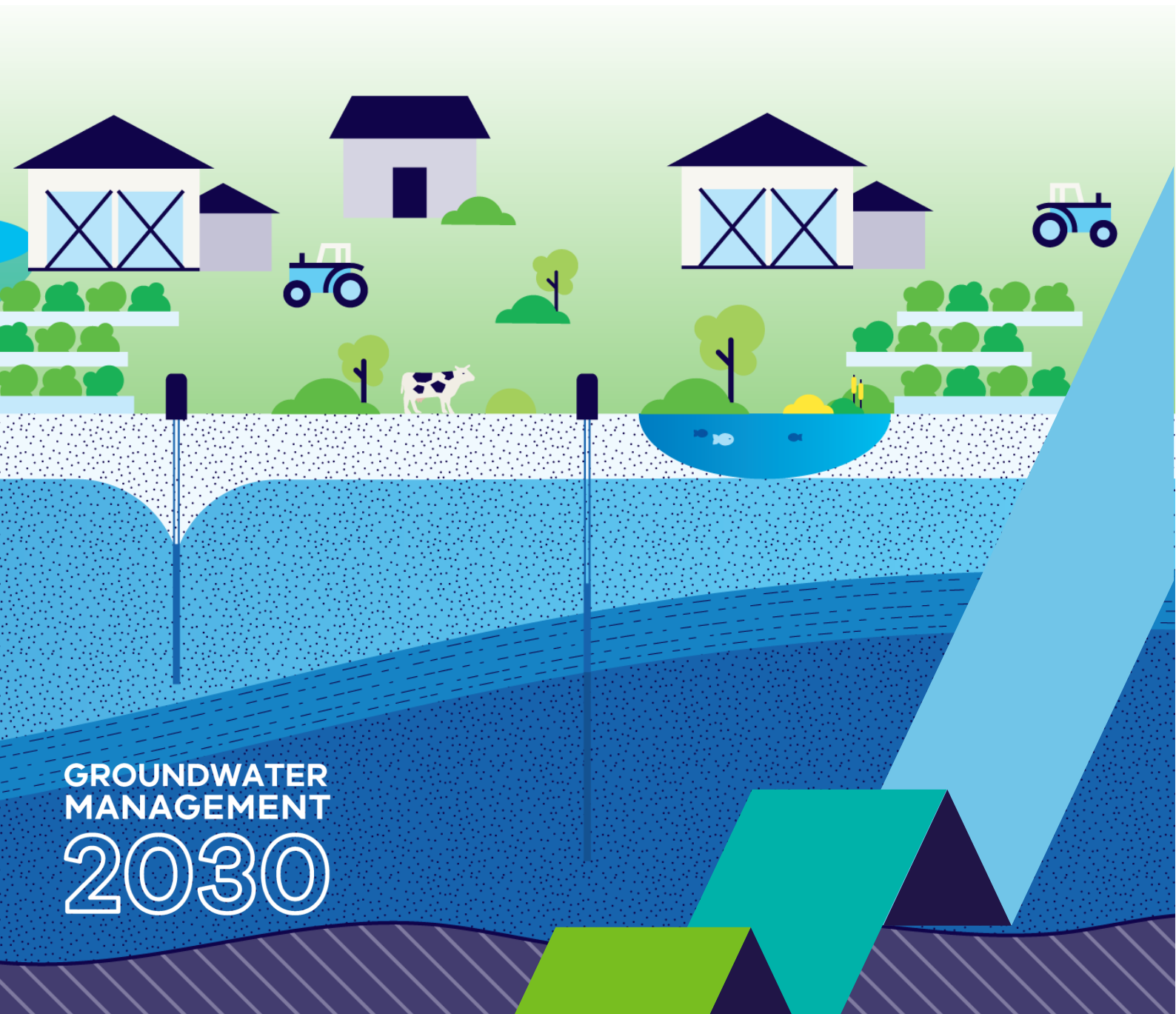


# GROUNDWATER SUSTAINABLE YIELD ASSESSMENT: METHODOLOGY REPORT

Part 1. Methodology Overview



GROUNDWATER  
MANAGEMENT  
2030

## Acknowledgements

The Sustainable Yield Assessment for Victoria was undertaken by DEECA in collaboration with Southern Rural Water, Goulburn–Murray Water, Grampians Wimmera Mallee Water, and Lower Murray Water corporations.

A technical advisory panel provided specialist advice in the development of the assessment method. The panel comprised specialists from Deakin University (Prof. Wendy Timms), Jacobs (Dr Richard Evans) and HydroGeoLogic (Mr Hugh Middlemis).

The assessment was completed with contributions from external industry specialists, who developed the technical details of the methodology and carried out assessments of groundwater resources. These included Jacobs Pty Ltd, GHD Pty Ltd, CDM Smith Pty Ltd, HARC Pty Ltd and Monash University (Dr Tim Peterson).

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We acknowledge and respect Victorian Traditional Owners as the original custodians of Victoria's land and waters, their unique ability to care for Country and deep spiritual connection to it.

We honour Elders past and present whose knowledge and wisdom has ensured the continuation of culture and traditional practices.

DEECA is committed to genuinely partnering with Victorian Traditional Owners and Victoria's Aboriginal community to progress their aspirations.



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# Glossary

Term	Definition
Allocation	The assignment of water within a given water year against a water entitlement held by a person or authority, determined by a water corporation and expressed as a percentage of the entitlement. Most groundwater allocations are triggered by declines in groundwater level.
Cap	A colloquial/general term for an upper limit for total water entitlements that can be issued from a waterway, catchment basin or groundwater area for a set time period. This includes Permissible Consumptive Volumes (under the <i>Water Act 1989</i> ) and Permissible Annual Volumes and Allowable Annual Volumes (under the <i>Groundwater (Border Agreement) Act 1985</i> ).
Consumptive use	Water removed from the available supply without return to the water resource system. All extractive uses, including water used for agriculture, industry and commerce, including stock and domestic purposes.
Domestic and stock	Water taken for household use, kitchen garden, fire prevention and watering of livestock. Victorians have basic rights to water for under section 8 of the Victorian <i>Water Act 1989</i> . These rights allow a person to take water from a bore, dam, river or stream to use for domestic and stock purposes.
Entitlement	A right to use water in a waterway, water in storage works of a water corporation, and groundwater. It also includes the right to water corporations to supply water. Water entitlements include bulk entitlements (generally issued to water corporations), environmental entitlements, water rights, surface water and groundwater licences. The term also can be used to mean the volume of water authorised to be taken and used by the holder.
Groundwater Level Restriction Triggers (GLRT)	A new term defined as – “A defined groundwater level for a system that triggers restrictions on use”, generally implemented through water shortage declarations, approved management plans for a Water Supply Protection Area, Local Management Plans and in some cases through licences or Bulk Entitlements.
Groundwater Management Area (GMA)	An area where groundwater has been intensively developed or has the potential to be. Groundwater Management Areas generally have a Permissible Consumptive Volume set by Minister for Water through statutory declaration.
Groundwater Management Unit (GMU)	Refers to both Groundwater Management Areas and Water Supply Protection Areas.
Licensed use (water)	The volume of water taken under a licence(s) to take and use water for consumptive use. It excludes the volume of water taken for domestic and stock purposes under Section 8, <i>Water Act 1989</i> .
Licence to take and use	A fixed-term entitlement under section 51 of the <i>Water Act 1989</i> to take and use water from a waterway, catchment dam, spring, soak or aquifer. Each licence is subject to conditions set by the Minister for Water and specified on the licence.
Limits of take under licence	Refers to both caps on entitlements and any management prescriptions that limit take and entitlements such as groundwater level restrictions triggers that restrict use in a particular season.
Normalised hydrograph	The hydrograph of the Suite comprising the mean and standard deviation of all the groundwater levels for the observation bores in the Suite.

Permissible Consumptive Volume (PCV)	The maximum volume of water entitlements that can be allocated in an area or a water system.
Suite	Refers to the grouping of similar groundwater level responses observed in monitoring bores within a specific groundwater system. See also 'Normalised hydrograph'.
Sustainable Yield	The groundwater extraction regime measured over a 20-year planning timeframe, allowing for acceptable levels of impact that protect dependent values.
Sustainable yield metric	A measure that defines the acceptable level of impact that protects dependent 'values' for the assessed sustainable yield volume.
Unincorporated Area (UA)	Groundwater areas which are not defined as Groundwater Management Units and do not have a defined Permissible Consumptive Volume.
Use (water)	The volume of water taken (such as groundwater extracted) for consumptive use.
Water Supply Protection Area (WSPA)	An area declared under section 27 the Victorian <i>Water Act 1989</i> to protect the groundwater or surface water resources or both through the development of a statutory management plan.
Waterway	A river, creek, stream or watercourse, a natural channel in which water regularly flows (whether the flow is continuous or not), a lake lagoon, swamp, or marsh.
Winterfill SDL	Winterfill sustainable diversion limit volumes (SDLs) have been developed across Victoria and represent the upper limit on winterfill diversions, beyond which there is an unacceptable risk that additional extractions may degrade the environment. The SDL_BASIN dataset is a spatial representation of river basins, which represent an aggregate of the intermediate SDL catchments. These basins do not reflect the Victorian surface water river basins as defined by the Australian Water Resources Council. Winterfill SDL data is held in the SDL_DATA layer.

# Summary

The Sustainable Yield (SY) assessment is a 4-year initiative that reviewed groundwater availability in Victoria. It commenced in 2020 and was overseen by the Victorian Department of Energy, Environment, and Climate Action (DEECA).

The objectives of the SY assessment were to develop methods for estimating groundwater availability and sustainable yield volumes, apply those methods across Victoria, and report on the results and implications for groundwater resource management. Groundwater assessments are an important tool for evaluating changes to water availability and its effect on users and the environment. Sustainable yield is an estimate of available groundwater that minimises adverse impacts on assessed values (e.g., environment and consumptive users). The assessment fulfils Priority Area 1 under GM2030 “Water availability and limits on take: DEECA working with the rural water corporations will carry out a state-wide technical assessment and review of the limits of take under licences”. The information gained will inform broader groundwater reform initiatives, such as those under the Groundwater Management 2030 (GM2030).

The methodology of the SY assessment aimed to develop a generic method for assessing future changes in Victoria’s groundwater availability and evaluate whether such changes can cause broader adverse impacts. The methodology prioritised simplicity and cost-effectiveness, tailored to address uncertainties that affect decision-making. The method was divided into separate components for confined and unconfined aquifers.

The approach of the SY assessment followed these steps:

## 1) Define the measures of sustainable yield

- Sustainable yield was defined as ‘the groundwater extraction regime measured over a specified planning timeframe, allowing for acceptable levels of impact that protect dependent values.’
- Measures (referred to as sustainable yield metrics) to determine the sustainable yield volume were defined for each assessed value, with proposed metrics as follows:
  - consumptive users: 2 m drawdown in unconfined aquifers, 10 m drawdown in confined aquifers
  - environmental values: 2 m drawdown in unconfined aquifers (N/A for confined aquifers)
  - seawater intrusion (from consumptive users): minimum level of 1.5 m Australian Height Datum (mAHD) within 300 m of coast (N/A for confined aquifers).
  - Waterway flow: 10% of Mean Annual Flow (MAF) (ML/yr) in unconfined aquifer GMUs with groundwater-surface water connectivity.

## 2) Estimate groundwater resource volume

- Groundwater resources were defined by aquifer type (confined, unconfined, semi-confined) and management areas (Groundwater Management Areas (GMA), Water Supply Protection Areas (WSPA and Unincorporated Areas (UA)).
- Historic groundwater monitoring data (groundwater use volumes, groundwater levels) was the primary source of information for the statistical modelling.
- Hydrogeological conceptual models were developed for each aquifer to inform method selection and data needs for the assessment.
- The method was developed, tested and applied statewide for each aquifer type (confined, unconfined, semi-confined) and management area type (Groundwater Management Units (GMUs) or UAs).

- Statistical models were used in the GMUs to assess the groundwater response to climate and use.
- Results were synthesised for each reporting area, including:
  - drawdown/use relationships for each GMU
  - throughflow volumes for confined aquifers
  - recharge volumes for unconfined aquifers
  - estimates of uncertainty and/or errors for the outputs.

### **3) Compare the estimates sustainable yield volumes against entitlements and use to review the limits on take**

- The SY volumes were compared against use and entitlements to assess the potential risk to sustainability (current and future) and review the limits of take under licences.

## About this report

This report outlines the technical approach and methodology of the SY assessment. DEECA developed the methodology in partnership with:

- Contractors Jacobs, GHD Pty Ltd and CDM Smith, who were responsible for developing the technical aspects of the methodology and conducting assessments of groundwater resources.
- Representatives from Southern Rural Water Corporation, Goulburn-Murray Rural Water Corporation, Grampians Wimmera Mallee Rural Water Corporation, and the DEECA Environmental Waterways and Water Licensing Policy teams, who possessed extensive experience and expertise in water and groundwater resource management and policy, and offered advice on technical, management and policy aspects of the project.
- A technical review panel, consisting of three subject matter experts in groundwater assessment and modelling, who provided expert peer review of the methodologies.

The methodology was developed in stages so that assessments could be undertaken in parallel with the methodology refinement. This enabled DEECA to meet the project completion date of June 2024. The methodology is described and reported in 8 parts:

- Part 1: Methodology overview (this report)
- Part 2: Confined aquifers – throughflow method (report by Jacobs, 2024)
- Part 3: Confined aquifers – drawdown-use method (report by GHD Pty Ltd, 2024)
- Part 4: Unconfined aquifers – recharge estimation and drawdown-use methods (report by CDM Smith, 2025)
- Part 5: Sustainable Yield synthesis paper – confined aquifers synthesis approach (DEECA)
- Part 6: Sustainable Yield synthesis paper – semi-confined aquifers mapping approach (DEECA)
- Part 7: Sustainable Yield synthesis paper – semi-confined aquifers synthesis approach (DEECA)
- Part 8: Sustainable Yield synthesis paper – Mapping, Boundaries, and Naming Conventions for Confined Aquifer UAs (DEECA)

Part 1, the methodology overview (this report), provides context for the assessment by discussing current resources and understanding, expected outcomes, objectives, outputs, scope, and principles for the proposed approach to the methodology.

Parts 2 to 8 of the methodology provide additional details of the methods. Parts 2 to 4 were developed and reported on by the contractors, and parts 5 to 8 were developed by DEECA.

This report is structured as follows:

- Summary
- Section 1: Introduction
- Section 2: Project objectives
- Section 3: Approach and methodology
- Section 4: Define measures of sustainable yield
- Section 5: Groundwater resource assessment
- Section 6: Derive sustainable yield volumes
- Section 7: Reporting results and review of the limits of take under licences

Case studies that examine the suitability of methods are provided in sections 5 to 7 of this report.

This report serves as a technical document tailored for water resource managers and is not aimed at a general audience.

Some figures and tables referenced in this report are not embedded in the body of the report but are provided in the Appendix (following section 7).

The SY assessment involves certain assumptions and limitations. A summary of these is provided in the "Assumptions" section, while detailed assumptions and limitations are outlined in the consultant reports (Parts 2, 3, and 4). A key design principle of the SY method was to develop it using simple generic approaches, necessitating further investigation in certain areas to enhance outputs.

The SY Synthesis Results Report (<https://www.water.vic.gov.au/water-sources/groundwater/groundwater-management-2030/sustainable-yield-assessment/?a=777716>) and an the Overview Report (<https://www.water.vic.gov.au/water-sources/groundwater/groundwater-management-2030/sustainable-yield-assessment/?a=777718>) are available on the DEECA website.

# Assumptions

## Confined aquifers – drawdown-use method (GHD Pty Ltd, 2024)

Area	Assumptions
Data: Groundwater levels	<ul style="list-style-type: none"> <li>Groundwater level data used for the Suite hydrographs were averaged across areas that typically show the greatest declines, generally associated with intensive groundwater extraction. This provides a regional approximation of groundwater levels.</li> <li>The classification of Suites remains valid, despite being defined in 2014. Although post-2014 data were included in the modelling, no formal reassessment was undertaken to determine if Suite boundaries have diverged or changed over time.</li> </ul>
Data: Groundwater use	<ul style="list-style-type: none"> <li>All licensed bores are assumed to be correctly assigned to the aquifer from which they extract water.</li> <li>In cases where screen interval data are missing, technical judgment was applied to assign bores to the most appropriate aquifer based on available data.</li> <li>Groundwater use for domestic and stock purposes is assumed to remain unchanged. Extraction volumes from these bores are generally low and considered negligible in terms of their impact on groundwater levels and the modelling results.</li> <li>Historical groundwater use prior to 2004 was estimated through hindcasting. GHD developed a complex model that incorporates climate trends and allocation history to reconstruct historical usage. This is considered the best available dataset for metered use before 2004. Some GMUs were calibrated using only hindcasted data, while others used a combination of hindcasted and metered data.</li> <li>Metered groundwater use is recorded at the licence level rather than for individual bores. Where multiple bores are associated with a single licence, water use volumes were distributed evenly across all bores on that licence.</li> </ul>
Pre-development levels	<ul style="list-style-type: none"> <li>The pre-development groundwater level (used as the baseline for assessing drawdown due to development) was determined through a GMU-by-GMU review. The pre-development level was defined as the highest observed level in the record, with minimal seasonal fluctuation and no indication of pumping influence.</li> <li>In GMUs lacking early groundwater data, the earliest available groundwater level was used as a proxy. This approach was applied in GMUs such as Newlingrook GMA, Cut Paw Paw GMA, Orbost GMA, and Corinella GMA.</li> </ul>
Drawdown-Use relationship	<ul style="list-style-type: none"> <li>The drawdown–use relationship method assumes that aquifers are sufficiently stressed by groundwater extraction for a statistically meaningful relationship to be derived. However, this assumption may not hold for GMUs with relatively low extraction volumes.</li> </ul>

## Confined aquifers – throughflow method (Jacobs, 2024)

Area	Assumptions
Darcy's equation	<p>The estimation of throughflow in confined aquifers is based on Darcy's Law, which assumes:</p> <ul style="list-style-type: none"> <li>• The aquifer is fully saturated and behaves as a porous medium. Basement layers, due to their limited yield, are excluded from the analysis.</li> <li>• Groundwater flow is laminar (not turbulent).</li> <li>• Hydraulic conductivity and gradient are uniform within the evaluated segment.</li> <li>• The flow is one-dimensional (horizontal), and vertical gradients are negligible.</li> <li>• The aquifer properties do not change significantly across the evaluated cross-section.</li> <li>• There are no significant sources or sinks (e.g. recharge, pumping) along the flow path.</li> </ul>
Throughflow Calculation parameters and data sources	<p>Throughflow is calculated using the Darcy equation: <math>Q = K_h \times i \times a</math>, where <math>Q</math> is the throughflow rate, <math>K_h</math> is horizontal hydraulic conductivity, <math>i</math> is the hydraulic gradient, and <math>a</math> is the cross-sectional area of the aquifer.</p> <p>The source of data for the Darcy components is:</p> <p>Hydraulic Gradient (<math>i</math>)</p> <p>Derived from modelled predevelopment groundwater elevation surfaces based on the following Catchment Management Authority (CMA) regional numerical models:</p> <ul style="list-style-type: none"> <li>• Murray Basin Hydrogeological Map Series &amp; Wimmera CMA "EcoMarkets" model (Hocking et al., 2010b)</li> <li>• North Central CMA "EcoMarkets" model (Hocking et al., 2010a)</li> <li>• Goulburn Broken CMA "EcoMarkets" model (Hocking et al., 2010c)</li> <li>• Glenelg Hopkins CMA model (SKM, 2009b) and SRW hydrographical mapping project (SKM &amp; GHD, 2009)</li> <li>• Port Phillip CMA "EcoMarkets" model (GHD, 2010a)</li> <li>• West Gippsland CMA "EcoMarkets" model (GHD, 2010b) and SRW hydrographical mapping project (SKM &amp; GHD, 2009)</li> </ul> <p>Hydraulic Conductivity (<math>K_h</math>)</p> <p>Values were collated for relevant Victorian Aquifer Framework (VAF) layers from:</p> <ul style="list-style-type: none"> <li>• PCV Review Projects (Jacobs, 2019; GHD, 2020)</li> <li>• Aquifer Property Mapping (CDM Smith, 2018)</li> <li>• Other available literature and data sources</li> </ul> <p>Cross-Sectional Area (<math>a</math>)</p> <ul style="list-style-type: none"> <li>• Estimated using aquifer geometry derived from the VAF layers.</li> </ul>

---

Model  
Assumptions

- Averaging of the spatial data to create a mesh and define flow tubes is assumed not to introduce significant error to the throughflow estimates.
  - It is assumed that confined aquifers are continuous enough across flow paths for Darcy-based calculations to be meaningful, and that boundary effects or partial confinement do not dominate in the selected sections.
  - Confined aquifer boundaries are defined where the modelled predevelopment potentiometric surface equals the top of the confined VAF layer. In cases where aquifers are only partially saturated or overlaid by aquitards (e.g. West Wimmera GMA), they are excluded from the analysis.
  - Where GMU boundaries differ from VAF geometry, the VAF-defined geometry is used.
  - The predevelopment potentiometric surfaces used may reflect early-stage development or external influences (e.g., oil/gas extraction). These areas were excluded from the analysis where clear groundwater level drawdown was evident
-

## Unconfined aquifers – recharge estimation and drawdown-use methods (CDM Smith, 2024)

Area	Assumptions
Data: Groundwater use	<ul style="list-style-type: none"> <li>All licensed bores are assumed to be correctly assigned to the aquifer from which they extract water.</li> <li>In cases where screen interval data are missing, technical judgment was applied to assign bores to the most appropriate aquifer based on available data.</li> <li>Groundwater use for domestic and stock purposes is assumed to remain unchanged across future scenarios. Extraction volumes from these bores are generally low and considered negligible in terms of their impact on groundwater levels and the modelling results.</li> <li>Metered groundwater use is recorded at the licence level rather than for individual bores. Where multiple bores are associated with a single licence, water use volumes were distributed evenly across all bores on that licence. 2721 number of licences were affected by this issue with over 1000 licences with more than 3 bores.</li> <li>The spatial distribution of licensed bores influences accuracy of the results. If location details are incorrect, the model is in error.</li> <li>Unmetered bores (&lt;10 or 20 ML/yr) were excluded from the analysis, potentially underestimating total groundwater use by 5% (DELWP, 2020).</li> <li>Licensed bores were included or excluded based on depth criteria for each GMU. Bore classifications were based on reported screen or total depths, which may contain errors.</li> </ul>
Data: Groundwater level	<ul style="list-style-type: none"> <li>Groundwater levels were interpolated between available monitoring bores, with accuracy depending on bore density and distribution. Errors may arise in areas with sparse monitoring data.</li> </ul>
Land use	<ul style="list-style-type: none"> <li>There are no land use changes in the model.</li> </ul>
Climate change projections	<ul style="list-style-type: none"> <li>Climate was mapped statewide using gridded data from SiLO (The Australian Bureau of Meteorology) with climate scenarios developed based on the Victorian Climate Change Guidelines (DELWP 2016 &amp; 2020).</li> <li>Climate change scenarios of low, medium, and high were considered, along with a no-climate-change scenario for the periods of 2021-2040 and 2041-2065.</li> <li>The chosen scenarios cover likely climate futures using historic climate signatures over 30-year period replicated into the future overlaid with climate change signatures (e.g. % reduction in rainfall and Evapotranspiration).</li> <li>Future climate scenarios do not include non-stationarity in the modelled scenarios.</li> </ul>
Recharge modelling	<ul style="list-style-type: none"> <li>HydroSight uses a 1- or 2-layer soil model and SoilFlux models use a single soil profile, which may not accurately represent localised soil drainage across the GMU.</li> <li>Both Hydrosight and SoilFlux tend to overestimate recharge due to methodological assumptions.</li> </ul>

	<ul style="list-style-type: none"> <li>• SoilFlux assumes a constant watertable elevation with watertable elevation categorised as “&lt;5m”, “5-10m”, “10-20m”, “&gt;20m”. For the purposes of climate change scenarios assumptions were made about what watertable depth scenario would be used for each climate scenario (e.g. future scenarios may assume a “&lt;5m” depth to watertable (i.e. shallow watertable) moves to a “5-10m” depth to watertable) based on modelled HydroSight results for a GMU.</li> <li>• SoilFlux reporting periods differed from those modelled in Hydrosight due to use of prior modelled outputs. These did not include future climate scenarios, rather the results were interpreted for a “dry”, “average” or “wet” climate to align them with the low, medium and high climate change scenarios modelled using Hydrosight.</li> </ul>
HydroSight analyses	<ul style="list-style-type: none"> <li>• HydroSight assumes that aquifer responses to climate and pumping remain consistent over time.</li> <li>• It does not account for aquifer properties or variations in thickness.</li> <li>• Calibration relied on the coefficient of efficiency (CoE), which may not always indicate accurate hydrograph modelling as it may miss differences in trends.</li> <li>• Future climate projections were attached to historical data, introducing uncertainty in long-term simulations.</li> <li>• The impact radius of pumping bores was capped at five per observation bore, which may exclude some relevant influences</li> </ul>
HydroMap (Watertable mapping)	<ul style="list-style-type: none"> <li>• HydroMap does not enforce groundwater elevation constraints near water bodies, allowing unrealistic artesian conditions in some areas. These were removed in final review of mapped watertable elevations.</li> <li>• HydroMap includes additional forcing functions using topography and climate to improve kriging of watertable levels.</li> </ul>
Recharge merge approach	<ul style="list-style-type: none"> <li>• HydroSight data is preferred over SoilFlux for point estimates, while SoilFlux provides better spatial coverage and was used to infill the gaps from the HydroSight analyses.</li> <li>• The merging process introduces potential errors due to differences in spatial resolution, temporal resolution and averaging methods.</li> </ul>
Estimates of uncertainty	<ul style="list-style-type: none"> <li>• The study provides quantitative errors in mapped groundwater levels but does not provide formal error estimates for mapped recharge and groundwater levels .</li> <li>• Climate scenario results serve as a quasi-upper and lower bound for uncertainty as climate change.</li> </ul>
Drawdown/use relationships	<ul style="list-style-type: none"> <li>• Modelled drawdown in aquifers is unlimited and may exceed aquifer constraints in smaller / thinner aquifers.</li> <li>• Drawdown/use relationships were forced to fit a (0,0) point to represent pre-development. This has skewed the drawdown/use linear relationship in some instances.</li> </ul>

# 1. Introduction

Groundwater assessments are conducted within the framework of the *Water Act 1989* (specifically under Division 1C (Long-term water resource assessments) and Division 2 (Water resources assessment program)) to evaluate whether any changes to water availability have occurred or may occur that could affect environmental and consumptive users.

Long-term water resource assessments primarily examine changes in availability over the historical record. The results of these assessments are used to inform the Sustainable Water Strategies, which assess future water use and availability to evaluate future needs. Where a change in resource status has occurred since entitlements were established, and this alteration affects the environment, adjustments to the entitlement framework may be recommended under the Sustainable Water Strategies. No adjustments to groundwater entitlements have been recommended in the Sustainable Water Strategies.

The SY assessment method was both backward- and forward-looking. It reviewed historical use and entitlements and assessed future changes to climate and groundwater use. Sustainable yield represents an estimation of available groundwater that minimises adverse impacts on assessed values and serves as foundational work to inform broader groundwater reform initiatives under Groundwater Management 2030 (GM2030). The SY project was undertaken to estimate the sustainable yield across the entire state. This project, provided under the Water Resources Assessment Program, aimed to develop a simple or generic method for assessing future changes in Victoria's groundwater availability from climate change and groundwater use and to evaluate whether such changes have the potential to cause adverse impacts on a broad scale. This is of particular significance considering that while most GMUs are fully allocated, groundwater usage currently accounts for approximately 35% of entitlements and could legally increase by 65% (**Figure A1**). Additionally, climate change may lead to a reduction in recharge.

The outcomes of the SY assessment inform a review of management settings, including the reconsideration of limits on take under licences, and contribute to the ongoing review of Victoria's groundwater management framework initiated in 2022. This framework aims to protect future groundwater use and availability to meet emerging demands (DELWP, 2022). Toward this end, 2 fundamental matters are considered:

1. What is an acceptable level of resource condition for different aquifer systems? Resource managers often inquire about how to know whether an aquifer is responding as expected. The challenge lies in the lack of an established acceptable level of drawdown for most aquifers in Victoria. There is no standard or nationally agreed position regarding the acceptable level of drawdown. Furthermore, crucial information concerning licensed bores (such as pump depths and screen intervals) is not readily available to inform the establishment of acceptable limits.
2. The adequacy and effectiveness of current groundwater management mechanisms (such as caps and limits on take) in managing and mitigating the risks of regional drawdown requires scrutiny. Thirty percent of the state is subject to caps on entitlements. In these areas, the primary concern is how to address potential adverse regional drawdown, as few of these regions have mitigation measures tied to groundwater levels or conditions. For the remaining 70% of the state without entitlement caps, the question arises as to whether caps should be implemented.

Extensive datasets and hydrogeological information are now available for most aquifers. Numerous studies have been conducted since the last state-wide assessments were undertaken, including the following:

- Groundwater use metering has been implemented in most licensed groundwater bores since the mid-2000s, with data loggers installed in selected study areas (Sinclair Knight Merz, 2014).

- Since the early 2000s, the number of observation bores drilled has increased, helping to fill spatial gaps in the state-wide groundwater-level bore network. Since 2017, 500 bores have had data loggers installed, resulting in an increase in monitoring frequency from monthly to hourly intervals.
- Mapping of groundwater-level temporal trends, known as hydrograph Suites (Sinclair Knight Merz, 2014; GHD Pty Ltd, 2014a and 2014b) (**Figure A2, Figure A3, Figure A4, Figure A5**). These Suites aid in the interpretation of regional and local groundwater processes, including identifying areas with potential inter-aquifer connections (GHD Pty Ltd, 2014c).
- Digital and geospatial datasets have been generated for aquifer extent (Figure A6, Figure A7, Figure A8), thicknesses, groundwater elevations (DSE, 2011; DSE, 2012), aquifer properties (such as hydraulic conductivity and transmissivity), recharge (CDM Smith, 2018a), and groundwater-dependent ecosystems (CDM Smith, 2018b).
- State-wide reviews and precursor studies to the SY project include:
  - data inventory (CDM Smith, 2017)
  - groundwater use (DELWP, 2020a and 2020b)
  - climate change impact on groundwater (GHD Pty Ltd, 2020a and 2020b)
  - groundwater-surface water interactions (Jacobs, 2019a and 2019b)
  - special area reviews (Jacobs, 2019c; GHD Pty Ltd, 2020c, 2020d, 2020e, 2020f and 2020g).

Collectively, these studies have improved the conceptualisation of groundwater processes and potential management risks both at the state-wide and regional levels.

- Development of new statistical models for groundwater assessment relationships (e.g. Peterson and Western, 2014) based on the enhanced data obtained through monitoring groundwater level, metering groundwater use and climate (Peterson & Fulton, 2019; Cheng, 2019; Cheng, 2022). In addition, a review of approaches and frameworks for groundwater assessment and modelling has been conducted (DSE, 2010; Jacobs, 2020a and 2020b).

Specific tasks completed under the SY project included:

- define the project objectives
- develop a method to estimate groundwater availability and sustainable yield volumes
- apply the method across Victoria
- report the results and assess the potential risk to sustainability and review the limits of take under licences

This report outlines the project's methodology, as illustrated in **Figure 1**.



Figure 1: SY assessment process and methodology

## 2. Project objectives

The SY assessment aimed to provide technical advice on the sustainable yield volume and review of limits of take by enhancing understanding of groundwater through improved groundwater resource assessments and statistical modelling, and incorporating up-to-date information on catchment characteristics, use and climate change.

The broad objectives of the SY assessment method include:

- to develop simple and cost-effective generic methods for evaluating sustainable yield volumes that can be applied across the state and easily updated to inform community discussions.
- to develop specific methods for conducting detailed assessments of sustainable yield volumes in higher priority areas where simple or generic methods may not be strictly applicable. This objective is set in the context of climate change, the potential for increased extraction, specific local groundwater values, local aquifer complexity, and greater awareness of the environmental impacts of groundwater use.

Sustainable yield represents an estimate of available groundwater that will have limited adverse impacts on assessed 'values' and serves as an essential foundational work to inform broader groundwater reform options under GM2030. The objective of the assessment was to provide technical advice on the sustainable yield volume, which effectively serves as the output required to inform various potential management outcomes, including a review of the limits of take under licences. Recommendations relating to possible future management regime is not part of the SY project itself, that will be undertaken as part of the GM2030 process. The specific outcomes of the SY project include informing discussions on the appropriateness and effectiveness of current groundwater management mechanisms in managing or mitigating risks of regional drawdown. Additionally, there is a question regarding whether caps on entitlements should be established for the entire state and what measures of acceptable resource conditions should be considered.

Matters that were out of scope for the SY assessment include:

- Groundwater demand: the project does not address this aspect as demand management is primarily regulated through limits on take under licences. Further studies may be warranted to assess the potential impacts of on groundwater demand.
- Future changes in land use: Significant changes in land use are not anticipated across most of the state.
- Economic impacts associated with changes in groundwater availability: Assessing economic impacts is not a focus of the project due to resource constraints. This aspect may be addressed in subsequent studies if deemed necessary.
- Potential adverse impacts of groundwater extraction on regional groundwater salinity and land subsidence: Such assessments require modelling and assessment of flow, solute transport and land subsidence.
- Potential adverse impacts of take of saline groundwater on inter and intra aquifer flow.
- The potential for and impact of managed aquifer recharge projects on the determination of sustainable yield.

The specific outputs of the SY assessment include:

- Sustainable yields, expressed as megalitres per year (ML/yr), for the current GMUs, and UAs.
- Review of the limits of take under licences.

### 3. Approach and methodology

The SY assessment approach and methodology have evolved over time. The approach adopted prioritises simplicity and cost-effectiveness, with refinements introduced only where required to address uncertainties that materially affect decision-making. Methods were chosen based on their alignment with the key drivers of availability and dependent values, with the methodology divided into separate components for confined and unconfined aquifers.

The overall approach follows the scientific method, which involves proposing a hypothesis and testing it through the following steps.

1. Define measures of sustainable yield.
2. Estimate groundwater resource volume.
3. Compare the sustainable yield volumes against entitlements and use to review the limits on take.

In this context, the hypothesis represents the proposition or initial position regarding measures of sustainable yields for values dependent on groundwater. Steps 2 and 3 involve testing this hypothesis. To accomplish this, the project applied new cost-effective approaches based on statistical modelling for resource quantification and sustainable yield estimation. These approaches seek to make clear the effects of uncertainties surrounding these estimates.

Defining measures of sustainable yield entails listing the possible values (such as consumptive use, and environmental), identifying the connection between groundwater and values (separately for confined and unconfined aquifers), and assigning values based on existing management policies. These measures are called “metrics” or “sustainable yield metrics” for the purpose of this project. Typically, they are expressed as metres change in regional groundwater levels (annual recovered) from pre-development levels. Therefore, a metric represents the change in regional recovered groundwater drawdown intended to have limited adverse impacts on assessed values. There is also an additional flow metric for waterways.

While the assessment encompasses the entire state, it conducted assessments at the most detailed level feasible. Initially, the focus was on the current GMUs. For areas outside GMUs, new assessment areas were defined for the project, referred to as UAs. For instance, in the case of unconfined aquifers, boundaries may align with minor catchment areas defined by the Victorian surface water winterfill sustainable diversion limit. Aquifer extents informed the confined aquifers UAs. The methodology allows for analysis and reporting at other scales and criteria if necessary, including consideration of hydrogeological features such as groundwater salinity, flow directions, and connections to waterways.

The adopted approach to resource quantification relies on statistical modelling, utilising extensive datasets on groundwater use and groundwater levels accumulated over many years in developed groundwater areas. This approach aimed to establish relationships between groundwater use and groundwater drawdown in each specific area. In the case of unconfined aquifers, this modelling also incorporated the relationship to climate variables. In regions where data is scarce, comprising approximately 70% of the state with minimal groundwater use data and limited development pressure, simpler methods focusing on recharge and throughflow were employed.

For developed areas, the metric (metre drawdown) was applied to the drawdown-use relationship to derive the sustainable yield volume for the area – calculated as the ratio of throughflow or recharge. For non-developed areas, the sustainable yield volume was derived by assuming the ratio of throughflow or recharge of similar groundwater systems in developed areas. The assessment for unconfined aquifers also includes various climate change scenarios and multiple values.

## 4. Define measures of sustainable yield

This section provides sustainable yield definition, outlines the measures used in the assessment, and presents the reporting areas of the assessment.

### 4.1. Sustainable yield definition and measures

In the context of the SY assessment:

- **Sustainable yield** refers to the groundwater extraction regime measured over a specified planning **timeframe**, allowing for acceptable levels of impact that protect dependent values.
- **Groundwater extraction** means the total consumptive uses within an aquifer or system, comprising water withdrawn for agricultural, industrial, commercial, stock, and domestic purposes.
- The specified planning timeframe is set at 20 years.
- **Dependency** means hydraulic connection to the values.
- **Values** mean:
  - consumptive use of water
  - the environment, including waterways, wetlands and terrestrial vegetation
  - cultural values, including Traditional Owner values.
- The ‘acceptable level of impact that protects dependent values’ is defined in **Table 1**.

**Table 1: Metrics for confined and unconfined aquifers**

Value	Acceptable level of impact – “metric” (metres in reduction in groundwater level)
<b>For confined aquifers</b>	
<b>Consumptive use</b>	10
<b>For unconfined aquifers</b>	
<b>Consumptive use</b>	2
<b>Consumptive use (seawater intrusion)</b>	1.5 mAHD <sup>b</sup>
<b>Environment - Waterways</b>	2.0
<b>Environment - Wetlands</b>	2.0
<b>Environment - Terrestrial vegetation</b>	2.0
<b>Environment - Stygofauna, including cave systems</b>	2.0
<b>Environment - Estuarine and marine</b>	2.0
<b>Environment - Springs</b>	2.0

- a. “Reduction in groundwater level” means the change in the seasonally recovered level measured in an observation bore or group of observation bores from pre-development period. Environmental metrics have used the upper threshold of 2.0m based on the advice in the ‘Ministerial Guidelines for Groundwater Licensing and the Protection of High Value Groundwater Dependent Ecosystems,’ DSE 2015.
- b. AHD means Australian Height Datum.

The definition of sustainable yield is based on the Australian national definition (National Groundwater Committee, 2004), with the Victorian terms for values replacing the national terms ('dependent economic, social, and environmental values'). The Victorian terms reflect the intent of the Victorian Water Act 1989 (s40 Matters to be considered), which includes considerations of users, the environment, and Traditional Owner cultural values. The Water Act 1989 mandates the consideration of Traditional Owner cultural values in areas identified through the *Traditional Owner Settlement Act 2010* via s8 (Domestic and Stock rights) and under s40 of the Water Act 1989. The addition of cultural values to the definition of sustainable yield acknowledges Traditional Owner values, reflecting the emerging strategic context of Groundwater Management 2030 and the Central and Gippsland Region Sustainable Water Strategy 2022 (DELWP, 2022a).

The designated timeframe of 20 years is commonly employed in groundwater planning and review procedures. This duration allows sufficient time for the groundwater system to reach equilibrium. It also offers a suitable period for assessing the management regime and implementing adaptive controls, if necessary, to ensure sustainable resource management.

There is currently no standard or nationally agreed position regarding measures of acceptable impacts on groundwater. The Victorian State of the Environment (CESV, 2018) highlighted the lack of defined metrics for reporting on groundwater sustainability and recommended they be developed. In line with this recommendation, the SY project adopts both the concept and the term, aiming to establish clear measures for assessing groundwater sustainability.

The measures of acceptable impacts (metrics) are based on the application of existing Victorian licensing policies and guidelines, which are then scaled up for regional groundwater resources. These metrics, along with their corresponding sustainable yield volumes, will be employed in subsequent discussions and engagements with various stakeholders. The SY project provides volumes for selected ranges for comparison and analysis, as well as the volume for the project metric. Metrics are defined as changes in groundwater levels because they are monitored state-wide, are measurable (in contrast to flows or water budgets, which are inferred), and are currently utilised in some groundwater management plans for allocation management and resource condition reporting.

The change in groundwater level is measured relative to the pre-development condition of the aquifer, characterised by minimal or no groundwater development. In most areas, this pre-development condition predates 1975, with gradual development occurring until the 1990s. The period from 1950 to 1974 is utilised as the pre-development period, subject to the availability of temporal data.

The basis for the assigned metrics for the assessment is as follows:

**Consumptive use metric – 10 metres (m) for confined aquifers, and 2 m for unconfined aquifers.**

The standard practice for licensing has historically involved approving applications for new licences and transfers if interference with a neighbouring bore remains below 10% of the available drawdown (which is the head above the pump intake). In addition, the policy allows for up to 20% interference in cases where there is extensive knowledge of the groundwater system's behaviour. These policies are outlined in the Groundwater Management Strategy established by the state-wide Groundwater Advisory Committee (State-wide Groundwater Advisory Committee, 1993), Principle 10, and by Goulburn Murray Water in the Mid-Loddon local management rules (Goulburn Murray Water, 2009). The majority of groundwater licences in Victoria were issued between the 1970s and 1990s, and this policy framework reflects the historical decisions made in licensing.

The 10% threshold is adopted to define the metrics for consumptive use. To render this percentage measurable, it is converted into metres, representing the reduction in water level. While regional water levels are generally well-mapped, specific information on pump intake, screen depths, bore depths, and pumping water levels in bores is unavailable. Aquifer thickness and saturated thickness also vary significantly. As a result, for unconfined aquifers, the available head is calculated as the saturated thickness of the aquifer – typically ranging from 15 to 20 m for sedimentary systems and around 50 m

for volcanic systems. Therefore, 10% of 20 m equals 2 m for sedimentary systems, while 10% of 50 m equals 5 m for volcanic systems. The adopted metric for unconfined aquifers is 2m.

Current policies regarding acceptable bore interference relate to drawdown at the bore user's location, whereas the metric for unconfined aquifers relates to drawdown at the observation bore(s). Since observation bores are intentionally positioned away from direct interference from pumping bores, the regional drawdown experienced will be less than that observed by adjacent pumping bores with direct interference. Regarding confined aquifers, due to the wide range of aquifer thickness, the 10% rule is not a suitable proxy for calculating available drawdown, which is typically around 10 m. The project metric of 10 m is based on groundwater management plans for confined aquifers, where landholders and the Minister for Water have accepted regional groundwater level drawdowns.

#### **Seawater intrusion metric – 1.5 m mAHD for unconfined aquifers within 300 m of the coastline.**

The threshold of 1.5 mAHD for seawater intrusion is based on recommendations outlined in the draft management framework for seawater intrusion (Jacobs, 2014). This framework suggests maintaining groundwater levels above sea level within 300 m of the coast, with a minimum elevation of at least 0.3 m above sea level at a distance of 1,000 m from the coast. The 1.5mAHD threshold is derived from established measures implemented in 2 groundwater systems adjacent to the coast (Koo Wee Rup and Deutgam GMUs). These measures have been successfully enforced for several years, effectively preventing seawater intrusion.

#### **Environmental metric including wetlands, terrestrial vegetation, and waterways – 2.0 m for unconfined aquifers.**

A metric of 2.0m has been adopted for the assessment. According to the Ministerial Guidelines, 2.0m serves as the threshold for distinguishing between moderate and high risk to environmental values in individual licence assessments. This threshold is to distinguish between areas that may require additional management controls. For the sustainable yield assessment, which includes all licensed take, the metric needs to represent cumulative impacts of all licensed take on the resource. The Ministerial Guidelines for the Protection of High-Value Groundwater Dependent Ecosystems (DSE, 2015) allow for a range based on different risk thresholds, ranging from 0.1 to 2.0 m.

In addition to this metric, there will be an assessment of sustainable yield volume against 10% of the MAF. This is based on the State-wide Groundwater Advisory Committee in the Groundwater Management Strategy (1993), advised limiting groundwater extraction to less than 10% of MAF. This principle was reiterated in the Groundwater Dependent Ecosystems Guidelines (DSE, 2015), advising limits to issuing of groundwater licenses to 10% of MAF or Q90 in the waterway. It is important to note that the groundwater take volume only relates to that taken from the connected groundwater within the catchment area of a waterway.

'Dependency' is defined as the hydraulic connection to the values, which is identified through the source/pathway/receptor model. In this model, the source represents the location of the extraction bore, the pathway denotes the groundwater in the aquifer, and the receptor is the value that is hydraulically connected to the aquifer.

For consumptive users, interference is determined for bores that are in the same aquifer or groundwater system, and in most cases, the same groundwater Suite. For environmental values, the assessment is applied to the groundwater system (highlands, upland valleys, alluvial valleys, sedimentary plains and volcanics), as well as the type of reporting area (GMUs or UAs). For waterways, there is an additional criterion based on the depth to water table for sedimentary and volcanic plains. Connectivity to waterways requires the depth to water table to be less than 6 m at the waterway location.

## 4.2. Sustainable yield reporting areas

For the SY assessment, sustainable yield volumes are estimated and reported based on the existing management arrangements, such as:

- GMUs (**Figure A9**)
- UAs
  - Surface Water Sustainable Diversion Limit minor river catchments (Winterfill sustainable diversion limit) for unconfined aquifers (**Figure A10**)
  - Confined (**Figure A11**) and semi-confined aquifers (**Figure A12**). These areas are named according to the Victorian Aquifer Framework (VAF) layer and the region. For more details on confined UAs, please refer to *Part 8: Sustainable Yield synthesis paper – Mapping, Boundaries, and Naming Conventions for Confined Aquifer UAs (DEECA)*

Assessment outputs are available at more refined scales, including gridded outputs for unconfined and confined aquifers. These outputs can be customised and updated to facilitate community discussions.

For UAs, the application of Victorian surface water diversion limit minor river catchments as reporting areas allows for comparison between groundwater sustainable yield volumes and surface water (winterfill) diversion limits. The consideration of surface water–groundwater interaction may be crucial for establishing the basis for estimating sustainable yield volumes for groundwater in the unconfined aquifers in UAs.

The new reporting zones for confined aquifers in UAs are established by closing the gaps between existing GMUs and aquifer extent. Some areas are divided based on land use, distinguishing between forested and agricultural land.

Semi-confined aquifers have also been identified through inter-aquifer leakage assessments (GHD Pty Ltd, 2014c) and mapped across GMUs and UAs. For more details on how semi-confined aquifers are mapped, please refer to *Part 6: Sustainable Yield synthesis paper – semi-confined aquifers mapping approach (DEECA)*.

## 5. Groundwater resource assessment

### 5.1. Groundwater data

Over the past 20 years, groundwater data has significantly expanded and become more readily available (**Table 2** and **Table 3**). Significant investments have been made in metering groundwater use, monitoring groundwater levels and waterways, and collecting remote sensing data, such as land use and topography maps.

**Table 2: Water availability – measured data**

Type	Number and spatial distribution	Period and frequency
<b>Groundwater level</b>	There are approximately 2,700 monitored state observation bores, with around 1,500 currently being monitored. These sites cover over 65% of the GMUs since the early 2000s.	The monitoring network was established progressively since the 1970s, with approximately one-third of the network set up by 1975, another third by 1990, and the remainder by 2000. Initially, monitoring was conducted bi-annually or quarterly, but the frequency increased to monthly in GMUs since the 2000s. Data loggers have also been installed on approximately 500 bores since 2017, enabling the collection of hourly data.
<b>Groundwater use</b>	There are approximately 5,100 metered bores in total.	Since 2004, data on licensed bores has been collected (mostly) annually, with additional data loggers installed on licensed bores in some GMUs in southern and western Victoria since 2020. This data, including annual entitlements and usage, is stored in the Victorian Water Register.
<b>Waterways</b>	There are approximately 950 gauged streams, with about 650 of them equipped with telemetry systems.	Monitoring commenced in the late 1800s, with around 300 sites established by the 1950s and approximately 600 sites by the 1970s. These sites are distributed across each basin and catchment. Data is collected daily, with data loggers now deployed on 60% of sites, providing minute-by-minute data.
<b>Climate</b>	The Australian Bureau of Meteorology measures daily rainfall, evapotranspiration, temperature and wind conditions across the state at over 210 sites.	Data is monitored daily for all parameters, with higher frequencies (such as by the minute) for rainfall and temperature.

**Table 3: Water availability – inferred data**

Type	Number and spatial distribution
<b>Lithology – aquifer extent</b>	The GIS dataset encompasses 10 primary aquifers and 4 aquitards, derived from an updated hydrogeological map series at a scale of 1:500,000. It includes information on the tops and bottoms of each layer, and their thickness.
<b>Aquifer properties</b>	The state-wide mapping reference encompasses hydraulic conductivity, transmissivity, and storativity data for the Upper Tertiary Quaternary Aquifer (UTQA), Upper Tertiary Aquifer Fluvial (UTAF), Upper Tertiary Aquifer Marine (UTAM), and Lower Tertiary Aquifer (LTA) aquifers. Additionally, it includes recharge information for the unconfined aquifers.
<b>Potentiometric surfaces</b>	<p>Potentiometric surfaces are available for:</p> <ul style="list-style-type: none"> <li>• Wimmera-Mallee: Murray Basin Hydrogeological Map Series and Wimmera Catchment Management Authority (CMA) ‘EcoMarkets’ model (Hocking Et Al., 2010b)</li> <li>• Goulburn-Murray: North Central ‘EcoMarkets’ CMA model (Hocking Et Al., 2010a) and Goulburn Broken CMA ‘Ecomarkets’ model (Hocking Et Al., 2010c)</li> <li>• Otway-Torquay: Glenelg Hopkins ‘EcoMarkets’ CMA model (SKM, 2009b) and Southern Rural Water hydrographical mapping project (SKM &amp; GHD, 2009)</li> <li>• Central: Port Phillip ‘EcoMarkets’ CMA model (GHD, 2010a)</li> <li>• Gippsland: West Gippsland ‘EcoMarkets’ CMA model (GHD, 2010b) and SRW hydrographical mapping project (SKM &amp; GHD, 2009)</li> </ul>
<b>Groundwater level trends – Suites</b>	A catalogue of grouped hydrographs, referred to as Suites, along with corresponding GIS maps, is available according to the upper, middle, lower and bedrock layers. Statistical analyses have been conducted on most of these Suites.
<b>Topography</b>	A digitised elevation model (DEM) is available at both 20-metre and 100-metre scales across the entire state, providing detailed topographic information.
<b>Land use</b>	The Victorian Land Use Information System (VLUIS) includes various categories representing different land uses, such as plantation types, agricultural land uses, national and state parks, and urban centres.
<b>Climate</b>	<ul style="list-style-type: none"> <li>• SILO gridded raster datasets including rainfall, pan evaporation and temperature.</li> <li>• The Australian Bureau of Meteorology annual projections for assessing the impact of climate change on water availability (DELWP, 2020c)</li> <li>• Victorian Climate Projections: seasonally adjusted climate change temporal datasets generated for models (DELWP, 2019b)</li> </ul>

<b>Waterways</b>	<ul style="list-style-type: none"> <li>• The Australian Bureau of Meteorology provides statistics on streamflow analyses, encompassing MAF, daily maximum and minimum flows, and the number of days with no flow.</li> <li>• The DEECA conducts Victorian state-wide baseflow analyses for all stream gauges (DSE, 2012a).</li> <li>• Waterway groundwater connectivity mapping (DSE, 2012b).</li> </ul>
<b>Groundwater values datasets</b>	<ul style="list-style-type: none"> <li>• Wetlands (DELWP, 2021b)</li> <li>• Waterways (DELWP, 2021a)</li> <li>• Caves, estuarine areas, springs, terrestrial vegetation (Bureau of Meteorology, 2021)</li> <li>• Bore locations (licensed and domestic and stock) (DELWP, 2020)</li> </ul>

## 5.2. Modelling approach

There have been a variety of models developed for and applied to the assessment of groundwater resources. These include data-driven approaches (such as empirical, statistical and artificial intelligence models) and physical-based approaches (such as numerical models). Statistical modelling techniques do not incorporate groundwater flow processes but can identify relationships and non-linearities in the available data. While these techniques are relatively easy to develop and use, they have a limited ability to establish cause-and-effect relationships. Despite this limitation, statistical models have been successfully applied in Victorian groundwater assessments, particularly in establishing relationships between groundwater use and groundwater levels (Peterson & Fulton, 2019; Cheng, 2019; Cheng, 2022). Statistical models are also cost-effective, requiring less data preparation and computing time compared to physical-based models like numerical modelling.

Both statistical and physical-based modelling techniques require expert knowledge. In numerical modelling, expertise involves a broad understanding of hydrogeology, groundwater flow processes, mathematical equations governing groundwater flow (and potentially solute transport), numerical methods for solving these equations, and techniques for model calibration and validation. In statistical techniques, expertise is primarily needed to select and pre-process relevant data and derivatives for meaningful input, as well as to evaluate, validate and interpret the outputs.

Numerical models typically provide results applicable to broad areas, such as groundwater drawdown maps or water budgets for an aquifer or system. In contrast, statistical modelling techniques are generally applied within the spatial scale relevant to the available data, which can vary from point-specific to regional or larger scales. They are tailored to address specific problems, such as groundwater level responses. Statistical models offer the advantage of easy updates as new data becomes available; a feature not commonly found in numerical physical-based models. In addition, revising statistical models could potentially be automated to allow for incremental changes instead of batch updates, thereby saving significant resources and time.

Within the sustainable yield assessment, the statistical technique was applied in:

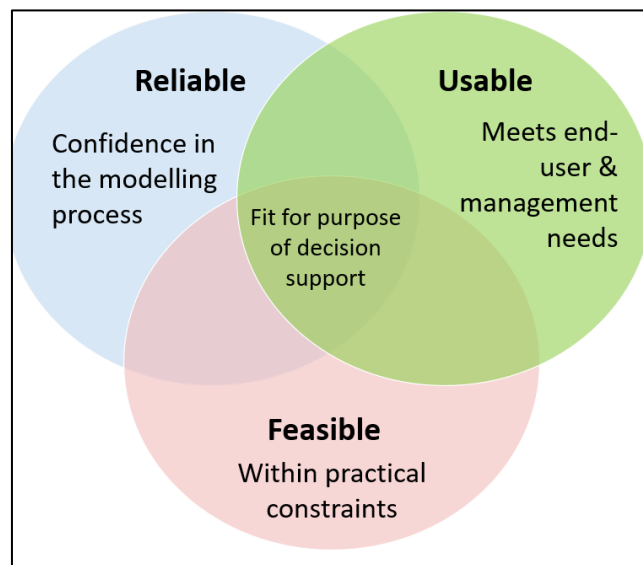
- confined aquifers, where it is applied to the Suite hydrographs, providing results at representative Suite of the GMUs.
- unconfined aquifers, where it is applied to bores across the state, and the kriging interpolation method is used to regionalise bore-scale results to a state-wide scale.

Each value is accompanied by a measure of uncertainty, indicating the quality of the result and assessment. Uncertainty analysis is an integral part of statistical techniques, expressed as upper and lower uncertainty bands.

In confined aquifers, throughflow is also calculated for each aquifer in GIS format using Darcy's equation, a standard and widely applied approach in groundwater resource studies. Darcy's equation provides a volume output without a groundwater level component. Since the output cannot be directly measured in the field, verification from observation is challenging. The accuracy of the results also depends on several input parameters, including aquifer thickness ( $b$ ), hydraulic gradient ( $H_L/L$ ), and hydraulic conductivity ( $K$ ). Large uncertainties in hydraulic conductivity often contribute significantly to the overall uncertainty in the method. It is also essential to consider the hydrogeological conceptualisation (particularly in areas where the groundwater resource is non-renewable or in closed systems), as throughflow may not accurately reflect the available groundwater resource.

Groundwater systems are inherently complex, and no single technical assessment can fully capture the complexity. Decisions regarding groundwater management should therefore be made carefully, considering the uncertainties inherent in complex system outcomes. Recognising and quantifying the uncertainties are crucial for making informed decisions. Uncertainties can arise from various sources, including data limitations, model simplifications, parameter uncertainty, and inherent variability in hydrogeological processes.

Incorporating uncertainty analysis techniques into groundwater modelling can offer valuable insights into the reliability, usability and feasibility of modelling results (Peeters and Middlemis, 2023) (**Figure 2**). By addressing uncertainties, decision-makers can better manage groundwater resources amid complexity. Previous assessments that have informed caps on entitlement allocation often lack quantitative uncertainty descriptions, hindering decision-making processes. In this project, various methods are employed for confined and unconfined aquifers, with different approaches to uncertainty analysis outlined in the following sections.



**Figure 2: Insights gained from fit-for-purpose groundwater modelling that incorporates uncertainty analysis techniques (adopted from Peeters & Middlemis, 2023)**

### 5.3. Statistical modelling

The statistical modelling approach adopted for the SY project focuses on predicting groundwater levels in relation to groundwater use, and for unconfined aquifers, climate variables. The proposed statistical modelling techniques utilise batches of data points to develop models, with separate datasets for confined and unconfined aquifers. For confined aquifers, the datasets include groundwater levels and groundwater use, while for unconfined aquifers, additional climate variables

such as rainfall and evapotranspiration are considered. Climate variables are excluded from confined aquifers due to the lack of observed influence on historical groundwater levels over the past three decades (GHD Pty Ltd, 2020a and 2020b). The primary objective of statistical modelling is to predict the 'seasonally recovered' groundwater level compared to pre-development levels and establish the relationship between groundwater use (and climate) and drawdown. The general work steps are as follows:

- data retrieval
- data preparation
- statistical modelling
- evaluation and uncertainty analysis
- model results and outputs.

These steps are outlined separately for confined and unconfined aquifers, along with case studies to illustrate the methodology. The assessments were conducted by contractors GHD Pty Ltd for confined aquifers and CDM Smith for unconfined aquifers. The following breakout box highlights the "modern" methods used in the SY assessment. It also outlines additional "modern" methods that could contribute to future studies of high-risk aquifers. A summary of these aspects is provided below, with a detailed methodology outlined in Part 3 and Part 4 of the methodology report.

### **Modern methods applied in the SY assessment**

The following "modern" methods were applied in the SY assessment:

- PASTAS statistical modelling – Confined aquifers
- HydroSight statistical modelling – Unconfined aquifers
- SoilFlux model – Unconfined aquifers
- HydroMap - Unconfined aquifers
- GIS mapping – Confined and unconfined aquifers

Other additional modern methods include:

- Physically based numerical modelling
- Environmental isotope tracers
- Passive aquifer test methods

#### **5.3.1. Confined aquifer statistical modelling – Part 3 of the methodology report**

This section provides a summary of the steps for confined aquifer statistical modelling conducted by GHD Pty Ltd. The detailed methodology is outlined in Part 3 of the methodology report.

## Data

The scope of the study includes 25 Victorian GMUs:

- WSPAs: Lower Campaspe Valley, Katunga, Glenelg, Condah, Koo-Wee-Rup, Sale and Yarram.
- GMAs: West Wimmera, Murrayville, Mid Loddon, Portland, Paaratte, Newlingrook, Gellibrand, Gerangamete, Jan Juc, Cut Paw Paw, Moorabbin, Frankston, Boneo, Corinella, Moe, Rosedale, Stratford and Giffard.

These GMUs represent areas of high and low use in confined aquifers (**Table 4** and **Table 5**).

**Table 4: High-use GMUs in confined aquifers**

Confined GMAs with high use (> 8 GL/yr)	Average Use (2016-2021) (ML/yr)
<b>Mallee</b>	
N/A	
<b>Otways</b>	
N/A	
<b>North Central Victoria</b>	
Katunga WSPA	27,785
Lower Campaspe Valley WSPA	38,255
Mid Loddon GMA	21,450
<b>Central (Port Phillip Bay and Westernport Bay)</b>	
N/A	
<b>Gippsland</b>	
Sale WSPA	11,029
Rosedale GMA	8,828
Yarram WSPA	11,482
Stratford GMA	22,625

**Table 5: Low-use GMUs in confined aquifers**

Confined GMAs with low use (< 8 GL/yr)	Average Use (ML/yr)
<b>Mallee</b>	
Murrayville WSPA	5,408
<b>Otways</b>	
Portland GMA	2,606
Glenelg WSPA (revoked)	5,957
Gellibrand GMA	0

<b>Paaratte GMA</b>	321
<b>Condah WSPA</b>	2,782
<b>Newlingrook GMA</b>	145
<b>Gerangamete GMA</b>	3,524
<b>Jan Juc GMA</b>	2,801
<b>North Central Victoria</b>	
N/A	
<b>Central (Port Phillip Bay and Westernport Bay)</b>	
<b>Moorabbin GMA</b>	1,096
<b>Koo-Wee-Rup WSPA</b>	3,610
<b>Corinella GMA</b>	60
<b>Frankston GMA</b>	230
<b>Cut Paw Paw GMA</b>	99
<b>Boneo GMA</b>	Extraction (2011-2021): 448 Injection (2011-2021): 322 Net extraction (2011-2021): 126
<b>Gippsland</b>	
<b>Orbost GMA</b>	294
<b>Giffard GMA</b>	2,475
<b>Moe GMA</b>	826

The groundwater level and use data (see **Table 2**) was made available from the DEECA Water Management Information System (WMIS). Groundwater Suites were also provided for use as a modelling domain (see **Table 3**). The groundwater Suites were reviewed to identify the most representative Suite for each GMU based on the volume of groundwater extraction, the relevance of the Suite (Suites that cover the intended aquifer of GMU), the extent of the Suite compared to the GMU, and presence of active State Observation Bore Network bores within the Suite area.

## Data preparation

Groundwater level data for the model was obtained through the normalised hydrographs for all representative Suite(s) for each GMU (**Figure A4**). Since metered use data in all Victorian GMUs is unavailable prior to 2004, historical data gaps were filled using 3 hindcasting methods for groundwater use time series data:

- developing a relationship between annual use and rainfall
- developing a relationship between rainfall and bore growth factor to hindcast use data. This involved back-estimating the growth factor of extraction bores and plotting the number of bores over time
- developing a relationship between percentage of entitlement of use and rainfall to hindcast the extraction data.

## Statistical modelling

The groundwater level for each Suite within a GMU is modelled using a Transfer Function Noise (TFN) model. This model allows for the linear transformation of one or more deterministic input series, with the residuals of the transfer model being autocorrelated. Specifically, in this case, the TFN model relates groundwater levels to groundwater use. TFN can be expressed mathematically in its simplest form as (Box and Jenkins, 1970):

$$h(t) = \int_{-\infty}^t S_m(\tau)\theta_m(t - \tau)d\tau + d + e_t$$

where,

$h$ : head

$t$ : time

$S_m$ : time series of stress  $m$

$\tau$ : represents the time at which past stresses are applied to the system, affecting the groundwater head at the current time (lag time)

$\theta_m$ : impulse response function for stress  $m$

$d$ : base elevation of the model

$e$ : residuals

There can be an arbitrary number of stresses ( $M$ ) that can contribute to the head, including groundwater use and climate parameters. To apply the TFN model, there are several interfaces. Pastas package (version 19.0) within the Python programming language was used to model groundwater levels based on use data.

## Evaluation and uncertainty analysis

The model is assessed through different evaluation criteria, including the coefficient of determination and root mean square error as measures of precision and accuracy, respectively.

Model uncertainty is assessed through the 95% confidence interval thickness (95 PPU thickness) and the percentage of observed annual recovered levels within the 95% confidence intervals (%Obs in 95PPU).

## Model results and outputs

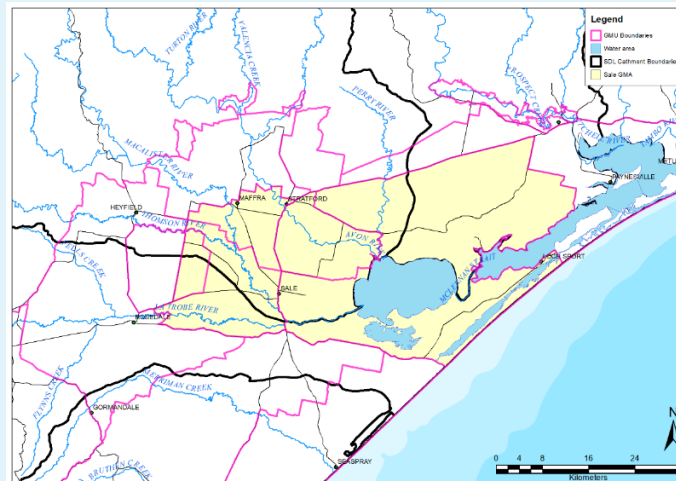
The desired outcome is to quantify the relationship between drawdown and groundwater use for each Suite within each GMU. To achieve this, the statistical model outputs were used to predict drawdowns under a range of potential future extraction scenarios. For this purpose, 19 scenarios were developed, comprising both plausible and implausible groundwater use scenarios. Plausible scenarios represent conditions that have been experienced and measured through available groundwater use data or groundwater level records. Implausible scenarios, on the other hand, represent purely hypothetical conditions proposed to aid in establishing the relationship between groundwater drawdown and use.

## Case study: Stage 1 pilot study on the application of the TFN statistical method in selected GMUs

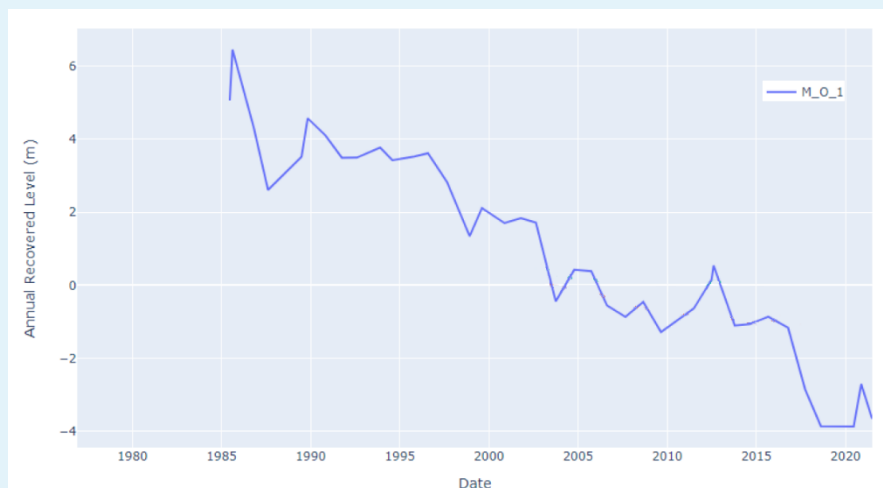
In the Stage 1 pilot study, the TFN statistical method was applied to 6 GMUs, including Katunga WSPA, Koo Wee Rup WSPA, Murrayville GMA, Lower Campaspe WSPA, Sale WSPA, and Yarram WSPA, as detailed in Part 3 of the methodology. The results of the case study confirm that the TFN modelling technique is suitable for statistically correlating historical groundwater level and groundwater use data, based on employed model performance evaluation criteria. **Table 6** presents the use-drawdown results for Sale WSPA (**Figure 3**) for representative Suite M\_O\_1 (**Figure 4**), where  $h$  is drawdown (metres), and  $Q$  is volume (groundwater use) (ML/year).

**Table 6: Use-drawdown results for Sale WSPA, representative Suite M\_O\_1**

GMU	Representative Suite	Relationship
Sale	M_O_1	$h \propto (0.0008 \times Q) - 1.4016$



**Figure 3: Sale WSPA locality map**



**Figure 4: Sale WSPA representative Suite M\_O\_1 hydrograph**

The successful application of the TFN statistical method in the case study indicates it is appropriate for broader use across confined GMUs in Victoria. As a result, the method was applied to the remaining 19 confined GMUs in Victoria, with further refinements implemented across all 25 GMUs.

Results for the confined aquifer were verified using historic drawdown and use data for each GMU and other data/information sourced from literature or prior studies. The verification process is discussed further in the Synthesis Results Report.

### 5.3.2. Unconfined aquifer statistical modelling - Part 4 of the methodology report

This section provides a summary of the steps for unconfined aquifer statistical modelling assessment conducted by CDM Smith. The detailed methodology is outlined in Part 4 of the methodology report.

#### Data

All state-wide observation bores in the unconfined aquifer were utilised in the assessment. Groundwater level and groundwater use data were obtained from the DEECA Water Information System (see **Table 2**). Additionally, reports and results from previous Hydrosight studies for 11 GMUs were provided (Cheng, 2022; Peterson and Fulton, 2019), along with SoilFlux recharge data. For the unconfined assessment, 42 GMUs were assessed and reported on.

**Table 7: High-use GMUs in unconfined aquifers**

Unconfined GMAs with high use (> 3.4 GL/yr)	Average Use (2016-2021) (ML/yr)
<b>Mallee</b>	
West Wimmera (Neuarpur)	13,860
<b>Otway</b>	
Nullawarre GMA	10,909
Glenelg WSPA	5,957
Hawkesdale GMA	5,040
Warrion WSPA	3,555
<b>North Central Victoria</b>	
Mid Goulburn GMA	3,535
Mid Loddon GMA	21,450
Loddon Highlands WSPA	7,407
Shepparton IR	86,860
Lower Ovens GMA	8,948
Lower Campaspe Valley WSPA (both)	38,225
<b>Central (Port Phillip Bay and Westernport Bay)</b>	
Koo-Wee-Rup WSPA (all depths)	3,610
<b>Gippsland</b>	
Wa De Lock GMA	7,750
Denison WSPA	7,679

\* These GMAs are part of the South-West Limestone GMA.

Table 8: Low-use GMUs in unconfined aquifers

Unconfined GMAs with low use (< 3.4 GL/yr)	Average Use (ML/yr)
<b>Mallee</b>	
West Wimmera (excl. Neuarpur)	8,082
<b>Otways</b>	
Heywood GMA	1,688
Colongulac GMA	1,331
Glenormiston GMA	1,273
Newlingrook GMA	47
Merrimu GMA	15
<b>North Central Victoria</b>	
West Goulburn GMA	1,359
Upper Goulburn GMA	1,992
Central Victorian Mineral Springs GMA	1,154
Cardigan GMA	895
Upper Ovens WSPA	1,317
Upper Murray GMA	814
Broken GMA	1,217
Strathbogie GMA	974
Kiewa GMA	876
Lancefield GMA	303
Eildon GMA	200
Barnawartha GMA	61
<b>Central (Port Phillip Bay and Westernport Bay)</b>	
Bungaree WSPA	2,700
Nepean GMA	2,812
Moorabbin GMA	981
Deutgam WSPA	625
Wandin Yallock WSPA	638
Frankston GMA	418
<b>Gippsland</b>	
Wy Yung WSPA	970
Moe GMA	858
Leongatha GMA	184
Tarwin GMA	10

## Data preparation

The groundwater level data underwent a cleaning process to address erroneous data stemming from pumping tests, sampling, corrections to measuring points, and removal of data resulting from telemetry failures. The groundwater elevations were adjusted to match a DEM to maintain consistency in mapping analyses. No adjustments for seasonality were made to the annual metered use data or hindcasting to address data gaps preceding the onset of metering in 2004. However, Hydrosight incorporates these adjustments as part of the model calibration process. Evapotranspiration was calculated on a state-wide basis using Morton's potential evapotranspiration method, leveraging climate data.

## Statistical modelling

The groundwater levels for each bore were modelled using a TFN model, using the Hydrosight interface. Hydrosight solves the following equation to estimate recharge and drawdown (Shapoori et al., 2015):

$$h(t) = \int_{-\infty}^t \left( \frac{S_t}{S_{cap}} \right)^\gamma \theta_p(t - \tau) d\tau - \int_{-\infty}^t E_t \left( 1 - \frac{S_t}{S_{cap}} \right) \theta_E(t - \tau) d\tau - \int_{-\infty}^t Q_t \theta_F(t - \tau) d\tau + d + e_t$$

where,

$h$ : head

$t$ : time

$\tau$ : represents the time at which past stresses are applied to the system, affecting the groundwater head at the current time (lag time)

$\gamma$ : pore index parameter that controls the nonlinear relationship between soil moisture  $S_t$  and soil-moisture storage capacity  $S_{cap}$

$d$ : base elevation of the model

$e$ : residuals

$S_{cap}$ : soil-moisture storage capacity

$S_t$ : soil moisture at time  $t$

$P$ : rate of precipitation

$E$ : potential evapotranspiration rate

$Q$ : pumping rate

$\theta_p$ : impulse response functions for free drainage

$\theta_E$ : impulse response functions for groundwater evapotranspiration

$\theta_F$ : impulse response functions for pumping

While different platforms (Pastas and Hydrosight) are used to model groundwater levels in confined and unconfined aquifers, the same basic TFN approach is applied to both confined and unconfined aquifers. For unconfined aquifers, adjustments are made to consider additional processes like climate parameters.

This equation was applied to all bores across the state. Drawdown was estimated from changes in head over time, while recharge is estimated using the free drainage parameter within the equation. Specifically chosen bores in areas with significant groundwater extraction are analysed for pumping effects, typically within a radius of 2 to 5 kilometres (km) from each bore. Priority GMUs were chosen as they represent key groundwater use areas where recharge studies have not been previously

conducted in depth. These areas also correspond with major zones of intensive use, accounting for more than 70% of groundwater extraction in the unconfined aquifer (excluding Shepparton Irrigation Region use) (**Table 7**). These 11 GMUs include Mid-Loddon, Lower Ovens, Denison, Wa-De-Lock, Hawkesdale, Yangery, Nullawarre, KooWeeRup WSPA, Deutgam WSPA, Lower Campaspe Valley WSPA, and Glenelg WSPA. A total of 27 bores were selected within these areas to assess the effects of pumping and climate. The remaining 30% of unconfined aquifer use is distributed across another 27 GMUs, with usage intensity being very low in most areas (**Table 8**).

To estimate the impact of groundwater extraction on bores that could not be modelled individually, the relationship of groundwater use to drawdown from modelled observation bores was assigned to un-modelled extraction bores to estimate groundwater levels for all un-modelled bores across the state. The results of the analyses were combined to produce a spatially continuous dataset of estimated groundwater level at all available bores across the state.

The key steps to producing statewide recharge and drawdown maps were:

1. point scale analyses using HydroSight models, which statistically model groundwater levels using climate (rainfall and evapotranspiration) and metered use to calibrate models to measured levels
  - a. modelling of watertable bores in HydroSight to determine drawdown and recharge under historic and future climate scenarios (referred to as 'climate only' bores in the assessment)
  - b. modelling of GMUs with high levels of groundwater take (>3,700 ML/yr) in HydroSight with inclusion of pumping from bores within 5 km of monitoring bore and climate scenarios
2. statewide mapping of drawdown and recharge using HydroMap (a kriging tool)
  - a. regionalisation of drawdown–use relationships from high-use GMUs to other areas of the state with licensed bores to determine drawdown at those points
  - b. kriging of each scenario (use and climate) to develop reduced water level maps, drawdown maps and recharge maps for each scenario
  - c. merging of HydroSight recharge outputs with the SoilFlux statewide recharge layers (updated with climate change scenario outputs)

For future scenarios, 3 climate change scenarios (low, medium and high) and 4 pumping scenarios (zero use, current use, Permissible Consumptive Volume, and 200% of the Permissible Consumptive Volume) were considered to predict recharge and groundwater level.

## Evaluation and uncertainty analysis

For statistical model calibration, the coefficient of efficiency statistic was calculated. CoE offers an unbiased evaluation of the calibrated head's fit to observed data, ranging from '0' (or a negative value), indicating extremely poor calibration, to '1', representing perfect calibration.

To estimate uncertainty, a joint approach was employed to capture the calibrated head's fit to observed head (maximum and minimum calibration residuals) and the variability in annual head results (maximum and minimum), averaged for the project reporting periods.

There is no estimate of uncertainty for the regionalisation method or the mapping process to quantify likely error in mapped levels or recharge rates. The uncertainty results, whilst quantitative, represent a qualitative uncertainty band for the mapped statewide results differentiating areas where bores were modelled and areas where there were no monitoring bores to model.

To estimate the likely range of SY volumes without an uncertainty estimate, the climate change scenarios have been used to provide the lower and upper band of the results. This is a substitute for an uncertainty estimate, acknowledging that climate is the dominant driver for levels and recharge in the unconfined aquifers and this variability may exceed the uncertainty of the method.

## Model results and outputs

For the bore scale, the results and outputs include recharge, groundwater elevation, and drawdown for various pumping and climate scenarios.

The climate scenarios used align with DEECA's climate guidelines (DELWP, 2020). They include:

- baseline period: 25-year average annual climate from 1950 to 1974 (inclusive)
- development period: 23-year average annual climate from 1975 to 1997 (inclusive)
- current period: 23-year average annual climate from 1998 to 2020 (inclusive)
- projected future climate periods: a high greenhouse gas emissions scenario (Representative Concentration Pathway (RCP) 8.5) for 2040 and 2065, represented by a 20-year average annual climate from 2021 to 2040 and a 25-year average annual climate from 2041 to 2065 (inclusive)
- low, medium, and high future greenhouse gas emissions scenarios.

The RCP8.5 scenario considers high rates of greenhouse gas emissions, suitable for precautionary water supply planning. It incorporates global climate modelling uncertainty and uncertainties around future greenhouse gas emissions and concentrations. The low, medium and high scenarios represent the 10th, 50th and 90th percentile outcomes from 42 available global climate models. Part 4, Appendix B provides more detail on the process to derive the climate data series for these scenarios.

For the 27 selected bores within the 11 GMUs (Mid-Loddon, Lower Ovens, Denison, Wa-De-Lock, Hawkesdale, Yangery, Nullawarre, WSPAs: KooWeeRup, Deutgam, Lower Campaspe Valley, Glenelg), the pumping scenarios include zero use, current use, the Permissible Consumptive Volume, and 200% of the Permissible Consumptive Volume. An additional 3000 bores were assessed for climate only (i.e. these monitoring bores did not show a high correlation with pumping) for the statewide recharge assessment. About half of these were accepted for use in the regionalisation process.

The combination of pumping and climate scenarios results in 32 future scenarios plus 3 historic reporting periods (1950–74, 1975–1997, 1998–2020).

This resulted in:

- 32 maps of annual maximum recovered levels for 2021-40 and 2041-65
- 32 drawdown maps (relative to the baseline period of 1950–1974 for annual maximum recovered levels)
- 32 maps of annual minimum levels for 2021-40 and 2041-65
- 32 drawdown maps (relative to the baseline period of 1950–1974 for annual minimum levels)
- 9 recharge maps (recharge does not change under different pumping scenarios): 3 historic periods, 3 for 2021-40 low, medium and high climate change, and 3 for 2041-65 low, medium and high climate change scenarios.

These results have been used to develop the drawdown/use relationships and to assess the sustainable yield volumes for each of the values and their metrics. Additionally, the streamflow analyses have been used to assess waterway flow metrics in each of the GMUs where the reach is gaining and has groundwater use within its catchment.

Recharge is measured in mm/year, and water table elevation is in mAHD. The Hydrosight results are at bore scale and should be regionalised using interpolation methods. Hydromap (interface for kriging interpolation method) was applied to regionalise the bore data into state-wide regional raster (0.2 km

grid). Extra parameters were used in the interpolation, including a DEM for water level mapping and climate for recharge mapping.

## Case study: TFN statistical method in the Mid Loddon GMA

The TFN statistical method was applied to the Mid Loddon GMA (Figure 5), as detailed in Part 4 of the methodology. The case study confirmed the suitability of the TFN modelling technique for statistically correlating historical groundwater levels, groundwater use and climate data for individual bores, with a CoE ranging from 0.78 to 0.98. Drawdown was calculated from annual recovered levels for each reporting period for each modelled bore. These results were used as input to the waterlevel mapping.

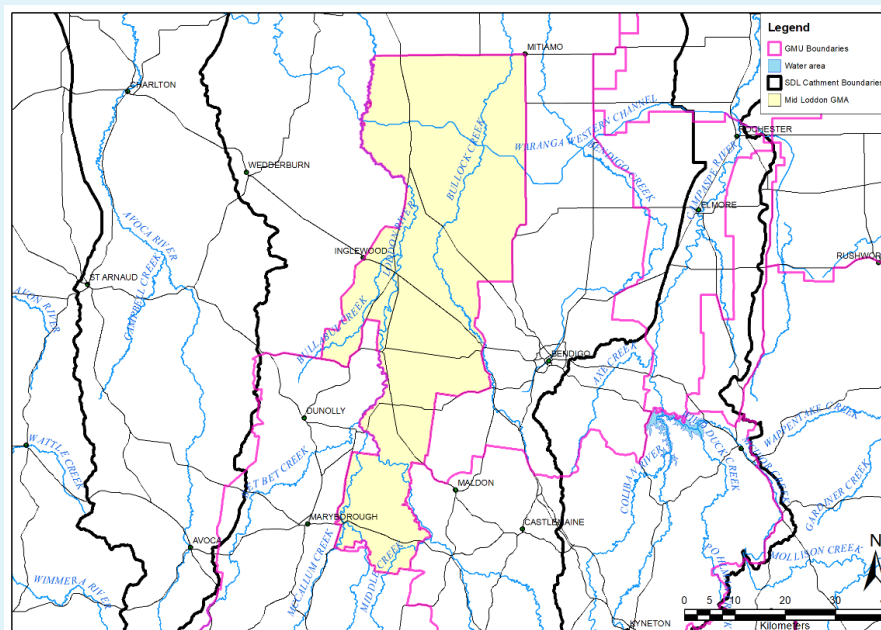
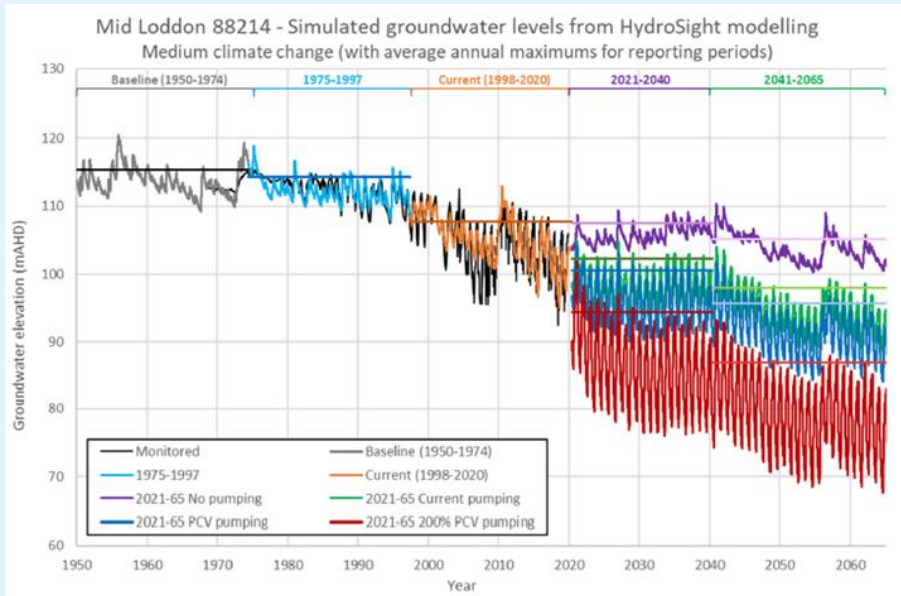


Figure 5. Mid Loddon GMA locality map



**Figure 6. Mid Loddon GMA simulated groundwater levels for bore 88214 showing different reporting periods for which drawdown was calculated.**

Drawdown at any one location may exceed 2m, especially at key monitoring sites in intensive use areas. The risk of this is shown in consumptive use exceedance plots which show how many users may be affected by drawdowns greater than 2m.

The regionalisation method across the GMA was deemed appropriate, providing waterlevels (**Figure 7**) and recharge outputs (**Figure 8**) as gridded outputs. Examples are shown below for Mid Loddon GMU.

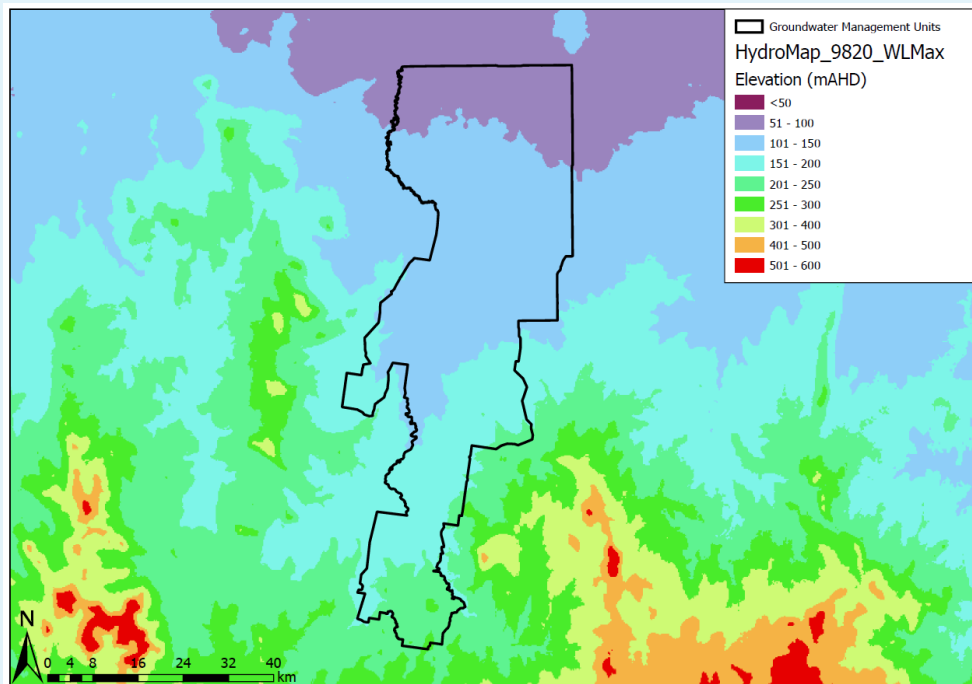


Figure 7. Mid Loddon GMA average annual maximum waterlevels for the 1998 to 2020 period (historical climate and use)

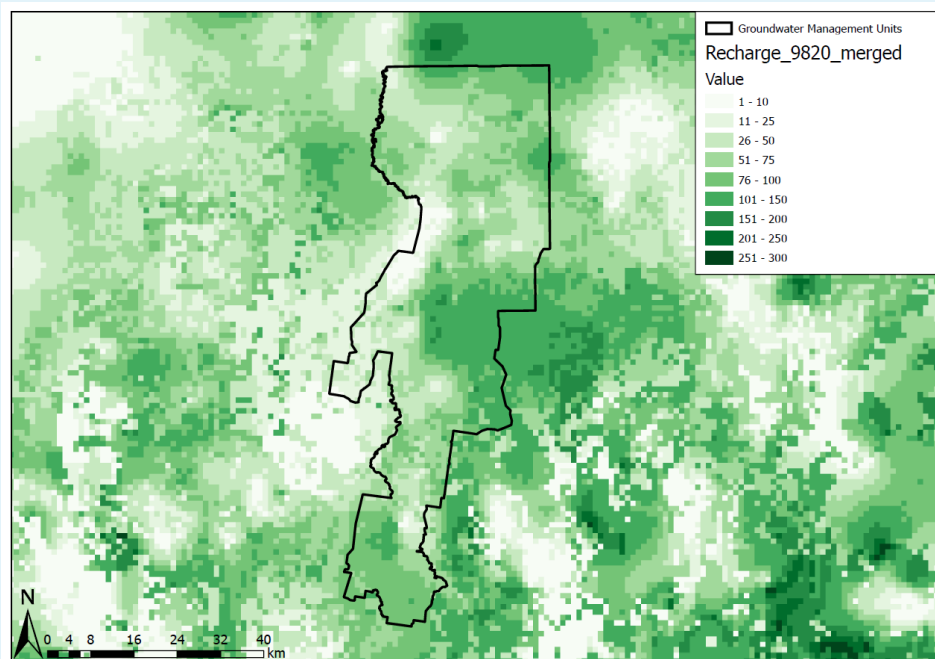


Figure 8: Mid Loddon GMA average recharge for the 1998 to 2020 period (historical climate and use)

**Table 9** presents the regionalised use-drawdown results for the Mid Loddon GMA across 3 climate scenarios and 2 time periods, where  $h$  is drawdown (metres), and  $Q$  is volume (groundwater use) (ML/year). The current use at 2020 results in a drawdown of 1.0 m compared to the baseline period (1950–1974). It is noted that no relationship is available for historical climate-only or future climate scenarios.

**Table 9: Use-drawdown results for the Mid Loddon GMA**

GMU	Climate change scenario and reporting period	Relationship
Mid-Loddon	2040: low emissions scenario	$h \propto 0.000025 \times Q + 1.7233$
	2040: medium emissions scenario	$h \propto 0.000036 \times Q - 0.1909$
	2040: high emissions scenario	$h \propto 0.000025 \times Q + 3.8341$
	2065: low emissions scenario	$h \propto 0.000036 \times Q + 6.0947$
	2065: medium emissions scenario	$h \propto 0.000024 \times Q + 5.8043$
	2065: high emissions scenario	$h \propto 0.000035 \times Q + 11.9914$

Results for the unconfined aquifer were verified using historic drawdown and use data for each GMU and other data/information sourced from literature or prior studies. The verification process is discussed further in the Synthesis Report.

## 5.4. Confined aquifer – throughflow modelling approach - Part 1 of the methodology report

This section provides a summary of the steps for confined aquifer -throughflow modelling approach conducted by Jacobs. The detailed methodology is outlined in Part 1 of the methodology report.

Pre-development throughflow is estimated for all confined aquifers using Darcy's equation, which is as follows:

$$\text{Throughflow rate} = \text{Hydraulic conductivity } (K) \text{ (m/day)} \times \text{Hydraulic gradient } (H_L/L) \times \text{Cross sectional area } (A) \text{ (m}^2\text{)}$$

Darcy's equation is an analytical approach assuming homogeneous components to the 3 elements. To better represent the spatial distribution and uncertainties of these elements, the method is applied over the aquifer areas using a 5x5 km grid. At the GMU (or UA) scale, pre-development throughflows are estimated by summing gridded throughflows along cross-sections perpendicular to groundwater flow.

### 5.4.1. Data

Five regional confined aquifer systems were utilised in the assessment:

- Upper Tertiary Aquifer (fluvial) (UTAF (105))
- Upper Mid-Tertiary Aquifer (UMTA (107))
- Lower Mid-Tertiary Aquifer (LMTA (109))
- Lower Tertiary Basalts (LTB (112))
- Lower Tertiary Aquifer (LTA (111))

Aquifer extent, aquifer hydraulic conductivity and pre-development confined aquifer potentiometric surfaces were made available from DEECA (**Table 2** and **Table 3**). Pre-development confined aquifer potentiometric surfaces for 5 confined aquifers were derived from the following sources:

- Wimmera-Mallee Groundwater Management Basin: Murray Basin Hydrogeological Map Series and Wimmera CMA 'Ecomarkets' model (Hocking, Et Al., 2010a).
- Goulburn-Murray Groundwater Management Basin: North Central 'Ecomarkets' CMA model (Hocking, Et Al., 2010b) and Goulburn Broken CMA 'Ecomarkets' model (Hocking. Et Al., 2010c).
- Otway-Torquay Groundwater Management Basin: Glenelg Hopkins 'Ecomarkets' CMA model (SKM, 2009) and Southern Rural Water hydrographical mapping of southern Victoria (SKM and GHD Pty Ltd, 2009).
- Central Groundwater Management Basin: Port Phillip 'Ecomarkets' CMA model (GHD Pty Ltd, 2010a).
- Gippsland Groundwater Management Basin: West Gippsland 'Ecomarkets' CMA model (GHD Pty Ltd, 2010b) and SRW hydrographical mapping of southern Victoria (SKM and GHD Pty Ltd, 2009).

#### 5.4.2. Data preparation

The aquifer GIS layers are divided into 5x5 km cells to calculate thickness and hydraulic gradient in each cell. Management boundaries in a number of GMUs did not occupy the whole width of a flow-tube, such that the flow-tube contained a number of UA flow cells. In these instances, the whole extent of the flow-tube (that includes the additional UA flow cells) should be acknowledged and accounted for when adopting the throughflow outputs for a GMU, including in the estimation of the sustainable yield. Similarly, for some GMUs, the management boundaries did not occupy the entire length of the flow-tube, such that the flow-tube contained UA flow cells upgradient or downgradient of the GMU. In these instances, throughflow rates have been calculated for both the entire flow-tube and the length of the GMU. If a GMU receives flow from an UA or contributes flow to an UA, the entire length of the flow path (i.e. the entire flow-tube) should be acknowledged and accounted for when adopting throughflow outputs for a GMU, including in the estimation of the sustainable yield. The same principle applies if flow occurs between GMUs, as is the case for the Upper Mid Tertiary Aquifer layer that flows from the West Wimmera GMA to the Murrayville GMA.

#### 5.4.3. Modelling

Darcy's equation is employed to calculate gridded pre-development throughflow rates (5x5 km cell) based on 3 components: thickness (b), hydraulic gradient (HL/L), and hydraulic conductivity (K). The 50th percentile (P50 K) of the K database is adopted, and the calculation is executed through a GIS semi-automated throughflow tool. Groundwater flow is conceptualised in 3-dimensions (termed 'flow-tubes') and delineated, in *plan* view, orthogonal to modelled predevelopment potentiometric contours. Pre-development P50 K throughflows at the GMU (or UA) scale are estimated by summing P50 K gridded throughflows along cross-sections perpendicular to groundwater flow. Where feasible, multiple cross-sections within a flow-tube are selected for analysis, and the average P50 K pre-development throughflow is derived. This approach provides a detailed understanding of pre-development throughflow dynamics across the aquifer.

#### 5.4.4. Evaluation and uncertainty analysis

The reliability of the hydraulic conductivity dataset is assessed based on the areal density, measured as the number of data points per 1000 km<sup>2</sup>. The assessment criteria are as follows:

- high reliability: if the areal density exceeds 20 data points per 1000 km<sup>2</sup>
- moderate reliability: if the areal density ranges between 10 and 20 data points per 1000 km<sup>2</sup>
- low reliability: if the areal density is less than 10 data points per 1000 km<sup>2</sup>

Uncertainty in the best estimate pre-development throughflow outputs (P50 K) and at the flow-tube scale is evaluated through the following calculations:

- lower range best estimate (P50 K) throughflow: calculated as the minimum cross-sectional throughflow using the P50 K
- upper range best estimate (P50 K) throughflow: calculated as the maximum cross-sectional throughflow using the P50 K
- lower range minimum 20th percentile (P20 K) throughflow: calculated as the minimum cross-sectional throughflow using the P20 K

#### 5.4.5. Model results and outputs

The pre-development throughflow in ML/yr is provided as output at various scales, including the 5×5 km cell, the flow-tube and the GMU. The GIS semi-automated throughflow tool can be employed to calculate the pre-development throughflow for UAs across the state.

#### **Case study: Pilot study on the application of the GIS throughflow method to selected GMUs**

The GIS throughflow method was applied to 4 GMUs, including Koo Wee Rup WSPA, Murrayville GMA, Lower Campaspe WSPA, and Sale WSPA in the Stage 1 pilot study (as described in Part 2 of the methodology). The main outcome of the pilot study was the development of a GIS semi-automated tool for calculating pre-development throughflows of confined VAF layers at a gridded 5×5 km scale. At the GMU or UA scales, pre-development throughflow is estimated by summing gridded throughflows along cross-sections perpendicular to groundwater flow.

The results of the GIS throughflow method for the 4 areas yield P50 K pre-development throughflows similar to previous studies (SKM, 1998). For example, in the Sale WSPA, the average P50 K predevelopment throughflow is calculated at 19,267 ML/yr, compared to 13,003 ML/yr in the 1998 calculation. However, one of the advantages of the current methodology is the availability of pre-development throughflow lower and upper uncertainty ranges, which were not previously available. For instance, in the Sale WSPA, the P50 throughflow ranges from 12,282 ML/yr to 25,665 ML/yr.

Regarding the Murrayville WSPA, the current understanding of aquifer behaviours suggests that vertical recharge and throughflow are minimal, and the source of fresh groundwater in the Mallee dates back to wetter periods about 16,000 years ago. The establishment of caps for entitlement in the area is based on the proportion of groundwater from stored reserves (BGARC, 2001). Although pre-development throughflow has been estimated for the Murrayville WSPA, the conceptual understanding of the resource remains unchanged (i.e. that it is ancient with negligible recharge and throughflow).

### **5.5. Semi-confined aquifers statistical modelling - Parts 6 and 7 of the methodology report**

For semi-confined aquifers, the assessments of both unconfined and confined aquifers are undertaken, and the SY volume is determined based on the degree of connectivity between these aquifers. This approach prevents double accounting of groundwater resources in semi-confined aquifers.

First, semi-confined GMUs and UAs are mapped across the state. The areas identified as 'semi-confined' are listed in **Table 10** for the GMUs and in **Table 11** for the UAs. For details on the mapping methodology, refer to *Part 6: Sustainable Yield Synthesis Paper – Semi-Confined Aquifers Mapping Approach (DEECA)*.

We assessed the Suite hydrographs for GMUs and nested bores for UAs across the state to evaluate semi-confined aquifer connectivity using two key parameters: trend similarity and fluctuation magnitude. The correlation coefficient (R) and fluctuation ratio (FR) were calculated to quantify connectivity. The correlation coefficient measures the similarity between annual groundwater level time series, while the FR compares the magnitude of water level fluctuations between the upper and lower aquifers. For a detailed explanation of how connectivity is identified, refer to *Part 7: Sustainable Yield Synthesis Paper – Semi-Confined Aquifers Synthesis Approach (DEECA)*. Connectivity was classified as follows:

**Highly connected:**  $R > 90\%$  and  $0.8 < FR < 1.2$

**Partially connected:**  $60\% < R < 90\%$  and  $0.4 < FR < 0.8$  or  $1.2 < FR < 1.6$

**No significant connection:**  $R < 60\%$  and  $FR < 0.4$  or  $FR > 1.6$

## Method outcome for semi-confined aquifers

The analysis revealed varying degrees of connectivity across GMUs and the UAs.

### Highly connected GMUs

The Lower Ovens GMA exhibits a high degree of connectivity between the upper unconfined and lower confined aquifers.

### Partially connected GMUs

The Mid Loddon GMA, Lower Campaspe Valley WSPA, Broken GMA, and Kiewa GMA exhibit partial connectivity. Therefore, a single SY volume is proposed based on the unconfined aquifer assessment for both aquifers. However, it is acknowledged that further investigation is needed to refine the SY estimation if independent SY volumes are required for each aquifer.

### Highly connected UAs

West of Mid Loddon (UTAF-NE1) UA demonstrates a high degree of connectivity.

### Partially connected UAs

North of Mid Loddon (UTAF-NE2) UA exhibits partial connectivity.

Table 10: Semi-confined GMUs across the state

GMU	GMU depth range (m)	Target VAF and Formations	Degree of connectivity
<b>Mid Loddon</b>	All formations below surface	Upper Layer (UL): UTB (Newer Volcanics – highlands only) UTQA (Shepparton) Middle Layer (ML): UTAF (Calivil)	Partially connected
<b>Mid Goulburn 1070 (overlain by Shepparton I.R. GMA)</b>	All formations from 25 m below ground surface to 50 m into bedrock or 200 m from the surface (whichever is the greater depth)	UL: UTQA (Lower Shepperton) ML: UTAF (Calivil)	No significant connection
<b>Mid Goulburn 1071</b>	All formations from ground surface to 50 m into bedrock or 200 m from the surface (whichever is the greater depth)	UL: UTQA (Shepperton) ML: UTAF (Calivil)	Not assessed
<b>West Goulburn North (overlain by Shepparton I.R. GMA)</b>	All formations from 25 m below ground surface	UL: UTQA (Lower Shepperton) ML: UTAF (Calivil)	Not assessed
<b>Lower Campaspe Valley</b>	All formations below the surface with the exception of all formations from the surface to 25 m below the surface north of the Waranga West Channel	UL: UTB (Newer Volcanics – highlands only), UTQA (Shepparton) ML: UTAF (Calivil)	Partially connected
<b>Broken</b>	All formations from ground surface to 50 m into bedrock or 200 m from the surface (whichever is the greater depth)	UL: UTQA (Shepparton) ML: UTAF (Calivil)	Partially connected
<b>Lower Ovens</b>	All formations from ground surface to 50 m into bedrock or 200 m from the surface (whichever is the greater depth)	UL: UTQA (Shepparton) ML: UTAF (Calivil)	Highly connected
<b>Kiewa</b>	All formations from ground surface to 50 m into bedrock or 200 m from the surface	UL: UTQA (Shepparton) ML: UTAF (Calivil)	Partially connected

(whichever is the greater depth)		
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**Table 11: Semi-confined UAs across the state**

<b>GMU</b>	<b>GMU depth range (m)</b>	<b>Target VAF and Formations</b>	<b>Degree of connectivity</b>
<b>North of Mid Loddon (UTAF-NE2)</b>	All formations below the surface	UP: UTQA (Shepparton) ML: UTAM (Parilla Sand), UTAF (Calivil)	Partially connected
<b>West of Mid Loddon (UTAF-NE1)</b>	All formations below the surface	UP: UTQA (Shepparton) ML: UTAM (Parilla Sand), UTAF (Calivil)	Highly connected
<b>Northwest Port Philip (UTAF-PP1)</b>	All formations below the surface	UL: UTB (Newer Volcanics) ML: UTAF (Brighton Group)	Not assessed.

## 6. Estimate sustainable yield volumes

### 6.1. Estimate sustainable yield volumes

The sustainable yield volumes are estimated according to the aquifer type (confined, unconfined, semi-confined) and whether it is a GMU or UA as follows:

#### Confined aquifer GMUs

- For confined aquifer GMUs (25 GMUs), the sustainable yield volumes are estimated by comparing the estimates of groundwater resource (via the statistical modelling of use-drawdown relationship) for the representative suite with the sustainable yield metrics. That is:
- Sustainable yield = the volume estimated from the statistical method for each GMU (Representative Suite) relating to the consumptive use metric (i.e. 10 m).

#### Confined aquifer UAs

- For confined aquifer UAs:
- Sustainable yield = the percentage of the throughflow equivalent to the average percentage of the throughflow of the confined GMUs with accepted use-drawdown relationship.

#### Unconfined aquifer GMUs

- For unconfined aquifer GMUs:
- Sustainable yield is the volume derived from the statistical method for each area (GMA) relating to the value's metric, including GMU scale (2m), consumptive use (2 m), environmental (2 m), waterways (2 m and <10% MAF/Q90) and seawater intrusion (1.5 mAHD). It requires consideration of current climate (1998–2020) and the low, medium and high climate scenarios in 2040 and 2065.
- The drawdown is an average of drawdown for each grid cell for the relevant values across each the GMU.
- The drawdown in each grid cell is an average of the maximum recovered levels for each reporting period for GMU scale, consumptive use and environmental (terrestrial, waterways and wetlands) values (**Figure 6**). The assessment used this method to avoid using results from any 'one' year which may be either a very wet or very dry year. This means results represent the longer-term climate variability not annual seasonality.
- The drawdown for seawater intrusion is taken from the minimum water levels for the reporting period within 1km of the coastline due to grid cell limitation (1km).
- The sustainable yield volume for each GMU represents a 2m drawdown over the entire GMU to encapsulate all dependent values connected to the watertable. This 2m drawdown is the difference between the average of the annual maximum recovered levels for the baseline period and the simulated 2021-40 period.
- The sustainable yield volume is taken from the current climate (or no climate change) scenario for 2021-40, which includes the Millenium drought climate sequence in the modelled scenario. This is referred to as the SY 2040 (no climate change) result.
- The range in the sustainable yield volume is taken from the low and high climate change volumes for 2021-40 for a 2m drawdown.

#### Unconfined aquifer UAs

- For unconfined aquifer UAs:

- Sustainable yield = the percentage of the recharge volume for the unconfined aquifer UA. The percentage is determined from comparison of the accepted sustainable yield volume in GMUs from the use-drawdown relationship compared with recharge volumes in those GMUs with similar systems (e.g. same region, land use, aquifer or system type). The percentage will change for each climate change scenario: 2040 and 2065. The sustainable yield volume in UAs is taken from the 2040 results from the medium climate change scenario.

## Semi-confined aquifer GMUs and UAs

- There are areas in Victoria where aquifers may exhibit characteristics of both confined and unconfined systems, and which may be described as semi-confined aquifers. The development of an approach to estimate sustainable yield for these semi-confined aquifers is necessary to prevent the double accounting of groundwater resources. For semi-confined GMUs and UAs, the following principles provide a framework for estimating sustainable yield based on the degree of connectivity of semi-confined aquifers (
- **Table 12):**
  1. Semi-confined aquifers that are highly connected, a single sustainable yield volume is proposed for both aquifers.
  2. Semi-confined aquifers that are partially connected, a single sustainable yield volume is proposed based on the unconfined aquifer assessment for both aquifers, but further assessment is required to refine the SY estimation if independent SY volumes are required for each aquifer.
  3. Semi-confined aquifers that show no significant connections between the aquifers have separate sustainable yield for each aquifer based the assessment method for the respective aquifer.
- For more details on the semi-confined aquifers synthesis approach and how their connectivity is identified, please refer to *Part 7: Sustainable Yield synthesis paper – semi-confined aquifers synthesis approach (DEECA)*.

**Table 12: Principles for assessing semi-confined aquifer behaviour**

Degree of connectivity	Principle
<b>High connectivity</b>	Sustainable yield estimation relies solely on the unconfined aquifer assessment to avoid double accounting.
<b>Partial connectivity</b>	A single sustainable yield volume is proposed based on the unconfined aquifer assessment for both aquifers, but further assessment is required to refine the SY estimation if independent SY volumes are required for each aquifer.
<b>No connectivity</b>	Sustainable yield volumes are estimated separately for unconfined and confined aquifers based on their respective assessments.

### 6.1.1. Confined aquifer GMUs – Part 5 of the Methodology Report

For the 25 confined aquifer GMUs, the results of the statistical modelling and the throughflow are synthesised through the following steps:

1. Apply the drawdown-use assessment to establish a relationship between drawdown and groundwater use, accompanied by uncertainty bands for each representative Suite for each GMU. This relationship is utilised to calculate drawdown and uncertainty bands for volumes of different

uses (e.g. PCV, entitlement, average use) and to calculate volume and uncertainty bands for a consumptive use metric.

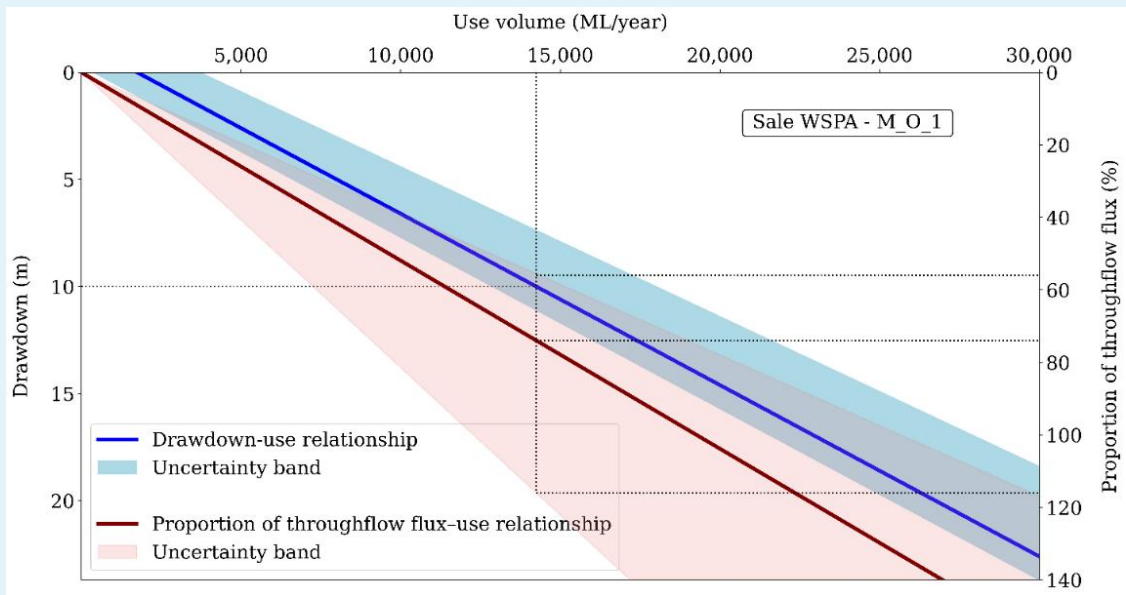
2. Apply the throughflow flux assessment to establish a relationship between pre-development throughflow flux and the percentage of throughflow flux, accompanied by uncertainty bands for each GMU. This relationship is utilised to calculate the proportion of pre-development flux and the uncertainty bands for different use volumes.
3. Combine the results of the drawdown-use assessment and the pre-development throughflow flux assessments to provide consolidated tables and graphs.
4. Compare results to historic drawdown and use to validate drawdown/use relationship. This step is discussed further in the Synthesis Report.

Part 5 of the methodology provides details about the synthesis approach for confined aquifers.

### **Case study: Application of the synthesis approach for the Sale WSPA**

The outlined synthesis approach was applied to the Sale WSPA. The synthesised information for the representative Suite M\_O\_1 is presented in Error! Reference source not found. The sustainable yield for the Sale WSPA is estimated to be 14,300 ML/yr based on the following considerations:

- The Sale WSPA is a confined aquifer GMU with statistical method assessment.
- The sustainable yield volume is derived by comparing the estimates of groundwater resource (via the statistical modelling of use drawdown relationship) for the representative Suite with the sustainable yield metric.
- The sustainable yield is calculated as the volume derived from the statistical method for the representative Suite M\_O\_1, corresponding to the consumptive use metric (i.e. 10 m). This results in a value of 14,252 ML/yr, rounded to the nearest 100 ML, leading to a sustainable yield of 14,300 ML/yr.



**Figure 9: A visual representation of the synthesis information for the Sale WSPA, representative Suite M\_O\_1**

**Table 13: The synthesis information for the Sale WSPA, representative Suite M\_O\_1**

Assessment area	GMU	Sale WSPA	
	Representative Suite	M_O_1	
	Aquifer	Boisdale Formation (UTAF, 105)	
	Water system depth boundary (m below natural surface)	All formations between 25 m to 200 m below surface	
Context	Permissible Consumptive Volume (ML/yr)	21,238	
	Licensed entitlement (ML/yr)	21,203	
	Licensed avg use (ML/yr)	11,029	
Synthesis results	Use at avg	Drawdown (m) [lower band, upper band]	7.42 (8.54–5.09)
		Proportion of throughflow flux (%) [lower band, upper band]	57 (43–90)
	Use at PCV	Drawdown (m) [lower band, upper band]	15.59 (16.71–12.23)
		Proportion of throughflow flux (%) [lower band, upper band]	110 (83–173)
	Use at 10 m drawdown	Volume (ML/yr) [lower band, upper band]	14,252 (12,850–18,050)
		Proportion of throughflow flux (%) [lower band, upper band]	74 (56–116)

## 6.1.2. Unconfined aquifer GMUs – Part 4 of the Methodology

The synthesis approach for unconfined aquifers includes 3 metrics ('consumptive use', 'environmental' and 'seawater intrusion'), three climate scenarios (low, medium and high), and two timelines (2040 and 2065). Only the GMU scale result for all values is shown in the case study below.

The synthesis for the unconfined aquifers entails three steps:

1. Apply the drawdown/groundwater elevation-use assessment to establish a relationship between drawdown/groundwater elevation and groundwater use for the 3 climate scenarios in 2040 and 2065. These relationships are utilised to calculate drawdown and uncertainty bands for volumes of different uses (e.g. PCV, entitlement, average use) and to calculate volume and uncertainty bands for different metrics.
2. Apply the recharge assessment to establish a relationship between recharge and percentage of recharge to extraction for each GMU for the three climate scenarios in 2040 and 2065. These relationships are utilised to calculate the proportion of recharge and the uncertainty bands for different use volumes.
3. Combine the results of the drawdown/groundwater elevation-use assessment and the recharge assessment to provide consolidated tables and graphs.
4. Compare results to historic drawdown and use to validate drawdown/use relationship
  - It should be noted that the environmental metric also includes Q90 (regulated rivers) and MAF (unregulated rivers) metrics for waterways.

### Case study: Applying the synthesis approach to the Mid Loddon GMA

The outlined synthesis approach was applied to the Mid Loddon GMA. **Figure 10** and **Table 14** show the synthesis information for the Mid Loddon GMA for consumptive use and environmental metrics. The preliminary sustainable yield volume is 19,800 ML/yr. This is based on the following:

- The Mid Loddon GMA is an unconfined aquifer GMU with statistical method assessment.
- The sustainable yield volumes are derived by comparing the estimates of groundwater resource (via the statistical modelling of use-drawdown relationship) with the consumptive use and environmental metrics (i.e. 2 m) under current climate conditions (see **Figure 11** ).
- The preliminary sustainable yield volumes which include all consumptive use and environmental values is estimated to be 19,800 ML/yr, rounded to the nearest 100 ML. The final determination of the sustainable yield volume will be made after engagement with stakeholders and values and metrics are agreed.

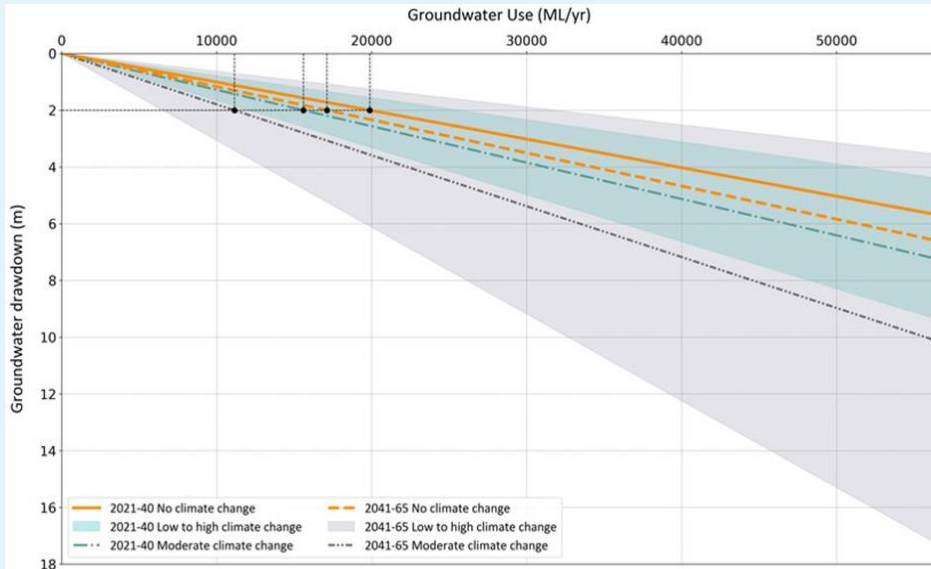


Figure 10. Example plot of groundwater usage - drawdown relationships for the Mid Loddon GMA (all values)

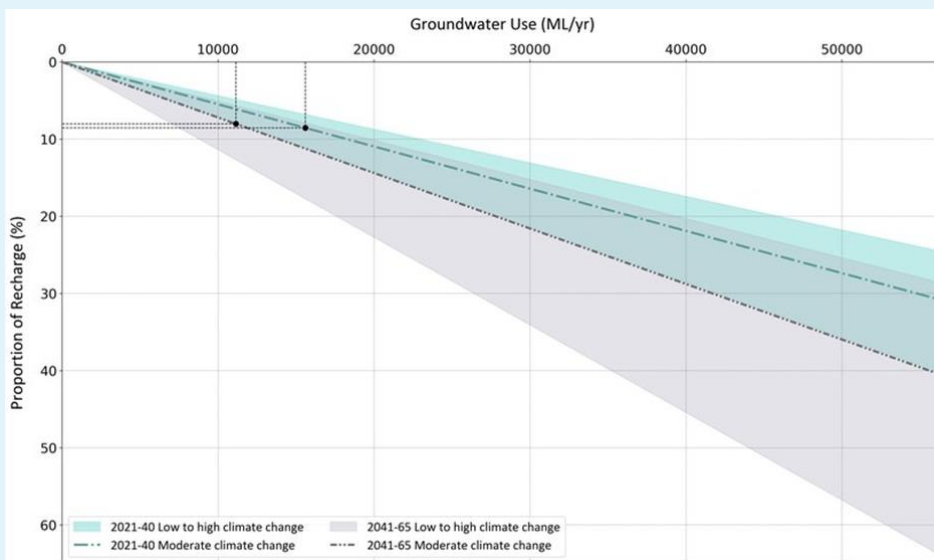


Figure 11: Example plot of groundwater usage -recharge relationships for the Mid Loddon GMA (all values)

Table 14: The synthesis information for the Mid Loddon GMA

Assessment area	GMU	Mid Loddon GMA
	Representative Suite/bore	M_F_2, 88214
	Aquifers	Quaternary alluvial (UTAQ, 101) Boisdale Formation (UTAF, 105) Newer Volcanics (UTB, 111)
	Water system depth boundary (m below natural surface)	All formations below the surface.
Context	Permissible Consumptive Volume (ML/yr)	34,037

	Licensed entitlement (ML/yr)		33,917
	Licensed avg use (ML/yr)		21,450
Synthesis results	Use at avg	Drawdown (m) [HCC, LCC]	3.4 (1.0 to 6.0)
		Proportion of recharge volume MCC (%) [LCC to HCC]	9.7% (7.7% to 12.7%)
	Use at PCV	Drawdown (m) [HCC, LCC]	3.8 (3.1 – 6.6)
		Proportion of recharge volume MCC (%) [LCC to HCC]	15.4% (12.3% to 20.2%)
	Use at 2 m drawdown	Volume (ML/yr) [LCC to HCC]	19,900 (12,000 to 25,700)
		Proportion of recharge volume MCC (%) [LCC to HCC]	9% (9% to 11%)

### 6.1.3. Confined aquifer UAs

The synthesis information for the LTA-NW1 UA in Wimmera Mallee is presented in **Table 15**. For more details on confined UAs, please refer to *Part 8: Sustainable Yield synthesis paper – Mapping, Boundaries, and Naming Conventions for Confined Aquifer UAs (DEECA)*.

- The SY for the LTA-NW1 UA is estimated to be 800 ML/yr, based on the following considerations:
- The LTA-NW1 UA falls under the confined aquifer and was assessed using the throughflow method leading to 2,670 ML/y throughflow volume.
- The percentage of throughflow applied to this area is 30%, which is derived from the average percentage of throughflow across confined GMUs with accepted use-drawdown relationship.
- The sustainable yield is calculated as 30% of the throughflow volume for the area, resulting in 801 ML/yr. This value is rounded to the nearest 100 ML, resulting in a final sustainable yield of 800 ML/yr.

**Table 15: The synthesis information for the confined aquifer LTA-NW1 UA**

Assessment area	Unincorporated Area	LTA-NW1
	Aquifer	(LTA, 111)
Context	Licensed entitlement (ML/yr)	0
	Licensed avg use (ML/yr)	0
Synthesis results	Predevelopment throughflow flux (ML/yr)	2,670 [2,446- 2,910]
Sustainable yield volume as a percentage of predevelopment throughflow flux (ML/yr)		800

### 6.1.4. Unconfined aquifer UAs

The synthesis information for the North Mid Loddon UA is presented in **Table 16**. The sustainable yield for the North Loddon UA is 18,700 ML/yr, based on the following considerations:

- The North Loddon UA is an unconfined aquifer with recharge method assessment leading to 623,000 ML/yr recharge volume.
- The percentage of recharge applied to this area is 3%, which is derived from the average percentage of recharge across the unconfined aquifer GMUs with accepted use-drawdown relationship.
- The North Loddon UA covers an area approximately 3.5 times larger than the Mid Loddon GMA. It exhibits variable water quality and yield, factors that have not been specifically considered in this estimate or in delineating the UA.
- The North Loddon UA is covered by the same Suite groups as Mid Loddon GMA, indicating a comparable aquifer response, particularly in terms of climate sensitivity.

**Table 16: The synthesis information for the unconfined aquifer North Loddon UA**

Assessment area	Unincorporated Area	North Loddon
	Aquifer	Quaternary alluvial (UTAQ, 101) Boisdale Formation (UTAF, 105)
Context	Licensed entitlement (ML/yr)	8,500
	Licensed avg use (ML/yr)	900
Synthesis results	Recharge volume (ML/yr)	623,102
Sustainable yield volume as a percentage (3%) of recharge (ML/yr)		18,700

### 6.1.5. Semi-confined aquifer GMUs and UAs– Part 7 of the Methodology Report

The Lower Ovens GMA is identified as a semi-confined aquifer. **Table 17** shows the degree of connectivity for the semi-confined Lower Ovens GMA, indicating high connectivity. For more details on the semi-confined aquifers synthesis approach and how their connectivity is identified, please refer to *Part 7: Sustainable Yield synthesis paper – semi-confined aquifers synthesis approach (DEECA)*. The significant hydraulic connection between the upper unconfined and lower confined aquifers suggests that recharge from the unconfined aquifer is the primary source of groundwater for both layers. The throughflow of the confined aquifer maybe indicative of the recharge from rainfall. As a result, estimating a sustainable yield volume for each aquifer based on unconfined assessment method and for the confined aquifer based on the confined assessment method may overestimate (double account) the available resource for the confined aquifer. Therefore, to avoid the potential for double accounting the semi-confined aquifers that are highly connected, a single sustainable yield volume is proposed for both aquifers based on assessment method for the unconfined aquifer. However, since the use–drawdown relationship was developed based on three groundwater level patterns; two of these were validated, while the third (northern zone) did not represent the area of pumping or primary interest. Because of this limitation, although a sustainable yield of 15,500 ML/yr was estimated for the GMA, it is not accepted. Further investigation is required to determine a SY volume for the area.

**Table 17: Degree of connectivity of the Lower Ovens GMA in order to estimate sustainable yield**

Semi-confined GMU	GMU depth range (m)	Degree of connectivity	Sustainable yield volume (ML/yr)
<b>Lower Ovens GMA</b>	All formations from ground surface to 50 metres into bedrock or 200 metres from the surface (whichever is the greater depth)	Highly connected	No SY volume

# 7. Reporting results and review of the limits of take under licences

## 7.1. Key considerations

Sustainable yield is an estimation of the available groundwater that minimises adverse impacts on assessed values and serves to review the limits of take under licences and as foundational work to inform broader groundwater reform initiatives under Groundwater Management 2030 (GM2030). The primary objective is to provide technical advice on sustainable yield volumes to facilitate discussions on various management outcomes. While these outcomes are not directly part of the SY project, they will be addressed under the GM2030 process. The specific outcomes sought include reviewing current limits of take and determining whether current groundwater management mechanisms to manage and/or mitigate regional drawdown risks are appropriate and effective.

Key results and management implications include:

- Sustainable yield volume (ML/yr) for each reporting area.
- Uncertainty in sustainable yield volumes.
- Assessment of the potential risk to sustainability (current and future), that is the potential for groundwater level declines below acceptable levels and taking into account the review of limits of take under licences.

The risk to groundwater sustainability is assessed by comparing current use with sustainable yield volumes to identify current risk. Future sustainability risks are evaluated by considering climate change scenarios and the potential for increased groundwater use.

Different climate change scenarios are assessed for unconfined aquifers, as they are significantly influenced by climatic variations. In contrast, confined aquifers are not directly affected by climate change due to their limited connection to the atmospheric environment.

Currently, groundwater use is approximately 40% of licensed entitlement, indicating potential for increased use. This may occur through license holders increasing take up to 100% of their entitlement and/or trading their unused part of their entitlement which may be used by the new entitlement holder. Therefore, licence entitlements are compared against SY volumes to assess future sustainability risks for both confined and unconfined aquifers.

### 7.1.1. Current risk

The current risk to groundwater sustainability is assessed by comparing current use with sustainable yield volumes.

Risk to sustainability is defined by declining groundwater level.

- Current use < Sustainable yield volume
- Current use > Sustainable yield volume
- No category – No sustainable yield volume is derived for the areas with no current use.

### 7.1.2. Future risk

Future sustainability risks are assessed by considering potential increases in groundwater use in both confined and unconfined aquifers. Currently, groundwater use is approximately 40% of licensed entitlement, indicating the potential for increased use. This may occur through licence holders increasing the take up to 100% of their entitlement and/or trading their unused part of their entitlement

which may be used by the new entitlement holder. Moreover, future sustainability risks are evaluated by assessing climate change scenarios for unconfined aquifers.

## 7.2. Case studies on risk to sustainability and review of the limits of take under licences

### 7.2.1. Confined aquifer GMU – Sale WSPA

Based on the summary of key assessment information for the Sale WSPA, the critical considerations regarding results and implications for management include:

- The sustainable yield volume for the Sale WSPA is 14,300 ML/yr.
- The uncertainty in sustainable yield ranges from 12,850 ML/yr to 18,050 ML/yr

In respect to the potential risk to sustainability (current and future), that is the potential for groundwater level declines below acceptable levels, taking account of the review limits of take under licences:

- Historical average use (2016-2021) (11,029 ML/yr) is less than the sustainable yield volume indicating no current risk for this GMU.
- The licensed entitlement exceeds the sustainable yield by 7,000 ML or 50%. Licensed use legally authorises the use of groundwater up to the full entitlement. Long-term increase in groundwater use above the sustainable yield is likely to exacerbate long-term declines in groundwater levels and pose potential adverse impacts to consumptive users in the Sale WSPA. There is no “groundwater level restriction triggers” in place in the Sale WSPA.

### 7.2.2. Unconfined aquifer GMU – Mid Loddon GMA

Based on the summary of key assessment information for the Mid Loddon GMA, the critical considerations regarding results and implications for management include:

- The sustainable yield volume for the Mid Loddon GMA is 19,800 ML/yr. The climate sensitivity range is 12,060 to 25,700 ML/yr.

In respect to the potential risk to sustainability (current and future), that is the potential for groundwater level declines below acceptable levels, taking account of the review limits of take under licences:

- Historical average use of (2016-2021) 21,450 ML/yr is slightly higher than the sustainable yield volume, indicating a current risk for this GMU.
- The licensed entitlement exceeds the sustainable yield by 14,000 ML or 70%.
- Licensed use legally authorises the take and use of groundwater up to the full entitlement. Long-term increase in groundwater use above the sustainable yield is likely to exacerbate long-term declines in groundwater levels and pose potential adverse impacts to consumptive users in the Mid Loddon GMA. The “groundwater level restriction triggers” have been set for the Mid Loddon GMA.

### 7.2.3. Confined aquifer UA – LTA-NW1 UA

Based on the summary of key assessment information for the LTA-NW1 UA in Wimmera Mallee, the critical considerations regarding results and implications for management include:

- The sustainable yield volume for the LTA-NW1 UA is 800 ML/yr.

In respect to the potential risk to sustainability (current and future), that is the potential for groundwater level declines below acceptable levels, taking account of the review limits of take under licences:

- Historical average use is 0 ML/yr, indicating no current risk for this UA.
- The licensed entitlement is 0 ML/yr. There is no cap in place for the UA.

#### 7.2.4. Unconfined aquifer UA – North Loddon UA

Based on the summary of key assessment information for the North Loddon UA, the critical considerations regarding results and implications for management include:

- The sustainable yield volume for the North Loddon UA is 18,700 ML/yr. The range considering climate sensitivity is 15,000 ML/yr to 24,500 ML/yr.

In respect to the potential risk to sustainability (current and future), that is the potential for groundwater level declines below acceptable levels, taking account of the review limits of take under licences:

- Current use is approximately 1000 ML/yr, indicating no current risk for this UA.
- The licensed entitlement is 8,500 ML/yr. There is no cap in place for the UA.

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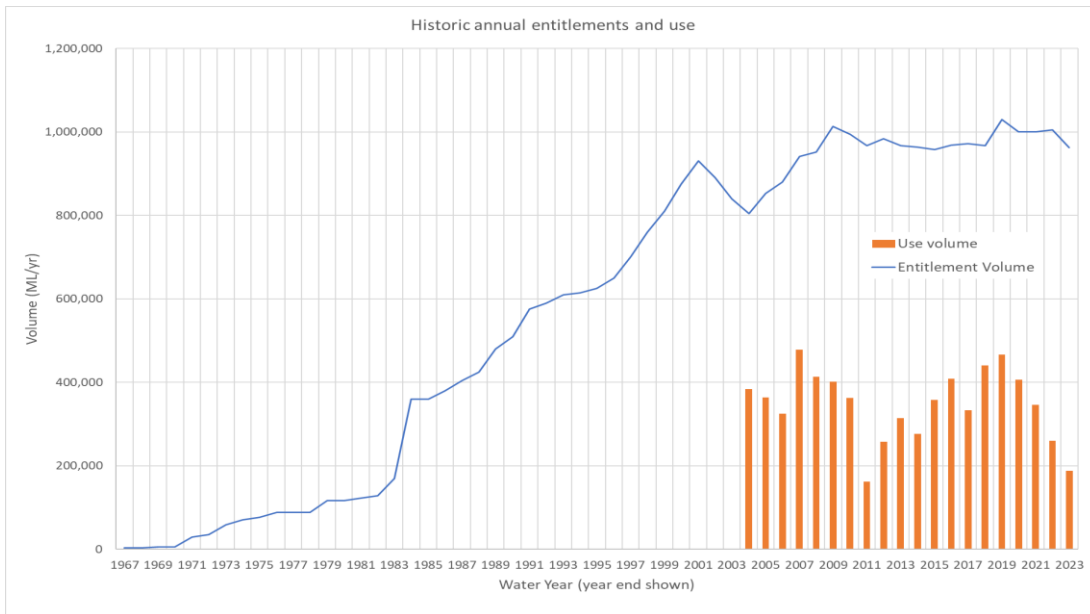
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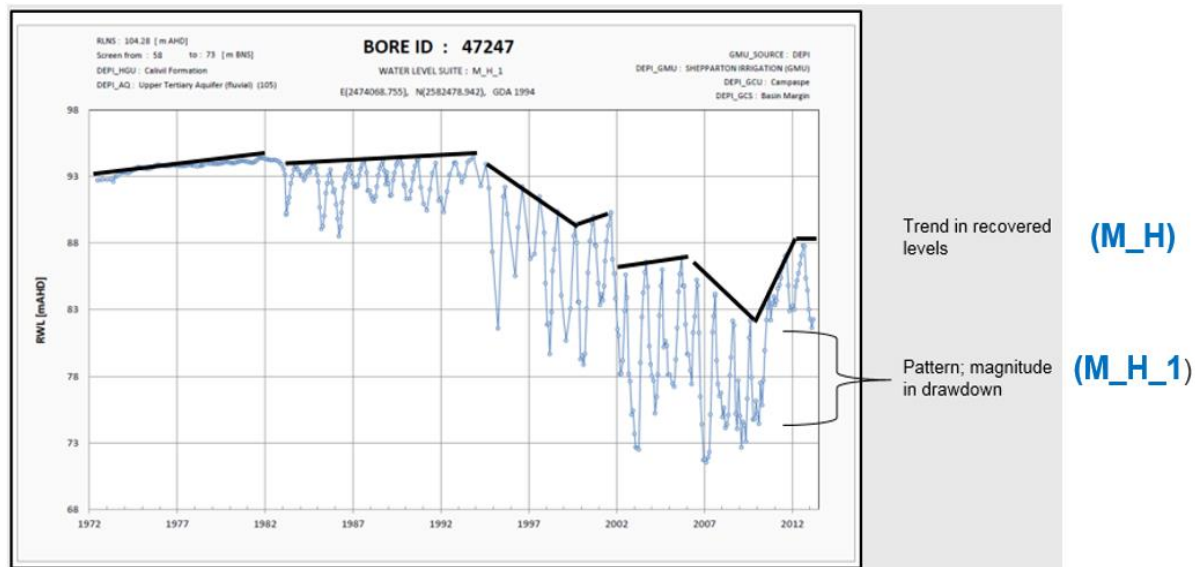
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# Appendix



**Figure A1: Groundwater entitlement and use in Victoria (1969–2018)**

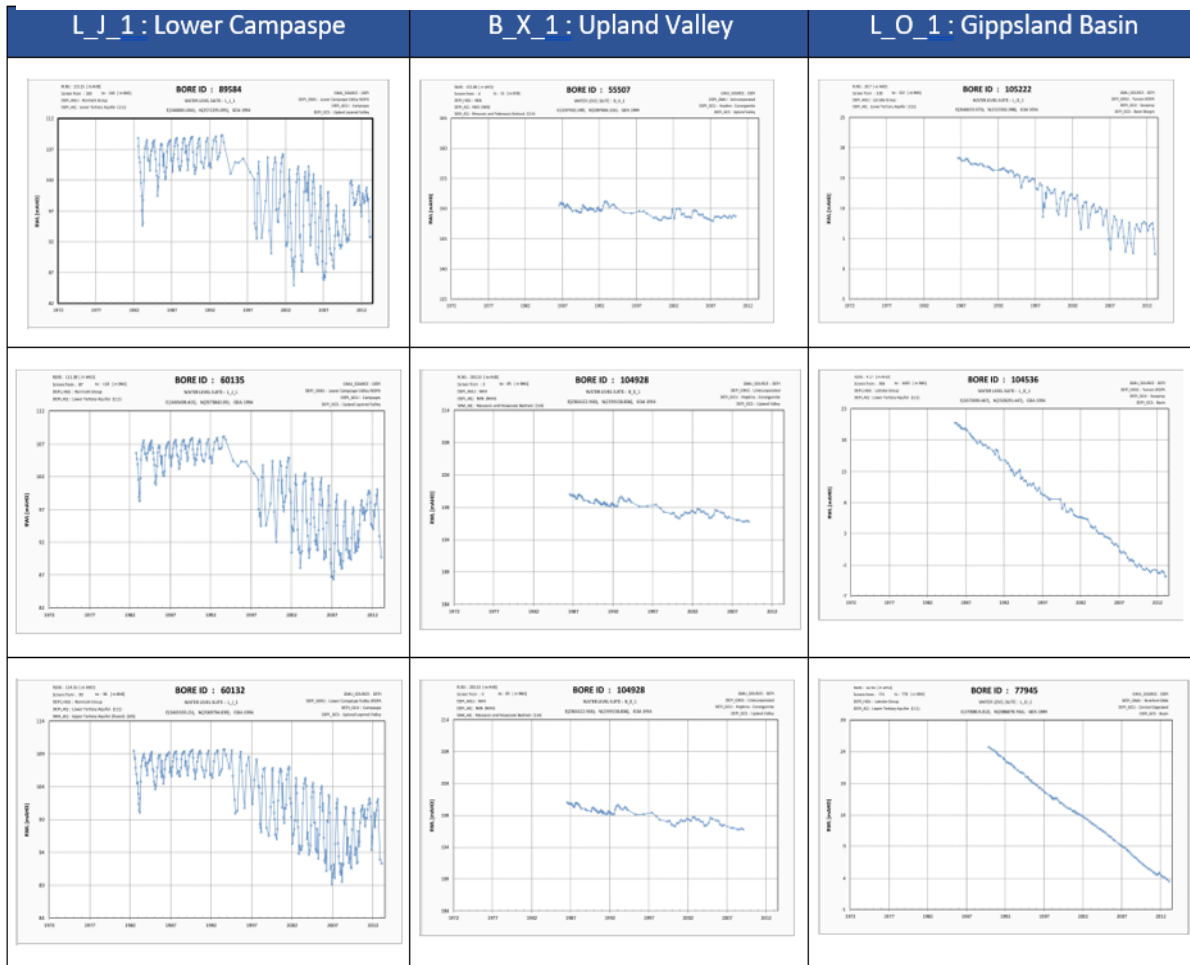
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**Figure A2: Example of hydrograph Suites – identified by the patterns and trends of recovered groundwater levels**

**Note: M = middle aquifer, H = Suite name, 1 = areas with greatest seasonal fluctuation (2, 3, ... represents decreasing seasonal fluctuation with the same trend)**

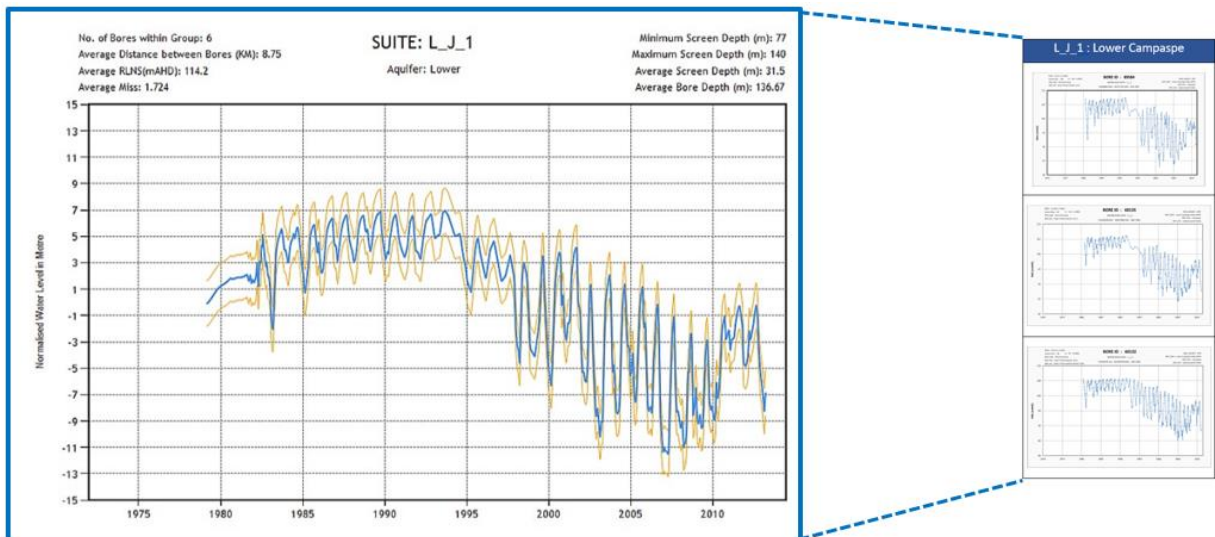
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**Figure A3: Example of hydrographs grouped according to patterns and trends for Suites**

**Note: these represent different Suites (lower aquifer – Suite J-1, bedrock aquifer – Suite X-1, lower aquifer – Suite L-0)**

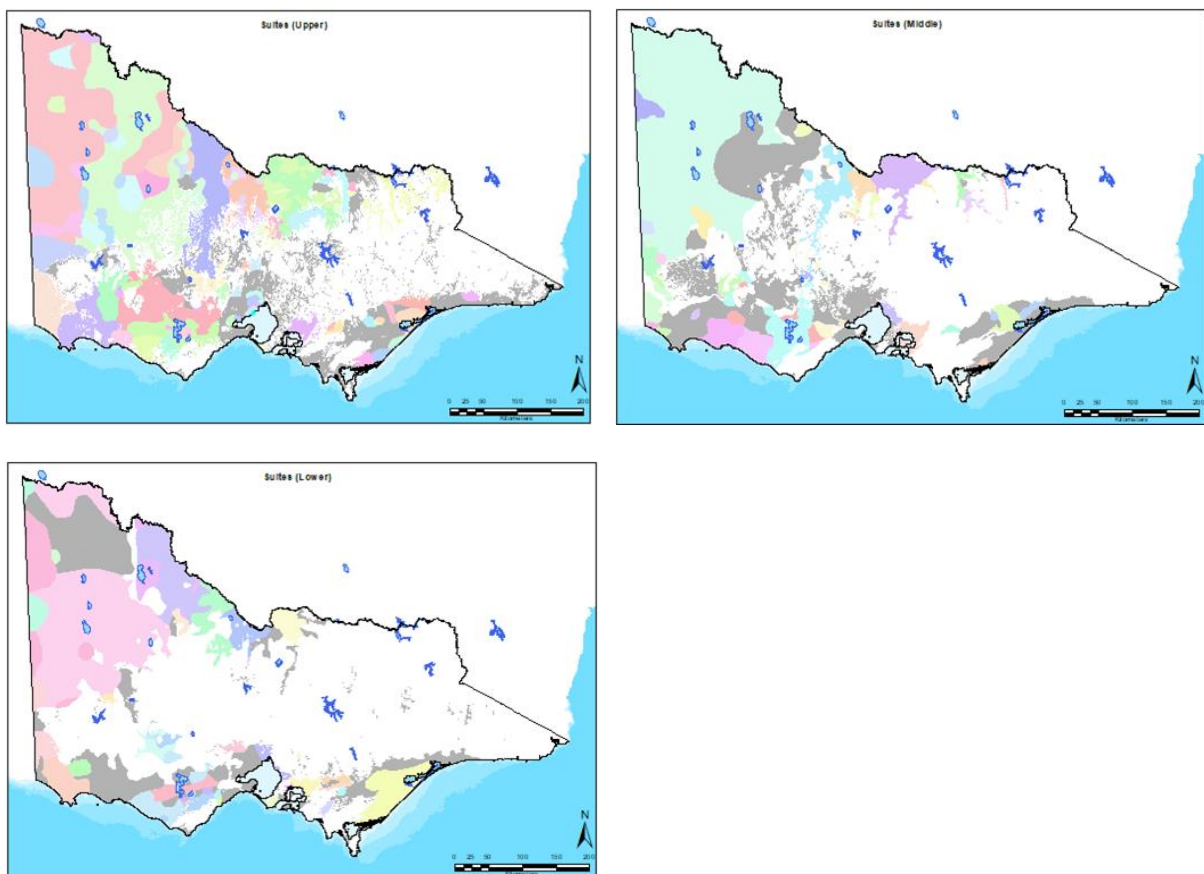
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**Figure A4: Example showing normalised hydrograph for a Suite**

Created through statistics on the bores in each Suite

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**Figure A5: Mapping and distribution Suites for upper, middle and lower aquifers**

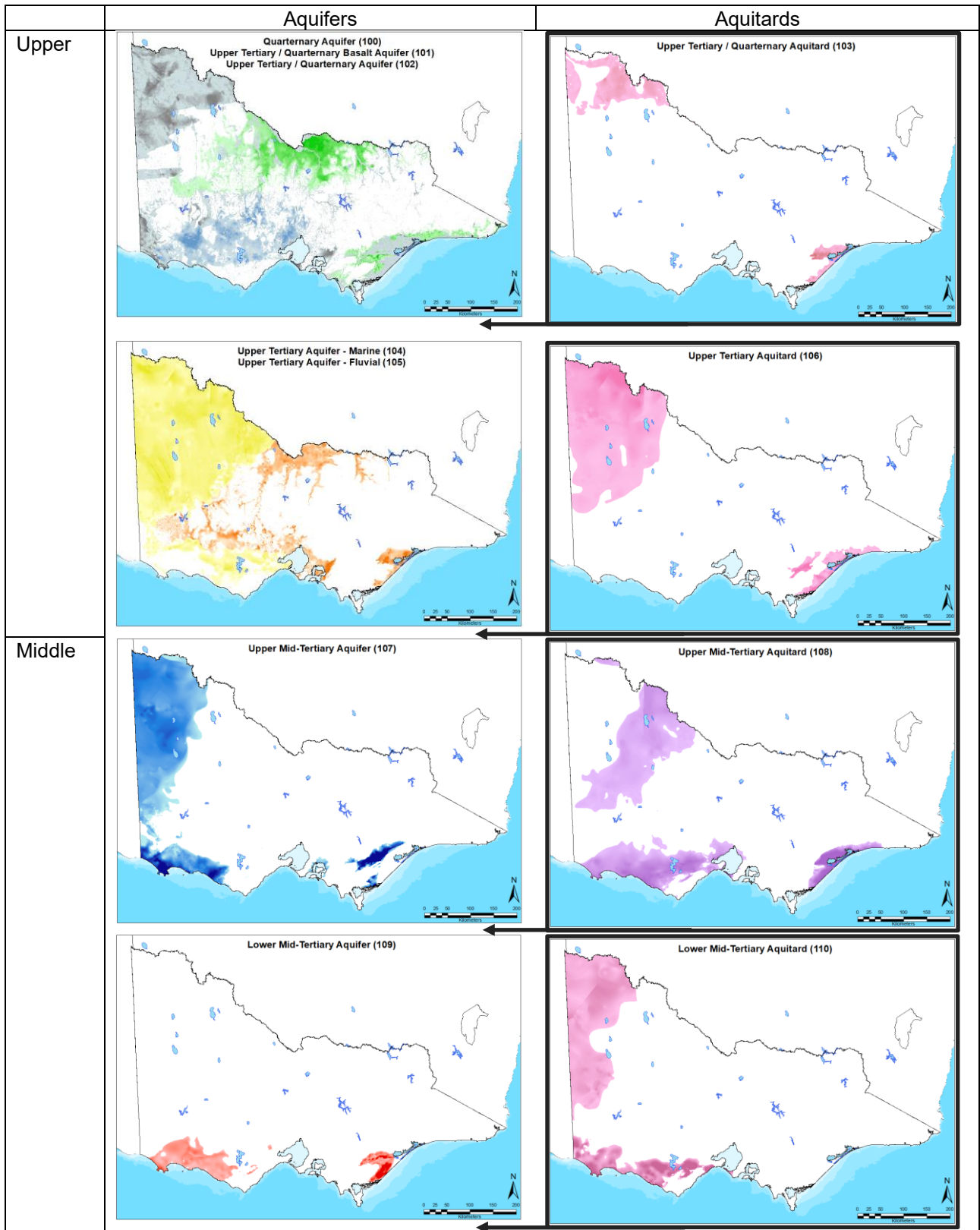
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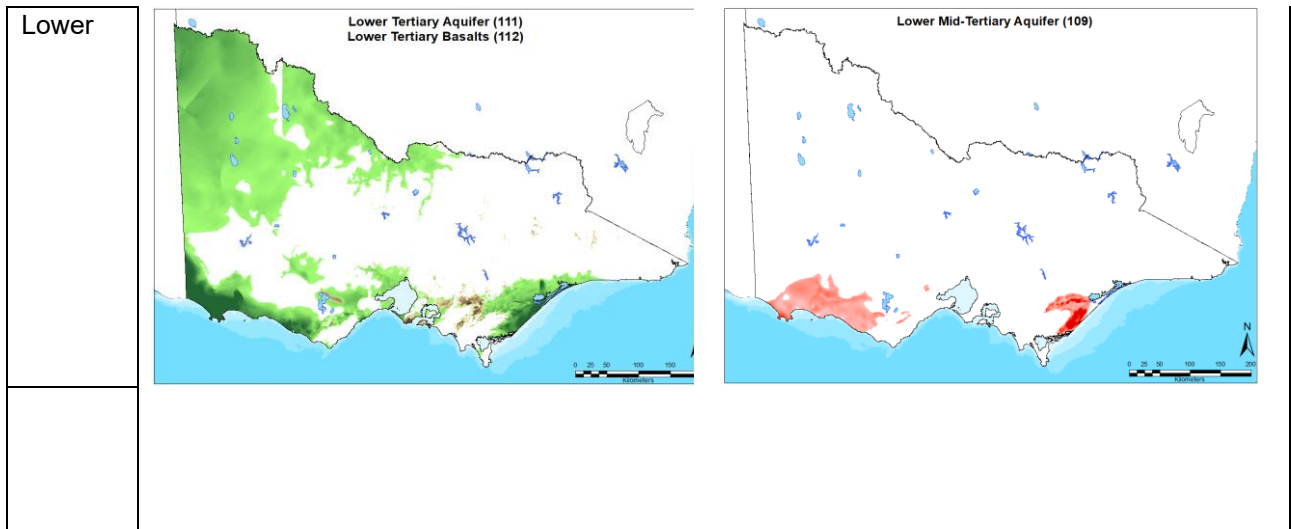
Aquifer Name	Aquifer Code	Aquifer Number	Hydrogeological Units (HGUs) present				
			Otway Basin	Central Coast Basins	Gippsland Basin	Murray Basin - North West	Murray Basin - North East
Quaternary Aquifer	QA	100	Various aeolian deposits (1001), various fluvial, lacustrine, alluvial and colluvial sediments (1002)	Various aeolian deposits (1001), various fluvial, lacustrine, alluvial and colluvial sediments (1001), Quaternary sandy limestone, calcarenite and shell deposits (1003)	Various aeolian deposits (1001), various fluvial, lacustrine, alluvial and colluvial sediments (1002)	Various aeolian deposits (1001), various fluvial, lacustrine, alluvial and colluvial sediments (1002), Monoman Formation / Channel Sand (1140)	Various aeolian deposits (1001), various fluvial, lacustrine, alluvial and colluvial sediments (1002)
Upper Tertiary / Quaternary Basalt Aquifer	UTB	101	Quaternary stony rises, tuffs, undiff Quaternary basalt (inc Newer Volcanics) (1005).	Quaternary stony rises, tuffs, undiff Quaternary basalt (inc Newer Volcanics) (1005).	ABSENT	ABSENT	Undiff Quaternary basalt (inc Newer Volcanics) (1005), unnamed Quaternary trachyte (1004)
Upper Tertiary/Quaternary Aquifer	UTQA	102	ABSENT	ABSENT	Haunted Hill Formation (1015), Eagle Point Sand (1016)	Shepparton Fm (1008-1010)	Shepparton Fm (1008-1010)
Upper Tertiary/Quaternary Aquitard	UTQD	103	ABSENT	ABSENT	Boisdale Fm (Nunin Clay) (1017), Jemmys Point Fm (1061), Sale Grp (1061)	Blanchetown Clay (1014)	ABSENT
Upper Tertiary Aquifer (marine)	UTAM	104	Whalers Bluff Formation (1049), Moorabool Viaduct Fm (1034), Hanson Plain Sand (1030), Dorodong Sand (1031), Grange Burn Formation (1032)	Moorabool Viaduct Formation (1034)	ABSENT	Loxton Parilla Sand (1019), Moorna Fm (1020), Chowilla Fm (1022)	Parilla Sand (1019)
Upper Tertiary Aquifer (fluvial)	UTAF	105	Unnamed duricrust (1028), undifferentiated Upper Tertiary Aquifer (fluvial) (1023)	Brighton Group (1033), Baxter Sandstone (1035)	Boisdale Fm (Wurruk Sand) (1036)	Calivil Fm (1023)	Calivil Fm (1024), undifferentiated Upper Tertiary Aquifer (fluvial) (1023)
Upper Tertiary Aquitard	UTD	106	ABSENT	ABSENT	Hazelwood Formation (1058), Yalloom Formation (1058)	Bookpurnong Fm (1038), Lower Loxton Clays (1039), Geera Clay (younger) (1134), Winnambool Formation (younger) (1135), Renmark Group (younger) (1136)	ABSENT
Upper Mid-Tertiary Aquifer	UMTA	107	Port Campbell Limestone (1050), Portland Limestone (1046), Gannet Limestone (1041), Bochara Limestone (1048), Heywood Marl (1048), Haytesbury Group (1048)	Balesford Limestone (1051), Sherwood Formation (1095), Yallock Formation (1129)	Balook Fm (1060), LVG: Yarragon Fm (1057), LVG: Morwell M1-2 aquifers (1059), Aberton Fm (1064), Cobie Subgroup (1053), Gurnard Fm (1053), Turnum Fm (1053)	Murray Group Limestone (1052), Nelson Fm (1052), Genselig Group (1052), Duddo Limestone (1046), Morgan Limestone (1043), Winnambool Formation (interleaving) (1137)	ABSENT
Upper Mid-Tertiary Aquitard	UMTD	108	Gellibrand Marl (1068)	Torquay Group (1072), Fyansford Fm (1054), Newport Silt (1069), Maddingley Coal (1132)	Seaspray Group (1062), Lakes Entrance Fm (1063), Tambo River Fm (1062), Gippsland Limestone (1063), Giffard Sandstone Member (1062)	Winnambool Fm (1067), Geera Clay (1066), undifferentiated UMTA (interleaving - older) (1139)	ABSENT
Lower Mid-Tertiary Aquifer	LMTA	109	Clifton Fm (1074)	Maude Fm (1070)	LVG: M2C aquifer (1141), Seaspray Sand (1141)	ABSENT	ABSENT
(Lower) Tertiary Basalts	LTB	112	Phase 2 (Gellibrand) Basalts (1081)	ABSENT	ABSENT	ABSENT	ABSENT
Lower Mid-Tertiary Aquitard	LMTD	110	Wangoom Sand (1079), Narrawaturk Marl (1080), Upper Mepunga Fm (1084), Sturgess Point Member (1083), Nirranda Group (1078)	Demons Bluff Group (1085), Anglesea Fm (1085)	Flounder Fm (1086)	Etrick Fm (1078), Boga Silt (1077)	ABSENT
(Lower) Tertiary Basalts	LTB	112	Phase 2 Basalts (1081)	Phase 2 Basalts (1081), Mornington Volcanics (1111)	Thorpdale Volcanics (1112)	ABSENT	ABSENT
Lower Tertiary Aquifer	LTA	111	Lower Mepunga Fm (1100), Dihwyn Fm (1093), Yaugher Volcanics (1093), Pember Mudstone (1095), Pebble Point Fm (1097), Timboon Sand (1101), Riverbank Member (1099), Burnangule Member (1094), Moomowooing Sand Member (1096), Wurdji Gravel Member (1099), Brucknell Member (1100), Wangertip Group (1091), Dartmoor Fm (1091), Knight Group (1091)	Eastern View Fm (1096), Werribee Fm (1102), Yalook Fm (1103), Childers Fm (1107)	Childers Fm (1107), M2 / M2C aquifer (when basal aquifer) (1142), Latrobe Group (1104), Traralgon Fm (1104), Burog Fm (1108), Honeysuckle Gravels (1106), Yarram Fm (1105)	Upper, Middle and Lower Renmark Group (inc Warina Sand, Olney Fm (1087-09), White Hills Gravels (1071)	Upper, Middle and Lower Renmark Group (1087-09), White Hills Gravels (1071)
Lower Tertiary Basalts	LTB	112	Older Volcanic Group (Phase 1) (1110)	Mornington Volcanics (1111), Older Volcanic Group (Phase 1) (1110)	Carragung Volcanics (1113), Older Volcanic Group (Phase 1) (1110)	ABSENT	Older Volcanic Group (Phase 1) (1110)
Cretaceous and Permian Sediments	CPS	113	Paaratte Fm (1119), Belfast Mudstone (1120), Flaxman Fm (1121), Nullawarre Greensand (1122), Waarre Fm (1123)	NOT MAPPED	NOT MAPPED	Monash Formation (1115), Millewa Group (1116)	Urana Formation (1117)
Mesozoic and Palaeozoic Bedrock	BSE	114	Eumeralla Fm (1125), Casterton Fm (1125), Crayfish subgroup (1125), all Palaeozoic Basement Rocks (1124-28)	Permian Glacial Sediments, all Palaeozoic Basement Rocks (1124-28)	Strzelecki Group (1125), all Palaeozoic Basement Rocks (1124-28)	all Palaeozoic Basement Rocks (1124-28)	Permian Glacial Sediments, Strzelecki Group (1125), all Palaeozoic Basement Rocks (1124-28)

Figure A6: Victorian aquifer framework

Aquifer/aquitard names (code and number) in relation to Geological formations

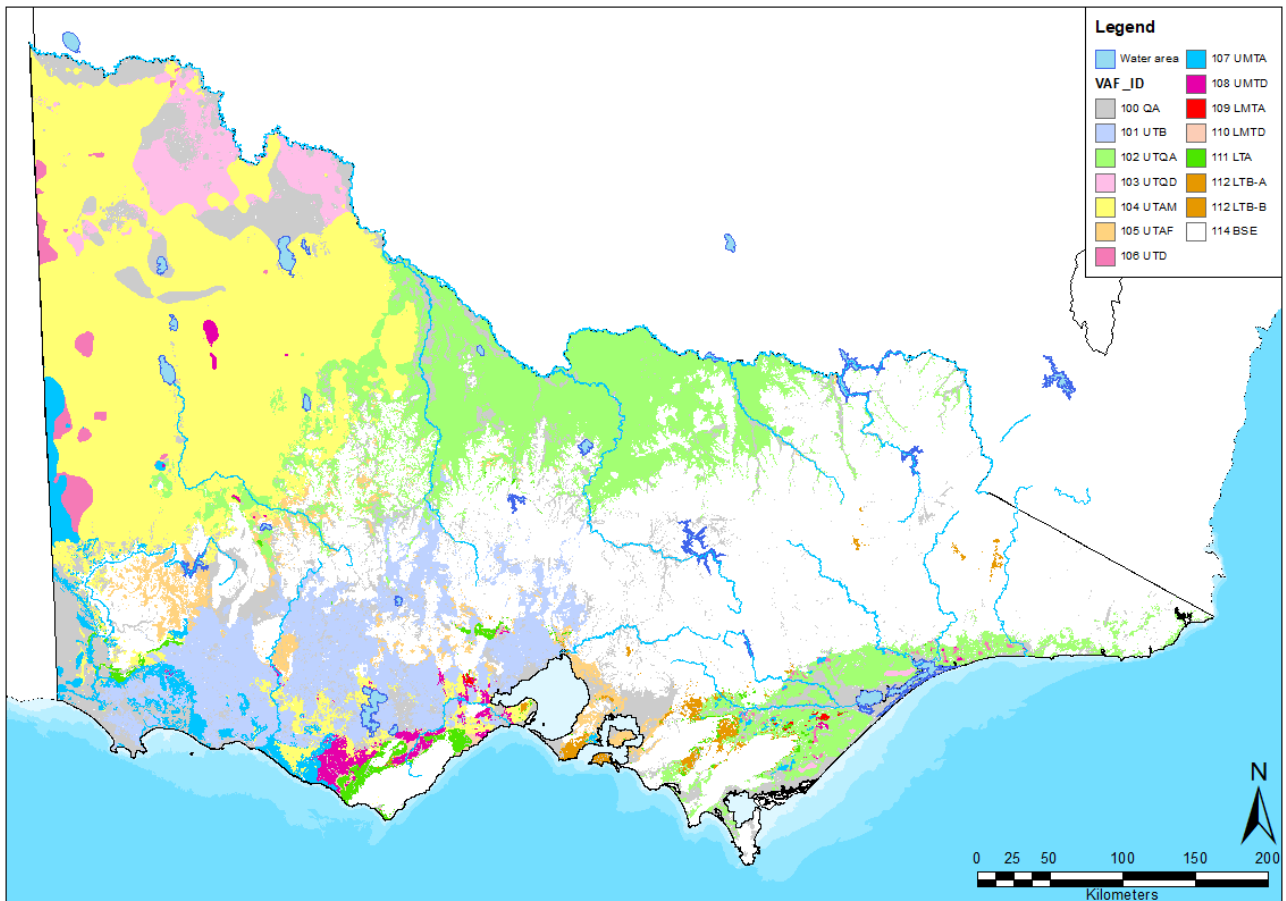
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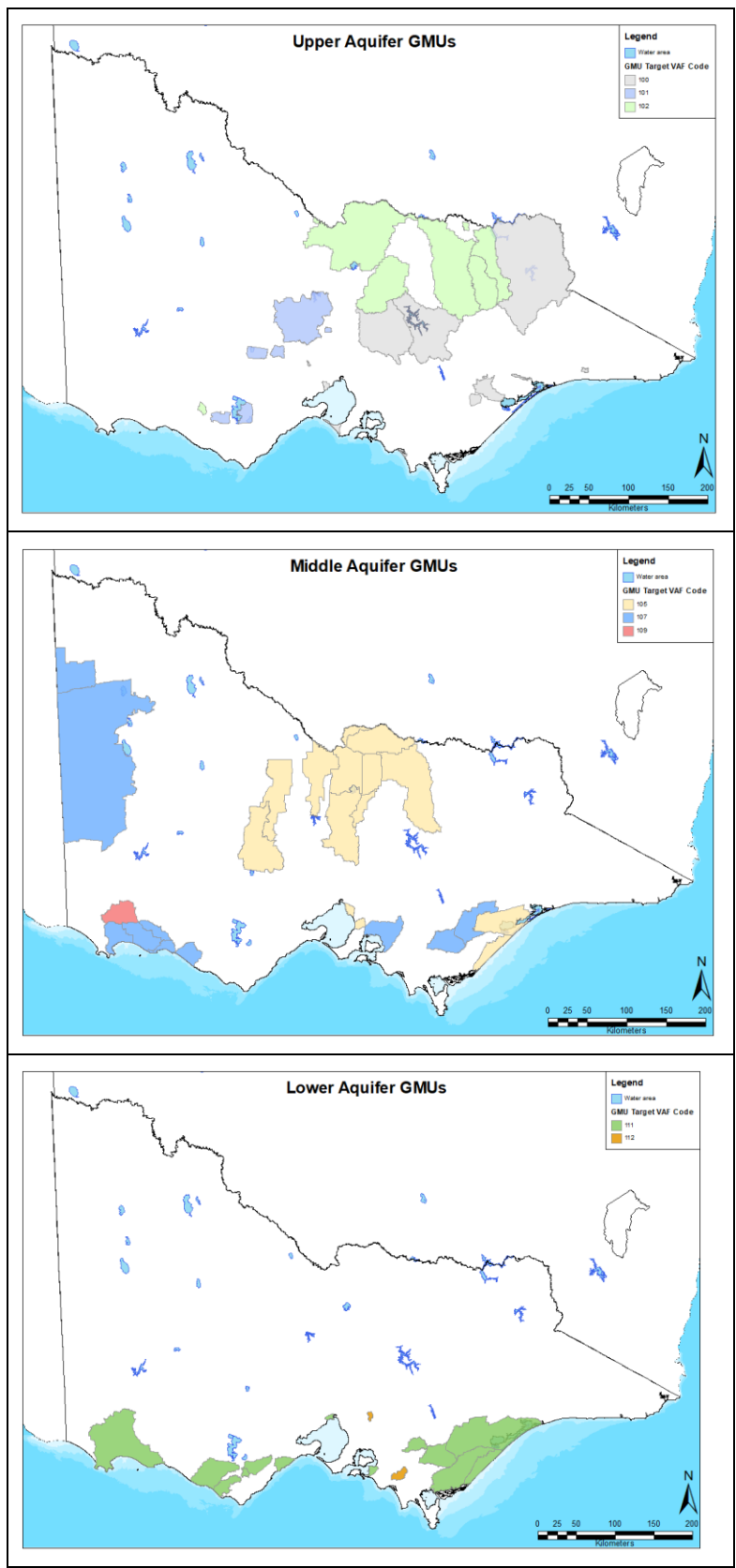
**Figure A7: Victorian aquifer and aquitards extent**

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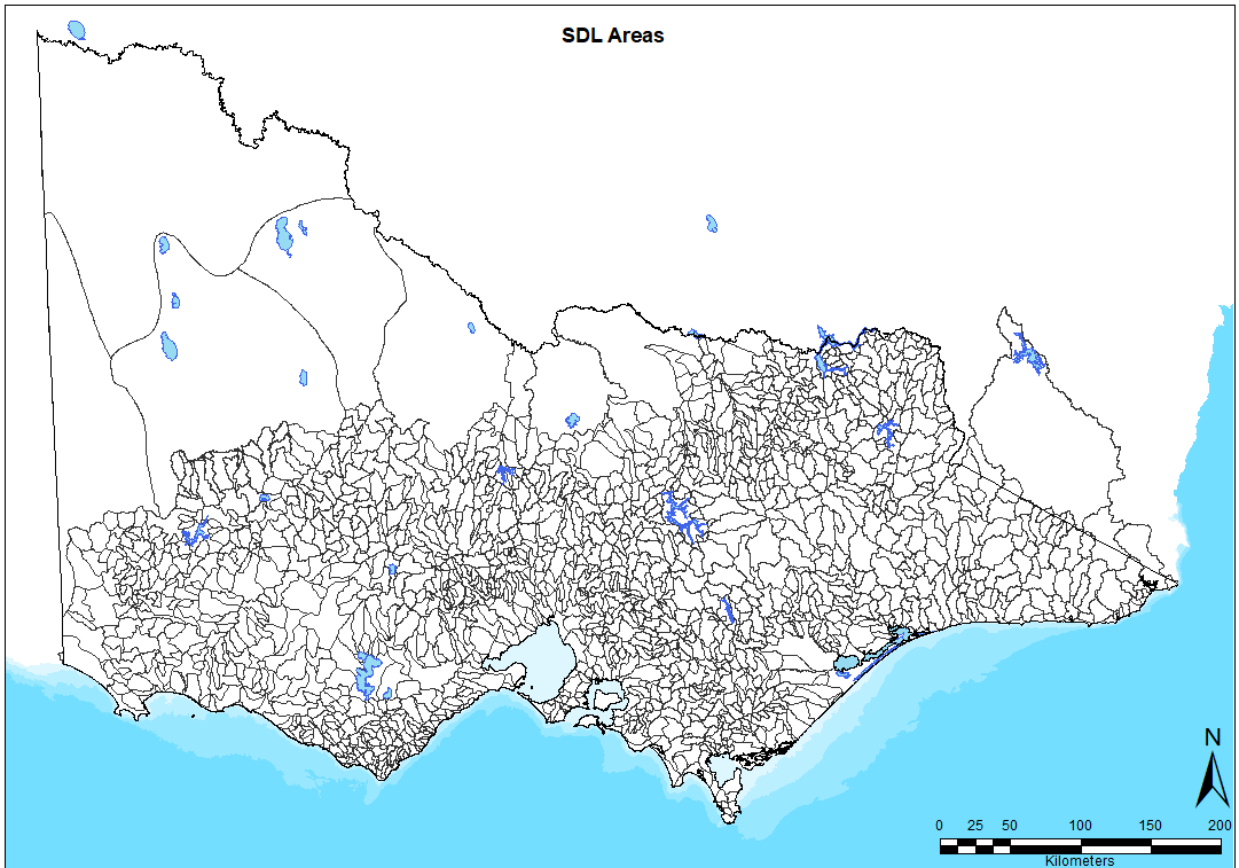
**Figure A8: Watertable aquifer units**

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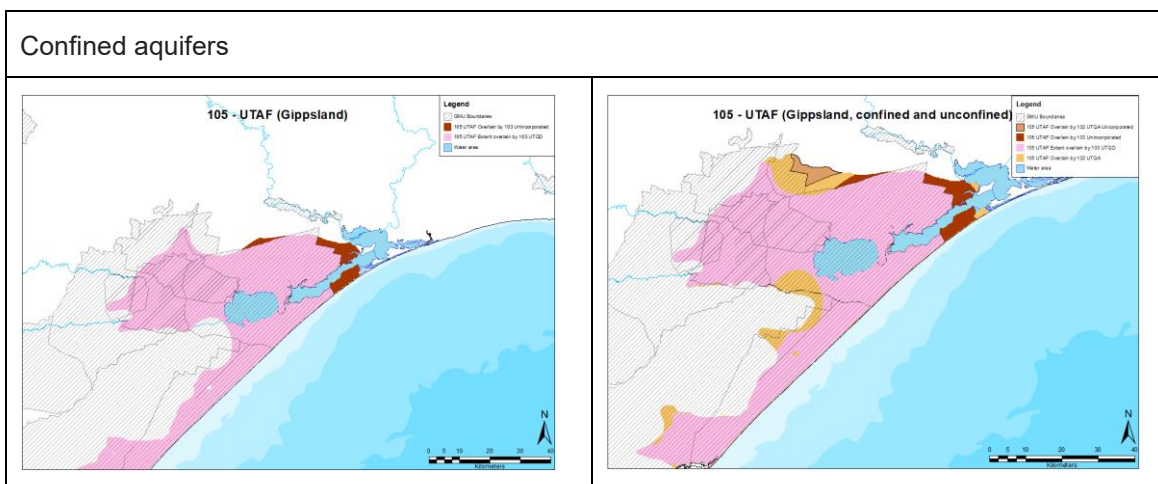
**Figure A9: GMAs upper, middle, and lower basement for unconfined and confined aquifers**

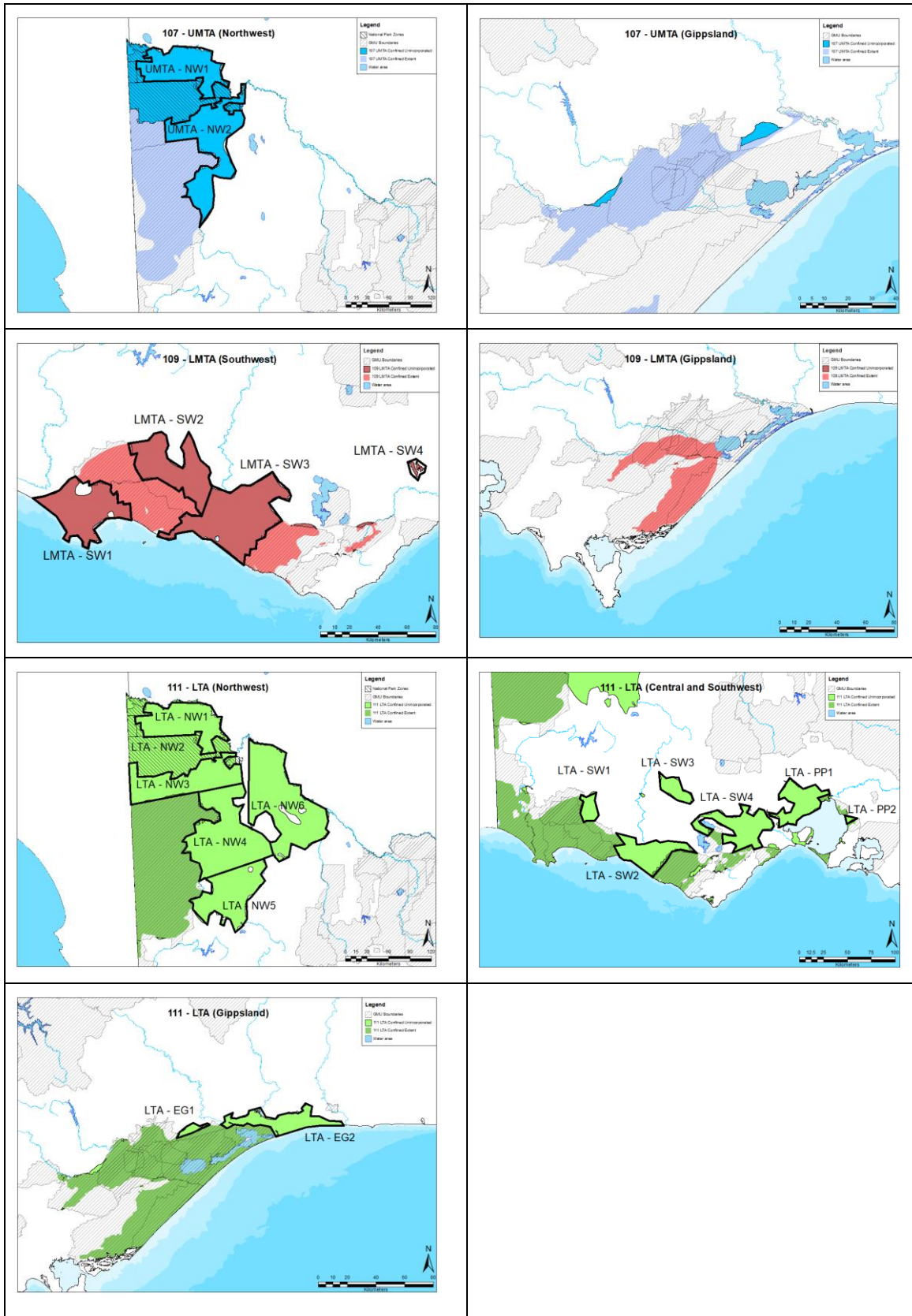
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**Figure A10: Surface water winterfill sustainable diversion limit**

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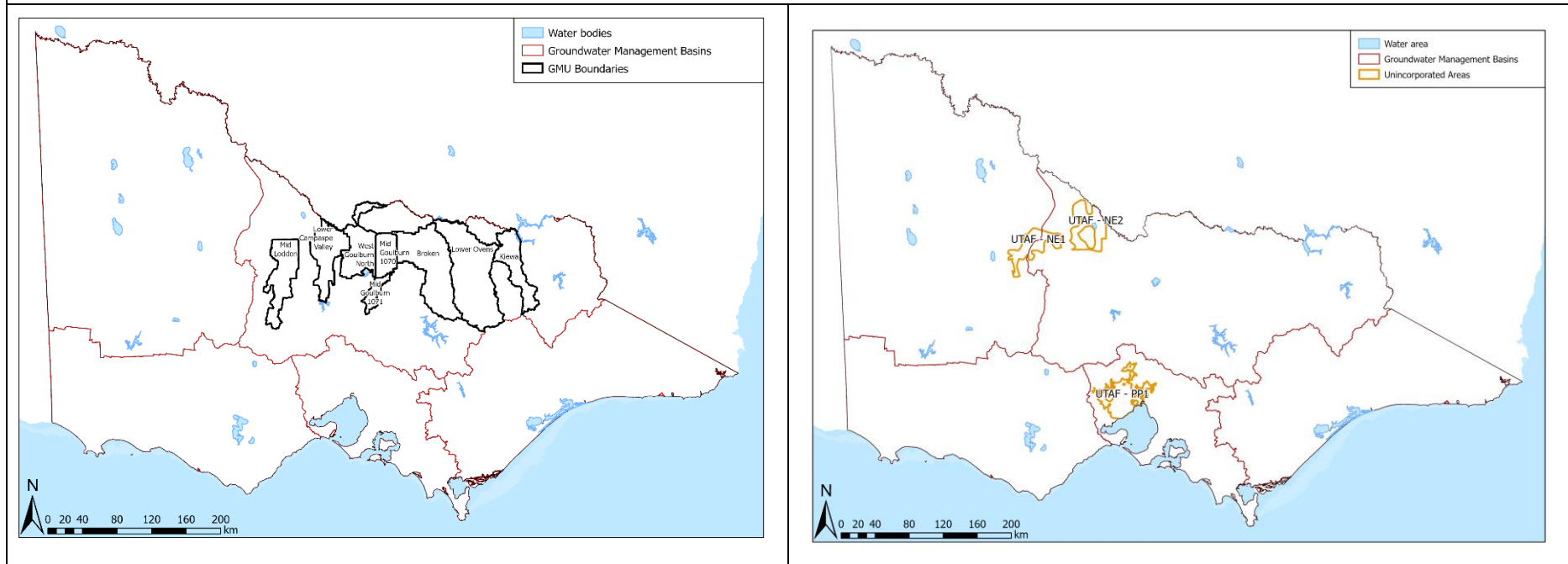




**Figure A11: Confined aquifer UA reporting areas**

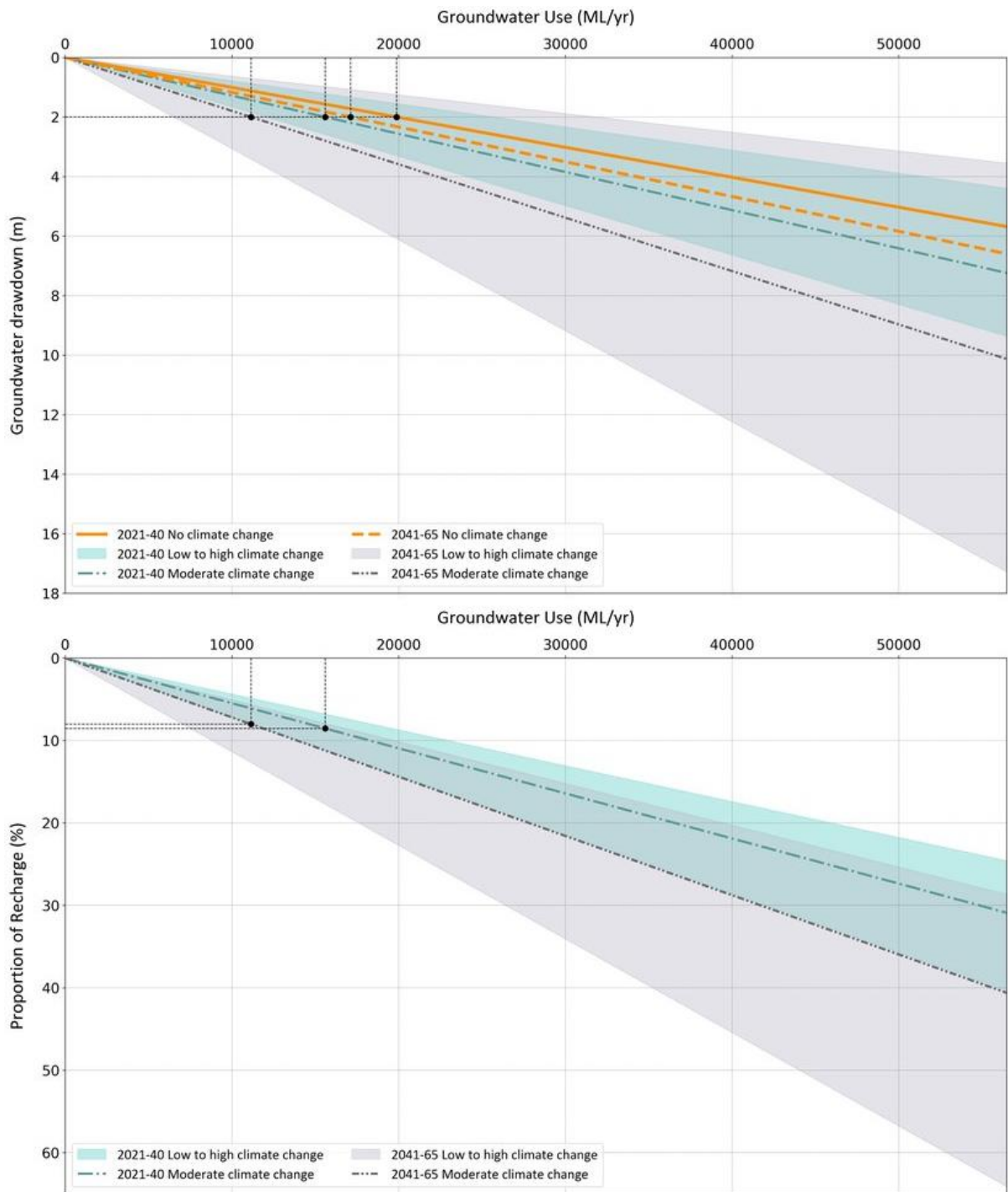
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### Semi-confined aquifers – GMUs and UAs



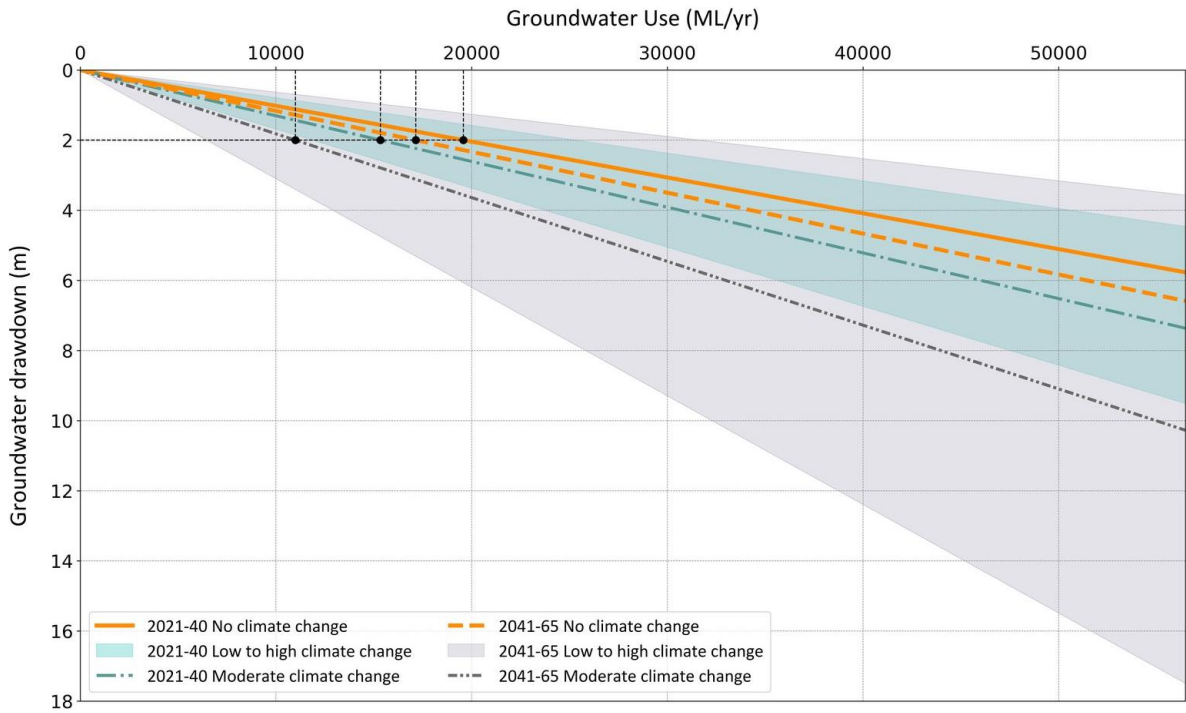
**Figure A12: Semi-confined aquifer reporting areas**

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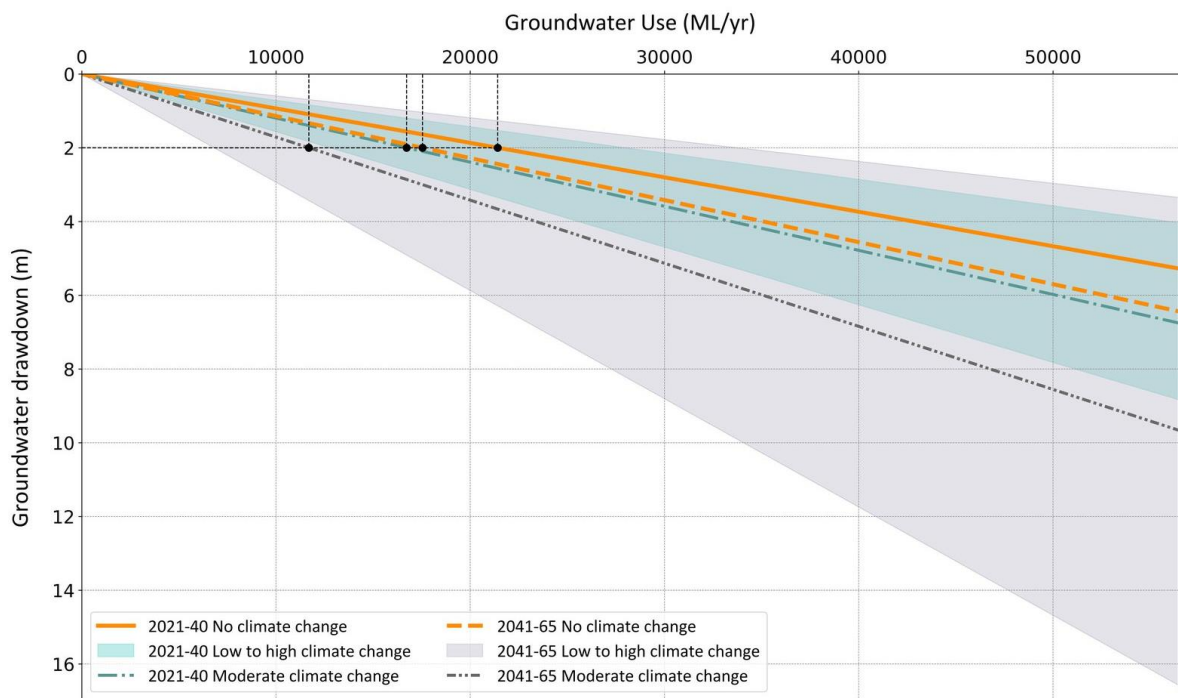


**Figure A13. Upper Plot: Mid Loddon GMA statewide modelled drawdown-use relationship for climate change scenarios for 2021-40 and 2041-65. Lower Plot: Mid Loddon GMA statewide**

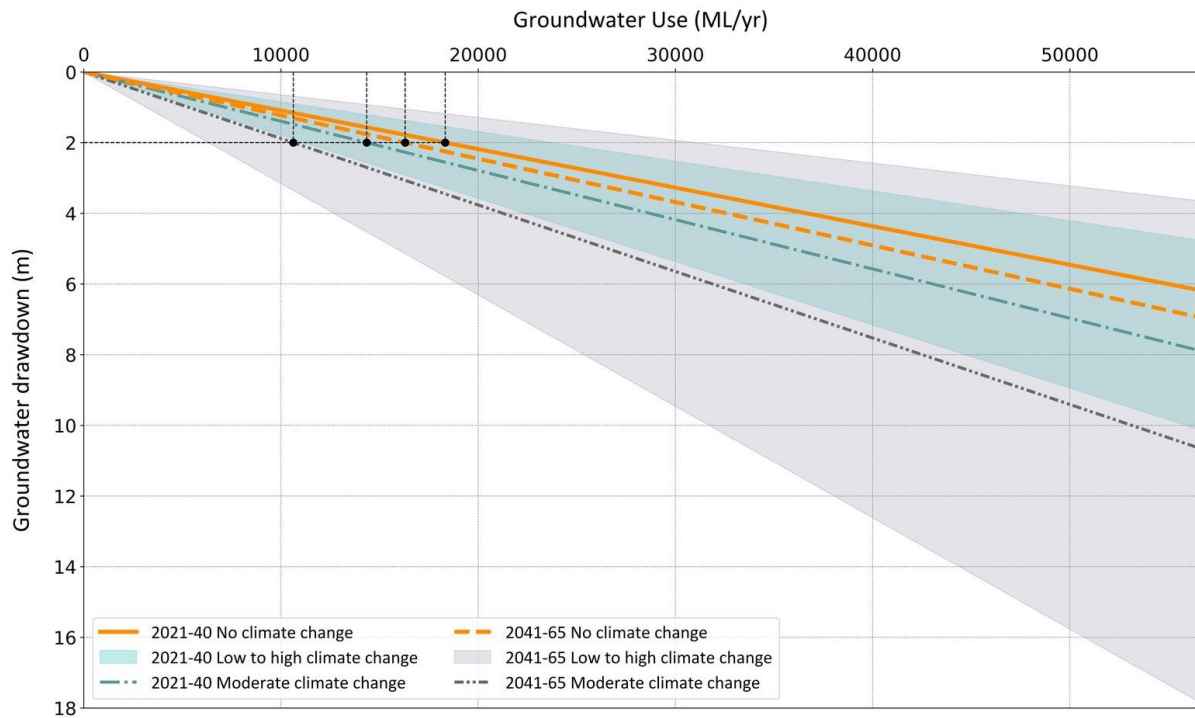
**modelled drawdown-use as percentage of recharge relationship for climate change scenarios for 2021-40 and 2041-65.**



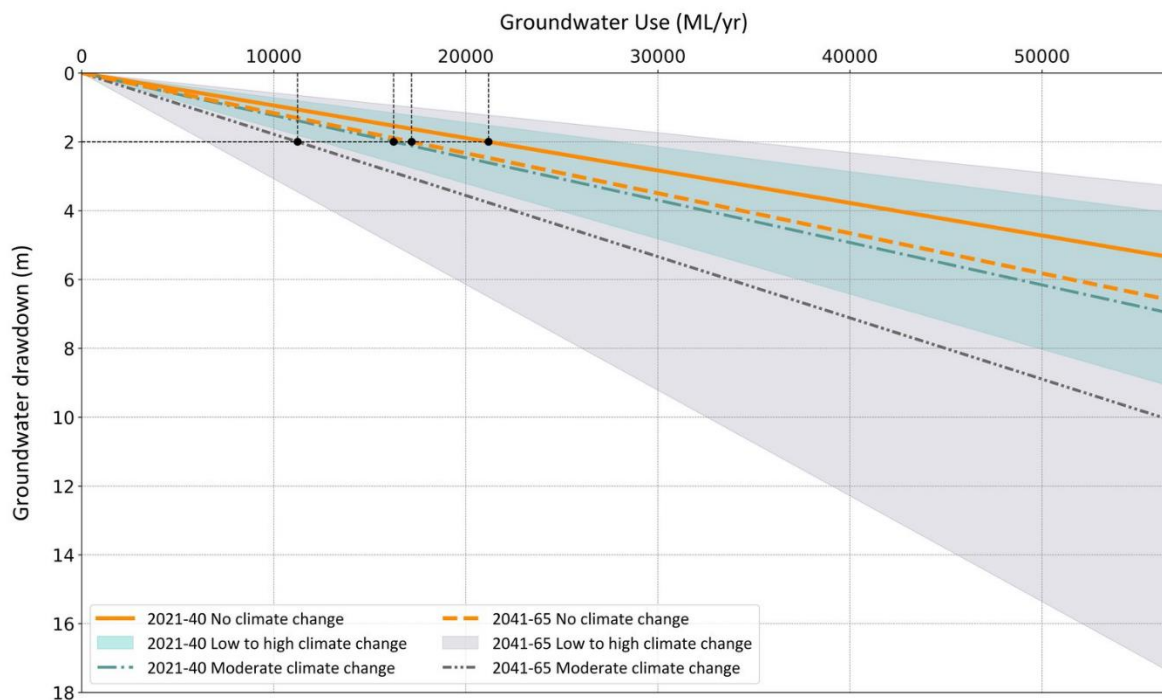
**Figure A14: A visual representation of the synthesis information for the Mid Loddon GMA for consumptive use metric**



**Figure A15: A visual representation of the synthesis information for the Mid Loddon GMA for environmental metric - terrestrial GDE**



**Figure A16: A visual representation of the synthesis information for the Mid Loddon GMA for environmental metric - wetlands GDE**



**Figure A17: A visual representation of the synthesis information for the Mid Loddon GMA for environmental metric - waterways GDE**

Table A1. Consumptive users' synthesis table for Mid Loddon GMA

<b>Assessment area</b>	<b>GMU</b>			MID LODDON GMA			
	<b>Representative Bore</b>			88214			
	<b>Aquifer</b>			Semi-Confined			
	<b>Water system depth boundary (m below natural surface)</b>			All formations below the surface.			
<b>Catchment</b>	<b>Permissible Consumptive Volume (ML/yr)</b>			34,037			
	<b>Licensed Entitlement (ML/yr)</b>			33,917			
	<b>Licensed avg use (ML/yr)</b>			21,451			
<b>Synthesis results</b>	<b>All dependent values</b>	Avg Use 17,771 (ML/yr)	2021- 2040	Drawdown from baseline (m)	No CC	3.3	
					MCC (LCC to HCC)	4.4 (1.0 to 6.0)	
			2041- 2065	Drawdown from baseline (m)	No CC	3.7	
					MCC (LCC to HCC)	3.7 (1.4 to 11)	
			PCV use 28,238 (ML/yr)	2021- 2040	Drawdown from baseline (m)	No CC	3.9
						MCC (LCC to HCC)	5.1 (3.1 to 6.7)
		2041- 2065		Drawdown from baseline (m)	No CC	3.7	
					MCC (LCC to HCC)	7.5 (2.0 to 12)	
		Use at 1 metre drawdown	2021- 2040	Volume (ML/yr)	No CC	9,789	
					MCC (HCC to LCC)	7,669 (5,940 to 12,658)	
					Proportion of recharge (%)	NA	
			2041- 2065	Volume (ML/yr)	No CC	8,573	
					MCC (HCC to LCC)	5,497 (3,229 to 15,825)	
					Proportion of recharge (%)	NA	
		Use at 2 metre drawdowns	2021- 2040	Volume (ML/yr)	No CC	19,578	
					MCC (HCC to LCC)	15,339 (11,880 to 25,316)	
					Proportion of recharge (%)	NA	
			2041- 2065	Volume (ML/yr)	No CC	8.39% (8.49% to 11.01%)	
					MCC (HCC to LCC)	8.39% (8.49% to 11.01%)	
					Proportion of recharge (%)	NA	
		2041- 2065	Volume (ML/yr)	No CC	17,147		
				MCC (HCC to LCC)	10,994 (6,458 to 31,651)		
				Proportion of recharge (%)	NA		
		2041- 2065	Proportion of recharge (%)	No CC	7.91% (7.33% to 16.06%)		
MCC (HCC to LCC)	7.91% (7.33% to 16.06%)						
MCC (HCC to LCC)	7.91% (7.33% to 16.06%)						

**Table A2. Statewide drawdown-use synthesis table for Mid Loddon GMA**

MID LODDON GMA					
Consumptive users (bores)	Avg Use 17,771 (ML/yr)	2021-2040	Drawdown from baseline (m)	No CC	3.4
				MCC (LCC to HCC)	4.4 (1.0 to 6.0)
		2041-2065	Drawdown from baseline (m)	No CC	3.7
				MCC (LCC to HCC)	3.7 (1.4 to 11)
	PCV use 28,238 (ML/yr)	2021-2040	Drawdown from baseline (m)	No CC	3.8
				MCC (LCC to HCC)	5.0 (3.1 to 6.6)
		2041-2065	Drawdown from baseline (m)	No CC	3.7
				MCC (LCC to HCC)	7.4 (2.0 to 12)
	Use at 1 metre drawdown	2021-2040	Volume (ML/yr)	No CC	9,940
				MCC (HCC to LCC)	7,801 (6,030 to 12,861)
			Proportion of recharge (%)	No CC	NA
				MCC (HCC to LCC)	4.27% (4.31% to 5.59%)
		2041-2065	Volume (ML/yr)	No CC	8,563
				MCC (HCC to LCC)	5,575 (3,270 to 15,914)
	Proportion of recharge (%)	No CC	NA		
		MCC (HCC to LCC)	4.01% (3.71% to 8.08%)		
Use at 2 metre drawdowns	2021-2040	Volume (ML/yr)	No CC	19,880	
			MCC (HCC to LCC)	15,603 (12,061 to 25,722)	
		Proportion of recharge (%)	No CC	NA	
			MCC (HCC to LCC)	8.54% (8.62% to 11.19%)	
	2041-2065	Volume (ML/yr)	No CC	17,127	
			MCC (HCC to LCC)	11,151 (6,539 to 31,828)	
	Proportion of recharge (%)	No CC	NA		
		MCC (HCC to LCC)	8.02% (7.42% to 16.15%)		

**Table A3. Terrestrial GDE synthesis table for Mid Loddon GMA**

MID LODDON GMA					
Terrestrial GDEs	Avg Use 17,771 (ML/yr)	2021-2040	Drawdown from baseline (m)	No CC	3.1
				MCC (LCC to HCC)	4.1 (0.82 to 5.7)
		2041-2065	Drawdown from baseline (m)	No CC	3.4
				MCC (LCC to HCC)	3.4 (1.2 to 11)
	PCV use 28,238 (ML/yr)	2021-2040	Drawdown from baseline (m)	No CC	3.5
				MCC (LCC to HCC)	4.6 (2.8 to 6.2)
		2041-2065	Drawdown from baseline (m)	No CC	3.4
				MCC (LCC to HCC)	7.0 (1.8 to 12)
	Use at 0.1 metre drawdown	2021-2040	Volume (ML/yr)	No CC	1,071
				MCC (HCC to LCC)	836 (639 to 1,399)
			Proportion of recharge (%)	No CC	NA
				MCC (HCC to LCC)	0.46% (0.46% to 0.61%)
		2041-2065	Volume (ML/yr)	No CC	877
				MCC (HCC to LCC)	584 (341 to 1,687)
			Proportion of recharge (%)	No CC	NA
				MCC (HCC to LCC)	0.42% (0.39% to 0.86%)
	Use at 1 metre drawdown	2021-2040	Volume (ML/yr)	No CC	10,706
				MCC (HCC to LCC)	8,362 (6,393 to 13,989)
			Proportion of recharge (%)	No CC	NA
				MCC (HCC to LCC)	4.57% (4.57% to 6.09%)
2041-2065		Volume (ML/yr)	No CC	8,772	
			MCC (HCC to LCC)	5,845 (3,407 to 16,868)	
		Proportion of recharge (%)	No CC	NA	
			MCC (HCC to LCC)	4.20% (3.87% to 8.56%)	
Use at 2 metre drawdowns	2021-2040	Volume (ML/yr)	No CC	21,411	
			MCC (HCC to LCC)	16,725 (12,786 to 27,978)	
		Proportion of recharge (%)	No CC	NA	
			MCC (HCC to LCC)	9.15% (9.14% to 12.17%)	
	2041-2065	Volume (ML/yr)	No CC	17,544	
			MCC (HCC to LCC)	11,689 (6,814 to 33,736)	
		Proportion of recharge (%)	No CC	NA	
			MCC (HCC to LCC)	8.41% (7.73% to 17.12%)	

**Table A4. Waterways GDE synthesis table for Mid Loddon GMA**

MID LODDON GMA					
Waterway GDEs	Avg Use 17,771 (ML/yr)	2021-2040	Drawdown from baseline (m)	No CC	3.2
				MCC (LCC to HCC)	4.2 (0.78 to 5.9)
		2041-2065	Drawdown from baseline (m)	No CC	3.5
				MCC (LCC to HCC)	3.5 (1.1 to 12)
	PCV use 28,238 (ML/yr)	2021-2040	Drawdown from baseline (m)	No CC	3.6
				MCC (LCC to HCC)	4.7 (2.8 to 6.3)
		2041-2065	Drawdown from baseline (m)	No CC	3.5
				MCC (LCC to HCC)	7.4 (1.8 to 12)
	Use at 0.1 metre drawdown	2021-2040	Volume (ML/yr)	No CC	1,059
				MCC (HCC to LCC)	812 (623 to 1,397)
			Proportion of recharge (%)	No CC	NA
				MCC (HCC to LCC)	0.44% (0.45% to 0.61%)
		2041-2065	Volume (ML/yr)	No CC	859
				MCC (HCC to LCC)	562 (326 to 1,728)
			Proportion of recharge (%)	No CC	NA
				MCC (HCC to LCC)	0.40% (0.37% to 0.88%)
	Use at 1 metre drawdown	2021-2040	Volume (ML/yr)	No CC	10,592
				MCC (HCC to LCC)	8,121 (6,231 to 13,969)
			Proportion of recharge (%)	No CC	NA
				MCC (HCC to LCC)	4.44% (4.45% to 6.08%)
		2041-2065	Volume (ML/yr)	No CC	8,590
				MCC (HCC to LCC)	5,622 (3,256 to 17,282)
			Proportion of recharge (%)	No CC	NA
				MCC (HCC to LCC)	4.04% (3.70% to 8.77%)
Use at 2 metre drawdowns	2021-2040	Volume (ML/yr)	No CC	21,184	
			MCC (HCC to LCC)	16,243 (12,461 to 27,937)	
		Proportion of recharge (%)	No CC	NA	
			MCC (HCC to LCC)	8.89% (8.91% to 12.15%)	
	2041-2065	Volume (ML/yr)	No CC	17,180	
			MCC (HCC to LCC)	11,244 (6,513 to 34,564)	
		Proportion of recharge (%)	No CC	NA	
			MCC (HCC to LCC)	8.09% (7.39% to 17.54%)	

**Table A5. Stream gauge results for Mid Loddon GMA**

Mid Loddon GMA				
Stream gauge/Catchment:		<b>407203 - Loddon River @ Laanecoorie (Regulated)</b>		
Base flow index (1975-2020)		<b>0.46</b>		
MAF	2040	Flow (ML/yr)	MCC (HCC to LCC)	138,216 (94,632 to 167,770)
		Change from 1975-2020 (ML/yr)	MCC (HCC to LCC)	-26,275 (-69,859 to 3,279)
	2065	Flow (ML/yr)	MCC (HCC to LCC)	122,992 (63,287 to 159,561)
		Change from 1975-2020 (ML/yr)	MCC (HCC to LCC)	-41,500 (-101,204 to -4,930)
Groundwater extraction in upgradient catchment as % of MAF flow	2040	Current use (ML/yr)	MCC (LCC to HCC)	6.1% (8.9% to 5.0%)
		PCV use (ML/yr)	MCC (LCC to HCC)	14% (21% to 12%)
	2065	Current use (ML/yr)	MCC (LCC to HCC)	6.9% (13% to 5.3%)
		PCV use (ML/yr)	MCC (LCC to HCC)	16% (32% to 12%)
Q90 flow	2040	Flow (ML/yr)	MCC (HCC to LCC)	16.19 (11.08 to 19.65)
		Change from 1975-2020 (ML/yr)	MCC (HCC to LCC)	-3 (-8 to 1)
	2065	Flow (ML/yr)	MCC (HCC to LCC)	14.41 (7.41 to 18.69)
		Change from 1975-2020 (ML/yr)	MCC (HCC to LCC)	-4 (-11 to 0)
Groundwater extraction in upgradient catchment as % of Q90 flow	2040	Current use (ML/yr)	MCC (LCC to HCC)	143% (209% to 118%)
		PCV use (ML/yr)	MCC (LCC to HCC)	338% (493% to 278%)
	2065	Current use (ML/yr)	MCC (LCC to HCC)	161% (313% to 124%)
		PCV use (ML/yr)	MCC (LCC to HCC)	379% (737% to 292%)

**Table A6. Wetlands GDE synthesis table for Mid Loddon GMA**

MID LODDON GMA					
Wetlands GDEs	Avg Use 17,771 (ML/yr)	2021-2040	Drawdown from baseline (m)	No CC	3.0
				MCC (LCC to HCC)	4.0 (0.98 to 5.5)
	2041-2065	Drawdown from baseline (m)	No CC	3.3	
			MCC (LCC to HCC)	3.3 (1.3 to 10)	
	PCV use 28,238 (ML/yr)	2021-2040	Drawdown from baseline (m)	No CC	4.3
				MCC (LCC to HCC)	5.5 (3.4 to 7.3)
	2041-2065	Drawdown from baseline (m)	No CC	3.3	
			MCC (LCC to HCC)	7.9 (2.0 to 13)	
	Use at 0.1 metre drawdown	2021-2040	Volume (ML/yr)	No CC	916
				MCC (HCC to LCC)	718 (559 to 1,189)
			Proportion of recharge (%)	No CC	NA
		2041-2065	Volume (ML/yr)	No CC	815
				MCC (HCC to LCC)	531 (317 to 1,552)
			Proportion of recharge (%)	No CC	NA
	Use at 1 metre drawdown	2021-2040	Volume (ML/yr)	No CC	9,165
				MCC (HCC to LCC)	7,175 (5,590 to 11,887)
			Proportion of recharge (%)	No CC	NA
		2041-2065	Volume (ML/yr)	No CC	8,150
				MCC (HCC to LCC)	5,314 (3,172 to 15,520)
			Proportion of recharge (%)	No CC	NA
Use at 2 metre drawdowns	2021-2040	Volume (ML/yr)	No CC	18,329	
			MCC (HCC to LCC)	14,351 (11,179 to 23,775)	
		Proportion of recharge (%)	No CC	NA	
	2041-2065	Volume (ML/yr)	No CC	16,300	
			MCC (HCC to LCC)	10,628 (6,343 to 31,040)	
		Proportion of recharge (%)	No CC	NA	
			MCC (HCC to LCC)	7.64% (7.20% to 15.75%)	