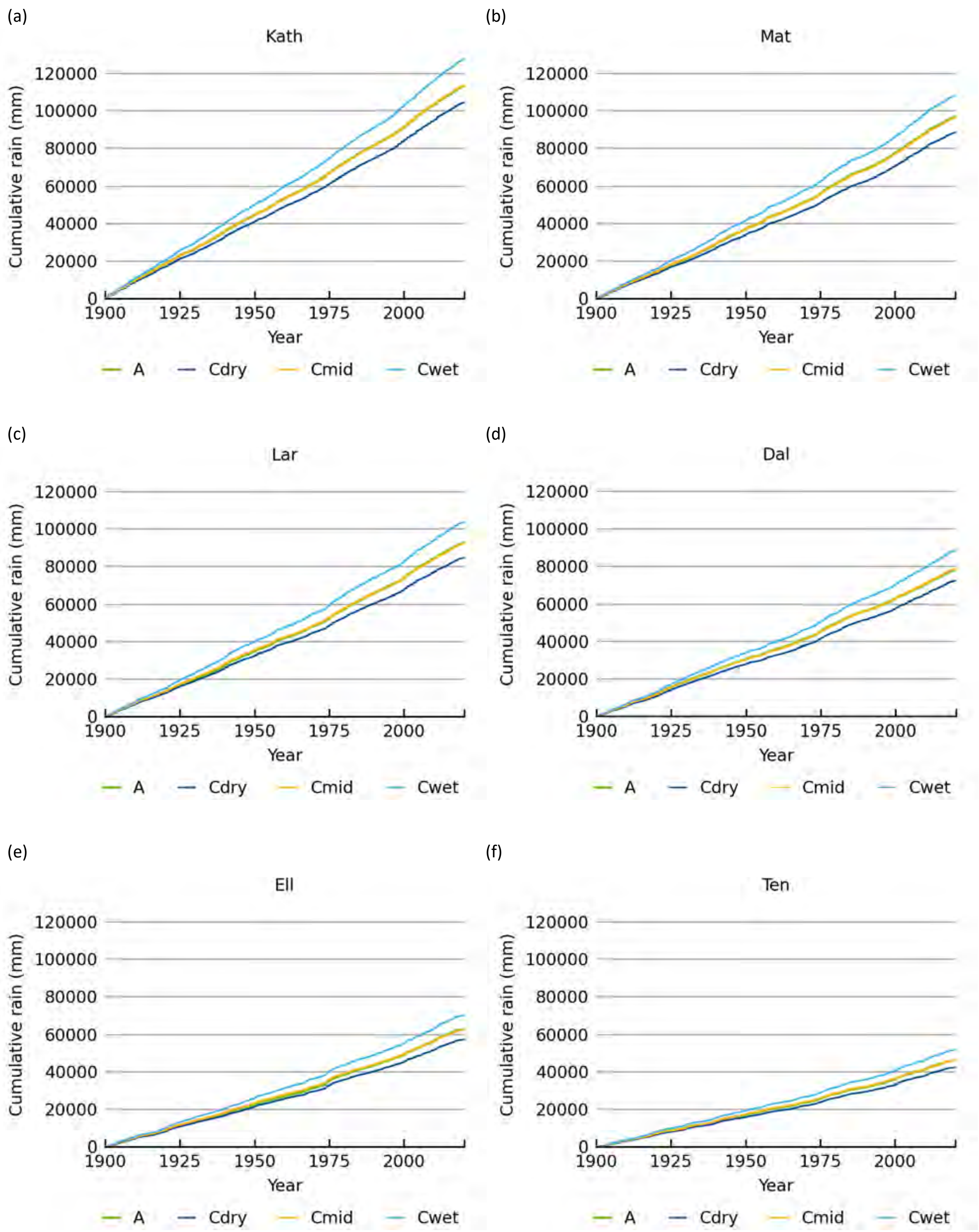

Figure 4-1 Cumulative rainfall for Scenario A compared to the Cdry, Cmid, and Cwet climate sequences at SILO Data Drill sites: (a) Katherine, (b) Mataranka, (c) Larrimah, (d) Daly Waters, (e) Elliot and (f) Tennant Creek

A = historical rainfall retrieved from the SILO Data Drill; Cdry = dry scaled rainfall; Cmid = mid scaled rainfall; Cwet = wet scaled rainfall.

4.1.2 Potential evaporation

The cumulative historical (A) potential evaporation (PET) and the three scaled PET sequences (Cdry, Cmid, and Cwet) at the six representative sites, used in the recharge models, are shown in Figure 4-2.

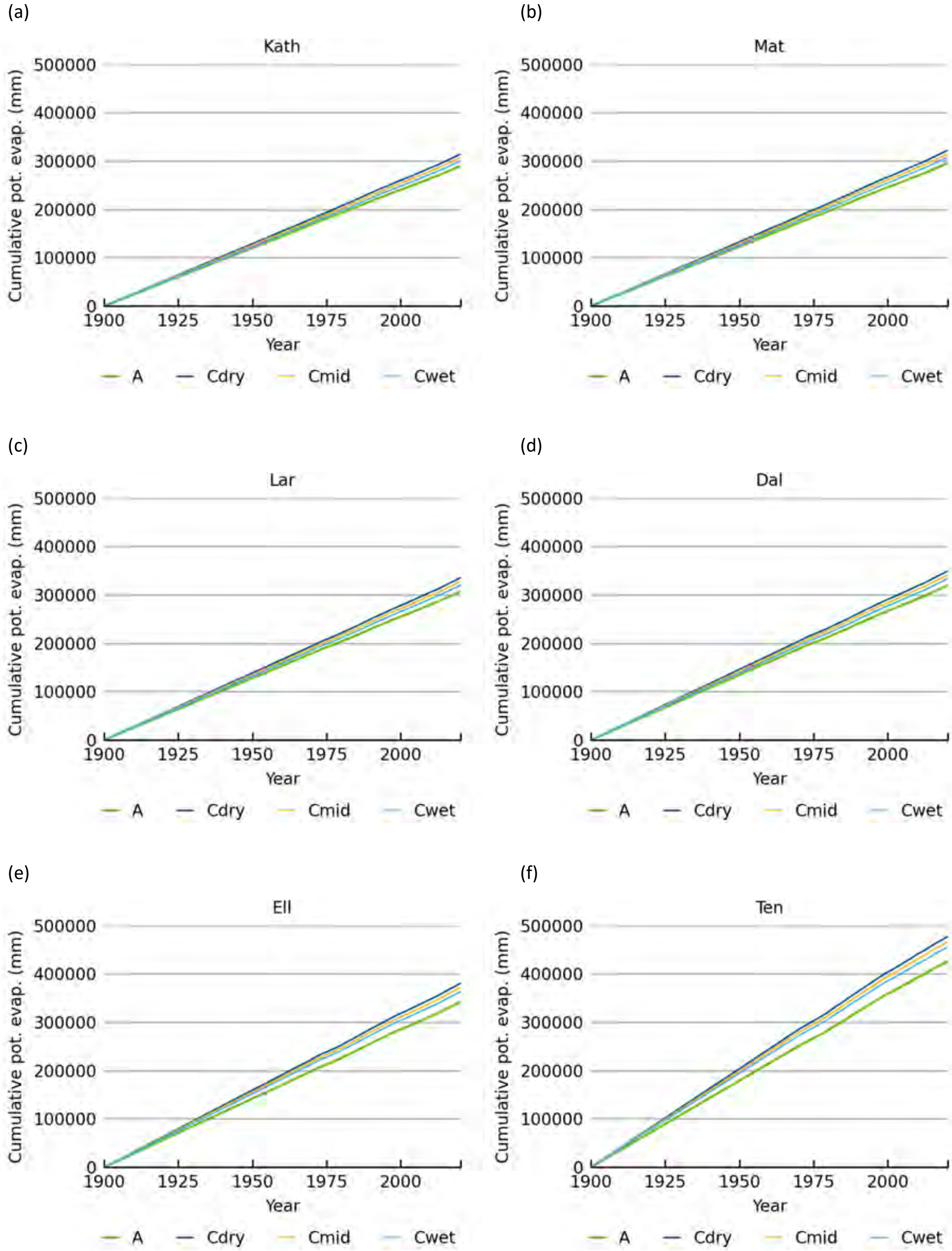

Figure 4-2 Cumulative potential evaporation for Scenario A compared to the Cdry, Cmid, and Cwet climate sequences at SILO Data Drill sites: (a) Katherine, (b) Mataranka, (c) Larrimah, (d) Daly Waters, (e) Elliot and (f) Tennant Creek

A = historical potential evaporation retrieved from the SILO Data Drill; Cdry = dry scaled potential evaporation; Cmid = mid scaled potential evaporation; Cwet = wet scaled evaporation.

4.2 Generation of groundwater development scenarios

The current extraction regime used for scenario A and C was generated by identifying existing licensed bores used for horticulture supplies. Stock and domestic extraction, which is a small component of the total water extracted from within the two water management zones and represents only about 5% of the entitlements identified for horticultural use and has been excluded.

Mean annual extraction rates licensed for horticultural supplies were converted to equivalent daily extraction rates and applied continuously over the duration of each scenario. Scenarios B and D employed an extraction regime that also included hypothetical future groundwater development. The total mean annual extraction rate was converted to an equivalent daily extraction rate and applied over the duration of each scenario.

In the WWMZ, under wet, medium, and dry climate conditions, scenarios B and D featured increases of 9 GL/year, 12 GL/year, and 15 GL/year respectively over current conditions (Scenario A). In the FTWMZ, extractions for current or future development were not simulated.

4.3 Adopted model scenarios and naming conventions

The scenarios examine how different levels of groundwater development might affect water resources in the CLA over a specific period in the future (2055 to 2065), using historical and future climate data.

- The historical climate inputs comprise a 50-year replicate of historical climate sequences taken from the observed climate (rainfall and PET) from water years (defined as the period 1 September to 31 August) from 1910 to 1960 (described in Section 4.1).
- The future climate inputs comprise the 50-year climate sequences derived from scaling rainfall and PET from water years 1910 to 1960 (described in Section 4.1).

The scenarios comprise a warm-up period of 109 years of historical climate data used to prime the CLA groundwater model to 2019 and thereafter using the 50-year historical and future climate sequences and groundwater development inputs to evaluate the representative conditions at 2060.

The first scenario (Scenario A) represents a 'recent climate' scenario and is based on the 50-year (1910 to 1960) historical climate sequence with current levels of groundwater development. Scenario A will be used as the baseline against which assessments of relative change under scenarios B9, B12 and B15 will be made.

The second scenario (Scenario B) is also a 'recent climate' scenario, and it uses the same 50-year climate sequences as Scenario A. It assumes growth in groundwater use according to the hypothetical future development outlined in Section 4.2. Scenario B assesses water availability under hypothetical future groundwater development (Table 4-1).

The third scenario (Scenario C) represents a 'future climate' with current development. It is based on the 50-year future climate sequences derived from scaling rainfall and PET described in Section 4.1. Scenario C uses the current level of groundwater development (Table 4-2).

The fourth scenario (Scenario D) considers 'future climate' and future development. It uses the same future climate sequences as Scenario C but assumes growth in groundwater use according to the hypothetical future development outlined in Section 4.2 (Table 4-3).

Table 4-1 Model configurations under Scenario B

SCENARIO	MODEL CONFIGURATION
B9	1 × 50-year historical climate and current development of zero GL/year + 3 × 3 GL/y hypothetical future enterprises (i.e. total hypothetical future extraction sums to an additional 9 GL/y)
B12	1 × 50-year historical climate and current development of zero GL/year + 3 × 4 GL/year hypothetical future enterprises (i.e. total hypothetical future extraction sums to an additional 12 GL/y)
B15	1 × 50-year historical climate and current development of zero GL/year + 3 × 5 GL/year hypothetical future enterprises (i.e. total hypothetical future extraction sums to an additional 15 GL/y)

Table 4-2 Model configurations under Scenario C

SCENARIO	MODEL CONFIGURATION
Cdry	1 × 50-year future dry climate corresponding to a 10% reduction in mean annual rainfall and 10% increase in potential evaporation, relative to the historical climate (1910 to 2019), and current development of zero GL/year
Cmid	1 × 50-year future mid climate corresponding to a 2% reduction in mean annual rainfall and 7.5% increase in potential evaporation, relative to the historical climate (1910 to 2019), and current development of zero GL/year
Cwet	1 × 50-year future wet climate corresponding to a 10% increase in mean annual rainfall and a 5% increase in potential evaporation, relative to the historical climate (1910 to 2019), and current development of zero GL/year

Table 4-3 Model configurations under Scenario D

SCENARIO	MODEL CONFIGURATION
Ddry9	1 × 50-year future dry climate and current development + 3 × 3 GL/y hypothetical future enterprises (i.e. total hypothetical future extraction sums to an additional 9 GL/y)
Ddry12	1 × 50-year future dry climate and current development + 3 × 4 GL/y hypothetical future enterprises (i.e. total hypothetical future extraction sums to an additional 12 GL/y)
Ddry15	1 × 50-year future dry climate and current development + 3 × 5 GL/y hypothetical future enterprises (i.e. total hypothetical future extraction sums to an additional 15 GL/y)
Dmid9	1 × 50-year future mid climate and current development + 3 × 3 GL/y hypothetical future enterprises (i.e. total hypothetical future extraction sums to an additional 9 GL/y)
Dmid12	1 × 50-year future mid climate and current development + 3 × 4 GL/y hypothetical future enterprises (i.e. total hypothetical future extraction sums to an additional 12 GL/y)
Dmid15	1 × 50-year future mid climate and current development + 3 × 5 GL/y hypothetical future enterprises (i.e. total hypothetical future extraction sums to an additional 15 GL/y)
Dwet9	1 × 50-year future wet climate and current development + 3 × 3 GL/y hypothetical future enterprises (i.e. total hypothetical future extraction sums to an additional 9 GL/y)
Dwet12	1 × 50-year future wet climate and current development + 3 × 4 GL/y hypothetical future enterprises (i.e. total hypothetical future extraction sums to an additional 12 GL/y)
Dwet15	1 × 50-year future wet climate and current development + 3 × 5 GL/y hypothetical future enterprises (i.e. total hypothetical future extraction sums to an additional 15 GL/y)

4.4 Reported metrics

4.4.1 Mean annual water balances

Mean annual water balances are documented for the two management zones (WWMZ and FTWMZ) within the CLA model domain and for the entire area of the DR2 model domain within the Victoria River catchment (refer to Section 2.6). Mean annual water balances are reported for the ten-year period 2055 to 2065, and water balance components are reported in GL/year.

4.4.2 Groundwater-level metrics

CLA groundwater levels are documented for 10 sites within the Victoria catchment. The locations of the reporting sites are presented in Figure 4-3.

The mean groundwater level for each of the sites was calculated to provide a simple measure of the effects of each scenario on the groundwater systems of the CLA. The mean groundwater level for each of the scenarios was calculated from the ten-year period 2055 to 2065 and are reported in mAHD.

4.4.3 Groundwater drawdown

To demonstrate the spatial extent of the effects associated with each scenario, the change in groundwater elevation or groundwater drawdown has been calculated for the time step corresponding to 31 August2060 of each scenario and presented as contours. Drawdowns calculated under scenarios B, C and D use Scenario A as the reference elevation. The minimum drawdown contour of ±1 m has been used to represent the extent of impacts, as this is probably the resolution that could be measured in the field.

4.4.4 Groundwater discharge metrics

Groundwater discharge to springs and evapotranspiration are presented as hydrographs in m^3/day for the areas in the upper reaches of the Victoria catchment within the DR2 model. The discharge at these features was calculated by summing fluxes at the seepage face Dirichlet BC nodes used to represent the springs and diffuse evapotranspiration.

Mean groundwater discharge has also been calculated to provide simple measures that reflect changes to the discharge regime under each scenario. The mean groundwater discharge for the projected 2060 conditions was calculated from the ten-year period 2055 to 2065 and are reported as GL/year.

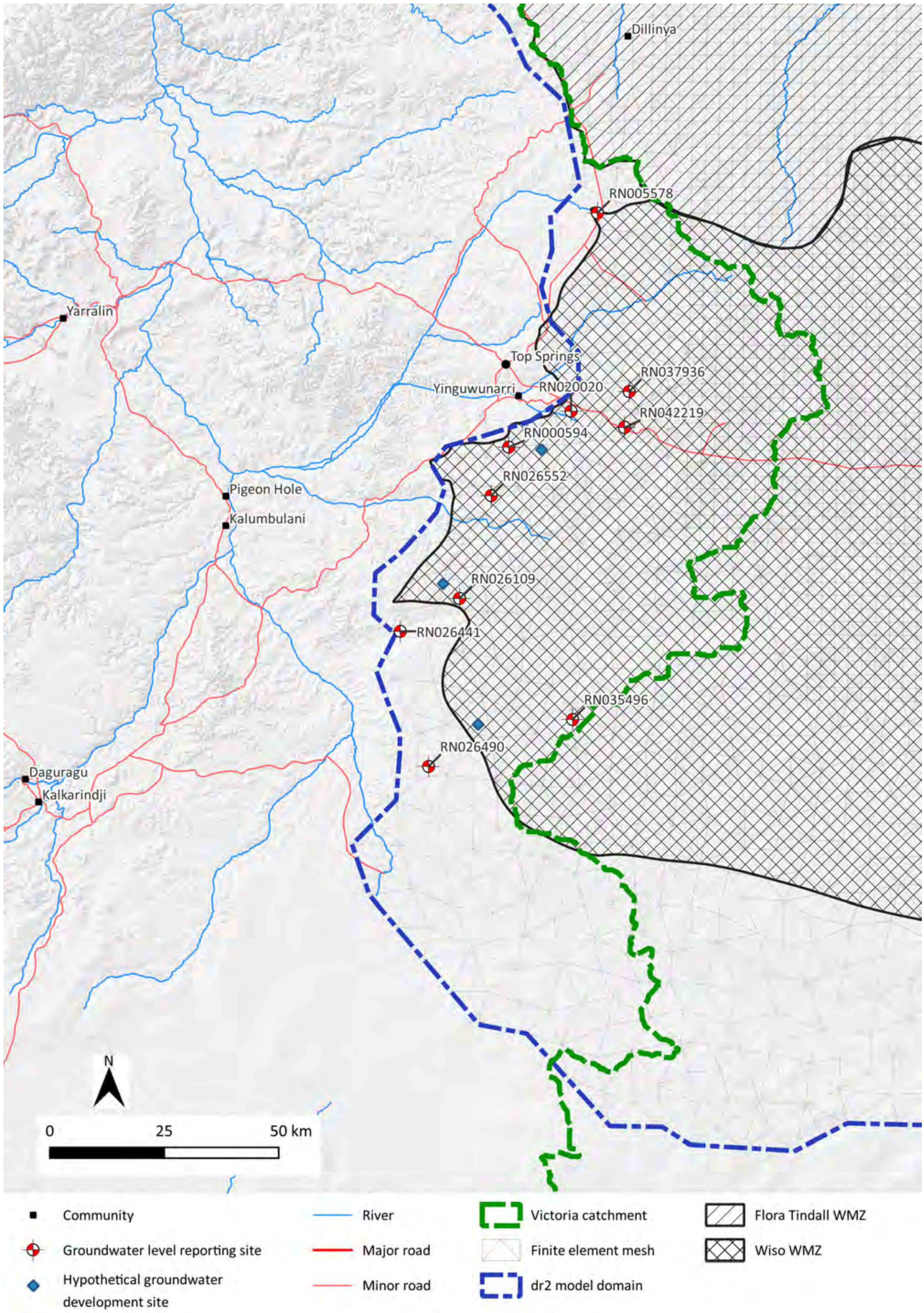

Figure 4-3 Schematic depicting the water balance areas, groundwater-level sites and groundwater discharge sites used for reporting the results of the scenario modelling

5 Scenario model results

5.1 Historical climate (scenarios A and B)

5.1.1 Groundwater balances

The mean annual groundwater balances for the period 2055-2065 under scenarios A, B9, B12 and B15 are presented for the Victoria catchment within the DR2 model domain in Table 5-1, the Wiso Water Management Zone (WWMZ) in Table 5-2 and the Flora Tindall Water Management Zone (FTWMZ) in Table 5-3. Each table row corresponds to a specific component of the water balance in GL/year, and the columns represent each scenario considered.

In the Victoria catchment (Table 5-1), there is a decrease in groundwater discharging to springs ranging from 11.1 GL/year in scenario A to 9.9 GL/year in B9, 9.5 GL/year in B12 and 8.7 GL/year in B15, which correspond to reductions from scenario A for B9 = -11%, B12 = -14% and B15 = -17%.

The net flow from the Victoria catchment was also estimated to decrease from -9.9 GL/year in scenario A to -9.1 GL/year in B9, -8.9 GL/year in B12 and -8.7 GL/year in B15, which correspond to reductions from scenario A for B9 = -6%, B12 = -8% and B15 = -11%.

Estimated reduction in spring discharge to and groundwater outflows were attributed to the hypothetical future groundwater extractions in the Victoria catchment.

In the WWMZ (Table 5-2), decreases in spring discharge were estimated to decrease, from 7.0 GL/year in scenario A, to 5.8 GL/year in B9, 5.5 GL/year in scenario B12 and 5.1 GL/year in scenario B15, which correspond to reductions from scenario A for B9 = -17%, B12 = -22% and B15 = -28%.

An increase in groundwater extraction in the WWMZ is balanced by reduced capture of groundwater into storage compared to Scenario A (a -30% reduction for B9, -35% for B12 and -38% for B15). The net inflow to the WWMZ increases slightly from 7.9 GL/year inflow in scenarios A and B6 to net inflows of 8.0 GL/year in scenarios B12 and B15.

In the FTWMZ (Table 5-3), there is no change in groundwater discharging as springs, as these features are beyond the influence of pumping within the modelled timeframe. The other water balance components do not change appreciably as none of the hypothetical groundwater developments are within the FTWMZ and climate inputs are consistent across the scenarios. Note that the discharge to rivers flows to the Flora River and not the Victoria River.

Table 5-1 Mean annual water balances (GL/year) under scenarios A and B representative of 2060 conditions (2055 to 2065) for the portion of the Victoria catchment within the DR2 model domain

	A	B9	B12	B15
Inflow (gains)				
Recharge (diffuse)	36.3	36.4	36.4	36.4
Release from storage	0.1	1.2	2.5	4.4
From river	0.0	0.0	0.0	0.0
Sub-total	**36.4**	**37.6**	**39.0**	**40.8**
Outflow (losses)				
Evapotranspiration	0.0	0.0	0.0	0.0
Extraction	0.0	9.0	12.0	15.0
Capture into storage	15.6	9.6	8.6	8.0
To rivers	0.0	0.0	0.0	0.0
To springs	11.1	9.9	9.5	9.1
Sub-total	**26.7**	**28.5**	**30.1**	**32.1**
Net flow **In (+ve) / out (–ve)**	**-9.7**	**-9.1**	**-8.9**	**-8.7**

Scenarios: A = Historical climate and current development; B9 = Historical climate sequences with current development and additional future development of 9 GL/year; B12 = Historical climate sequences with current development and additional future development of 12 GL/year; B15 = Historical climate sequences with current development and additional future development of 15 GL/year.

Table 5-2 Mean annual water balances (GL/year) under scenarios A and B representative of 2060 conditions (2055 to 2065) for the Wiso Water Management Zone

	A	B9	B12	B15
Inflow (gains)				
Recharge (diffuse)	20.7	20.7	20.7	20.7
Release from storage	0.1	1.4	2.8	4.8
From river	0.0	0.0	0.0	0.0
Sub-total	**20.8**	**22.1**	**23.6**	**25.6**
Outflow (losses)				
Evapotranspiration	0.0	0.0	0.0	0.0
Extraction	0.0	9.0	12.0	15.0
Capture into storage	21.7	15.2	14.1	13.5
To rivers	0.0	0.0	0.0	0.0
To springs	7.0	5.8	5.5	5.1
Sub-total	**28.7**	**30.0**	**31.5**	**33.5**
Net flow **In (+ve) / out (-ve)**	**+7.9**	**+7.9**	**+8.0**	**+8.0**

Scenarios: A = Historical climate and current development; B9 = Historical climate sequences with current development and additional future development of 9 GL/year; B12 = Historical climate sequences with current development and additional future development of 12 GL/year; B15 = Historical climate sequences with current development and additional future development of 15 GL/year.

Table 5-3 Mean annual water balances (GL/year) under scenarios A and B representative 2060 conditions (2055 to 2065) for the Flora Tindall Water Management Zone

	A	B9	B12	B15
Inflow (gains)				
Recharge (diffuse)	134.6	134.8	134.8	134.8
Release from storage	118.4	118.8	119.0	118.8
From river	0.3	0.3	0.3	0.3
Sub-total	**253.3**	**253.8**	**254.0**	**253.8**
Outflow (losses)				
Evapotranspiration	0.0	0.0	0.0	0.0
Extraction	0.0	0.0	0.0	0.0
Capture into storage	85.3	85.3	85.2	85.2
To rivers†	155.7	156.0	156.1	156.1
To springs	3.9	3.9	3.9	3.9
Sub-total	**244.9**	**245.3**	**245.3**	**245.2**
Net flow In (+ve) / out (-ve)	**−8.4**	**−8.5**	**−8.7**	**−8.6**

Scenarios: A = Historical climate and current development; B9 = Historical climate sequences with current development and additional future development of 9 GL/year; B12 = Historical climate sequences with current development and additional future development of 12 GL/year; B15 = Historical climate sequences with current development and additional future development of 15 GL/year.
†Note that this is discharge to the Flora River.

5.1.2 Groundwater levels

The groundwater levels for the ten reported sites are presented in Figure 5-1, Figure 5-2 and Figure 5-3. Each plot shows the historical response (green) and the locations of the groundwater-level reporting sites are presented in Figure 4-3.

The groundwater levels under Scenario A show an upward trend for all sites over the 50-year model run from 2019 to 2070. The mean groundwater levels for the period 2055 to 2065, representative of 2060 conditions, are presented in Table 5-4.

Table 5-4 Mean groundwater levels (mAHD) under scenarios A and B representative of 2060 conditions (2055 to 2065)

SCENARIO	RN000594	RN005578	RN020020	RN026109	RN026490	RN035496	RN026441	RN026552	RN037936	RN042219
A	190.0	169.7	160.5	166.4	150.1	151.4	158.5	181.8	159.6	158.6
B9	187.8	169.7	160.3	162.2	148.9	150.6	158.0	179.9	159.3	157.7
B12	187.1	169.7	160.2	160.8	148.4	150.3	157.9	179.3	159.3	157.4
B15	186.4	169.7	160.1	159.4	148.0	150.0	157.7	178.6	159.2	157.1

mAHD = metres above Australian Height Datum. Scenarios: A = Historical climate and current development; B9 = Historical climate sequences with current development and additional future development of 9 GL/year; B12 = Historical climate sequences with current development and additional future development of 12 GL/year; B15 = Historical climate sequences with current development and additional future development of 15 GL/year.

(a)

(b)

(c)

(d)

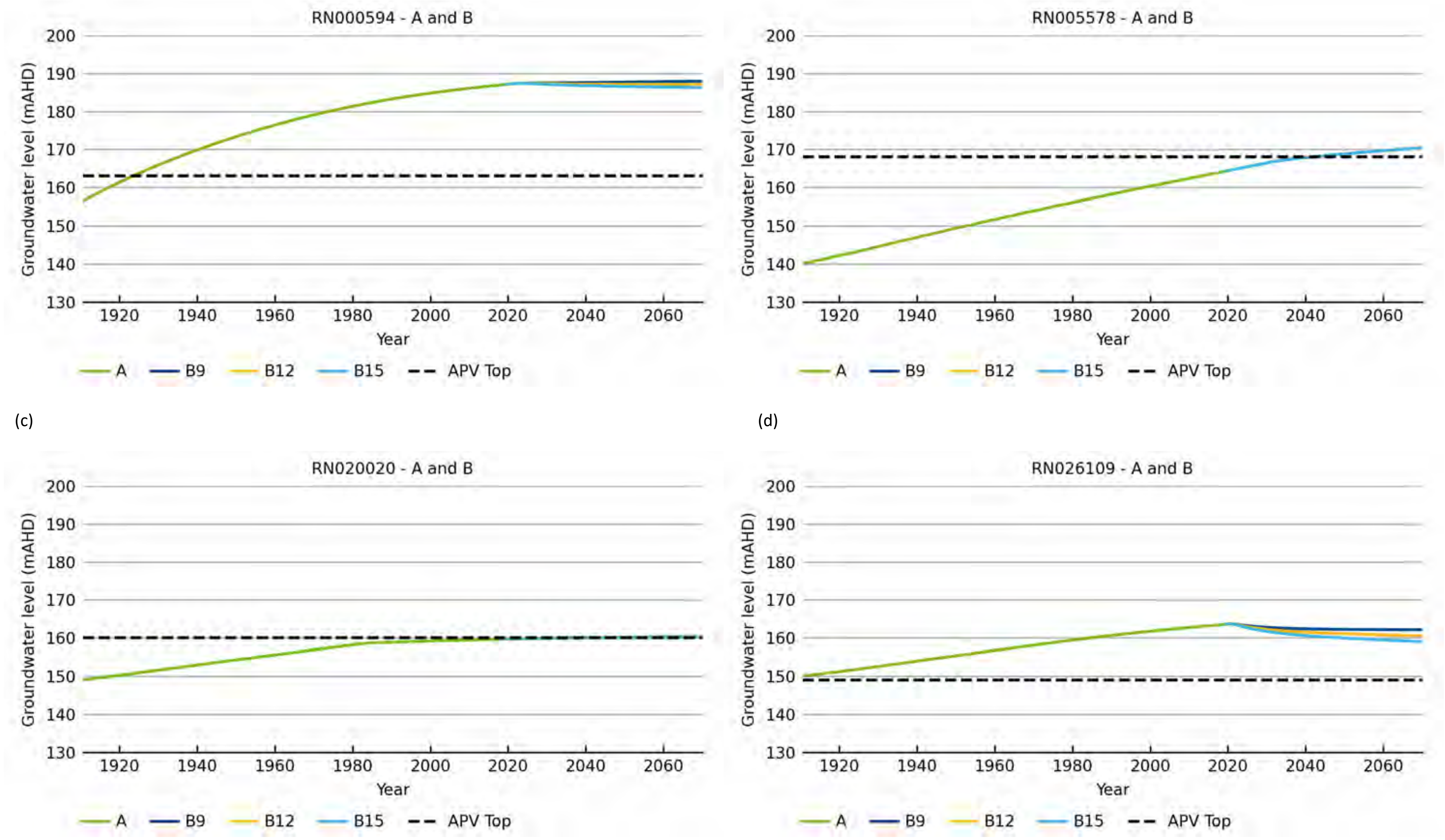

Figure 5-1 Hydrographs of groundwater levels (mAHD) under scenarios A and B for the reporting sites (a) RN000594, (b) RN005578, (c) RN020020 and (d) RN026109

APV Top = contact between Cambrian Limestone Aquifer and the Antrim Plateau Volcanics

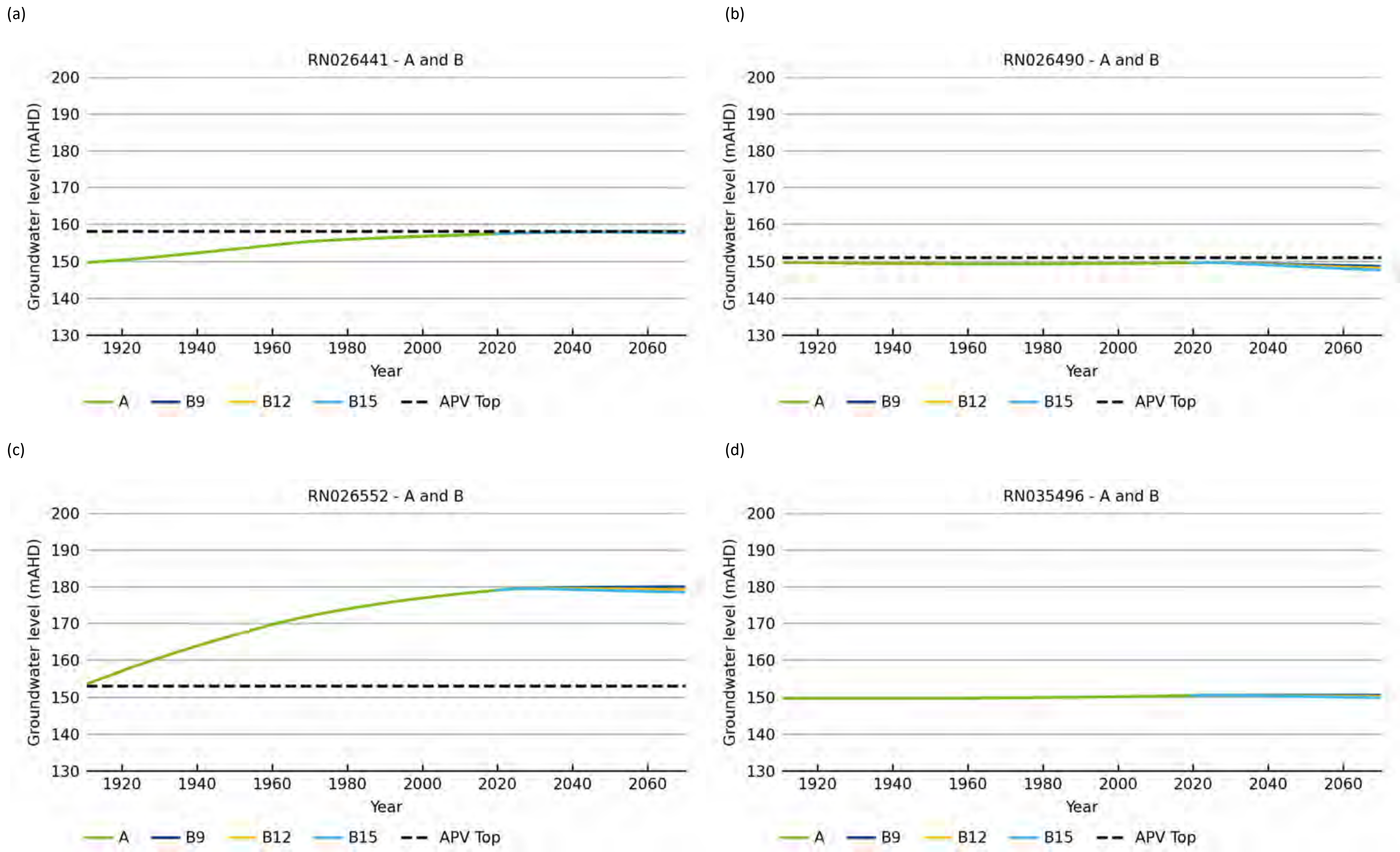

Figure 5-2 Hydrographs of groundwater levels (mAHD) under scenarios A and B for the reporting sites (a) RN026441, (b) RN026490, (c) RN026552 and (d) RN035496

APV Top = contact between Cambrian Limestone Aquifer and the Antrim Plateau Volcanics

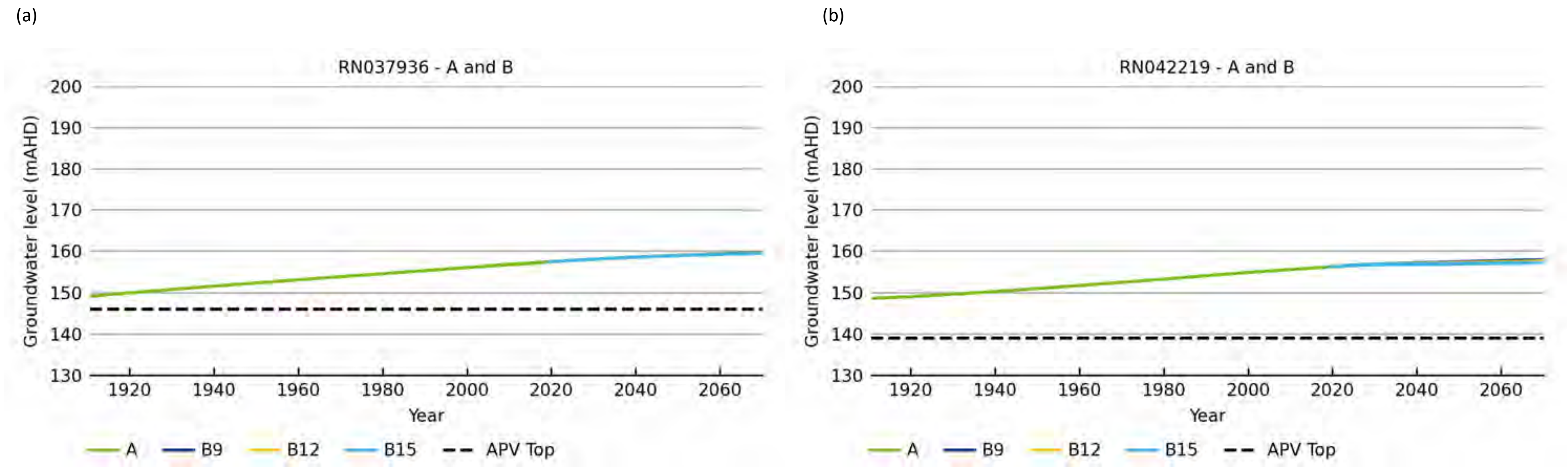

Figure 5-3 Hydrographs of groundwater levels (mAHD) under scenarios A and B for the reporting sites (a) RN037936 and (b) RN042219

APV Top = contact between Cambrian Limestone Aquifer and the Antrim Plateau Volcanics

5.1.3 Groundwater drawdown

The drawdown contours at 31 August 2060 under scenarios B9, B12 and B15 relative to Scenario A are presented in Figure 5-4.

The drawdown contours under Scenario B9 at 31 August 2060, assuming future groundwater extraction of 9 GL/year, are presented in Figure 5-4a. The Scenario B9 maximum drawdown (<15 m) is centred on each of the hypothetical developments, and the 1 m drawdown contour extends about 15 to 20 km from the pumping centres.

The drawdown contours under Scenario B12 at 31 August 2060, assuming current and future groundwater extraction totalling 12 GL/year, are presented in Figure 5-4b. The maximum drawdown (<20 m) is centred on each of the pumping centres, and the 1 m drawdown contour extends 15 to 20 km to the south and east of the pumping centres.

The drawdown contours under Scenario B15 at 31 August 2060, assuming current and future groundwater extraction of 15 GL/year, are presented in Figure 5-4c. The maximum drawdown (<30 m) is centred on each of the pumping centres, and the 1 m drawdown contour extends 15 to 20 km to the south and east of the pumping centres.

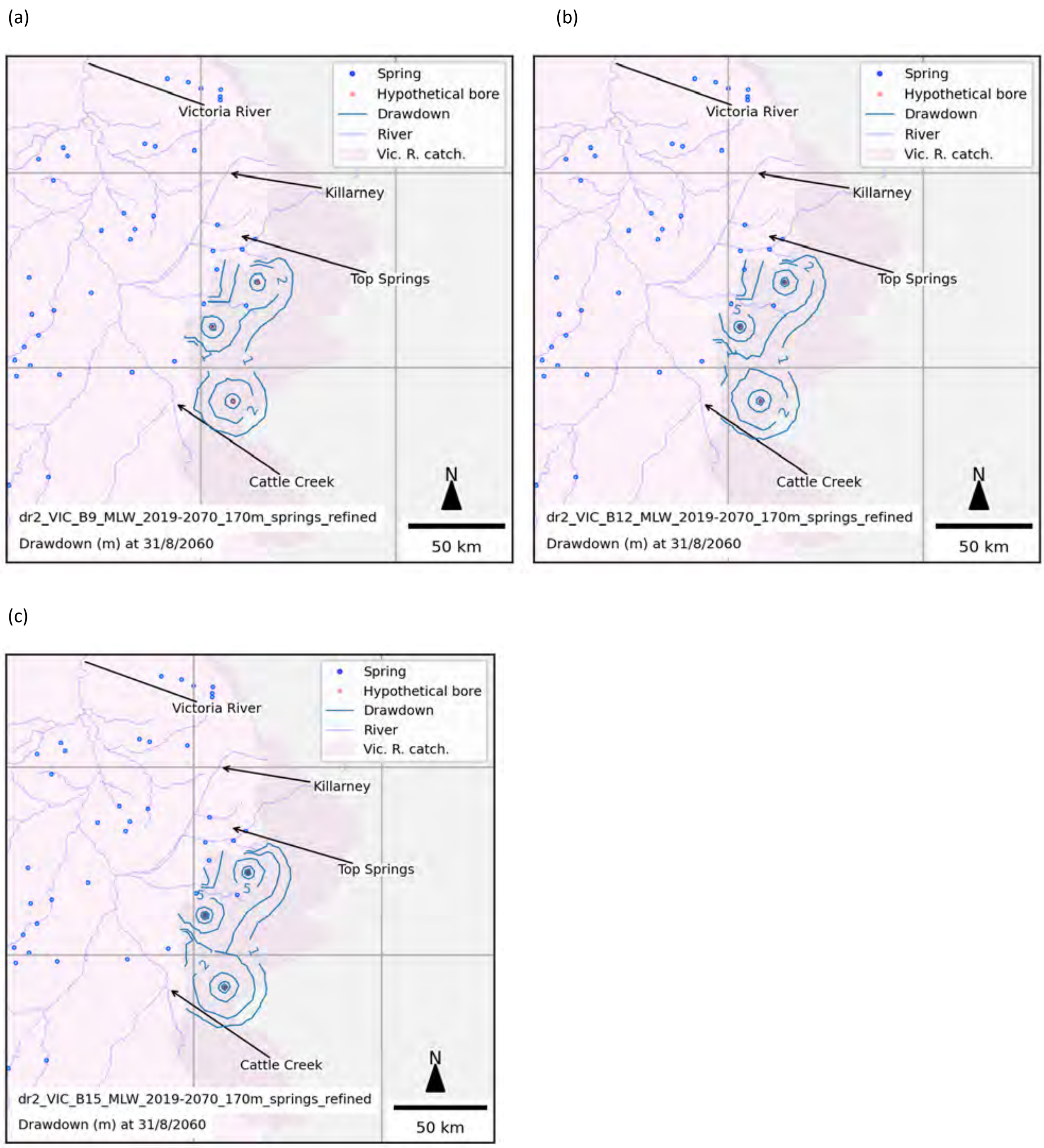

Figure 5-4 Drawdown contours relative to Scenario A for 2060 under scenarios (a) B9, (b) B12 and (c) B15

5.1.4 Groundwater discharge

Table 5-5 presents the mean groundwater discharge to springs and evapotranspiration for the Victoria catchment portion of the CLA for the ten-year period from 2055 to 2065 (representative of 2060 conditions) under scenarios A, B9, B12 and B15. It also shows the percentage change in discharge relative to Scenario A.

Groundwater discharges under scenarios A, B9, B12 and B15 are presented in Figure 5-5.

Table 5-5 Mean diffuse groundwater discharges (springs and evapotranspiration) in the Victoria catchment portion of the Cambrian Limestone Aquifer for the 2060 representative conditions (2055 to 2065)

SCENARIO	MEAN DISCHARGE (SPRINGS AND EVAPOTRANSPIRATION) (GL/Y)	% CHANGE
A	11.1	na†
B9	9.9	-11
B12	9.5	-14
B15	9.1	-18

Scenarios: A = Historical climate and current development; B9 = Historical climate sequences with current development and additional future development of 9 GL/year; B12 = Historical climate sequences with current development and additional future development of 12 GL/year; B15 = Historical climate sequences with current development and additional future development of 15 GL/year.
†na = not applicable.

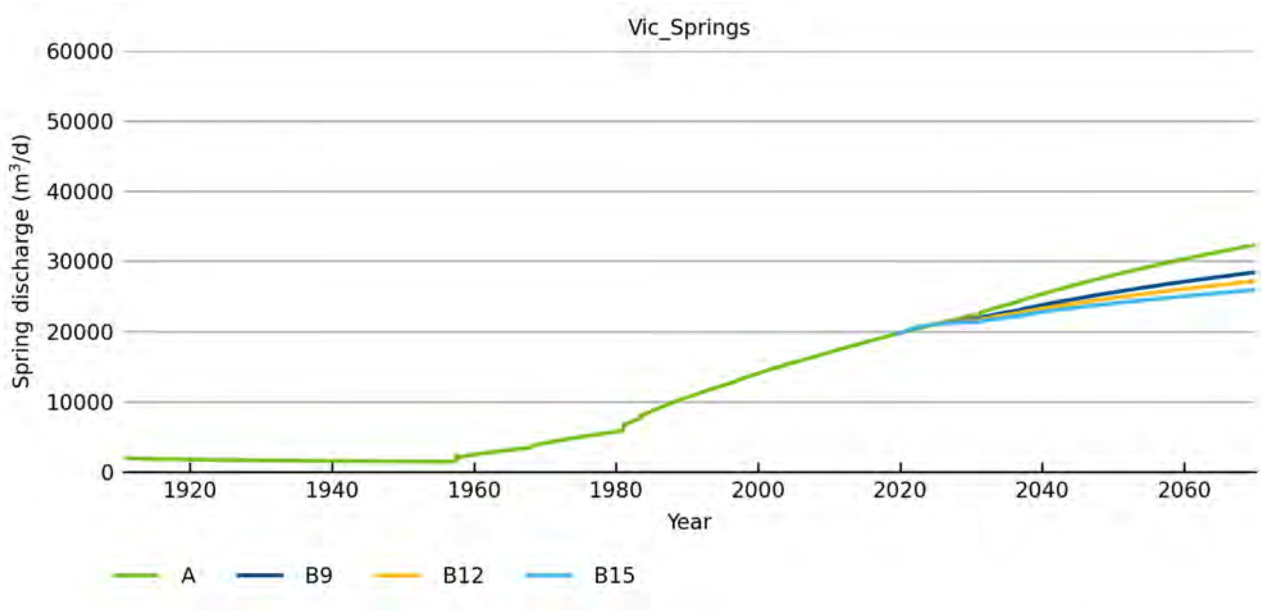

Figure 5-5 Groundwater discharge (springs and evapotranspiration) in the Victoria catchment portion of the Cambrian Limestone Aquifer under scenarios A, B9, B12 and B15

5.2 Future climate (scenarios C and D)

Two scenarios were used to examine the effects of current and hypothetical future developments in conjunction with the three future climate sequences on the catchment water balance, groundwater levels and discharge to the springs and evapotranspiration in the Victoria catchment and the Flora River in the FTWMZ. The three input sequences (dry, mid and wet) represent changes in the mean annual rainfall of approximately −10%, −2% and +10% and in PET of +10%, +7.5% and +5%, respectively, from the historical climate sequence employed in Scenario A.

5.2.1 Groundwater balances

The mean annual water balances for the three reporting areas – the portion of the DR2 model domain within the Victoria catchment, the WWMZ and the FTWMZ – for the ten-year period from 2055 to 2065 are presented in Table 5-6, Table 5-7 and Table 5-8, respectively. Each row of the table corresponds to a specific component of the water balance, and the columns represent each scenario considered (i.e. the dry, mid, and wet climate sequences of scenarios C and D).

In the Victoria catchment, recharge under Scenario A is 36.3 GL/year. Recharge decreases under Scenario Cdry to 24.0 GL/year (−34% change relative to Scenario A) and 32.4 GL/year under Cmid (−15% change relative to Scenario A) and increases under Scenario Cwet to 51.2 GL/year (+41% change relative to Scenario A). Discharge to the springs follows a similar trend with Cdry = −34%, Cmid = −11% and Cwet = +42% relative to Scenario A. The mean annual water balances for the future climate sequences (i.e., scenarios C and D) indicate that, although the future rainfall for the mid-climate sequences is similar to the historical rainfall (Section 4.1.1), the Cmid recharge value is less than that under Scenario A by a factor of about 0.9.

Under Scenario C, the net outflow from the Victoria catchment increases from approximately 8.6 GL/year (−11% change relative to Scenario A) under Scenario Cdry to 10.8 GL/year (+11% change relative to Scenario A) under Scenario Cwet. The changes in outflow are directly related to the applied recharge.

Under Scenario Ddry, the net outflow to the Victoria catchment reduces from about 8.0 GL/year under Scenario Ddry9 (a decrease of 1.7 GL/year or -18% relative to Scenario A) to about 7.6 GL/year under Scenario Ddry15 (a decrease of 2.1 GL/year or -22%). This is due to the hypothetical future groundwater extraction capturing groundwater flow that would otherwise flow outside the catchment.

Recharge varies significantly across scenarios with Scenario Cwet showing the highest recharge at 51.2 GL/year and Scenario Cdry showing the lowest at 24.0 GL/year.

In the WWMZ, recharge under Scenario A is 20.7 GL/year. Recharge decreases to 13.7 GL/year under Scenario Cdry (−34% change relative to Scenario A) and 19.1 GL/year under Scenario Cmid (−8%) and increases to 30.5 GL/year under Scenario Cwet (+47%). Discharge to the springs follows a similar trend with Cdry = −30%, Cmid = −8% and Cwet = +45% relative to Scenario A.

In the WWMZ, the discharge to springs under Scenario A is 6.8 GL/year. Discharge to springs decreases to 4.8 GL/year under Scenario Cdry (−29% change relative to Scenario A) and 6.4 GL/year under Scenario Cmid (−6%) and increases to 10.0 GL/year under Scenario Cwet (+47%).

Groundwater inflows to the WWMZ under Scenario A are about 7.9 GL/year, and the regime does not change under all scenarios with either current or hypothetical future groundwater development (i.e. scenarios C and D). However, inflows are reduced under Scenario Cdry (7.1 GL/year, −10% relative to Scenario A) and Cmid (7.5 GL/year, −5%) and increase under Cwet (8.7 GL/year, +10%).

In the WWMZ, scenarios D9, D12, and D15 represent 9, 12, and 15 GL/year increases in extraction over Scenario C, respectively. Note that there are no flows to or from rivers or to areal evapotranspiration in the WWMZ region because the depth of the water is greater than the depth at which these processes operate.

In the FTWMZ, recharge under Scenario A is 134.6 GL/year. Recharge decreases in the Cdry and Cmid scenarios and increases in the Cwet scenario. Specifically, recharge decreases to

89.4 GL/year (−34% change relative to Scenario A) under Scenario Cdry and to 115.7 GL/year (−14%) under Scenario Cmid, while it increases to 182.3 GL/year (+36%) in under Cwet.

Discharge to the Flora River under Scenario A is 155.7 GL/year. Under scenarios C and D, it is lowest under Scenario Cdry and Ddry (142.1 GL/year, −9% relative to Scenario A) and highest in under scenarios Cwet and Dwet (195.1 GL/year, +25%). Discharge under Cmid is 154.4 GL/year (−1% relative to Scenario A).

Because none of the hypothetical future development sites are in the FTWMZ, scenarios D9, D12, and D15 have the same extraction as the A and C scenarios (i.e., 0 GL/year). Three of the hypothetical future groundwater development sites are in the Victoria catchment portion of the WWMZ. The water balances indicate that there will be virtually no impact beyond the Victoria catchment within the time frame considered in this study.

Table 5-6 Mean annual water balances (GL/year) under scenarios C and D representative 2060 conditions (2055 to 2065) for the portion of the Victoria catchment within the DR2 model domain

	CDRY	CMID	CWET	DDRY9	DDRY12	DDRY15	DMID9	DDRY12	DMID15	DWET9	DWET12	DWET15
Inflow (gains)												
Recharge (diffuse)	24.0	32.4	51.2	24.0	24.0	24.0	32.4	32.4	32.4	51.2	51.2	51.2
Release from storage	0.4	0.1	0.1	4.0	6.0	8.2	1.6	3.3	5.3	0.9	1.5	2.3
From river	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sub-total	24.5	32.5	51.2	28.0	30.0	32.2	34.0	35.7	37.7	52.1	52.7	53.5
Outflow (losses)												
Evapotranspiration	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Extraction	0.0	0.0	0.0	9.0	12.0	15.0	9.0	12.0	15.0	9.0	12.0	15.0
Capture into storage	8.5	13.4	24.7	4.8	4.4	4.2	7.7	7.0	6.6	18.5	16.8	15.2
To rivers	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
To springs	7.3	9.8	15.8	6.2	5.8	5.5	8.6	8.3	7.9	14.5	14.1	13.7
Sub-total	15.8	23.2	40.5	20.0	22.2	24.6	25.3	27.3	29.4	42.0	42.8	43.8
Net flow In (+ve) / out (-ve)	**-8.6**	**-9.3**	**-10.8**	**-8.0**	**-7.8**	**-7.6**	**-8.6**	**-8.4**	**-8.2**	**-10.1**	**-9.9**	**-9.7**

Scenarios: Cdry = Future dry climate sequence with current development; Cmid = Future mid climate sequence with current development; Cwet = Future wet climate sequence with current development; Ddry9 = Future dry climate sequences with current development and additional future development of 9 GL/year; Ddry12 = Future dry climate sequences with current development and additional future development of 12 GL/year; Ddry15 = Future dry climate sequences with current development and additional future development of 15 GL/year; Dmid9 = Future mid climate sequences with current development and additional future development of 9 GL/year; Dmid12 = Future mid climate sequences with current development and additional future development of 12 GL/year; Dmid15 = Future mid climate sequences with current development and additional future development of 15 GL/year; Dwet9 = Future wet climate sequences with current development and additional future development of 9 GL/year; Dwet12 = Future wet climate sequences with current development and additional future development of 12 GL/year; Dwet15 = Future wet climate sequences with current development and additional future development of 15 GL/year.

Table 5-7 Mean annual water balances (GL/year) under scenarios C and D representative of 2060 conditions (2055 to 2065) for the Wiso Water Management Zone

	CDRY	CMID	CWET	DDRY9	DDRY12	DDRY15	DMID9	DDRY12	DMID15	DWET9	DWET12	DWET15
Inflow (gains)												
Recharge (diffuse)	13.7	19.1	30.5	13.7	13.7	13.7	19.1	19.1	19.1	30.5	30.5	30.5
Release from storage	0.6	0.2	0.1	4.2	6.4	8.7	1.8	3.6	5.7	1.1	1.9	2.8
From river	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sub-total	14.0	18.9	30.1	17.6	19.7	22.0	20.5	22.3	24.4	31.0	31.8	32.7
Outflow (losses)												
Evapotranspiration	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Extraction	0.0	0.0	0.0	9.0	12.0	15.0	9.0	12.0	15.0	9.0	12.0	15.0
Capture into storage	16.4	20.3	29.1	12.2	11.8	11.4	14.1	13.3	12.8	22.4	20.6	18.9
To rivers	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
To springs	4.9	6.5	10.2	3.7	3.4	3.0	5.3	4.9	4.5	8.8	8.4	8.0
Sub-total	20.9	26.3	38.7	24.6	26.7	29.0	27.9	29.7	31.8	39.6	40.4	41.3
Net flow In (+ve) / out (-ve)	**+7.1**	**+7.5**	**+8.7**	**+7.1**	**+7.1**	**+7.1**	**+7.5**	**+7.5**	**+7.5**	**+8.7**	**+8.7**	**+8.7**

Scenarios: Cdry = Future dry climate sequence with current development; Cmid = Future mid climate sequence with current development; Cwet = Future wet climate sequence with current development; Ddry9 = Future dry climate sequences with current development and additional future development of 9 GL/year; Ddry12 = Future dry climate sequences with current development and additional future development of 12 GL/year; Ddry15 = Future dry climate sequences with current development and additional future development of 15 GL/year; Dmid9 = Future mid climate sequences with current development and additional future development of 9 GL/year; Dmid12 = Future mid climate sequences with current development and additional future development of 12 GL/year; Dmid15 = Future mid climate sequences with current development and additional future development of 15 GL/year; Dwet9 = Future wet climate sequences with current development and additional future development of 9 GL/year; Dwet12 = Future wet climate sequences with current development and additional future development of 12 GL/year; Dwet15 = Future wet climate sequences with current development and additional future development of 1 5GL/year.

Table 5-8 Mean annual water balances (GL/year) under scenarios C and D representative of 2060 conditions (2055 to 2065) for the Flora Tindall Water Management Zone

	CDRY	CMID	CWET	DDRY9	DDRY12	DDRY15	DMID9	DDRY12	DMID15	DWET9	DWET12	DWE715
Inflow (gains)												
Recharge (diffuse)	89.4	115.7	182.3	89.4	89.4	89.4	115.7	115.7	115.7	182.3	182.3	182.3
Release from storage	117.3	122.8	160.1	117.2	117.2	117.2	122.8	122.8	122.8	160.0	160.0	160.0
From river	0.2	0.3	0.3	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3
Sub-total	**206.9**	**238.8**	**342.6**	**206.9**	**206.9**	**206.9**	**238.7**	**238.7**	**238.7**	**342.5**	**342.5**	**342.5**
Outflow (losses)												
Evapotranspiration	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Extraction	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Capture into storage	51.3	68.8	120.4	51.3	51.3	51.3	68.8	68.8	68.8	120.4	120.4	120.4
To rivers†	142.1	154.4	195.1	142.1	142.1	142.1	154.4	154.4	154.4	195.1	195.1	195.1
To springs	2.4	3.3	5.5	2.4	2.4	2.4	3.3	3.3	3.3	5.5	5.5	5.5
Sub-total	**195.8**	**226.5**	**321.2**	**195.8**	**195.8**	**195.8**	**226.5**	**226.5**	**226.5**	**321.1**	**321.1**	**321.1**
Net flow In (+ve) / out (-ve)	**-11.1**	**-12.3**	**-21.4**	**-11.1**	**-11.1**	**-11.1**	**-12.2**	**-12.2**	**-12.2**	**-21.4**	**-21.4**	**-21.4**

Cdry = Future dry climate sequence with current development; Cmid = Future mid climate sequence with current development; Cwet = Future wet climate sequence with current development; Ddry9 = Future dry climate sequences with current development and additional future development of 9GL/year; D'dry12 = Future dry climate sequences with current development and additional future development of 12GL/year; Ddry15 = Future dry climate sequences with current development and additional future development of 15GL/year; D'mid9 = Future mid climate sequences with current development and additional future development of 9GL/year; D'mid12 = Future mid climate sequences with current development and additional future development of 12GL/year; Dmid15 = Future mid climate sequences with current development and additional future development of 15GL/year; Dwet9 = Future wet climate sequences with current development and additional future development of 9GL/year; Dwet12 = Future wet climate sequences with current development and additional future development of 12GL/year; Dwet15 = Future wet climate sequences with current development and additional future development of 15GL/year

†Note that this is discharge to the Flora River.

5.2.2 Groundwater levels

This section presents the simulated groundwater levels at ten CLA reporting sites under scenarios C and D. The locations of the ten groundwater-level reporting sites are presented in Figure 4-3.

Hydrographs of groundwater levels under scenarios C and D at the ten reporting sites are presented in Figure 5-6 through Figure 5-14. They all show Scenario A (green solid line) for reference.

The groundwater levels respond in a manner as would be expected for the three climate sequences. That is, the dry sequences show the lowest groundwater levels, the wet sequences show the highest groundwater levels, and the mid sequences' groundwater levels sit somewhere in between the two extremes.

Table 5-9 presents the mean groundwater level at the ten CLA reporting sites for the ten-year period (2055 to 2065) of each climate sequence under scenarios C and D. Each table row corresponds to a specific scenario, and the columns represent the mean groundwater level for each reporting site.

Compared to Scenario A, mean groundwater levels are lower at all but two of the reporting sites under Scenario Cdry, generally comparable to or slightly lower under Scenario Cmid, and generally higher under Scenario Cwet. Two sites (RN026490 and RN035496) show no change from Scenario A under Cdry, three sites (RN026490, RN035496, and RN026441) show no change under Cmid. Two sites (RN026490 and RN035496) show no change from Scenario A under Cwet.

Mean groundwater levels under Scenario Ddry9 are 0.2 to 8.0 m lower than under Scenario A, mean groundwater levels under Scenario Ddry12 are 0.2 to 8.7 m lower, and mean groundwater levels under Scenario Ddry15 are 0.2 to 9.4 m lower.

Mean groundwater levels under Scenario Dmid9 are 0.1 to 4.6 m lower than under Scenario A, mean groundwater levels under Scenario Dmid12 are 0.1 to 6.0 m lower, and mean groundwater levels under Scenario Dmid15 are 0.1 to 7.4 m lower.

Mean groundwater levels under Scenario Dwet9 are between 2.1 m lower and 5.4 m higher than under Scenario A, mean groundwater levels under Scenario Dwet12 are between 3.5 m lower and 4.7 m higher, and mean groundwater levels under Scenario Dwet15 are between 4.9 m lower and 10.7 m higher.

The groundwater levels at the northern portion of the CLA in the Victoria catchment (RN005578 and RN037936) indicate that there will be virtually no impact beyond the Victoria catchment arising from the hypothetical future developments within the time frame considered in this study.

Dry climate scenarios (Cdry, Ddry9, Ddry12 and Ddry15) generally show lower water levels than mid and wet scenarios. Water levels tend to decrease with higher development (e.g. from 9 to 15 GL/year).

Mid climate (Cmid, Dmid9, Dmid12 and Dmid15) water levels are intermediate between dry and wet scenarios. Development affects water levels, but the change is not as drastic as in dry scenarios.

Wet climates (Cwet, and Dwet9, Dwet12 and Dwet15) exhibit the highest water levels across all scenarios. Development scenarios (of 9, 12 or 15 GL/year) show some impact, but water levels remain relatively high.

Table 5-9 Mean groundwater levels (mAHD) under scenarios C and D representative of 2060 conditions (2055 to 2065)

SCENARIO	RN000594	RN005578	RN020020	RN026109	RN026490	RN035496	RN026441	RN026552	RN037936	RN042219
A	190.0	169.7	160.5	166.4	150.1	151.4	158.5	181.8	159.6	158.6
Cdry	184.3	167.4	160.0	164.8	150.1	151.4	158.4	177.8	158.3	157.9
Cmid	188.7	168.7	160.4	166.0	150.1	151.4	158.5	180.9	159.2	158.4
Cwet	197.6	171.9	161.1	168.6	150.1	151.4	158.7	187.1	161.3	159.6
Ddry9	182.1	167.4	159.8	160.7	148.9	150.6	157.9	175.9	158.1	157.0
Dmid9	186.5	168.7	160.1	161.8	148.9	150.6	158.0	179.0	159.0	157.5
Dwet9	195.5	171.9	160.9	164.4	148.9	150.6	158.2	185.2	161.1	158.7
Ddry12	181.3	167.4	159.7	159.3	148.4	150.3	157.7	175.3	158.0	156.7
Dmid12	185.8	168.7	160.1	160.4	148.4	150.3	157.8	178.3	159.0	157.2
Dwet12	194.8	171.9	160.8	162.9	148.4	150.3	158.0	184.6	161.0	158.4
Ddry15	180.6	167.4	159.7	157.9	148.0	150.0	157.6	174.6	157.9	156.4
Dmid15	185.1	168.7	160.0	159.1	148.0	150.0	157.7	177.7	158.9	156.9
Dwet15	194.1	171.9	160.8	161.5	148.0	150.0	157.9	184.0	160.9	158.1

mAHD = metres above Australian Height Datum. Scenarios: A = Historical climate and current development; Cdry = Future dry climate sequences current development; Cmid = Future mid climate sequences current development; Cwet = Future wet climate sequences current development; Ddry9 = Future dry climate sequences current development and future development of 9 GL/year; Ddry12 = Future dry climate sequences current development and future development of 12 GL/year; Ddry15 = Future dry climate sequences current development and future development of 15 GL/year; Dmid9 = Future mid climate sequences current development and future development of 9 GL/year; Dmid12 = Future mid climate sequences current development and future development of 12 GL/year; Dmid15 = Future mid climate sequences current development and future development of 15 GL/year); Dwet9 = Future wet climate sequences current development and future development of 9 GL/year; Dwet12 = Future wet climate sequences current development and future development of 12 GL/year; Dwet15 = Future wet climate sequences current development and future development of 15 GL/year.

(a) (b) (c) (d)

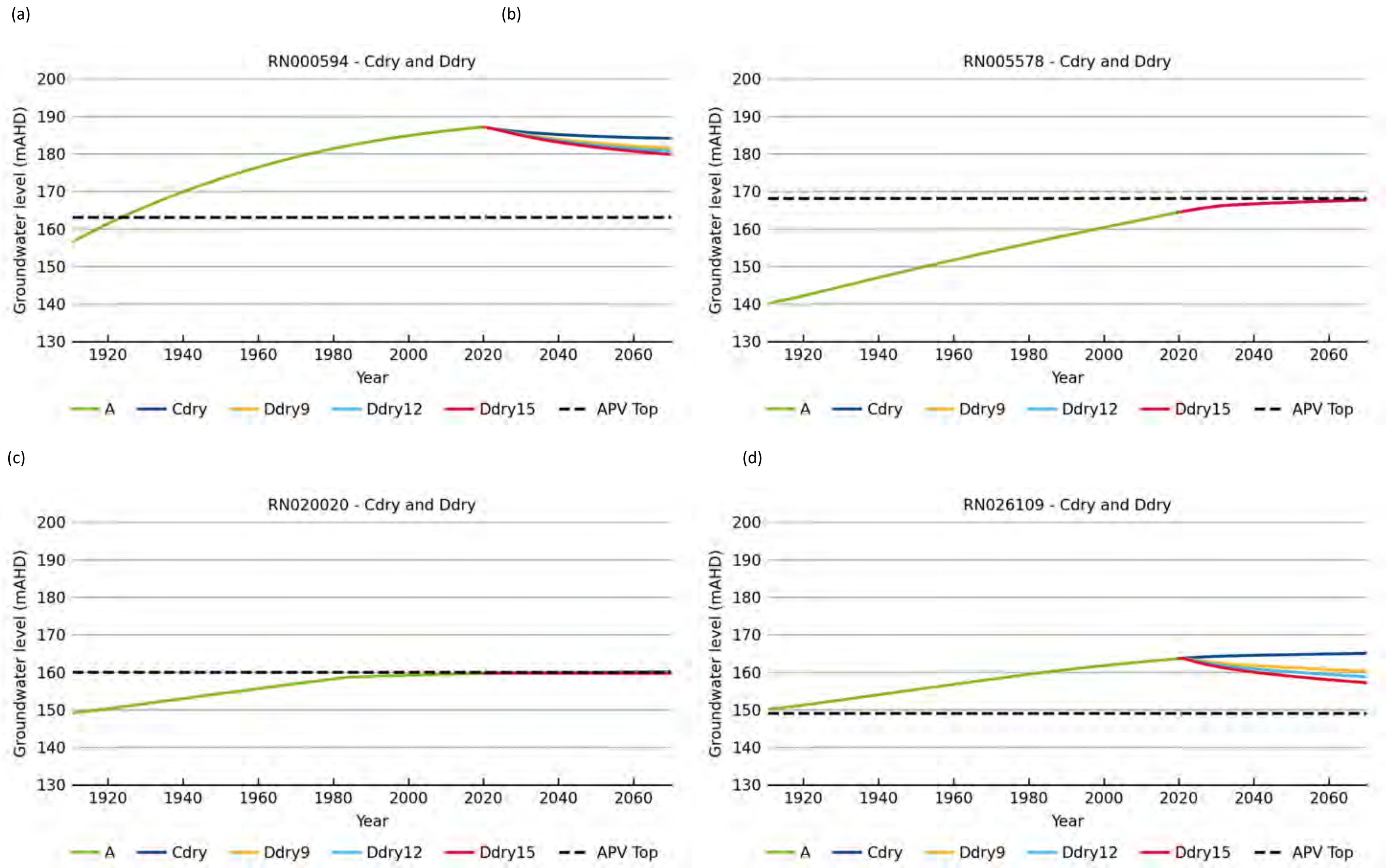

Figure 5-6 Hydrographs of groundwater levels under scenarios A, Cdry, Ddry9, Ddry12 and Ddry15 at sites (a) RN000594, (b) RN005578, (c) RN020020 and (d) RN026109

APV Top = contact between Cambrian Limestone Aquifer and the Antrim Plateau Volcanics

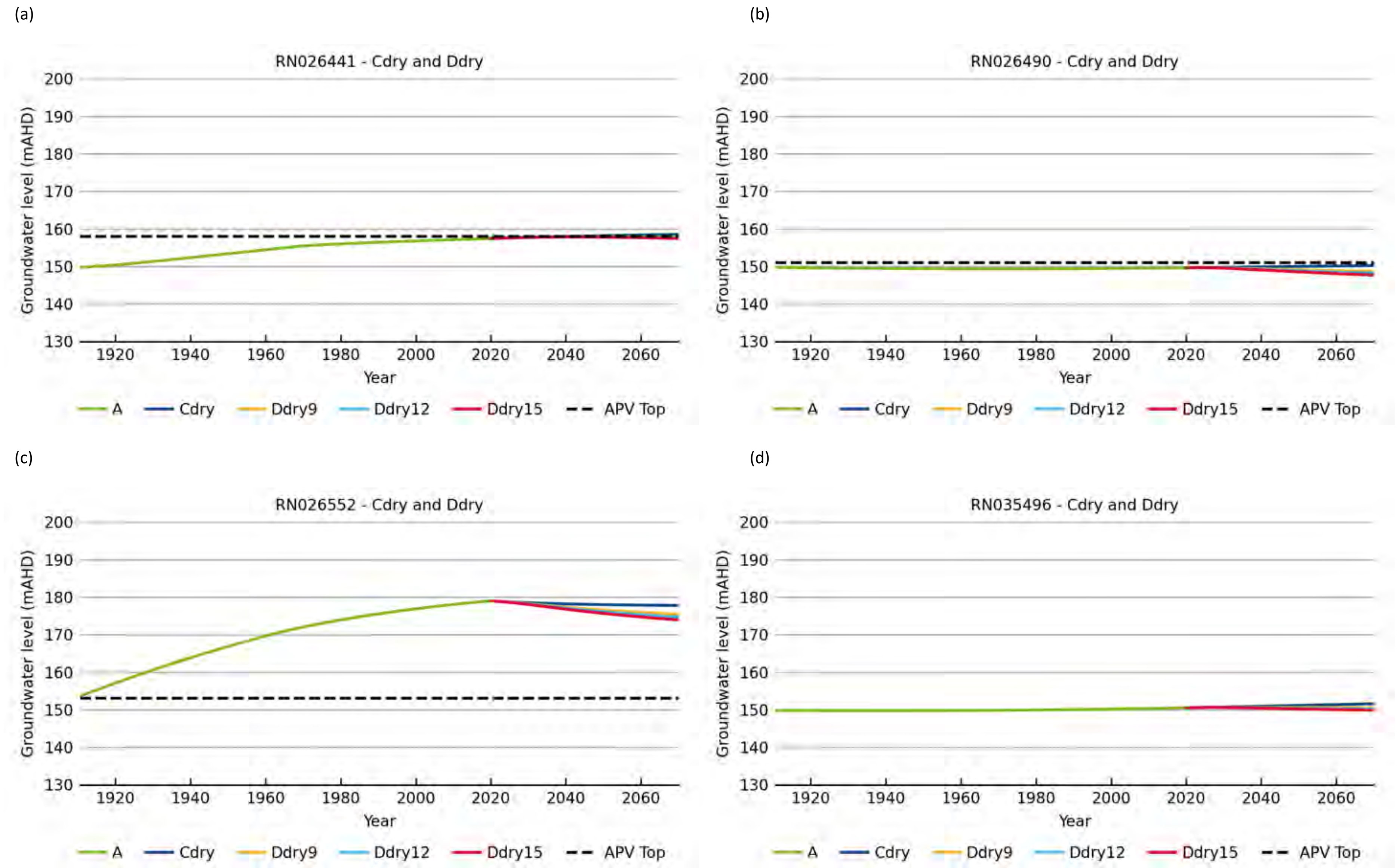

Figure 5-7 Hydrographs of groundwater levels under scenarios A, Cdry, Ddry9, Ddry12 and Ddry15 at sites: (a) RN026441, (b) RN026490, (c) RN026552 and (d) RN035496

APV Top = contact between Cambrian Limestone Aquifer and the Antrim Plateau Volcanics

(a)

(b)

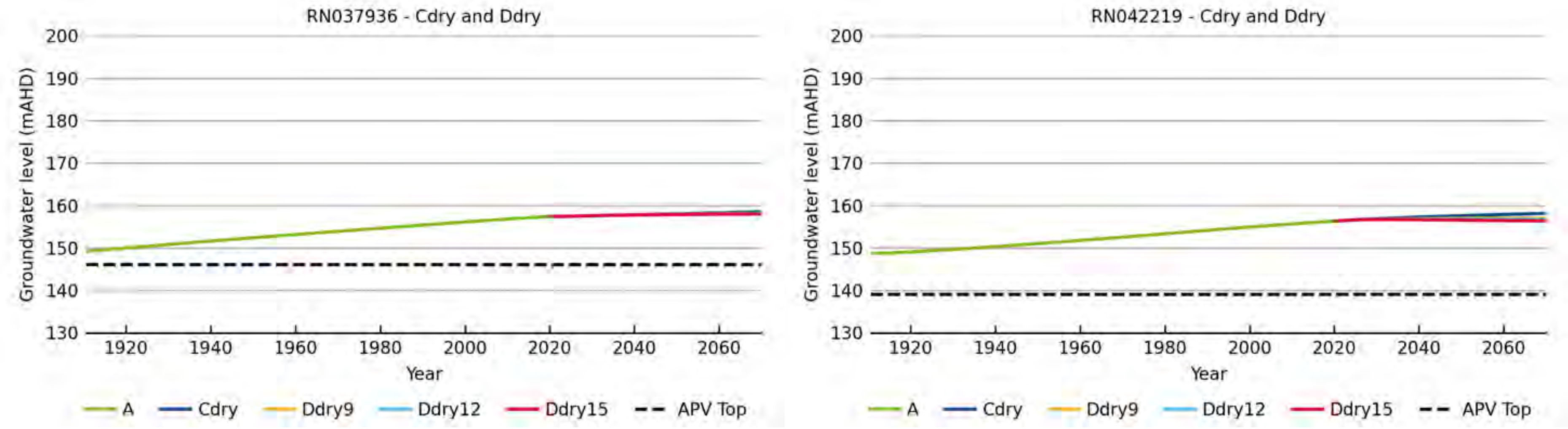

Figure 5-8 Hydrographs of groundwater levels under scenarios A, Cdry, Ddry9, Ddry12 and Ddry15 at sites: (a) RN037936 and (b) RN042219

APV Top = contact between Cambrian Limestone Aquifer and the Antrim Plateau Volcanics

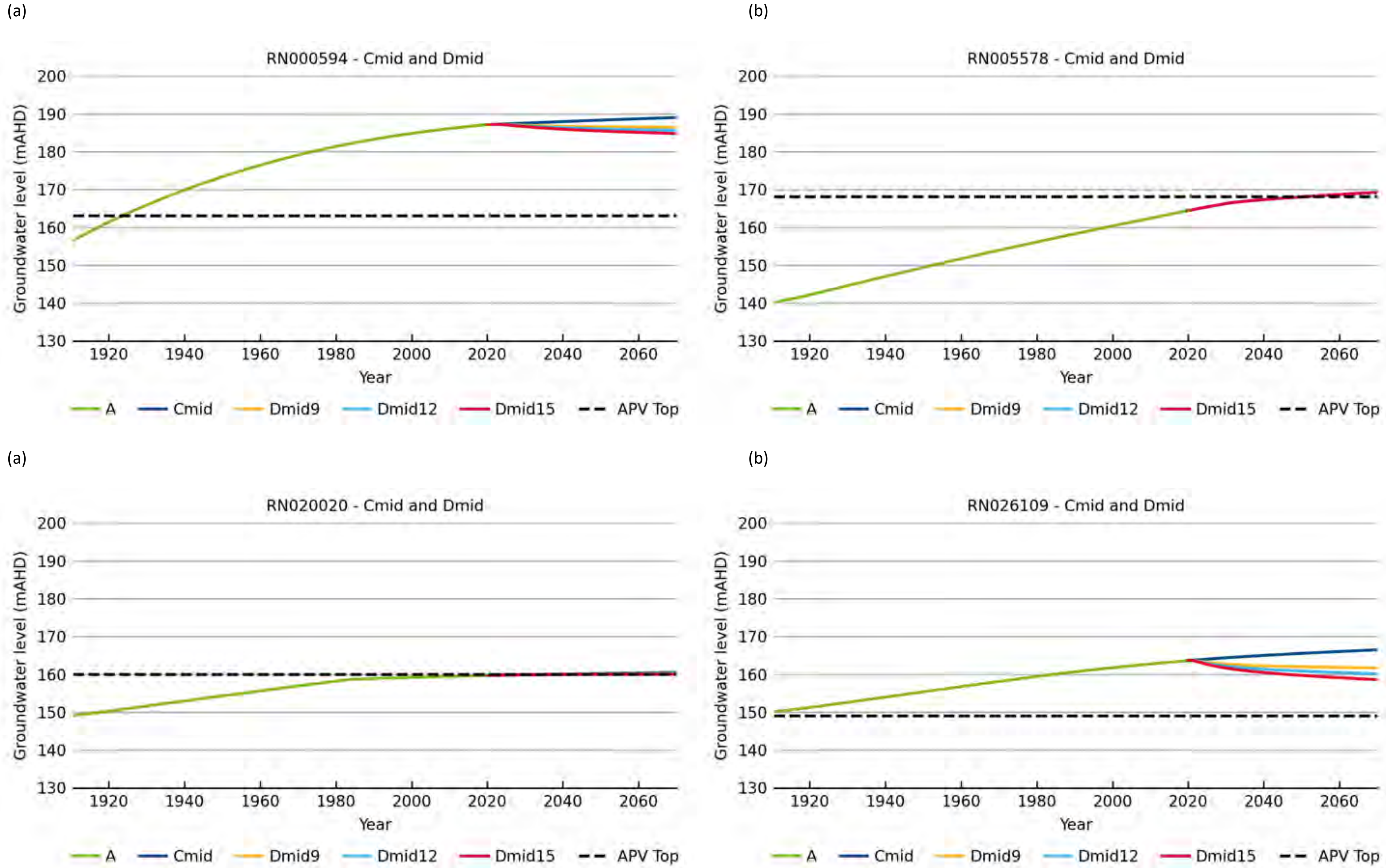

Figure 5-9 Hydrographs of groundwater levels scenarios A, Cmid, Dmid9, Dmid12 and Dmid15 at sites (a) RN000594, (b) RN005578, (c) RN020020 and (d) RN026109

APV Top = contact between Cambrian Limestone Aquifer and the Antrim Plateau Volcanics

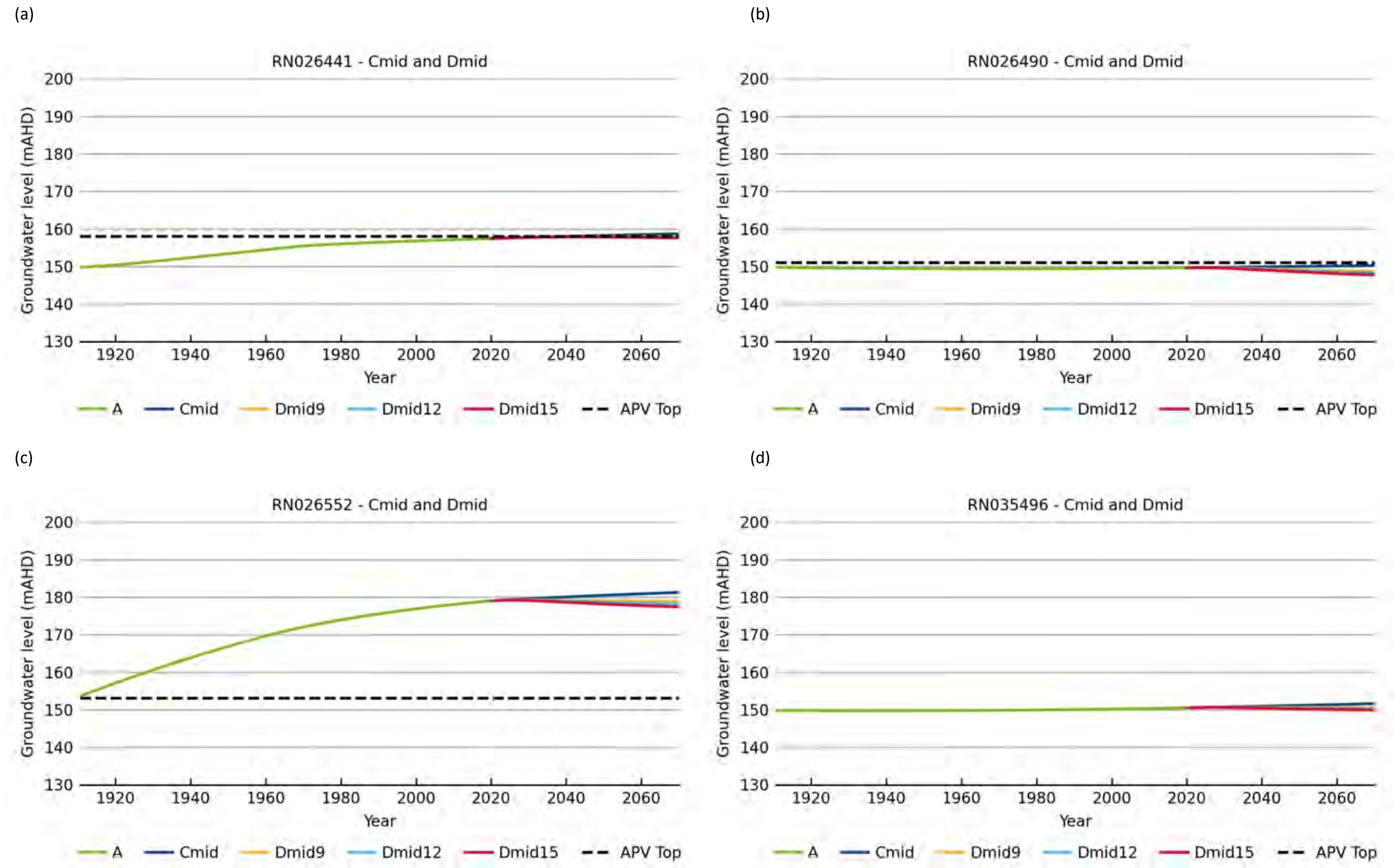

Figure 5-10 Hydrographs of groundwater levels under scenarios A, Cmid, Dmid9, Dmid12 and Dmid15 at sites (a) RN026441, (b) RN026490, (c) RN026552 and (d) RN035496

APV Top = contact between Cambrian Limestone Aquifer and the Antrim Plateau Volcanics

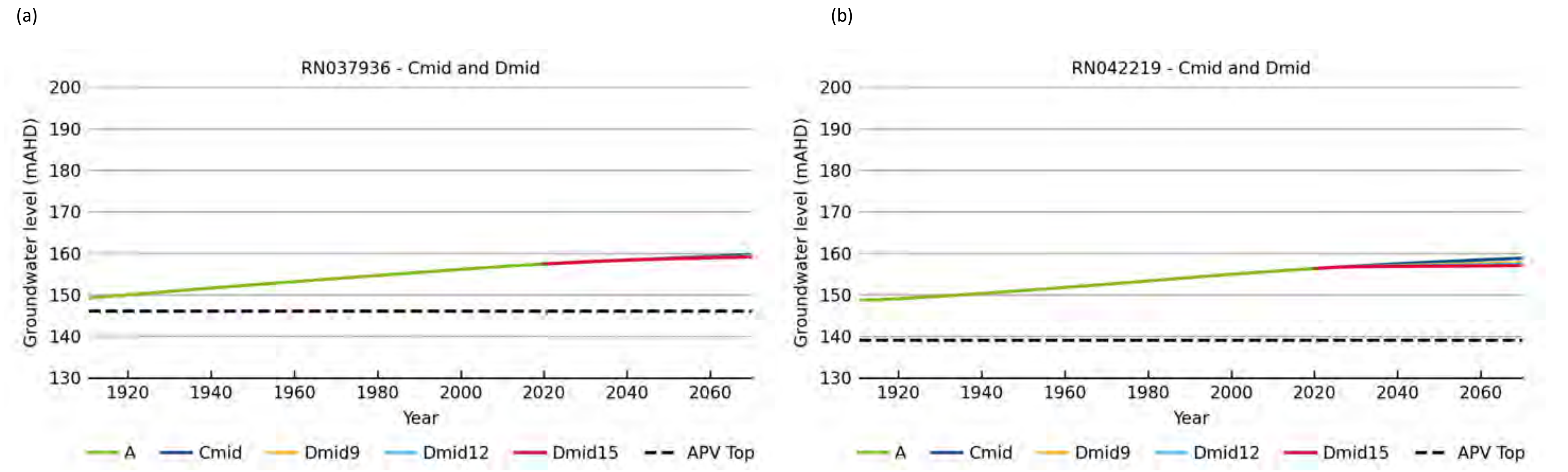

Figure 5-11 Hydrographs of groundwater levels under scenarios A, Cmid, Dmid9, Dmid12 and Dmid15 at sites (a) RN037936 and (b) RN042219

APV Top = contact between Cambrian Limestone Aquifer and the Antrim Plateau Volcanics

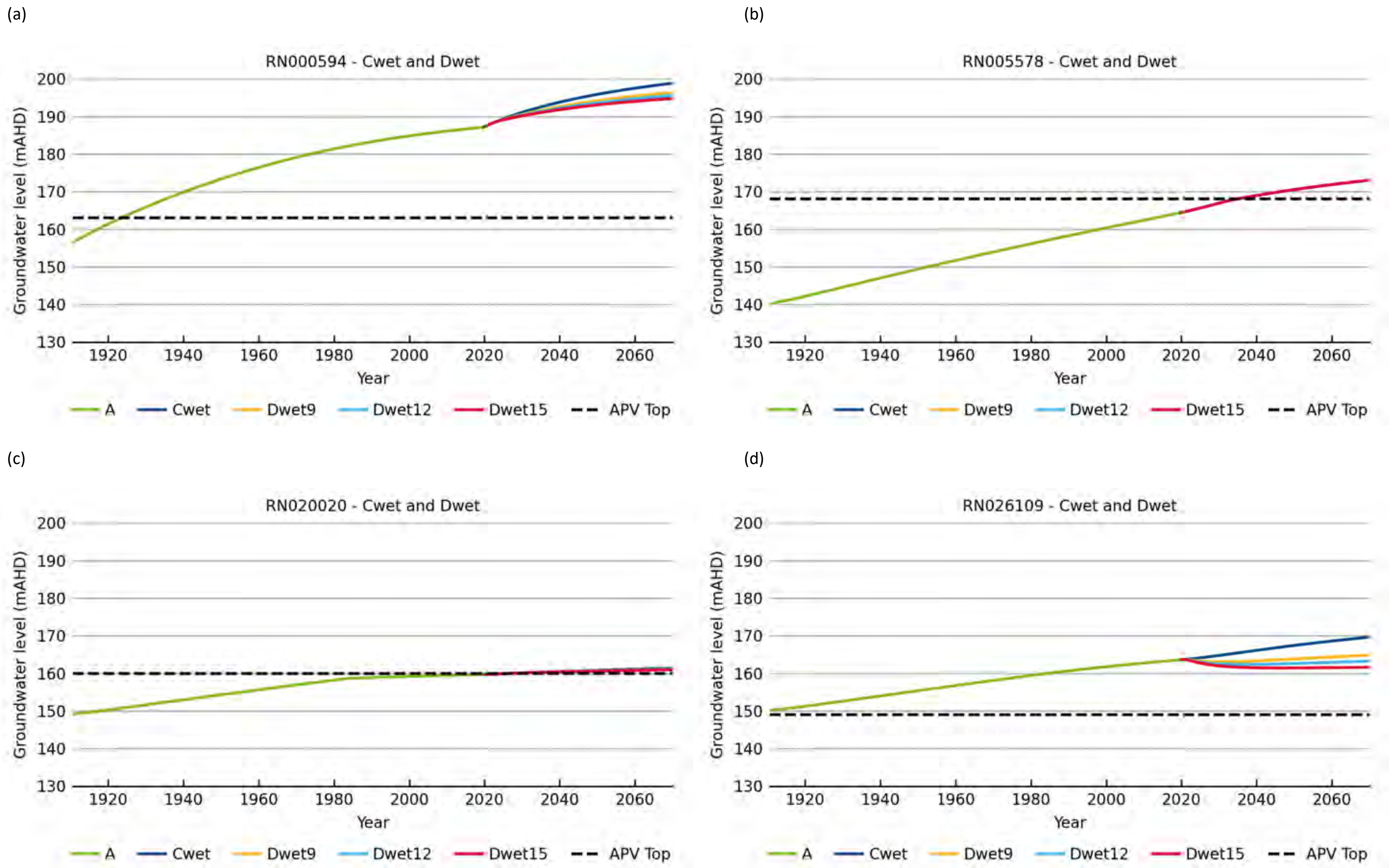

Figure 5-12 Hydrographs of groundwater levels under scenarios A, Cwet, Dwet9, Dwet12 and Dwet15 at sites (a) RN000594, (b) RN005578, (c) RN020020 and (d) RN026109

APV Top = contact between Cambrian Limestone Aquifer and the Antrim Plateau Volcanics

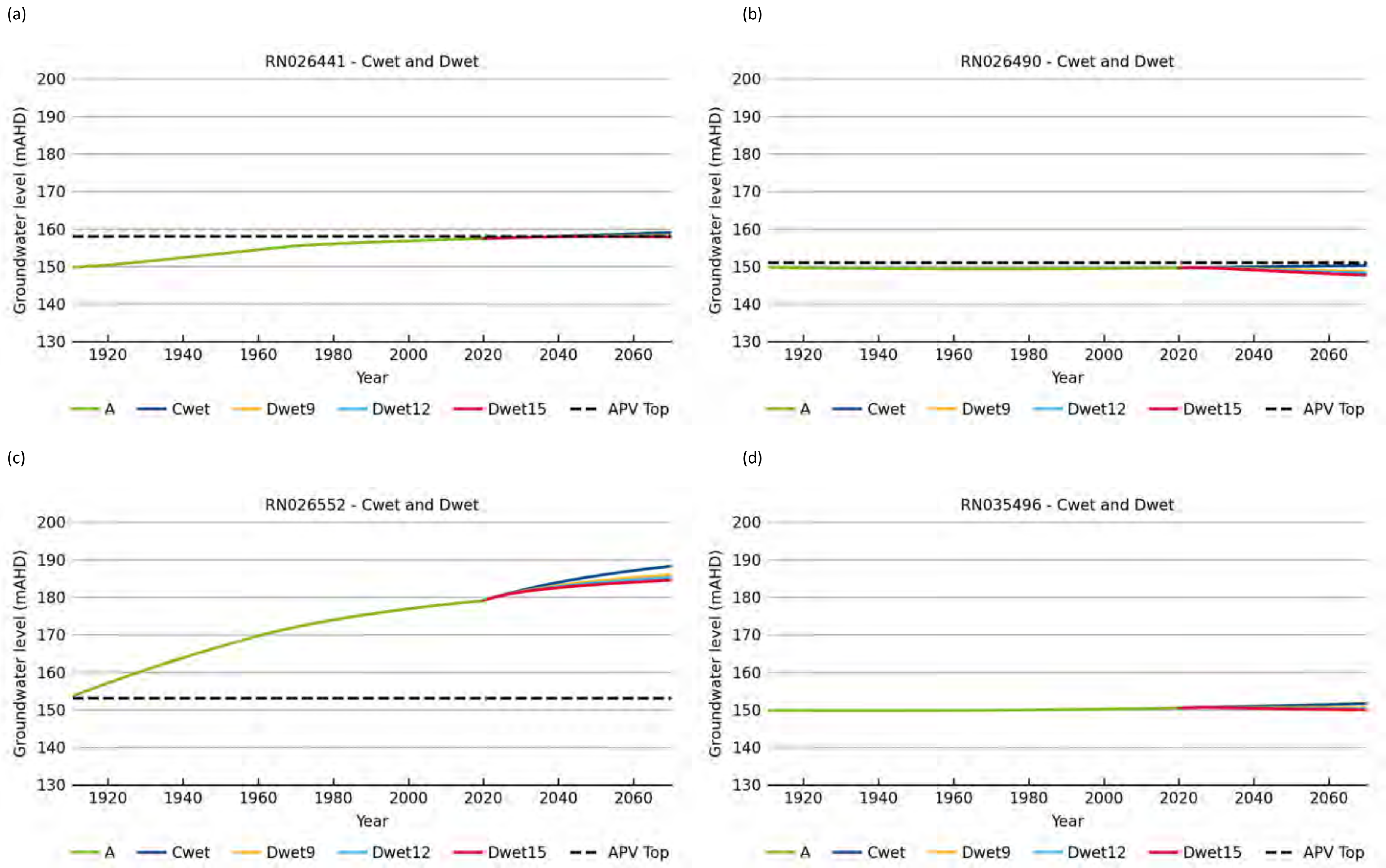

Figure 5-13 Hydrographs of groundwater levels under scenarios A, Cwet, Dwet9, Dwet12 and Dwet15 at sites (a) RN026441, (b) RN026490, (c) RN026552 and (d) RN035496

APV Top = contact between Cambrian Limestone Aquifer and the Antrim Plateau Volcanics

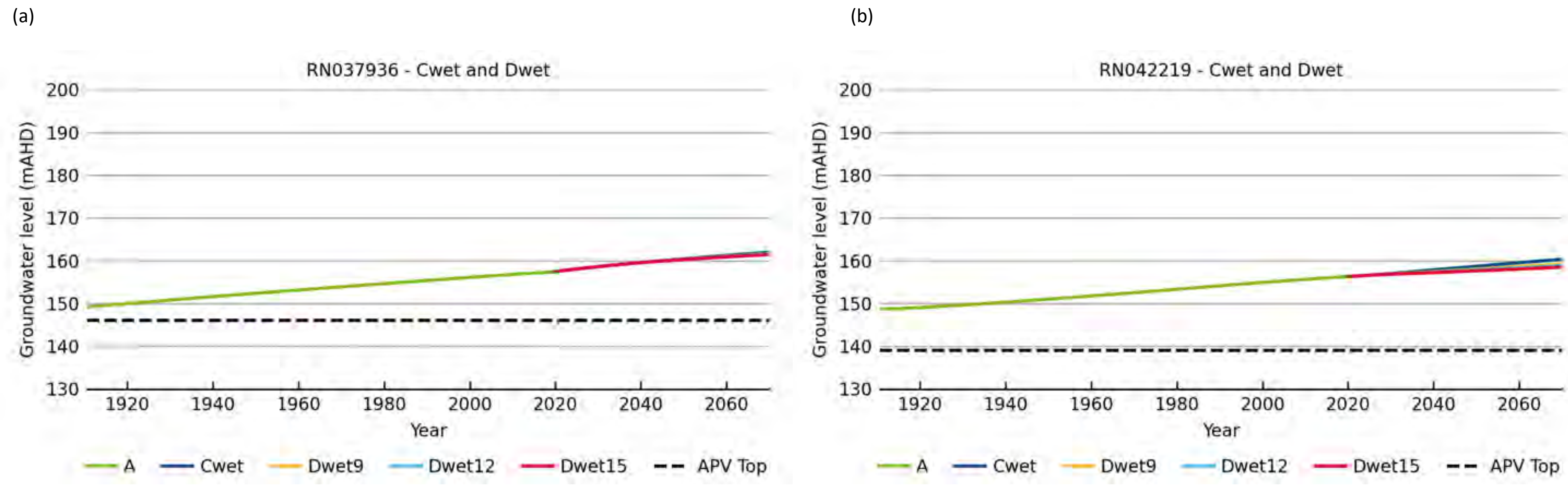

Figure 5-14 Hydrographs of groundwater levels under scenarios A, Cwet, Dwet9, Dwet12 and Dwet15 at sites (a) RN037936 and (b) RN042219

APV Top = contact between Cambrian Limestone Aquifer and the Antrim Plateau Volcanics

5.2.3 Groundwater drawdown - Cdry and Ddry scenarios

The drawdown contours on 31 August 2060 under Cdry climate and current groundwater extraction (relative to A) are shown in Figure 5-15a. The drawdown contours at 31 August 2060 under Ddry9, Ddry12 and Ddry15 dry climate and hypothetical future groundwater extraction (relative to A) are shown in Figure 5-15b, Figure 5-15c and Figure 5-15d, respectively.

The drawdown contours at the northern portion of the CLA in the Victoria catchment indicate that there will be virtually no impact beyond the Victoria catchment caused by the hypothetical future developments within the time frame considered.

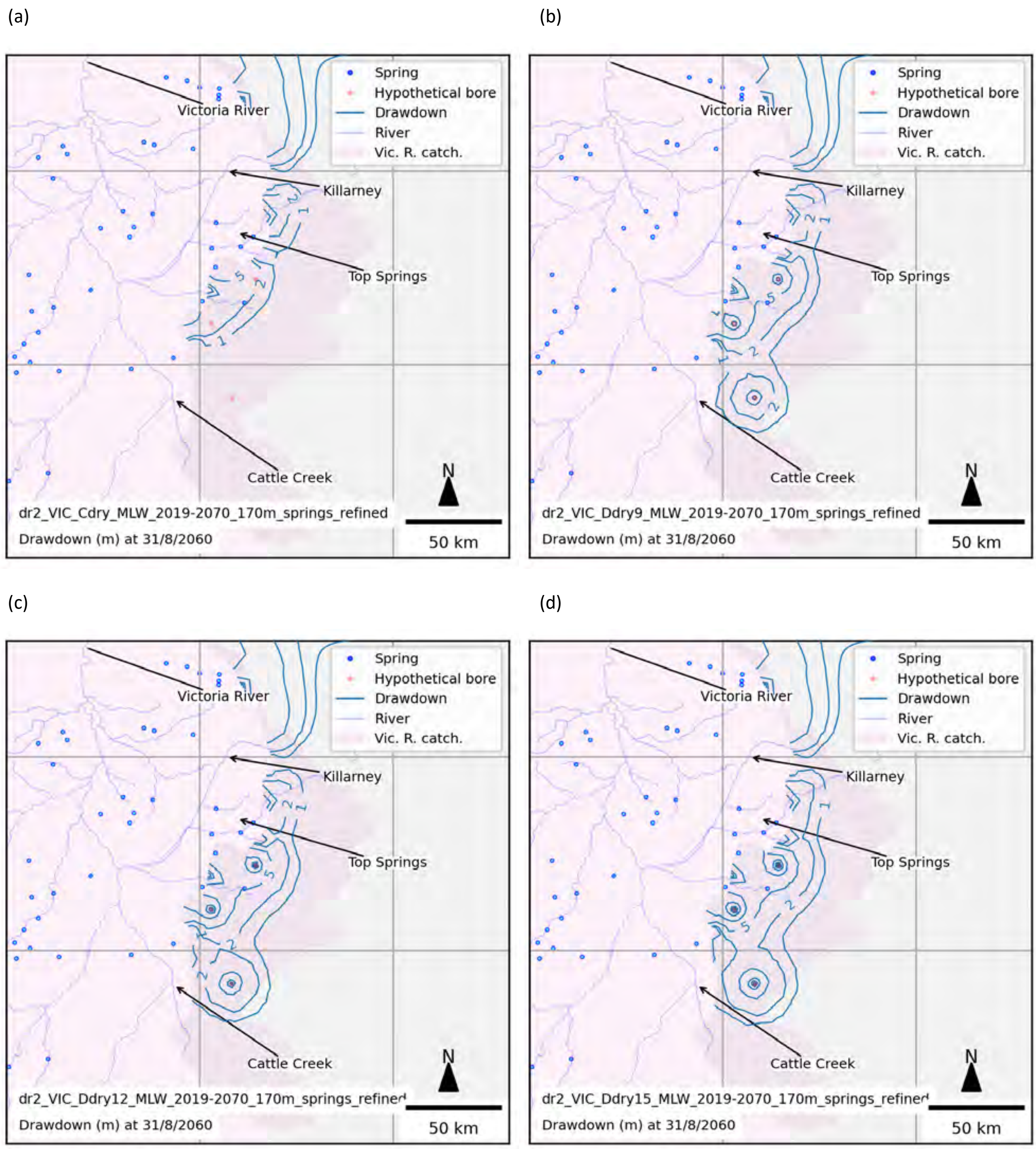

Figure 5-15 Drawdown contours relative to Scenario A under scenarios (a) Cdry, (b) Ddry9, (c) Ddry12 and (d) Ddry15 representative of dry climate conditions at the year 2060

5.2.4 Groundwater drawdown - Cmid and Dmid scenarios

The drawdown contours at 31 August 2060 under Cmid climate and current groundwater extraction (relative to A) are shown in Figure 5-16a. The drawdown contours at 31 August 2060 under Dmid9, Dmid12 and Dmid15 mid climate and hypothetical future groundwater extraction (relative to A) are shown in Figure 5-16b, Figure 5-16c and Figure 5-16d, respectively.

The drawdown contours at the northern portion of the CLA in the Victoria catchment indicate that there will be virtually no impact beyond the Victoria catchment caused by the hypothetical future developments within the time frame considered.

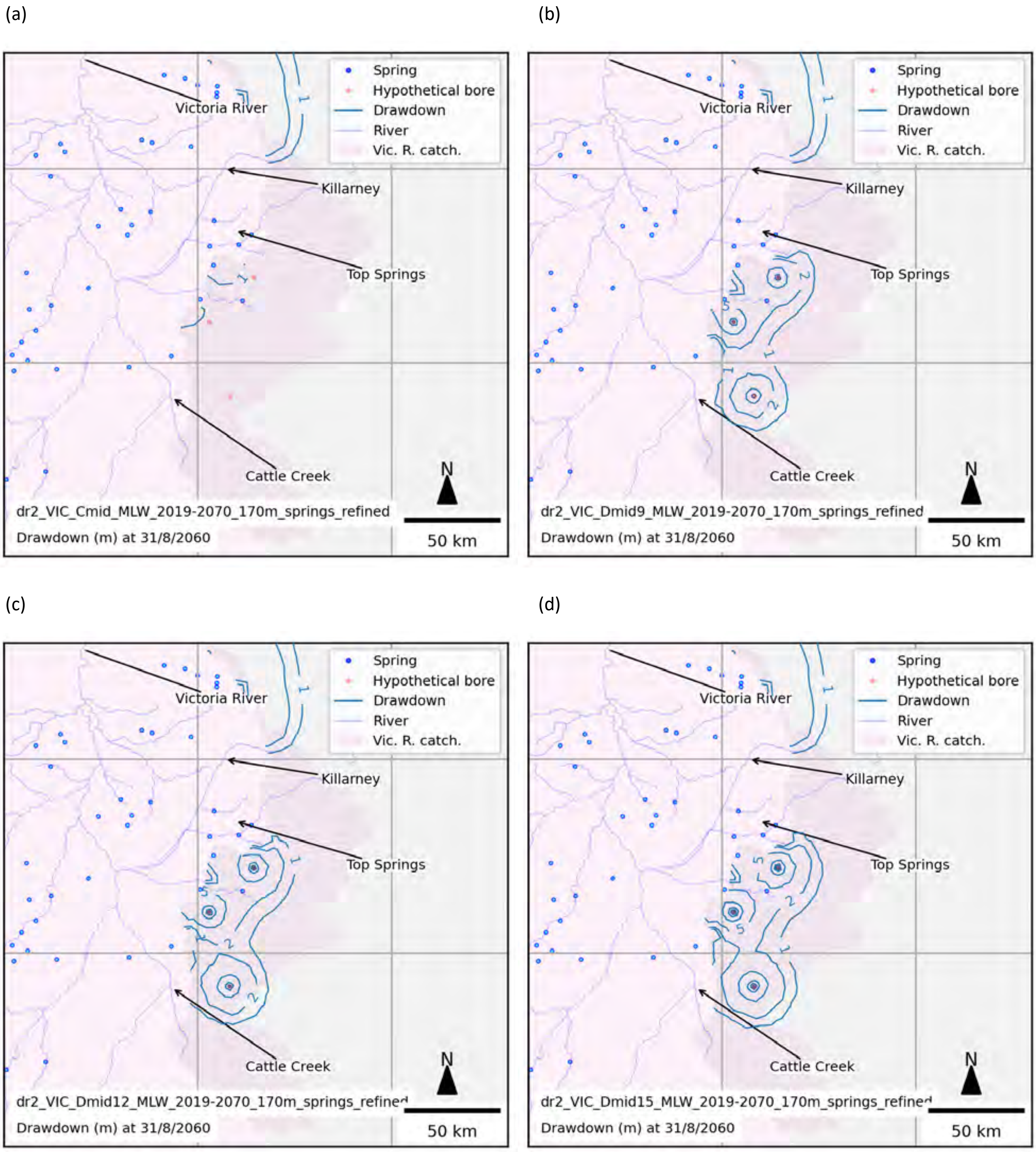

Figure 5-16 Drawdown contours relative to Scenario A under scenarios (a) Cmid, (b) Dmid9, (c) Dmid12 and (d) Dmid15 representative of mid climate conditions at year 2060

5.2.5 Groundwater drawdown - Cwet and Dwet scenarios

The drawdown contours at 31 August 2060 under Cwet climate and current groundwater extraction (relative to A) are shown in Figure 5-17a. The drawdown contours at 31 August 2060 under Dwet9, Dwet12 and Dwet15 wet climate and hypothetical future groundwater extraction (relative to A) are shown in Figure 5-17b, Figure 5-17c and Figure 5-17d, respectively.

The drawdown contours indicate that there will be virtually no impact beyond the Victoria catchment due to the hypothetical future developments within the time frame considered.

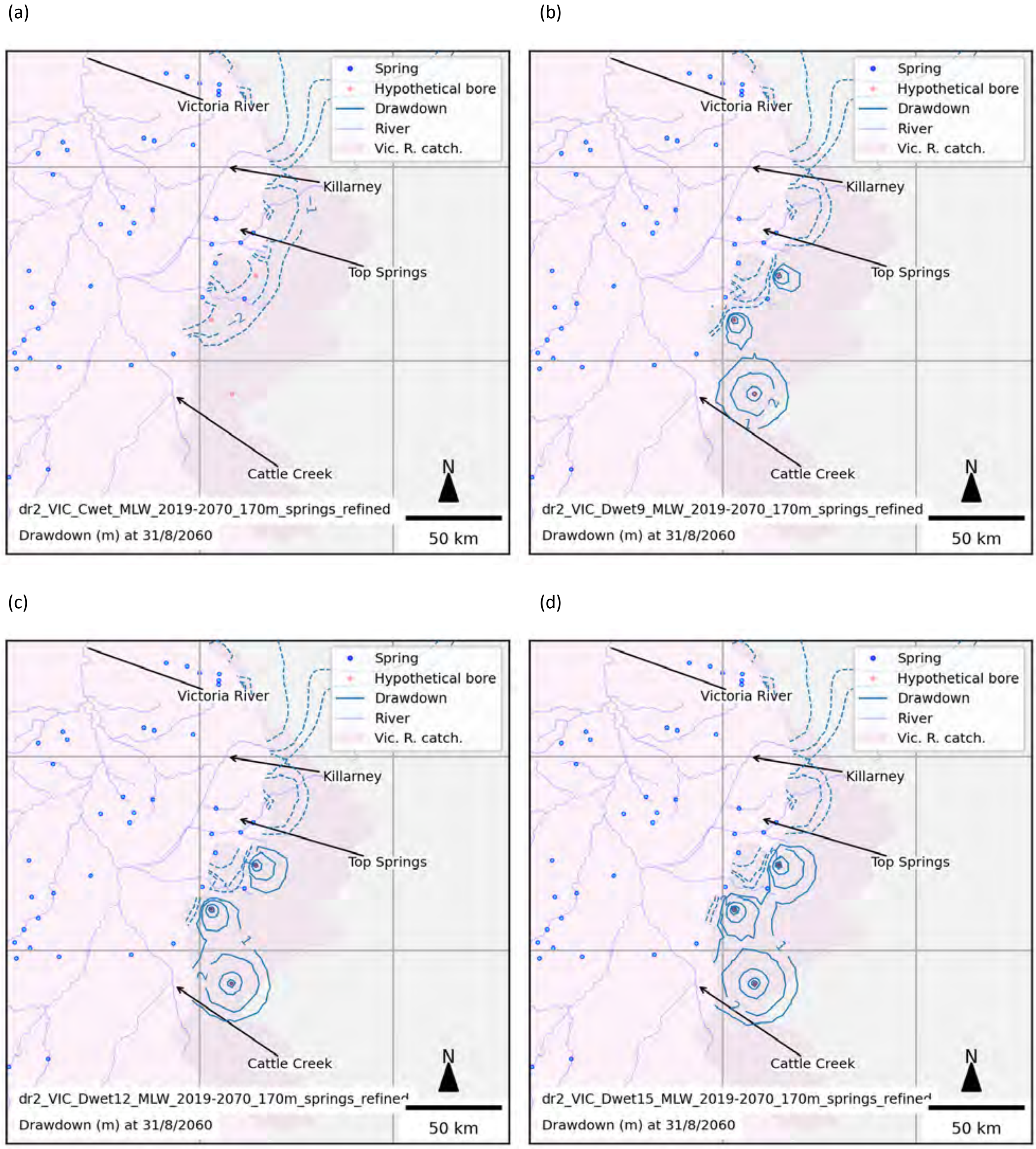

Figure 5-17 Drawdown contours relative to Scenario A under scenarios (a) Cwet, (b) Dwet9, (c) Dwet12 and (d) Dwet15 representative of wet climate conditions at the year 2060

Dash contours indicate negative drawdown or an increase in groundwater levels relative to A.

5.2.6 Groundwater discharge

This section presents the simulated groundwater discharge (springs and evapotranspiration) under scenarios C and D.

The results of this analysis are summarised in Table 5-10, which shows the mean groundwater discharge for the ten-year period (2055 to 2065). Each row corresponds to a specific scenario, and the columns represent the mean groundwater discharge and the percentage change from Scenario A.

The mean groundwater discharge at the springs under Scenario C highlights the effects of future climate alone while under Scenario D it highlights the effects of future climate plus increased extraction.

Under the C scenarios (Cdry, Cmid, Cwet), the mean groundwater discharge to springs ranges from 7.3 GL/year in dry conditions to 15.8 GL/year in wet conditions. This indicates a significant variability in discharge based on climate conditions.

Under the D scenarios (Ddry9, Dmid9, Dwet9, Ddry12, Dmid12, Dwet12, Ddry15, Dmid15, Dwet15), the discharge varies more widely, with values as low as 5.5 GL/year in Ddry15 and as high as 14.5 GL/year in Dwet9. This range demonstrates the compounded effect of increased groundwater extraction and climate variations.

The percentage change from Scenario A indicates that both scenarios C and D generally show decreased discharge in dry and mid conditions, but increased discharge in wet conditions. For example, Cdry shows a 34% decrease relative to Scenario A while Cwet shows a 42% increase.

The groundwater discharge for the C and D scenarios under dry, mid and wet climate conditions are presented in Figure 5-18, Figure 5-19 and Figure 5-20 respectively. The plots reflect the results summarised in Table 5-10.

Table 5-10 Mean groundwater discharge (springs and evapotranspiration) in the Victoria catchment portion of the Cambrian Limestone Aquifer under scenarios C and D

SCENARIO	MEAN GROUNDWATER DISCHARGE (GL/y)	% CHANGE FROM SCENARIO A
A	11.1	na†
Cdry	7.3	−34
Cmid	9.8	−12
Cwet	15.8	+42
Ddry9	6.2	−44
Dmid9	8.6	−22
Dwet9	14.5	+30
Ddry12	5.8	−48
Dmid12	8.3	−26
Dwet12	14.1	+26
Ddry15	5.5	−51
Dmid15	7.9	−29
Dwet15	13.6	+23

Scenarios: A = Historical climate and current development; Cdry = Future dry climate sequences current development; Cmid = Future mid climate sequences current development; Cwet = Future wet climate sequences current development; Ddry9 = Future dry climate sequences current development and future development of 9 GL/year; Ddry12 = Future dry climate sequences current development and future development of 12 GL/year; Ddry15 = Future dry climate sequences current development and future development of 15 GL/year; Dmid9 = Future mid climate sequences current development and future development of 9 GL/year; Dmid12 = Future mid climate sequences current development and future development of 12 GL/year; Dmid15 = Future mid climate sequences current development and future development of 15 GL/year); Dwet9 = Future wet climate sequences current development and future development of 9 GL/year; Dwet12 = Future wet climate sequences current development and future development of 12 GL/year; Dwet15 = Future wet climate sequences current development and future development of 15 GL/year.
†na = not applicable.

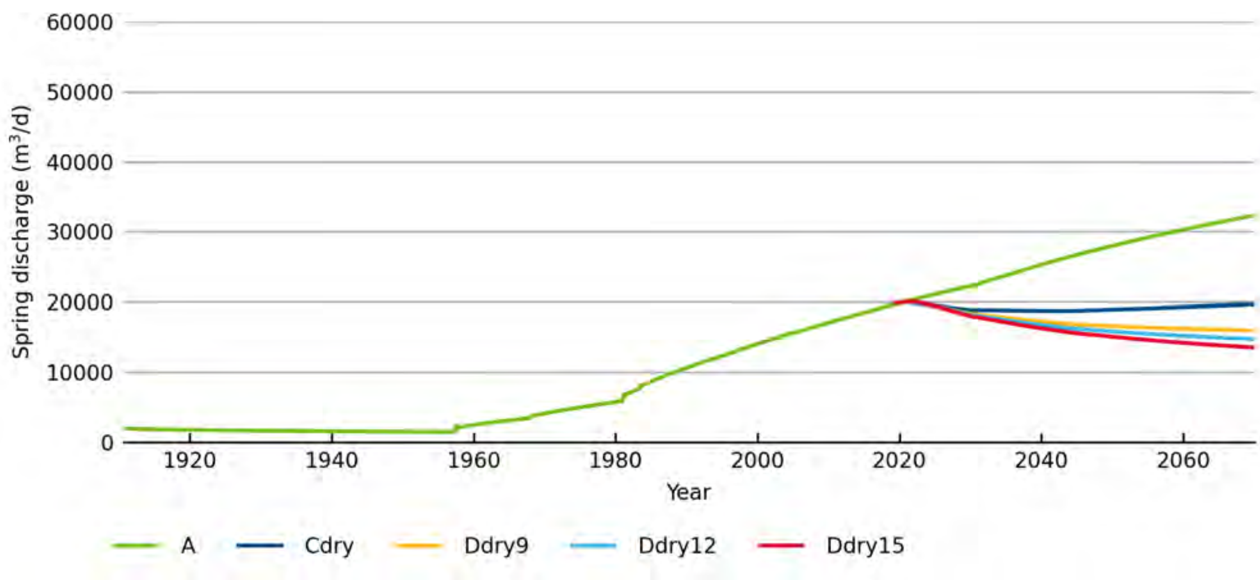

Figure 5-18 Groundwater discharge to springs and evapotranspiration under scenarios A, Cdry, Ddry9, Ddry12 and Ddry15

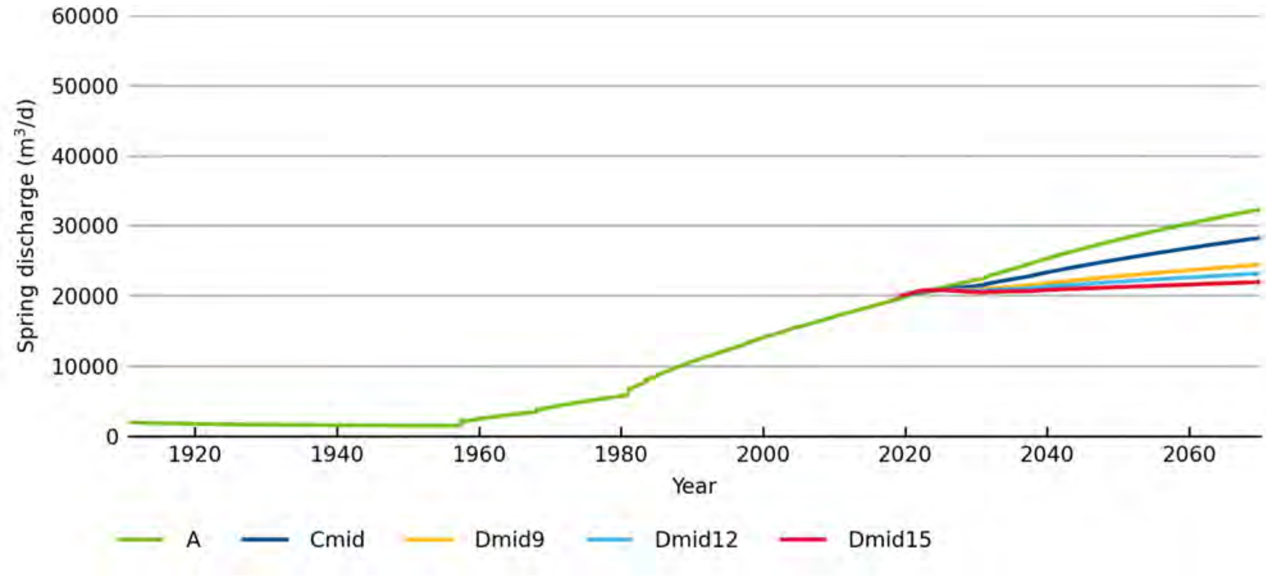

Figure 5-19 Groundwater discharge to springs and evapotranspiration under scenarios A, Cmid, Dmid9, Dmid12 and Dmid15

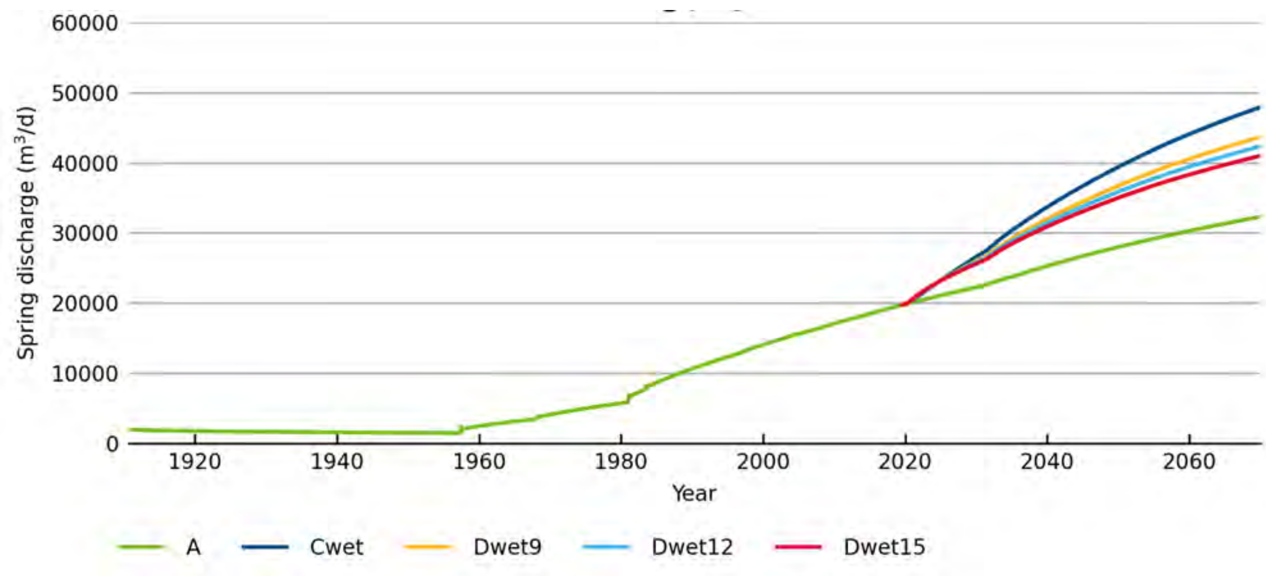

Figure 5-20 Groundwater discharge to springs and evapotranspiration under scenarios A, Cwet, Dwet9, Dwet12 and Dwet15

6 Discussion

6.1 Projected future conditions

The effects of the climate and groundwater development under the representative future conditions on the availability of groundwater in the CLA within the Victoria catchment are discussed in the following subsections.

6.2 Groundwater balances

The variation in the major components of the groundwater budget are presented for the Victoria catchment in Figure 6-1, the Wiso Water Management Zone (WWMZ) in Figure 6-2 and the Flora Tindall Water Management Zone (FTWMZ) in Figure 6-3.

Recharge (green) shows the volume of diffuse recharge for each scenario. It is highest under the Cwet and Dwet scenarios and lowest under the Cdry and Ddry scenarios.

Change in storage (dark blue) indicates the net change in storage, with values less than under Scenario A indicating a reduction in storage. The most significant increases are observed in the Cwet and Dwet scenarios.

Flow In / Out (yellow) represents the net flow in or out of the reporting area, with negative values indicating outflow. The outflows are relatively stable across scenarios, with some minor variations.

To springs (pale blue) shows the volume of water discharged to springs, or in the case of the FTWMZ, to the Flora River. It is highest in the Cwet and Dwet scenarios and lowest in the Cdry and Ddry scenarios, showing the impact of climate conditions on spring discharge.

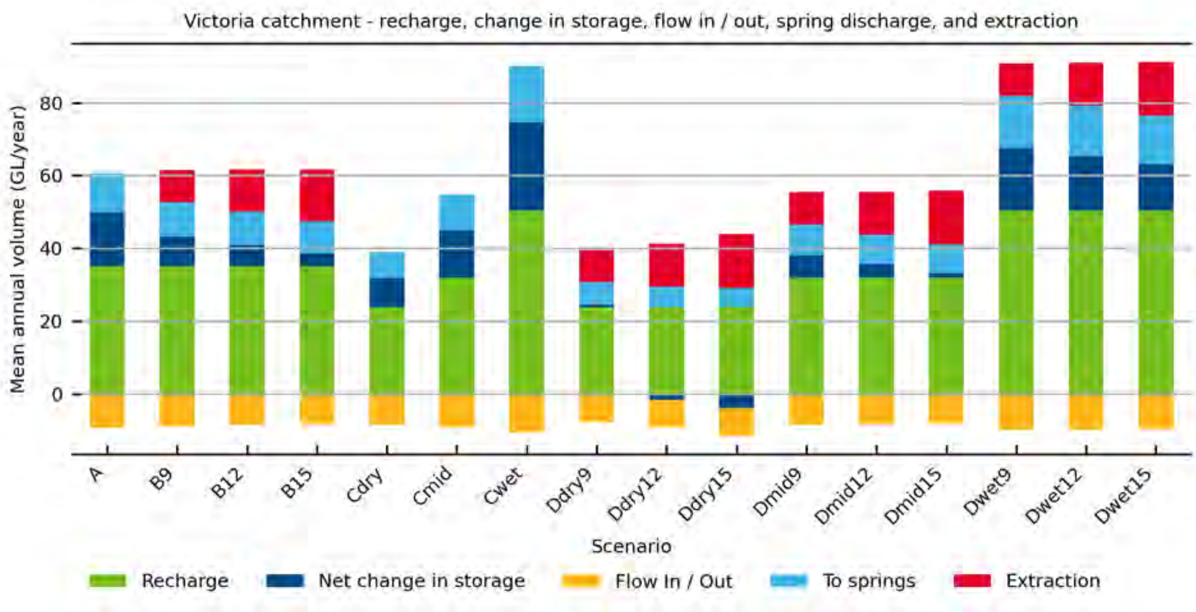

Figure 6-1 Main components of the mean annual water balance for the Victoria catchment representative of 2060 conditions (2055 to 2065)

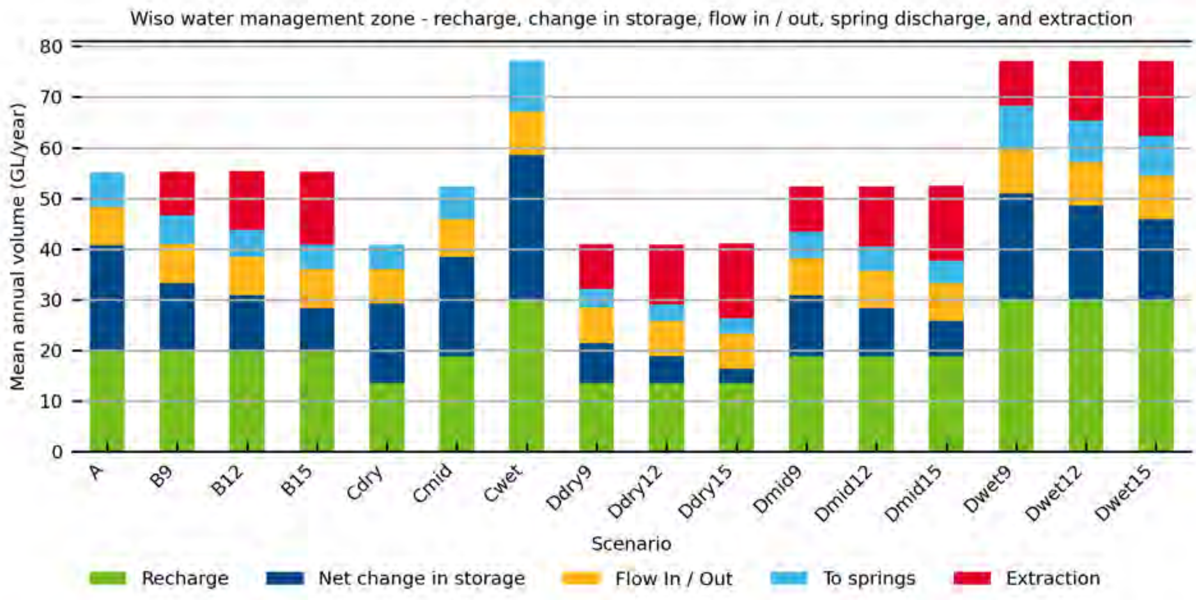

Figure 6-2 Main components of the mean annual water balance for the Wiso Water Management Zone representative of 2060 conditions (2055 to 2065)

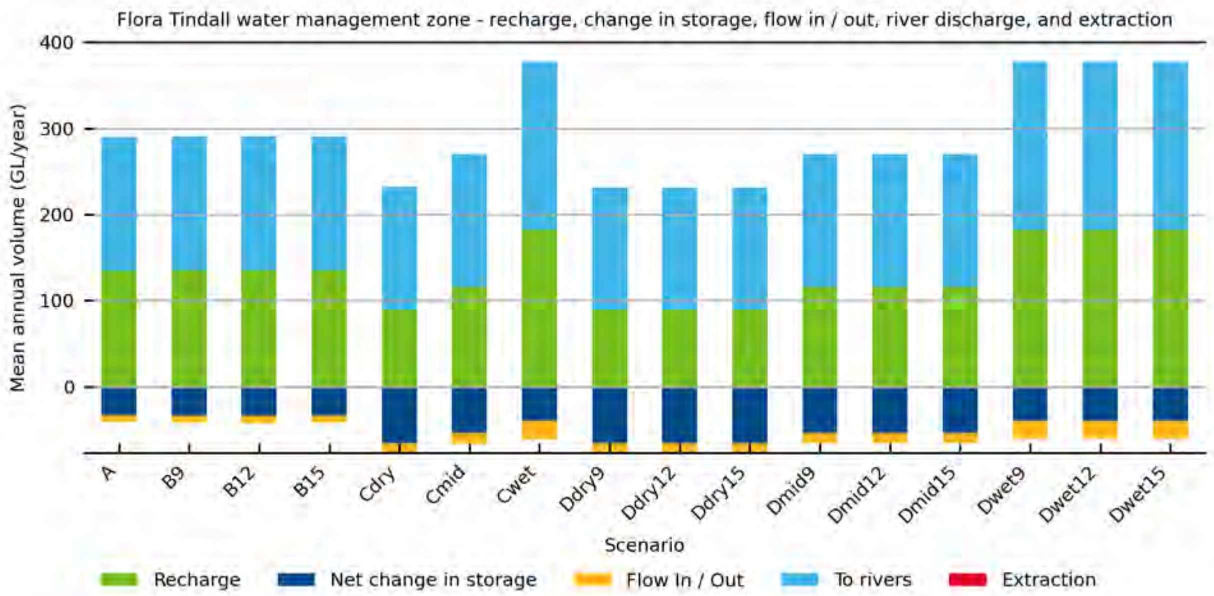

Figure 6-3 Main components of the mean annual water balance for the Flora Tindall Water Management Zone representative of 2060 conditions (2055 to 2065)

6.2.1 Scenarios A and B representative (2060) conditions

The decreasing changes to the discharge to springs for the Victoria catchment and WWMZ mean that the groundwater extraction is intercepting groundwater that would otherwise be available for discharge to the springs along the margin of the CLA.

The changes in groundwater spring discharge for the three water balance reporting areas under Scenario B relative to Scenario A are:

- Victoria catchment: B9 = −11%, B12 = −14%, B15 = −18%
- WWMZ: B9 = −18%, B12 = −22%, B15 = −28%
- FTWMZ: B9 = 0%, B12 = 0%, B15 = 0%.

The changes in the groundwater inflows/outflows from the three reporting areas under Scenario B relative to Scenario A are:

- Victoria catchment: B9 = −8%, B12 = −10%, B15 = −12% (i.e. groundwater outflows decrease because groundwater extraction captures groundwater)
- WWMZ): B9 = +2%, B12 = +2%, B15 = +3% (i.e. groundwater inflows increase because groundwater extraction induces groundwater flow into the water management zone)
- FTWMZ: B9 = +7%, B12 = +3%, B15 = +5% (i.e. groundwater outflows increase, although the changes are less than 5% of the inflow/outflow).

The water balance results indicate a decrease in the volume of water in the storage for the Victoria catchment and WWMZ, which mean that the groundwater extraction is intercepting groundwater that would otherwise be in storage. The changes in the net storage of groundwater in the three reporting areas under Scenario B relative to Scenario A are:

- Victoria catchment: B9 = −46%, B12 = −62%, B15 = −77% (i.e. groundwater is released from storage and net storage decreases)
- WWMZ: B9 = −36%, B12 = −48%, B15 = −60% (i.e. groundwater is released from storage and net storage decreases)
- FTWMZ: B9 = +1%, B12 = +2%, B15 = +2% (i.e. groundwater is captured into storage, although the changes are less than 0.1% of the storage volumes reported).

6.2.2 Scenarios C and D representative (2060) conditions

The influence of future climate compared to additional groundwater extraction can be observed by comparing the water balance components under scenarios C and D.

6.3 Groundwater levels

The mean groundwater levels representative of future 2060 conditions at the reporting sites for each scenario are presented in Figure 6-4 and Figure 6-5. The plots show trends associated with climate, pumped volumes and location relative to pumping centres. Generally, the groundwater levels show much a greater response to changes in climate than to pumping.

Changes in the mean groundwater levels are also reflected in the changes to storage reported in the water balance. Wet climate scenarios show water levels and storage greater than under Scenario A, while all other scenarios showing reduced water levels and storage relative to Scenario A (see Figure 6-1).

Wet scenarios consistently show higher water levels, followed by mid and then dry scenarios. Climate has a significant impact on water levels, with wetter climates maintaining higher levels. Increased development reduces water levels (see Table 5-9), although not to the same extent as climate.

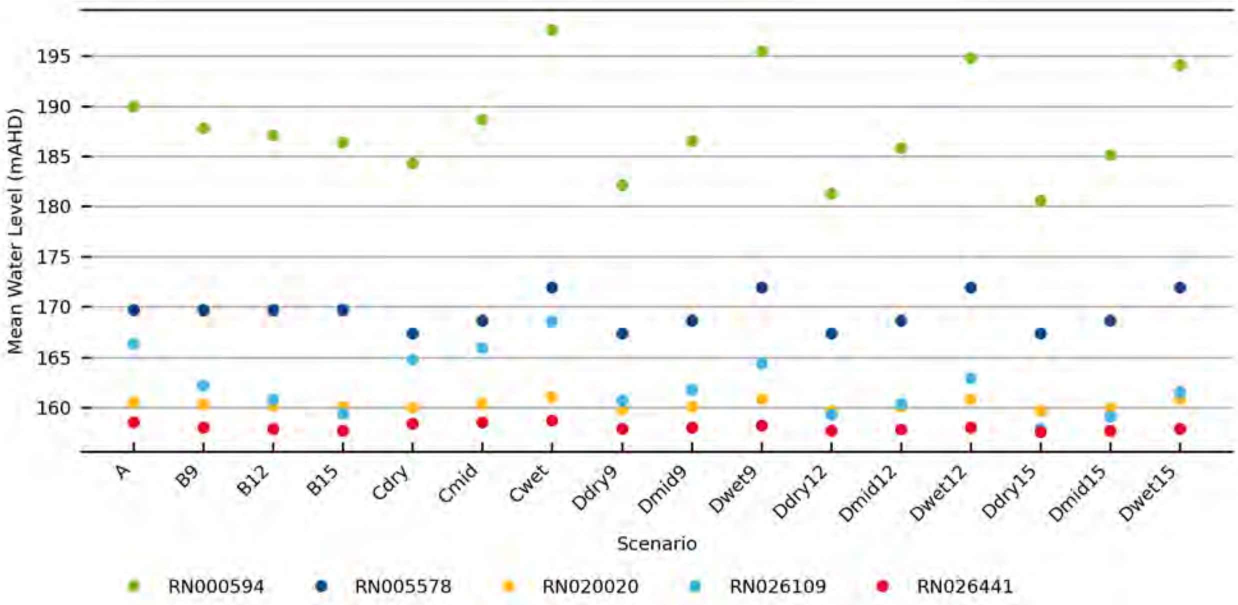

Figure 6-4 Mean groundwater levels for the period from 2055 to 2065 under all scenarios for sites RN000594, RN005578, RN020020, RN026109 and RN026441

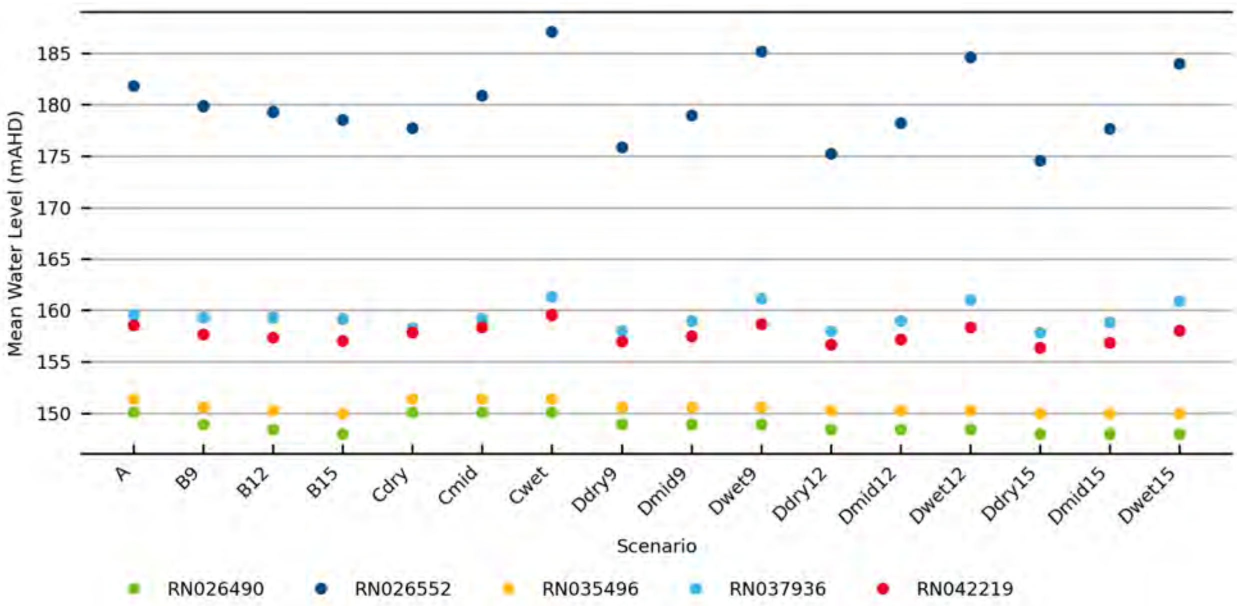

Figure 6-5 Mean groundwater level for the period from 2055 to 2065 under all scenarios for sites RN026490, RN026552, RN035496, RN037936 and RN042219

6.3.1 Scenarios A and B representative (2060) conditions

The patterns observed in the drawdown contours are reflected in the groundwater levels under each scenario, but the effects of climate are also evident. Reporting sites closer to the pumping developments show the greatest reduction in groundwater levels.

RN019012 and RN028082 are closest to the pumping bores in the current pumping scenarios A and C, whereas RN028082 and RN029013 are centred on the future hypothetical pumping developments in scenarios B and D.

The differences or ‘drawdown’ between the mean groundwater level under Scenario B relative to Scenario A are presented in Table 6-1. The difference in mean groundwater levels from the Scenario A baseline results reflect the gain or loss of groundwater from storage over this period associated with Scenario B.

Comparing scenarios A and B shows the effect of groundwater pumping on the drawdown. Drawdown is between −4.3 and 0 m under Scenario B9, between −5.7 and 0 m under Scenario B12, and between −7.0 and 0 m under Scenario B15. That is, groundwater levels are generally lower under Scenario B than under Scenario A.

Table 6-1 Difference or ‘drawdown’ in mean groundwater levels representative of 2060 conditions (2055 to 2065) for ten Cambrian Limestone Aquifer reporting sites under Scenario B relative to Scenario A (m)

SCENARIO	RN000594	RN005578	RN020020	RN026109	RN026490	RN035496	RN026441	RN026552	RN037936	RN042219
B9	−2.2†	0.0	−0.2	−4.3	−1.3	−0.8	−0.5	−1.9	−0.2	−0.9
B12	−2.9	0.0	−0.3	−5.7	−1.7	−1.1	−0.7	−2.5	−0.3	−1.2
B15	−3.6	0.0	−0.3	−7.1	−2.1	−1.4	−0.8	−3.2	−0.4	−1.5

Scenarios: A = Historical climate and current development; B9 = Historical climate sequences with current development and additional future development of 9 GL/year; B12 = Historical climate sequences with current development and additional future development of 12 GL/year; B15 = Historical climate sequences with current development and additional future development of 15 GL/year.

†Negative values indicate mean groundwater levels are less than under Scenario A and positive values indicate mean groundwater levels are greater than under Scenario A.

6.3.2 Scenarios C and D representative (2060) conditions

The differences or ‘drawdown’ between the mean groundwater levels representative of 2060 conditions under scenarios C and D relative to Scenario A are presented in Table 6-2. Groundwater levels show a greater drawdown under the dry and mid future climate scenarios than the historical climate scenarios. Negative drawdown values indicate mean groundwater levels are less than under Scenario A and positive values indicate mean groundwater levels are greater than under Scenario A.

Comparing scenarios A and C shows the effect of climate on the drawdown. Drawdown is between −5.7 and 0 m under Scenario Cdry, between −1.3 and 0 m under Scenario Cmid, and between 0 and +7.6 m under Scenario Cwet (i.e. groundwater levels are generally higher under Scenario Cwet than under Scenario A).

Across almost all reporting sites, the Ddry scenarios result in significant drawdowns compared to Scenario A. The severity of the drawdown increases with the intensity of the scenario, which increases from Ddry9 to Ddry12 to Ddry15. The greatest drawdowns are observed in Ddry15, particularly at sites RN026109 and RN026552.

The Cmid scenarios show slight decreases in groundwater levels at most sites compared to Scenario A, although some sites show no change. Scenario Dmid presents moderate drawdowns compared to Scenario A, with increasing drawdowns as the scenario intensity increases (from Dmid9 to Dmid12 to Dmid15).

Groundwater levels are generally higher under the Dwet scenarios, especially Dwet9 and Dwet12, than under Scenario A. However, the Dwet scenarios also display some drawdowns at certain sites, indicating that increased recharge does not uniformly affect all locations. For instance, RN026490 consistently shows lower levels under Dwet scenarios than under Scenario A.

Drawdowns under Scenario D at all sites except RN026490 and RN035496 are between 0.1 to 5.8 m greater than the drawdowns under Scenario B (see Table 6-1). RN026490 and RN035496 show no change in drawdown from the corresponding hypothetical development scenario, indicating that the difference at these two sites is due to the climatic regime.

Certain sites (e.g., RN026490 and RN035496) show localized stability across various scenarios, particularly in response to changes in the volume extracted by hypothetical development sites. This suggests that these sites are far enough from the extraction points to remain unaffected. It could also indicate the presence of geological or hydrological factors that provide a buffer against such changes.

Table 6-2 Difference or 'drawdown' in mean groundwater levels representative of 2060 conditions (2055 to 2065) for Cambrian Limestone Aquifer reporting sites under scenarios C and D relative to Scenario A (m)

SCENARIO	RN000594	RN005578	RN020020	RN026109	RN026490	RN035496	RN026441	RN026552	RN037936	RN042219
Cdry	−5.7†	−2.3	−0.5	−1.6	0.0	0.0	−0.1	−4.0	−1.3	−0.7
Cmid	−1.3	−1.0	−0.1	−0.4	0.0	0.0	0.0	−0.9	−0.4	−0.2
Cwet	+7.6	+2.2	+0.6	+2.2	0.0	0.0	+0.2	+5.3	+1.7	+1.0
Ddry9	−7.9	−2.3	−0.7	−5.7	−1.2	−0.8	−0.6	−5.9	−1.5	−1.6
Dmid9	−3.5	−1.0	−0.4	−4.6	−1.2	−0.8	−0.5	−2.8	−0.6	−1.1
Dwet9	+5.5	+2.2	+0.4	−2.0	−1.2	−0.8	−0.3	+3.4	+1.5	+0.1
Ddry12	−8.7	−2.3	−0.8	−7.1	−1.7	−1.1	−0.8	−6.5	−1.6	−1.9
Dmid12	−4.2	−1.0	−0.4	−6.0	−1.7	−1.1	−0.7	−3.5	−0.6	−1.4
Dwet12	+4.8	+2.2	+0.3	−3.5	−1.7	−1.1	−0.5	+2.8	+1.4	−0.2
Ddry15	−9.4	−2.3	−0.8	−8.5	−2.1	−1.4	−0.9	−7.2	−1.7	−2.2
Dmid15	−4.9	−1.0	−0.5	−7.3	−2.1	−1.4	−0.8	−4.1	−0.7	−1.7
Dwet15	+4.1	+2.2	+0.3	−4.9	−2.1	−1.4	−0.6	+2.2	+1.3	−0.5

Cdry = Future dry climate sequences current development; Cmid = Future mid climate sequences current development; Cwet = Future wet climate sequences current development; Ddry9 = Future dry climate sequences current development and future development of 9 GL/year; Ddry12 = Future dry climate sequences current development and future development of 12 GL/year; Ddry15 = Future dry climate sequences current development and future development of 15 GL/year; Dmid9 = Future mid climate sequences current development and future development of 9 GL/year; Ddry12 = Future mid climate sequences current development and future development of 12 GL/year; Dmid15 = Future mid climate sequences current development and future development of 15 GL/year); Dwet9 = Future wet climate sequences current development and future development of 9 GL/year; Dwet12 = Future wet climate sequences current development and future development of 12 GL/year; Dwet15 = Future wet climate sequences current development and future development of 15 GL/year.
†Negative values indicate mean groundwater levels are less than under Scenario A and positive values indicate mean groundwater levels are greater than under Scenario A.

6.4 Groundwater drawdown

6.4.1 Scenarios A and B representative (2060) conditions

The drawdown contour plots show the same patterns as the groundwater levels at reporting sites. The total areas showing more than 1 m drawdown under scenarios B9, B12 and B15 relative to Scenario A (consistent with contour values) are summarised in Table 6-3.

6.4.2 Scenarios C and D representative (2060) conditions

The drawdown contour plots under scenarios C and D are similar to the B contour plots. The total areas under scenarios C and D showing more than 1 m drawdown relative to Scenario A (consistent with contour values) are summarised in Table 6-3. The scenarios showing the greatest area where drawdown is more than 1 m are under the dry climate sequence. The largest area is under Scenario Ddry15 and is due to the compounding effects of reduced recharge and the greatest level of groundwater development. The scenarios with the smallest area of impact are the wet climate sequences, and the smallest area is under Cwet, which has no additional development.

Table 6-3 Total area of greater than 1 m drawdown relative to Scenario A, maximum drawdown and minimum drawdown at 2060 for each scenario

SCENARIO	AREA OF DRAWDOWN GREATER THAN 1 m RELATIVE TO SCENARIO A (km^2)	MAXIMUM DRAWDOWN (m)	MINIMUM DRAWDOWN (m)
B9	2759	14.4	−0.1
B12	3283	20.0	−0.2
B15	3669	26.0	−0.2
Cdry	3966	11.4	−0.4
Cmid	1986	5.0	−0.1
Cwet	0.0	0.5	−10.5
Ddry9	5897	18.2	−0.4
Ddry12	6270	24.1	−0.4
Ddry15	6580	30.5	−0.4
Dmid9	4559	15.3	−0.2
Dmid12	5042	21.0	−0.2
Dmid15	5394	27.1	−0.2
Dwet9	1283	9.2	−10.5
Dwet12	2028	14.5	−10.5
Dwet15	2704	20.1	−10.5

Scenarios: B9 = Historical climate sequences with current development and additional future development of 9 GL/year; B12 = Historical climate sequences with current development and additional future development of 12 GL/year; B15 = Historical climate sequences with current development and additional future development of 15 GL/year; Cdry = Future dry climate sequences current development; Cmid = Future mid climate sequences current development; Cwet = Future wet climate sequences current development; Ddry9 = Future dry climate sequences current development and future development of 9 GL/year; Ddry12 = Future dry climate sequences current development and future development of 12 GL/year; Ddry15 = Future dry climate sequences current development and future development of 15 GL/year; Dmid9 = Future mid climate sequences current development and future development of 9 GL/year; Ddry12 = Future mid climate sequences current development and future development of 12 GL/year; Dmid15 = Future mid climate sequences current development and future development of 15 GL/year); Dwet9 = Future wet climate sequences current development and future development of 9 GL/year; Dwet12 = Future wet climate sequences current development and future development of 12 GL/year; Dwet15 = Future wet climate sequences current development and future development of 15 GL/year.

6.5 Groundwater discharge

The mean groundwater discharge (springs and evapotranspiration) for the 10-year period (2055 to 2065) representative of future 2060 conditions at the springs for each scenario are summarised in Figure 6-6. The plots show trends associated with climate and pumped volumes. Generally, the groundwater discharge show much greater response due to changes in climate than pumping.

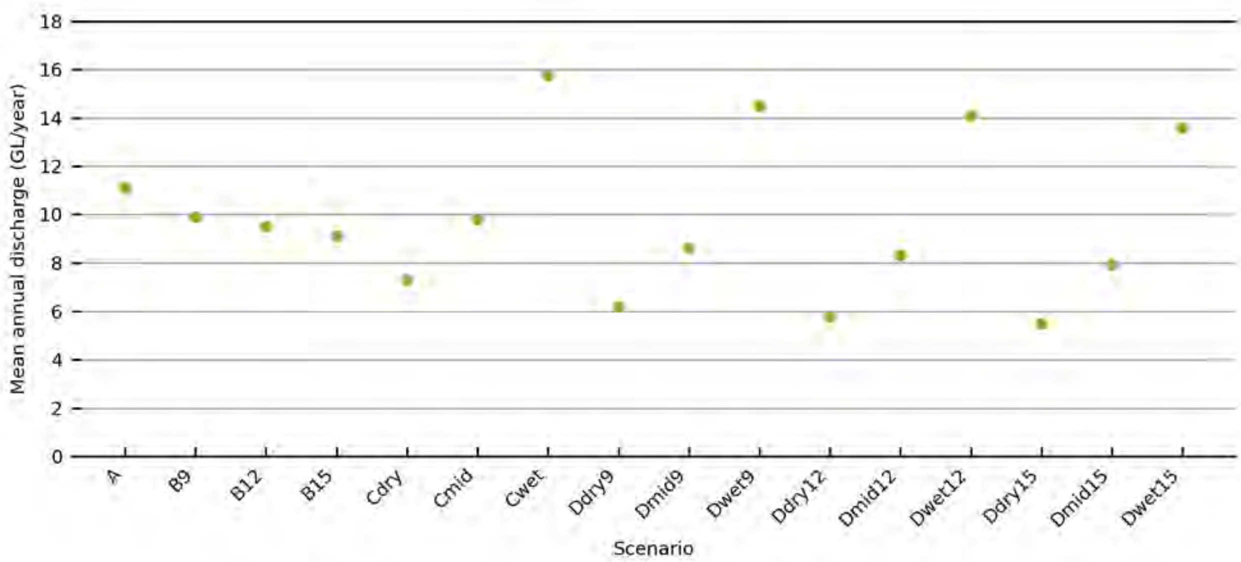

Figure 6-6 Mean annual groundwater discharge (springs) for the period from 2055 to 2065 under all scenarios

6.5.1 Scenarios A and B representative (2060) conditions

The changes to mean annual discharge to springs under Scenario B relative to Scenario A for the representative 2060 conditions (Table 6-4) show around a 10% to 20% decrease in discharge to the springs associated with the hypothetical future groundwater developments (Scenario B).

The changes to mean annual discharge to the Flora River under Scenario B relative to Scenario A for the representative 2060 conditions (Table 6-5) indicate that there is no difference in the discharge to the river associated with the hypothetical future groundwater developments. As discussed in the previous sections, this is related to the distance of the hypothetical future groundwater developments from the river (>200 km) and the 50-year time frame, which is insufficient for these effects to propagate to the Flora River.

Table 6-4 Mean annual discharge to the springs and evapotranspiration in the Victoria catchment under Scenario B relative to Scenario A and percentage change for the 10-year period (2055 to 2065) representative of 2060 conditions

	B9	B12	B15
Diffuse discharge (GL/year) relative to Scenario A	−1.2	−1.6	−1.9
Percentage change from Scenario A	−11%	−14%	−17%

Scenarios: A = Historical climate and current development; B9 = Future dry climate sequences current development and future development of 9 GL/year; B12 = Future dry climate sequences current development and future development of 12 GL/year; B15 = Future dry climate sequences current development and future development of 15 GL/year.

Table 6-5 Mean annual discharge to the Flora River under Scenario B relative to Scenario A and percentage change for the 10-year period (2055 to 2065) representative of 2060 conditions

	B9	B12	B15
Discharge (GL/year) relative to Scenario A	+0.2	+0.2	+0.1
Percentage change from Scenario A	+0%	+0%	+0%

Scenarios: A = Historical climate and current development; B9 = Future dry climate sequences current development and future development of 9 GL/year; B12 = Future dry climate sequences current development and future development of 12 GL/year; B15 = Future dry climate sequences current development and future development of 15 GL/year.
†na = not applicable.

6.5.2 Scenarios C and D representative (2060) conditions

Mean groundwater discharge to the springs and evapotranspiration in the Victoria catchment under the C scenarios (Cdry, Cmid, Cwet) ranges from 7.3 GL/year in dry conditions to 15.8 GL/year in wet conditions. This indicates significant variability in discharge based on climate conditions.

Under the D scenarios, the discharge ranges from 5.5 GL/year in Ddry15 to 14.5 GL/year in Dwet9. This range demonstrates the compounded effects of increased groundwater extraction and climate variations.

Mean annual discharge the springs and evapotranspiration in the Victoria catchment under scenarios Cdry and Ddry shows a significant decrease relative to discharge under Scenario A for the representative (2060) conditions. Specifically, Cdry shows a 34% decrease. In contrast, Cwet shows a 42% increase from Scenario A (Table 6-6).

Mean annual discharge to the Flora River under all Cdry and Ddry scenarios show about a 9% decrease in discharge relative to Scenario A for the representative (2060) conditions (Table 6-7). The distance of the future hypothetical developments from the river and the 50-year time frame of the scenarios indicate that the influence from the future hypothetical developments is limited, and the effects are dominated by the reduced recharge to the entire model domain.

Table 6-6 Mean annual discharge to the springs in the Victoria catchment under scenarios C and Ddry relative to Scenario A and percentage change for the 10-year period (2055 to 2065) representative of 2060 conditions

	CDRY	CMID	CWET	DDRY9	DDRY12	DDRY15	DMID9	DMID12	DMID15	DWET9	DWET12	DWET15
Diffuse discharge (GL/year) relative to Scenario A	-3.7	-1.3	+4.7	-4.9	-5.3	-5.6	-2.5	-2.8	-3.2	+3.4	+3.0	+2.5
Percentage change from Scenario A	-34%	-11%	+42%	-44%	-47%	-51%	−22%	−26%	−29%	+30%	+26%	+23%

Cdry = Future dry climate sequences current development; Cmid = Future mid climate sequences current development; Cwet = Future wet climate sequences current development; Ddry9 = Future dry climate sequences current development and future development of 9GL/year; Ddry12 = Future dry climate sequences current development and future development of 12GL/year; Ddry15 = Future dry climate sequences current development and future development of 15GL/year.

Table 6-7 Mean annual discharge to the Flora River under scenarios C and Ddry relative to Scenario A and percentage change for the 10-year period representative of 2060 conditions

	CDRY	CMID	CWET	DDRY9	DDRY12	DDRY15	DMID9	DMID12	DMID15	DWET9	DWET12	DWET15
Discharge (GL/year) relative to Scenario A	−13.5	−1.3	39.4	−13.6	−13.6	−13.6	-1.3	-1.3	-1.3	39.4	39.4	39.4
Percentage change from Scenario A	−9%	−1%	+25%	−10%	−10%	−10%	-1%	-1%	-1%	+25%	+25%	+25%

Cdry = Future dry climate sequences current development; Cmid = Future mid climate sequences current development; Cwet = Future wet climate sequences current development; Ddry9 = Future dry climate sequences current development and future development of 9GL/year; Ddry12 = Future dry climate sequences current development and future development of 12GL/year; Ddry15 = Future dry climate sequences current development and future development of 15GL/year.

7 Conclusions

The DR2 groundwater flow model was used to examine the effects of four scenarios, encompassing climate change and groundwater development, on the water resources of the Cambrian Limestone Aquifer (CLA) in the Victoria catchment. From this analysis, the following key findings have emerged:

- For predicted future climate scenarios that are wetter than historical conditions, groundwater development is anticipated to negatively affect spring discharge.
- It is estimated that current levels of groundwater extraction from the CLA in the Victoria catchment (stock and domestic use and community water supply at Top Springs) will not reduce groundwater discharge from the CLA to the Flora River.
- Similarly, it is estimated that hypothetical future groundwater extraction (as simulated) will not reduce discharge from the CLA to the Flora River before the year 2060. This was attributed to the considerable distance between the simulated locations of extraction and the Flora River. However, reductions in discharge to the Flora River may occur over larger timescales; i.e. greater than 50 years.
- The extensive spatial coverage, thickness and variable hydraulic properties of the karstic groundwater systems also significantly influences the time lags for hydrological impacts of both climate variability and groundwater extraction to propagate through each system.
- Estimated decreases in groundwater discharge to springs were not linearly proportional to increases in hypothetical groundwater extraction. This was attributed to a large proportion of groundwater extraction being sourced from aquifer storage, as well as from the capture of groundwater throughflows that would otherwise flow beyond the boundaries of the Victoria catchment and the WWMZ.
- The relative impact of changes in future climate was estimated to be greater than that of future hypothetical groundwater extraction (as simulated) on conditions in the CLA in the east of the Victoria River catchment. This was attributed to changes in relatively larger magnitude of changes in recharge resulting from changes in future climate.

References

Abusaada M and Sauter M (2013) Studying the flow dynamics of a karst aquifer system with an equivalent porous medium model. Ground Water 51(4), 641–650. DOI: 10.1111/j.1745-6584.2012.01003.x.

Bruwer Q and Tickell S (2015) Daly Basin groundwater resource assessment – North Mataranka to Daly Waters in the Northern Territory of Australia. NT Department of Land Resource Management. Viewed 02 August 2017, https://territorystories.nt.gov.au/10070/495513.

Crosbie RS and Rachakonda PK (2021) Constraining probabilistic chloride mass-balance recharge estimates using baseflow and remotely sensed evapotranspiration: the Cambrian Limestone Aquifer in northern Australia. Hydrogeology Journal 29(4), 1399–1419. DOI: 10.1007/s10040-021-02323-1.

CSIRO (2009) Water in the Ord-Bonaparte region of the Timor Sea Drainage Division. A report to the Australian Government from the CSIRO Northern Australia Sustainable Yields Project.

NT Department of Environment Parks and Water Security (2018) NT Water groundwater licence extraction points. Open Data Portal, NT Government. Viewed 02 March 2024, https://data.nt.gov.au/dataset/nt-water-groundwater-licence-extraction-points.

NT Department of Environment Parks and Water Security (2023) Georgina Wiso Background Report 2023-2031. Report13/2023. Department of Environment, Parks and Water Security: Northern Territory, Australia.

Deslandes A, Gerber C, Lamontagne S, Wilske C and Suckow A (2019: Environmental tracers in the Beetaloo Basin: aquifer and groundwater characterization. CSIRO, Australia.

DHI (2008) Mike SHE User Manual. Danish Hydraulic Institute, Denmark.

Diersch H-JG (2008) FEFLOW® 5.4 Users Manual. WASY – Institute for Water Resources Planning and System Research, Berlin, Germany.

Doherty J (2003) Ground water model calibration using pilot points and regularization. Groundwater 41(2), 170–177. DOI: 10.1111/j.1745-6584.2003.tb02580.x.

Doherty J (2020) A simple lumped parameter model for unsaturated zone processes. Watermark Numerical Computing.

Doherty J (2004) PEST Model-independent parameter estimation – User manual (5th edn). Watermark Numerical Computing.

Ghasemizadeh R, Hellweger F, Butscher C, Padilla I, Vesper D, Field M and Alshawabkeh A (2012) Review: Groundwater flow and transport modeling of karst aquifers, with particular reference to the North Coast Limestone aquifer system of Puerto Rico. Hydrogeology Journal 20(8), 1441–1461. DOI: 10.1007/s10040-012-0897-4.

Ghasemizadeh R, Yu X, Butscher C, Hellweger F, Padilla I and Alshawabkeh A (2015) Equivalent porous media (EPM) simulation of groundwater hydraulics and contaminant transport in karst aquifers. PLoS ONE 10(9), e0138954. DOI: 10.1371/journal.pone.0138954.

Hughes J, Yang A, Marvanek S, Wang B, Petheram C and S P (2023) River model calibration and scenario analysis for the Roper catchment. A technical report from the CSIRO Roper River Water Resource Assessment for the National Water Grid. CSIRO, Australia.

Hughes J, Yang A, Marvanek S, Wang B, Gibbs M and Petheram C (2024a) River model calibration for the Victoria catchment. A technical report from the CSIRO Victoria River Water Resource Assessment for the National Water Grid. CSIRO, Australia.

Hughes J, Yang A, Wang B, Marvanek S, Gibbs M and Petheram C (2024b) River model scenario analysis for the Victoria catchment. A technical report from the CSIRO Victoria River Water Resource Assessment for the National Water Grid. CSIRO, Australia.

Jackson L and Jolly P (2004) Prediction of Springflows at G8110307 on the Wickham River for the Period 1885 to 2003. Northern Territory.

Jeffrey SJ, Carter JO, Moodie KB and Beswick AR (2001). Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environmental Modelling and Software 16(4), 309–330. DOI: 10.1016/S1364-8152(01)00008-1.

Jolly P, Knapton A and Tickell S (2004) Water availability from the aquifer in the Tindall Limestone south of the Roper River. Report No 34/2004D. Natural Systems Division, Conservation and Natural Resources Group, NT Department of Infrastructure, Planning and Environment. Viewed 13 August 2007, https://territorystories.nt.gov.au/10070/673850/0/0.

Karp D (2008) Surface and groundwater interaction the Mataranka Area. Report No. 17/2008D. NT Department of Natural Resources, Environment, the Arts and Sport, Palmerston. Viewed 03 September 2015, https://territorystories.nt.gov.au/10070/674028/0/0.

Kerle E and Cruickshank S (2014) End of dry season stream flow measurements, Roper River, October 2014. Report 13/2015D. NT Department of Land Resource Management, Palmerston. Viewed 01 May 2023, https://territorystories.nt.gov.au/10070/503458.

Kirby S, Faulks J and Waterways TE (2005) Victoria River catchment : an assessment of the physical and ecological condition of the Victoria River and its major tributaries. Tech. Report No 40/2004

Knapton A (2005) Preliminary groundwater modelling of the Oolloo Dolostone. NT Department of Natural Resources, Environment and the Arts, Alice Springs.

Knapton A (2006) Regional groundwater modelling of the Cambrian Limestone Aquifer system of the Wiso Basin, Georgina Basin and Daly Basin. NT Department of Natural Resources, Environment and the Arts, Alice Springs.

Knapton A (2009) Gulf water study: An integrated surface – groundwater model of the Roper River catchment, Northern Territory. Part C – FEFLOW groundwater model. Technical Report No. 32/2009D. Water Resources Branch, NT Department of Natural Resources, Environment, the Arts and Sport. Viewed 01 May 2023, https://territorystories.nt.gov.au/10070/580684.

Knapton A (2020) Upgrade of the coupled model of the Cambrian Limestone Aquifer and Roper River systems. CloudGMS and NT Department of Environment, Parks and Water Security, Palmerston. Viewed 01 May 2023, https://territorystories.nt.gov.au/10070/827500.

Knapton A, Taylor AR, Pethram C and Crosbie RS (2023) An investigation into the effects of climate change and groundwater development scenarios on the water resources of the Roper catchment using two finite element groundwater flow models. A technical report from the CSIRO Roper River Water Resource Assessment for the National Water Grid. CSIRO, Australia.

Lauritzen SE and Karp D (1993) Speleological assessment of karst aquifers developed within the Tindall Limestone, Katherine, NT. Report WRD93063. Northern Territory Power and Water Authority, Darwin. Viewed 01 May 2023, https://territorystories.nt.gov.au/10070/672995/0/49.

Lehner, B. and Grill G. (2013) Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems. Hydrological Processes, 27(15): 2171–2186.

McJannet D, Yang A and Seo L (2023) Climate data characterisation for hydrological and agricultural scenario modelling across the Victoria, Roper and Southern Gulf catchments. A technical report from the CSIRO Victoria River and Southern Gulf Water Resource Assessments for the National Water Grid. CSIRO, Australia.

NT Government (2023) Territory Water Plan: A plan to deliver water security for all Territorians, now and into the future. Office of Water Security. Viewed 17 September 2024, https://watersecurity.nt.gov.au/territory-water-plan#:~:text=Priority%20actions%20in%20the%20plan,and%20productivity%20in%20water%20use.

Power and Water Authority (1987) Baseflow Water Quality Surveys in Rivers in the Northern Territory Volume 5: Fitzmaurice and Victoria Rivers. Report 10/1987. Darwin.

Puhalovich A (2005) Groundwater modelling of the Tindall Limestone Aquifer. Final report for the Department of Planning, Infrastructure and Environment (NT), Darwin by EWL Sciences Pty Ltd, Darwin.

Randal, M.A. (1973) Groundwater in the Northern Wiso Basin and Environs, Northern Territory. Department of Minerals & Energy, Bureau of Mineral Resources, Geology & Geophysics. Bulletin 123, Australian Government Publishing Services, Canberra. ISBN 0642002312.

Scanlon BR, Mace RE, Barrett ME and Smith B (2003) Can we simulate regional groundwater flow in a karst system using equivalent porous media models? Case study, Barton Springs Edwards aquifer, USA. Journal of Hydrology 276(1), 137–158. DOI: 10.1016/S0022-1694(03)00064-7.

Stratford D, Kenyon R, Pritchard J, Merrin L, Linke S, Ponce Reyes R, Buckworth R, Castellazzi P, Costin B, Deng R, Gannon R, Gao S, Gilbey S, Lachish S, McGinness H and Waltham N (2024) Ecological assets of the Victoria catchment to inform water resource assessments. A technical report from the CSIRO Victoria River Water Resource Assessment for the National Water Grid. CSIRO, Australia.

Taylor AR, Crosbie RS, Turnadge C, Lamontagne S, Deslandes A, Davies PJ, Barry K, Suckow A, Knapton A, Marshall S, Hodgson G, Tickell S, Duvert C, Hutley L and Dooley K (2023) Hydrogeological assessment of the Cambrian Limestone Aquifer and the Dook Creek Aquifer in the Roper catchment, Northern Territory. A technical report from the CSIRO Roper River Water Resource Assessment for the National Water Grid. CSIRO, Australia.

Thomas M, Philip S, Stockmann U, Wilson PR, Searle R, Hill J, Gregory L, Watson I and Wilson PL (2024) Soils and land suitability for the Victoria catchment, Northern Territory. A technical report from the CSIRO Victoria River Water Resource Assessment for the National Water Grid. CSIRO, Australia.

Tickell S (2005) Groundwater resources of the Tindall Limestone. NT Department of Natural Resources, Environment and the Arts, Darwin. Viewed 01 May 2023, https://territorystories.nt.gov.au/10070/613966/0/0.

Tickell SJ (2016) Stable isotopes and carbon dating of groundwaters in the Tindall aquifer, Water Resources Division, Northern Territory Department of Land Resource Management, Technical Report No. 12/2016D ISBN: 9781743501061

Tickell SJ and Bruwer Q (2018) Georgina Basin groundwater assessment: Daly Waters to Tennant Creek. Department of Environment and Natural Resources, Northern Territory Government, Palmerston., https://territorystories.nt.gov.au/10070/361119.

Tickell SJ and Rajaratnam L (1998) Water Resources Of The Victoria River District. Report 11/1998D. Department of Lands Planning and Environment, Natural Resources Division Northern Territory. Available online: <https://territorystories.nt.gov.au/10070/229442>.

Wagenaar D and Tickell S (2013) Late dry season stream flows and groundwater levels, upper Roper River, October 2013. Report No 10/2013D. NT Department of Land Resource Management, Palmerston. Viewed 01 May 2023, https://territorystories.nt.gov.au/10070/571259/0/0.

Water Studies (2001) Regional groundwater impact modelling, Venn Agricultural Area.

Waugh P and Kerle E (2014) End of wet season stream flow measurements, Roper River, May 2014. NT Department of Land Resource Management, Palmerston. Viewed 01 May 2023, https://territorystories.nt.gov.au/10070/492338/0/0.

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