Groundwater flow modelling of the Cambrian Limestone Aquifer in the Undilla Sub-basin, Georgina Basin using a finite element groundwater flow model

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

Anthony Knapton[1], Andrew R Taylor[2], Russell S Crosbie[2]

[1] CloudGMS Pty Ltd; [2] CSIRO

ISBN 978-1-4863-2087-5 (print)

ISBN 978-1-4863-2088-2 (online)

Citation

Knapton A, Taylor AR and Crosbie RS (2024) Groundwater flow modelling of the Cambrian Limestone Aquifer in the Undilla Sub-basin, Georgina Basin using a finite element groundwater flow model. A technical report from the CSIRO Southern Gulf Water Resource Assessment for the National Water Grid. CSIRO, Australia.

Copyright

Important disclaimer

CSIRO Southern Gulf 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 Northern Territory and Queensland governments.

The Assessment was guided by two committees:

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

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

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

This report was reviewed by Dr Cuan Petheram (CSIRO) and Mr Warrick Dawes (CSIRO).

Photo

Indarra Falls – a tufa dam on Lawn Hill Creek (a tributary of the Gregory River). Source: CSIRO.

Director's foreword

Sustainable development and regional economic prosperity are priorities for the Australian, Queensland 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 Southern Gulf 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 Southern Gulf catchments. 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, Queensland 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

The Southern Gulf Water Resource Assessment Team

Project Director	Chris Chilcott
Project Leaders	Cuan Petheram, Ian Watson
Project Support	Caroline Bruce, Seonaid Philip
Communications	Emily Brown, Kate Cranney, Jo Ashley, Nathan Dyer

Activities

Agriculture and socio-economics	Tony Webster, Caroline Bruce, Kaylene Camuti[1], Matt Curnock, Jenny Hayward, Simon Irvin, Shokhrukh Jalilov, Diane Jarvis[1], Adam Liedloff, Stephen McFallan, Yvette Oliver, Di Prestwidge[2], Tiemen Rhebergen, Robert Speed[3], Chris Stokes, Thomas Vanderbyl[3], John Virtue[4]
Climate	David McJannet, Lynn Seo
Ecology	Danial Stratford, Rik Buckworth, Pascal Castellazzi, Bayley Costin, Roy Aijun Deng, Ruan Gannon, Steve Gao, Sophie Gilbey, Rob Kenyon, Shelly Lachish, Simon Linke, Heather McGinness, Linda Merrin, Katie Motson[5], Rocio Ponce Reyes, Jodie Pritchard, Nathan Waltham[5]
Groundwater hydrology	Andrew R. Taylor, Karen Barry, Russell Crosbie, Margaux Dupuy, Geoff Hodgson, Anthony Knapton[6], Stacey Priestley, Matthias Raiber
Indigenous water values, rights, interests and development goals	Pethie Lyons, Marcus Barber, Peta Braedon, Petina Pert
Land suitability	Ian Watson, Jenet Austin, Bart Edmeades[7], Linda Gregory, Ben Harms[10], Jason Hill[7], Jeremy Manders[10], Gordon McLachlan, Seonaid Philip, Ross Searle, Uta Stockmann, Evan Thomas[10], Mark Thomas, Francis Wait[7], Peter Zund
Surface water hydrology	Justin Hughes, Matt Gibbs, Fazlul Karim, Julien Lerat, Steve Marvanek, Cherry Mateo, Catherine Ticehurst, Biao Wang
Surface water storage	Cuan Petheram, Giulio Altamura[8], Fred Baynes[9], Jamie Campbell[11], Lachlan Cherry[11], Kev Devlin[4], Nick Hombsch[8], Peter Hyde[8], Lee Rogers, Ang Yang

Note: Assessment team as at September, 2024. All contributors are affiliated with CSIRO unless indicated otherwise. Activity Leaders are underlined.

[1]James Cook University; [2]DBP Consulting; [3]Badu Advisory Pty Ltd; [4]Independent contractor; [5] Centre for Tropical Water and Aquatic Ecosystem Research. James Cook University; [6]CloudGMS; [7]NT Department of Environment, Parks and Water Security; [8]Rider Levett Bucknall; [9]Baynes Geologic; [10]QG Department of Environment, Science and Innovation; [11]Entura

Shortened forms

SHORT FORM	FULL FORM
AHD	Australian Height Datum
CLA	Cambrian Limestone Aquifer
CMB	chloride mass balance
IQR	interquartile range
NAWRA	Northern Australia Water Resource Assessment
NGMA	Nicholson Groundwater Management Area
NT	Northern Territory
RMS	root mean square
SILO	Scientific Information for Land Owners
SRMS	scaled root mean square

Units

UNIT	DESCRIPTION
GL	gigalitre
km	kilometre
L	litre
m	metre
mAHD	metres above Australian Height Datum
mm	millimetre
s	second

Preface

Sustainable development and regional economic prosperity are priorities for the Australian, NT and Queensland governments. In the Queensland Water Strategy, for example, the Queensland Government (2023) looks to enable regional economic prosperity through a vision that states ‘Sustainable and secure water resources are central to Queensland’s economic transformation and the legacy we pass on to future generations.’ 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.’

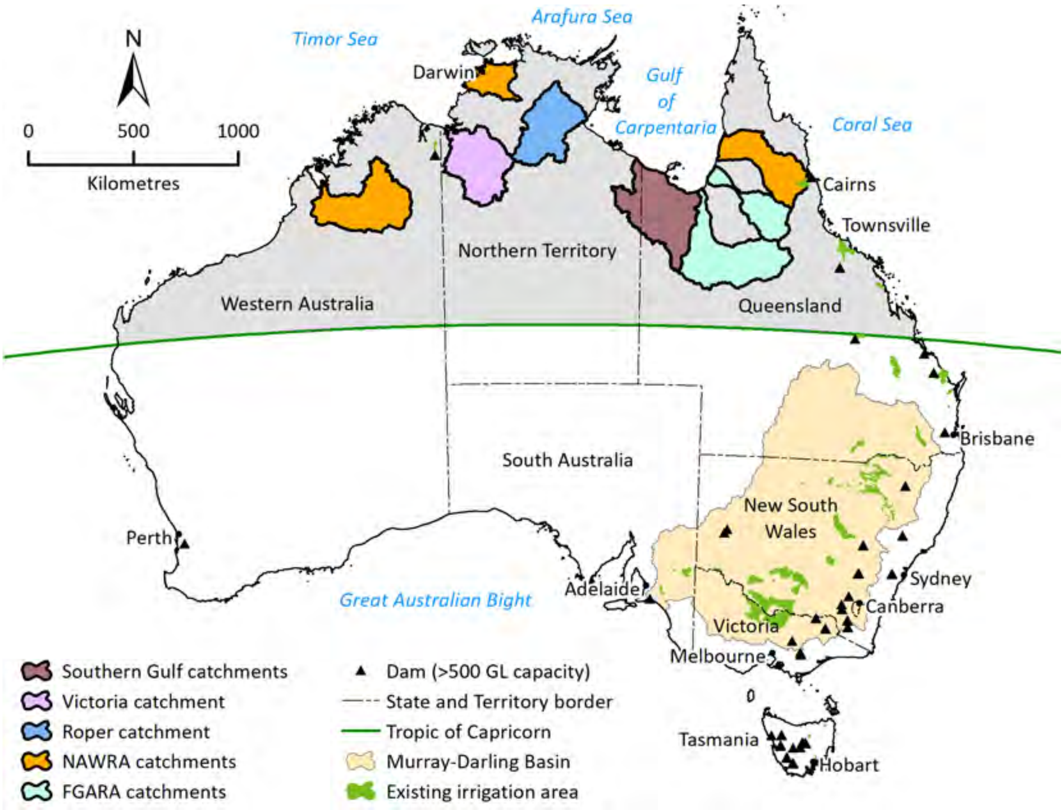
Governments are actively seeking to diversify regional economies, considering a range of factors, including Australia’s energy transformation. The Queensland Government’s economic diversification strategy for North West Queensland (Department of State Development, Manufacturing, Infrastructure and Planning, 2019) includes resources – mining and mineral processing; agriculture – beef cattle production, cropping and commercial fishing; tourism with an outback focus; and small business, supply chains and emerging industry sectors. In its 2024–25 Budget, the Australian Government announced large investment in renewable hydrogen, low-carbon liquid fuels, critical minerals processing and clean energy processing (Budget Strategy and Outlook, 2024). This includes investing in regions that have ‘traditionally powered Australia’ – as the North West Minerals Province, situated mostly within the Southern Gulf catchments, has done.

For very remote areas like the Southern Gulf catchments (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.

How people perceive those risks is critical, especially in the context of areas such as the Southern Gulf catchments, where approximately 27% 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 12% of the Southern Gulf catchments 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 Southern Gulf 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.



Preface Figure 1-1 Map of Australia showing the Assessment area (Southern Gulf catchments) and other recent CSIRO Assessments

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

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 catchments and the economic possibilities and environmental impacts of development. Furthermore, it considers many of the different resource and asset types in an integrated way, rather than separately.

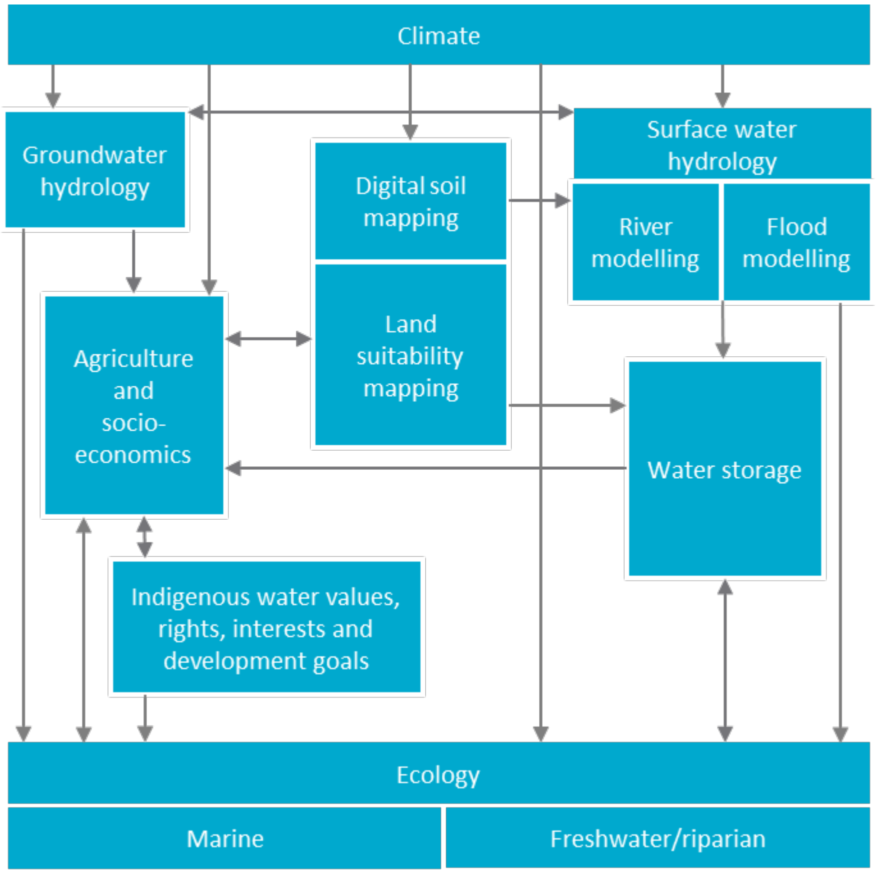
The Assessment has agricultural developments as its primary focus, but it also considers opportunities for and intersections between other types of water-dependent development. For example, the Assessment explores the nature, scale, location and impacts of developments relating to industrial, urban and aquaculture development in relevant locations. The outcome of no change in land use or water resource development is also valid.

The Assessment was designed to inform consideration of development, not to enable any particular development to occur. 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, 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 Indigenous reconciliation and to conducting ethical research with the free, prior and informed consent of human participants. The Assessment allocated significant time to consulting with Indigenous representative organisations and Traditional Owner groups from the catchments to aid their understanding and potential engagement with its requirements. The Assessment did not conduct significant fieldwork without the consent of Traditional Owners. CSIRO met the requirement to create new scientific knowledge about the catchments (e.g. on land suitability) by synthesising new material from existing information, complemented 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 eight activity groups, each contributing its part to create a cohesive picture of regional development opportunities, costs and benefits, and 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 activity (Preface Figure 1-2) has one or more corresponding technical reports.
- A catchment report synthesises key material from the technical reports to provide well-informed (but not necessarily scientifically trained) readers with the information required to inform decisions about the opportunities, costs and benefits, and 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/southerngulf. 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 Undilla Sub-basin is located to the south-east of the northern part of the Georgina Basin. It covers an area of approximately 50,900 km², which represents about 15% of the total Georgina Basin area.

The Undilla Sub-basin lies in the wet-dry tropics of northern Australia. Its rainfall and runoff are characterised by a 4-month wet season during which the majority of runoff occurs and an 8-month dry season during which there is little surface runoff and groundwater provides baseflow to the perennial rivers in the area.

Mean annual rainfall for the township of Camooweal, located roughly in the centre of the Undilla Sub-basin, is about 420 mm. Mean annual areal potential evapotranspiration is 2932 mm, and annual variation is relatively small. Rainfall is very seasonal, with about 90% falling during the wet season (November to April), and runoff is highest in February and March.

The major productive aquifers in the study area with potential for development for irrigated agriculture occur in the karstic rocks of the Camooweal Dolostone and Thorntonia Limestone units and is referred to as the Cambrian Limestone Aquifer (CLA).

Potential for groundwater development of the CLA in the Undilla Sub-basin is limited by its low recharge rates and the cultural, environmental and economic significance of the aquatic ecosystems it maintains. The perennial rivers in the study area – Lawn Hill Creek and Gregory and O'Shannassy rivers – source their dry-season (May to October) flow from the CLA.

Current rates of extraction from the CLA in the Undilla Sub-basin are poorly defined. Although mining water use from the CLA is expected to be significant locally, precise extraction amounts are not well documented but are anticipated to be minimal within the study area.

The Queensland portion of the Undilla Sub-basin is subject to the Water Plan (Gulf) 2007 declared by the Queensland Government (Queensland Government, 2018). Groundwater resources of the Undilla Sub-basin that are within the Gulf plan area are managed under the Nicholson Groundwater Management Area (NGMA).

Increased groundwater development from the CLA within the Undilla Sub-basin for irrigation or other land use is likely to increase future demands on groundwater resources. Additional groundwater extraction from the high-transmissivity CLA could lower groundwater levels and thereby reduce the baseflow of the rivers during the dry season.

A groundwater model of the aquifer system within the Undilla Sub-basin was developed to evaluate the initial conceptualisation of the groundwater system in the CLA, including water balance estimates. The model will also guide future data collection efforts. It is expected that subsequent studies will update and refine the groundwater model, enhancing its utility as a tool for assessing groundwater development and its impact on groundwater resources, particularly in terms of discharge to rivers.

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

Objectives and scope

The objective of this modelling investigation was to develop a Class 1 groundwater flow model. A Class 1 groundwater flow model is basic and often conceptual, with simple assumptions about aquifer properties, boundary conditions and flow dynamics. Such models typically rely on limited data and are used for broad, regional assessments or to highlight key uncertainties that may need more detailed study. Accordingly, the groundwater flow model of the Undilla Sub-basin was developed to provide a preliminary evaluation of aspects of the groundwater resources in the area and provide insights to help focus future data collection.

Model description

The FEFLOW groundwater model represents the CLA in the Undilla Sub-basin, which encompasses an area of approximately 50,900 km^2. This model, known as Undilla1 (Undilla Sub-basin groundwater flow model v1), is distinct from other models of the CLA developed further to the north in the northern Georgina, Wiso and Daly basins (Knapton, 2020).

The Undilla1 groundwater flow model consists of a two-dimensional finite element model developed using FEFLOW. It incorporates the interaction between groundwater and surface water occurs using specified head boundary conditions (i.e. 1st type Dirichlet). The model does not include loss of groundwater due to evapotranspiration as the regional watertable is generally below the maximum root depth, the rivers are deeply incised into the CLA resulting in a very narrow riparian zone, and evapotranspiration loss in the unsaturated zone is accounted for in the chloride mass balance (CMB) recharge estimates.

The Undilla1 groundwater model was developed with all available aquifer data and calibrated with all available rainfall, river flow and groundwater-level data. The recharge inputs to the FEFLOW model were generated by scaling the CMB estimates of recharge (Crosbie and Rachakonda, 2021; Raiber et al., 2024).

Reported metrics

For the CLA in the Undilla1 model:

- Water levels are documented for eight groundwater reporting sites.
- Groundwater discharge is reported as a combination of spring discharge and lateral outflow where the streams are incised into the CLA along the Lawn Hill Creek (912103A) and the Gregory River (912101A).
- Model water balances are reported for four areas within the model domain: the Lawn Hill subcatchment; the Gregory subcatchment; the Nicholson Groundwater Management Area identified in the Water Plan (Gulf) 2007, which includes the O’Shannassy River; and the entire model domain.

Conclusions

A two-dimensional numerical groundwater flow model has been developed to examine the groundwater resources of the Undilla Sub-basin, which provides baseflow to Lawn Hill Creek and Gregory River. The model broadly reproduces the observed behaviour of groundwater levels and discharge from the CLA in the Undilla Sub-basin. From this study, the following key findings have emerged:

- The conceptualisation of the groundwater flow system indicates that there is a localised system discharging to springs well above the stream level and a regional groundwater system discharging to lower springs and through the bed of the river. To adequately model the observed discharge record, the Undilla Sub-basin may require multiple layers to resolve this partitioning.
- There is considerable uncertainty in the dynamic range of groundwater levels in the Undilla Sub-basin, as the model is currently constrained by single water levels recorded at the time of bore construction. Collecting time series data at sites such as the reporting sites used in this study would reduce the uncertainty in the groundwater-level dynamics.
- Groundwater discharge reported at 912101A is considered representative of flows in the Gregory River; however, there is less confidence that the discharge reported at 912103A is representative of flows in Lawn Hill Creek. Conducting manual measurements of stream flows at these sites once or twice a year during the dry season would improve the confidence in this data.
- Portions of the observed flow record can be reproduced for 912103A on Lawn Hill Creek. However, the model appears to under-report observed flows at 912103A in the period from 1975 to 1980.
- Previous studies have assumed that groundwater contributing to the discharge at Lawn Hill Creek and Gregory River is sourced as far west as the Alexandria-Wonarah Basement High. However, the groundwater level surface indicates that there is a groundwater divide separating flows to the east and flows to the south. This assessment is supported by the groundwater flow model.
- Recharge is estimated by scaling the rainfall by the CMB recharge distribution and is between 7 and 25 mm/year, depending on the area of interest. The recharge is 14 mm/year in the Gregory catchment, 25 mm/year in the Lawn Hill catchment and about 15 mm/year in the NGMA. The mean recharge for the entire model domain is about 7 mm/year.
- Based on the transmissivity values, the recharge for areas with black soil cover may be an order of magnitude lower.
- The transmissivities in the north-eastern third of the model domain are considered reasonable for the type of aquifer (<1,000 to 10,000 m^2/day). However, the highest transmissivity values (>20,000 m^2/day), which are predominantly in the south-western two-thirds of the model domain, are much higher than expected. The higher values reflect the very low groundwater gradient and are likely a result of recharge being overestimated in areas with black soil.

Contents

Director's foreword i

The Southern Gulf Water Resource Assessment Team ii

Shortened forms iii

Units iv

Preface v

Executive summary ix

1 Introduction 1

1.1 Background 1

2 Overview of the Undilla Sub-basin 2

2.1 Location of the Undilla Sub-basin 2

2.2 Gregory River and Lawn Hill Creek 4

2.3 Hydrogeology of the Undilla Sub-basin 6

2.4 Water management areas 9

2.5 Reporting metrics 10

3 Numerical flow model 12

3.1 Introduction 12

3.2 Previous hydrogeological investigations and modelling 12

3.3 Conceptual model 17

3.4 Undilla1 (CLA) groundwater flow model description 17

3.5 Undilla1 calibration results 20

3.6 Calibrated heads 23

3.7 Sensitivity 28

3.8 Uncertainty analysis 30

3.9 Limitations 36

4 Conclusions 37

References 38

Figures

Preface Figure 1-1 Map of Australia showing the Assessment area (Southern Gulf catchments) and other recent CSIRO Assessments vi

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

Figure 2-1 Location of the Undilla Sub-basin and its relationship to the Southern Gulf (Nicholson and Leichhardt) catchments and the groundwater systems of the Cambrian Limestone Aquifer in the Daly, Wiso and Georgina basins 3

Figure 2-2 Continuous stream flows at (a) 912101A – Gregory River and (b) 912103A – Lawn Hill Creek 4

Figure 2-3 Local hydrogeology of the Undilla Sub-basin (after Stewart et al., 2020) showing the extents of Cenozoic sediment cover (yellow hashed regions) and mapped karst features including dolines (after Grimes, 1988) 5

Figure 2-4 Location of groundwater level and flow reporting sites and the NGWA used for water balance reporting 11

Figure 3-1 Regional groundwater heads and inferred groundwater flow lines 13

Figure 3-2 Annual median recharge estimates derived from chloride mass balance after (a) Crosbie and Rachakonda (2021) and (b) Raiber et al. (2024) 15

Figure 3-3 Finite element mesh geometry showing pilot point locations and identifiers and specified head boundary conditions along Lawn Hill Creek, Gregory River and the throughflow boundary to the south 19

Figure 3-4 Scatter plot showing fit between (a) modelled and measured groundwater levels and (b) modelled and measured groundwater discharge at both 912101A on the Gregory River and 912103A on Lawn Hill Creek 21

Figure 3-5 Histogram of residuals for (a) obsgrp1 – heads, (b) obsgrp2 – groundwater discharge at 912101A on the Gregory River and (c) obsgrp3 – groundwater discharge at 912103A on Lawn Hill Creek 22

Figure 3-6 Calibrated transmissivity distribution 23

Figure 3-7 Calibrated groundwater levels at selected sites 17045, 31025, 33965 and 35639 24

Figure 3-8 Calibrated groundwater levels at selected sites 51446, RN018425, RN018622 and RN025992 24

Figure 3-9 Calibrated head contours at 31 August 2019 26

Figure 3-10 Calibrated modelled vs measured groundwater discharge at 912101A on the Gregory River 27

Figure 3-11 Calibrated modelled vs measured groundwater discharge at 912103A on the Lawn Hill Creek 27

Figure 3-12 Relative parameter sensitivities for a) all observations, b) obsgrp1 – groundwater heads, c) obsgrp2 – Gregory River discharge and d) obsgrp3 – Lawn Hill Creek discharge......... 29

Figure 3-13 Box and whisker chart of transmissivity values at pilot points (t1 to t43) indicating the interquartile range (box) and the minimum–maximum range (whiskers), including outliers 31

Figure 3-14 Box and whisker chart of transmissivity values at pilot points (t44 to t83) indicating the interquartile range (box) and the minimum–maximum range (whiskers), including outliers 32

Figure 3-15 Median (p50) and range of simulated groundwater levels for the period 1910 to 2019 at reporting sites (a) 17045 and (b) 31025 32

Figure 3-16 Median (p50) and range of simulated groundwater levels for the period 1910 to 2019 at reporting sites (a) 33965 and (b) 35639 33

Figure 3-17 Median (p50) and range of simulated groundwater levels for the period 1910 to 2019 at reporting sites (a) 51446 and (b) RN018425 33

Figure 3-18 Median (p50) and range of simulated groundwater levels for the period 1910 to 2019 at reporting sites (a) RN018622 and (b) RN025992... 33

Figure 3-19 Median (p50) and range of simulated groundwater discharge for the period 1910 to 2019 at reporting sites (a) 912101A and (b) 912103A 34

Figure 3-20 Groundwater budget components for the period 1910 to 2019 at reporting areas a) Gregory River and b) Lawn Hill Creek 35

Figure 3-21 Groundwater budget components for the period 1910 to 2019 at reporting areas a) Nicholson Groundwater Management Area (NGMA) and b) model domain.............................. 35

Tables

Table 2-1 Major hydrostratigraphic units of the Undilla Sub-basin 7

Table 2-2 Groundwater-level reporting sites... 10

Table 2-3 Gauging sites and the corresponding river branch name... 10

Table 3-1 Groundwater balance estimates for the Gregory subcatchment, 1970 to 2019 17

Table 3-2 Mean groundwater levels (mAHD) for the eight reporting sites for the 109-year period (1910 to 2019) under Scenario A (historical climate and current development)........................ 25

Table 3-3 Mean annual water balance (GL/year) for the 109-year climate sequence (1910 to 2019) for the Nicholson Groundwater Management Area (NGMA) 28

Table 3-4 Initial parameter ranges (par0) for boundary conditions (h1 and h2), recharge scaling factor (r1) and storage coefficient (s1) 30

1 Introduction

1.1 Background

The carbonate rocks of the Camooweal Dolostone (equivalent to Oolloo Dolostone in the Daly Basin) and Thorntonia Limestone (equivalent to the Gum Ridge Formation of the Georgina Basin) host widespread karstic aquifers forming part of the Cambrian Limestone Aquifer (CLA). The CLA is the largest, most productive and potentially most promising aquifer system within the Undilla Sub-basin for future groundwater-based development (CSIRO, 2009; Taylor et al., 2021; Tickell, 2003). Parts of these aquifers coincide with land recently identified as potentially suitable for agricultural intensification. To inform a first cut evaluation of the potential opportunities and risks associated with future groundwater resource development of these aquifers, CSIRO engaged CloudGMS Pty Ltd to develop, run, process and evaluate the results of a new finite element groundwater model of the CLA in the Undilla Sub-basin. This study is part of the Southern Gulf Water Resource Assessment, which was commissioned by the Australian Government.

The objective of this modelling investigation was to develop a Class 1 groundwater flow model of the CLA in the Undilla Sub-basin. A Class 1 groundwater flow model is basic and often conceptual, with simple assumptions about aquifer properties, boundary conditions and flow dynamics. These models typically rely on limited data and serve as tools for broad, regional assessments or to highlight key uncertainties that may need more detailed study. The groundwater flow model of the Undilla Sub-basin provides a preliminary evaluation of aspects of the groundwater system conceptualisation in the CLA, including water balance estimates, and provide insights to help focus future data collection

The focus of this report is on the dynamics of groundwater in the CLA of the Undilla Sub-basin and discharge to the surface water features identified in the model domain. No groundwater development scenarios were considered. Companion technical reports on river model calibration (Gibbs et al., 2024a) and simulation scenarios (Gibbs et al., 2024b) provide details of the river model build and calibration for the Nicholson and Leichhardt catchments (see Figure 2-1) and present the results of simulations of hypothetical surface water development.

A companion technical report on ecological assets in the Southern Gulf catchments (Merrin et al., 2024) identified potential ecological assets in the catchments that may be susceptible to changes in streamflow and groundwater levels.

This report is structured as follows. Chapter 2 provides an overview of the Undilla Sub-basin relevant to the groundwater modelling of the CLA. Chapter 3 describes the development of the numerical groundwater model used to represent groundwater flow in these parts of the CLA. Finally, Chapter 4 presents a summarised overview of the key findings and conclusions drawn from the entire scenario-modelling process.

2 Overview of the Undilla Sub-basin

2.1 Location of the Undilla Sub-basin

The groundwater modelling study is centred on the Undilla Sub-basin, which is in the eastern central Georgina Basin in the south-west Gulf of Carpentaria (Kruse et al., 2013). It covers an area of approximately 50,900 km^2, which represents about 15% of the total Georgina Basin area. The location of the Undilla Sub-basin relative to the Georgina Basin and Southern Gulf Water Resource Assessment catchments is presented in Figure 2-1.

The Georgina Basin contains a relatively thin stratigraphic succession of predominantly carbonate sediments up to 450 m thick. It is deposited on a tectonically stable platform. Deposition in the central portion of the basin commenced with a marine transgression in the early middle Cambrian and may have extended into the late Cambrian. The basin is bounded to the north-east and east by Palaeo-Mesoproterozoic strata of the South Nicholson Basin, Lawn Hill Platform and Mount Isa Inlier.

The South Nicholson Basin, which also underlies the Undilla Sub-basin, is a Paleo- Mesoproterozoic intracratonic sedimentary basin composed mostly of folded and faulted sandstones, siltstones and dolostones that in some places have been intruded by minor igneous rocks (Ahmad et al., 2013).

The major productive aquifers in the study area with potential for development for irrigated agriculture occur in the karstic rocks of the Camooweal Dolostone and Thorntonia Limestone units and are referred to as the Cambrian Limestone Aquifer (CLA).

The study area has a tropical savanna (Aw) climate with a distinct winter dry season to a hot semi-arid (BShw) climate with some monsoonal influence. Rainfall is very seasonal with about 90% falling during the wet season (November to April), and runoff is highest in February and March. This is followed by an 8-month dry season during which there is little surface runoff and groundwater provides baseflow to the perennial rivers in the area.

Mean annual rainfall for the township of Camooweal, located roughly in the centre of the Undilla Sub-basin, is 420 mm (with a standard deviation of 182 mm). Maximum recorded annual rainfall was 1003 mm in 1974; the lowest was 100 mm in 2001. Mean annual areal potential evapotranspiration is 2932 mm with a relatively small annual variation (standard deviation of 271 mm). Areal potential evaporation exceeds mean rainfall in every month of the year. Rainfall and runoff generation both decline with distance from the coast but otherwise show little spatial variation. At Camooweal, the mean annual maximum temperature is 32.5 °C and the mean annual minimum is 17.3 °C.

The vegetation is a mosaic of treeless grasslands and low open savanna woodlands.

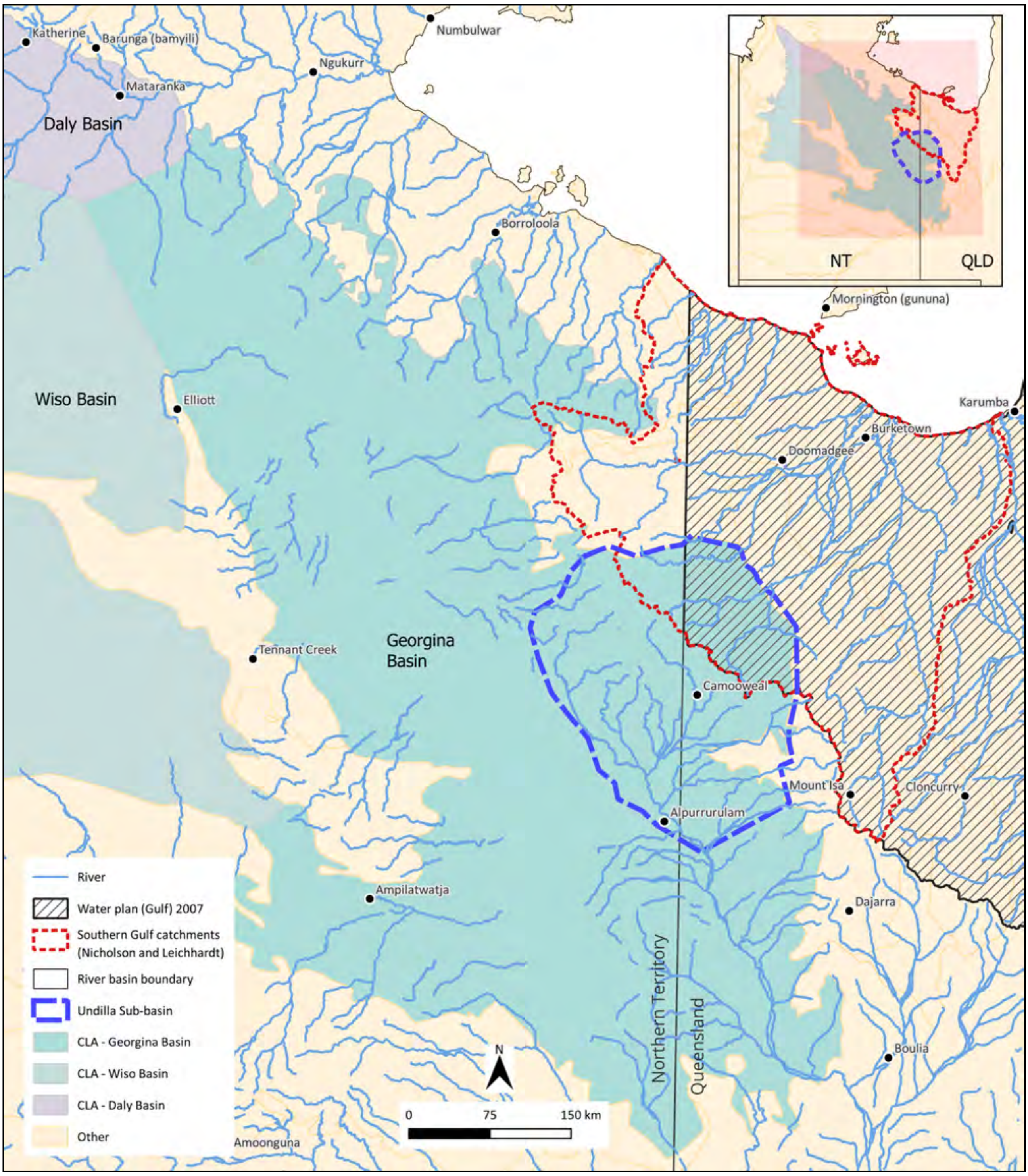


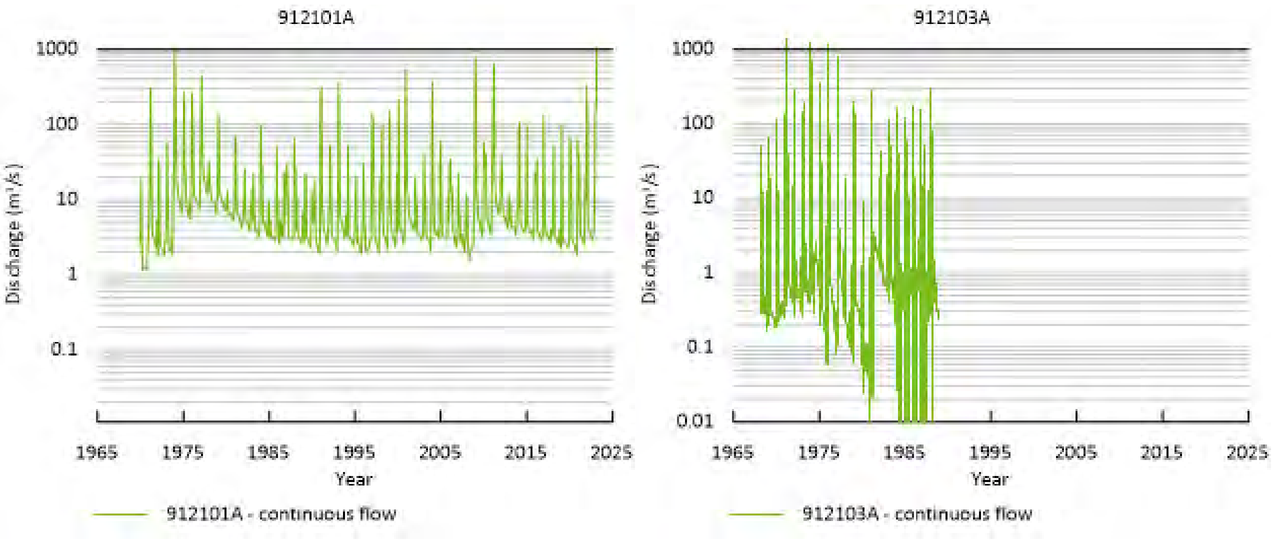
Figure 2-1 Location of the Undilla Sub-basin and its relationship to the Southern Gulf (Nicholson and Leichhardt) catchments and the groundwater systems of the Cambrian Limestone Aquifer in the Daly, Wiso and Georgina basins

2.2 Gregory River and Lawn Hill Creek

2.2.1 Flow regime

The Gregory River and Lawn Hill Creek are perennial streams within the Nicholson catchment, which covers an area of about 51,632 km^2. The streams have a distinct seasonal flow regime with 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 Gregory River and Lawn Hill Creek maintain persistent streamflow or baseflow due to groundwater discharge from regional aquifers (CSIRO, 2009; Jolly and Tickell, 2011; Tickell, 2003).

Using the flow record at 912101A (see Figure 2-3 for location), and assuming the total runoff is represented by the area under the curve in Figure 2-2, the regional-scale baseflow component from the CLA can be estimated. By annualising the minimum flow rate for each year, this baseflow is calculated to be about 3 m^3/second, or about 15% of the total annual runoff in the Gregory catchment.


(a)

(b)

Figure 2-2 Continuous stream flows at (a) 912101A – Gregory River and (b) 912103A – Lawn Hill Creek

The dry-season baseflow of the Roper River, about 400 km to the north-east, is also sourced from the regional carbonate aquifers of the Daly and Georgina basins. The headwaters of the Roper River are incised into the Tindall Limestone. The limestone aquifers in the Daly Basin supply about 4 m^3/second of baseflow to the Roper River.

2.2.2 Groundwater contribution to surface flow

The Gregory River and Lawn Hill Creek source their dry-season flow from the Camooweal Dolostone and Thorntonia Limestone. Reaches of rivers where significant spring inflows and groundwater discharge through the streambed is known to occur are shown in Figure 2-3.

Monthly streamflow data exist for gauging stations 912101A and 912105A on the Gregory River, and 912103A on Lawn Hill Creek (see Figure 2-3). Gauge 912101A has data from the late 1960s to the present, while gauge 912103A has data from the late 1960s to 1990, likely due to the station being abandoned. Evaluation of these data has revealed that the accuracy of historical flows measured at gauges 912101A and 912103A has been reduced due to the formation of tufa dams during the dry season. Tufa dams are formed naturally through the localised precipitation of carbonate minerals on instream rock bars as surface water is progressively concentrated by evaporation. As these dams build, the gauged river height upstream increases, leading to an overestimate of the actual streamflow rate.

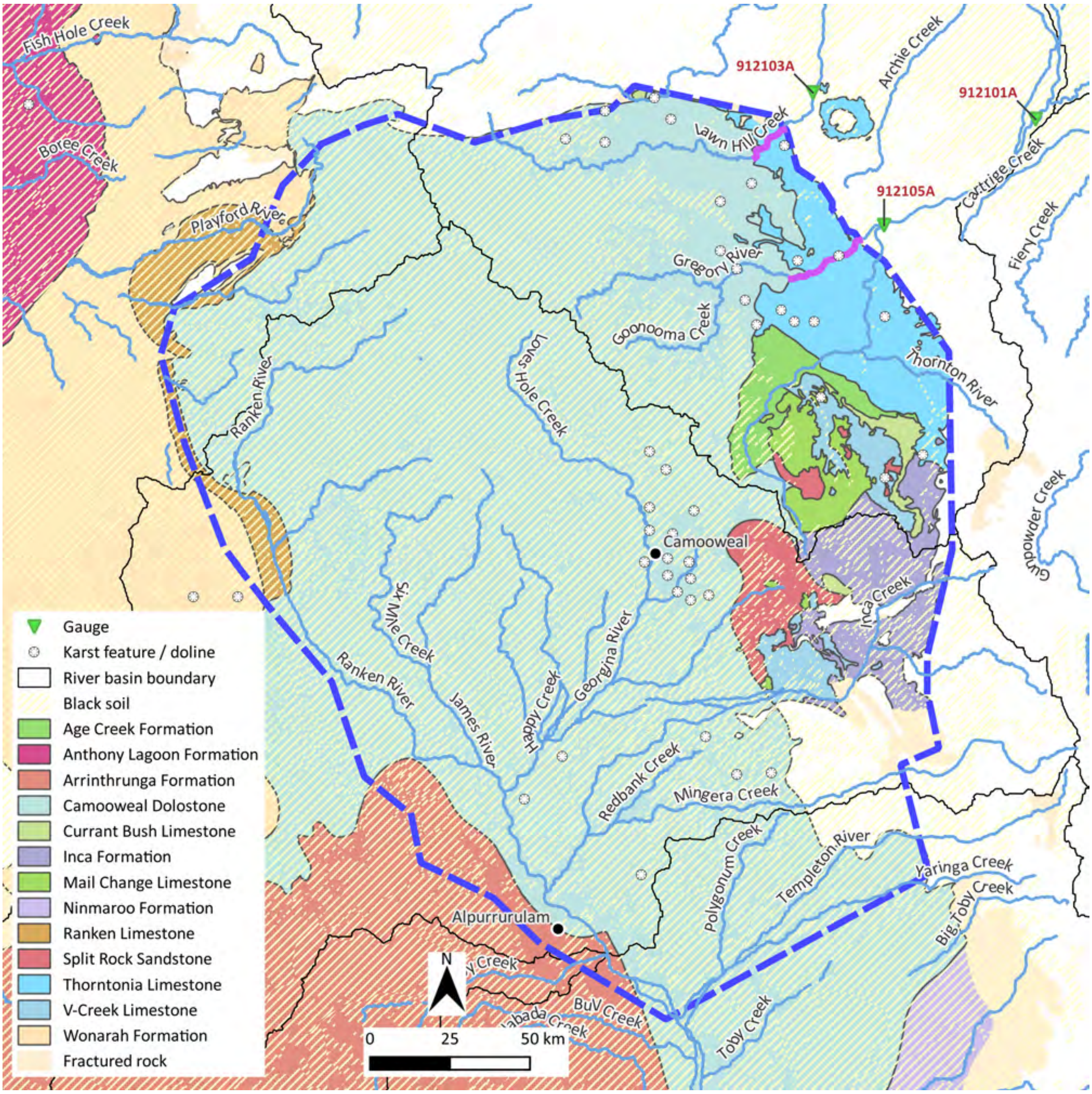


Figure 2-3 Local hydrogeology of the Undilla Sub-basin (after Stewart et al., 2020) showing the extents of Cenozoic sediment cover (yellow hashed regions) and mapped karst features including dolines (after Grimes, 1988)

The data at gauge 912101A are thought to be less affected by tufa formations and to provide a more reliable indication of the long-term variability in dry-season flow conditions in the Gregory River (CSIRO, 2009). However, at 912103A, the period from 1975 to 1980 appears to significantly under-report flows, as the corresponding period at 912101A shows the greatest flows.

Analysis of flows at 912101A indicates a lag time of at least 2 years between the peak of annual rainfall (not shown) peaks and the peak of dry-season (in this case August) streamflow. This suggests there is significant inertia and hence storage within the surrounding aquifer (CSIRO, 2009).

2.2.3 Surface water – groundwater connectivity

Surface water – groundwater connectivity is strongly controlled by the prevailing geological conditions. Regions where the carbonate sediments outcrop exhibit high connectivity with the rivers (CSIRO, 2009; Jolly and Tickell, 2011; Tickell, 2003). Connectivity is via karstic features (e.g. caves, caverns and springs) associated with the carbonate rocks of the Camooweal Dolostone and the Thorntonia Limestone. The inferred locations of areas with high connectivity between the surface water and groundwater are presented in Figure 2-3.

2.3 Hydrogeology of the Undilla Sub-basin

The study area is roughly consistent with the Undilla Sub-basin along the eastern margin of the central and eastern Georgina Basin. The Georgina Basin is a broad north-west to south-east trending intracratonic basin that covers an area of some 325,000 km^2, of which 60% is in the central eastern part of the NT and the remainder in north-western Queensland.

Cambrian and Ordovician marine carbonates and clastics and Devonian continental sediments were deposited in a gently down-warping basin. These sediments thicken progressively in a south-south-easterly direction, rarely exceeding 400 m in thickness in the northern half of the basin and reaching about 5000 m in thickness in the south. The basin has been deformed in the late Devonian to early Carboniferous by minor to moderate folding in the south, grading to moderate to severe folding and extensive overthrusting along the south-western margin.

The central portion of the Georgina Basin is divided by the Alexandria–Wonarah Basement High (Howard, 1971) into a western Barkly Sub-basin and an eastern Undilla Sub-basin, which extends into western Queensland.

To the south-east, the Georgina Basin is overlapped by units of the Mesozoic Eromanga Basin, which contain aquifers providing some flowing bores in the study area.

There are three major aquifer types in the Undilla Sub-basin: fractured rocks, karstic carbonate rocks (Thorntonia Limestone, Wonarah Formation and Camooweal Dolostone) and Cenozoic aged alluvial sediments. These aquifer types are briefly described below, and their areal extent is shown in Figure 2-3.

Table 2-1 summarises the important hydrogeological units or hydrostratigraphy relevant to the Undilla Sub-basin.

Table 2-1 Major hydrostratigraphic units of the Undilla Sub-basin

FORMATION	DISCHARGE	FORMATION CHARACTER	TRANSMISSIVITY RANGE (m^2/day)	STORAGE COEFFICIENT
Thorntonia Limestone	Gregory River and Lawn Hill Creek	Karstic limestone	600–7000	0.01–0.04
Wonarah Formation	na†	Aquitard	<100	0.001
Camooweal Dolostone	na	Karstic dolostone	2000–5000	0.01–0.04
Cenozoic	na	Clayey residual ‘black soil’	na	na

†na = not applicable.

2.3.1 Fractured rocks

A variety of Precambrian (older than 500 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 (500 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. 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.

2.3.2 Karstic carbonate rock – Thortonia Limestone, Wonarah Formation, Ages Creek Limestone and Camooweal Dolostone

In the Undilla Sub-basin, the dominant stratigraphy comprises the peritidal to marine, early middle Cambrian Thorntonia Limestone of the Narpa Group, unconformably overlain by low- to moderate-energy marine silty dolostone, calci/dolomudstone and siliciclastic mudstone of the Wonarah Formation, overlain by the bioclastic Ranken Limestone and in turn by high-energy barrier and protected back-barrier carbonate rocks of the Camooweal Dolostone of the Barkly Group. Cenozoic sediments cover much of the Cambrian carbonate rocks.

The Thorntonia Limestone is the basal unit in the Undilla Sub-basin. It is composed of middle to late Cambrian limestone and dolomitic limestone with chert nodules and a dolomite maximum thickness of 104 m (60 m in outcrop). It lies unconformably on Precambrian basement.

The Wonarah Formation ranges in thickness from 118 m in drillhole BMR 11 (Cattle Creek) to greater than 191 m in drillhole NTGS00/1. It consists mostly of silty dolostone with calci/dolomudstone and siliciclastic mudstone interbeds. The formation is conformably overlain by the Ranken Limestone and Camooweal Dolostone. The Wonarah Formation disconformably overlies the Thorntonia Limestone. In the Barkly Sub-basin, to the north-east, on or about the western flank of the Alexandria–Wonarah Basement High, the Anthony Lagoon Formation is a lateral equivalent of the Wonarah Formation and consists of dolomitic–siliciclastic siltstone interbedded with dolostone. Correlative units include the Inca Formation, Gowers Formation, Beetle Creek Formation, Currant Bush Limestone and Blazan Shale of the Undilla Sub-basin (Kruse and Radke, 2008; Kruse et al., 2010).

The Camooweal Dolostone (formerly Camooweal Dolomite) is notionally 240 to 300 m thick (Shergold et al., 1976) but is usually less than 200 m thick in drill intersections (Kruse and Radke, 2008). The formation consists of dolostone; minor marl and quartz sandstone; basal intraclast, ooid and oncoid dolostone; and quartz sandstone. Its depositional environment is basal high-energy peritidal to shallow subtidal barrier, passing upward into restricted to epeiric back-barrier. The Camooweal Dolostone is part of the Barkly Group and is conformable between Ranken Formation and Wonarah Formation below and Arrinthrunga Formation above to the west.

The Camooweal Dolostone is middle Cambrian – the lower age limit based on underlying fossiliferous Ranken Limestone and Wonarah Formation and the upper age limit based on apparent conformity with overlying unfossiliferous, notionally upper Cambrian Arrinthrunga Formation.

Canyon topography occurs in the rocks of the Camooweal Dolostone, the Thorntonia Limestone, and to a lesser extent the Age Creek Formation in the east of the Undilla Sub-basin. The sculpturing of these carbonate rocks by the Lawn Hill Creek and the O’Shannassy and Gregory river systems has produced deep canyons, in places more than 50 m deep, with steep cliffs of massive and medium-bedded dolomite and dolomitic limestones. The development of this topography has undoubtedly been aided by the solution and widening of vertical and near-vertical joint planes, as evidenced by the sub-rectangular drainage pattern (Eberhart, 2003; Grimes, 1988).

The major aquifers in the study area occur within the carbonate rocks of the Georgina Basin These carbonate rocks are part of an extensive area that extends across a large part of the NT and into Queensland. The CLA has very high permeabilities due to an extensive network of interconnected solution cavities.

The aquifers of the CLA are typical of karstic aquifers where 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 200 m below the top of the formation. The karstic nature of the aquifers means that, on a local scale, groundwater flow is via preferential pathways, however, on 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.

The CLA is the main contributor to dry-season flow in Lawn Hill Creek and the Gregory River (Jolly and Tickell, 2011; Tickell, 2003).

The Thorntonia Limestone is perhaps the best middle Cambrian limestone (as opposed to dolostone) aquifer in the north-eastern part of the Georgina Basin. Outcrops of the Thorntonia Limestone are massive bedded with open bedding planes and joints. These features suggest fracture openings as the most likely source of porosity, but the drillers logs of several bores suggest that intergranular porosity is more important. Furthermore, none of the logs examined use the words ‘cavities’, ‘caves’, ‘caverns’, ‘broken ground’, ‘lost circulation’ or the like, which are the usual drillers’ terms for indicating fractures and solution openings.

Primary porosity in the Camooweal Dolostone occurs in porous carbonates and in interbedded quartz sandstones, the carbonates having either intercrystalline or intergranular porosity. The importance of each is yet unknown. Although Johnson et al. (1964:18) describe as much as 10% intergranular porosity in dolostone cuttings from drillhole BMR 11 (Cattle Creek), they clearly state that the aquifers encountered in the well were ‘cavernous horizons with loose deposits of dolostone, pebbles and crystals and vuggy horizons’. The lowermost parts of the sequence at the well reputedly contained some beds with an intergranular porosity in excess of 20%.

2.3.3 Cenozoic sediments

The Cenozoic sediments form a mantle of lateritised claystone, and sandstone with grey-black clay-rich soil plains occupy much of the area.

These soils develop by the surface accumulation of residual clays due to the ongoing dissolution of underlying Cambrian carbonate rocks by infiltrating rainwater. Ferruginous deposits contribute dark ironstone pebbles, and windblown sand provides a surficial veneer.

Seasonal wetting and drying of these soils produce a characteristic gilgai (small depressions that forms in clay-rich soils), particularly in arid and semi-arid regions, with associated deep cracks. These features appear to be due to the consequent alternating heave and settlement within the soils, which results in larger components being transported upward to the surface. Very low, circular rises of decametre-scale diameter with a scatter of purple and maroon small chert pebbles probably denote zones of upwelling in these seasonally active soil convection cells. These pebbly rises are recognised to be reasonably reliable indicators of the subsoil Camooweal Dolostone. Large, tabular rafts of the Camooweal Dolostone are brought to the surface by this same process.

The main influence of these Cenozoic sediments is to reduce the recharge to the underlying CLA. The effect of reduced recharge depends on the lithology of the unit, which is predominantly clay and/or clayey sand.

2.4 Water management areas

The Queensland portion of the study area is managed under the Water Plan (Gulf) 2007 and includes the Nicholson Groundwater Management Area (NGMA).

The Water Plan (Gulf) 2007 endeavours to maintain the permanence of water flows in the Gregory River and Lawn Hill Creek to provide aquatic habitat for native aquatic plants and animals, particularly during dry season.

The Water Plan (Gulf) 2007 lists an additional ecological outcomes for groundwater in the plan area, including: (a) maintenance of groundwater contributions to the flow of water in watercourses, lakes and springs; and (b) the support of ecosystems dependent on groundwater, including, for example, riparian vegetation, wetlands and waterholes.

2.5 Reporting metrics

Reporting metrics for the Undilla1 model include calibration statistics regarding fit with observed heads and groundwater discharges. Key outputs include base groundwater-level heads at selected bores in the model domain, head contours, discharges and water balances for the 109-year period from 1910 to 2019. The 109-year period was chosen for consistency with the Roper River Water Resource Assessment (Knapton et al., 2023); however, other parts of the Southern Gulf Assessment use a 132-year time frame.

2.5.1 Groundwater-level metrics

Water level elevations are documented for eight groundwater-level sites distributed across the model domain. The sites are presented in Table 2-2 and their locations are presented in Figure 2-4.

Table 2-2 Groundwater-level reporting sites

GROUNDWATER-LEVEL SITE	STATE	LOCALITY
17045	Queensland	Camooweal township
31025	Queensland	Thorntonia Station homestead
33965	Queensland	Divide between Lawn Hill and Gregory subcatchments
35639	Queensland	Undilla Station homestead
51446	Queensland	Norfolk Station homestead
RN025992	NT	Gallipoli Station homestead
RN018425	NT	Avon Downs Station homestead
RN018622	NT	Alpurrurulam Community (Lake Nash)

2.5.2 Groundwater discharge

Groundwater discharge is reported as discharge from springs along the Lawn Hill Creek (912103A) and the Gregory River (912101A).

Table 2-3 Gauging sites and the corresponding river branch name

GAUGE SITE	BRANCH
912101A	Gregory River (NGMA – Node 4)
912103A	Lawn Hill Creek (NGMA – Node 3)

NGWA = Nicholson Groundwater Management Area.

2.5.3 Annual water balances

Although the Water Plan (Gulf) 2007 is the only water resource plan in the study area, mean annual water balances, determined from the entire 109-year period of the model run, are presented for four different areas within the study area. The mean annual water balance presented for the Lawn Hill and Gregory subcatchment areas within the model domain, the NGMA identified in the Water Plan (Gulf) 2007 and the entire model domain. The location of the NGMA area within the model domain is presented in Figure 2-4.

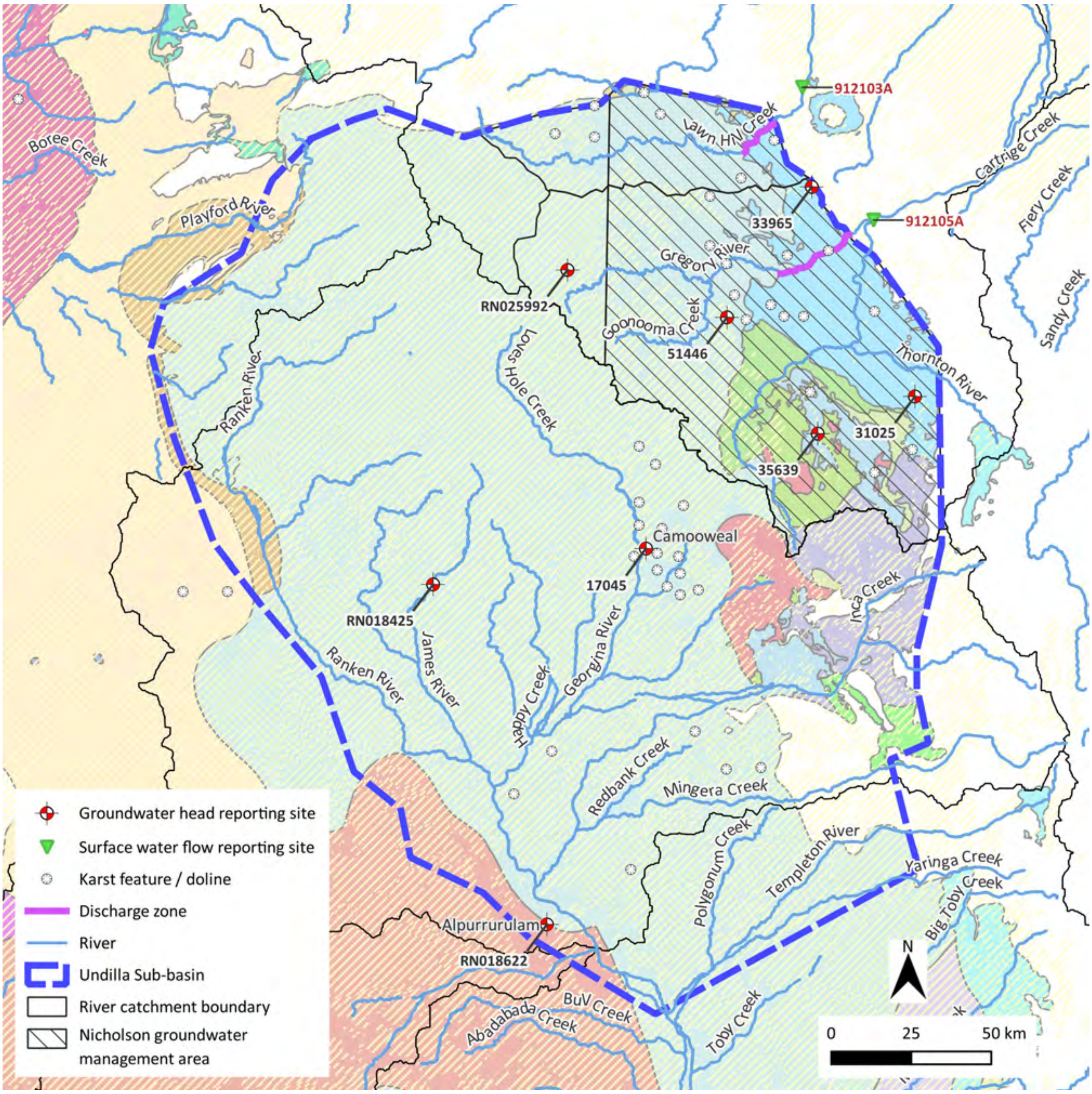


Figure 2-4 Location of groundwater level and flow reporting sites and the NGWA used for water balance reporting

3 Numerical flow model

3.1 Introduction

A key aim of this study is to build a Class 1 initial groundwater flow model, as no known groundwater models exist for the Undilla Sub-basin portion of the Georgina Basin, except for a local-scale (900 km²) groundwater flow model of the Alpurrurulam Community (Lake Nash) borefield, about 120 km south-west of Camooweal (Knapton, 2014). This new groundwater flow model aims to obtain an order-of-magnitude estimate of the groundwater resources in the Camooweal Dolostone and Thorntonia Limestone in this data-sparse part of the Georgina Basin. The following sections present the available data used to develop the conceptual and numerical models of the CLA in the Undilla Sub-basin.

3.2 Previous hydrogeological investigations and modelling

3.2.1 Review of groundwater flow

The aquifers are mainly dolostones and limestones ranging in age from middle Cambrian to early Ordovician. Although the carbonate aquifers are fractured rocks, conditions of storage and movement of water in the central part of the basin are more akin to conditions which pertain for porous aquifers. A regional aquifer system has been developed with the water under confined conditions and with recharge occurring mainly at distant zones along the margins of the basin. Unconfined aquifers, locally recharged, occur along the basin margin, but it has not been possible to assess how far towards the basin these conditions extend.

A total of 458 groundwater standing water levels were obtained from 5507 bores identified in the NT Department of Environment, Parks and Water Security groundwater database, driller-submitted bore statements, and the Queensland Government groundwater database (NT Department of Environment Parks and Water Security, 2019; Queensland Department of Regional Development Manufacturing and Water, 2023). The bore collar elevations were estimated from the Shuttle Radar Topography Mission (SRTM). Groundwater-level contours were generated using Surfer, and to remove artefacts associated with different sampling dates, the grid was ‘smoothed’ using a median filter for water levels at bores within 5000 m of each other. The resulting contours (Figure 3-1) are consistent with those presented by Randal (1978). Regionally, the groundwater levels are higher to the west of the study area and decrease to the south and north-north-west. The groundwater divide corresponds with the Alexandria–Wonarah Basement High.

North of the Alexandria–Wonarah Basement High, the groundwater flow within the CLA is from the south to the north, where it discharges to the lower section of Elsey Creek and the upper Roper River and its major tributaries (Roper Creek and Waterhouse River) in the Roper catchment.

South of the Alexandria–Wonarah Basement High, the groundwater flow within the CLA is from the north to the south, where it possibly discharges to the Eromanga Basin.

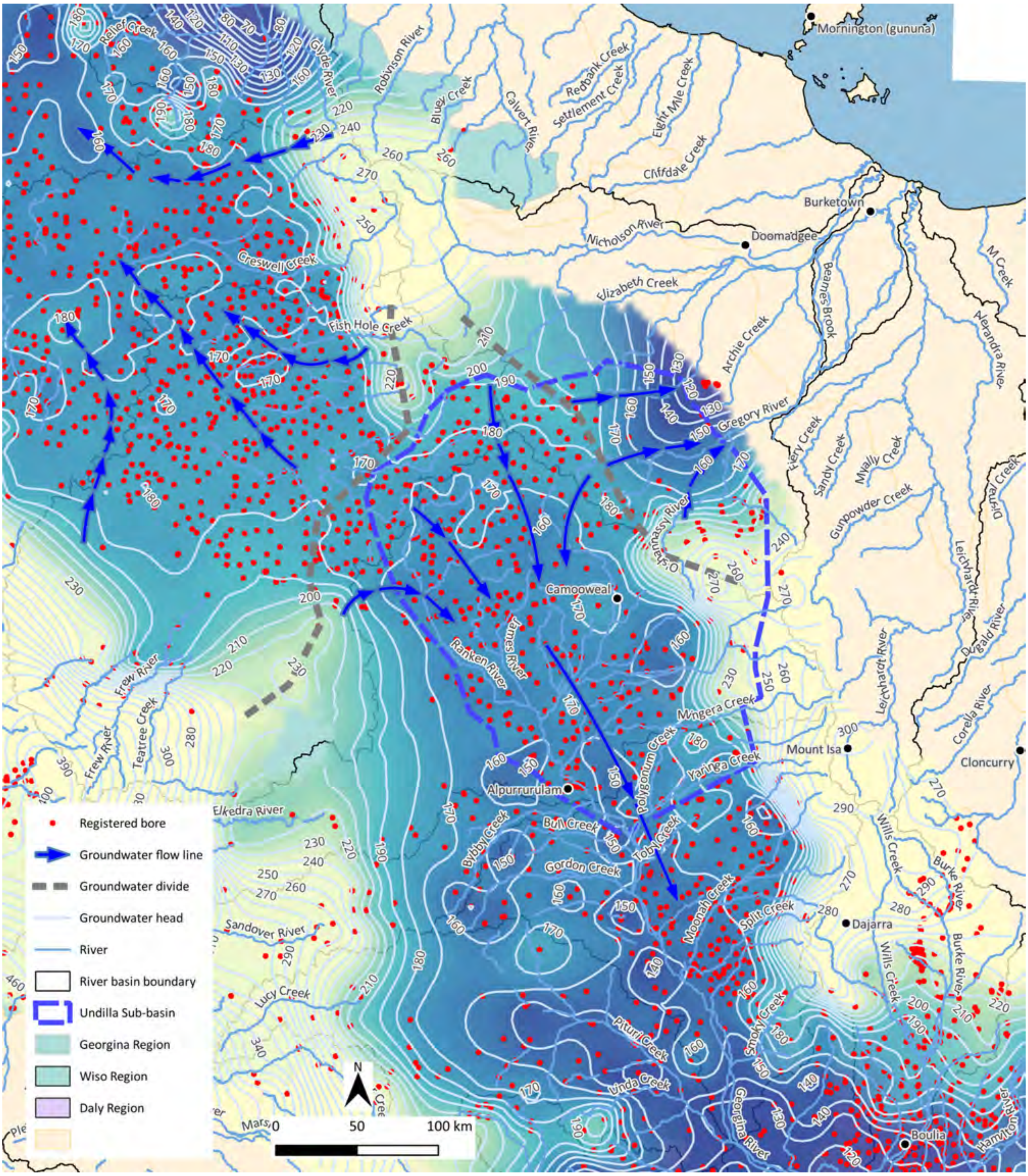


Figure 3-1 Regional groundwater heads and inferred groundwater flow lines

Randal (1978) mapped the regional watertable surface of the south-eastern Georgina Basin from boreholes and identified a groundwater divide at a minimum elevation of about 175 m above Australian Height Datum (mAHD) some 60 km north of Camooweal. From here the regional gradient of the watertable is eastwards and southwards.

The steep groundwater gradients along the east and west margins of the Georgina Basin are expected to be due to a combination of inflows associated with a mountain front recharge mechanism driven by runoff from the adjacent hills and reduced transmissivity where the CLA thins along the margins of the basin.

Once groundwater enters the Georgina Basin, the gradient reduces due to low groundwater fluxes combined with the high transmissivity of the aquifers within the basin, and a low gradient of less than 0.0001 (40 m over 440 km) is evident to the south (refer to Figure 3-1).

Randal (1978) indicates that the regional watertable is below the level of these springs which must therefore be fed by local rainfall seepage. The regional slope of the watertable, as shown by water bores, is to the south, and water movement must be in this direction (Randal, 1967, 1978). No springs have been reported from the southern part of the Georgina Basin, and the water may eventually leak vertically into the overlying aquifers of the Great Artesian Basin.

The gradient to the east is about 0.0005 (40 m over 70 km), suggesting that either the recharge is significantly higher in this area or the transmissivity of the Thorntonia Limestone in this area is less than in the western and southern Undilla Sub-basin.

3.2.2 Review of groundwater recharge

Recharge is thought to occur via four 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 Cenozoic 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.

Groundwater recharge appears to be restricted to areas where the clay soils have been stripped back and the underlying carbonate bedrock exposed (Eberhard, 2003). This occurs in dolines and cave entrances that act as the major groundwater recharge points in the area, due to the low permeability of the black soil which prevents diffuse infiltration. Groundwater recharge is therefore highly localised and dependent on wet-season rainfall events of sufficient intensity to cause surface runoff within the small cave catchment areas. When these precipitation events occur then rapid and direct recharge occurs, often associated with severe flooding of cave passages.

Recharge to the groundwater of the outcropping carbonates is thought to be dominated by macropore and local indirect recharge to doline features. Water balance analysis for the portion of the Undilla Sub-basin contributing to the discharge to Lawn Hill Creek and Gregory River estimates the recharge to the CLA to be about 5 to 7 mm/year. These rates of recharge are consistent with the range of values estimated for the aquifer using the chloride mass balance (CMB) method.

Direct interception of runoff occurs extensively along the basin margin into the outcrop of the Thorntonia Limestone and perhaps also the Camooweal Dolostone.

Direct recharge to most of the units, both carbonate and non-carbonate, occurs in their outcrop zones adjacent to the Mount Isa Inlier. However, recharge by stream action also could be considerable in these zones because of the presence of sandy beds in the upper reaches of the streams. Sandy streambeds are particularly common in the zones of gradient change where the streams pass from the steep terrain of the inlier into the gentler plains and pediments of the Georgina Basin. Spurs in the potentiometric surface along the margins of the basin probably define the zones where recharge is greatest. Most of the rock units are jointed or fractured along the basin margin and provide many zones for the entry of recharge water.

Recharge to Camooweal Dolostone and Thorntonia Limestone is indicated over its outcrops. Many other recharge zones occur, and probably accretion to the groundwater reservoirs takes place to varying degrees over a considerable part of the basin. Recharge need not take place only at outcrop zones. Randal (1967) considered that recharge can take place in the Barkly Tableland over low rises that are the remnants of old lateritised sediments, and which are now covered by light-textured soils, and over isolated areas of sandy and gravelly soils, both of which occur throughout the basin. Randal also indicated the possibility of recharge through the pedocalcic soils where they are thin and extensively cracked. That path, however, is probably relevant only in the very early part of the monsoonal season, as continued wetting ultimately causes the clayey soils to swell and close.

The dominant recharge mechanism in the areas of outcropping Camooweal Dolostone and Thorntonia Limestone is via preferential pathways, but this mechanism is not well understood and poorly represented numerically. The recharge was therefore estimated as diffuse recharge using a scaling of the annual recharge estimates from CMB (Crosbie and Rachakonda, 2021; Raiber et al., 2024), as shown in Figure 3-2. The CMB recharge estimates in the 2021 study are about six to ten times greater than the estimates from the 2024 study (Figure 3-2).

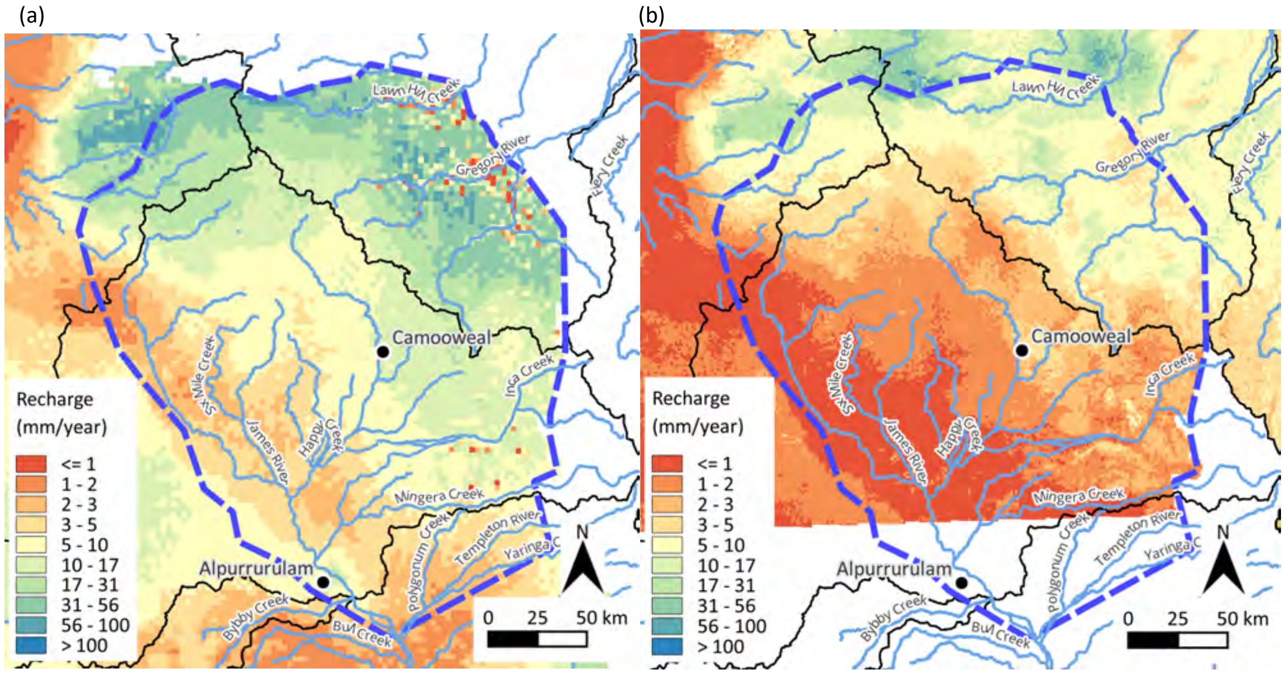


Figure 3-2 Annual median recharge estimates derived from chloride mass balance after (a) Crosbie and Rachakonda (2021) and (b) Raiber et al. (2024)

The mean recharge values within the Gregory subcatchment, using the 50th percentile (p50) or median estimates from CMB recharge by Crosbie and Rachakonda (2021) and Raiber et al. (2024), are 27 and 6 mm/year, respectively. For the Lawn Hill subcatchment, the mean recharge values are 32 and 12 mm/year, respectively.

Crosbie and Rachakonda (2021) found that, for the low-recharge, long-flow-path arid areas in the south of the CLA, the residence time of the water may be thousands or tens of thousands of years, and the assumption that measurements of chloride deposition over the past 60 years are applicable on this timescale is questionable. The assumption of steady-state chloride deposition is a source of unquantified uncertainty in the recharge estimates.

3.2.3 Review of groundwater discharge

Groundwater discharge from the CLA provides the dry-season flow for reaches of the Lawn Hill Creek and Gregory River. Discharge is predominantly from springs, and some diffuse discharge also occurs along portions of rivers (see Figure 2-4).

Randal (1978) found that some springs that exist along the Gregory River and occur mainly around canyon topography in the carbonate rocks of the Camooweal Dolostone cannot be readily related to the regional groundwater system of the Undilla Sub-basin. These springs discharge at elevations many tens of metres above the regional potentiometric surface of the main carbonate aquifers. Randal (1978) also suggested that the chemical characteristics of these spring waters are different from those of the groundwater in the regional aquifers, although he indicated that this may be due to dilution.

Randal (1978) suggested that a possible source of these springs is local runoff which intercepted on the slopes of the dissected plateaux and which moves along joints and fissures to reappear in the watercourses. Because of the greater exposure of rock in this canyon area, and its heavy dissection, many fissures and cavities are available for the interception, storage and movement of large amounts of water. Hence the springs could be active for long periods after rain. The reported gradual reduction in flow rates for the spring-fed streams is probably attributable to cyclic variations in rainfall.

No springs have been reported from the southern part of the Georgina Basin, and the water may eventually leak vertically into the overlying aquifers of the Great Artesian Basin. Groundwater is inferred to flow to the south of the Undilla Sub-basin as throughflow.

Assuming that the minimum annual flows at 912101A are representative of the groundwater discharge to the Gregory River, a lower bound of groundwater discharge can be estimated. The minimum flows range from 1.2 to 11.9 m^3/second and have a mean of 3.3 m^3/second and a median of 2.8 m^3/second. This corresponds to a range of 36 to 374 GL/year and a mean annual discharge of 104 GL/year. Normalising for the subcatchment area (9727 km^2), this is equivalent to a depth of 4 to 11 mm/year and a mean of 4 mm/year. These values are consistent with the more recent CMB recharge estimates by Raiber et al. (2024).

3.2.4 Summary of historical water budget components

The rainfall, recharge from chloride mass balance (Crosbie and Rachakonda, 2021; Raiber et al., 2024) and baseflow from minimum flows at 912101A have been used to estimate the water balance components for the Gregory subcatchment (area = 9727 km^2). The estimates presented in Table 3-1 are expressed as millimetres per year for the available period of flow record from 1970 to 2019. The evaporation component has been calculated assuming a closure of the water balance using the other estimated components. Some of the figures obtained are only first-pass estimates, although they are considered the best available data as at the time of model development.

Table 3-1 Groundwater balance estimates for the Gregory subcatchment, 1970 to 2019

COMPONENT	MEAN (mm/year)	RANGE (mm/year)
Precipitation	458	168–946
Recharge	17	6–27
Baseflow	11	6–22
Evapotranspiration	430	119–934

3.3 Conceptual model

The major aquifers in the CLA are karstic and are 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. Previous modelling studies have demonstrated that, at a basin-wide scale, karstic aquifers can 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 CLA) and relatively low storage coefficient / specific yield with estimates ranging from <0.01 to 0.06 (i.e., <1% to 6%).

Areas with sinkhole development show increased permeability, while preferential flow often follows major structural features and discharges at springs. Recharge and discharge processes are likely to dominate in regions where black soil is absent, further influencing groundwater flow dynamics.

3.4 Undilla1 (CLA) groundwater flow model description

3.4.1 Introduction

The groundwater flow model of the unconfined and confined areas of the CLA within the Undilla Sub-basin is referred to as the Undilla1 groundwater flow model. This model covers an area of 50,900 km^2 as presented in Figure 2-1.

3.4.2 Previous modelling

No previous modelling exists for the portion of the north-east Georgina Basin discharging to the Gregory River and Lawn Hill Creeks. Groundwater flow of the CLA for the Georgina Basin to the north-west of the Alexandria–Wonarah Basement High is modelled using the DR2 groundwater flow model as detailed in Knapton (2020). Local-scale (900 km^2) groundwater flow modelling has also been conducted for the Alpurrurulam Community (Lake Nash) borefield about 120 km to the south-west of Camooweal (Knapton, 2014).

3.4.3 Groundwater model development

The Undilla1 groundwater flow model of the CLA in the Undilla Sub-basin is a two-dimensional, single-layer finite element numerical model.

The Undilla1 groundwater model was developed using the FEFLOW simulation code (Diersch, 2008). The CLA groundwater system is conceptually characterised as an equivalent porous medium. 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.

3.4.4 Finite element mesh

The model domain is roughly coincident with the extent of the Undilla Sub-basin and covers an area of 50,900 km^2. The northern and eastern boundaries are coincident with the margin of the Georgina Basin, the north-western boundary is coincident with the Alexandria–Wonarah Basement High, and the western and southern boundaries are coincident with the mapped occurrence of the Camooweal Dolostone (see Figure 2-3).

The elements of the finite element mesh are roughly equidimensional (mean = 28 km^2, standard deviation = 12 km^2) with some refinement around the Lawn Hill Creek and Gregory River (~1 to 2 km^2). The finite element mesh geometry showing pilot point locations and specified head boundary conditions along Lawn Hill Creek, Gregory River and the throughflow boundary to the south is presented in Figure 3-3.

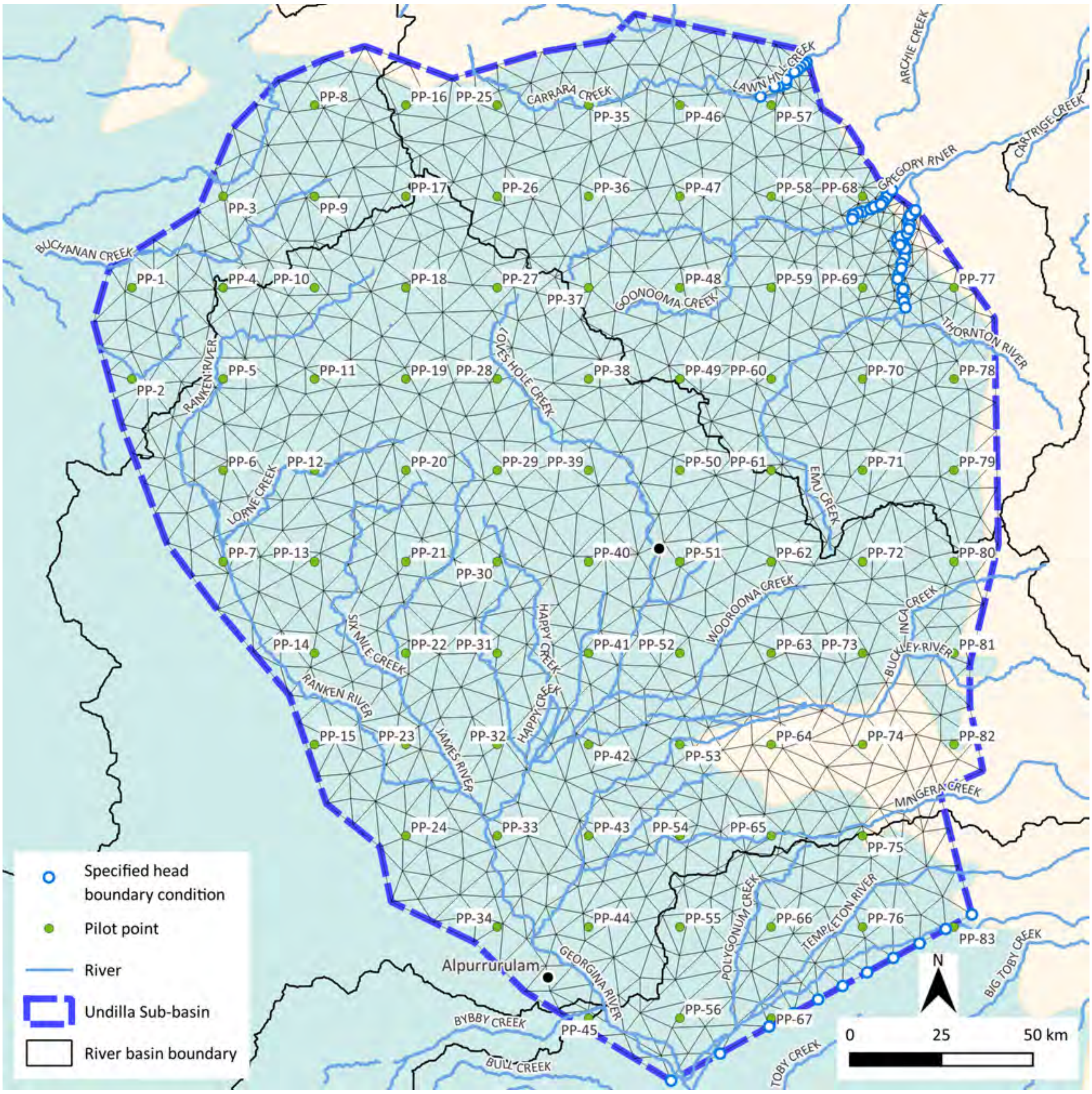


Figure 3-3 Finite element mesh geometry showing pilot point locations and identifiers and specified head boundary conditions along Lawn Hill Creek, Gregory River and the throughflow boundary to the south

3.4.5 Groundwater model inputs and parameters

Recharge is applied to the top slice of the groundwater model using annual recharge estimates from the CMB method to scale the rainfall record. Rainfall data were obtained for a site located at latitude 19.5°S and longitude 138°E, extracted on 22 March 2024 from the Scientific Information for Land Owners (SILO) Data Drill (https://www.longpaddock.qld.gov.au/silo/). SILO is maintained and hosted by the Science and Technology Division of the Queensland Government's Department of Environment and Science and provides a comprehensive database of climate data for Australia (Jeffrey et al., 2001). The recharge estimate is empirical and does not account for processes such as preferential or bypass flow.

The transmissivity parameter distribution was applied to the elements in the model via pilot points and the interpolation code PLPROC (Doherty, 2024). Pilot points were placed throughout the model domain at 25 km × 25 km spacing to allow for a flexible spatial parameterisation. The pilot point locations and their identifiers are presented in Figure 3-3.

For this initial assessment, storage coefficient was applied as a single value to the entire model domain.

The groundwater model includes boundary conditions that define the interaction between the rivers and the groundwater system. Discharge from the rivers is implemented using specified head boundary conditions, whose locations are presented in Figure 3-3.

Discrete springs are not included in the model as pathways are too poorly understood and at a scale too small to be adequately represented. Extraction for stock and domestic and horticultural use is not included.

3.4.6 Undilla1 calibration

The calibration process used a combination of pilot points (Doherty, 2003) and PEST_HP, an automated nonlinear parameter estimation code (Doherty, 2024). PEST_HP iteratively calibrated the model by adjusting the pilot point parameters and recharge parameter 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 (474 head observations) in the CLA and discharge measurements: 638 for the Gregory River (912101A) and 242 for Lawn Hill Creek (912103A). The discharge measurements were weighted to emphasise the dry-season values, which are assumed to represent groundwater discharge.

Groundwater levels at each bore consist of a single water level recorded at the time of construction. This has been assumed to correspond to the end of the dry season for the year 2019. This assumption is likely to introduce a significant bias where bores were installed during periods not representative of recent conditions.

The results of the calibration process are detailed in the following sections.

3.5 Undilla1 calibration results

The results of the calibration process are presented through scatter plots and histograms of residuals between measured and modelled outputs, along with summary statistics. The final transmissivity distribution, hydrographs of groundwater levels at the reporting sites, and head distribution for 2019 are included. Additionally, discharge hydrographs at the two streamflow gauge sites and mean annual water balances are detailed in the following sections.

3.5.1 Calibration statistics

Scatter plots of measured and modelled groundwater levels and discharge are presented in Figure 3-4a and Figure 3-4b, respectively.

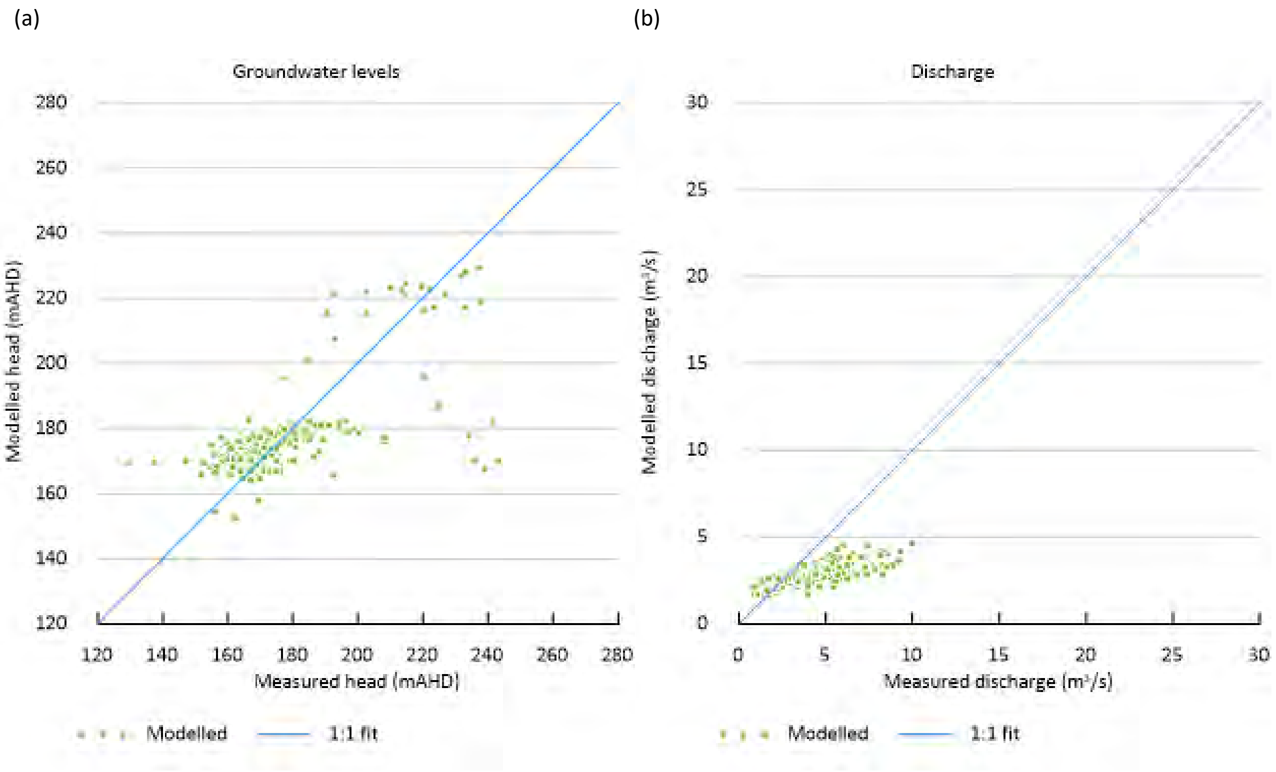


Figure 3-4 Scatter plot showing fit between (a) modelled and measured groundwater levels and (b) modelled and measured groundwater discharge at both 912101A on the Gregory River and 912103A on Lawn Hill Creek

The residuals for the three observation groups (obsgrp1 – heads, obsgrp2 – discharge at 912101A and obsgrp3 – discharge at 912103A) are plotted in Figure 3-5. Observations about the residual distributions for each observation group are provided below.

The mean deviation of modelled to measured values for obsgrp1 from the expected value is 1.5 m. The positive value indicates a slight overestimation on average. A relatively high root mean square (RMS) value of 11.9 m indicates a large spread of residuals around the mean, although this is a reasonable scaled RMS (SRMS) of 10% relative to the maximum range of observed values.

The mean deviation of modelled to measured values for obsgrp2 from the expected value is 0.5 m^3/second. The positive value indicates a slight overestimation on average. The RMS value of 1.1 m^3/second indicates residuals are relatively tightly clustered around the mean, although this is a relatively large SRMS of 18% relative to the maximum range of observed values.

The mean deviation of modelled to measured values for obsgrp3 from the expected value is −0.56 m^3/second. The negative value indicates a slight underestimation on average. The RMS value of 0.8 m^3/second indicates residuals are relatively tightly clustered around the mean, although this is a relatively large SRMS of 24% relative to the maximum range of observed values.

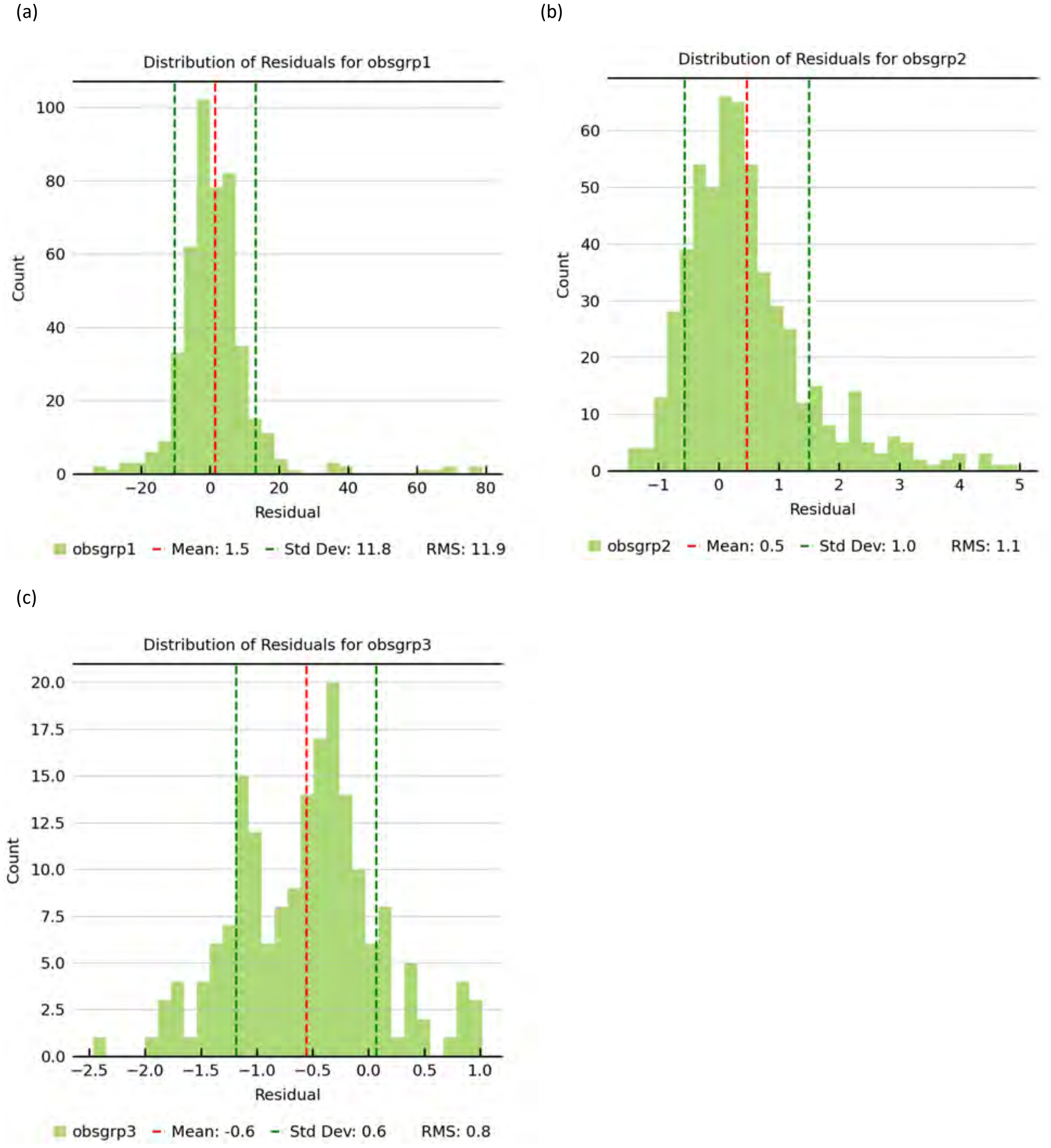


Figure 3-5 Histogram of residuals for (a) obsgrp1 – heads, (b) obsgrp2 – groundwater discharge at 912101A on the Gregory River and (c) obsgrp3 – groundwater discharge at 912103A on Lawn Hill Creek

3.5.2 Transmissivity distribution

The base model calibration distribution is presented in Figure 3-6. The transmissivities range from about 16 m^2/day to 50,000 m^2/day (i.e. 10^1.2 to 10^5 m^2/day in Figure 3-6). The lower transmissivities are in the area to the east of Camooweal where outcropping Inca Formation, Mail Change Limestone and Split Rock Sandstone are present (Figure 2-3).

The transmissivities in the north-eastern third of the model domain are considered reasonable for the type of aquifer. However, the highest transmissivity values, which are predominantly in the south-western two-thirds of the model domain, are much higher than expected. The higher values reflect the low groundwater gradient and are likely a result of recharge being over estimated (Crosbie and Rachakonda, 2021) in areas with black soil.

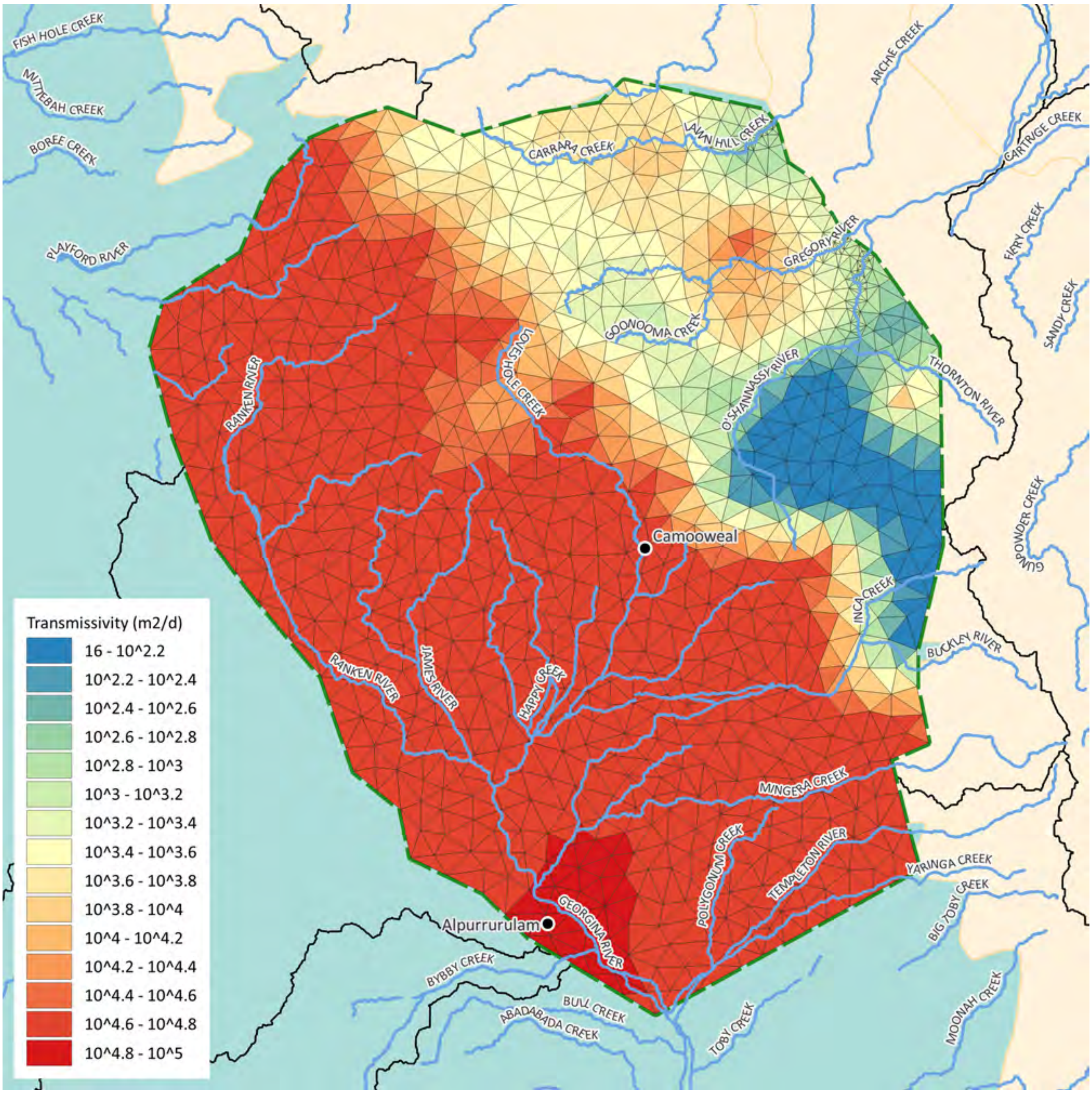


Figure 3-6 Calibrated transmissivity distribution

3.6 Calibrated heads

3.6.1 Groundwater levels at selected locations

The groundwater levels for the eight CLA reporting sites over the 109-year model run from 1910 to 2019 are presented in Figure 3-7 and Figure 3-8. The locations of the reporting sites are presented in Figure 2-4. Note that there are no time series observations to verify the dynamic ranges of the simulated groundwater levels.

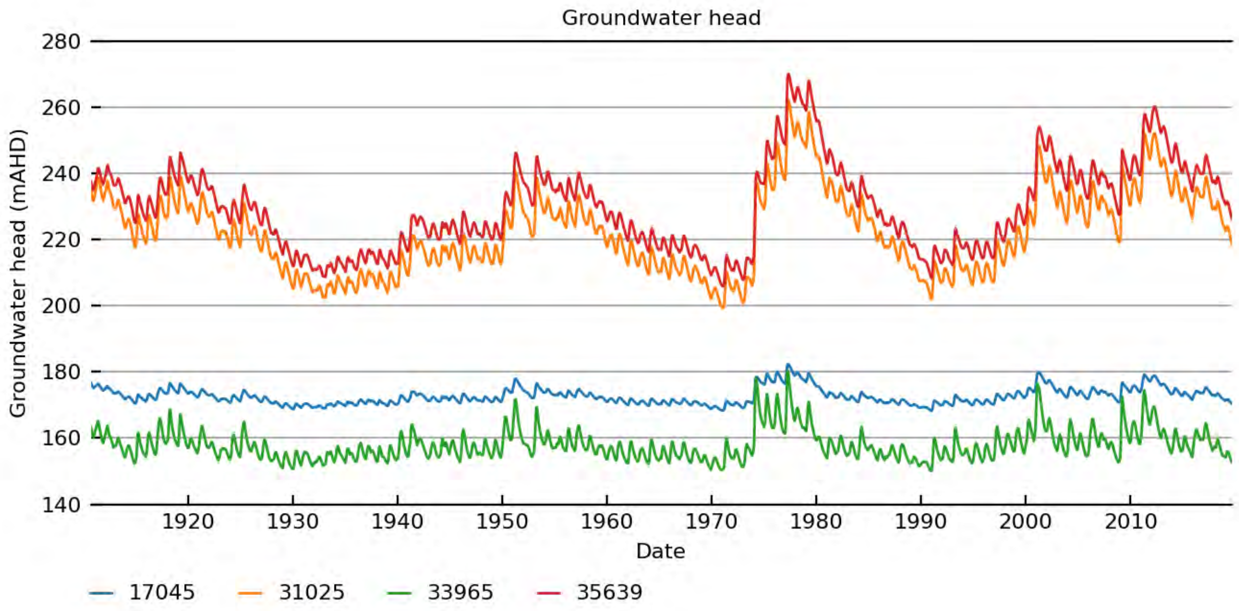


Figure 3-7 Calibrated groundwater levels at selected sites 17045, 31025, 33965 and 35639

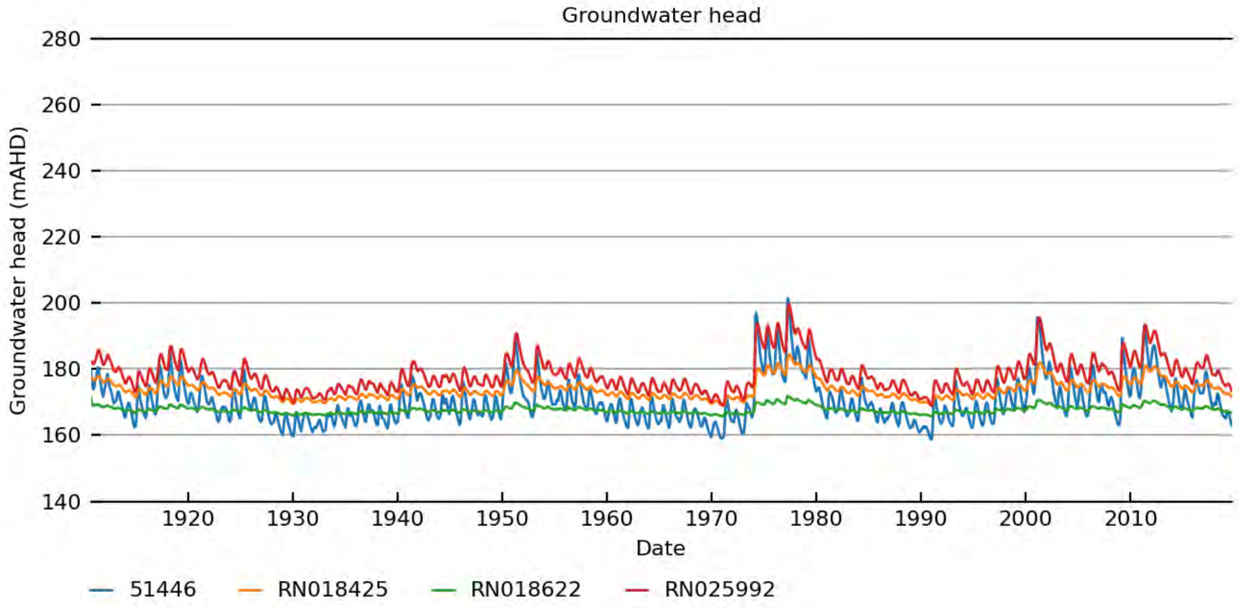


Figure 3-8 Calibrated groundwater levels at selected sites 51446, RN018425, RN018622 and RN025992

The mean groundwater level over the 109-year model run for each site was determined to provide an indicator of the spatial and temporal changes to groundwater levels across different parts of the aquifer.

Table 3-2 Mean groundwater levels (mAHD) for the eight reporting sites for the 109-year period (1910 to 2019) under Scenario A (historical climate and current development)

17045	31025	33965	35639	51446	RN018425	RN018622	RN025992
167.6	226.2	161.9	230.4	173.9	169.2	169.5	178.5

3.6.2 Groundwater contours at 31 August 2019

The groundwater contours on 31 August 2019 in Figure 3-9 are broadly consistent with the regional groundwater level contours presented in Figure 3-1. The south-western portion of the model domain shows low gradients with heads decreasing from north to south. There is a subtle groundwater divide separating the catchment of the Rankin River to the west from the Gregory and Lawn Hill subcatchments to the east, and there are the elevated groundwater heads in the area to the east of Camooweal where the Inca Formation, Mail Change Limestone and Split Rock Sandstone outcrop.

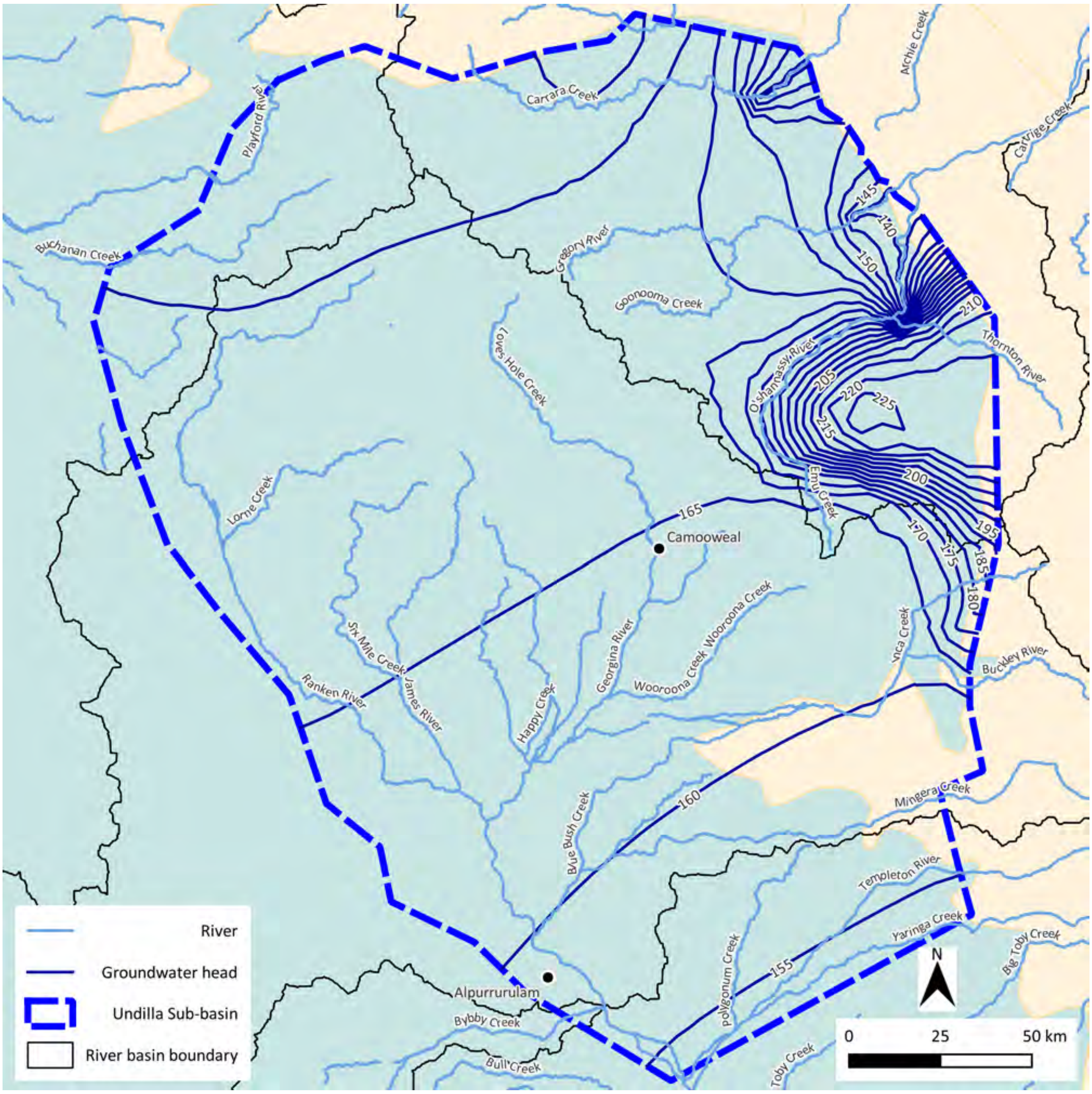


Figure 3-9 Calibrated head contours at 31 August 2019

3.6.3 Groundwater discharge

The mean groundwater discharges to the Gregory River and Lawn Hill Creek for the period 1910 to 2019 are 2.9 m^3/s and 1.3 m^3/s respectively. The modelled groundwater discharges compared to measured flows at 912101A on the Gregory River are presented in Figure 3-10 and at 912103A on Lawn Hill Creek are presented in Figure 3-11.

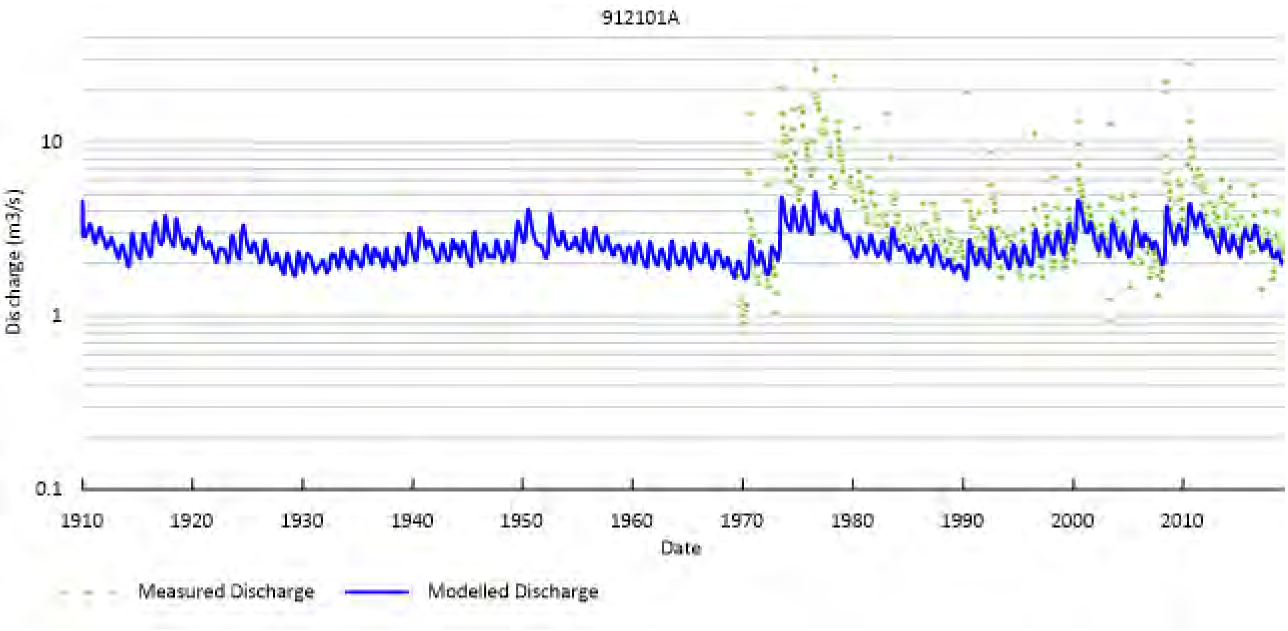


Figure 3-10 Calibrated modelled vs measured groundwater discharge at 912101A on the Gregory River

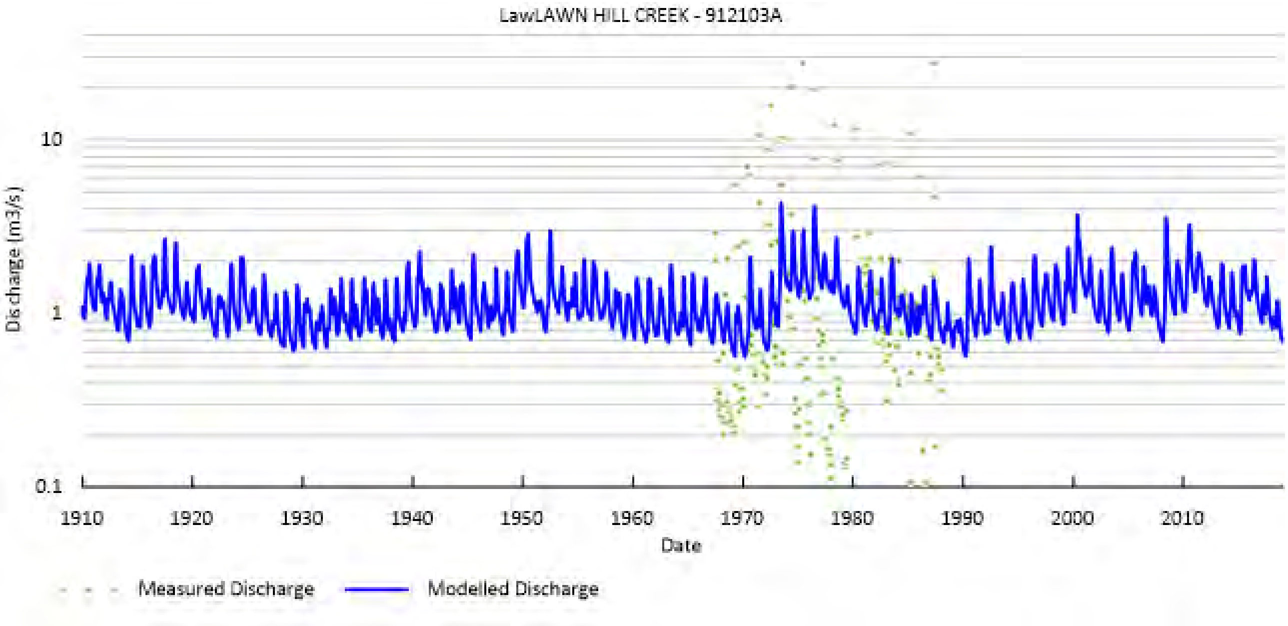


Figure 3-11 Calibrated modelled vs measured groundwater discharge at 912103A on the Lawn Hill Creek

3.6.4 Annual water balance

The mean annual groundwater balances for the 109-year climate sequence are presented for the Gregory River and Lawn Hill Creek subcatchments, the Nicholson Groundwater Management Area (NGMA) and the entire model domain (Table 3-3).

Within the model domain, the Gregory subcatchment area is 9727 km^2 and the Lawn Hill catchment area is 2,344 km^2, which equates to recharge values of 14 and 25 mm/year, respectively. The NGMA covers an area of 10,266 km^2, and the recharge is about 15 mm/year. The mean recharge for the entire model domain (area = 50,867 km^2) is about 7 mm/year.

Table 3-3 Mean annual water balance (GL/year) for the 109-year climate sequence (1910 to 2019) for the Nicholson Groundwater Management Area (NGMA)

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

†NGMA = Nicholson Groundwater Management Area.

3.7 Sensitivity

The sensitivity analysis was undertaken using the first iteration of a PEST_HP estimation run where the relative sensitivity is calculated by dividing the change in the history matching objective function (phi) to a 1% change in the adjustable parameter values. The adjustable parameters and objective function used in the analysis are discussed in the following sections.

3.7.1 Adjustable parameters

The sensitivity analysis examined the effect of all 87 parameters: scaling factor for the steady-state recharge (r1), seepage face head values along the Lawn Hill Creek and Gregory River (h1), the southern boundary (h2), storage parameter for the entire model domain (s1) and transmissivity values for 83 pilot points (t1 to t83).

3.7.2 History match objective function

The history matching objective function (phi) was calculated from the difference between the estimated steady-state groundwater levels and the simulated steady-state groundwater levels. The objective function consisted of the weighted sum of squared residuals using 458 groundwater-level measurements from all registered water bores in the model domain assigned the calibrated steady-state heads, 638 monthly flow observations from the Gregory River at 912101A and 242 monthly flow measurements for Lawn Hill Creek at 912103A.

3.7.3 Undilla1 groundwater flow model sensitivity to adjustable parameters

The relative sensitivity of the history matching objective function (phi) to changes in the adjustable parameters, as determined using PEST and normalised to the maximum sensitivity value for each observation group, are presented in Figure 3-12.

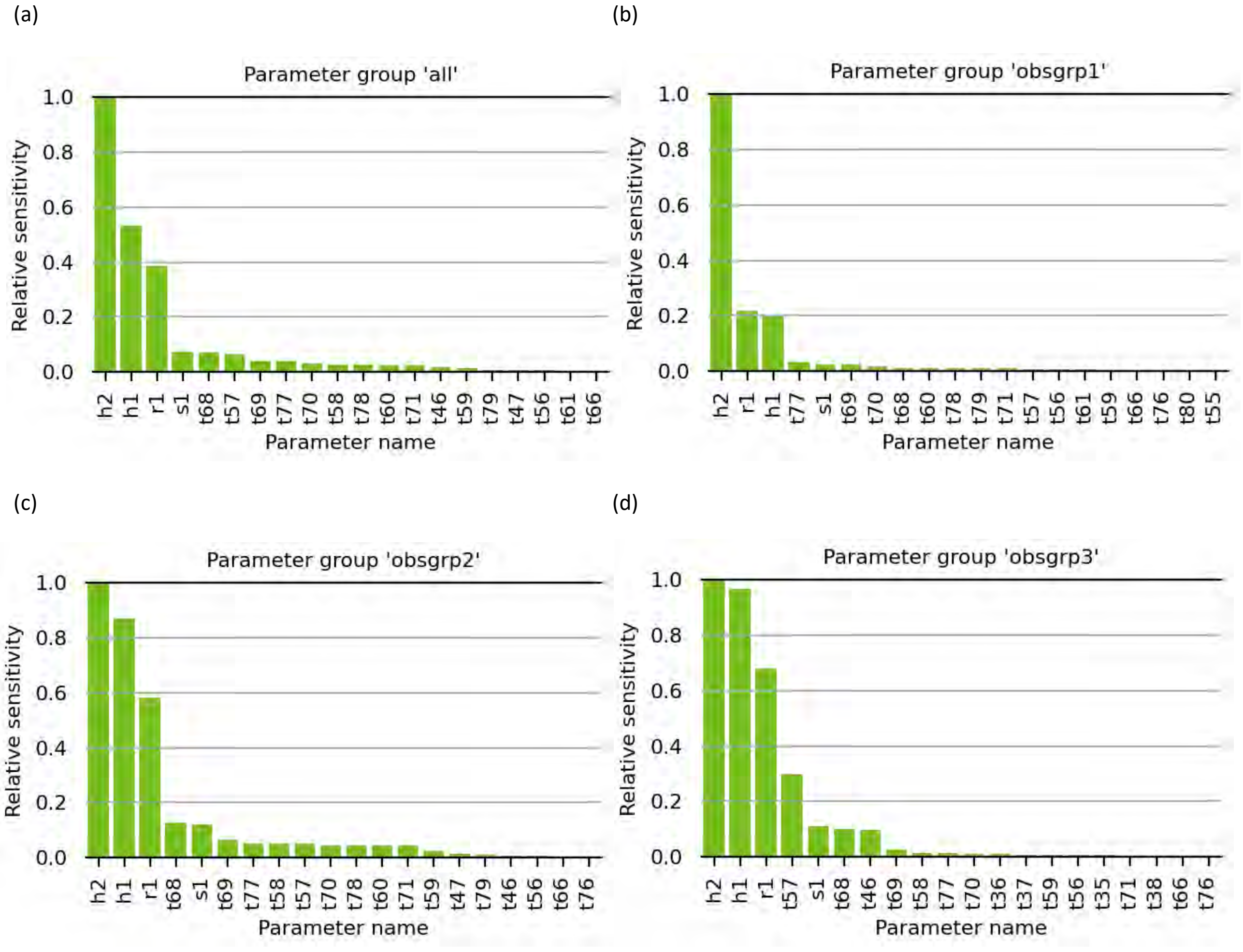


Figure 3-12 Relative parameter sensitivities for a) all observations, b) obsgrp1 – groundwater heads, c) obsgrp2 – Gregory River discharge and d) obsgrp3 – Lawn Hill Creek discharge

The Undilla1 flow model history matching objective function referred to as parameter group 'all' (Figure 3-12a) is most sensitive to the elevation of the southern specified head boundary condition (h2), recharge scaling factor (r1), the elevation of the seepage face nodes representing the Lawn Hill Creek and Gregory River (h1) and to a lesser extent the transmissivity values, with the most sensitive (t57, t69, t69, t77 and t70) being adjacent to the discharge nodes along Lawn Hill Creek and Gregory River.

Parameter group 'obsgrp1' of the objective function (Figure 3-12b), which is composed of the representative end of dry-season head observations, is relatively insensitive to all parameters except the specified head value along the southern boundary of the model domain (h2). The recharge scaling factor (r1) and elevation of the seepage face nodes representing the Lawn Hill Creek and Gregory River (h1) show some influence on 'obsgrp1'.

Parameter group 'obsgrp2' of the objective function (Figure 3-12c), which is composed of the flow record at 912101A along the Gregory River, is sensitive to the specified head value along the southern boundary of the model domain (h2), the elevation of the seepage face nodes representing the Lawn Hill Creek and Gregory River (h1). The recharge scaling factor (r1) and the storage value (s1) show some influence on ‘obsgrp2’.

Parameter group ‘obsgrp3’ of the objective function (Figure 3-12d), which is composed of the flow record at 912103A along Lawn Hill Creek, is sensitive to several factors. These include the specified head value along the southern boundary of the model domain (h2), the elevation of the seepage face nodes representing Lawn Hill Creek and Gregory River (h1), the recharge scaling factor (r1), and the storage value (s1). Transmissivity at pilot point t57, located near the boundary conditions representing Lawn Hill Creek, also shows influence on ‘obsgrp3’.

The sensitivities determined by PEST are also indicative of which parameters are likely to be constrained in the uncertainty analysis (Section 0).

3.8 Uncertainty analysis

An uncertainty analysis was conducted using PESTPP-IES (White, 2018), employing the same parameters as those used in the sensitivity analysis. PEST-IES was run for three iterations to enable reasonable history-matching and provide uncertainty quantification.

3.8.1 Parameter uncertainty

The initial parameter ranges (par0) are presented in Table 3-4. The parameter ranges for the aquifer properties (s1 and t1 to t83) were selected as they covered the typical ranges that could be expected, although the maximum transmissivity value was determined during the initial model setup to reproduce the very shallow groundwater gradient in the western portion of the model domain. The range for the recharge scaling factor was selected to allow enough freedom to capture the uncertainty in recharge rates.

Table 3-4 Initial parameter ranges (par0) for boundary conditions (h1 and h2), recharge scaling factor (r1) and storage coefficient (s1)

PARAMETER (UNIT)	MEAN	MEDIAN	MINIMUM	MAXIMUM
h1† (mAHD)	138.3	138.6	120.0	150.0
h2 ‡ (mAHD)	152.8	153.3	130.0	170.0
r1 (-)	3.3E05	2.0E05	1.0E04	1.0E06
s1 (-)	7.4E-03	6.4E-04	1.0E-05	1.0E-01
t1 to t83 (m^2/day)	30,000	30,000	1.0	50,000

†h1 = elevation of river boundary conditions. ‡h2 = elevation of boundary conditions along the southern boundary

After the third PEST-IES iteration the mean and range of the h1, h2, r1 and s1 parameters from the par2 or final parameter ensemble are listed below:

- The mean recharge scaling factor is 2.1e5 and ranges from 1.3e5 to 4.4e5.
- The mean specified elevation representing the discharge to rivers (h1) is 142.6 mAHD and ranges from 124.3 to 150.0 mAHD.
- The mean specified elevation at the southern boundary (h2) is 157.5 mAHD and ranges from 146.6 to 164.0 mAHD.
- The mean storage value (s1) is 0.0005 and ranges from 0.0001 to 0.0037.

The range in transmissivity values from the 100 realisations used at pilot points t1 to t43 are presented in Figure 3-13 and for t44 to t83 are presented in Figure 3-14. The locations of the pilot points are presented in Figure 3-3.

In Figure 3-13 and Figure 3-14, the par0 (initial parameter ensemble) box and whisker plots represent the prior distributions of transmissivity, and the par2 (final parameter ensemble) box and whisker plots represent the ranges in transmissivity after two iterations of PEST-IES. The boxes represent the interquartile range (IQR) and the whiskers indicate the 1.5 × IQR range for each pilot point. After the second PEST-IES iteration, the par2 ranges are generally consistent with the par0 values, though they typically display smaller ranges.

Transmissivity values at pilot points t16, t25, t26, t35 to t37, t46 to t49, t58, t59, t68, t77 and t78 all correspond to the higher transmissivities area within the Lawn Hill and Gregory subcatchments dominated by Camooweal Dolostone and Thorntonia Limestone.

Transmissivity values at pilot points t57, t60, t61, t69 to t71 and t79 to t81 all correspond to the lower transmissivities area to the east of Camooweal where outcropping Inca Formation, Mail Change Limestone and Split Rock Sandstone.

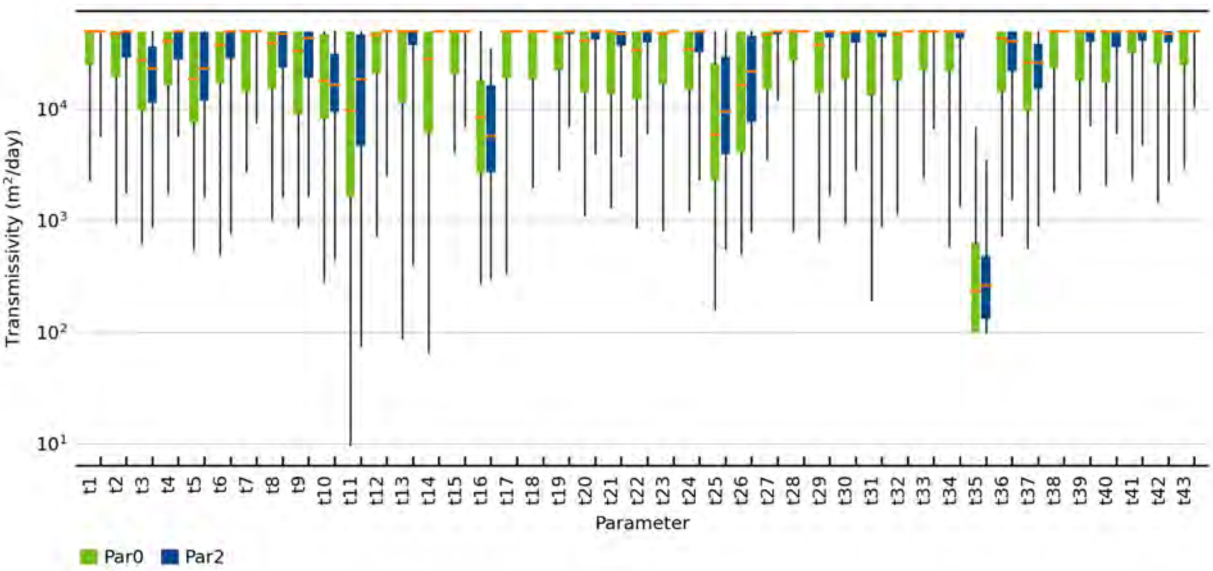


Figure 3-13 Box and whisker chart of transmissivity values at pilot points (t1 to t43) indicating the interquartile range (box) and the minimum–maximum range (whiskers), including outliers

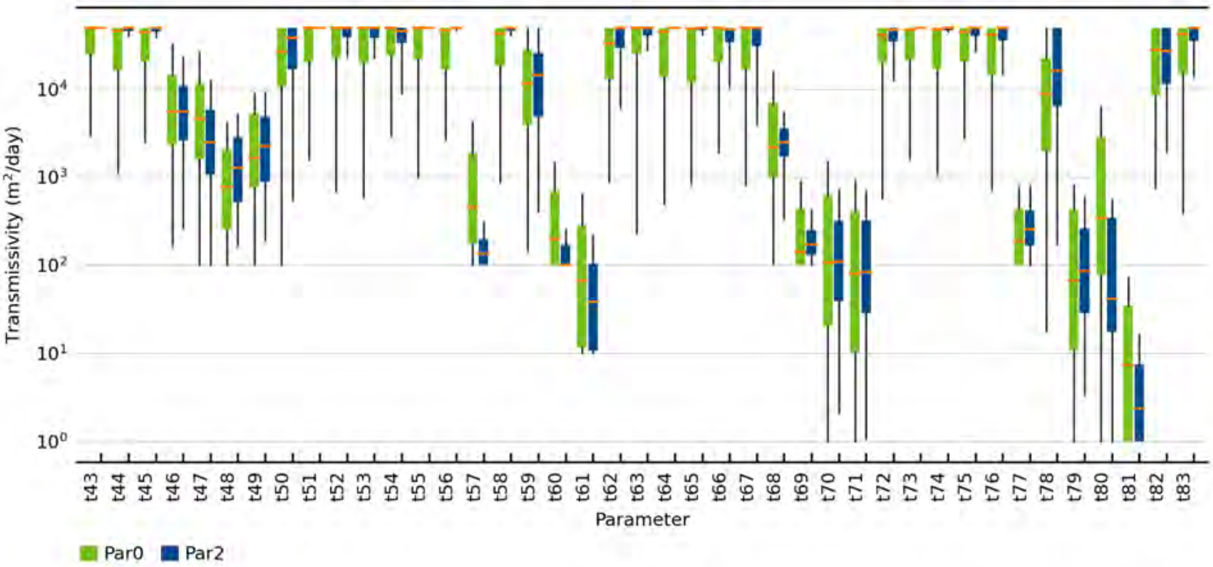


Figure 3-14 Box and whisker chart of transmissivity values at pilot points (t44 to t83) indicating the interquartile range (box) and the minimum–maximum range (whiskers), including outliers

3.8.2 Groundwater levels

The range and median (p50) groundwater levels from the 120 realisations at the eight reporting sites are presented in Figure 3-15 to Figure 3-18.

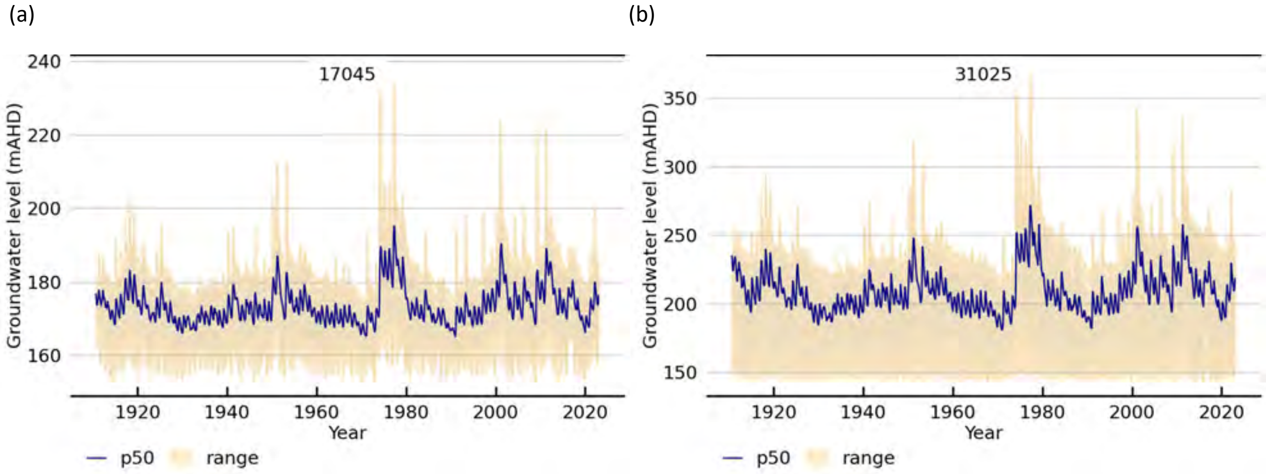


Figure 3-15 Median (p50) and range of simulated groundwater levels for the period 1910 to 2019 at reporting sites (a) 17045 and (b) 31025

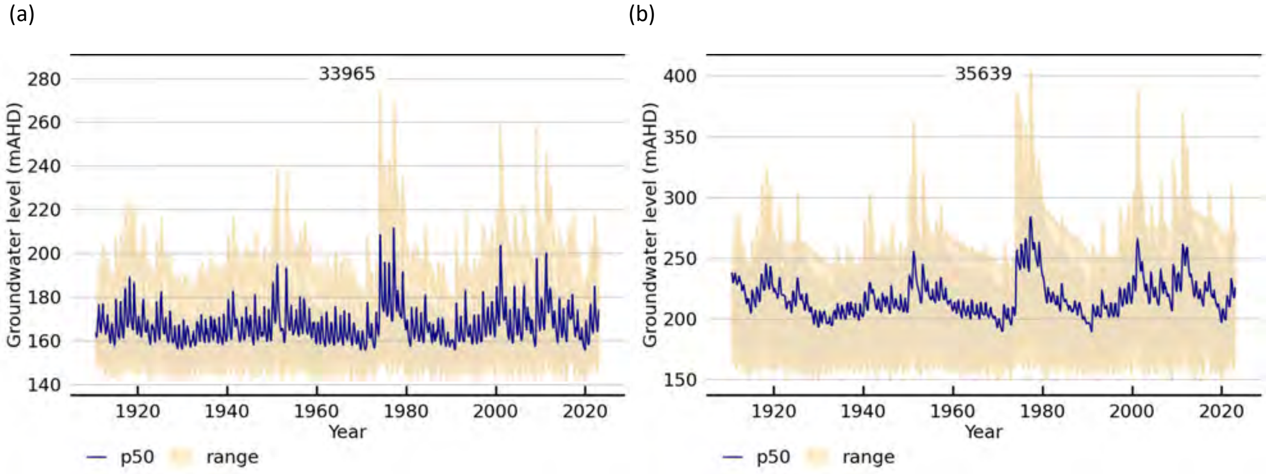


Figure 3-16 Median (p50) and range of simulated groundwater levels for the period 1910 to 2019 at reporting sites (a) 33965 and (b) 35639

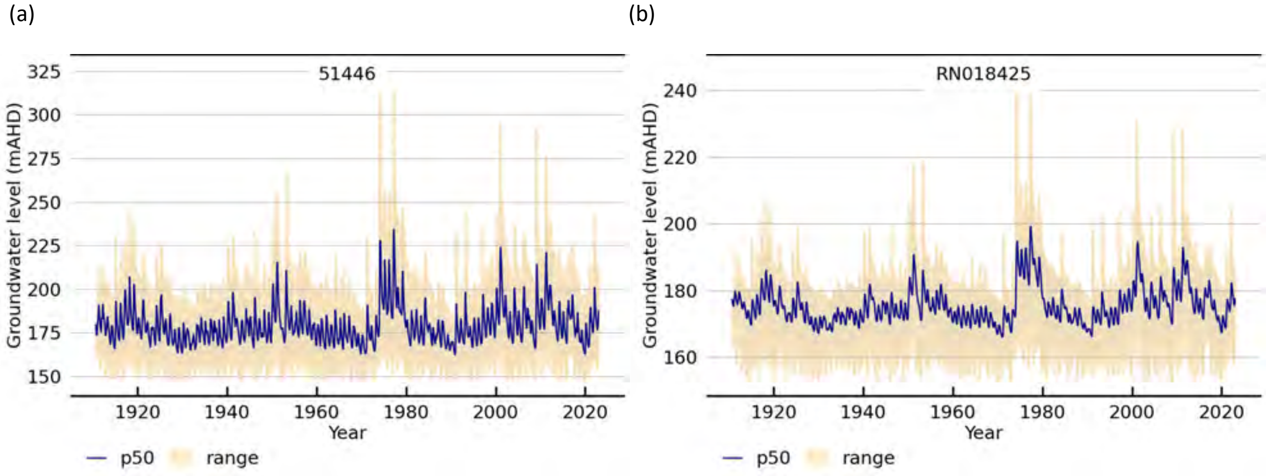


Figure 3-17 Median (p50) and range of simulated groundwater levels for the period 1910 to 2019 at reporting sites (a) 51446 and (b) RN018425

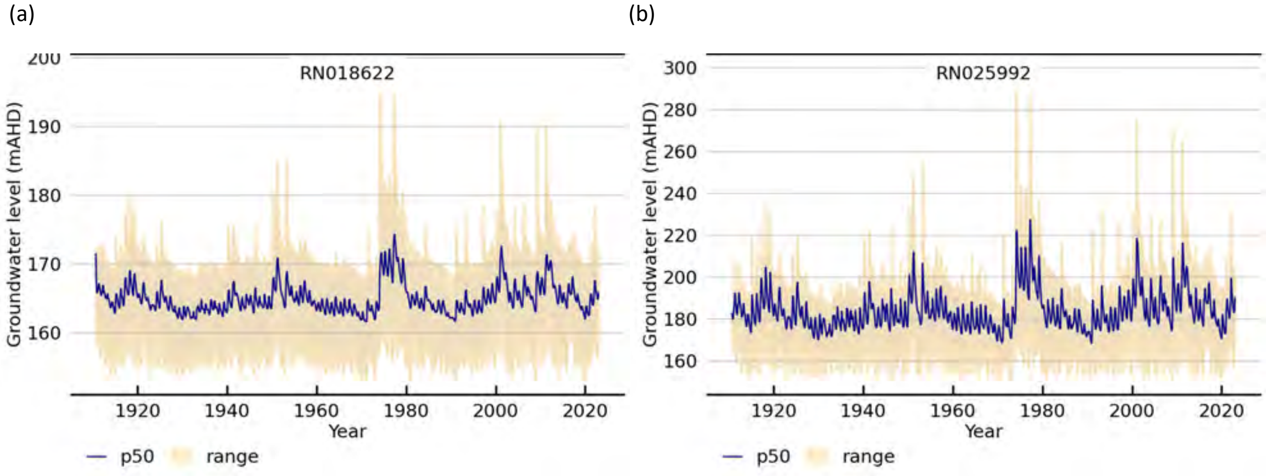


Figure 3-18 Median (p50) and range of simulated groundwater levels for the period 1910 to 2019 at reporting sites (a) RN018622 and (b) RN025992

3.8.3 Discharge

The simulated 50th percentile and range of discharges from the 100 realisations compared to the observed discharges at 912101A on the Gregory River and 912103A on Lawn Hill Creek are presented in Figure 3-19a and Figure 3-19b, respectively.

The simulated range envelops most observations less than 10 m^3/s, although for the period from 1975 to 1980, the low recorded flows at 912103A are not reflected in the simulated range.

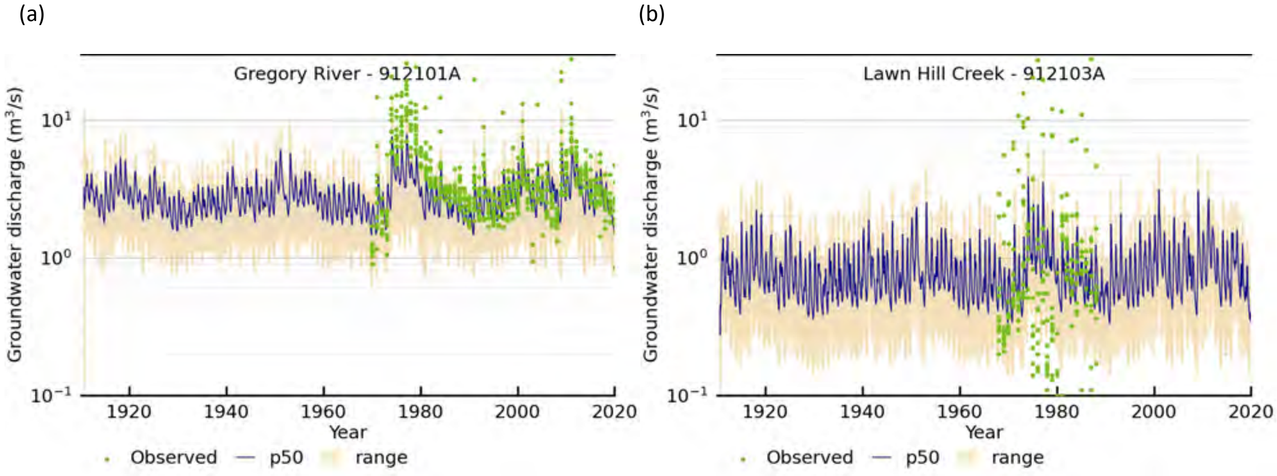


Figure 3-19 Median (p50) and range of simulated groundwater discharge for the period 1910 to 2019 at reporting sites (a) 912101A and (b) 912103A

3.8.4 Mean annual water balances

Mean annual water balances were calculated for each reporting area for the period 1910 to 2019 across 100 realisations, and the results are summarised as box and whisker plots. The box represents the interquartile range (IQR), and the whiskers indicate the 1.5 × IQR range for each component of the water balance. The results for the Gregory River and Lawn Hill Creek are presented in Figure 3-20a and Figure 3-20b, respectively. The results for the NGMA and model domain are presented in Figure 3-21a and Figure 3-21b, respectively. The water balance components are: Dirichlet_In (flow from the river boundary conditions into the model domain), Dirichlet_Out (flow to the river boundary conditions from the model domain), Areal_In (recharge), Areal_Out (evapotranspiration), Stor_In (water released from storage), Stor_Out (water captured into storage), Transfer_In (flows into the area of interest), and Transfer_Out (flows out of the area of interest).

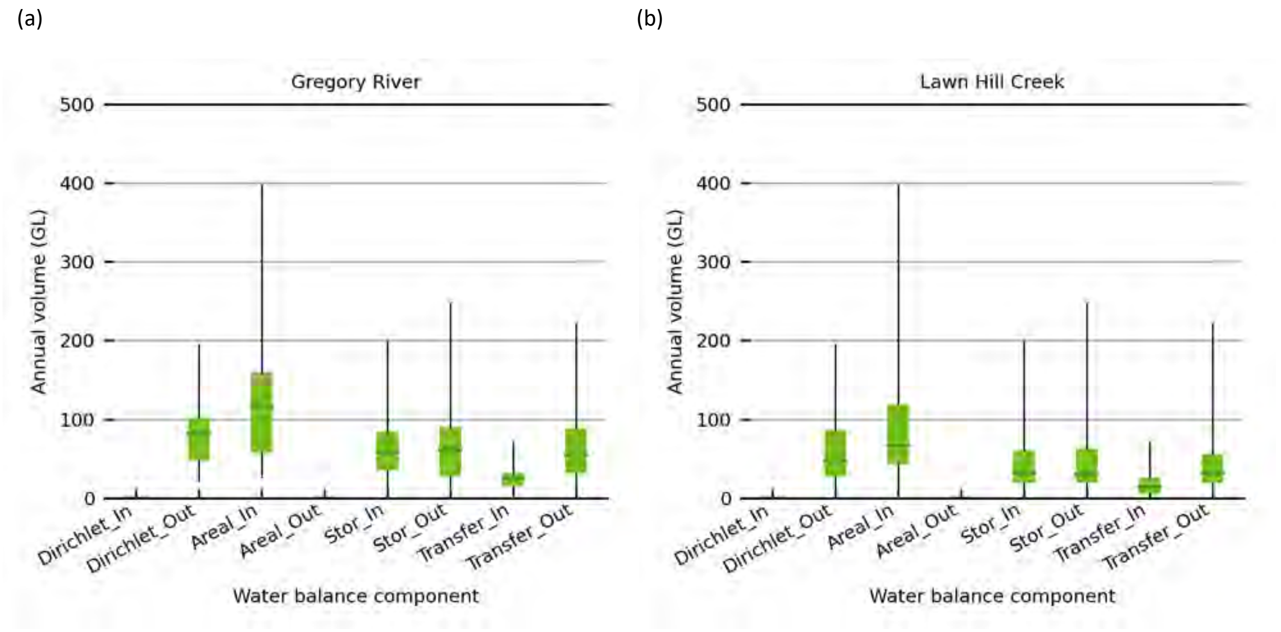


Figure 3-20 Groundwater budget components for the period 1910 to 2019 at reporting areas a) Gregory River and b) Lawn Hill Creek

Dirichlet_In = flow from the river boundary conditions into the model domain; Dirichlet_Out = flow to the river boundary conditions from the model domain; Areal_In = recharge; Areal_Out = evapotranspiration; Stor_In = water released from storage; Stor_Out = water captured into storage; Transfer_In = flows into the area of interest; Transfer_Out = flows out of the area of interest.

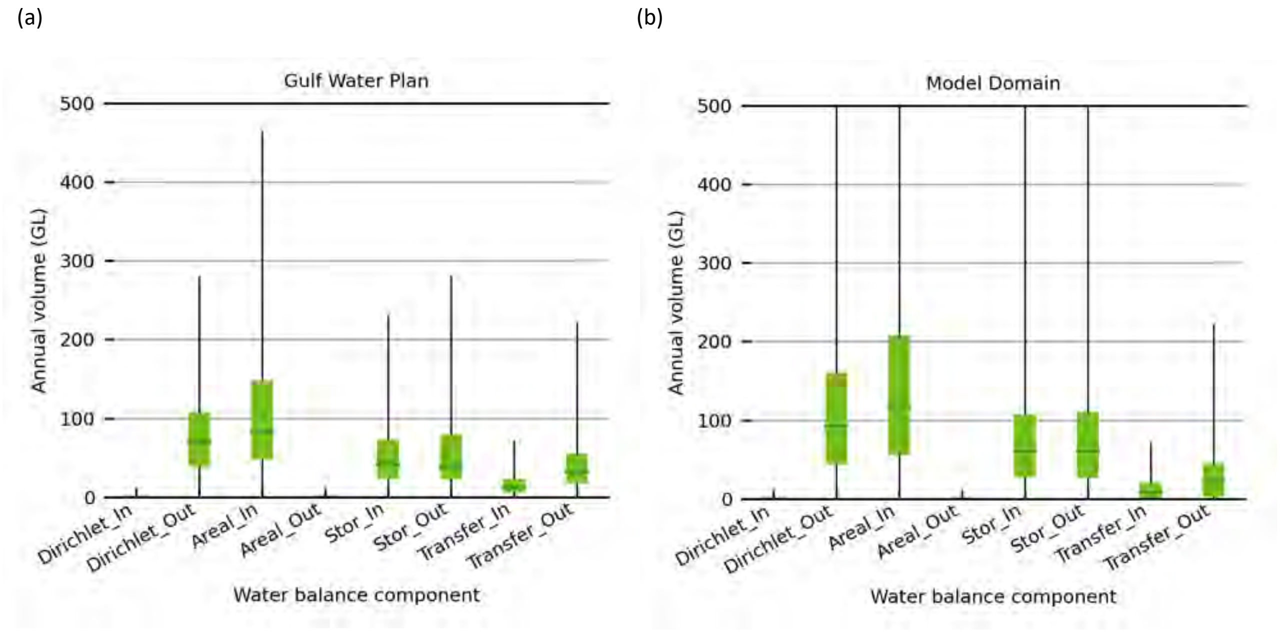


Figure 3-21 Groundwater budget components for the period 1910 to 2019 at reporting areas a) Nicholson Groundwater Management Area (NGMA) and b) model domain

Dirichlet_In = flow from the river boundary conditions into the model domain; Dirichlet_Out = flow to the river boundary conditions from the model domain; Areal_In = recharge; Areal_Out = evapotranspiration; Stor_In = water released from storage; Stor_Out = water captured into storage; Transfer_In = flows into the area of interest; Transfer_Out = flows out of the area of interest.

3.9 Limitations

Current assumptions and limitations of the Undilla1 groundwater flow model are:

- Groundwater levels are currently constrained by single water levels recorded at the time of bore construction and this has been assumed to correspond to the end of the dry season. This is likely to introduce a large bias where bores were installed in periods not representative of recent conditions.
- The equivalent porous medium approach has been used to represent karst systems. However, the regional groundwater flow model, which assumes roughly homogeneous and isotropic conditions at the element scale, and is not suitable for analysis of local scale karst terrains, such as when tracking pollutant flow.
- Recharge is assumed to be diffuse; however, bypass flow via macropores and sinkholes is known to be an important recharge mechanism. The method used to calculate recharge is empirical and does not include estimates of bypass flow, leading to an underestimation of recharge during years with above-average rainfall.
- There is little understanding of actual river–aquifer interactions, especially with respect to the flows from the groundwater system to discrete springs.
- Individual springs are not considered in the Undilla1 groundwater flow model as the distributions of the discrete pathways are too poorly understood and at a scale too small to be adequately represented.

4 Conclusions

A two-dimensional numerical groundwater flow model has been developed to examine the groundwater resources of the Undilla Sub-basin, which provides baseflow to Lawn Hill Creek and Gregory River. The model successfully reproduced the observed behaviour of groundwater levels and discharge from the CLA in the Undilla Sub-basin. From this study, the following key findings have emerged:

- The conceptualisation of the groundwater flow system indicates that there is a localised system discharging to springs well above the stream level and a regional groundwater system discharging to lower springs and through the bed of the river. To adequately model the observed discharge record, the Undilla Sub-basin may require multiple layers to resolve this partitioning.
- There is considerable uncertainty in the dynamic range of groundwater levels in the Undilla Sub-basin, as the model is currently constrained by single water levels recorded at the time of bore construction. Collecting time series data at sites such as the reporting sites used in this study would reduce the uncertainty in the groundwater-level dynamics.
- Groundwater discharge reported at 912101A is considered representative of flows in the Gregory River; however, there is less confidence that the discharge reported at 912103A is representative of flows in Lawn Hill Creek. Conducting manual measurements of stream flows at these sites once or twice a year during the dry season would improve the confidence in these data.
- Portions of the observed flow record can be reproduced for 91213A on Lawn Hill Creek. However, the model appears to under-report observed flows at 912103A in the period from 1975 to 1980.
- Previous studies have assumed that groundwater contributing to the discharge at Lawn Hill Creek and Gregory River is sourced as far west as the Alexandria-Wonarah Basement High. However, the groundwater level surface indicates that there is a groundwater divide separating flows to the east and flows to the south. This assessment is supported by the groundwater flow model.
- Recharge is estimated by scaling the rainfall by the CMB recharge distribution and is between 7 and 25 mm/year, depending on the area of interest. The recharge is 14 mm/year in the Gregory subcatchment, 25 mm/year in the Lawn Hill subcatchment and about 15 mm/year in the NGMA. The mean recharge for the entire model domain is about 7 mm/year.
- Based on the transmissivity values, the recharge for areas with black soil cover may be an order of magnitude lower.
- The transmissivities in the north-eastern third of the model domain are considered reasonable for the type of aquifer (<1,000 to 10,000 m^2/day). However, the highest transmissivity values (>20,000 m^2/day), which are predominantly in the south-western two-thirds of the model domain, are much higher than expected. The higher values reflect the very low groundwater gradient and are likely a result of recharge being overestimated in areas with black soil.

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.

Ahmad M, Dunster JN and Munson TJ (2013) Chapter 15: McArthur Basin. In: Ahmad M and Munson TJ (compilers) Geology and mineral resources of the Northern Territory. Northern Territory Geological Survey, Special publication 5.

Budget Strategy and Outlook (2024) Budget 2024-25. A future made in Australia. Viewed 11 September 2024, https://budget.gov.au/content/factsheets/download/factsheet-fmia.pdf.

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 South-West Gulf region. In: CSIRO (2009) Water in the Gulf of Carpentaria Drainage Division. A report to the Australian Government from the CSIRO Northern Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia, 121–185. DOI: 10.4225/08/5859749d4c71e.

Department of State Development, Manufacturing, Infrastructure and Planning (2019) North west Queensland economic diversification strategy 2019. Viewed 12 September 2024, https://www.statedevelopment.qld.gov.au/regions/regional-priorities/a-strong-and-prosperous-north-west-queensland/north-west-queensland-economic-diversification-strategy.

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 (2024) PEST_HP: a parameter estimation software package for highly parameterized models. Watermark Numerical Computing, Brisbane, Australia.

Eberhard S (2003) Nowranie Caves and the Camooweal Karst Area, Queensland: hydrology, geomorphology and speleogenesis, with notes on aquatic biota. Helictite 38(2), 27–38.

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.

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

Gibbs M, Hughes J and Yang A (2024b) River model calibration for the Southern Gulf catchments. A technical report from the CSIRO Southern Gulf Water Resource Assessment for the National Water Grid. CSIRO, Australia.

Grimes K G (1988) The Barkly Karst Region, north-west Queensland. Proceedings of 17th Biennial Conference of the Australian Speleological Federation (Tropicon), ASF, Cairns, 16–24. DOI: 10.13140/2.1.1678.5929.

Howard PF, 1971. Discovery of phosphorite in northern Australia. American Institute of Mining Engineers, Transactions 250, 269–273.

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.

Johnson N E A, Nichols R A H and. Bell M E D. 1964 Completion Report, B.M.R. 11 Well. Cattle Creek. N.T. Bureau of Mineral Resources Geology And Geophysics. Record 1964/45.

Jolly P and Tickell S (2011) Tufa dams of northern Australia. Northern Territory branch of the International Association of Hydrogeologists. https://www.iah.org.au/wp-content/uploads/2015/04/3_IAHNT-Tufa-Report.pdf.

Knapton (2014) Alpurrurulam Community (Lake Nash) borefield groundwater modelling report. Power Water Corporation. Unpublished

Knapton A (2020) Upgrade of the Coupled Model of the Cambrian Limestone Aquifer and Roper River Systems. CloudGMS and Department of Environment, Parks and Water Security, Northern Territory Government, Palmerston. https://territorystories.nt.gov.au/10070/827500.

Knapton A, Taylor AR, Petheram 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.

Kruse PD, Dunster JN and Munson TJ, 2013. Chapter 28: Georgina Basin. In: Ahmad M and Munson TJ (compilers) Geology and mineral resources of the Northern Territory. Northern Territory Geological Survey, Special publication 5.

Kruse PD and Radke BM, 2008. Ranken-Avon Downs, Northern Territory. 1:250 000 geological map series explanatory notes, SE 53-16, SF 53-04. Northern Territory Geological Survey, Darwin.

Kruse PD, Maier RC and Khan M, 2010. Walhallow-Brunette Downs-Alroy-Frew River, Northern Territory. 1:250 000 geological map series explanatory notes, SE 53-07, SE 53-11, SE 53-15, SF 53-03. Northern Territory Geological Survey, Darwin.

Merrin L, Stratford D, Kenyon R, Pritchard J, 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 Southern Gulf catchments to inform water resource assessments. A technical report from the CSIRO Southern Gulf Water Resource Assessment for the National Water Grid. CSIRO, Australia.

NT Department of Environment Parks and Water Security (2019) Northern Territory bore locations, water quality and groundwater levels. Open Data Portal, NT Government. Downloaded 12 April 2023, https://data.nt.gov.au/dataset/nt-bore-locations-water-quality-and-groundwater-levels.

Queensland Department of Regional Development Manufacturing and Water (2023) Groundwater Database – Queensland. Open Data Portal, Queensland Government. Licence sourced in 12 April 2023, https://data.qld.gov.au/dataset/groundwater-database-queensland .

Queensland Government (2018) Water Plan (2007) Gulf. Visited 10 October 2004, https://www.legislation.qld.gov.au/view/html/inforce/current/sl-2007-0268

Queensland Government (2023) Queensland Water Strategy. Water. Our life resource. Viewed 11 September 2024, https://www.rdmw.qld.gov.au/qld-water-strategy/strategic-direction.

Raiber M, Taylor AR, Dupuy M, Priestley S, Crosbie RS, Barry K, Knapton A and Hodgson G (2024) Characterising groundwater resources of the Gilbert River Formation, Camooweal Dolostone and Thorntonia Limestone in the Southern Gulf catchments, Queensland and Northern Territory. A technical report from the CSIRO Southern Gulf Water Resource Assessment for the National Water Grid. CSIRO, Australia.

Randal MA (1978) Hydrogeology of the southeastern Georgina Basin and environs, Queensland and Northern Territory. Publication 366, Geological Survey of Queensland, Brisbane.

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.

Shergold JH, Druce EC, Radke BM and Draper JJ, 1976. Cambrian and Ordovician stratigraphy of the eastern portion of the Georgina Basin, Queensland and eastern Northern Territory. XXV International Geological Congress, Sydney, Excursion Guide 4C.

Stewart AJ, Liu SF, Highet LM, Woods M, Czarnota K, Bonnardot M, Brown C, Clark A and Connors K (2020) Solid geology of the North Australian Craton, 1:1 000 000 scale, 1st edition. DOI: 10.26186/135277.

Taylor AR, Barron OV, Harrington GA, Chilcott C, Davies PJ, Wohling D and Gilfedder M (2021) Rapid appraisal of new groundwater-based irrigation infrastructure opportunities across Australia. A technical report from CSIRO to the National Water Grid Authority. CSIRO Technical Report. EP2021-0769: CSIRO, Australia. https://publications.csiro.au/publications/publication/PIcsiro:EP2021-0769.

Tickell SJ (2003) Water resource mapping: Barkly Tablelands. Natural Systems Division, Department of Infrastructure Planning and Environment, Darwin, NT. https://territorystories.nt.gov.au/10070/674454.

White J. (2018) A model-independent iterative ensemble smoother for efficient history-matching and uncertainty quantification in very high dimensions. Environmental Modelling & Software 109, 191-201. https://doi.org/10.1016/j.envsoft.2018.06.009.

As Australia's national science agency and innovation catalyst, CSIRO is solving the greatest challenges through innovative science and technology.

CSIRO. Unlocking a better future for everyone.

Contact us

1300 363 400
+61 3 9545 2176
csiroenquiries@csiro.au
csiro.au

For further information

Environment
Dr Chris Chilcott
+61 8 8944 8422
chris.chilcott@csiro.au

Environment
Dr Cuan Petheram
+61 3 6237 5669
cuan.petheram@csiro.au

Environment
Dr Ian Watson
+61 7 4753 8606
Ian.watson@csiro.au