Technical Assessment of State Wide Groundwater Sustainable Yields

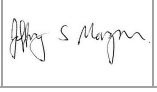
Confined Aquifers: Stage 2 (Statewide) Report

DEECA

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→ The Power of Commitment



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Executive Summary

Project background

Victoria's groundwater resources are adaptively managed by the Department of Energy, Environment and Climate Action (DEECA), considering emerging issues, changes to the resource, its use, development pressures, and the system response. Maximising resource development provides economic benefit, which must be balanced against minimising unacceptable impacts to the environment.

DEECA is reviewing the sustainable yields of Victoria's groundwater resources, which were initially estimated nearly 25 years ago, forming the basis for the declaration of the current Permissible Consumptive Volumes (PCVs) across Victoria. This review is necessary to ensure the continued sustainable planning and management of the state's groundwater resources, and to meet the future challenges of climate change and water shortage. The review is informed by a significant amount of new groundwater data collected by DEECA since the original PCVs were established.

This report documents Stage 2 (Statewide application) of a study undertaken by GHD to estimate sustainable yield volumes for confined aquifers across the State of Victoria, specifically through testing of the use-drawdown method and comparison to DEECA groundwater sustainability metrics. DEECA is currently trialling various approaches, and this project has been undertaken concurrently with two related state-wide studies focused on unconfined aquifers and confined aquifers (focusing on groundwater throughflow).

Approach

The foundation of GHD's approach is the use of Transfer Function Noise (TFN) modelling to estimate a relationship between groundwater level and groundwater use within a Groundwater Management Unit (GMU). This involved the following approach, consistent with DEECA's groundwater assessment framework:

- Identifying and relying upon Suite hydrographs (an 'average' hydrograph developed using nearby monitoring bores exhibiting like groundwater trends) as representative of groundwater levels within a GMU
- Cleansing and vetting groundwater level data prior to updating the currency of the Suite hydrographs to 2022
- Compiling hydrogeological conceptual elements specifically related to the method, for each GMU
- Undertaking analysis to estimate the most appropriate data inputs for the TFN time series
- Developing a defensible approach to hindcasting a groundwater use data time series to match the Suite hydrograph water level time series
- Undertaking analysis to determine whether spatial extraction densities influence the TFN model fit
- Trialling a combination of stressors in the TFN, consistent with the aquifer conceptualisation, to estimate the best match to the groundwater use and water level time series (i.e., model calibration)
- Developing and running forecast groundwater use time series in the TFN to estimate drawdown under a range of potential future extraction scenarios
- Determining a relationship between drawdown of recovered water level and groundwater use for each GMU, and comparison of the predicted drawdown ranges with the DEECA sustainability metrics

Uncertainty analysis

In the application of the TFN modelling, uncertainty of the calibration models was assessed through two measures: the thickness of the 95% prediction intervals; and the percentage of observed annual recovered levels within the 95% prediction intervals. The smaller the 95% prediction interval thickness and the greater the percentage of observations within the 95% prediction intervals, the less model uncertainty.

In the predictive modelling, uncertainty was assessed through Markov Chain Monte Carlo (MCMC) predictions which were undertaken on each of the forecasted scenarios for each GMU. The MCMC simulations optimise/estimate the parameters of the Pastas model. The MCMC realisations were compared with the 95% prediction intervals to see if the realisations fell within the prediction intervals.

Uncertainty was also considered through adopting 19 different forecast scenarios to develop a groundwater use to drawdown relationship, where a range of possible outcomes are generated; these were not randomly generated.

Findings

The statewide application of GHD's approach was conducted for 25 GMUs. From these 25 GMUs, only one could not undergo the application of the full methodology due to no historic extraction data being available, which is an essential input into the method.

Across the 25 GMUs, a total of 43 Suites and GMU combinations were identified as potentially representative, 42 of which underwent predictive modelling. The most commonly adopted input combination for predictive modelling based on model calibration runs and their statistics, was that of annual recorded extraction with hindcast method H2 (i.e., rainfall and bore age factors considered) and annual recovered levels, with 14 Suites (or 33% of Suites tested) adopting this combination. For comparison, the second most adopted model was one of annual recorded extraction including external influence with hindcast method H2 or two yearly average annual extraction with hindcast method H2.

Based on the results of the modelling and resultant drawdown to use relationships developed for each of the GMUs, the methodology was found to be appropriate to varying degrees, based on the most representative Suite for each GMU, as outlined below:

- An excellent applicability for 11 GMUs
- A good applicability for 4 GMUs
- A moderate applicability for 6 GMUs
- A poor applicability for 3 GMU
- Not applicable for 1 GMU (Gellibrand GMA)

A summary of the findings is presented in the table below for all Suites that underwent predictive modelling. It is noted that the blue rows indicate the preferred Suite based on the predictive modelling for the GMU.

GMU	Suite(s) assessed	Model calibration criteria	Model calibration uncertainty analysis criteria			Use – drawdown relationship	Volume (ML/year) for 10 m of drawdown over 20 years (Volumes rounded to the nearest 100 ML)	Method applicability
		R^2	RMSE	95 PPU TH	%Obs in 95PPU	R^2		
Corinella GMA	M_S_88	71.6	0.14	0.64	93.62	50.3	7,700 (2,300 – 14,600)	Moderate
Cut Paw Paw GMA	L_U_1	83.9	0.38	2.05	95.83	25.2	5,000 (1,000 – 6,800	Moderate
Frankston GMA	L_U_1	89.2	0.3	1.9	93.62	38.6	1,400 (900 – 1,700)	Moderate
Frankston GMA	M_T_3	88.7	0.18	0.68	95.92	76.5	3,100 (2,100 – 3,600)	Excellent
Koo Wee Rup WSPA	M_S_1	56.6	0.55	2.3	97.83	83.6	24,100 (17,500 – 35,000)	Good
Koo Wee Rup WSPA	M_S_2	43.4	0.32	1.35	95.65	86.3	49,200 (46,700 – 103,300)	Good
Koo Wee Rup WSPA	M_S_3	32.6	0.9	3.74	100	79.6	28,500 (23,500 – 50,600)	Moderate
Moorabbin GMA (1)	M_T_3	89.1	0.18	0.57	93.75	83	10,900 (9,500 – 11,300)	Excellent
Moorabbin GMA (1)	M_T_2	52.8	0.52	2.49	97.92	44.3	15,400 (13,500 – 33,500)	Moderate

GMU	Suite(s) assessed	Model calibration criteria	Model calibration uncertainty analysis criteria			Use – drawdown relationship	Volume (ML/year) for 10 m of drawdown over 20 years (Volumes rounded to the nearest 100 ML)	Method applicability
		R^2	RMSE	95 PPU TH	%Obs in 95PPU	R^2		
Murrayville GMA	M_AC_2	95.7	0.44	2.07	100	90.9	8,000 (7,200 – 8,800)	Excellent
West Wimmera GMA	M_AD_1	95.3	0.15	1.19	91.18	75.4	171,200 (137,100 – 216,900)	Excellent
West Wimmera GMA	M_E_8	69.8	0.13	0.54	93.33	88.2	491,600 (320,700 – 1,005,600)	Excellent
Katunga WSPA	M_I_2	94.7	1.02	4.37	93.62	93.7	25,900 (20,900 – 31,000)	Good
Katunga WSPA	M_I_1	86.8	1.92	8.19	100	84.1	27,900 (10,500 – 42,000)	Good
Lower Campaspe Valley WSPA	M_H_1	92.7	1.15	5.12	94	88.7	33,700 (26,400 – 41,200)	Good
Lower Campaspe Valley WSPA	M_H_2	74.8	1.92	5.45	77.55	89.8	30,900 (23,800 – 56,500)	Moderate
Lower Campaspe Valley WSPA	M_H_3	97.8	0.49	2.46	90	76.3	45,300 (27,000 – 51,700)	Excellent
Mid Loddon GMA	M_F_2	88.8	0.93	4.87	92.31	64.3	25,100 (9,000 – 40,600)	Excellent
Mid Loddon GMA	M_F_3	36.8	0.76	3.24	95.92	87.3	103,400 (89,300 – 116,800)	Moderate
Giffard GMA	U_AF_1	79.6	0.27	1.11	97.14	88.3	33,600 (26,100 – 35,400)	Excellent
Giffard GMA	U_AG_1	71.6	0.09	0.65	90	39.7	97,700 (48,000 – 124,200)	Moderate
Moe GMA	L_PP_88	57.2	0.37	18.62	89.58	10.2	44,300 (8,000 – 48,900)	Poor
Moe GMA	L_Q_1	85.9	1.01	4.55	91.67	85.9	2,000 (1,200 – 2,600)	Good
Orbost GMA	U_Y_1	74.4	0.18	0.83	94.74	90.6	4,200 (3,000 – 5,400)	Excellent
Rosedale GMA	M_O_2	93	1.12	6.36	97.73	76.9	8,500 (4,500 – 15,100)	Moderate
Sale WSPA	M_O_1	92.8	0.69	2.99	100	91.5	14,300 (12,900 – 18,000)	Excellent
Sale WSPA	M_P_1	98.3	0.11	1.05	93.02	60.2	51,700 (49,600 – 52,600)	Excellent
Sale WSPA	U_AB_1	93.1	0.09	0.52	95.56	63.6	166,300 (121,800 – 169,000)	Excellent
Stratford GMA	L_O_1	97.9	1.51	12.54	93.02	16.8	13,700 (-3,400 – 13,800)	Poor

GMU	Suite(s) assessed	Model calibration criteria	Model calibration uncertainty analysis criteria			Use – drawdown relationship	Volume (ML/year) for 10 m of drawdown over 20 years (Volumes rounded to the nearest 100 ML)	Method applicability
		R^2	RMSE	95 PPU TH	%Obs in 95PPU	R^2		
Yarram WSPA	L_O_2	93.5	1.33	5.24	91.89	36.4	9,200 (3,400 – 17,900)	Poor
Yarram WSPA	L_O_1	98.3	1.33	6.79	100	86.2	5,500 (4,000 – 6,500)	Good
Condah WSPA	L_A_1	94.4	0.69	3.43	96.3	92.6	4,400 (3,000 – 5,000)	Excellent
Condah WSPA	L_A_2	97.9	0.28	2.5	100	70.6	6,900 (4,800 – 7,400)	Excellent
Gellibrand GMA	L_Y_3	NA	NA	NA	NA	NA	NA	NA
Gerangamete GMA	L_Y_1	84.6	3.98	20.81	93.75	35.6	1,700 (-1,100 – 5,600)	Poor
Glenelg WSPA	L_AF_1	97.1	0.14	0.72	89.66	84.2	45,800 (30,700 – 46,500)	Excellent
Glenelg WSPA	M_AF_1	90.8	0.2	0.91	96.55	91.5	32,800 (24,400 – 33,500	Excellent
Glenelg WSPA	U_D_8	88.2	0.14	0.77	93.1	13.2	^88,000 (43,100 – 110,000)	Moderate
Jan Juc GMA	L_X_2	97.2	0.57	4.22	95.59	14.6	9,600 (3,500 – 15,200)	Moderate
Newlingrook GMA	L_AA_99	79.1	0.16	0.82	100	44.6	7,900 (1,200 – 11,100)	Moderate
Paaratte GMA	L_AA_99	89.2	0.11	0.64	95.45	80	6,500 (3,200 – 9,800)	Excellent
Portland GMA	L_A_2	98.3	0.26	2.32	96.3	59.5	7,200 (4,500 – 7,600)	Good
Portland GMA	L_C_1	83.3	0.26	1.31	100	74.9	15,500 (10,200 – 16,300)	Excellent

Notes:

(1) These volumes are the two yearly average annual volumes (ML/year)
(^) This symbol denotes volumes that relate to unconfined aquifers and indicate 2 m of drawdown over 20 years

Next steps

Based on the findings of this assessment, GHD recommends the following next steps:

- DEECA to address the recommendations provided within this report relating to major data gaps
- If the major data gaps can be addressed, consider re-running the models to confirm that improved results can be obtained
- While GHD has assessed the applicability of the method for each of the GMUs (based on statistical measures), DEECA should review the results for each method to determine if applicable and what level of applicability is suitable for DEECA's purposes
- DEECA should consider GMU specific risks when developing the metrics and adopting a sustainable yield for each GMU

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Appendices

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Appendix B	Pastas guidance documentation
Appendix C	Data review and preparation – method documentation
Appendix D	Memo on externalities
Appendix E	Electronic data files

Definitions and abbreviations

Glossary of terms

Term	Definition
Accuracy	A term to reflect the closeness of a result to actual conditions.
Aquifer	A geological formation, group of formations or part of a formation, which contains sufficient saturated permeable material to transmit and yield significant quantities of water.
Alluvial	Pertaining to, or composed of, alluvium or other deposits from streams and rivers.
Alluvium	A general term for unconsolidated material deposited during recent geological time by a stream or other body of running water. Typically forms a sorted or semi-sorted sediment in stream beds, floodplains, deltas or as fan at the base of a mountain slope.
Annual rainfall	In the context of this study, this term refers to rainfall measured over the water year, a one year period commencing 1 July and concluding 30 June the subsequent year.
Annual recovered level	The maximum normalised level from a Suite within a particular water year after the main period of irrigation.
Aquitard	A geological formation or group of formations that is saturated but does not allow water to flow freely to a pumping bore. However, aquitards may transmit appreciable amounts of water between adjacent aquifers.
Bedrock	A general term for rock, usually solid, that underlies soil or other unconsolidated material.
Confined aquifer	An aquifer which is isolated from the atmosphere by an impermeable layer. Pressure in confined aquifers is generally greater than atmospheric pressure.
Discharge	Any process by which water is removed from an aquifer. Includes water that flows to a surface feature, such as a spring, river or wetland, as well as water which flows to an adjacent aquifer.
Drawdown	The occasional, seasonal or permanent lowering of the water table or reduction in pressure (head) of an aquifer resulting from the extraction of groundwater. With reference to this report, drawdown typically refers to groundwater level decline or 'groundwater pressure fluctuation' caused by abstractive response). In a confined aquifer, groundwater level decline is generally in response to drawdown caused by (typically) seasonal pumping. Drawdown in this report is calculated from the normalised pre-development level and modelled levels for a Suite.
Flux, flux volumes, flux rates	The state, volume or rate of flow from one geological unit or aquifer to another where the direction of flow can change.
Groundwater Dependent Ecosystem	An ecosystem that is partially or wholly reliant on groundwater for its survival. This can include terrestrial, subsurface and marine ecosystems.
Groundwater licence	A take and use licence and a works licence (to cover bore operation), which are required in Victoria to access groundwater for purposes other than domestic and stock use
Groundwater Management Unit	A Groundwater Management Unit (GMU) can be a groundwater management area (GMA), Water Supply Protection Area (WSPA) or Unincorporated Area.
Groundwater monitoring bore	A bore installed with the purpose to; determine the nature and properties of subsurface ground conditions; provide access to groundwater for measuring level, physical and chemical properties; and permit the collection of groundwater samples and conduct of aquifer testing.
Groundwater pumping (production) bore	A bore installed with the primary purpose to extract groundwater from a particular hydrogeological formation by means of a pump.
Hydrostratigraphy	The identification and distinction of hydrogeological units based on their hydraulic properties.
Irrigation	Watering land by any means for the purpose of growing plants.
Irrigation season	The period in which major irrigation diversions occur, usually starting in September-October and ending in April-May.

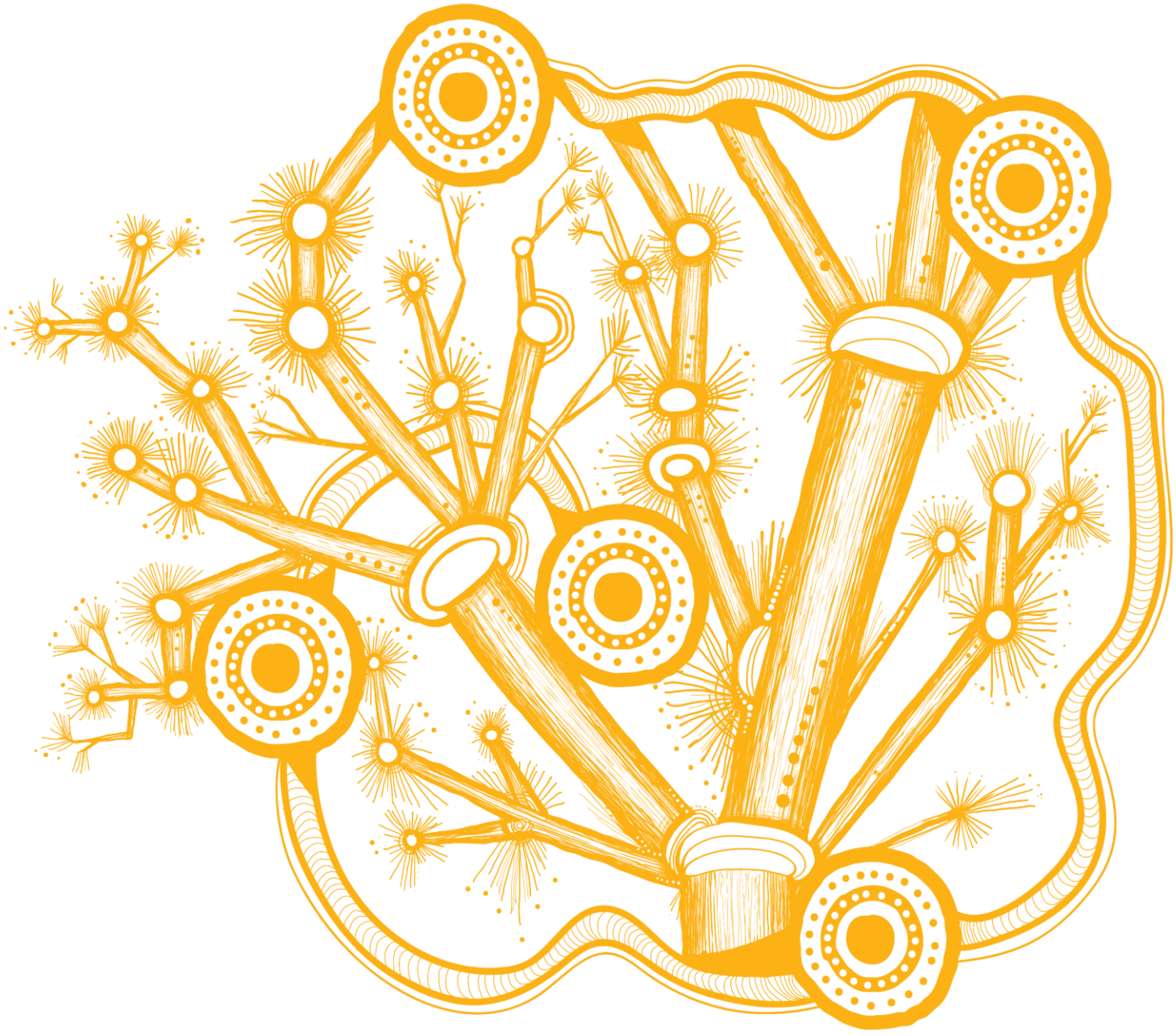
Term	Definition
Metered Use	The (annual) volume of water recorded on metered bores by the Rural Water Corporations.
Pre-development level (m)	The adopted normalised annual recovered level for a Suite in a given GMU that represents pre-development conditions.
Permissible Consumptive Volume (PCV)	The cap or volume of water declared by the Minister that may be taken for use from an area.
Predicted groundwater level	The groundwater level in an aquifer expected to occur through predictive analysis or inference of likely aquifer stresses.
Recharge	The process of adding water, or the amount of water added, to the volume of water stored in an aquifer.
Primary Representative Suite	The Suite identified to most likely represent the groundwater level response in the GMU due to extraction. This is based on the following factors in order of weighting: 1. Volume of extraction occurring within Suite (higher volumes are prioritised) 2. Relevance of Suite (i.e., does it cover the intended aquifer/confined aquifer of the GMU) 3. Spatial coverage (greater coverage is prioritised) 4. Number of SON bores in the Suite area (the presence of more bores is prioritised) 5. Whether Suite observation borees are close to extraction points
Standing water level	The level of water in a well or bore that is not being affected by pumping of groundwater.
Stratigraphy	The study of rock layers and layering, especially of their distribution, deposition and age.
Suite	Monitoring bores that show similar water level responses are classified into groups, or Suites. Each Suite is defined by: – VAF Layer (Upper, Middle, Lower, Basement) – Suite Code – Fluctuation Code
Suite Area	A mapped area of the State where State Observation Bore Network (SOBN) exhibit the same Suite.
Suite Hydrograph	A normalised water level hydrograph of a Suite, which has been derived through statistical analysis of the individual State Observation Bores constituting the Suite.
Suite Status	A qualitative classification applicable to a Suite, which is calculated quantitatively based on the Resource Condition. Two classifications of Suite Status are presented in this report, namely “Acceptable” and “On Watch”
Uncertainty	The level of confidence that information such as a data set or model simulation can be relied upon.
Unconfined aquifer	An aquifer which has the upper surface exposed to the atmosphere.
VAF Layer	The Victoria Aquifer Framework (VAF) classifies the state’s aquifers into either of four levels: – Upper – Middle – Lower – Basement
Water table	The surface between the vadose zone and the saturated zone of unconfined groundwater. This can also be defined as the surface at which groundwater pressure is equal to atmospheric pressure.
Yield	The rate at which water can be extracted from a pumping well, typically measured in L/sec or ML/sec.

Acronyms

Acronym	Definition
B	Basement (1 of 4 aquifer layers applied to classify Suite hydrographs)
DEECA	Department of Energy, Environment and Climate Action ·
GMA	Groundwater Management Area
GMU	Groundwater Management Unit
G-MW	Goulburn Murray Water
GWMW	Grampians Wimmera Mallee Water
H1	Hindcast method 1
H2	Hindcast method 2
H3	Hindcast method 3
HGU	Hydrogeological unit
ID	Insufficient data (Suite classification code)
LMW	Lower Murray Water
L	Lower (1 of 4 aquifer layers applied to classify Suite hydrographs)
M	Middle (1 of 4 aquifer layers applied to classify Suite hydrographs)
ML	Megalitre
OUT	Outlier (Suite classification code)
PCV	Permissible Consumptive Volume
QD	Data quality issue (Suite classification code)
RWC	Rural Water Corporation
S1	Spatial method S1
S2	Spatial method S2
S3	Spatial method S3
SAFE	Secure Allocations, Future Entitlements
SRW	Southern Rural Water
SOBN or SON	State Observation (Bore) Network
TFN	Transfer Function Noise (model)
U	Upper (1 of 4 aquifer layers applied to classify Suite hydrographs)
UA	Unincorporated area
VAF	Victorian Aquifer Framework
VWA	Victoria Water Accounts
WMIS	Water Measurement Information System
WSPA	Water Supply Protection Area

Acknowledgement of Country

GHD acknowledges Aboriginal and Torres Strait Islander peoples as the Traditional Custodians of the land, water and sky throughout Australia on which we do business. We recognise their strength, diversity, resilience and deep connections to Country. We pay our respects to Elders of the past, present and future, as they hold the memories, knowledges and spirit of Australia. GHD is committed to learning from Aboriginal and Torres Strait Islander peoples in the work we do.



1. Introduction

1.1 Aim

The aim of this project is to provide the information necessary to enable the Victorian Department of Energy, Environment and Climate Action (DEECA) to make informed decisions about management of groundwater resources to support planning and policy decisions regarding groundwater, particularly in respect to limits for allocation (Permissible Consumptive Volumes) and sustainable groundwater use.

1.2 Objective

The objective of this study is to undertake improved technical assessments to inform groundwater sustainable yield for confined aquifers across the State of Victoria, specifically through testing of the use-drawdown method. This study will support DEECA's planning and policy decisions, through the estimation of groundwater sustainable yields by way of consideration of groundwater sustainability metrics.

1.3 Problem statement

In the late 1990s, DEECA's predecessor agencies established sustainable yields for GMUs across the state. These sustainable yields were required to ensure that groundwater users had access to economically develop the resource, and to also ensure that abstractive benefit and environmental protection were continued for future generations.

It has been recognised by DEECA that historically, the sustainable yields were often based upon limited data, had uncertainties in both the estimates themselves but also consideration of the risks to the environmental values, and did not consider climate change. Since their original establishment, additional data in terms of abstraction metering, improved monitoring networks and further technical studies have been undertaken, that have improved the hydrogeological understanding and thus could further improve sustainable yield estimation.

DEECA continues to seek a better understanding of the sustainability of the state's groundwater resources, through efforts to align with national groundwater management practice. To this end, DEECA requires generic methodologies for assessing both groundwater availability and potential adverse impact from groundwater development. In mid-2021, DEECA commissioned technical studies associated with the state's unconfined aquifer systems, and in late 2021 commissioned assessment of the state's confined aquifer systems (i.e., this study, plus an additional study focused on the throughflow analysis method for confined aquifers).

DEECA's key requirements in developing this study was a method that is:

- Simple and repeatable
- Applicable across all of the state's confined aquifer systems
- Relies on groundwater observations/measured data
- Readily updated as more data becomes available
- Able to quantify uncertainty
- Relatable to a metric that can be applied to measure the level of acceptable impact

1.4 Purpose of this report

The purpose of this report is to document the technical method developed by GHD in assessing groundwater availability and reviewing the sustainable yields for each confined Groundwater Management Unit (GMU), and to discuss the associated uncertainties as they relate to various hydrogeological factors and potential adverse impact of groundwater use for Victoria's confined aquifers.

1.4.1 Review and refinement

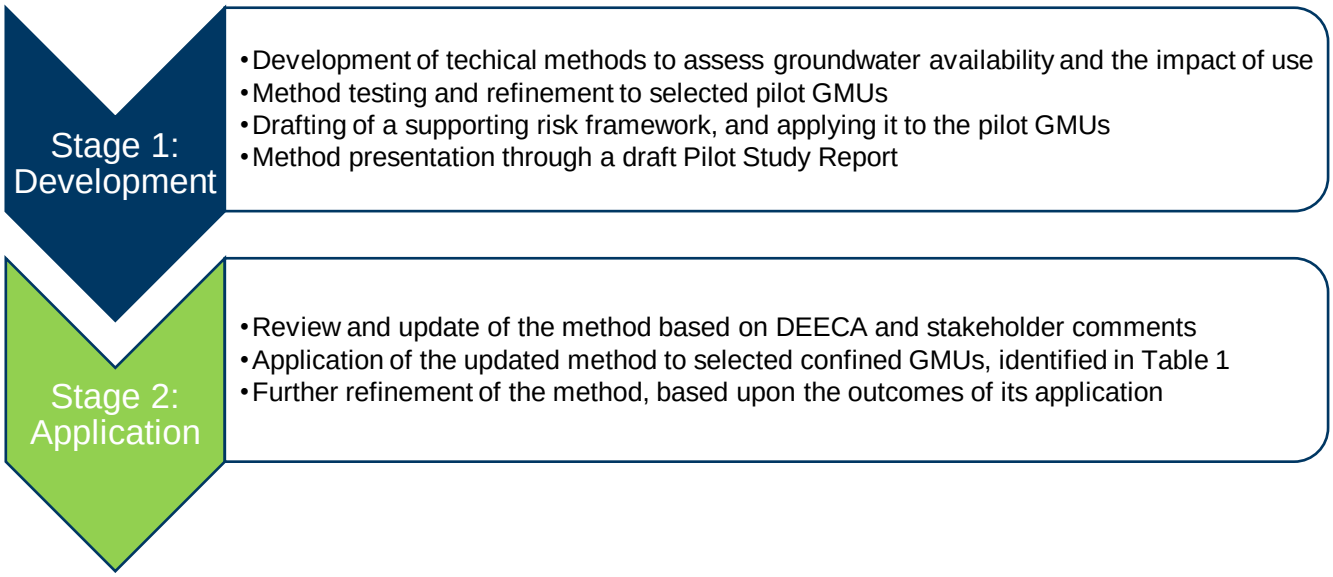
A preliminary method was developed and tested in 2022 based on a selection of pilot areas (refer to Stage 1 Project Report: GHD, 2022). A number of improvements were subsequently made to the method based on review comments provided by project stakeholders including the Technical Review Panel (TRP), Rural Water Corporations (RWCs) and DEECA. The method improvements and modifications include the following changes to the modelling approach:

- Use of annual recovered levels rather than average annual levels (refer section 3.3.3)
- Not conducting the de-annualisation approach with the change in adopted levels (refer section 3.3.4)
- Inclusion of external groundwater extraction to the GMU where relevant (not including spatial analysis) (refer section 3.3.4.7)
- Use of two yearly average annual extraction in addition to the annual extraction (refer to section 3.3.4.8)
- Refined method for the selection of representative Suite(s) (refer to section 2.6.4)
- Improvements to model calibration and uncertainty analysis (refer to section 3.4.1.3)

This report focusses specifically on the further development, testing and application of GHD's method at the statewide scale, which relates to the **Stage 2: Application** project scope item outlined in the following section.

1.5 Scope

This project scope is summarised through the following diagram:



The confined GMUs relevant this statewide study are located across Victoria and are outlined in Table 1.

Table 1 Confined GMUs relevant to this study

Region	GMU
Central Region	Corinella Groundwater Management Area (GMA)
	Cut Paw Paw GMA
	Frankston GMA
	Koo Wee Rup Water Supply Protection Area (WSPA)
	Moorabbin GMA
Wimmera-Mallee Region	Murrayville GMA
	West Wimmera GMA
Goulburn-Murray Region	Katunga WSPA
	Lower Campaspe Valley WSPA
	Mid Loddon GMA
Gippsland Region	Giffard GMA
	Moe GMA
	Orbost GMA
	Rosedale GMA
	Sale WSPA
	Stratford GMA
	Yarram WSPA
Otway-Torquay Region	Condah WSPA
	Gellibrand GMA
	Gerangamete GMA
	Glenelg WSPA
	Jan Juc GMA
	Newlingrook GMA
	Paaratte GMA
	Portland GMA

1.6 Limitations

This report: has been prepared by GHD for DEECA and may only be used and relied on by DEECA for the purpose agreed between GHD and DEECA as set out in section 1 of this report.

GHD otherwise disclaims responsibility to any person other than DEECA arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this report. GHD disclaims liability arising from any of the assumptions being incorrect.

GHD has prepared the [Pastas model] ("Model") for, and for the benefit and sole use of, DEECA to support development of the proposed method and must not be used for any other purpose or by any other person. The Model is a representation only and does not reflect reality in every aspect. The Model contains simplified assumptions to derive a modelled outcome. The actual variables will inevitably be different to those used to prepare the Model. Accordingly, the outputs of the Model cannot be relied upon to represent actual conditions without due consideration of the inherent and expected inaccuracies. Such considerations are beyond GHD's scope. The information, data and assumptions ("Inputs") used as inputs into the Model are from publicly available sources or provided by or on behalf of the DEECA (including possibly through stakeholder engagements). GHD has not independently verified or checked Inputs beyond its agreed scope of work. GHD's scope of work does not include review or update of the Model as further Inputs become available.

The Model is limited by the mathematical rules and assumptions that are set out in the Report or included in the Model and by the software environment in which the Model is developed.

The Model is a customised model and not intended to be amended in any form or extracted to other software for amending. Any change made to the Model, other than by GHD, is undertaken on the express understanding that GHD is not responsible, and has no liability, for the changed Model including any outputs.

GHD has prepared this report on the basis of information provided by DEECA and others who provided information to GHD (including Government authorities)], which GHD has not independently verified or checked beyond the agreed scope of work. GHD does not accept liability in connection with such unverified information, including errors and omissions in the report which were caused by errors or omissions in that information.

Accessibility of documents

If this report is required to be accessible in any other format, this can be provided by GHD upon request and at an additional cost if necessary.

1.7 Report structure

The structure of this technical report has been summarised in Table 2.

Table 2 Report structure

Section	Title	Purpose
1.8	Technical assumptions and limitations	This section discusses the limitations and assumptions associated with the data and models.
2	Background	This section provides the reader with an understanding of basic principles associated with groundwater sustainability and the use of spatial Suites and Suite hydrographs to represent regional aquifer conditions.
3	Method	This section provides an overview of the technical tasks undertaken in developing modelling approaches, forecasting groundwater levels, assessing risks and comparing with sustainability metrics as part of a comprehensive sustainable yield reporting process.
4	Results summary	This section summarises the key results of the application of the methodology to the 25 GMUs.
5	Discussion summary	This section discusses method suitability in achieving the overall project objective. This section also provides a critical review of the various aspects of the method undertaken and the results obtained.
6	Model results presentation	This section provides an outline of how the model results are presented in the subsequent chapters.
7 to 31	GMU specific chapters	These sections document the application of the approach and method for each of the GMUs included in the Stage 2 study.
32	Recommendations	This section provides some recommendations to DEECA based on the review of available data, application of the methodology and outcomes of the assessment.
33	References	List of references cited throughout the document.

1.8 Technical assumptions and limitations

A summary of the technical assumptions and limitations is presented in Table 3.

Table 3 Technical assumptions and limitations

Area of methodology	Limitation or assumption
Conceptualisation	Licenced bore use is not attributed to aquifer monitored. It has been associated to a VAF layer based on bore depth where available. In some instances, bore depth is not available and has been reallocated where possible. Licenced bores have also been assigned to Suites where possible based on the spatial location. There is a possibility that the assignments do not accurately reflect the aquifers that are screened and thus may not reflect the relevant Suites.
Conceptualisation	Not all GMUs had representative Suites selected at this time, and further investigation was needed to nominate a representative Suite.
Input data: Climate	GHD relied upon climate data from SILO to estimate relationships between groundwater use and climate (e.g., hindcasting use data). SILO uses mathematical interpolation techniques to construct spatial grids and infill gaps in time series datasets. Uncertainties are introduced through the use of interpolated data.
Input data: Groundwater levels	WMIS SOBN data is a key input for water level time series data into the model. There are a few limitations to the dataset such as: – Individual bore data does not provide for an efficient approach to catchment-scale analysis (i.e., one bore is unlikely to represent the whole catchment) – SOBN is focused on the GMUs and developed areas. Limited monitoring exists in UAs, or on the margins of the GMUs. To simplify the volume of monitoring data, spatial Suites have previously been developed and a Suite hydrograph has been developed. The Suite hydrograph provides an averaged water level response and therefore this simplification introduces uncertainties. Further uncertainty applies in mapping the area where the Suites, and Suite hydrograph are considered to apply. There may be areas of a GMU that are not covered by a Suite. The water level response in individual bores constituting a Suite may change over time and thus the definition of Suites may require periodic review. The Suites present an inherent limitation in how local values are captured over regional scales.
Input data: Groundwater levels	Levels may be influenced by the condition of the bore at the time of monitoring, and this may not represent levels within the aquifer monitored. Thus, water level measurements were removed if they noted a data condition code indicating poor conditions at the bore at the time of monitoring.
Input data: Groundwater levels	Levels may be influenced by the method (or type) of monitoring or check being conducted. Level measurements that noted maintenance checks or pumping tests were removed as they were not considered representative of levels at the bore at the time of monitoring.
Input data: Groundwater levels	Outliers were found within the datasets provided. GHD created a script to automatically remove outliers based on a three-sigma (standard deviation) method of a rolling mean. As this is an automated process there is a chance that 'real' water levels have been removed or that some anomalous data may still be present in the data set.
Input data: Groundwater levels	The Reduced Water Level (RWL) and Depth Below Natural Surface (DBNS) are calculated based on the elevation of the measuring point. Where the elevation of the measuring point was not available, the water level could not be calculated and thus the data was excluded. Through this process, data availability is reduced. If the measuring point elevation is known, additional water levels could be utilised within the Suite Hydrograph Tool.
Input data: Groundwater levels	There were errors when using the Data Upload Tool to upload the cleansed water level data due to issues with C#. Python scripts were set up to run the tool instead. This step could be streamlined in future.
Input data: Groundwater levels	It was assumed that the observation bores selected for the Suite hydrographs were still representative (of that Suite) and that no changes to the Suite boundaries or polygons were needed.

Area of methodology	Limitation or assumption
Input data: Groundwater levels	Some Suites appear multiples times across Victoria and thus changes to a Suite hydrograph may be reflective of changes occurring elsewhere in the state rather than the area of interest. This may represent one example of changes that are required to the existing Suite boundaries or polygons.
Input data: Groundwater levels	The assumption that the maximum water level for a given Suite for each water year is representative of the annual recovered water level.
Input data: Groundwater use	The use of groundwater for purposes other than stock and domestic use requires an extraction licence in Victoria. As a result, stock and domestic groundwater use is not measured in Victoria and for this reason, stock and domestic groundwater use is not considered in this study.
Input data: Groundwater use	Groundwater use data is available within GMUs (and also Unincorporated Areas) from licensed extraction bores, through (primarily) manual readings of the bore flow meter. Groundwater use data may also be collected from metered bores within UAs. There are numerous limitations associated with the metering of licensed bores in Victoria, for example, licences under 10 Megalitres (ML) in Southern Rural Water's (SRW) jurisdiction or 20 ML in Goulburn-Murray Water's (GMW) and Grampians Wimmera Mallee Water's (GWMW) jurisdictions, are not required to be metered, as it was historically considered not financially viable (DEECA, 2020a).
Input data: Groundwater use	For the majority of GMUs, annual use data is generally available from 2004 to 2021 (total use within a GMU). Groundwater use data (annual volume) for individual bores has a shorter record, being generally available from 2009 to 2021.
Input data: Groundwater use	For the majority of groundwater users, metered use is reported on an annual basis only (i.e., total annual volume in ML). The changing aspects of groundwater use across each GMU were not available on a monthly basis, owing to the annualised limitations in water use data mentioned previously.
Input data: Groundwater use	The metered use data for each GMU is reported collectively and not classified into its respective aquifer system layer or Suite.
Input data: Groundwater use	Entitlement information was not available prior to mid-2000s either on an annual or bore by bore basis, for most GMUs across the state.
Input data: Groundwater use	Supplied data contained anomalies. For example, in the dataset "Use_Ent_Perbore_VAF.shp" provided by DEECA, when the use per water year was tabulated, the Murrayville GMA and West Wimmera GMA showed little or no extraction in the water years 2009/10 and 2010/11 and little to no entitlement data. Thus the 2011/2012 entitlement dataset was used in hindcasted method 3.
Input data: Groundwater use	In the dataset "Use_Ent_Perbore_VAF.shp", GHD needed to update the associated GMU names in the field "Water_Syst" as they were using either old GMU names or were blank. This was done in the first instance by changing the name to the equivalent current GMU name. Where this was not a straight forward update, e.g., Katunga (GMU) to KATUNGA WSPA, then the spatial location information associated with the bore was used. It is noted that spatial location was the latter method adopted as some of the bores did not plot within the boundaries of the State of Victoria, e.g., some bores plotted in Bass Strait, thus it was assumed the previously assigned GMU was likely to be correct over the spatial information.
Input data: Groundwater use	GHD assumed that the bore names of the licenced data ("Use_Ent_Perbore_VAF.shp"), match those in the WMIS datasets ("GW_site_data.csv") and that associated completion dates are accurate.
Input data: Groundwater use	The licenced use per GMU was collated from the dataset "Use_Ent_Perbore_VAF.shp". It is noted that when the use per water year was tabulated, Murrayville GMA has little or no extraction in the water years 2009/10 and 2010/11. For these years, the GMU specific data set from file "Murrayville use 2016-2021.xlsx" was used.
Input data: Groundwater use	There are differences in the sum of groundwater extraction by GMU at the pilot bores when comparing the datasets. For annual data, the Victorian Water Accounts or RWC provided datasets (i.e., Murrayville GMA) is taken as the source of truth since these represent official government reported figures. However, for the spatial distribution analysis, the groundwater extraction data on a bore-by-bore basis is needed and thus another dataset had to be used. The differences between the datasets were generally minor.
Input data: Groundwater use	Groundwater use for Lower Murrumbidgee was not available by groundwater bore and thus couldn't be included in spatial distribution modelling.

Area of methodology	Limitation or assumption
Input data: Groundwater use	For dataset “Water Accounts to 2018.xlsx”, Lower Campaspe Valley WSPA doesn’t have data back to 2004 like the other GMUs.
Input data: Groundwater use	File “67441.csv”- no volume specified in dataset.
Input data: Groundwater use	For file “Tagged meter sites by date.kmz”, it is difficult to extract data from the KMZ file to obtain the spatial information plus the attributed data.
Input data: Groundwater use	Similar to “Use_Ent_Perbore_VAF.shp”, files “2009-2020 GW BEE-WRK Ent and Usage v1.xlsx”, “2009-2020GWStatewideAnnualUse.xlsx” and “Copy of SRW GW usage data.xlsx” also show: – Assigned GMUs are out of date or need updating to reflect the current GMUs – Spatial information and bore depth data missing The latter dataset also doesn’t have the transaction date correlating with the use date.
Input data: Groundwater use	It is unknown when extraction commenced at many GMUs. As such, extraction was hindcasted back to the start of the Suite hydrograph unless otherwise identified.
Input data: Groundwater use	The methods developed for hindcasting assume that there is a correlation between climate and groundwater use.
Input data: Groundwater use	It was assumed that using the two yearly average annual extraction data was a way of incorporating time lags into the modelling.
Input data: Aquifer extents	VAF data is associated to the licenced bore use locations to estimate usage by aquifer within a GMU. Layers are interpreted and may not be representative of actual conditions. This may influence margins of the aquifer where there could be a paucity of groundwater bores, i.e., groundwater users target the thicker, productive parts of an aquifer.
Selection of calibration models	The number of observed water levels and the range of water levels is not included in the model applicability ratings but is used to inform which is the preferred calibration model.
Input data: forecast use	The licenced bore data used in the spatial distribution method only has use data to 2019/2020. Thus, where the predictive modelling was based on a model with spatial distribution, the coverage of this dataset needed to be expanded to cover 2020/2021. For this, it was assumed that the percentage usage per bore in the year 2019/2020 was the same as 2020/2021.
Processing data: pre-development levels	For pre-development levels for GMUs where level data was not available prior to the known period of extraction, it was assumed that: – The earliest recorded annual recovered level data was representative of pre-development conditions – In the case where the maximum historic annual recovered level was not within the earliest part of the dataset, but occurred before the main period of development, this was the closest representation of the pre-development conditions
Processing data: drawdown-use relationships	Where the drawdown-use relationships varied significantly between each forecast scenario and all forecast scenarios were combined, it was assumed that adopting the relationship of all scenarios combined was more representative for that GMU.
Processing data: drawdown-use relationships	For some GMUs the extraction data used in the calibration models was only a small portion of the extraction data adopted in some of the forecast models. This could lead to low confidence estimates at higher volumes and skew the use-drawdown relationships developed.
Processing data: drawdown-use relationships	For some GMUs the adopted model incorporates extraction data external to the GMU (called “externalities”). To bring the results back to an extraction just related to the GMU, the average percentage of GMU extraction to combined GMU and externalities based on recorded data was calculated. This percentage was applied to the combined usage adopted in the modelling and incorporated into the use-drawdown graphs.

2. Background

2.1 Sustainable yield concepts

A nationally adopted definition of sustainable groundwater yield is:

"The groundwater extraction regime, measured over a specified planning timeframe, that allows acceptable levels of stress and protects dependent economic, social and environmental values" (National Groundwater Committee, Department of the Environment and Heritage, 2004).

This definition is a principle, and it does not provide the acceptable levels of stress that will protect economic, social and environmental values.

Effectively, the sustainable yield volume informs the allocation and management of groundwater resources by assessing groundwater availability and resource condition against sustainable yield metrics. To manage groundwater resources sustainably the assessed sustainable yield volume should maintain an equilibrium (in head or level) within the aquifer.

A summary of the historic context of PCV development in Victoria is provided in Appendix A.

2.2 Groundwater reform

In the 2010s, a revised groundwater management structure for Victoria was developed through the Secure Allocations, Future Entitlements (SAFE) project, funded by the Commonwealth Government. Groundwater management in Victoria significantly progressed through the SAFE project, which introduced management boundaries to cover all parts of the state, guidance for groundwater management decisions, including guidance on determining volumes of groundwater available for use.

The Victorian Aquifer Framework (VAF) was developed to provide a consistent approach to defining and naming the commonly accepted aquifers and aquitards that make up Victoria's groundwater systems, which had previously been classified by local stratigraphical relationships. The VAF provided a tiered approach to the definition of geological units, hydrogeological units and aquifers, as defined previously by GHD (2012). Using this framework, 3-dimension aquifer surfaces were developed through a consistent state-wide approach. The framework assists in the sustainable management of groundwater resources in Victoria and provides the basis for mapping aquifers and aquitards across the state.

2.3 Groundwater management arrangements

The principal management unit for groundwater resources in Victoria is the GMU. A GMU may be a GMA, a WSPA or an Unincorporated Area (UA). An UA is a region occurring outside of a GMA or WSPA. Of these administrative boundaries, only WSPAs are declared under the *Water Act 1989* (the Act), to ultimately provide sustainable management of groundwater resources.

A GMA represents an area where groundwater has been intensively developed or has the potential to be developed further. A local management plan is developed in a GMA to clearly document specific management objectives and describe water sharing arrangements that apply to all users in that area. Amendments to the boundaries of GMAs, and amalgamations of GMAs, have resulted as the scientific understanding of each area has improved over time.

A WSPA is similar to a GMA but relates to areas with a higher risk of groundwater resource impacts due to groundwater extraction. WSPAs must be declared by the Minister and a statutory groundwater management plan developed to define available resources, management objectives and specific rules such as seasonal restriction arrangements, limits on use, trading rules and carryover. The plan may also include caps or moratoriums on the issue of additional extraction licenses.

2.4 Confined aquifers

This study relates specifically to a selection of confined aquifers across Victoria. An aquifer is a geological formation or part of a formation, which contains sufficient saturated permeable material to transmit and yield significant quantities of water.

Aquifers fall within a spectrum ranging from confined to unconfined, with semi-confined being in between (refer Figure 1). There is no clear geological distinction between confined and unconfined aquifers. Confined aquifers are overlain by a confining bed, or low permeability geological layer, which prevents the direct infiltration of rainfall recharge into the aquifer. Potentiometric levels in confined aquifers may be influenced by the trend in water levels in overlying unconfined aquifers, the extent to which has been considered by others as variably significant (Harrington and Brown 2007; Barnett 2008). Changes in water table aquifer loading and unloading, for example through rainfall, evapotranspiration and pumping, leads to measurable changes to the hydrostatic pressure in the underlying confined aquifer. It is possible for both short-term (e.g., seasonal) fluctuations and longer term (e.g., interannual) trends in unconfined aquifer water levels to affect the pressure responses of underlying confined aquifers (Harrington and Cook, 2011).

Pressure in confined aquifers is generally greater than atmospheric pressure. If pressures are high enough in a confined aquifer, the head level may occur above the surface of the ground, resulting in artesian (or flowing) groundwater conditions. In a confined aquifer, when pressure is released, the aquifer is not dewatered (provided water levels remain above the top of the aquifer). Therefore, the aquifer saturated thickness is not reduced.

Owing to their significant depth and relative isolation from the atmosphere, much of the groundwater within confined aquifers can typically be considered ‘ancient’, originating during palaeo-climatic periods and/or during geological formation. Due to this separation from the water table, confined aquifers are not rapidly influenced by modern recharge processes. An exception to this is the intake zones of confined systems, where the aquifer confining beds are thin to absent, or there are shorter travel times for recharge to become groundwater.

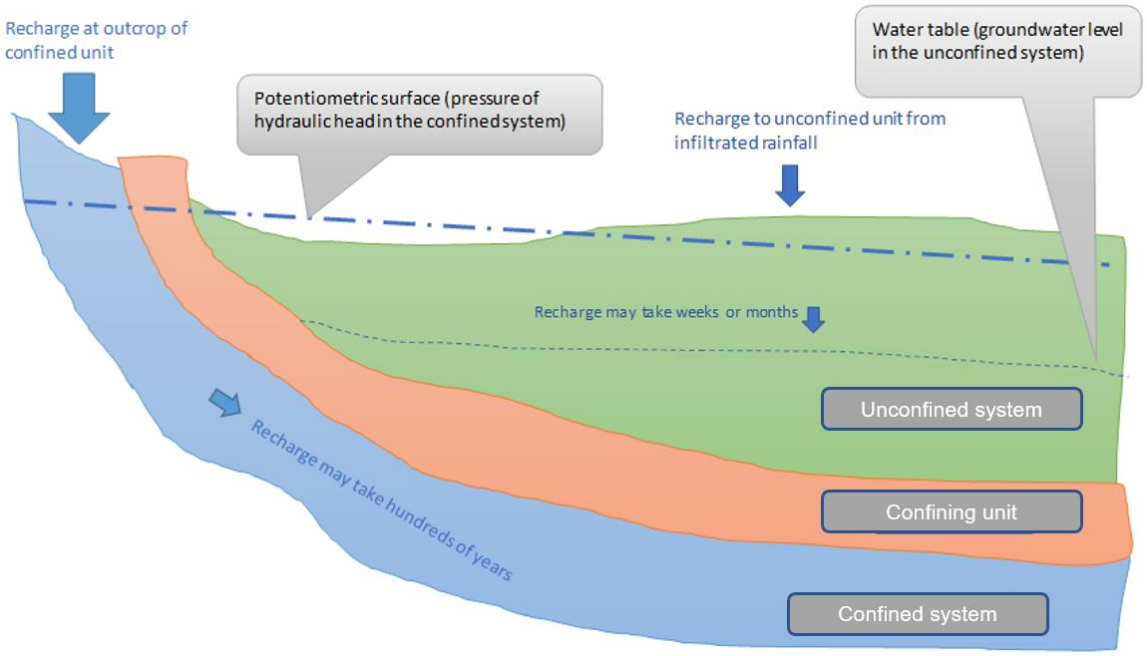


Figure 1 *Schematic of a typical aquifer setting*

Pumping causes a reduction in pressure in a confined system (assuming levels are maintained above the top of the aquifer), and therefore the reduction in water level reflects a change in the volume of water in the aquifer.

The magnitude of groundwater level drawdown as a result of abstractive use depends on the rate of discharge and also the spatial location with respect to the centre or zone of pumping. Greater drawdowns would occur at locations that are closer to the centre of pumping.

With reference to this study, drawdown refers to groundwater level decline or 'groundwater pressure fluctuation' caused by abstractive response. In a confined aquifer, groundwater level decline is generally in response to drawdown caused by (typically) seasonal pumping.

2.5 Storage conceptualisation

Groundwater storage can be significant in volume, but owing to various factors relating to its occurrence and flow characteristics, it can be difficult to quantify. To manage a resource, an understanding of ‘how much’ of the resource is available is required.

There are some aspects of groundwater that can be measured, and thus inform resource managers of the condition of the natural system, specifically:

- Groundwater use, i.e., how much is taken
- Change in groundwater levels (as a response to use)

In the context of this project, this ‘observation data’ is discussed below.

2.5.1 Groundwater use

Under the Act, licensed groundwater use points are metered and therefore the volume of groundwater take in an area is known each year. Stock and domestic bores are not metered as the volume of groundwater take from these bores is assumed to be small relative to licensed use.

On a state-wide scale, there is a clear relationship between annual rainfall and groundwater use. This relationship indicates that groundwater use generally increases during low rainfall periods, and generally decreases during higher (average or above average) rainfall periods.

The magnitude of groundwater use during dry periods will be driven by various factors across the state, including:

- Spatial and temporal variability of rainfall reductions
- Availability of alternative water sources such as surface water (allocations)
- Some areas, such as the arid western or north-western districts of Victoria have limited surface water availability and therefore groundwater is the main water source, irrelevant of climate trends
- In other areas, surface water may be the most easily accessible and the preferred lower-cost water source, and groundwater is only used when surface water supplies become scarce. These areas are more likely to see a greater increase in groundwater use during dry conditions.
- Increased water requirement for crops
- Capacity to access and extract greater groundwater volumes that may be allocated by not currently used

Regardless of whether abstraction from a system is just commencing in an area, or the confined aquifer is within a mature stage of development, groundwater levels in a confined aquifer will exhibit a seasonal response to pumping. This is because throughout Victoria, irrigation is the largest user of groundwater, and irrigation follows a seasonal pattern, with greater pumping during the drier months or growing season. Irrigation of agriculture continues to some extent irrespective of rainfall patterns. Therefore, further increases in irrigation water usage during droughts may not always be statistically significant when reviewing increases in entitlement on a GMU basis. Although many GMUs across Victoria are fully allocated, historical groundwater use in many cases remains low (i.e., <50%) compared to licensed allocations and the PCV.

Groundwater use for municipal (town) supply occurs throughout the year but there will be a trend to pump more during drier months, as more water is consumed, e.g., garden watering, with rainfall deficits. As surface water storages become less reliable (either during drought or during the irrigation season), there is also a shift to use groundwater. Conversely, during wetter years, there may be less reliance upon groundwater as storages are full and plant – soil moisture deficiencies are not as great.

Climate change effects such as drier than average autumn and spring seasons have already resulted in changes to the duration of the irrigation (and therefore pumping) season across Victoria (DEECA, 2020a). The typical pumping season in Victoria has broadly shifted from October to March to September to May, resulting in a longer period each year in which groundwater resources are required. This shift is somewhat dependent on local rainfall and evaporation, particularly seasonal rainfall during winter and spring, when evaporation is low. DEECA (2020a) has previously identified that summer rainfall does not necessarily reduce groundwater pumping requirements and that typically, use reduces as evaporation (and crop specific evapotranspiration) decreases.

2.5.2 Groundwater monitoring

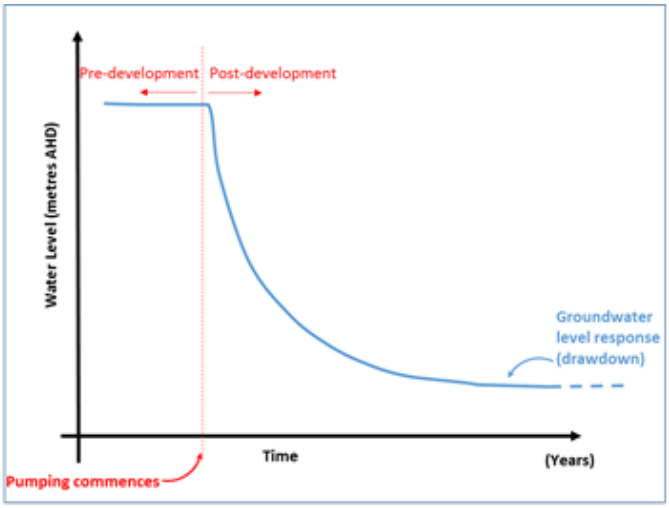
In addition to monitoring licensed abstractive take through metering and accounting of stock and domestic bore numbers, groundwater is also monitored through a state owned network of dedicated groundwater monitoring bores.

To understand the condition of groundwater resources throughout Victoria, with respect to established management arrangements, more than 1,400 State Observation Bore Network (SOBN) monitoring bores have been drilled, installed and monitored across the state, via the state's Groundwater Monitoring Contract.

As the resource manager, DEECA collects and manages groundwater monitoring data (primarily groundwater levels, pressure and quality) from these bores to report on the groundwater resource condition across the state.

GMAs and WSPAs have groundwater monitoring networks in place, typically focusing on measurement of groundwater level data at a minimum. The seasonal fluctuation of water levels results in greater drawdowns during the pumping season (represented as the deepest water levels on bore hydrographs), and recovery during the non-pumping season (represented as the shallowest water levels on bore hydrographs).

When a groundwater system is subject to abstractive pumping, the natural balance is disrupted by the stress imparted on the groundwater system.



When a bore or group of bores are pumped, groundwater is derived from storage around the bore(s), resulting in drawdown of groundwater levels as a response.

Previous studies completed by DEECA have shown that monitoring bores within the SOBN can exhibit the same underlying hydrograph response, whereby bores with similar hydrographs can be grouped together to form a 'Suite'. Through mapping the bore locations and applying some hydrogeological interpretation, a 'Suite area' can be defined and this is discussed further below.

2.6 Representative groundwater levels

2.6.1 Definition of Suites

It has been recognised by DEECA that many SOBN monitoring bore responses were similar and to this end, commissioned technical studies into the classification of hydrograph responses throughout the State. Suites of similar groundwater level responses have been defined previously (SKM, 2014) through the grouping of groundwater level trends measured through groundwater monitoring bores within the SOBN.

Owing to the statewide scale of this project, statistically representative spatial Suite data are favoured over bore specific groundwater level data to represent each GMU.

These Suites are described by a code, for example:

Aquifer Layer Monitored _ Suite Code _ Fluctuation code

The components of this code are described below:

- **Aquifer monitored** – The state has been divided into four logical aquifer system layers defined by regional geology and referred to as Upper (U), Middle (M), Lower (L) and Basement (B). It is noted that the VAF has been established by DEECA, and each aquifer within the VAF has been assigned to one of these specific layers. A Suite can only be found in one of the four aquifer system layers (U, M, L or B) as it corresponds to a particular hydrogeological unit (HGU) that has been assigned to a specific Aquifer Layer. A Suite may, however, be found in multiple areas within a particular aquifer system layer.
- **Suite code** – which is simply a lettered naming convention
- **Fluctuation code** – which is a numerical identifier that identifies bores with similar magnitude in seasonal fluctuations

For example, Suite *M_B_1*, represents a Suite in the middle aquifer system (i.e., middle Tertiary), which is designated a Suite code of 'B' and a fluctuation code of '1'.

The classification of bores into their respective monitoring Suites was undertaken previously (on a single occasion) through inspection of individual monitoring bore hydrographs, i.e., all 1,400 SOBN monitoring responses have been assigned a Suite code. The individual bores comprising each Suite have not been reviewed since 2014 and it has been assumed that the trend or form of the hydrograph has not changed significantly. Whilst GHD has previously suggested an approach to automatically classify bores into Suites, this is yet to be applied, and out of the scope of the current study.

For the purposes of this study, all Suites classified as outliers (classified 'OUT'), containing insufficient data (classified 'ID') or containing potential data quality issues (classified 'QD'), have been excluded from analysis and reporting outputs.

2.6.2 Suite hydrographs

Through statistical analysis, it is possible to combine like hydrograph responses into a single hydrograph, referred to as a 'Suite' hydrograph. Note that given that groundwater monitoring bores within any Suite are likely to show a range of groundwater elevations, Suite groundwater level data must be 'normalised' in order to provide a meaningful hydrograph output.

An average, maximum and minimum hydrograph can be determined, and through this, a single Suite hydrograph can be used to represent a much larger Suite area, providing benefits for rapidly assessing broad spatial areas. This process has been documented by GHD (2015), along with the spatial mapping of Suites.

Previous studies (GHD, 2015) also developed a Suite Hydrograph Tool, as a desktop-based platform to visualise Suite hydrograph data. Through subsequent studies (GHD, 2018), the Suite Hydrograph Tool was refined to enable the upload of groundwater level data directly from the DEECA WMIS, provisioning the update of Suite hydrographs.

2.6.3 Suite mapping

Suites were mapped (GHD, 2015) based upon hydrogeological interpretation, and applying a number of rules that were applied consistently across the state, including:

- Polygons were constructed around bores of the same Suite and group number
- Near the boundary of a group of bores with the same Suite code (and group number), an approximate buffer of approximately 20 km from each bore was applied. This distance was approximately based on visual examination of bore spacings throughout the aquifer system.
- Where the extent of the aquifer boundary was within this buffer distance, the boundary of the polygon was made near coincident with the aquifer boundary
- Where a bore had been labelled as QD, ID or OUT a smaller polygon was created around this bore, labelled with the same Suite and group number of the area surrounding this location
- In areas where there were no bores present, the polygon was labelled “ID”, indicating insufficient data. This occurred in areas where there were no bores within a distance approximately greater than 20 km. An exception to this rule was applied in the Mallee region of the state for those areas not subject to abstraction stress. In these areas, larger extrapolations were applied based on hydrogeological interpretation.
- Review against existing geological mapping to assess whether groupings made geological sense, resulting in modification of Suite polygons as required
- Review of mapping against licensed bore densities and regional understanding of extraction areas, resulting in modification of Suite polygons as required

2.6.4 Representative Suites

As described previously (GHD, 2018), there may be multiple Suites or multiple VAF layers covering a GMU. Suites are not GMU specific, nor necessarily aquifer specific, i.e., they can cover broad time-equivalent HGUs. Owing to this complexity, GHD (2018) previously established some key factors in selection of Suites to represent specific GMUs, including:

- The HGU where the bulk of the groundwater pumping (and therefore water level response) is occurring
- Suite representativeness, i.e., the proportion of a Suite that occurs within the GMU must be spatially significant
- Relevance of the Aquifer Layer, in terms of the VAF units that the GMU is intended to manage
- Spatial coverage of groundwater monitoring bores across a Suite or GMU
- Spatial coverage of groundwater extraction bores across the GMU
- Conceptualisation considerations such as improving the understanding of recharge processes, inter-aquifer connectivity or aquifer leakage

2.6.4.1 Rationale for adoption of representative Suites

This study has developed a rationale for the prioritisation and adoption of ‘Representative Suites’ for each GMU within this study. For the purpose of this study, this rationale overrides the previous (GHD, 2018) definition of ‘Representative Suite’ being the Suite with the highest proportion of coverage across a GMU. The process undertaken to identify representative Suites is summarised in Table 4.

Table 4 Summary of process to identify representative Suites

	Step 1	Step 2	Step 3
Description	There are generally multiple Suites that cover a GMU. These need to be identified along with key data to inform which Suite is likely most representative of the GMU. Collating this information in one place allows for a quick review of data and initial identification of likely representative Suite(s).	To identify the aquifer layer that has the majority of extraction occurring, data is then summarised by aquifer.	Due to some limitations to the dataset, association of licenced bores and their extraction volumes to a VAF layer and in turn Suite may not be possible. In some instances, these volumes make up a significant portion of usage within the GMU. In these instances, extraction needs to be re-assigned to an appropriate VAF Layer and or Suite.
Process	Filter and summarise all Suites in terms of extraction data, bore data and GMU.	Summarise extraction data by VAF Layer (Upper, Middle, Lower, Basement).	Review VAF Layer assignment for the average extraction summarised in Step 2, so that extraction aligns better with the extraction regime conceptualised. In particular, assign extraction to a Layer and Suite if currently unassigned.
Outcome	Ranking of Suites with 1 = most representative and blank if the Suite contains insufficient data.	Revised ranking of Suites with 1 = most representative and blank if the Suite contains insufficient data or is irrelevant to the confined GMU.	Revised ranking of Suites with 1 = most representative and blank if the Suite contains insufficient data or is irrelevant to the confined GMU. This represents the assigned Representative Suites (final outcomes) for each GMU.
Next step	Do not proceed to Step 2 if: – There are no other Suites identified in the GMU with extraction bores – There is insufficient data	Only proceed to Step 3 if: – There is a significant portion of usage that hasn't been assigned to a Suite or VAF layer – VAF layer assignment is not conceptually correct	

2.6.4.2 Suite prioritisation criteria

At each relevant step shown above, the identified representative Suites are ranked in terms of priority, with a value of '1' representing the highest priority. The ranking and prioritisation process applied to this analysis is based on the following order of criteria:

1. Volume of extraction; i.e., greater volumes are prioritised
2. Relevance of Suite; i.e., Suites that cover the intended aquifer/confined aquifer of GMU are prioritised
3. Spatial coverage; greater spatial coverage of a GMU is prioritised
4. SOBN bores; presence of active SOBN bores within the Suite area are prioritised
5. Whether Suite observation bores are close to extraction points

2.7 Groundwater assessment framework

A groundwater assessment framework has been developed previously for DEECA by Jacobs (2020a and 2020b) for application across the state. The framework incorporates a number of guiding principles to be routinely applied in groundwater assessments, including the below which are of most relevance to this study:

- Risk based
- Effort is commensurate with the risk
- Fit-for-purpose
- Gateway based progression
- Integration of policies within technical assessments
- Integration of existing guidelines
- Iterative
- Knowledge should be commensurate with system complexity
- Repeatable process
- Role of professional judgement in the assessment process
- Technical focus
- Uncertainty should be assessed and reported in a transparent way

To provide a consistent approach, this study conforms to the guiding principles and to the primary components of the framework, which are shown in Figure 2 in terms of how they have been implemented in GHD's method.

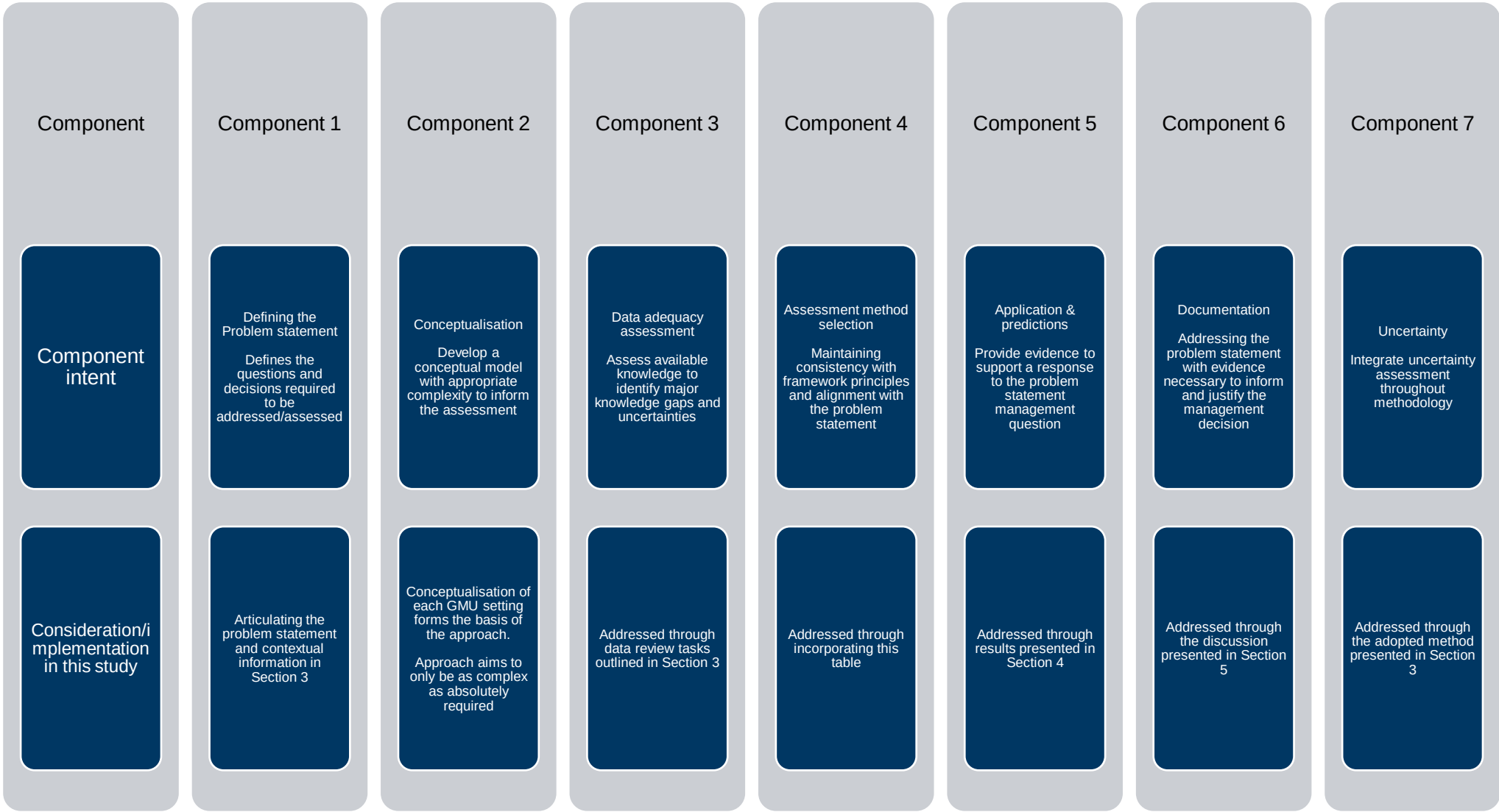


Figure 2 DEECA groundwater assessment framework

3. Method

3.1 Method overview

An overview of the method for Stage 2 of the project is shown in Figure 3. GHD's approach relies upon the use of time series modelling of SOBN data and groundwater abstraction data to predict future groundwater level responses. These responses can be converted into a metric to assess the condition of a confined aquifer.

Each of the steps in the GHD process are described in the sections below.

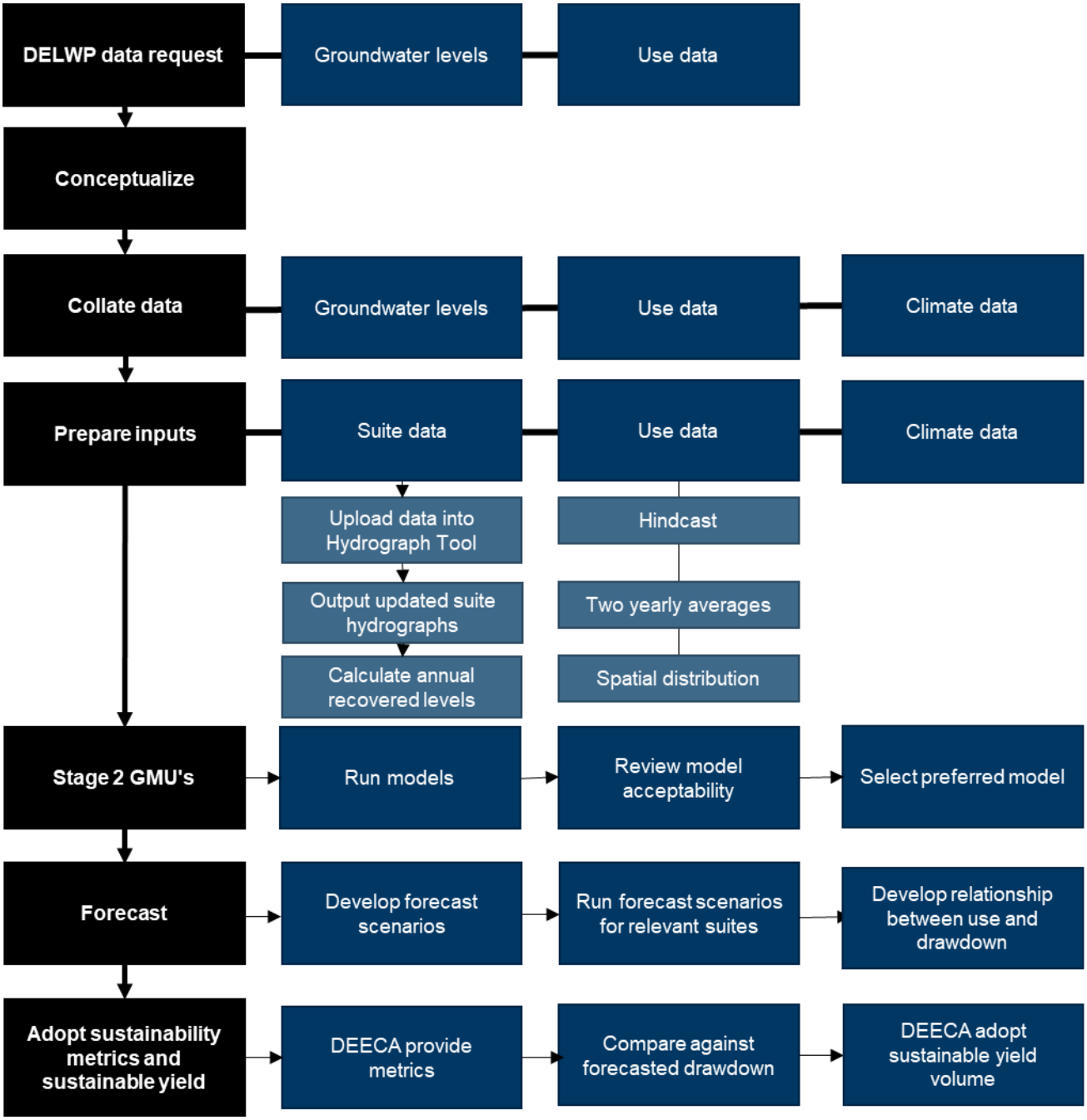


Figure 3 Overview of Stage 2 project methodology

3.2 Conceptualisation

Conceptualisation is required to compile information and data relating to each GMU that is relevant to estimating sustainable yield. The confinement of an aquifer covered by a GMU can vary depending upon the hydrogeological setting within a geological basin. The conceptualisation is important because the influences upon a hydrograph need to be understood so that these can be factored into the analysis. Some relevant conceptual elements include:

»Conceptualisation of the critical elements that govern the groundwater flow system in a GMU are key to this study. The various hydrostratigraphic, groundwater flow and groundwater use elements have been iteratively reviewed in the context of available data, model predictions and uncertainty«

- Likelihood of leakiness
- Selection of the most representative VAF layer
- Selection of the most representative Suite
- Understanding the various uses of groundwater across a GMU
- Understanding the temporal behaviour of groundwater pumping, e.g., town supply versus irrigation use
- Understanding the density of extraction and location with respect to the GMU monitoring network
- Understanding where the GMU can be physically developed, e.g., the likelihood of development on the margins of the GMU where an aquifer may thin (or be influenced by water quality)
- Understanding of the confinement status of the aquifer (i.e., is it fully confined in the GMU, semi-confined, or does it outcrop at the surface and become unconfined)

Unfortunately, there is no silver bullet or one size fits all solution. Conceptualisation is therefore an iterative process that constantly evolves as new data and information are available and the understanding of a groundwater system improves. Conceptualisation forms Component 2 of the DEECA groundwater assessment framework (refer Figure 2).

3.2.1 Semi-confined and transitional systems

In some instances, the GMU aquifer of interest is semi-confined, meaning the aquifer is partially overlain by a low permeability layer which allows some degree of interaction with overlying aquifer systems (i.e., there may be slow recharge or discharge to or from the GMU aquifer associated with overlying aquifers). During this study, if the aquifer of interest has been conceptualised as semi-confined, consideration has been made as to whether there is a need to incorporate climate into the modelling approach to represent a leaky aquifer system whereby some recharge is occurring.

In some instances, the confined aquifer may become unconfined (as depicted in the western margins of Figure 1), whereby a portion of the aquifer is directly recharged by rainfall. In these instances (i.e., a transitional aquifer system), the incorporation of recharge into the model was reviewed and considered.

3.2.2 Conceptualisation summaries

The hydrogeological conceptualisation elements relevant to this study for each of the relevant GMUs is presented in sections 7 to 31. The hydrogeological conceptualisation elements relevant to this study are summarised in the glossary of terms presented as Table 5 (the elements directly related to the modelling have been highlighted blue).

Data and information from numerous sources have been collated to develop the hydrogeological conceptual understanding of each GMU.

Table 5 Glossary of terms used in tabulated conceptualisations

Descriptive term	Explanation
Intended aquifer for GMU	The term 'intended aquifer' is used in this study to denote the aquifer(s) for which the GMU has been established. For most GMUs, the 'intended aquifer' tends to exhibit the greatest level of development. Therefore, the intended aquifer(s) require the resource management focus to ensure their sustainability. The intended aquifer(s) are identified by their stratigraphic name, VAF layer name and code (refer to SAFE reports). The intended aquifer largely coincides with the GMU depth limit.
GMU depth limit	Identifies the depth limitations of the GMU as obtained from the PCV Order Reports. However, some GMUs do not have a depth limit and are referred by aquifer name (e.g., Jan Juc GMA and West Wimmera GMA) or contour line reference (Paaratte GMA).
Confined status	Identifies the inferred confined status of the aquifer portion within the GMU, which could range from confined to unconfined, with semi-confined being in between.
Aquifer thickness within GMU	Identifies the aquifer thickness range of an aquifer within the boundaries of the GMU, based on the VAF data.
Aquifer extent	Aquifers can be defined as regionally extensive (e.g., Stratford GMA) or local (e.g., Jan Juc). While some aquifers may be regionally extensive, some GMUs are defined by only a portion of a broader aquifer system (e.g., Paaratte GMA covers a small portion of the regionally extensive LTA aquifer in south west Victoria).
Overlying aquitard/aquifer	Refers to aquitard or aquifer (identified by stratigraphic name, VAF layer and HGU code) that overlies the intended GMU aquifer.
Underlying aquitard/aquifer	Refers to aquitard or aquifer (identified by stratigraphic name, VAF layer and HGU code) that underlies the intended GMU aquifer.
Inferred inter-aquifer flow	Inferred potential for inter-aquifer leakage between intended aquifer and the overlying and/or underlying aquifer.
Inferred groundwater – surface water interaction	Inferred potential for inter-aquifer leakage between intended aquifer and surface water features or GDEs.
Representative Suite (s)	This is based on the process outlined in section 2.6.4.
Representative Suite trend	Based on the normalised Suite Hydrograph which is the statistically normalised trend incorporating all the relevant bores within the Representative Suite.
Groundwater quality	Average salinity based on WMIS and CDM Smith (2022) spatial segment(s) that have the highest spatial coverage across a GMU. Units are in milligrams per Litre (mg/L).
Groundwater yield	Based on data obtained from CDM Smith (2022). Units are in Litres per second (L/s), and data is based on spatial segment with highest coverage.
Number of active SOBN within GMU	Based on data provided by DEECA for bores screening the GMU intended aquifer.
Temporal groundwater level data range	Data range for the representative Suite hydrograph.
Spatial clustering of licensed bores in relation to Suites	Based on spatial analysis of the GMU, Suites and licenced bore location details to confirm whether bores are spatially clustered.
Licensed groundwater use (ML, based on average recorded historic extraction from the Victoria Water Accounts (VWA))	The average licenced groundwater usage based on historical metering data provided by DEECA from the VWA.
Minimum historic groundwater use (ML)	The minimum groundwater extraction within a water year based on historical metering data provided by DEECA from the VWA.
Maximum historic groundwater use (ML)	The maximum groundwater extraction within a water year based on historical metering data provided by DEECA from the VWA.
Entitlement (within the GMU Representative Suites) (ML)	The current (2020/21) licenced entitlement for the GMU based on entitlement data provided by DEECA.

Descriptive term	Explanation
Primary drivers of groundwater level variability	Inference of the primary influencer of groundwater level variability within a GMU. Consumptive licensed users are considered the primary drivers for confined aquifers. Consumptive users may include irrigators, industrial/commercial or urban users. Conceptual understanding of these uses is important as this information has been used to hindcast groundwater use data.
Secondary drivers of groundwater level variability	Inference of the secondary influencer of groundwater level variability within a GMU.
Groundwater use profile	Inference of the temporality of the various significant drivers of groundwater level variability across the GMU, specifically in terms of seasonality or consistency across the year. Inference of annual temporal groundwater use based on different consumptive user group such as irrigators, industrial/commercial or urban. This information is used to provide a conceptual hydrogeological understanding of usage throughout the year for a GMU.
External influences	Identifies if an influence outside of the GMU (other than another GMU) is likely to influence groundwater levels within the GMU.
Existing groundwater values	Groundwater values represent aspects of the environment that interact with, or rely on groundwater and that the Victorian community expect to be achieved and maintained. Groundwater values can relate to social, cultural and economic aspects and can be measured in terms of their sustainability through various indicators. Only consumptive groundwater values have been considered in this project, including: – Potable water supply – Licensed non-potable supply (irrigation, commercial, industrial) Groundwater values relating to non-consumptive values were not considered in the scope of this study. This summary has focused on those environmental values that have been identified as existing rather than potential.
Potential impact on values of groundwater	There are several potential impacts relevant to each GMU in maintaining groundwater values to be protected or maintained. The primary impact to consumptive user values considered in this study is declining water levels, which can be described as unsustainable pumping from a confined aquifer that could result in unsustainable decline in potentiometric surface, which could impact overall aquifer sustainability and availability for consumptive uses. Impacts such as water quality and aquifer integrity were not considered. The modelling undertaken through this study has been described previously (GHD, 2022 and as with any modelling approach, there are limitations. GHD's modelling approach focusses on groundwater level trends as an indicator of sustainability under a range of use scenarios and time periods. As such, the only risk to groundwater values that GHD's modelling approach can directly consider is that relating to declining water levels, as described above. However, changes in groundwater levels will influence the movement of groundwater and are associated with other risks, e.g., saltwater intrusion, flows supplying GDEs. The other risks to groundwater values outlined in this section are not able to be considered through GHD's modelling approach, but are summarised in our tabulated conceptualisations with the intent of highlighting the relevant risks specific to each GMU. Risk identification is a key aspect in developing sustainable yield estimates and adopting sustainability metrics.
Indicators of potential impact on values	Indicators have been used to consider potential impact to consumptive user values based on Suite trend analysis. The key indicator is the predicted drawdown level with respect to pre-development period that can be measured through GHD's method for estimating sustainable yield is the potentiometric surface measured from the top of aquifer.

3.3 Data review and preparation

This task involved the collation and processing of datasets, many of which would form the basis for this study. The first stage of the GHD approach relies upon time series modelling to develop a relationship between drawdown and use in a GMU. At this stage, a number of inputs are required for the time series modelling:

- Groundwater levels:
  - Raw data from SOBN to update the Suite hydrographs
  - Location of the SOBN
- Licensed groundwater use
  - Annual volumes
  - Location of take and use points
- Climate (rainfall and evaporation)

The critical input parameters for this study are groundwater levels and groundwater use data.

The limitations of this data are described in section 1.8. To address these limitations, and to support the time series modelling, pre-processing of the data was required, as described in the sections below.

3.3.1 Groundwater data availability

A key DEECA project requirement was to develop an approach that relies upon real (measured) data. Examples of data types that GHD has incorporated into its approach for sustainable yield estimation are summarised in Table 6, along with comments regarding the data limitations and the resultant uncertainties considered in this process. A detailed list of the data limitations and assumptions is provided in section 1.8. Assessing the adequacy of data is part of Component 3 of DEECA's groundwater assessment framework (refer Figure 2).

Table 6 Examples of data limitations and uncertainties

Data type	Data source	Use	Limitation	Uncertainty
Climate	SILO	GHD relied upon climate data to estimate relationships between groundwater use and climate (e.g., hindcasting use data).	SILO uses mathematical interpolation techniques to construct spatial grids and infill gaps in time series datasets.	Uncertainties are introduced through the use of interpolated data.
Groundwater use	Water register	Time series water use information. GHD required point of use data to estimate spatial use densities on time-series water level responses.	The location of licensed users is based upon co-ordinates registered on the WMIS/Water Register. Bore specific entitlement data is generally not available pre-2009.	There are some obvious errors in the location data, e.g., some licensed users plot in the ocean etc. However, overall, this is considered to be a small proportion of the total number.
Groundwater levels	WMIS (SOBN)	Time series water level information forms a key input into the method.	Individual bore data does not provide for an efficient approach to catchment-scale analysis. SOBN is focused on the GMUs and developed areas. Limited monitoring exists in UAs, or on the margins of the GMUs.	To simplify the volume of monitoring data, spatial Suites have been developed. Additionally, a Suite hydrograph has also been developed. The Suite hydrograph provides an averaged water level response and therefore this simplification introduces uncertainties. Further uncertainty applies in mapping the area where the Suites, and Suite hydrograph are considered to apply. There may be areas of a GMU that are not covered by a Suite.

Data type	Data source	Use	Limitation	Uncertainty
				The water level response in individual bores constituting a Suite may change over time and thus the Suites themselves may need to be periodically reviewed. Monitoring bore condition can also affect the water level response.
Aquifer extent and saturated thickness	VAF	Association to the licenced bore use locations to estimate usage by aquifer within a GMU.	Layer is interpreted and may not be representative of actual conditions.	Margins of the aquifer where there could be a paucity of groundwater bores, i.e., groundwater users target the thicker, productive parts of an aquifer.

These data gaps and uncertainties can translate into issues when undertaking modelling of a groundwater system, on a GMU basis. This can translate to uncertainty in cause and effect relationships, i.e., how a system responds to a given stress through groundwater pumping or changes to recharge processes (with leakage from overlying systems being the predominant form of recharge relevant to confined aquifers).

The response of aquifers to specific conditions may not be known until a system is stressed. In the absence of a stress event, e.g., a severe drought, stress testing may need to be modelled, once a best fit between time-series groundwater level and use data is understood within a GMU.

The modelling approach adopted in this study correlates historic groundwater use stresses with groundwater level responses. Once an acceptable correlation is achieved, the model is used to predict future groundwater level responses under a range of simulated conditions.

This study focuses on the relationship between groundwater use and drawdown, as the fundamental measure for resource sustainability. This concept is tested through empirical relationships (theoretical vs actual) that consider factors such as use trends, leakage (recharge) and the spatial variability in the influence of groundwater pumping

Through various iterations applied to relevant parameters and data types (Table 6), and iterative update of the GMU specific conceptual models, various predictive scenarios were developed and tested to improve the technical assessments of groundwater sustainable yields.

The following section overviews GHD's approach to improving the technical assessments of groundwater sustainable yields for selected confined GMUs.

3.3.2 Climate data

Climate data was obtained from SILO for each of the pilot GMUs. Climate data was extracted based on the closest SILO point data set to the GMU centroid. Thus, each GMU has an associated climate dataset. The climate data, specifically rainfall and evaporation was aggregated on an annual basis by water year for input into the model if required.

3.3.3 Groundwater levels data

DEECA provided multiple groundwater level data sets, some of which required processing or manipulation in preparation for model input. The primary steps in this process are outlined below, with further detail on each step provided in Appendix C:

- Initial processing and cleaning
- Outlier removal
- Final preparation of data (pre-processing including mapping of columns to match Data Upload Tool requirements, undertaking QA checks and collating into a single csv file)

- Installation of the existing DEPI Data Upload Tool (an add-in to the DEPI Hydrograph Tool, which allows for the update of Suite hydrographs based on the previous assignment of SOBN to Suite groupings)
- GMU hydrograph summarisation

In the tender document RFT T2001-0334, DEECA provided an example trial to determine a relationship between yield and drawdown, and this approach relied upon using the annual recovered water level, i.e., the maximum water level measured after the seasonal water level low point (Figure 4).

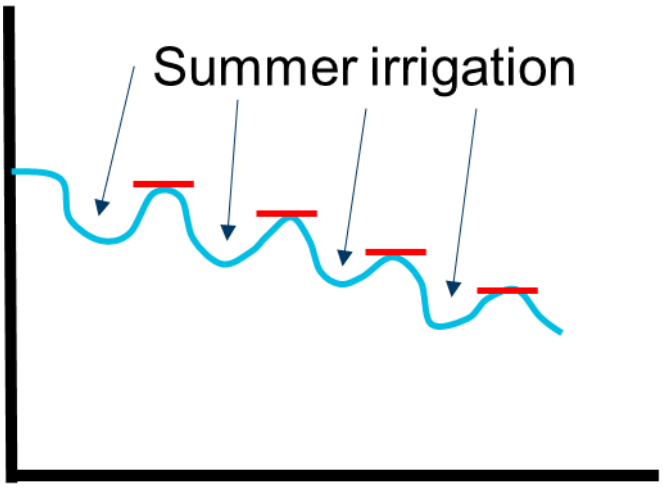


Figure 4 Seasonal groundwater level variation due to irrigation

The recovered water level therefore represents the 'available drawdown' leading into the forthcoming groundwater pumping season. To determine the annual recovered water level, GHD took the maximum water level for a given Suite for each water year. This maximum water level was considered to represent the recovered water level and attributed to the date in which the observed maximum reading has occurred. It is noted that the recovered annual level in one water year is likely to be related to the extraction that occurred in the previous water year. All annual recovered levels cited in this report are normalised levels based on the Suites.

GHD considered variations on the raw water level time series, including the use of annual average water levels, and annual recovered water levels during the Stage 1 Pilot Study. Based on instruction from DEECA, GHD undertook Stage 2 of this study using annual recovered levels.

3.3.3.1 Pre-development levels

In order to calculate the drawdowns from the modelling recovered water level data, the first step was to define the pre-development level for each GMU. To estimate the pre-development level conditions, GHD reviewed the normalised Suite hydrographs of annual recovered levels and assumed that generally the early time data was the best representation of conditions prior to major development within a particular GMU. This early time series data was adopted as the baseline of pre-development conditions. There are exceptions to this, where the maximum annual recovered levels was adopted to capture the main period of drawdown.

The definition of each pre-development for each Suite within a GMU has been defined in each of the GMU chapters, considering its importance when evaluating forecast results against DEECA drawdown metrics (refer section 3.6).

3.3.4 Groundwater use data

3.3.4.1 Overview

The advent of groundwater development (extraction) applies a stress upon the aquifer system and causes a change (reduction) in water levels, which is superimposed upon any climate response. In a confined system, remote from the aquifer intake area (and ignoring leakage from stresses above or below the confined aquifer), water levels are influenced only by groundwater take. Therefore, the TFN model requires an understanding of the time series groundwater use.

3.3.4.2 Analysis and refinement of use data

Groundwater use data availability varies for each GMU. Generally, metering data is available from the VWA from 2004/2005 onwards, as metering of use became a common practice circa 2004. Metered use data was generally available from 2004 (or earlier) onwards on a GMU basis, and from 2009 onwards on a bore-by-bore basis. From the available datasets, a historical dataset of use for each GMU is collated on an annual basis.

The Suite hydrograph data generally commences at an earlier date than the available groundwater use data, as SOBN monitoring bore data extends back to the late 1960s/early 1970s in some parts of the state. Thus, the groundwater use data needs to be extended back to this earlier date, as extraction is one of the main stressors that effect groundwater level change. To do this, methods were developed to hindcast (or retrospectively fit) the data against recorded use data, the outputs of which were trialled in the modelling.

The Suite hydrographs also show seasonal variability as groundwater extraction can vary seasonally depending on the types of groundwater use. Methods were developed and trialled as part of the Stage 1 Pilot Study, however under direction from DEECA this refinement of groundwater use has not been investigated further as part of this Stage 2 study.

Another aspect of groundwater extraction that may influence the Suite hydrograph response is the spatial distribution of groundwater extraction. Suite hydrograph bores located in areas of higher extraction may show greater responses in the hydrograph than those located further away from groundwater extraction within a GMU. To account for this, methods were developed to account for the spatial distribution of groundwater use, the outputs of which were trialled in the modelling. Three of these methods were adopted as part of Stage 2 (refer to the Stage 1 report for the reasoning for not progressing the other methods).

For some GMUs, the potential impact of groundwater extraction beyond the GMU boundaries within neighbouring states or offshore may affect groundwater trends within the GMU. This potential external factor has been considered during conceptualisation of each GMU and where relevant, additional data was provided by DEECA and incorporated into the modelling.

3.3.4.3 Compilation of metering data

Groundwater use data was provided by DEECA in various formats and sources. Table 7 summaries the datasets received and how the use data was attributed (for example to a GMU or to a bore location). These datasets were collated into a single summary table to view all available data in one location.

Table 7 Summary of use data received

Data set	Data custodian	Use data attributed by
Murrayville use 2016-2021.xlsx	GWMW	Bore location
Murrayville use 2006-2021 by bore location-historicalUse.xlsx	GWMW	Bore location
Telopea downs use.xlsx	GWMW	Bore location
Water Accounts to 2018.xlsx	DEECA	GMU
2009-2020GWStatewideAnnualUse.xlsx	DEECA	Bore location
2009-2020 GW BEE-WRK Ent and Usage v1.xlsx	DEECA	Water authority and GMU
AMR_SRW data.xlsx	SRW	Bore location
Monthly records- Latrobe Mines GW Extraction.xlsx	DEECA	Mine location (Hazelwood, Loy Yang or Yallourn)
KWR Background Paper Final -SKM.pdf	DEECA	GMU
Use_Ent_Perbore_VAF.shp	DEECA	Bore location
SKM 2010, eco-Markets, Glenelg Hopkins GW model development report	SKM	GMU (Condah WSPA)
bd use data 1sb.xlsx	DEECA	Bore location (Gerangamete GMA)
Bore entitlements.xlsx	DEECA	Bore location (Gerangamete GMA)

Data set	Data custodian	Use data attributed by
Attachment 3 – Copy of KATUNGA GROUNDWATER USE AND LEVEL CHART FOR KATUNGA 2016 (A2759785).XLSX	GMW	GMU
SKM 2009 West Wimmera Hydrogeological Study (2007/08) Report	SKM	GMU
Lower Murrumbidgee Groundwater Source extraction data: **https://www.industry.nsw.gov.au/water/allocations-availability/water-accounting/usage-dashboard**	NSW Department of Planning and Environment	GMU
Vgdatarequest.xlsx	SA Department for Environment and Water	Bore location
Offshore extraction	DEECA	Bore location
VWA_GMU-data.xlsx	DEECA	GMU
reported use border zone.xlsx	DEECA	Zone

The annual VWA data was considered the most reliable data. Where gaps in this data existed, they were infilled using the other available datasets such as raw GMU specific data from RWCs. An example of this is Katunga WSPA, where GMW provided use data on a GMU basis from 1992. There is one exception to where data provided from RWCs was used instead of the VWA – for Murrayville GMA, where it was identified during testing after the Stage 1 Pilot that this data produced better model results and was more likely reflective of actual usage (refer to GHD 2023 technical memo on externalities in Appendix D). A summary of the groundwater extraction data sources that were used as input into the models is summarised in Table 8.

Table 8 List of data sources used for annual extraction model input

GMU	Data sources
Condah WSPA	SKM 2010, eco-Markets, Glenelg Hopkins GW model development (1989 – 2000) VWA (2004 – 2021)
Corinella GMA	VWA (2005 – 2021)
Cut Paw Paw GMA	VWA (2004 – 2021)
Frankston GMA	VWA (2004 – 2021)
Gellibrand GMA	VWA (2004 – 2021)
Gerangamete GMA	Extraction spreadsheets provided from DEECA (1982 – 2005) VWA (2004 – 2021)
Giffard GMA	VWA (2004 – 2021)
Glenelg WSPA	VWA (2004 – 2021) For external influence of border zone extraction: border zones 1A and 2A: DEECA (2006 - 2021)
Jan Juc GMA	VWA (2004 – 2021)
Katunga WSPA	GMW provided data (1992 – 2004) VWA (2004 – 2021) For external influence of Lower Murrumbidgee Groundwater Sources: NSW Department of Planning and Environment (2006 – 2021)
Koo Wee Rup WSPA	KWR Background Paper Final -SKM (1974 – 2004) VWA (2004 – 2021)
Lower Campaspe Valley WSPA	VWA (2010 – 2021)
Mid Loddon GMA	VWA (2004 – 2021)
Moe GMA	VWA (2006 – 2021)
Moorabbin GMA	VWA (2006 – 2021)

GMU	Data sources
Murrayville GMA	GWMW provided data (1995 – 2021) For external influence of Mallee Prescribed Wells Area: SA Department for Environment and Water (2004 – 2021)
Newlingrook GMA	VWA (2006 – 2021)
Orbost GMA	VWA (2004 – 2021)
Paaratte GMA	VWA (2009 – 2021)
Portland GMA	VWA (2006 – 2021)
Rosedale GMA	VWA (2004 – 2021) For external influence of Latrobe Valley Mines: DEECA (2004 – 2021) For external influence of offshore pumping: DEECA (2004 – 2021)
Sale WSPA	VWA (2004 – 2021) For external influence of Latrobe Valley Mines: DEECA (2004 – 2021)
Stratford GMA	VWA (2004 – 2021) For external influence of Latrobe Valley Mines: DEECA (2004 – 2021) For external influence of offshore pumping: DEECA (2004 – 2021)
West Wimmera GMA	SKM 2009 West Wimmera Hydrogeological Study (2007/08) VWA (2009 – 2021) For external influence of border zone extraction: border zones 4A to 10A: DEECA (2007, 2008 – 2021)
Yarram WSPA	VWA (2004 – 2021) For external influence of offshore pumping: DEECA (2004 – 2021)

The collated annual extraction data was further processed to undergo **hindcasting**. In the absence of pre 2004 extraction data (when the VWA datasets commenced), the use time-series had to be generated for earlier periods through hindcasting. The methods for this process are described further in the following sections.

3.3.4.4 Apportioning of groundwater use data

Spatial analysis was undertaken to apportion use to the relevant Suite. This was undertaken through:

- Using the DEECA 'Licenced Bore (ML)' spatial dataset, which identifies individual licensed bores and entitlements
- Overlaying the Suite layers to the 'Licenced Bore (ML)' spatial dataset
- Calculating the proportion of licensed use (ML) per Suite based on spatial location

This process helped to understand the spatial and aquifer specific nature of extractive use across a GMU which in turn informed the representative Suite for the GMU. It is noted that the apportioned data was not specifically used in the modelling.

3.3.4.5 Hindcasting of groundwater use data

3.3.4.5.1 Background

Many of the metered use datasets provided by DEECA have a time series extending between 2004/2005 and 2020/2021. From an individual bore basis, many annual records are only available from 2009/2010 to 2019/2020. This is not unexpected, as metering of licenced bores commenced in the early 2000s.

However, the water level time series (Suite hydrograph), which forms an input to the TFN model, in most cases extends over a much longer time period. In some cases, SOBN data extends as far back as the late 1960s.

This presents an issue for the TFN modelling as:

- It is preferrable to calibrate (match) to as much of the available water level time series as possible
- By excluding early time pumping stress, the dynamic modelling of the TFN may not fit as well to the early time water level time series (refer Figure 5)

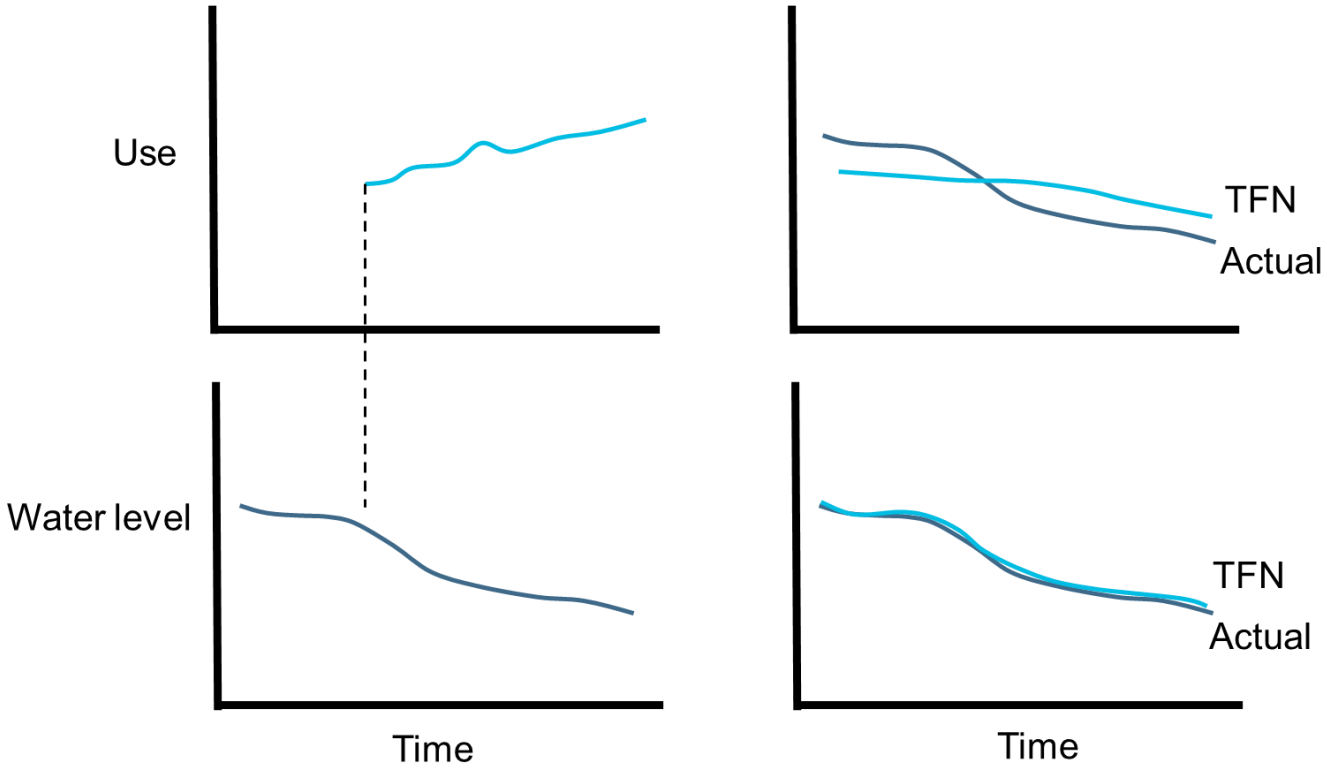


Figure 5 The need to consider early pumping stress on a system

To improve the fit of the TFN model to the entire Suite hydrograph, hindcasting of the annual extraction data was required.

3.3.4.5.2 Literature review on hindcasting

Initially, a review was undertaken to identify precedents or examples in the use of groundwater use hindcasting. One such example was identified by way of the Ovens Valley Groundwater Modelling (GHD 2012) undertaken for GMW. The hindcasting principles adopted in that project were reviewed and considered in the current study. The primary steps adopted for the Ovens Valley modelling are summarised below:

- Collate the history of use for each extraction bore (and each licence type, i.e., urban, irrigation, etc.)
- Identify the crop type for irrigation (if available)
- Establish a relationship between use and climate, e.g., proportion of entitlement pumped in a dry year versus a wetter year etc.
- Establish a relationship for the different crop types
- For time periods with data gaps:
  - estimate the climate
  - apply the 'relationship' to fill in the blanks (or replace the hindcast data where actual use data exists)
- For bores with no data, use the relationship developed for the bore type, e.g., calculate average use of all the irrigation bores, apply this to the irrigation bore that has no data, applying the seasonal factor

3.3.4.5.3 Conceptualisation of historic use

There can be many drivers for the development of groundwater. For example:

– Drought can result in a shift for insecure surface water to groundwater, or greater groundwater development
– Changes in groundwater management, e.g., the release of additional water under the PCV, or trading
– Changes in surface water management and access to secure volumes
– Identification of a highly productive area within an existing GMU that previously had limited groundwater development

3.3.4.5.4 Hindcasting methodology

To improve the fit of the TFN model to the entire Suite hydrograph, hindcasting of the annual extraction data was required. The process undertaken to hindcast the extraction data for this study was based on the literature review findings and conceptualisation outlined in the previous section, which has been synthesised into the three steps outlined in Figure 6 and discussed further below.



Figure 6 Hindcasting process

Step 1 – Identify any use trends from extraction data

The annual extraction data between 2004 and 2021 was plotted for each of the Pilot GMUs to be assessed. A linear line of best fit was applied to each graph to assess whether there was a simple linear trend that could be applied. In most instances, there was not an obvious linear trend that could be used to hindcast the extraction data and this led to other approaches being developed. Three methods were developed for hindcasting as summarised below.

Method H1: Relationship between use and rainfall

The most likely driver of changes in groundwater use is expected to be climate, particularly for the GMUs where irrigation is the predominant use of groundwater. Therefore, GHD undertook an initial review of annual licenced use and compared this to the annual rainfall. This indicated that generally groundwater extraction volumes on a yearly basis were linked to climate (specifically rainfall), by which greater groundwater extraction occurs during drier periods and less extraction during wet periods. This correlation is discussed with DEECA's Groundwater Use Catalogue (refer to discussion on limitations in 'groundwater use' section 1.8 of this report).

A summary of this method is as follows:

1. Plot annual use for a GMU against rainfall (where rainfall data is obtained from the closest grid point in SILO, based on the GMU centroid) for each GMU (refer to Figure 7 for an example for Katunga WSPA)
2. Find the line of best fit for each plot, noting that the type of line of best fit may vary by GMU and could include:
    a. Annual use or two yearly average annual use or irrigation use versus annual rainfall
    b. Annual use or two yearly average annual use or irrigation use versus two yearly average rainfall
    c. Annual use or two yearly average annual use or irrigation use versus rainfall over irrigation period (October to March)
    d. Annual use or two yearly average annual use or irrigation use versus rainfall over summer period (January to April)

    Refer to Figure 8 for an example of 2a, 2b, 2c and 2d for Katunga WSPA with annual rainfall.

2. Use this 'line of best fit' relationship to hindcast the extraction data (for Figure 8, this would be the correlation with two yearly annual average rainfall)
3. Check acceptability of hindcast dataset by comparing hindcasted dataset to the recorded annual use dataset for that GMU (refer to Figure 17 for an example using Katunga WSPA)

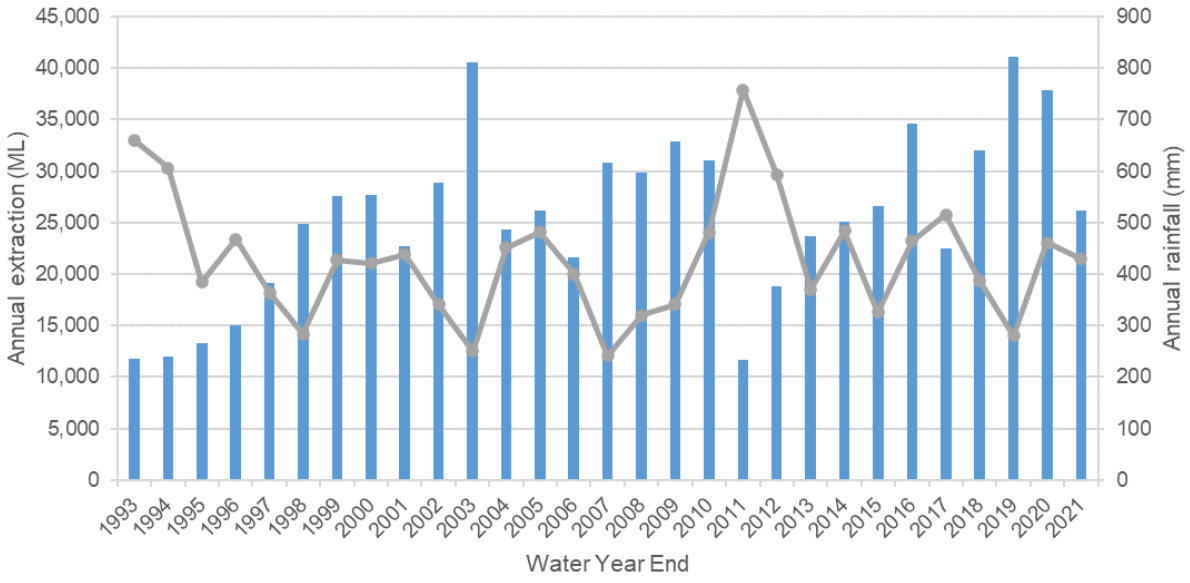


Figure 7 *Katunga WSPA - annual use and annual rainfall plot*

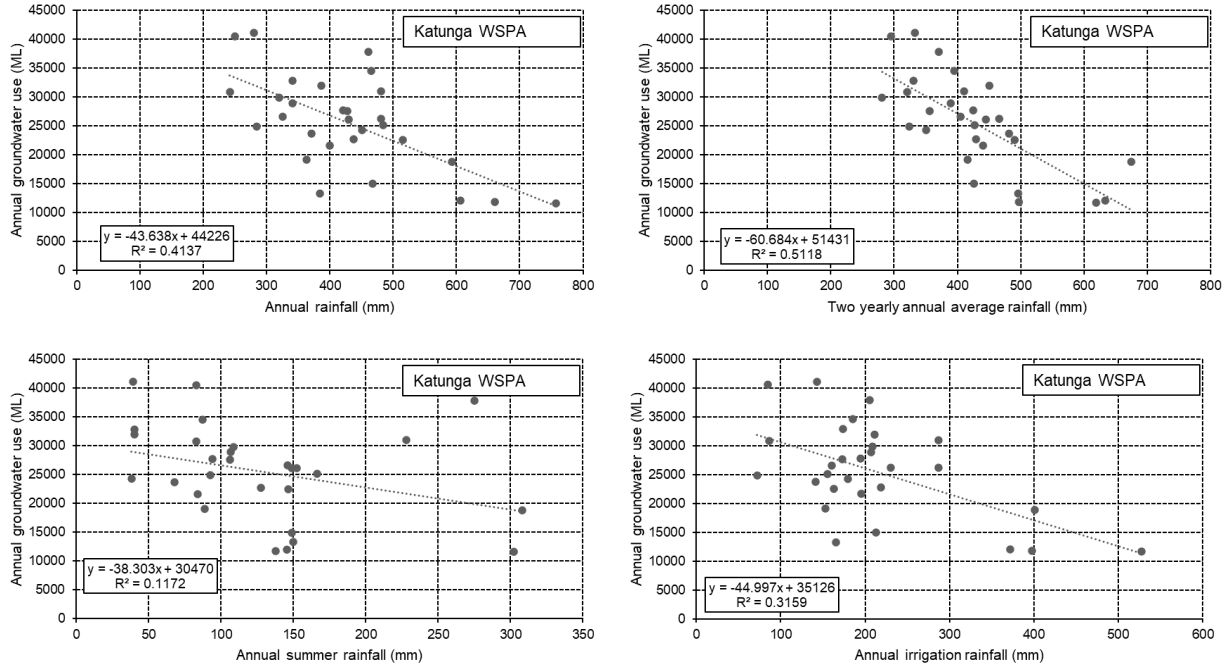


Figure 8 *Katunga WSPA – plots of annual groundwater use with various rainfall datasets*

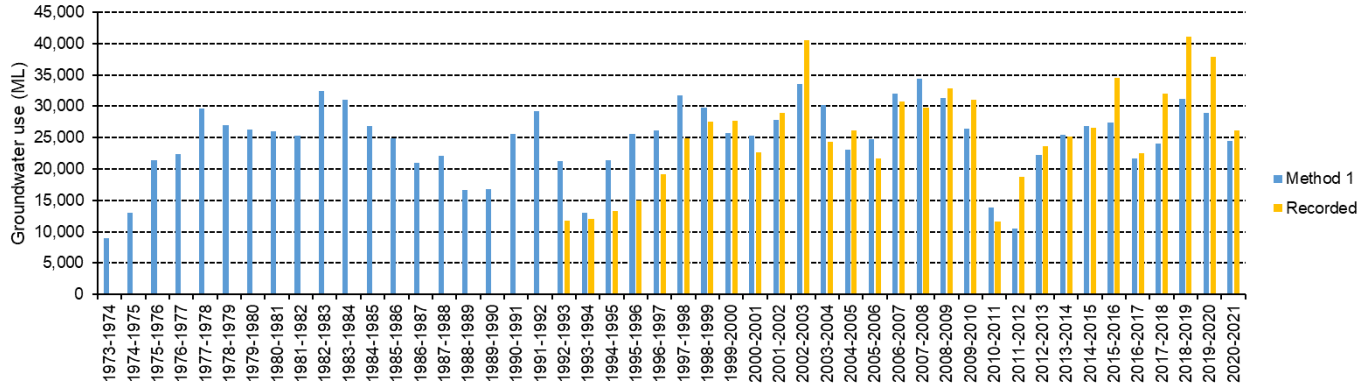


Figure 9 *Katunga WSPA – Method 1: Hindcasted data comparison*

Method H2: Combining method H1 with bore age considerations

In addition to the correlation discussed previously between climate and groundwater use, another factor to consider when hindcasting groundwater use data is the number of licenced bores in the GMU each year. It is a reasonable expectation that the number of licenced bores in Victoria would have increased with time as farmers seek to maximise the economic gain from their landholding, or the population or urban centres increases. This is another factor, in addition to rainfall that could have influenced the volume of groundwater historically pumped from a GMU.

A summary of this method is as follows:

1. Compile list of licenced bores for each GMU and their completion dates based on WMIS data
2. Plot number of bores over time to back-estimate a growth factor and incorporate licenced use
3. Develop a relationship to hindcast using climate trend and growth factor
4. Hindcast based on this method and compare results

DEECA provided a dataset "*Use_Ent_Perbore_VAF.shp*" of the licenced bores in Victoria and their associated use between 2009 and 2020. From this dataset, GHD updated the associated GMU names in the field "Water_Syst". This was done in the first instance by changing the name to the equivalent current GMU name, where this was not a straight forward update, e.g., Katunga (GMU) to KATUNGA WSPA, then the spatial location information associated with the bore was used. It is noted that spatial location was the latter method adopted as some of the bores did not plot within the boundaries of the State of Victoria, e.g., some bores plotted in Bass Strait, thus it was assumed the previously assigned GMU was likely to be correct over the spatial information.

Once the GMU names were updated, completion dates were associated with the licenced bore location where possible. GHD used the file *"GW_site_data.csv"* available from WMIS to obtain the completion dates. It is noted that not all bores in the "*Use_Ent_Perbore_VAF.shp"* file appeared in the "*GW_site_data.csv"* file. The completion date was then converted into the relevant water year in order to associate the bore to a use year (as a water use year is reported on a water year basis). Using this information, the cumulative number of bores in the GMU each year could be estimated (Figure 10 shows an example from the Pilot GMUs).

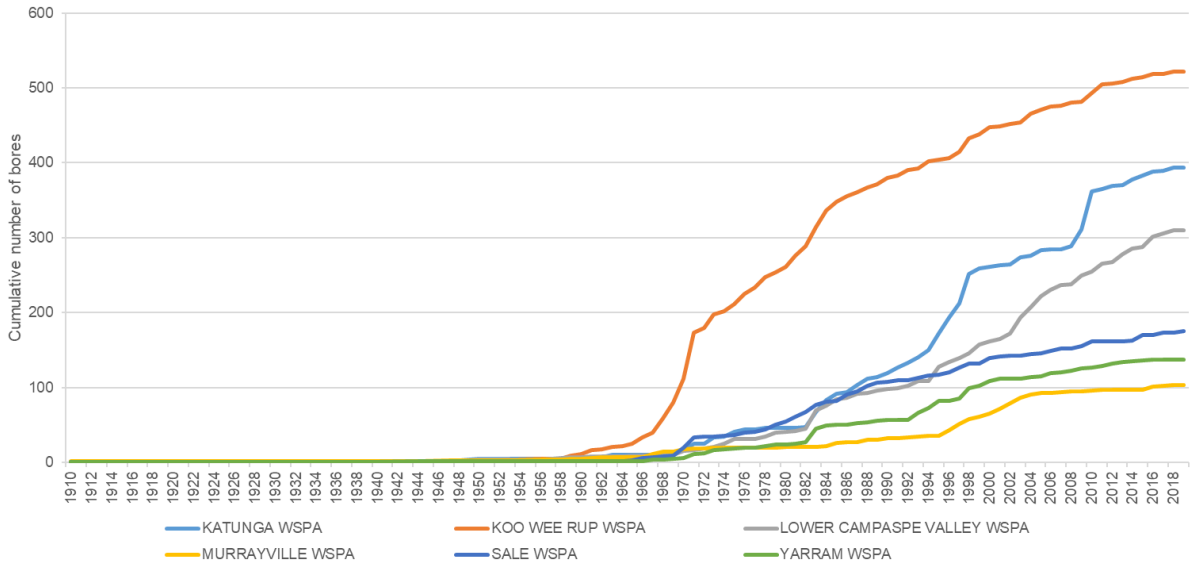


Figure 10 ***Cumulative number of licenced extraction bores in the Pilot GMUs***

The licenced use per GMU was collated from the dataset "*Use_Ent_Perbore_VAF.shp".* It is noted that when the use per water year was tabulated, Murrayville GMA has little or no extraction in the water years 2009/10 and 2010/11. For these years, the GMU specific data set from file "*murrayville use 2016-2021.xlsx*" was used.

Using the licenced annual usage collated from file "*Use_Ent_Perbore_VAF.shp"* and the cumulative number of bores per year, the licenced use per bore could be calculated for the years 2009-2019.

Plots were constructed of the rainfall (annual, annual of average two yearly, annual irrigation rainfall, annual summer rainfall) against the licenced use per bore and a linear line of best fit was applied to estimate the relationship between these two factors. An example is shown in Figure 11 for Katunga WSPA using the two yearly average annual rainfall dataset.

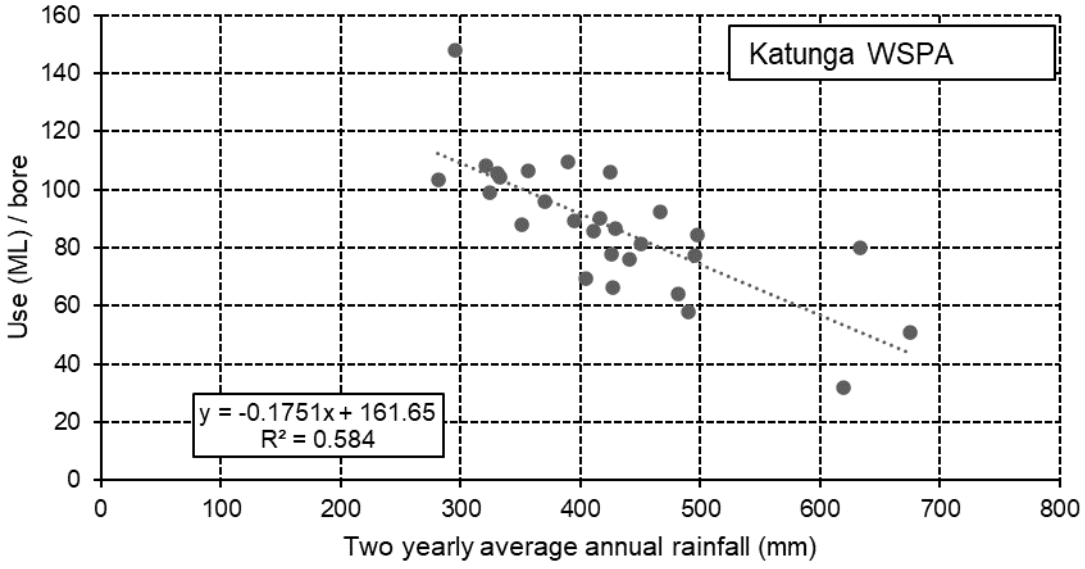


Figure 11 ***Katunga WSPA: two yearly average annual rainfall versus use per bore***

Based on this method, the calculation to estimate annual usage for a given year becomes:

Annual usage = (trendline equation) x cumulative number of bores

It is noted that in the trendline equation from the regressions, the x input factor is the rainfall data for a given water year.

The acceptability of the hindcast dataset was checked by comparing hindcasted dataset to the recorded annual use dataset for that GMU (an example is shown in Figure 12 for Katunga WSPA).

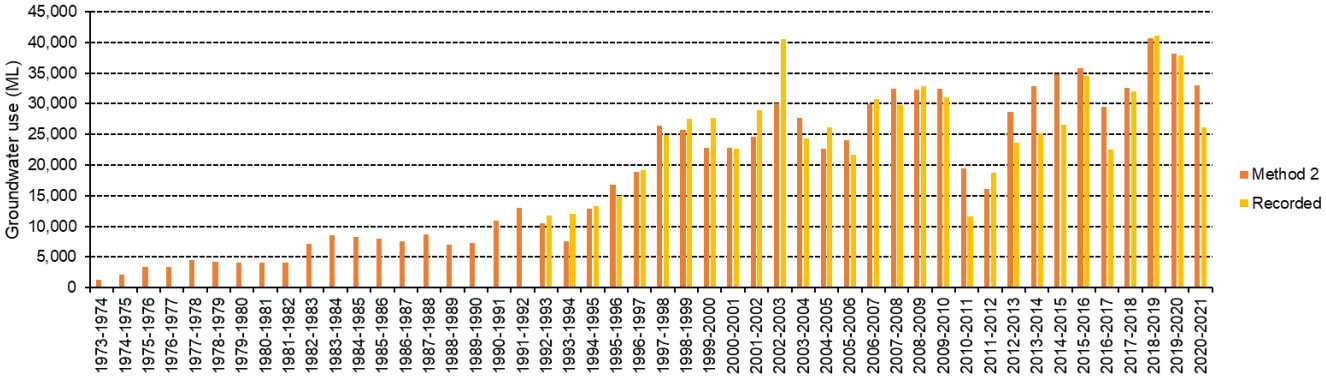


Figure 12 Katunga WSPA – Method 2: Hindcasted data comparison

Method H3: Relationship between percentage of entitlement and rainfall

It was identified that to run the models with spatial distribution and hindcasting, a hindcasting method had to be developed that could be applied at an individual bore level. This method was developed by utilising the DEECA provided dataset "*Use_Ent_Perbore_VAF.shp*" of the licenced bores in Victoria and their associated use and entitlement between 2009 and 2020.

Before this dataset could be used, a number of edits were required including updating the associated GMU names in the field "Water_Syst". This was done in the first instance by changing the name to the equivalent current GMU name, where this was not a straight forward update (e.g., Katunga (GMU) to KATUNGA WSPA) then the spatial location information associated with the bore was utilised. It is noted that spatial location was the latter method adopted as some of the bores did not plot within the boundaries of the State of Victoria, e.g., plotted in Bass Strait, thus it was assumed the previously assigned GMU was likely to be correct over the spatial information.

Additionally, the entitlement data was input into the dataset using positive values and the extraction negative thus the extraction data was changed to a positive number to be able to analyse the two volumes together.

A summary of this method is as follows and is described further below:

- Use the annual use and annual entitlement to estimate the percentage of entitlement for each Pilot GMU
- Plot the percentage of entitlement of use vs rainfall
- Find the line of best fit for each plot
- Use this 'line of best fit' relationship to hindcast the extraction data

As the entitlement data was on a bore-by-bore basis, these values were summed based on the GMU and water year. The groundwater use was then divided by the entitlement information for each GMU by year to give a percentage of entitlement. It is noted that little to no data for Murrayville GMA and West Wimmera GMA existed in this dataset for the years 2009/10 and 2010/11 and thus were excluded from the analysis.

Once the percentage of entitlement was derived, a variety of plots were developed including:

1. Percentage of entitlement versus rainfall
2. Percentage of entitlement versus two yearly average rainfall
3. Percentage of entitlement versus summer rainfall (January to April)
4. Percentage of entitlement versus irrigation rainfall (October to March)

For each of the graphs constructed for percentage of entitlement vs rainfall, a regression analysis was undertaken. Based on the lines of best fit developed, the one with the best correlation was adopted and applied to hindcast the groundwater use data. An example of these graphs for Katunga WSPA is shown in Figure 13.

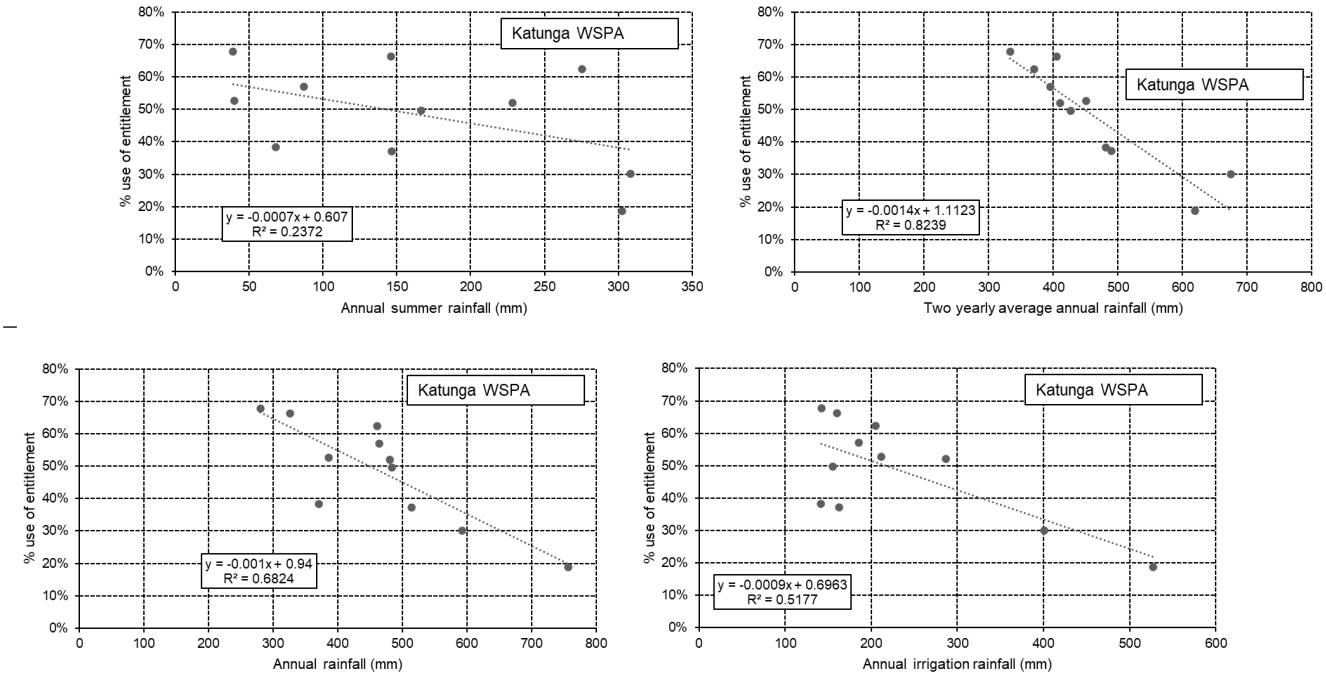


Figure 13 Katunga WSPA – percentage entitlement to rainfall plots

When applying the hindcasted equation, entitlement information was not available from DEECA for individual bores prior to 2009/10. Therefore, an issue arises that we do not know if an entitlement on a bore in 2009, was the same entitlement when the bore was first installed, say back in 1980.

Most commonly, an irrigator would apply for a volume entitlement based upon what their bore could pump. i.e., proponent's bore pumps 1 ML/day so proponent applies for 150 ML. If this bore could not pump the volume, other bores (points of take) could be installed to pump the full allocation, i.e., two bores with a split entitlement of 75 ML each. Depending upon the size of the property and business, it is not unreasonable for an irrigator to seek to increase their licensed volume attached to a bore, i.e., proponent's bore can pump 2 ML/day so proponent applies to increase entitlement from 150 ML to 200 ML. However, it was considered a reasonable assumption that only a small (unknown) proportion of the groundwater bores within a GMU would fit into this case.

Arguably, trading rules were introduced sometime after PCVs (early 2000s) were introduced, which freed up entitlements and enabled irrigators to transfer water and increase their volumes and this should be reflected in the post 2009 data.

Thus, moving forward we have assumed that the 2009 entitlement data is that which the bore was originally allocated except for Murrayville GMA and West Wimmera GMA, which we have assumed 2012 entitlement data as no early entitlement information was available.

Prior to trialling the hindcast use time series in the TFN model, a visual check of the hindcasted data was undertaken to determine if it provided a reasonable match with the available time-series use record (an example is shown in Figure 14 for Katunga WSPA). This information was used to help inform the selection of the preferred model (it is noted that all hindcasting methods were trialled).

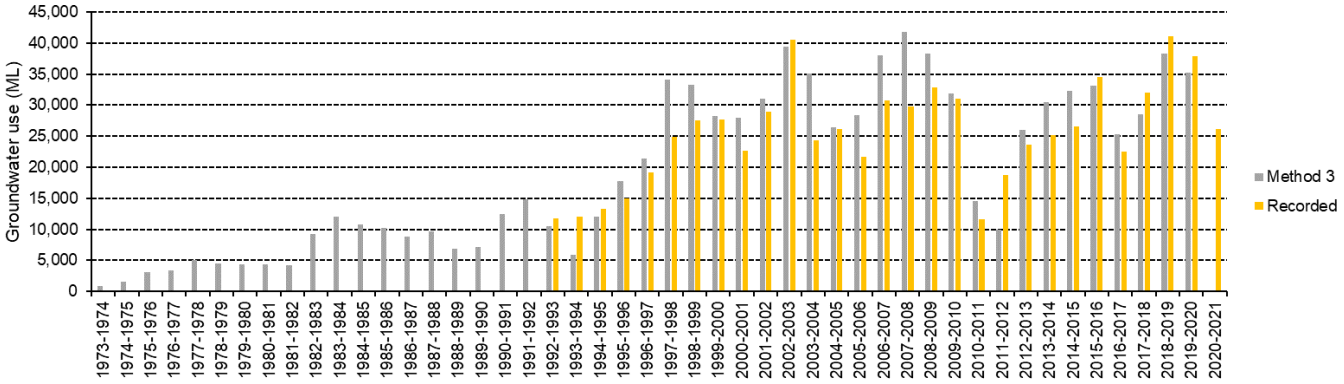


Figure 14 *Katunga WSPA – Method 3: Hindcasted data comparison*

3.3.4.6 Spatial distribution of groundwater use data

3.3.4.6.1 Background

In an ideal confined aquifer, the greatest stress occurring is that due to groundwater abstraction. Within Pastas, a series of stresses can be applied to assess the impact on the water level response. Pastas can implement either of two in-built models to reflect the response to groundwater pumping:

- Hantush – the response of a well under continuous extraction
- HantushWellModel – implementation of the Hantush well function which enables scaling with distance

In simple terms, the Hantush well function is an expansion of the Theis well function, however, unlike the latter, it is a mathematical model of transient flow of groundwater to a pumping well that can be applied to leaky confined (semi-confined) aquifers. A summary of the two models is provided in Table 9.

For this study, GHD applied the 'HantushWellModel'.

Table 9 *Pastas abstraction stress models*

Pastas model	Advantage	Disadvantage
Hantush	Estimates the uncertainty	Use for single wells only
HantushWellModel	Can simulate multiple wells	Does not directly estimate uncertainty Sensitive to initial input values

To model an improved fit to the Suite hydrographs of a confined GMU, there is a need to incorporate the abstractive stress into the TFN model. Groundwater levels in monitoring bores are influenced by both local and regional groundwater pumping. The magnitude of groundwater level decline is related to the volume pumped and the distance from the point of extraction.

Spatial distribution looks to improve the TFN model fit to the Suite hydrograph, whereby a pumping bore(s) is artificially 'placed' at a distance from the relevant hydrograph to impose a stress response to that hydrograph. Consider the example in Figure 15, where:

- A: shows the TFN model and a poor match to a (single) monitoring bore hydrograph
- B: shows an improved fit, as a pumping response stress has been added to the model

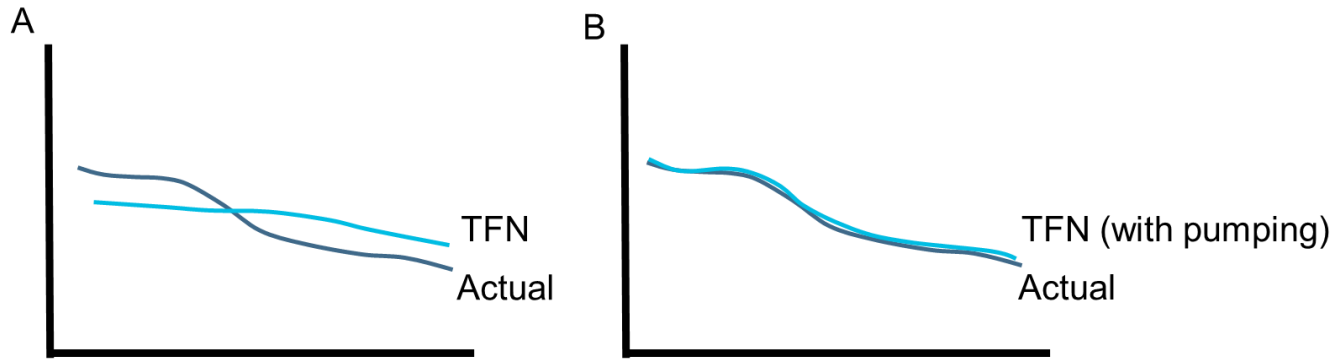


Figure 15 Improving TFN model fit to the Suite hydrograph

Let's say a Suite hydrograph comprises a single bore only and we need to simulate the effect of groundwater pumping near this bore (refer to Figure 16):

- Small volumes of groundwater use near to the bore may have little effect, however, large volumes in proximity to the bore will have a significant effect
- The cumulative effect of multiple bores pumping a small volume could be equivalent to a single bore pumping a larger volume
- If there were multiple bores around the monitoring bore, then each bore could be represented individually. However, this becomes impracticable when considered on a regional scale where there could be multiple bores located at various distances, each pumping differing volumes.

In reality, a Suite hydrograph comprises multiple monitoring bores located throughout a GMU; therefore, an approach that best replicates the spatially variable extraction throughout the GMU should be explored.

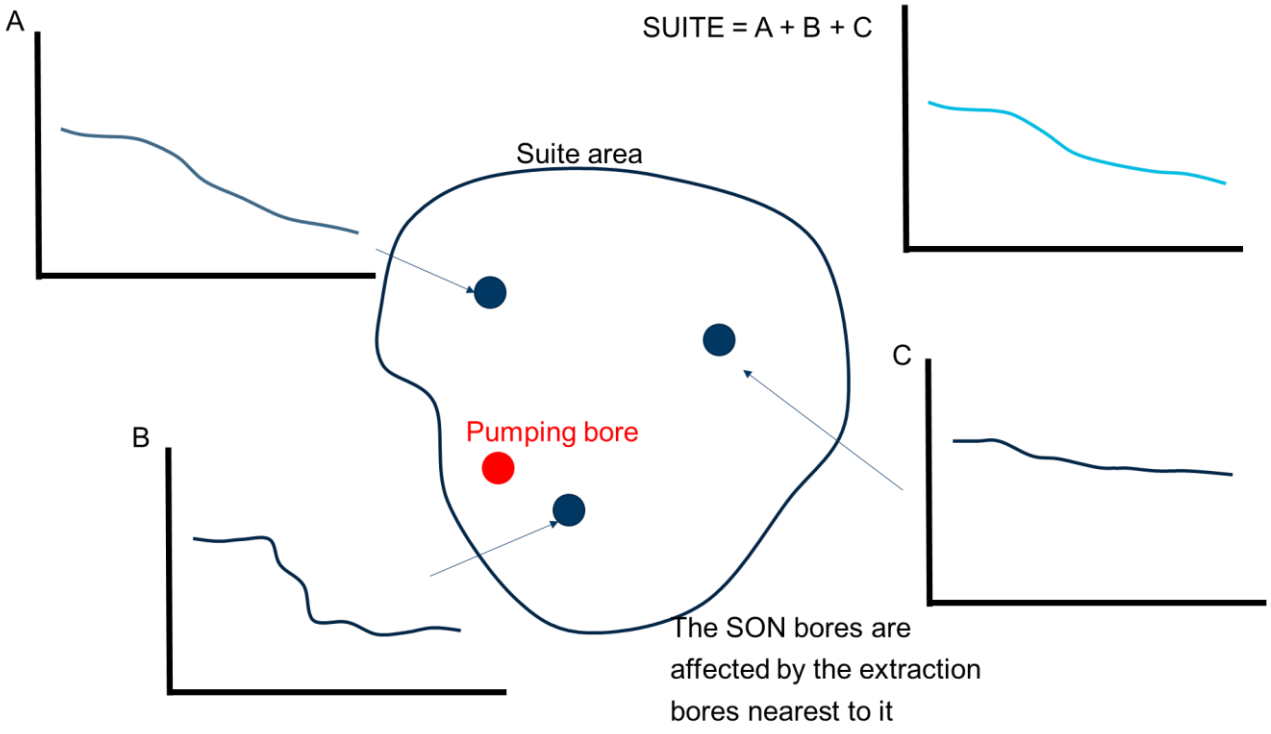


Figure 16 Spatial variability in the effect of groundwater pumping

Several spatial distribution methods were developed as part of the Stage 1 Pilot study, however only three of them were assessed as reasonable methods to trial. These three methods are discussed below and each have been trialled as part of Stage 2 where the GMU is included within the spatial licenced bore dataset.

Method S1 – Extractors with search radius of Suite centroid using a single stress model

This method involved:

- Estimating the Suite observation bore centroid (as depicted in Figure 17) using the SKM (2013) Suite observation bore dataset
- Creating a search radius for determining the top *n* bores based on a calculation of two times the average observation bore separation distance (the minimum search radius applied was 10 km, while the maximum was the square root of the GMU area). This approach provided a buffer around all observation bores and consistency across the analysis.
- Applying a maximum radial search distance (50 km was adopted) for the extraction bores from the GMU area
- Summing the licenced bore extraction within the search radius
- Creating one stress model of the time series extraction data from the sum of extraction bore data, for use in the TFN

It is noted that the above approach does not need bore distances as the model is effectively calibrated. This works by the volume in the stress model being the sum of volumes (per year) across all of the *n* bores identified.

Using this method would result in fewer stress models which would likely result in faster model run times. However, a downside is that when pumping increases and decreases relative to the others over the years, this may degrade calibration quality but is likely to be better than the base case (annual recovered levels and annual extraction of whole GMU) of all pumping occurring in the Suite area. However, it does not account for the differences between the Suite area centroid and centroid of the individual Suite bores (refer Figure 17).

A schematic with an overview of the process is provided in Figure 17.

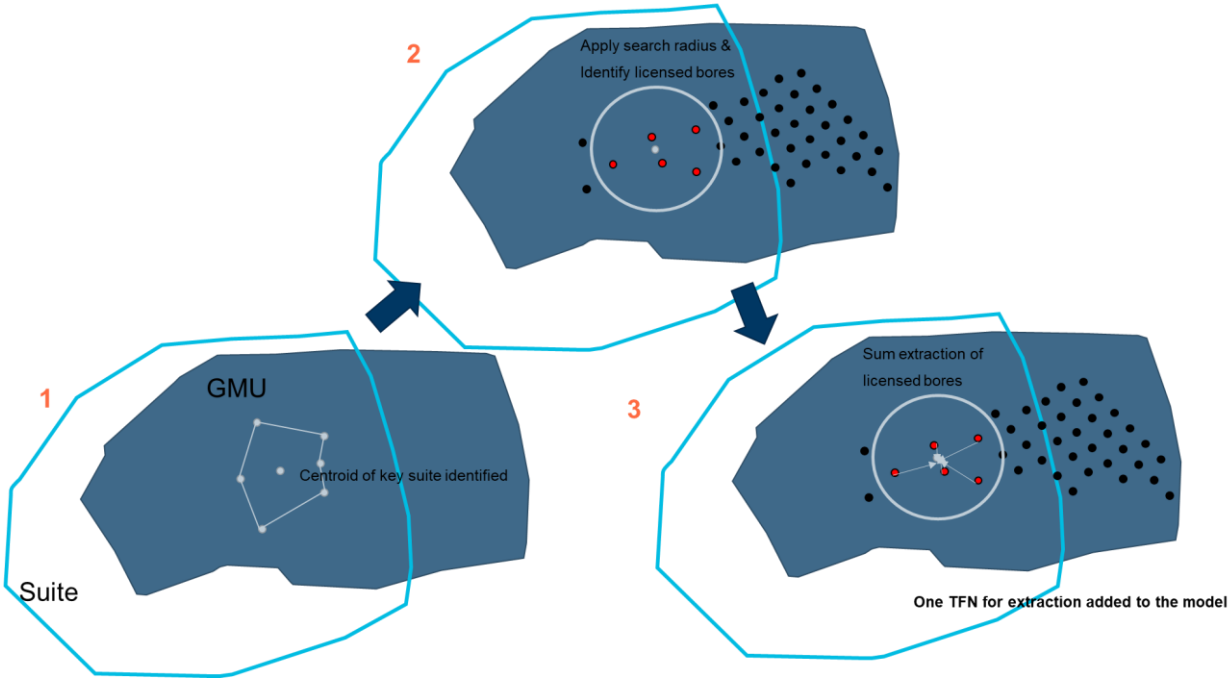


Figure 17 Conceptualisation of spatial distribution analysis method 1

Method S2 – Extractors within search radius of Suite centroid using multiple stress models

This approach is similar to method S1, it involves:

- Estimating the Suite observation bore centroid (as depicted in Figure 18) using the SKM 2013 Suite observation bore dataset
- Creating a search radius for determining the top *n* bores based on a calculation of two times the average observation bore separation distance (the minimum search radius adopted was 10 km and maximum was the square root of the GMU area). This approach provided a buffer around all observation bores and consistency across the analysis.
- Applying a maximum radial search distance (50 km was adopted) for the extraction bores from the GMU area
- Calculating all extraction bore distances from the Suite centroid
- Bore distances were then 'binned' into distances classes; in this method we have typically adopted 10 'bins'
- Groundwater extraction within each distance bin is summed
- Total pumping for each bin is applied as a distance-based stress model for each Suite

A schematic with an overview of the process is provided in Figure 18.

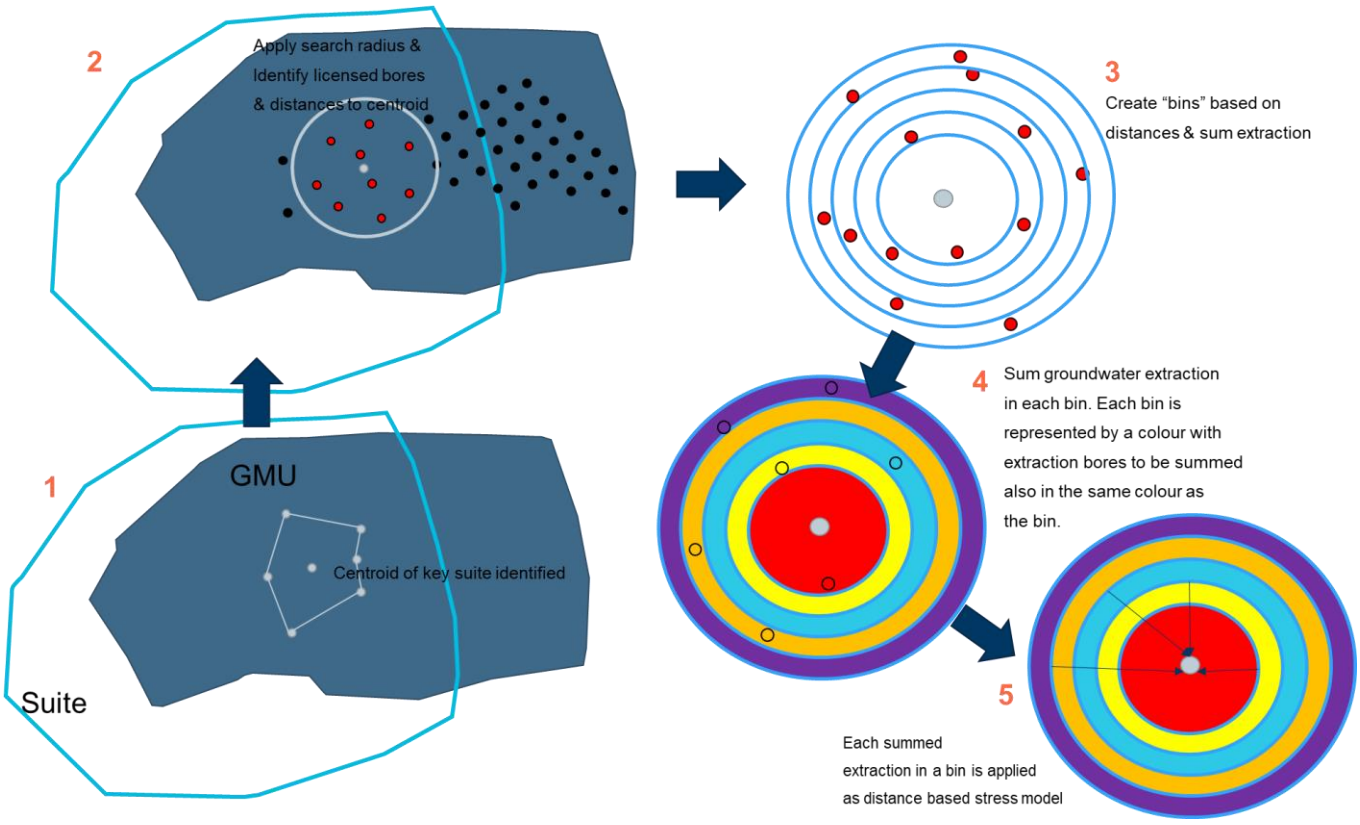


Figure 18 Conceptualisation of spatial distribution analysis method 2

Method S3 – Weighted to Suite hydrograph observation bores

Unlike the other options, this one focuses on the observation bore data that comprises the Suite hydrographs (Figure 19). The process involves the following:

1. Identifying/mapping the individual observation bores that constitute the Suite
2. Determining the centroid of the area encompassed by all the individual Suite observation bores, i.e., Suite bore centroid
3. For each observation bore, applying a radial buffer (two times average observation bore separation distance in each Suite)
4. Calculating the distance from each observation bore to every licenced bore within the observation bore search area
5. Binning the bore distances for each search area (in this instance we have adopted five distance classes)
6. The closest licenced bore to the observation bore distance of all overlapping search areas is taken as the distance for a given pumping bore for the model
7. Groundwater usage from each time series within each distance bin are summed
8. Total pumping for each bin is applied as a distance-based stress for each Suite hydrograph model

A schematic with an overview of the process is provided in Figure 19.

Conceptually, this is weighting the use data near each individual observation bore, which in turn is weighting the observation bore effect on the combined monitoring response or Suite hydrograph.

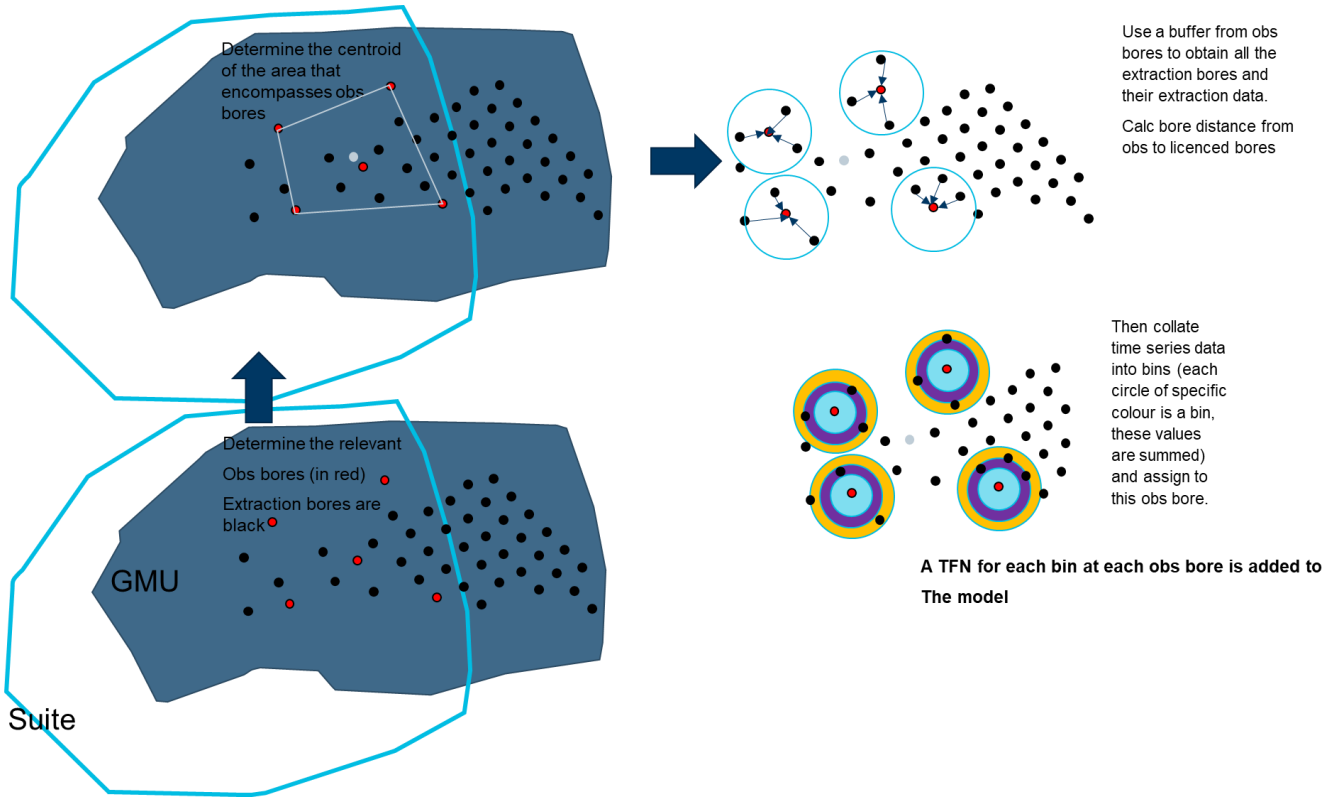
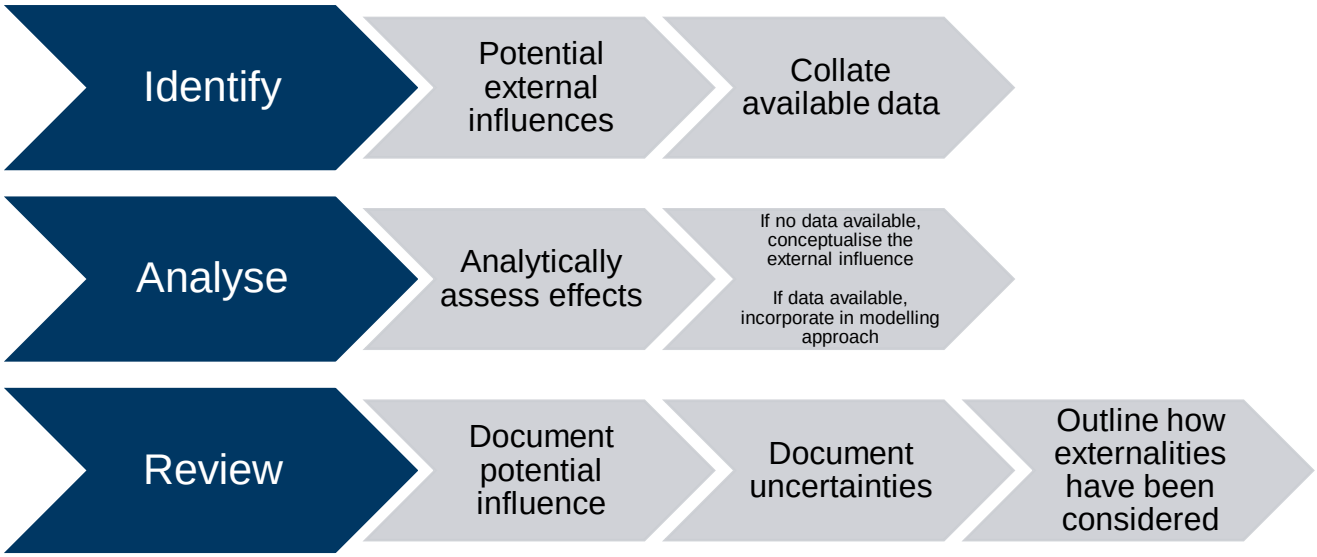


Figure 19 Conceptualisation of spatial distribution analysis method 3

The methods are applied directly within the model; thus, the model must be run to compare methods through the model results and goodness of fit. Each of the three methods were trialled in GMUs where spatial data was available and are discussed within the relevant GMU chapters.

3.3.4.7 Consideration of GMU externalities

For some GMUs, the potential impact of groundwater extraction beyond the GMU boundaries within neighbouring states or offshore may affect groundwater conditions within the GMU. The following approach has been adopted to consider influences of extraction occurring outside GMUs and is documented within the relevant GMU chapters:



Based on the trialling of methodologies incorporating externalities in Murrayville GMA (refer Appendix D), it was found that incorporating the total volumes from the external influence to provide the best results in modelling. Thus, this approach was adopted when incorporating externalities into modelling (second step under analyse in the figure above).

3.3.4.8 Two yearly average annual groundwater use

It is noted that the recovered annual level for each year generally occurs near the start of the water year and thus is strongly influenced by the extraction occurring in the previous year. The TFN model estimates groundwater levels based on the model input data using the process of convolution as discussed in section 3.4.1.

To place more weighting onto the previous year's extraction, upon direction from DEECA, a two yearly average annual extraction was tested within the model (in addition to the yearly annual extraction scenario) to investigate whether this further improved the model results. Figure 20 depicts how the annual groundwater extraction is converted into the two yearly annual average extraction.

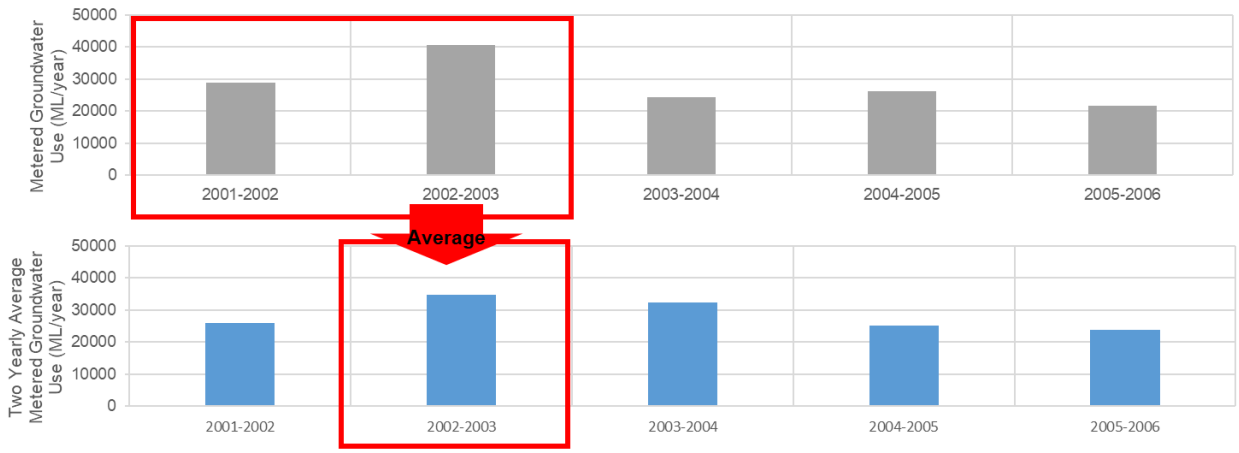


Figure 20 Example of conversion of annual extraction to two yearly average extraction between dates 2001/02 and 2005/06

3.4 Modelling

Ultimately, this study seeks to understand groundwater use versus drawdown relationships under a range of settings for each GMU, as a basis for defining acceptable groundwater level declines. To achieve this, modelling has been adopted as a tool to efficiently estimate a mathematical function in an analytic form that best fits the set of time-series data for each GMU.

The estimated empirical relationship can be applied to future use scenarios to predict resultant drawdowns. Subsequent to this project, DEECA will use the predicted drawdown outputs, along with developed water level metrics (defining acceptable level of stress) to inform potential future updates to Sustainable Yield allocations for each GMU. Recommending Sustainable Yield allocations is not within the scope of this GHD study.

3.4.1 Transfer Function Noise (TFN) model

Time series inputs into the TFN required pre-processing to:

- Provide consistency with the confined aquifer conceptualisation
- Understand the relevant considerations appropriate to the stress impulse functions
- Improve the fit to the modelling data

The principal underpinning GHD's approach is to predict future groundwater level response to stress based upon an understanding of groundwater level response to historical stress. To achieve this, mathematical modelling of the (groundwater) system was required to match historic behaviour and predict hypothetical future behaviour in groundwater level as a response to pumping stress.

A transfer function is a mathematical function that theoretically models the system's outputs for each possible input. The time series model is calibrated to a limited set of observations, and then it is considered to represent the dynamic properties of the system that generated the observations. The calibrated model can then be used to forecast future values.

In hydrogeology, they are often applied to predict groundwater levels based upon historical data. A popular time series analytical approach is that using the Transfer Function Noise (TFN) model, originally developed by Box & Jenkins (1970). The TFN is a multivariate model which attempts to translate one or more input variables (time series) into an output series using a statistical model.

It can be expressed mathematically in its simplest form as:

$$h(t) = \sum_{m=1}^{M} h_m(t) + d + r(t)$$

where;

h(t) = simulated heads

$h_m(t)$ = contribution of stress *m* to the head

d is the base elevation of the model

r(t) = residuals

t = time

There can be an arbitrary number of stresses *(M)* that can contribute to the head, including rainfall, evaporation, river levels and groundwater pumping. The contribution of a stress, *m*, to head, *h*, is via convolution expressed through the mathematical operation:

$$h_m(t) = \int_{-\infty}^{t} S_m(\tau)\theta_m\,(t-\tau)d\tau$$

where;

S_m = time series of stress *m*

θ_m = impulse response function for stress *m*

This equation shows that the TFN model considers previous years' extraction through convolution by way of the function (τ). Convolution represents a mathematical approach to combining two functions to make a third function, which expresses how the shape of one function is modified by the other. The impulse response function (θm) can take different forms depending upon the nature of the stress. For example, a Gamma function is applied to simulate areal recharge, and the Hantush function for groundwater pumping.

To apply the TFN model, there are open source (publicly available) programs that can be operated in Python (e.g., Pastas, Collenteur *et al.* 2019) or Matlab (HydroSight, Peterson and Western, 2014, 2018) environments. To undertake this study, the Pastas package (version 0.19.0) within the Python programming language has been used. Further details on Pastas are provided in Appendix B.

For this study, depending on the model configuration, either the Hantush or HantushWellModel is used for the groundwater pumping impulse response function. Both functions are based on three parameters A, a and b. The key difference between the two response functions is that the HantushWellModel allows for scaling with distance. The three parameters are calculated as:

$$A = \frac{1}{2\pi T} K_0\left(\sqrt{4b}\right)$$
$$a = cS$$
$$b = \frac{r^2}{4\lambda^2}$$

where;

A = is a scaling factor

a = shape parameter

b = shape parameter

T = transmissivity

K_0 = modified Bessel function of the second kind and order zero

S = storativity

r = distance

λ = leakage parameter

(Pastas v0.19.0 documentation, Collenteur *et al.* 2022)

For both methods, the model takes the values initially defined (calculated using the above three equations) and optimises them. These optimised values are the values applied to the TFN model. It is noted that these optimised values do not change with time.

As the method relies on the use of actual observation data, it is considered consistent with Component 4 of the DEECA groundwater assessment framework (refer Figure 2).

3.4.1.1 Inputs

There are several time series inputs that can be incorporated into the Pastas TFN modelling workflow. However, there are two minimum factors that need to be imported – groundwater levels and one stress (typically groundwater extraction). In terms of the modelling, the time series data considered for this project related to:

- Groundwater levels
- Groundwater extraction
- Climate (if needed)

GHD's application of TFN modelling through this study does not specifically consider mechanical changes to confined aquifers, nor to resultant changes to groundwater pressures, levels, storage or aquifer parameters. Each of these changes could occur as a result of confined aquifer pumping, or overlying water table aquifer dynamics. It is noted that load-induced changes in pressure are not typically accounted for even in conventional groundwater flow models such as MODFLOW (Harrington and Cook, 2011).

In terms of the possible error that could be produced through exclusion of loading effects in the applied modelling approach, research into this area undertaken by Harrington and Cook (2011) on measured data in the Otway Basin suggests that the corrected hydrograph is typically a fraction of the observed unconfined water table fluctuation and within a few centimetres of the observed data, with no change to the long-term water level trend (Harrington and Cook, 2011). This point on the trend is particularly noteworthy, since the model's calibration to long term trends is a key aspect of the GHD approach. On this basis as well as that of minimising complexity in this initial application of the TFN modelling approach to assessing groundwater sustainability in Victoria, the potential error relating to loading and unloading is considered to be negligible for the purpose of this study.

The types of groundwater extraction data utilised in the modelling was variably trialled. A number of variations of the input data were tested, this included:

- Annual recorded extraction data for the GMU (by water year)
- Two yearly average extraction data for the GMU (by water year)
- Annual recorded extraction for the GMU plus groundwater extraction from neighbouring external sources (by water year)
- Two yearly average extraction for the GMU plus groundwater extraction from neighbouring external sources (by water year)
- Annual hindcasted extraction data for the GMU (by water year)
- Annual hindcasted extraction data for the GMU plus groundwater extraction from neighbouring external sources (by water year)
- Annual extraction data by spatial location (by water year)
- Annual extraction hindcasted data by spatial location (by water year)

Figure 21 summaries the approach to model inputs.

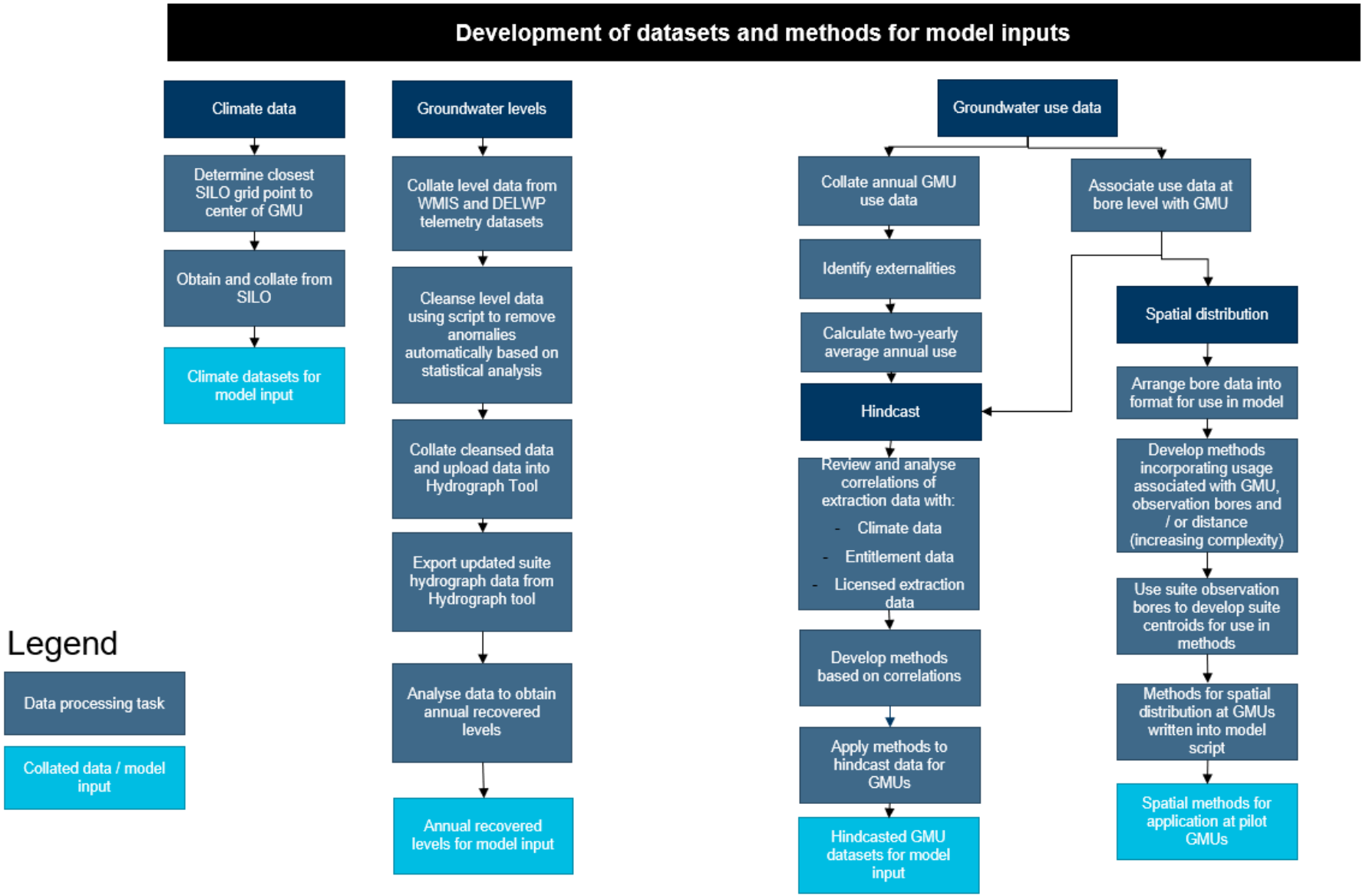


Figure 21 *Process of refinement of model inputs*

3.4.1.2 Modelling process

Figure 22 shows the processes undertaken when completing the initial modelling to estimate the best model outcome, based on the combination of available inputs, prior to progressing to the forecast modelling phase. Figure 22 shows the key combination of inputs tested in the models for each GMU, with each combination including the annual recovered levels.

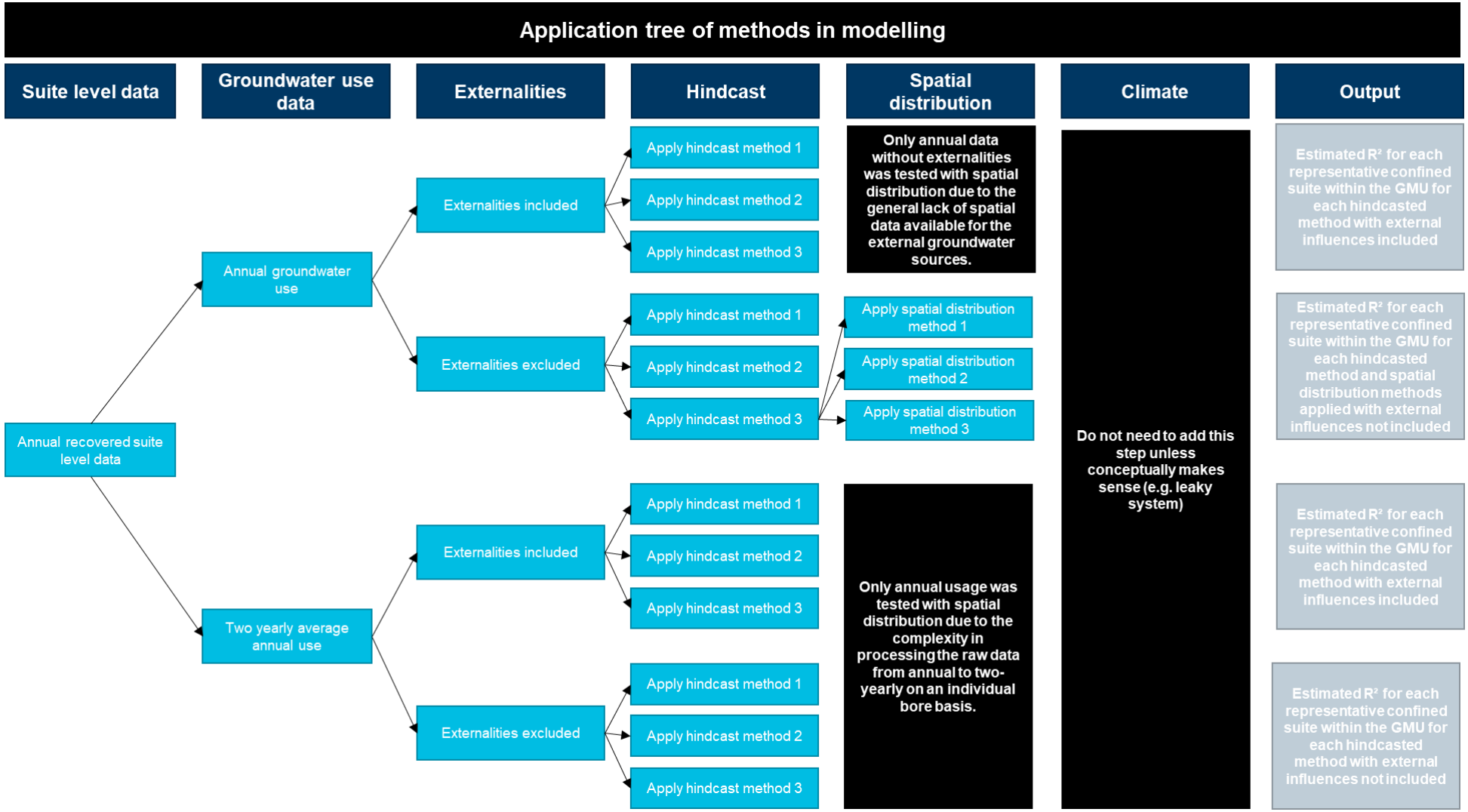


Figure 22 Application tree for modelling

3.4.1.3 Statistical measures for model calibration and uncertainty analysis

3.4.1.3.1 Model calibration statistical measures

For each model set up with the various input combinations, the model is assessed through statistics including the coefficient of determination (R^2) and root mean square error (RMSE). The RMSE draws upon the model residuals, which are the calculated differences between the observed values and the simulated values. There is no universally accepted range for RMSE, as it provides a direct measure of the average prediction error in the same units as the target variable (in the case of this study, groundwater levels). A description of the statistical analysis adopted is provided in Table 10.

A literature review identified limited peer reviewed articles that qualitatively describe R^2 in terms of acceptability. Santi *et al.* (2001) and Van Liew *et al.* (2003) represent two hydrological studies where typical values greater than 0.5 were considered acceptable (it is noted that these studies were modelling studies but not TFN modelling studies). A review of the Pilot Study results (GHD, 2022) has been undertaken and the findings used to form a proposed basis of acceptability, which is described below. In the context of groundwater level trends and for the purpose of this study, the following definition has generally been considered when reviewing model results:

- An excellent R^2, between 80% and 100%, indicates that the model's performance is positive and effective in delivering accurate results
- A good R^2, at 60% to 80%, indicates that the model's performance is above average and reliable across different scenarios. Further refinement of inputs may be required.
- A moderate R^2 at 40% to 60%, indicates that the model's performance is below average and should be used with caution. Further refinement of inputs is required.
- A poor R^2 at 0% to 40%, indicates that the model's performance is significantly below expectations and may not be suitable for practical applications
- A negative R^2 is not a mathematical impossibility, nor is it a result of modelling error – it simply indicates that the chosen model (with its constraints) fits the data very poorly

For Root Mean Square Error (RMSE), lower is better as it indicates better model accuracy. For the purpose of this study, a model RMSE of less than 1 metre has been adopted as being 'acceptable'. This is based on the consideration that this study pertains to regional (catchment scale) confined aquifers, generally of considerable thickness and under considerable potentiometric pressure. An error in RMSE (and therefore accuracy in terms of groundwater level) in the order of 1 metre is considered an acceptable model applicability rating for the purpose of this modelling application.

Also considered when assessing the model calibration is the number of annual recovered level observations is included within the model and the range of annual recovered levels included in the model, that is the difference between the maximum annual recovered level use in the model and the minimum annual recovered level used in the model.

From a review of the results and statistical summaries of the various models, well calibrated models were those with the lowest RMSE and highest R^2 value but also those that included a long historic record to capture pre-development periods and a larger range of levels.

The model calibration statistics, in association with model forecast statistics, have been used to develop a final model applicability rating (refer section 5.2).

Table 10 Statistical measures of model accuracy and precision

Statistic	Unit	Description
Root mean square error	m	The root mean square error (RMSE) is calculated as a square root of the sum of residuals squared by the number of observations as show in the equation below. As the RMSE value approaches zero the model is interpreted as being more accurate. $RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}[(z_{hi} - h_i)]^2}$

Statistic	Unit	Description
Coefficient of determination (R^2)		R-squared (R^2) is a statistical measure that represents the proportion of variance (or the degree of collinearity) between simulated and measured data. R^2 explains to what extent the variance of one variable affects the variance of a second variable. This is explained by an independent variable or variables in a regression model. As an example, if the R^2 of a model is 0.50 (or 50% if stated as a percentage), then approximately half of the observed variation can be explained by the model's inputs. It should be noted that R^2 is different from statistical correlation, which is concerned with the strength of the relationship between an independent and *dependent* variable. R^2 is widely used in hydrological modelling studies, thus serving as a benchmark for performance evaluation. R^2 is used in this study as a modelling output to provide a measure of the proportion of the total exhibited variance that is explained and unexplained. R^2 has been used by numerous others previously in groundwater level variability assessments (Sahoo and Jha, 2013; Peterson and Western, 2014) as it represents a well-established classical regression analysis. Disadvantages of using R^2 have been raised by others (Moriasi *et al.*, 2015), which include its oversensitivity to high extreme values (Krause *et al.*, 2005) and insensitivity to additive and proportional differences between model predictions and measured data (Legates and McCabe, 1999).

3.4.1.3.2 Uncertainty analysis measures

For each model set up with the various input combinations, the model uncertainty is assessed through the 95% prediction interval thickness (95 PPU thickness) and the percentage of observed annual recovered levels within the 95% prediction intervals (%Obs in 95PPU). A description of the measures used for the uncertainty analysis is provided in Table 11.

The uncertainty of each of the various models for a GMU were assessed based on these measures. The smaller the 95PPU thickness and the greater the percentage of observations within the 95% prediction interval, it was considered that the model had less uncertainty.

Table 11 Statistical measures of model uncertainty

Measure	Unit	Description
95 PPU thickness (95PPU TH)	Dimensionless	This is the average thickness between the 95% prediction interval bands produced by the model
Percentage of observed levels within 95 PPU (%Obs in 95 PPU)	%	The per cent of observations (in this case annual recovered levels) bracketed by the 95% prediction interval bands

3.4.1.4 Model selection

The calibration model selected to undertake predictive modelling for each Suite modelled in a GMU was based on whether the model included the pre-development period. As it was found during modelling that models that did not include the pre-development period were not able to provide reasonable use-drawdown relationships at smaller drawdowns, causing large intercept values in the predicted lines of best fit. Given this, models selected are generally those using hindcasted datasets.

The key considerations for selecting a model to progress to predictive modelling is as follows:

- Whether the model includes the defined pre-development period
- The RMSE and R^2 values (looking for models with the lowest RMSE and highest R^2 value)
- The 95% prediction interval thickness (models which have the smallest thickness)

- The number of observations that fall within the 95% prediction interval thickness (models that have the highest percentage)
- The models used for the other Suite(s) in the GMU

3.5 Predictive modelling – forecast water levels

Once a model with a reasonable fit between actual pumping stress and observed actual groundwater level response has been established, as determined through the various measures of goodness of fit, stress testing of the aquifer can now be applied. This has been undertaken using the established relationship as a basis to predict groundwater level responses under a range of (typically higher) stresses. These predicted groundwater level responses can be used as a basis to assess drawdown acceptability in the context of GMU conceptualisation, and the acceptable levels of impact to groundwater users and protected values.

3.5.1 Objective

There is a need to predict the groundwater level response to a range of potential groundwater use scenarios for the same period. This is required to assess predicted water levels under a range of use scenarios to assess sustainability for each of these cases.

The adopted groundwater use scenarios need not be accurate predictions of potential future use, but rather, should comprise both implausible, plausible and possible groundwater use scenarios. The scenarios are used in GHD's method to generate a relationship between GMU groundwater use and Suite groundwater level drawdown, as a tool to guide groundwater sustainability based on drawdown levels (or metrics). As such, the incorporation of implausible scenarios assists in assessing the upper boundaries of groundwater use sustainability. Despite this, each forecast scenario must be justifiable and should relate to a projected timeframe that aligns with DEECA's project requirements.

The projected timeframe adopted in this study is approximately 20 years into the future from the start of the prediction period. The model uses measured/monitored data to 2020-2021 and as such, prediction period is roughly from year 2021/2022 to year 2040. The end of the prediction roughly aligns to the year 2040, which is specifically referenced in terms of annual climate change projections by DEECA (2020) and the global climate models.

3.5.2 Approach

A range of plausible and implausible groundwater use scenarios was developed in collaboration with DEECA (Table 12). Plausible scenarios are effectively conditions experienced (and therefore measured) through the available groundwater use data or groundwater level record. Implausible scenarios are purely hypothetical conditions proposed with the intention of developing the linear relationship between aquifer (Suite) drawdown and groundwater use. GHD's initial method included scope to analyse the 'recharge stressor' (only where required).

Table 12 Stress test use scenarios

Scenario no.	Proposed scenario rationale	Rationale/comments
1	Current average use (from last 5 years) is maintained for next 20 years, i.e., status quo	Does not stress the PCV unless PCV highly allocated
2	Maximum historical use is maintained for next 20 years	Does not stress the PCV unless PCV highly allocated
3	Stepwise increase to GMU limit over next 20 years	Gradual ramping to the PCV
4	Gradual ramp to 2 x PCV Limit	Implausible stress test
5	Gradual ramp to 5 x PCV limit	Implausible stress test
6	Gradual ramp to 10 x PCV limit	Implausible stress test; may need to reconsider suitability of the 2x, 5x, 10x factors

Scenario no.	Proposed scenario rationale	Rationale/comments
7	Gradual ramp of existing use to existing licenced cap	Does not stress the PCV if licenced cap well below PCV
8	Ramping towards a 10 year drought with 5% increase in max historic use[1]	Stepped increase
9	Ramping towards a 10 year drought with 30% increase in max historic use[2]	Stepped increase
10	5% annual increase from 2025 to the cap	Stepped increase
11	10% annual increase from 2025 to the cap	Stepped increase
12	5% annual increase every 4 years from 2025 to/towards the cap	Stepped increase
13	10% annual increase every 4 years from 2025 to/towards the cap	Stepped increase
14	5 years at average, 4 years at hist. max, 4 years at hist max +10%, 4 years with ave+10%, 4 years with further 10%	Simulate periods of drought with increased use post-drought
15	5 years at average, 4 years at hist. max, 4 years at hist max +10%, 4 years with ave+20%, 4 years with further 20%	Simulate periods of drought with increased use post-drought
16	5 years at average, 5% reduction for 5 years, 10% for 5 years, 5% increase from average	
17	5 years at average, 10% reduction for 5 years, 20% for 5 years, 10% increase from average	
18	5% annual increase from 2025 to cap+10%	Implausible stress test
19	10% annual increase from 2025 to the cap+30%	Implausible stress test

The adopted approach to forecasting aquifer drawdown conforms to the Jacobs (2020a and 2020b) groundwater assessment principles, as it aims to:

- Minimise the risk of unacceptable impact on or by groundwater
- Considers the potential for and consequences of unacceptable impact to the environment that may arise
- Considers and describes the effect of uncertainty in making the assessment and how uncertainty influences the risk of unacceptable impact (to users or the environment)
- Utilises the simplest approach consistent with the other principles
- Involves modelling to predict future drawdown under a range of uses, and establishes relationships between use and drawdown for the hydrograph
- Determines relationships between yield and drawdown in Suite area(s) for each GMU

3.5.3 Predictive modelling

Once future groundwater use scenarios and a relevant assessment timeframe are established, predictive modelling can be undertaken through the calibrated TFN model, to generate groundwater level responses for the various scenarios proposed.

[1] Basis for this obtained through statistics performed on data within DEECA-MillenniumDrought-web-SB.pdf.pdf (water.vic.gov.au), where average increase during 2003-2011 was ~5%
[2] Basis for this obtained through statistics performed on data within DEECA-MillenniumDrought-web-SB.pdf.pdf (water.vic.gov.au), where maximum increase in use at the peak of the drought (2011) was ~30%

3.5.3.1 Model predictive uncertainty analysis

Uncertainty has been assessed during calibration but uncertainty also exists in the predictive scenarios. Uncertainty in these predictions were assessed through Markov Chain Monte Carlo (MCMC) predictions, which were undertaken on each of the forecasted scenarios for each of the potential representative Suites identified for a given GMU. MCMC predictions were undertaken on each of the forecasted scenarios for each Suite.

The MCMC simulations optimise/estimate parameters of the Pastas model. This is done by defining how many steps the walkers take (steps = 100 in this model), how many samples from the start of the walkers are removed (burn = 10 in this model) and how many samples are accepted (then = 5 in this model). The MCMC and the 95% prediction interval bands can be used to assess uncertainty within the modelled forecast. The MCMC realisations show the various potential model predictions which were compared with the 95% prediction interval bands; where most realisations fell within the prediction's intervals, the predictions were assessed as having an acceptable level of uncertainty tomorrow.

Uncertainty is also accounted for by using 19 forecast scenarios to develop a groundwater use to drawdown relationship (analogous to a Monte Carlo type simulation) where a range of possible outcomes are generated. It is noted however, that the forecast scenarios were not randomly generated, but rather based upon a series of estimated use behaviours.

3.5.3.2 Input data processes

To run the predictive modelling, 19 groundwater extraction input datasets were created to represent each of the forecast scenarios (Table 12). The forecasted scenarios draw upon one or more factors to calculate the annual extraction from 2021/2022 up to the year 2040/2041. These factors include:

- Licenced cap (i.e., the total licensed volume, which is generally very close to the PCV)
- Existing or current use (based on 2021/2021 data)
- Maximum historic use
- PCV

The use data was processed in Microsoft Excel to represent each of the forecast scenarios for each GMU. Where the predictive modelling was based on a model with spatial distribution, the following process was undertaken to distribute the forecasted annualised volumes to each bore in the spatial dataset:

- Identified which bores were extracting in the year 2019/2020 (last year of spatial dataset)
- Calculated the percentage of use of a given licenced bore to that of the annual use of the year 2019/2020
- Taking the percentage for a given bore (e.g., 5%) and multiplied it be the annual forecasted usage for given year (e.g., 11,482 ML) to estimate the forecasted volume at that bore for a given forecasted year (e.g., 5% x 11,482 ML = 574 ML)
- Repeating for all the bores for the relevant GMU for each year (including the year 2020/2021) to forecast the data out to 2040/2041

3.5.3.3 Model runs

The models were run for each of the forecast scenarios for the GMUs and the Suites that were considered representative (if identified). Where the key representative Suite had not yet been identified, the model was run for all confined Suites (except those that did not achieve an appropriate correlation).

3.5.3.4 Drawdown estimation for future scenarios

Since future scenarios simulate groundwater levels, they need to be converted to drawdown to allow comparison with DEECA's drawdown metrics. The modelled Suite annual recovered water levels from each forecast scenario were collated along with the annual input extraction volumes.

To calculate the drawdown based on the annual recovered levels simulated by the model, the pre-development conditions (pre commencement of extraction) need to be estimated. For many of the GMUs, the water level prior to groundwater development was unknown, due to:

- Uncertainty regarding the commencement of development in some GMUs
- Groundwater development preceding SOBN bore installation and temporal groundwater monitoring

As discussed in section 3.3.3.1, GHD estimated the pre-development levels for each Suite for each GMU. Generally, the early time series data was adopted as the baseline of pre-development conditions. Using this baseline pre-development value, the forecast water levels were converted into forecast drawdowns (from this baseline) for each of the 19 scenarios for each GMU. This predevelopment condition is shown in Figure 23 for Suite M_I_2 hydrograph of annual recovered levels in Katunga WSPA. In Figure 23, actual annual groundwater use is represented by the blue column graph between 1992/1993 and 2020/2021, the hindcasted groundwater use is represented by the orange columns between 1973/1974 and 1991/1992, and the forecasted use is represented by the grey columns after 2021/2022. The annual recovered water level behaviour based on recorded data is represented by the red line graph, where by the earliest data is taken to best reflect the pre-development levels. In the case of Figure 23, the pre-development annual recovered level is taken to be the maximum level in the early time series data which equates to 13.4 m. The modelled forecasted annual recovered levels are represented by the purple line in Figure 23. The calibration annual recovered levels are represented by the black line in Figure 23.

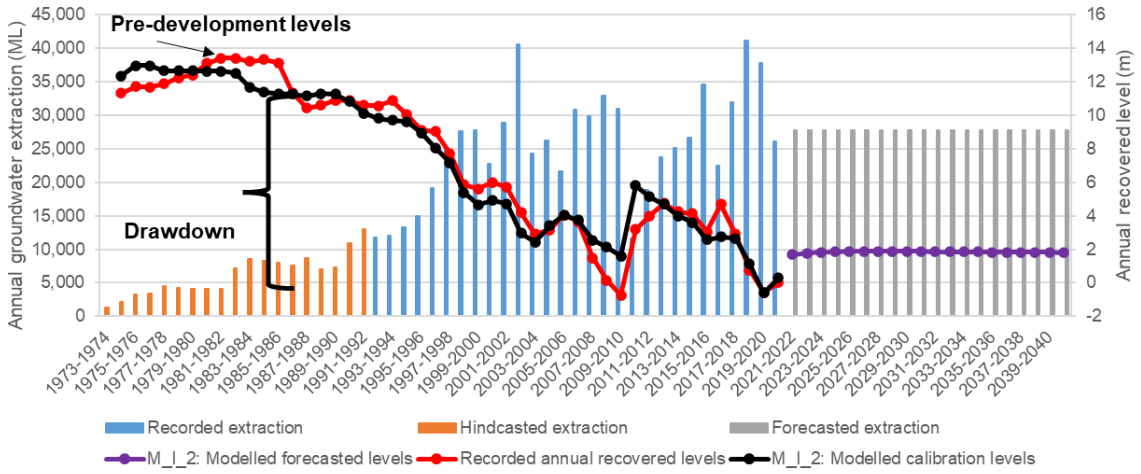
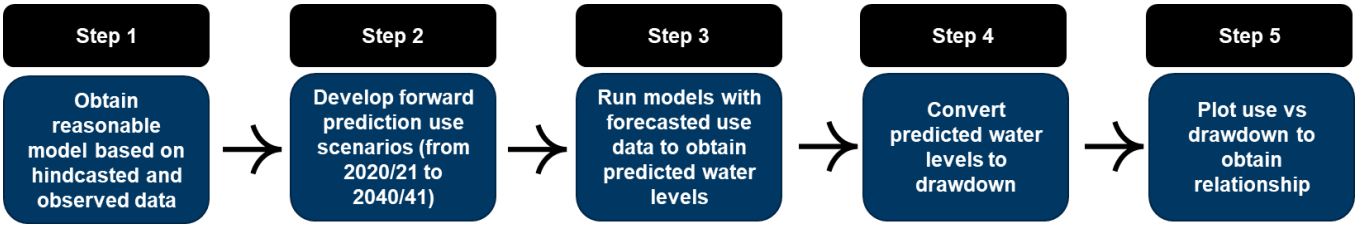


Figure 23 *Estimating pre-pumping water levels for Katunga WSPA Suite M_I_2*

For a Suite, the calculated drawdowns and volumes for each of the scenarios were plotted in individual graphs for each scenario, all scenarios together in the one graph and a graph of the scenarios for specific time periods, to develop the volume to drawdown relationship. For each scenario, a linear regression was applied and the coefficient of determination (R^2) was calculated.

An example use-drawdown plot for all the 19 forecast scenario drawdowns and volumes (both the recorded and forecasted volumes) over each year modelled for a GMU is shown in Figure 24 (it is noted that the graph has been clipped to not show volumes from the implausible scenarios); a linear line of best fit was added. Figure 24 presents an example for Suite M_I_2 within Katunga WSPA, where the resultant R^2 is excellent at 0.94. This linear trend defines the relationship between extraction and drawdown within this Suite.

This process was repeated using the simulated values for the 95% prediction interval limits for the Suite, to provide a relationship that estimates the lower and upper drawdown limit for a given volume. The method to obtain the use – drawdown relationship is schematically shown below.



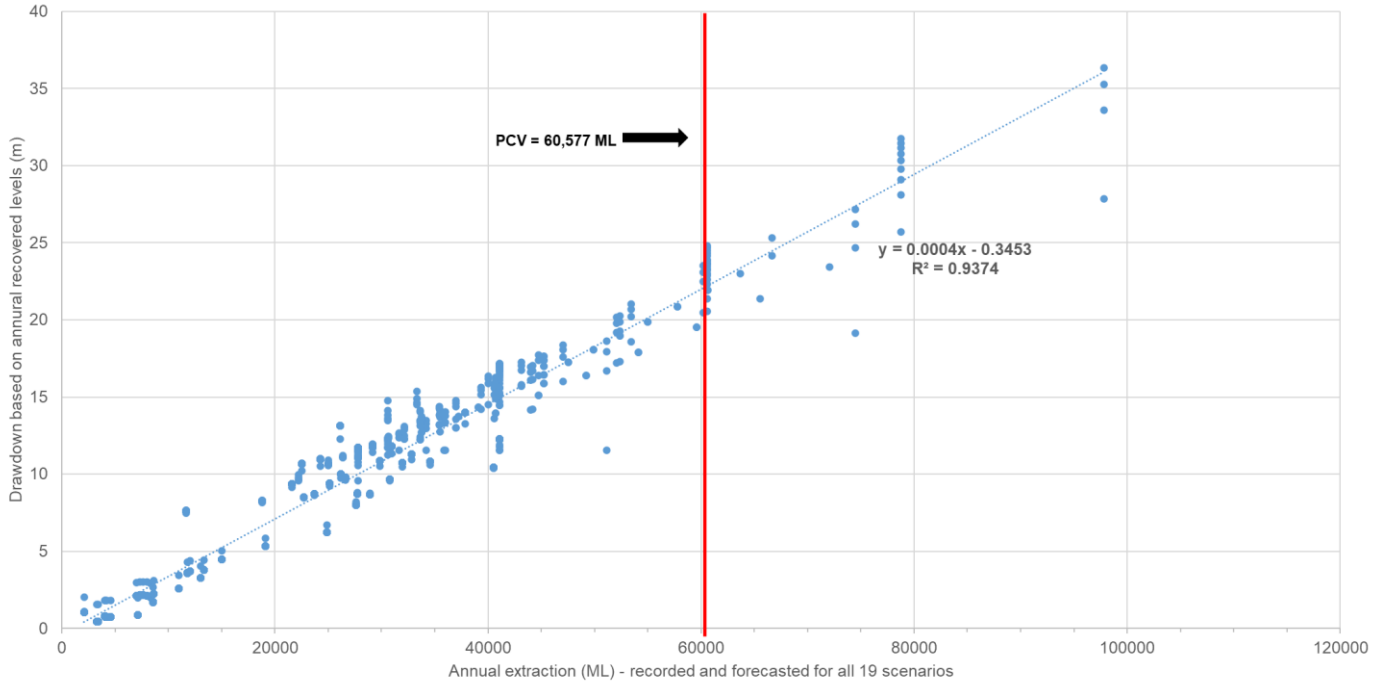


Figure 24 *Extraction vs drawdown for all forecast scenarios for Katunga WSPA Suite M_I_2*

3.6 Sustainability metrics and sustainable yield

3.6.1 Sustainability metrics

3.6.1.1 DEECA metrics

DEECA has developed a series of metrics that are proposed to protect values dependent on groundwater, which can also be used to assess and report on groundwater resource condition. DEECA's preliminary estimation of the groundwater sustainable yield metric related to confined aquifers, is outlined in Table 13. Where a representative Suite was identified to be an unconfined Suite, DEECA has provided groundwater sustainable yield metrics to use for unconfined aquifers, this is outlined in Table 14.

The basis of these metrics has been outlined previously by DEECA (2022). These metrics are used in this study to estimate the volume of groundwater take that will trigger the acceptability of groundwater drawdown and therefore, sustainable yield. At the time of writing this report, these metrics have been used as a draft guide for sustainable yield. GHD understands that the actual metrics to be used in each GMU forms an ongoing discussion between DEECA and its stakeholders. The application of current metrics does not preclude the results being used if a different metric is considered in future, since a range of water levels are predicted against a range of use volumes.

Table 13 *Groundwater sustainable yield metric – Confined aquifers (water supply)*

Value	Aquifer	Metric
Consumptive users – supply	Confined	Reduction in recovered groundwater level from pumping: – **< 5 m** – **5 to 10 m** – **> 10 m** (As measured from defined predevelopment levels)

Source: DEECA (2022)

Table 14 Groundwater sustainable yield metric – unconfined aquifers

Value	Aquifer	Metric
Consumptive users – supply	Unconfined	Reduction in recovered groundwater level from pumping: – **< 1 m** – **1 to 2 m** – **> 2 m** (As measured from defined predevelopment levels)

Source: DEECA (2022)

3.6.1.2 Other metrics

The method adopted and TFN modelling approach in general, has been designed to be entirely flexible (i.e., with as little hard-coding as possible). This provides DEECA and project stakeholders the flexibility in modifying metrics (e.g., on a GMU basis) via user-input parameters/options.

At this stage, only the DEECA (2020) metrics have been used in estimating sustainable yield for the GMUs. It is noted that DEECA may develop other metrics to be adopted on a GMU by GMU basis; these can be incorporated when developed.

3.6.1.3 Applying the metrics

Using the relationship developed through the previous step of forecasting aquifer response under a range of use scenarios, groundwater drawdown can be used to compare against metrics that define groundwater resource sustainability. In summary, the approach applied can be described as shown in Figure 25.

The method adopted and TFN modelling approach in general, has been designed to be entirely flexible (i.e., with as little hard-coding as possible). This provides DEECA and project stakeholders the flexibility in modifying metrics (e.g., on a GMU basis) via user-input parameters/options.

Following DEECA's advice, only the DEECA (2020) metrics have been used in estimating sustainable yield for the GMUs. It is noted that DEECA may develop other metrics to be adopted on a GMU by GMU basis; these can be incorporated when developed.

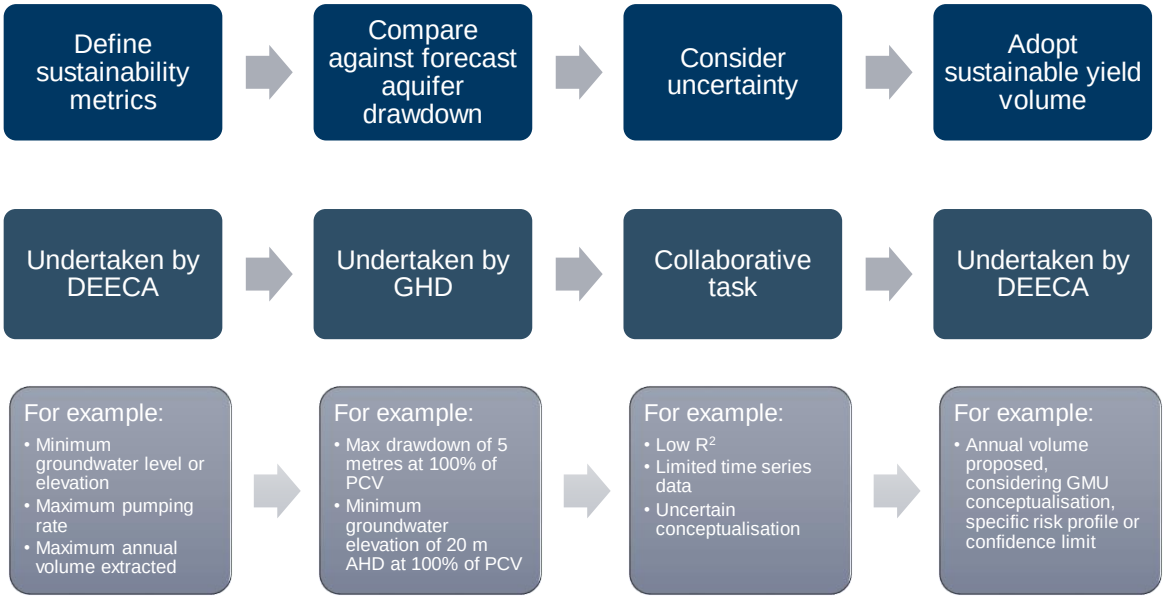


Figure 25 Method to apply sustainability metrics

3.6.1.4 Groundwater values

Groundwater values represent aspects of the environment that interact with or rely on groundwater and that the Victorian community expect to be achieved and maintained. Groundwater values can relate to social, cultural and economic aspects and can be measured in terms of their sustainability through various indicators.

3.6.1.5 Risks to groundwater values

There are several indicators relevant to each GMU in maintaining acceptable conditions to groundwater and values dependent on groundwater.

As per the scope of this study, the only risk to groundwater values that GHD's modelling approach directly considered is that relating to the direct risk of **declining water levels**, which could affect the consumptive values of groundwater.

Unsustainable pumping from a confined aquifer could result in unsustainable decline in potentiometric surface, which could impact overall aquifer sustainability and availability for consumptive uses.

It is broadly accepted that minimising water level decline in a confined aquifer to above the top of the confining layer or limiting pressure declines to recoverable (elastic) rather than permanent (inelastic) deformation of an aquifer, would minimise the release of pore water in the compressible sediments from storage. It is assumed that DEECA would seek to maintain groundwater levels/pressures above the top of the aquifer in its future definition of sustainability metrics and the adoption of sustainable yields.

Determining acceptable levels of impact is a policy matter and will be considered by DEECA through policy review process of GM2030 work program, not in this project.

Following this project, once acceptable levels of impact are defined for each GMU by DEECA (in consultation with relevant stakeholders) an acceptable range of drawdown magnitude and extraction volume can be defined.

Summary results

Summary results for all GMUs

4. Results summary

The statewide application of the method described in section 3 was conducted for 25 GMUs. From these, only one GMU could not undergo application of the full method due to data limitations (i.e., no historic extraction data being available, which is an essential input into the method).

Across the 25 GMUs, there was a total of 43 relevant Suites identified[3], 42 of which underwent predictive modelling. The preferred model input combination for predictive modelling based on model calibration runs, was that of annual recorded extraction with hindcast method H2 applied and annual recovered levels with 14 Suites (or 33% of Suites tested) adopting this combination (refer to Table 15). This was clearly the preferred model, with the next most adopted model being annual recorded extraction including external influence with hindcast method H2 or two yearly annual average recorded extraction with hindcast method H2, as shown in Table 15.

A summary of the key results for each GMU is presented in Table 16 including the final adopted representative Suite, the pre-development levels utilised in calculating the drawdown for the use-drawdown relationships, the adopted predictive model input combination and the estimated volumes for 5 m and 10 m of drawdown (along with the upper and lower estimates in brackets based on the 95% prediction interval results).

Table 15 Summary of adopted methods in predictive modelling based on nominated Suites

Extraction model input data (all models run with annual recovered levels)	Number of models adopted (based on GMU and Suite)
Annual recorded extraction with hindcast method H2	14
Annual recorded extraction including external influence with hindcast method H2	5
Two yearly annual average recorded extraction with hindcast method H2	5
Annual recorded extraction with hindcast method H3	3
Annual recorded extraction with hindcast method H3 with climate	3
Annual recorded extraction only	3
Annual recorded extraction including external influence with hindcast method H1	2
Annual recorded extraction with hindcast method H2 and climate	2
Two yearly annual average recorded extraction with hindcast method H2 and climate	2
Annual recorded extraction with hindcast method H3 with spatial distribution method S1	1
Annual recorded extraction with hindcast method H3 and spatial distribution method S1 with climate	1
Annual recorded extraction with historical data backfilled with 0 ML/year	1
Grand total	**42**

[3] 38 Suites when removing duplication of Suites across the GMUs

Table 16 Summary of Stage 2 GMU results

GMU	PCV (ML)	Average historic use (min – max) (ML)	Representative Suite (s)	Years of Suite Annual Recovered Level data	Pre-development annual recovered level (m) (Year/s; single point or average over range of years)	Preferred model input combination for predictive modelling	Volume (ML/year) for 5 m of drawdown over 20 years (Where ^ relates to unconfined aquifers and indicates 1 m of drawdown over 20 years) (Volumes rounded to the nearest 100 ML)	Volume (ML/year) for 10 m of drawdown over 20 years (Where ^ relates to unconfined aquifers and indicates 2 m of drawdown over 20 years) (Volumes rounded to the nearest 100 ML)
Corinella GMA	2,550	60 (14 – 129)	M_S_88	1968/1969 - 2020/2021	0.6 m (1968/1969 - 2004/2005)	Annual recorded extraction with hindcast method H2 and climate	3,800 (1,100 – 7,400)	7,700 (2,300 – 14,600)
Cut Paw Paw GMA	3,650	99 (12 – 424)	L_U_1	1972/1974 - 2020/2021	1.16 m (1989/1990)	Annual recorded extraction with hindcast method H2 and climate	1,900 (300 – 2,900)	5,000 (1,000 – 6,800)
Frankston GMA	3,200	230 (50 – 686)	L_U_1	1973/1974 - 2020/2021	1.16 m (1989/1990)	Annual recorded extraction with hindcast method H3 and spatial distribution method S1 with climate	900 (100 – 1,100)	1,400 (900 – 1,700)
			M_T_3	1972/1973 - 2020/2021	1.41 m (1996/1997)	Annual recorded extraction with hindcast method H3 with climate	2,300 (300 – 2,700)	3,100 (2,100 – 3,600)
Koo Wee Rup WSPA	12,915	3,610 (1,924 – 6,452)	M_S_1	1968/1969 - 2020/2021	1.88 (1996/1997)	Annual recorded extraction only	11,600 (7,500 – 18,400)	24,100 (17,500 – 35,000)
			M_S_2	1968/1969 - 2020/2021	1.14 m (1996/1997)	Annual recorded extraction only	24,200 (21,700 – 53,300)	49,200 (46,700 – 103,300)
			M_S_3	1970/1971 - 2020/2021	3.33 m (1970/1971)	Annual recorded extraction only	11,900 (6,800 – 25,600)	28,500 (23,500 – 50,600)

GMU	PCV (ML)	Average historic use (min – max) (ML)	Representative Suite (s)	Years of Suite Annual Recovered Level data	Pre-development annual recovered level (m) (Year/s; single point or average over range of years)	Preferred model input combination for predictive modelling	Volume (ML/year) for 5 m of drawdown over 20 years (Where ^ relates to unconfined aquifers and indicates 1 m of drawdown over 20 years) (Volumes rounded to the nearest 100 ML)	Volume (ML/year) for 10 m of drawdown over 20 years (Where ^ relates to unconfined aquifers and indicates 2 m of drawdown over 20 years) (Volumes rounded to the nearest 100 ML)
Moorabbin GMA	2,700	1,096 (545 – 1,987)	M_T_3	1972/1973 - 2020/2021	1.19 m (1973/1974)	Two yearly annual average recorded extraction with hindcast method H2 and climate	5,300 (4,500 – 5,700) *(this is two yearly average annual volumes)*	10,900 (9,500 – 11,300) *(this is two yearly average annual volumes)*
			M_T_2	1972/1973 - 2020/2021	1.63 m (1993/1994)	Two yearly annual average recorded extraction with hindcast method H2 and climate	7,000 (5,200 – 16,800) *(this is two yearly average annual volumes)*	15,400 (13,500 – 33,500) *(this is two yearly average annual volumes)*
Murrayville GMA	11,005	5,408 (2,866 – 8,331)	M_AC_2	1967/1968 - 2020/2021	8.60 m (1997/1998)	Annual recorded extraction including external influence within hindcast method H2	4,600 (4,100 – 5,200)	8,000 (7,200 – 8,800)
West Wimmera GMA	57,409	22,033 (15,601 – 27,310)	M_AD_1	1987/1988 - 2020/2021	1.00 m (1987/1988 - 1994/1995)	Annual recorded extraction with hindcast method H2	87,800 (65,600 – 116,900)	171,200 (137,100 – 216,900)
			M_E_8	1976/1977 - 2020/2021	0.58 m (1976/1977 - 1985/1986)	Annual recorded extraction with hindcast method H2	241,600 (154,000 – 505,600)	491,600 (320,700 – 1,005,600)
Katunga WSPA	60,577	27,785 (11,654 – 41,104)	M_I_2	1974/1975 - 2020/2021	13.41 m (1981/1982)	Annual recorded extraction with hindcast method H2	13,400 (8,400 – 18,600)	25,900 (20,900 – 31,000)
			M_I_1	1974/1975 - 2020/2021	18.52 m (1981/1982)	Annual recorded extraction including external influence within hindcast method H2	11,000 (-2,000 – 25,400)	27,900 (10,500 – 42,000)

GMU	PCV (ML)	Average historic use (min – max) (ML)	Representative Suite (s)	Years of Suite Annual Recovered Level data	Pre-development annual recovered level (m) (Year/s; single point or average over range of years)	Preferred model input combination for predictive modelling	Volume (ML/year) for 5 m of drawdown over 20 years (Where ^ relates to unconfined aquifers and indicates 1 m of drawdown over 20 years) (Volumes rounded to the nearest 100 ML)	Volume (ML/year) for 10 m of drawdown over 20 years (Where ^ relates to unconfined aquifers and indicates 2 m of drawdown over 20 years) (Volumes rounded to the nearest 100 ML)
Lower Campaspe Valley WSPA	55,875	29,689 (8,523 – 50,259)	M_H_1	1971/1972 - 2020/2021	11.06 m (1978/1979)	Annual recorded extraction with hindcast method H2	17,000 (9,700 – 24,600)	33,700 (26,400 – 41,200)
			M_H_2	1972/1977 - 2020/2021	7.28 m (1980/1981)	Annual recorded extraction with hindcast method H2	14,300 (7,100 – 31,500)	30,900 (23,800 – 56,500)
			M_H_3	1981/1982 – 2020/2021	9.78 m (1981/1982)	Annual recorded extraction with hindcast method H3	20,300 (10,400 – 26,700)	45,300 (27,000 – 51,700)
Mid Loddon GMA	34,037	17,689 (2,738 – 30,310)	M_F_2	1968/1969 - 2020/2021	9.01 m (1983/1984)	Annual recorded extraction with hindcast method H3 and climate	12,600 (1,900 – 23,900)	25,100 (9,000 – 40,600)
			M_F_3	1972/1973 - 2020/2021	2.31 m (1972/1973)	Annual recorded extraction with hindcast method H2	53,400 (39,300 – 66,800)	103,400 (89,300 – 116,800)
Giffard GMA	5,689	2,475 (845 – 5,548)	U_AF_1	1986/1987 - 2020/2021	1.46 m (1986/1987 - 1998/1999)	Annual recorded extraction with hindcast method H2	16,900 (13,600 – 18,700)	33,600 (26,100 – 35,400)
			U_AG_1	2001/2002 - 2020/2021	0.58 m (2001/2002 - 2002/2003)	Two yearly annual average recorded extraction with hindcast method H2	47,700 (23,000 – 67,700)	97,700 (48,000 – 124,200)
Moe GMA	8,200	826 (191 – 1,447)	L_PP_88	1973/1974 - 2020/2021	2.07 m (2004/2005)	Annual recorded extraction with hindcast method H2	19,300 (1,800 – 23,900)	44,300 (8,000 – 48,900)

GMU	PCV (ML)	Average historic use (min – max) (ML)	Representative Suite (s)	Years of Suite Annual Recovered Level data	Pre-development annual recovered level (m) (Year/s; single point or average over range of years)	Preferred model input combination for predictive modelling	Volume (ML/year) for 5 m of drawdown over 20 years (Where ^ relates to unconfined aquifers and indicates 1 m of drawdown over 20 years) (Volumes rounded to the nearest 100 ML)	Volume (ML/year) for 10 m of drawdown over 20 years (Where ^ relates to unconfined aquifers and indicates 2 m of drawdown over 20 years) (Volumes rounded to the nearest 100 ML)
			L_Q_1	1972/1973 - 2020/2021	7.00 m (1977/1978 - 1979/1980)	Annual recorded extraction with hindcast method H2	900 (500 – 1,400)	2,000 (1,200 – 2,600)
Orbost GMA	1,217	294 (59 – 578)	U_Y_1	2001/2002 - 2020/2021	0.66 m (2001/2002 - 2002/2003)	Two yearly annual average recorded extraction with hindcast method H2	2,200 (1,500 – 2,900)	4,200 (3,000 – 5,400)
Rosedale GMA	22,372	8,828 (3,117 – 18,923)	M_O_2	1977/1978 - 2020/2021	5.58 m (1979/1980)	Annual recorded extraction with hindcast method H3	2,200 (500 – 6,800)	8,500 (4,500 – 15,100)
Sale WSPA	21,238	11,029 (6,324 – 17,867)	M_O_1	1984/1985 - 2020/2021	6.45 m (1985/1986)	Two yearly annual average recorded extraction with hindcast method H2	8,000 (6,600 – 10,900)	14,300 (12,900 – 18,000)
			M_P_1	1978/1979 - 2020/2021	1.05 m (1978/1979 - 1979/1980)	Two yearly annual average recorded extraction with hindcast method H2	26,700 (24,600 – 27,600)	51,700 (49,600 – 52,600)
			U_AB_1	1976/1977 - 2020/2021	0.81 m (1976/1977)	Two yearly annual average recorded extraction with hindcast method H2	83,000 (59,300- 85,600)	166,300 (121,800 – 169,000)
Stratford GMA	27,686	22,625 (17,225 – 27,897)	L_O_1	1978/1979 - 2020/2021	22.87 m (1978/1979)	Annual recorded extraction including external influence within hindcast method H1	9,800 (-9,700 – 8,800)	13,700 (-3,400 – 13,800)

GMU	PCV (ML)	Average historic use (min – max) (ML)	Representative Suite (s)	Years of Suite Annual Recovered Level data	Pre-development annual recovered level (m) (Year/s; single point or average over range of years)	Preferred model input combination for predictive modelling	Volume (ML/year) for 5 m of drawdown over 20 years (Where ^ relates to unconfined aquifers and indicates 1 m of drawdown over 20 years) (Volumes rounded to the nearest 100 ML)	Volume (ML/year) for 10 m of drawdown over 20 years (Where ^ relates to unconfined aquifers and indicates 2 m of drawdown over 20 years) (Volumes rounded to the nearest 100 ML)
Yarram WSPA	25,690	11,482 (6,740 – 16,557)	L_O_2	1983/1984 - 2020/2021	14.93 m (1984/1985)	Annual recorded extraction with hindcast method H3 with spatial distribution method S1	-800 (-6,600 – 5,500)	9,200 (3,400 – 17,900)
			L_O_1	1978/1979 - 2020/2021	22.87 m (1978/1979)	Annual recorded extraction including external influence within hindcast method H2	3,400 (1,900 – 4,300)	5,500 (4,000 – 6,500)
Condah WSPA	7,475	2,782 (1,115 – 3,912)	L_A_1	1994/1995 - 2020/2021	10.91 m (1995/1996)	Annual recorded extraction with hindcast method H3	1,300 (800 – 2,300)	4,400 (3,000 – 5,000)
			L_A_2	1994/1995 - 2020/2021	4.69 m (1995/1996)	Annual recorded extraction with hindcast method H2	3,000 (2,000 – 3,600)	6,900 (4,800 – 7,400)
Gellibrand GMA	0	0 (0 – 0)	L_Y_3	1973/1974 - 2020/2021	NA	NA	NA	NA
Gerangamete GMA	239	3,524 (3 – 12,692)	L_Y_1	1973/1974 - 2020/2021	21.16 m (1973/1974)	Annual recorded extraction with historical data backfilled with 0 ML/year	30 (-2,700 – 4,100)	1,700 (-1,100 – 5,600)
Glenelg WSPA	33,262	7,383 (2,413 – 19,952)	L_AF_1	1974/1975 - 2020/2021	1.83 m (1974/1975 - 1991/1992)	Annual recorded extraction including external influence within hindcast method H2	20,800 (14,100 – 21,500)	45,800 (30,700 – 46,500)

GMU	PCV (ML)	Average historic use (min – max) (ML)	Representative Suite (s)	Years of Suite Annual Recovered Level data	Pre-development annual recovered level (m) (Year/s; single point or average over range of years)	Preferred model input combination for predictive modelling	Volume (ML/year) for 5 m of drawdown over 20 years (Where ^ relates to unconfined aquifers and indicates 1 m of drawdown over 20 years) (Volumes rounded to the nearest 100 ML)	Volume (ML/year) for 10 m of drawdown over 20 years (Where ^ relates to unconfined aquifers and indicates 2 m of drawdown over 20 years) (Volumes rounded to the nearest 100 ML)
			M_AF_1	1978/1979 - 2020/2021	2.00 m (1992/1993)	Annual recorded extraction including external influence within hindcast method H2	16,100 (11,900 – 16,900)	32,800 (24,400 – 33,500
			U_D_8	1980/1981 - 2020/2021	0.50 m (1980/1981 - 1981/1982)	Annual recorded extraction including external influence within hindcast method H1	^38,000 (9,700 – 60,000)	^88,000 (43,100 – 110,000)

GMU	PCV (ML)	Average historic use (min – max) (ML)	Representative Suite (s)	Years of Suite Annual Recovered Level data	Pre-development annual recovered level (m) (Year/s; single point or average over range of years)	Preferred model input combination for predictive modelling	Volume (ML/year) for 5 m of drawdown over 20 years (Where ^ relates to unconfined aquifers and indicates 1 m of drawdown over 20 years) (Volumes rounded to the nearest 100 ML)	Volume (ML/year) for 10 m of drawdown over 20 years (Where ^ relates to unconfined aquifers and indicates 2 m of drawdown over 20 years) (Volumes rounded to the nearest 100 ML)
Jan Juc GMA	14,250	2,801 (7 - 7,806)	L_X_2	1993/1994 - 2020/2021	3.16 m (1993/1994)	Annual recorded extraction with hindcast method H2	-400 (-2,700 – 2,700)	9,600 (3,500 – 15,200)
Newlingrook GMA	1,977	145 (8 - 738)	L_AA_99	1976/1977 - 2020/2021	0.66 m (1976/1977 - 1981/1982)	Annual recorded extraction with hindcast method H2	3,700 (600 – 5,500)	7,900 (1,200 – 11,100)
Paaratte GMA	4,606	321 (281 - 367)	L_AA_99	1976/1977 - 2020/2021	0.66 m (1976/1977 - 1981/1982)	Annual recorded extraction with hindcast method H3 with climate	3,200 (1,500 – 4,800)	6,500 (3,200 – 9,800)
Portland GMA	7,795	2,606 (2,121 - 3,244)	L_A_2	1994/1995 - 2020/2021	4.50 m (1994/1995 - 1996/1997)	Annual recorded extraction with hindcast method H2	3,100 (1,800 – 3,400)	7,200 (4,500 – 7,600)
			L_C_1	1974/1975 - 2020/2021	1.96 m (1974/1975)	Annual recorded extraction with hindcast method H2	7,200 (4,600 – 8,000)	15,500 (10,200 – 16,300)

5. Discussion summary

5.1 Suites

For each of the 25 GMUs, the process outlined in section 2.6.4 for selecting the relevant Suites and ultimately the Representative Suite was undertaken. Based on this process, the following summary of relevant Suites was identified:

- 10 GMUs were shown to be potentially represented by only one single Suite
- 10 GMUs were shown to be potentially represented by two Suites
- Four GMUs were shown to be potentially represented by three Suites (noting that the number of Suites was capped at three)
- One GMU did not have a representative Suite identified

The GMU where no Suites were identified following the representative Suite selection methodology was Jan Juc GMA. This was due to no Suites being identified as having an extraction bore within them. In this instance, all the Suites from the relevant aquifer were considered in the modelling.

Each of the Suites within a GMU underwent the model calibration process to review the model results and statistics for each model combination, which identified the model combination producing the best model fit that went through the pre-development period to progress to predictive modelling. Where a GMU had multiple Suites to progress to the modelling process (14 GMUs on total with multiple Suites):

43% had the same model type adopted for the predictive modelling for all Suites for that GMU

57% had different model types adopted for the predictive modelling for the Suites for that GMU

There is a limitation with the use of Suite data for some of the GMUs where insufficient extraction occurs within relevant Suites or the area of the GMU covered by the relevant Suites is limited. The available monitoring bores to inform Suite data, and the trends that the groupings for the Suites are based, may have changed since the assignment of Suites. A revision of the Suites and a more robust and accurate process for assigning use to Suites may improve the application of this methodology.

5.2 Appropriateness of applied methodologies

5.2.1 Extraction combinations modelled

In total, 19 different methods using extraction data were developed and tested on each of the selected representative Suites and GMUs. These methods each comprised annual recovered levels and one of the following extraction combinations:

- GMU annual extraction
- GMU annual extraction and hindcast method H1
- GMU annual extraction and hindcast method H2
- GMU annual extraction and hindcast method H3
- GMU annual extraction and spatial distribution method S1
- GMU annual extraction and spatial distribution method S2
- GMU annual extraction and spatial distribution method S3
- GMU annual extraction, hindcast method H3 and spatial distribution method S1
- GMU annual extraction, hindcast method H3 and spatial distribution method S2
- GMU annual extraction, hindcast method H3 and spatial distribution method S3
- GMU annual extraction with externalities annual extraction included

- GMU annual extraction with externalities annual extraction included and hindcast method H1
- GMU annual extraction with externalities annual extraction included and hindcast method H2
- GMU two yearly annual average extraction
- GMU two yearly annual average extraction and hindcast method H1
- GMU two yearly annual average extraction and hindcast method H2
- GMU two yearly annual average extraction with externalities annual extraction included
- GMU two yearly annual average extraction with externalities annual extraction included and hindcast method H1
- GMU two yearly annual average extraction with externalities annual extraction included and hindcast method H2

Not every GMU was run for all 19 combinations, due to several factors including when:

- There was no external influence identified for a GMU, negating the need for runs with external influence
- The Suite bore dataset did not contain any relevant Suite bores for that GMU and thus spatial methods could not be applied
- Historic extraction datasets were available to either the start of the Suite hydrograph period or to when major development started within the GMU, negating the need for runs with hindcasting

It is noted that in some instances, when the extraction methodology selected did not produce results as expected, climate data was also added to the model to try and improve the model results. This was not applied at every GMU, only those where it was logical that the aquifer may be receiving recharge.

For each GMU, each of the methodologies applied in calibration modelling were assessed based on the four statistical measures, the range in annual recovered levels the model is calibrating to and also whether the model incorporated the pre-development period. The two key model calibration measures were the R^2 as an indicator of the precision of the model and RMSE as an indicator of the accuracy of the model. Also taken into consideration are the uncertainty measures through the 95% prediction interval thickness along with the number of observation points within this band, as an indicator of uncertainty.

Most used extraction combinations

As discussed in section 4, the method using just the GMU annual extraction data with hindcast method H2 and the annual recovered levels, was the most adopted method. There were two second most adopted methodologies (based on the statistical results of the calibration modelling) these were:

- Annual recorded extraction including external influence with hindcast method H2
- Two yearly average annual extraction with hindcast method H2

Applying hindcasting enables more data to be input to the modelling and thus more data points on which to develop a correlation; generally, hindcast method H2 produced what was considered the best representation of historical use of the three hindcasting methods developed. It is noted that hindcasting introduces additional interpretation to the modelling and the model is not based solely on measured data. Recorded annual extraction with hindcast method H3 applied was the third most adopted method. In most cases the annual extraction datasets had to be hindcasted as the GMU recorded extraction was not long enough to capture the historical information needed to run the model back to pre-development periods (which is required to develop the use – drawdown graphs that are in reference to the pre-development period).

Least used extraction combinations

There were no predictive models run using the spatial distribution methods, generally due to either insufficient historical data included in these models (data only available from 2009) or the increasing complexity of hindcasting – with spatial distribution included – did not improve the models' statistical results. Regarding the application of hindcasting, the following is noted:

- Some of the hindcasting correlations developed showed poor R^2 results across all combinations tested for a given GMU. For example, Jan Juc GMA, where groundwater use is mostly for town water supply, which is intermittent, the Suite bores are not located in the main area where extraction occurs and climate (rainfall) is not a significant driver for variations in groundwater extraction (which the hindcasting correlations are based on).
- Comparisons of the hindcasted datasets for methods H2 and H3 with recorded datasets generally showed reasonable estimates. However, as expected, depending on the GMU some methods showed a better estimate than others.

Applicability of the adopted methods

Table 17 provides an overview of the applicability of the adopted calibration methods for the GMUs. The overall method applicability is assessed using Table 18 as a guide, considering the model applicability and the use-drawdown relationship. A description of the Coefficient of determination (R^2) ranges and RMSE is provided in section 3.4.1.3.1 which are key criteria for the assessments.

Table 17 Model applicability assessment matrix (Calibration)

		Coefficient of determination (R^2)			
		0.0 to 0.4	0.4 to 0.6	0.6 to 0.8	0.8 to 1.0
RMSE	<1.0	Poor	Moderate	Good	Excellent
	>1.0	Poor	Poor	Poor	Moderate

Table 18 Method applicability assessment matrix

		Model applicability rating (Calibration)			
		Poor	Moderate	Good	Excellent
R^2 from use – drawdown relationship	0.0 to 0.4	Poor	Poor	Moderate	Moderate
	0.4 to 0.6	Poor	Moderate	Moderate	Good
	0.6 to 0.8	Moderate	Moderate	Good	Excellent
	0.8 to 1.0	Moderate	Good	Excellent	Excellent

Table 19 Summary of method applicability by GMU

GMU	Suite(s) assessed	Model calibration criteria	Model calibration uncertainty analysis criteria				Use – drawdown relationship	Discussion of drawdown-use relationships	Method applicability
		R^2	RMSE	95 PPU TH	%Obs in 95PPU	Model applicability	R^2		
Corinella GMA	M_S_88	71.6	0.14	0.64	93.62	Good	50.3	Model calibration was between 0-150 ML/year groundwater extraction range. The greater the proposed extraction rates beyond this calibration range the more potential for drawdown forecast errors. In this GMU, drawdown prediction for extraction volumes up to 50 times the calibration range are being made to meet the 10 m drawdown metric.	Moderate
Cut Paw Paw GMA	L_U_1	83.9	0.38	2.05	95.83	Excellent	25.2	Model calibration was between approximately 50-450 ML/year groundwater extraction range (well below the current PCV of 3,650 ML/year). In this GMU prediction for extraction volumes up to 10 times the calibration range are being made to meet the 10 m drawdown metric.	Moderate
Frankston GMA	L_U_1	89.2	0.3	1.9	93.62	Excellent	38.6	The use-drawdown graph for Suite L_U_1 shows that the same use year on year an increase in drawdown is observed; this may be the influence of climate in the model. Model calibration was between approximately 50-700 ML/year groundwater extraction range (well below the current PCV of 3,200 ML/year, around 20% of the PCV).	Moderate
Frankston GMA	M_T_3	88.7	0.18	0.68	95.92	Excellent	76.5	This Suite requires much greater volumes to be extracted to cause a 5 m or 10 m drawdown compared to L_U_1. However, the correlation (R^2) for this suite is much higher than for L_U_1.	Excellent
Koo Wee Rup WSPA	M_S_1	56.6	0.55	2.3	97.83	Moderate	83.6	The use-drawdown relationship for this Suite is similar to that of Suite M_S_3. The R^2 of the relationship is relatively high given the low R^2 in the calibration model.	Good

GMU	Suite(s) assessed	Model calibration criteria	Model calibration uncertainty analysis criteria				Use – drawdown relationship	Discussion of drawdown-use relationships	Method applicability
		R^2	RMSE	95 PPU TH	%Obs in 95PPU	Model applicability	R^2		
Koo Wee Rup WSPA	M_S_2	43.4	0.32	1.35	95.65	Moderate	86.3	The use-drawdown for this Suite is significantly different than the other two Suites for this GMU and also has a large of predicted values based on the 95% prediction interval.	Good
Koo Wee Rup WSPA	M_S_3	32.6	0.9	3.74	100	Poor	79.6	The use-drawdown relationship for this Suite is similar to that of Suite M_S_1. The R^2 of the relationship is relatively high given the low R^2 in the calibration model.	Moderate
Moorabbin GMA	M_T_3	89.1	0.18	0.57	93.75	Excellent	83	In this GMU prediction for extraction volumes up to 6 times the calibration range are being made to meet the 10 m drawdown metric for this Suite (M_T_3). Even though this is the case, the resultant use - drawdown relationship produced an excellent R^2 value. Further checks and potential re-calibration may be required as rates increase for the GMUs.	Excellent
Moorabbin GMA	M_T_2	52.8	0.52	2.49	97.92	Moderate	44.3	Model calibration was between 0-1600 ML/year groundwater extraction range. The greater the proposed extraction rates beyond this calibration range the more potential for drawdown forecast errors. The predictive models for Suite M_T_2 failed to compute correctly for forecast scenario 4, 7 and 14. As such, the results from these forecast scenarios have been excluded from the assessment for this Suite. The resultant relationship has been defined as moderate but it should be considered if further work can be done to improve the relationship.	Moderate

GMU	Suite(s) assessed	Model calibration criteria	Model calibration uncertainty analysis criteria				Use – drawdown relationship	Discussion of drawdown-use relationships	Method applicability
		R^2	RMSE	95 PPU TH	%Obs in 95PPU	Model applicability	R^2		
Murrayville GMA	M_AC_2	95.7	0.44	2.07	100	Excellent	90.9	The model is based on a combined extraction regime from both Murrayville GMA and Mallee PWA but this was brought back to a Murrayville GMA use based on the average proportion of Murrayville GMA extraction in the combined use dataset. The resultant relationship of use-drawdown makes sense given the historical extraction and observed drawdowns.	Excellent
West Wimmera GMA	M_AD_1	95.3	0.15	1.19	91.18	Excellent	75.4	An excellent correlation drawdown to use for the representative Suite (M_AD_1) was produced. Although this Suite only covers 3% of the GMU area it contains the majority of extraction. In this Suite in this GMU, drawdown prediction for extraction volumes up to 6 times the calibration range are being made to meet the 10 m drawdown metric.	Excellent
West Wimmera GMA	M_E_8	69.8	0.13	0.54	93.33	Good	88.2	An excellent correlation drawdown to use for this Suite was produced. It's noted that for this Suite, in this GMU, drawdown prediction for extraction volumes up to 16 times the calibration range are being made to meet the 10 m drawdown metric. There is a significant difference in the use-drawdown relationships between the two suites.	Excellent
Katunga WSPA	M_I_2	94.7	1.02	4.37	93.62	Moderate	93.7	The use-drawdown relationships for both the Suites produced high R^2 values, however, the calibration models had high RMSE values which has lowered the applicability ratings of these model results.	Good
Katunga WSPA	M_I_1	86.8	1.92	8.19	100	Moderate	84.1		Good

GMU	Suite(s) assessed	Model calibration criteria	Model calibration uncertainty analysis criteria				Use – drawdown relationship	Discussion of drawdown-use relationships	Method applicability
		R^2	RMSE	95 PPU TH	%Obs in 95PPU	Model applicability	R^2		
Lower Campaspe Valley WSPA	M_H_1	92.7	1.15	5.12	94	Moderate	88.7	The use-drawdown relationship for this suite provides volumes for a given drawdown that are generally in between the volumes estimates for the other two Suites. The overall applicability of this correlation is good given the RMSE result of the calibration model.	Good
Lower Campaspe Valley WSPA	M_H_2	74.8	1.92	5.45	77.55	Poor	89.8	This Suite had the poorest calibration statistics of the three Suites for this GMU but produced the best use - drawdown correlation in terms of R^2. But given the poor calibration results the applicability has only been assigned as moderate.	Moderate
Lower Campaspe Valley WSPA	M_H_3	97.8	0.49	2.46	90	Excellent	76.3	This Suite had an excellent correlation ($R^{2)}$ for the calibration model and the use-drawdown graph. Its correlation shows a greater volume to be extracted to reach a 5 m or 10 m drawdown in comparison to the other Suites.	Excellent
Mid Loddon GMA	M_F_2	88.8	0.93	4.87	92.31	Excellent	64.3	An excellent correlation in the calibration model but poorer relationship of drawdown to use for the representative Suite (M_F_2). This Suite provides a more conservative estimate of the two Suites.	Excellent
Mid Loddon GMA	M_F_3	36.8	0.76	3.24	95.92	Poor	87.3	This Suite had the poorest calibration statistics of the three Suites for this GMU but produced the best use - drawdown correlation in terms of R^2. But given the poor calibration results the applicability has only been assigned as moderate. The results for this Suite show that a greater volume needs to be extraction compared to the volume estimate from Suite M_F_2 to achieve the same drawdown.	Moderate
Giffard GMA	U_AF_1	79.6	0.27	1.11	97.14	Good	88.3	An excellent correlation for the relationship of drawdown to use for this Suite. Originally, Suite U_AG_1 was the preferred Suite, but given that it did not show much drawdown and its results. Consideration will need to be made as whether U_AF_1 results are adopted instead.	Excellent

GMU	Suite(s) assessed	Model calibration criteria	Model calibration uncertainty analysis criteria				Use – drawdown relationship	Discussion of drawdown-use relationships	Method applicability
		R^2	RMSE	95 PPU TH	%Obs in 95PPU	Model applicability	R^2		
Giffard GMA	U_AG_1	71.6	0.09	0.65	90	Good	39.7	For this Suite, in this GMU prediction for extraction volumes up to 6 times the calibration range are being made to meet the 10 m drawdown metric Its noted that little to now drawdown was observed in this Suite which has impacted the results.	Moderate
Moe GMA	L_PP_88	57.2	0.37	18.62	89.58	Moderate	10.2	For this Suite, in this GMU prediction for extraction volumes up to 30 times the calibration range are being made to meet the 10 m metric. Additionally, L_PP_88 has a very low R^2 so consideration will need to be made as whether L_Q_1 results are adopted instead.	Poor
Moe GMA	L_Q_1	85.9	1.01	4.55	91.67	Moderate	85.9	The overall applicability of this correlation is good given the RMSE result of the calibration model and it nearly met the criteria to be defined as an excellent model applicability. Consideration will need to be made as whether L_Q_1 results are adopted for this GMU.	Good
Orbost GMA	U_Y_1	74.4	0.18	0.83	94.74	Good	90.6	An excellent relationship of drawdown to use for the representative Suite. It is noted that this Suite used hindcast method H3, which showed a good correlation (R^2=66) of rainfall to percentage of use to entitlement.	Excellent
Rosedale GMA	M_O_2	93	1.12	6.36	97.73	Moderate	76.9	The modelled calibration levels are lower than recorded pre-development levels (underestimates the levels at low extraction rates). This causes an approximate 3 m drawdown intercept in the use-drawdown graph.	Moderate
Sale WSPA	M_O_1	92.8	0.69	2.99	100	Excellent	91.5	This Suite consistently produced a high R^2 across the calibration and use-drawdown graph. It's anticipated that this Suite is most representative for Sale WSPA.	Excellent

GMU	Suite(s) assessed	Model calibration criteria	Model calibration uncertainty analysis criteria				Use – drawdown relationship	Discussion of drawdown-use relationships	Method applicability
		R^2	RMSE	95 PPU TH	%Obs in 95PPU	Model applicability	R^2		
Sale WSPA	M_P_1	98.3	0.11	1.05	93.02	Excellent	60.2	Suite M_P_1 does not show a reaction to pumping and these is a large difference in the use-drawdown relationship compared to Suite M_O_1.	Excellent
Sale WSPA	U_AB_1	93.1	0.09	0.52	95.56	Excellent	63.6	Suite U_AB_1 does not show a reaction to pumping. In the case of Suite U_AB_1 in particular, the low drawdowns associated with relatively high extraction rates may reflect that the analysis assumed the groundwater extraction in the Suite area occurred entirely from this aquifer, when in reality only a portion was; this may have skewed the predictive results.	Excellent
Stratford GMA	L_O_1	97.9	1.51	12.54	93.02	Moderate	16.8	The use-drawdown relationship for Stratford is relatively poor. It's noted that there is still significant extraction at the time of pre-development level in the model selected, it's likely the pre-development level is incorrect. This provides a poor R^2 and intercept of -8 m and nothing to calibrate on <18,000 ML/year.	Poor
Yarram WSPA	L_O_2	93.5	1.33	5.24	91.89	Moderate	36.4	For Suite L_O_2, the model did not match the pre-development level well and thus there is an offset in the results. There is also an underestimate of annual recovered levels at some flow rates which may be associated by offshore extraction influence. Further work should be done to improve the model fit.	Poor
Yarram WSPA	L_O_1	98.3	1.33	6.79	100	Moderate	86.2	This Suite had a different relationship to the representative Suite, however, the model that this relationship is based off takes into account offshore extraction whereas the model for the representative Suite does not.	Good
Condah WSPA	L_A_1	94.4	0.69	3.43	96.3	Excellent	92.6	Drawdown at 0 ML/year is around 3 m for Suite L_A_1, as the model underestimates the groundwater at the lower flow rates.	Excellent

GMU	Suite(s) assessed	Model calibration criteria	Model calibration uncertainty analysis criteria				Use – drawdown relationship	Discussion of drawdown-use relationships	Method applicability
		R^2	RMSE	95 PPU TH	%Obs in 95PPU	Model applicability	R^2		
Condah WSPA	L_A_2	97.9	0.28	2.5	100	Excellent	70.6	This Suite has an excellent relationship of drawdown to use and it produces less conservative results than Suite L_A_1.	Excellent
Gellibrand GMA	L_Y_3	NA	NA	NA	NA	NA	NA	No groundwater extraction information could be obtained for the assessment; the methodology developed for the project could not be applied.	NA
Gerangamete GMA	L_Y_1	84.6	3.98	20.81	93.75	Moderate	35.6	The use-drawdown relationship shows a large intercept value. There is a 6.5 m different between the recorded annual recovered level and the modelled annual recovered level at the taken pre-development date; this contributed to the y-intercept value. It's noted that licences have not been renewed for the Barwon Downs borefield, thus the average use used in the predictive scenarios is higher than existing use which has likely impact the results/use-drawdown relationships.	Poor
Glenelg WSPA	L_AF_1	97.1	0.14	0.72	89.66	Excellent	84.2	An excellent correlation was developed for this suites use-drawdown relationship.	Excellent
Glenelg WSPA	M_AF_1	90.8	0.2	0.91	96.55	Excellent	91.5	An excellent correlation was developed for this suites use-drawdown relationship; its noted that the border zone extraction included is from the middle aquifer. The relationship is the most conservative of the three Suites.	Excellent
Glenelg WSPA	U_D_8	88.2	0.14	0.77	93.1	Excellent	13.2	Suite U_D_8 is largely unaffected by the Glenelg WSPA/Border zone pumping rates, which influences the correlation of the use-drawdown relationship. This Suite is also unconfined.	Moderate

GMU	Suite(s) assessed	Model calibration criteria	Model calibration uncertainty analysis criteria				Use – drawdown relationship	Discussion of drawdown-use relationships	Method applicability
		R^2	RMSE	95 PPU TH	%Obs in 95PPU	Model applicability	R^2		
Jan Juc GMA	L_X_2	97.2	0.57	4.22	95.59	Excellent	14.6	The calibration model showed good statistical results for the selected model. However, this did not convert over to the use-drawdown relationship which might be due to the recovery dataset included in the calibration model. The recovery data was excluded from the use-drawdown relationship, however still yielded a low correlation and overestimated extractions. It's noted that this Suite does not occur in the main area of extraction in this GMU.	Moderate
Newlingrook GMA	L_AA_99	79.1	0.16	0.82	100	Good	44.6	The drawdown graph shows high sensitivity at low flow rates. In this GMU, drawdown prediction for extraction volumes up to 9 times the calibration range are being made to meet the 10 m drawdown metric. The current use-drawdown relationship is unlikely to provide a good estimate at higher flow rates.	Moderate
Paaratte GMA	L_AA_99	89.2	0.11	0.64	95.45	Excellent	80	The use-drawdown relationship developed has been rated as an excellent applicability. However, the calibration ranges used in the modelling were quite small compared to some of the forecasted scenarios. Greater the proposed extraction rates beyond this calibration range the more potential for drawdown forecast errors. In this GMU, drawdown prediction for extraction volumes up to 16 times the calibration range are being made to meet the 10 m drawdown metric.	Excellent
Portland GMA	L_A_2	98.3	0.26	2.32	96.3	Excellent	59.5	The analysis shows that less volume is to be extracted from L_A_2 compared to L_C_1 to cause 10 m of drawdown. Consideration should be made as to whether L_A_2 be adopted as a conservative estimate.	Good

GMU	Suite(s) assessed	Model calibration criteria	Model calibration uncertainty analysis criteria				Use – drawdown relationship	Discussion of drawdown-use relationships	Method applicability
		R^2	RMSE	95 PPU TH	%Obs in 95PPU	Model applicability	R^2		
Portland GMA	L_C_1	83.3	0.26	1.31	100	Excellent	74.9	An excellent correlation for the use-drawdown relationship was developed for this Suite. It is noted that the relationship may not provide reasonable estimates at high drawdowns due to the small range of extraction volumes used in calibration.	Excellent

5.3 Drawdown – use relationship and metrics

Drawing an analogy from a pumping bore, there are a number of assumptions underpinning the Theis equation for modelling the drawdowns in a confined aquifer, e.g., it is homogeneous, isotropic and an infinitely extensive aquifer etc. From a local perspective (i.e., at the bore scale), these assumptions may be valid. However, regionally there may be variations within the aquifer e.g., thickness, presence of boundaries, which result in a confined aquifer deviating from the ideal response.

In terms of a Theissian response, the following is expected for a confined aquifer:

- The more pumping, the greater the drawdown
- Given sufficient time, drawdowns should tend towards a stabilisation under a constant pumping rate (actually very small changes in drawdown with increasing duration of pumping)

Whilst the GHD approach has developed a relationship between use and drawdown, which enables application of a metric, it does not inform the sustainable limit for a GMU. From a management perspective, it would be less complex if a drawdown could be defined for a Suite area, which is directly relatable to sustainability in a confined aquifer, i.e., a lower bound drawdown (see Figure 26). Furthermore, if the number of Suites can be minimised it would simplify reporting on a GMU basis (hence the adoption of a representative Suite).

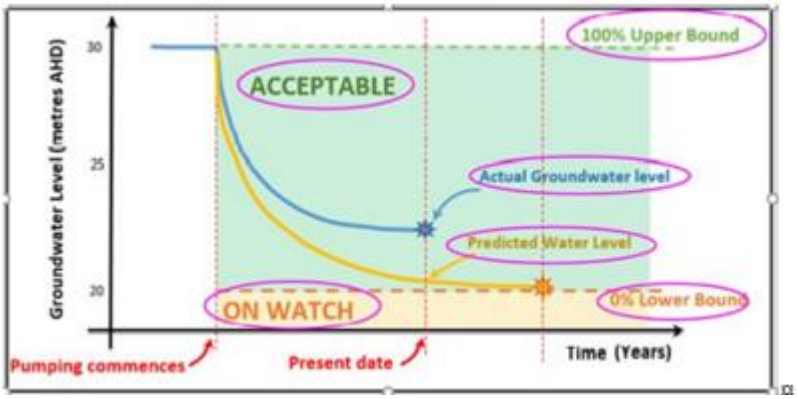


Figure 26 Resource management concept using water level bounds

In terms of constraining the drawdown, spatial mapping could be undertaken to excise areas that are likely to be unacceptable for high volume uses (e.g., irrigation/industrial/urban development). This would require developing a series of rules to support the mapping analysis, for example:

- Eliminate those parts of the Suite hydrograph area which are too thin to be developed, i.e., due to the transmissivity of the aquifer, or minimum length of bore screen required, rendering it problematic to develop areas on the [thinning] margins of the aquifer extent
- Eliminate those parts of the Suite area where groundwater quality is atypical (e.g., saline), or where a certain magnitude of drawdown could trigger a reversal in groundwater flow directions
- Eliminate/identify areas not covered by a Suite hydrograph (or where high uncertainty exists)
- Drawdowns should not be below the top of the aquifer (to protect aquifer integrity). Therefore, the top of the aquifer needs to be mapped (VAF layers), along with the regional potentiometric surface, to estimate the 'available drawdown' above the top of the aquifer.
- Drawdowns should be restricted to a percentage of the aquifer available drawdown (e.g., 50%?)
- Drawdowns should be not greater than X to protect Y number of stock and domestic bores (<50%) from being dewatered

Once the areas are excised, the estimated drawdowns derived from the use – drawdown relationship can be compared against the available drawdown.

Summary results

Detailed results for all GMUs

6. Model results presentation

This section provides an outline of how the model results are presented in the next chapters. This outline focusses on the key sections within the detailed model results chapters.

- **Conceptualisation** – this section provides a tabulated summary of the hydrogeological conceptualisation elements relevant to the GMU
- **Technical analysis** – this section outlines the data elements relevant to the GMU, including:
  - Data inputs, including groundwater level data and available groundwater use data
  - Suite selection approach
  - External factors potentially influencing groundwater in the GMU
  - Data analysis required to fill identified data gaps in preparation for modelling
- **Modelling** – this section outlines all aspects of the modelling of real data (i.e., between actual pumping stress and observed actual groundwater level response), including inputs, calibration and uncertainty analysis and model outputs
- **Predictive modelling** – this section outlines all aspects of the predictive modelling (i.e., using the real data to project into future time periods with a range of future use scenarios), including inputs, estimation of pre-development conditions, calibration and uncertainty analysis and model outputs (use – drawdown relationships)
- **Sustainability metrics** – this section outlines the application of GHD's model predictions to the DEECA metrics
- **GMU summary** – this section outlines the findings for the GMU based on the assessment undertaken, along with an outline of limitations and recommendations specific to the GMU

7. Katunga WSPA

7.1 Conceptualisation

The hydrogeological conceptualisation elements relevant to this study are summarised in Table 20 and a map of the GMU is presented in Figure 27. It is noted that a significant volume of information was collated to inform the hydrogeological conceptual understanding of the GMU. The information that is directly relevant to the modelling are in bold or colour coded within Table 20.

Table 20 Katunga WSPA – Tabulated conceptualisation

GMU summary

Katunga WSPA is situated in northern Victoria within the floodplains of the Murray and Goulburn Rivers as shown in Figure 27. The boundary of the Katunga WSPA follows an area of intensive groundwater use south of the Murray River along the Victoria – New South Wales (NSW) border. Katunga WSPA covers an area of 2,100 km^2 and within this area, the WSPA pertains to all formations below 25 m from surface; the PCV (60,577 ML/year) therefore primarily relates to confined aquifers, in particular the Calivil Formation (UTAF).

Groundwater within the Katunga WSPA is predominately used for irrigation purposes; however, it is also extensively used for dairy and other commercial and industrial purposes including urban water supplies (SKM, 2006[4]).

It is understood that groundwater extraction occurs to the north of Katunga WSPA in NSW for irrigation purposes. It is expected that extraction in NSW would occur during similar times of the year to Katunga WSPA. It is inferred that groundwater extraction in either state could result in cumulative declines in hydraulic heads in the confined aquifers, particularly the Deep Lead.

Katunga WSPA occurs within the Murray-Darling Basin and the Goulburn-Murray Water Resource Plan area under the Murray Darling Basin Plan.

Hydrostratigraphy summary

Aquifer	Formation	Relevant Suites (% coverage of GMU)	% of GMU covered by Suites	Number of SON bores	Groundwater use	Use volumes ML (2019/20)	Entitlement volumes ML (2019/20)	Understanding (Low, Medium, High)
Upper	Coonambidgal Formation (QA)	-	-	0	NA	0	0	Low
	Shepparton Formation (UTQA)	U_Q_2 (11%), U_QQ_1 (11%), U_QQ_2 (19%), U_QQ_3 (24%), U_Q_3 (31%), U_R_9 (2%), U_U_1 (1%), U_S_1 (0.2%), U_S_2 (1%), U_T_1	100%	13	Communal Domestic, domestic, stock, dairy, industrial, irrigation	1,861	3,100	High
Middle	Calivil Formation (UTAF)	M_I_1 (27%), M_I_2 (67%), M_J_9 (0%)	94%	14	Industrial, irrigation, domestic, dairy	28,449 (27,473)	47,521 (46,004)	High
Lower	Renmark Group (LTA)	L_L_2 (51%)	51%	2	Domestic, irrigation, dairy, irrigation	7,527	10,017	Medium
Basement	Cretaceous and Permian Sediments (CPS)	--	-	0	NA	0	0	Low
	Basement rocks (BSE)	B_M_1 (7%), B_M_2 (0.1%)	7%	1	NA	0	0	Low

Note that volumes listed above are based on the DEECA provided licenced bore dataset with associated VAF layers. Bores have been assigned to a VAF layer based on bore depth where available. In some instances, bore depth is not available and has been reallocated where possible; the reassigned volumes are indicated within the brackets.

Note that volumes listed above do not include 27,473 ML of unassigned use due to unknown depths. The volumes for BSE and CPS have been incorporated into the LTA based on feedback provided by RWCs.

[4] SKM 2006, Groundwater Management Plan for the Katunga Water Supply Protection Area

Characteristic and importance	Description	Degree of understanding
Intended aquifer (UTAF, highlighted blue in table above)		
Aquifer thickness within GMU (range, based on VAF)	Max: 77.8 m, Average: 24.8 m	High
Aquifer extent	Regional, extensive	High
Likelihood of inter-aquifer flow	Medium	Moderate
Likelihood of groundwater – surface water interaction	Medium	Moderate
Representative Suite	**M_I_2**	**Moderate. 83% of GMU extraction occurs within the middle aquifer and this Suite covers the greatest portion of the GMU**
Current hydrological condition of representative aquifer		
Representative Suite trend	Decreasing	High
Groundwater quality	Average of 3,000 mg/L	Moderate – data quite variable Calculated based on Katunga Annual Report, GMW 2021
Groundwater yield	0.5- 5 L/s	Low Based on CDM Smith (2022)
Groundwater levels		
Temporal groundwater level data range	**1974 to 2021**	**High**
Spatial clustering of licensed bores in relation to Suites	**No, spread across multiple Suites**	**Based on DEECA density mapping and licenced bore data**
Groundwater use		
Average licensed groundwater use	**27,785 ML**	**High (Based on average historical VWA data over 17 years)**
Minimum historic groundwater use	**11,654 ML**	**High (Based on historical VWA data, year 2010/11)**
Maximum historic groundwater use	**41,104 ML**	**High (Based on historical VWA data, year 2018/19)**
Entitlement (Groundwater allocation) (ML)	**60,203 ML**	**High (Based on licenced volumes in 2020/21)**

Characteristic and importance	Description	Degree of understanding
Significant drivers of groundwater level variability (primary)	**Pumping for irrigation and dairy**	**Moderate**
Secondary drivers of groundwater level variability	**Commercial/industrial (quarries/etc)**	**Moderate**
Groundwater use profile	**Influenced by seasonality**	**Moderate**
External Influence	**Lower Murrumbidgee Groundwater Source**	
Groundwater values and risks		
Existing Environmental Values to be protected, relevant to this GMU	Potable water supply Licensed non-potable supply (irrigation, commercial, industrial) Unlicensed non-potable supply (domestic and stock)	
Risks to groundwater values	Direct risks: – Drawdown which may affect access to groundwater by existing users	Moderate
Indicators used to assess impacts to groundwater	– Predicted drawdown in recovered water levels pre-determined metrics measured from a pre-determined level for the purpose of this modelling	Moderate

Legend

Extraction bores by aquifer
- UTAF (105)
- No depth (assumed to be middle aquifer)

SOBN (by aquifer)
- UTAF

Middle suite bore
- M_I_1
- M_I_2
- M_J_9

Middle aquifer suite
- M_I_1
- M_I_2

- M_J_9
- Groundwater Management Unit (GMU)
- Major town
- Rail
- Freeway & highway
- River

Riverina Hwy
MULWALA CANAL
Riverina Hwy
New South Wales
MURRAY RIVER
Murray Valley Hwy
Goulburn Valley Hwy
Katunga WSPA
Murray Valley Hwy
M_I_1
YARRAWONGA
New South Wales
M_I_2
GOULBURN RIVER
M_J_9
M_J_9
SHEPPARTON
Midland Hwy
Midland Hwy
BROKEN RIVER

Paper Size ISO A3

0 2.5 5 7.5 10

Kilometers

Map Projection: Lambert Conformal Conic
Horizontal Datum: GDA 1994
Grid: GDA 1994 VICGRID94

N

GHD

DEECA
Sustainable yield review - confined aquifers

Katunga WSPA
Site location and key features

Project No. **12564066**
Revision No. **0**
Date **16/01/2024**

Figure 27

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Print date: 16 Jan 2024 - 12:50

Data source: DELWP, VicMap, 2022; DELWP, GMUs, 2022; DELWP, SOBN, 2022; GHD, aquifer suites, 2018; DELWP, extraction bores, 2022 Created by: cperyer

7.2 Technical analysis

7.2.1 Hydrograph review and selection of representative Suites for further analysis

Suite hydrographs were generated for the confined Suites for Katunga WSPA as shown in Figure 28. Generally, the Suite hydrographs show the seasonal fluctuations and hence recovered water levels. The exception to this is Suite M_J_9, which shows a generally increasing trend. It is expected that there may be an issue with this Suite data and hence this Suite has not been used further for this analysis.

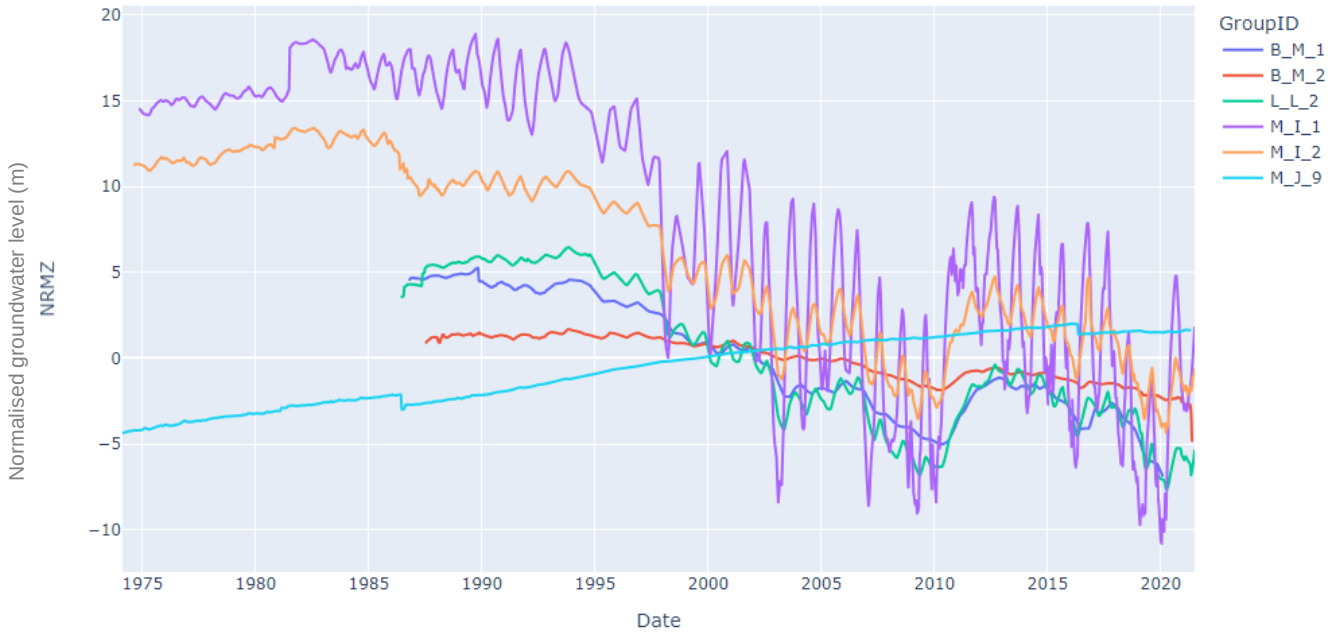


Figure 28 *Katunga WSPA Suite Hydrographs for all confined aquifers*

The representative Suites analysed for this GMU were Suites M_I_1 and M_I_2. These representative Suites were selected following the methodology outlined in section 2.6.4 which identified M_I_2 as the most representative followed by M_I_1. The process is summarised as follows:

- The greatest volume of extraction occurring within the Middle Aquifer
- The Middle Aquifer pertains to the UTAF which is the intended aquifer for this GMU
- Suite M_I_2 covers 67% of the GMU, M_I_1 covers 27% and M_J_9 covers 0%
- Suite M_I_2 has 7 active SOBN bores within the Suite area
- Suite bores for M_I_2 are close to extraction points

The normalised annual recovered Suite hydrographs for the representative Suites for Katunga WSPA, M_I_1 and M_I_2 are shown in Figure 29.

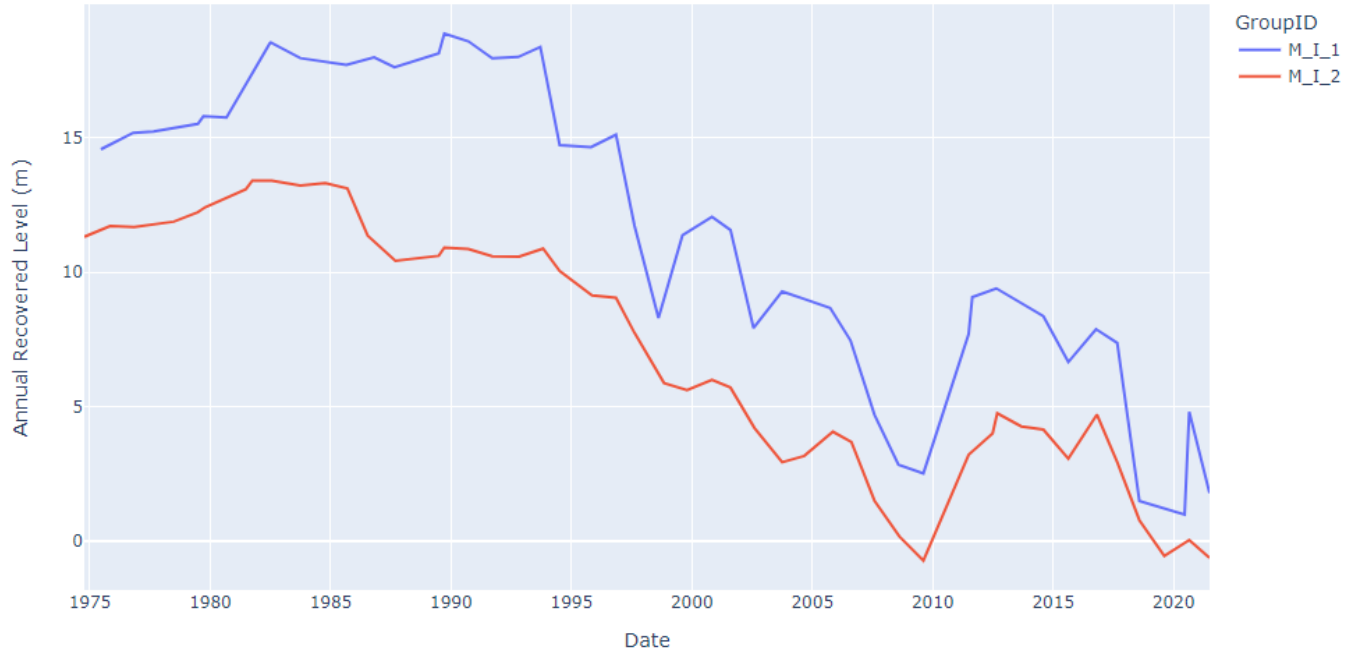


Figure 29 *Katunga WSPA Annual Recovered Level Suite Hydrographs for representative Suites*

7.2.2 Pre-development level

To estimate the pre-development level conditions, GHD reviewed the Suite hydrographs of normalised annual recovered levels and assumed that the maximum levels in the early time series data was the best representation of conditions prior to major development within Katunga WSPA. This the maximum levels in the early time series data was adopted as the baseline of pre-development conditions.

The pre-development annual recovered levels are taken to be the maximum level in the early time series data which equates to 13.41 m for Suite M_I_2 and 18.52 m for Suite M_I_1 in the year 1981/1982 (refer further details in section 7.4.3).

7.2.3 Externalities

As identified through the conceptualisation, Katunga WSPA may be influenced by extraction occurring north of the GMU in NSW for the Lower Murrumbidgee Groundwater Sources (deep aquifer). To test the influence of this extraction, data was obtained from the NSW Government to incorporate into the model.

Figure 30 shows the Katunga WSPA annual groundwater extraction volumes, the Lower Murrumbidgee extraction volumes and the combined volumes. Note that where extraction does not occur in both Katunga WSPA and Lower Murrumbidgee, that year of data cannot be incorporated into the model without hindcasting. It is noted that the Lower Murrumbidgee Groundwater Source (deep aquifer) extraction makes up around 89% of the total extraction when the two datasets are combined.

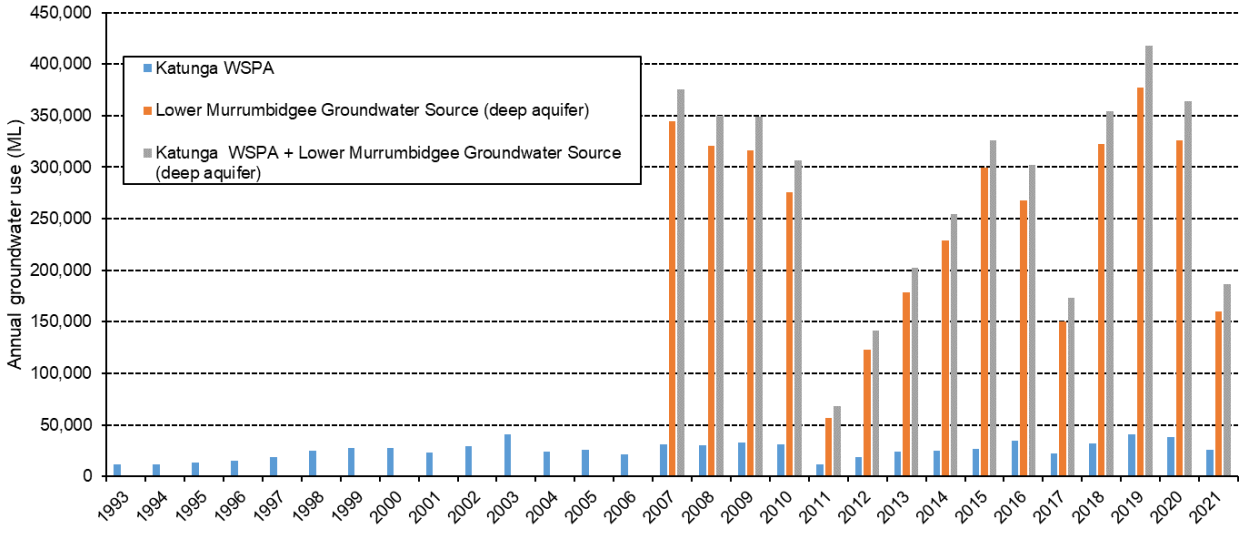


Figure 30 ***Katunga WSPA and Lower Murrumbidgee Groundwater Sources – groundwater use***

7.2.4 Hindcasting

Groundwater use data for Katunga WSPA is available from 1992/1993 to 2020/2021 and from 2006/2007 to 2020/2021 when incorporating the Lower Murrumbidgee Groundwater Sources. The hindcasting methodologies outlined in section 3.3.4.5 were applied to Katunga WSPA. A summary of the hindcasting results is shown in the following sections.

7.2.4.1 Hindcasting Method 1 (H1)

Applying method H1, four different correlations were developed as described below.

Figure 31:

- Annual rainfall vs annual groundwater extraction at Katunga WSPA
- Two yearly average annual rainfall vs annual groundwater extraction at Katunga WSPA
- Annual summer period rainfall vs annual groundwater extraction at Katunga WSPA
- Annual irrigation period rainfall vs annual groundwater extraction at Katunga WSPA

Figure 32:

- Annual rainfall vs annual combined extraction at Katunga WSPA and Lower Murrumbidgee Groundwater Source (external influence)
- Two yearly average annual rainfall vs annual combined extraction at Katunga WSPA and Lower Murrumbidgee Groundwater Source
- Annual summer period rainfall vs annual combined extraction at Katunga WSPA and Lower Murrumbidgee Groundwater Source (external influence)
- Annual irrigation period rainfall vs annual combined extraction at Katunga WSPA and Lower Murrumbidgee Groundwater Source (external influence)

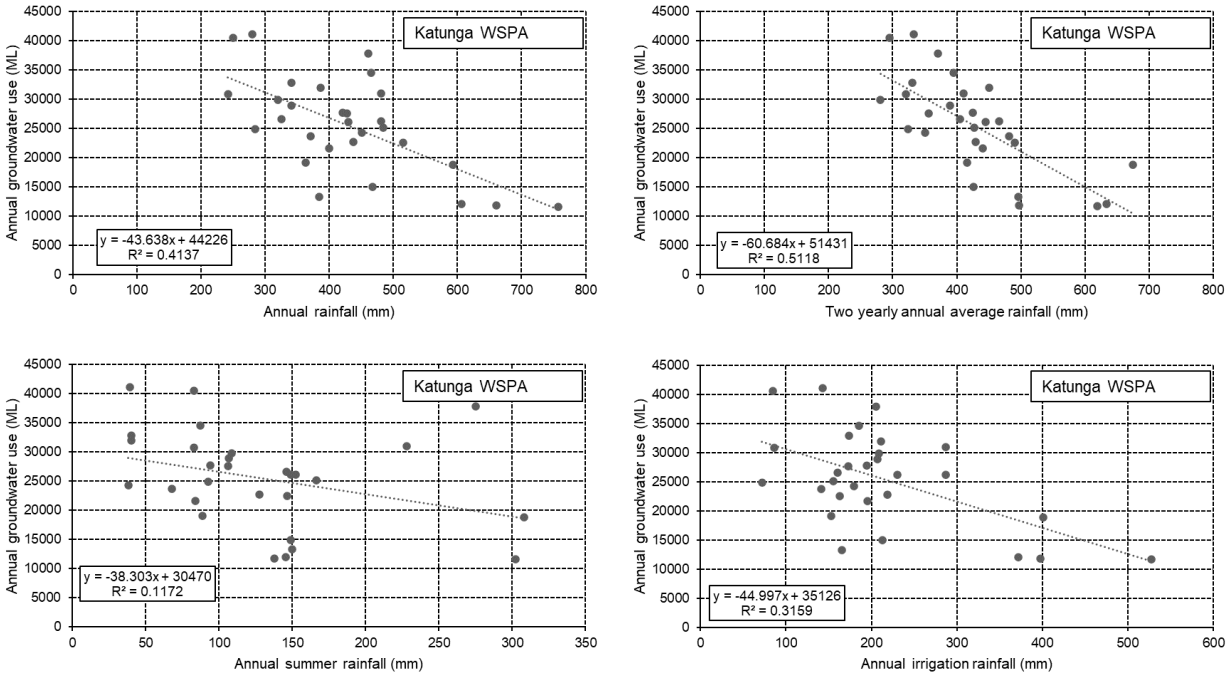


Figure 31 Katunga WSPA: Hindcast method 1 correlations (Katunga WSPA only)

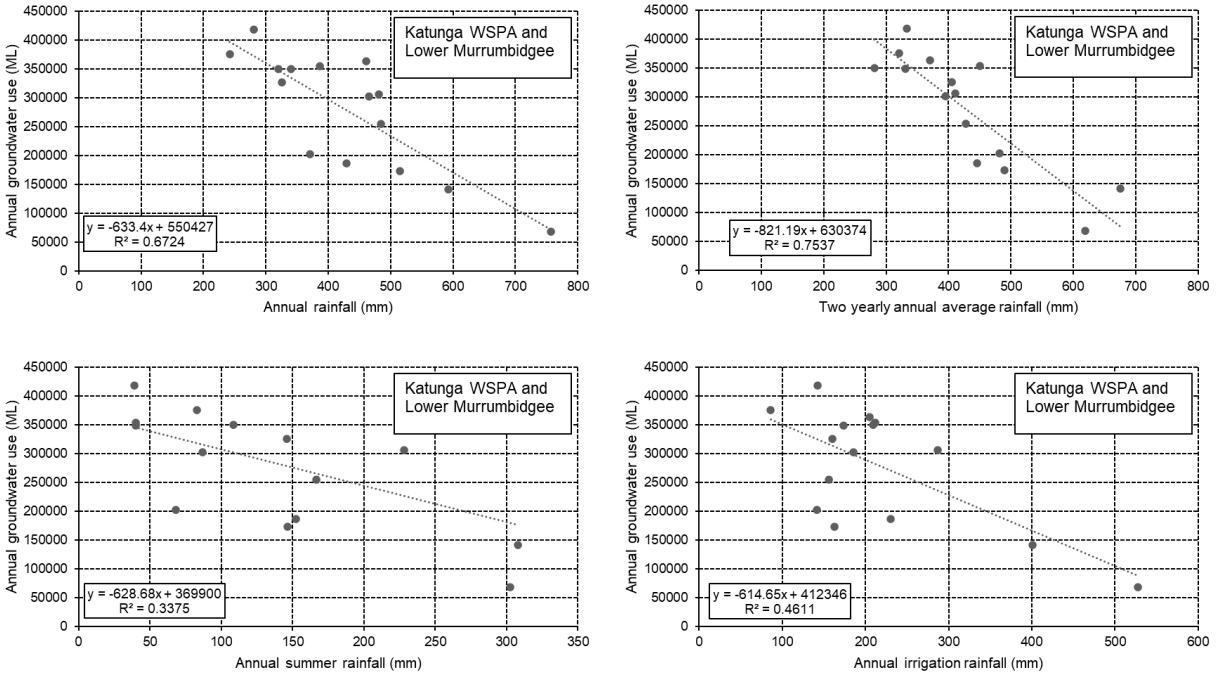


Figure 32 Katunga WSPA: Hindcast method 1 correlations (Katunga WSPA and Lower Murrumbidgee)

As shown in Figure 31 and Figure 32, the goodness-of-fit represented by the R^2, increases where the extraction from the Lower Murrumbidgee Groundwater Source (external influence) was included. The best goodness-of-fit result was shown to be the correlation of the two yearly average annual rainfall with the combined groundwater extraction from Katunga WSPA and Lower Murrumbidgee Groundwater Source.

When modelling Katunga WSPA only extraction using hindcast method 1, the correlation using two-year average annual rainfall was adopted. Similarly, when modelling Katunga WSPA with externalities using hindcast method 1, the correlation using two yearly average annual rainfall with the combined Katunga WSPA and Lower Murrumbidgee Groundwater Source was adopted.

7.2.4.2 Hindcasting Method 2 (H2)

Similar to method H1, eight correlations were developed using method H2 as described below.

Figure 33:

- Katunga WSPA use per Katunga WSPA bore vs annual rainfall
- Katunga WSPA use per Katunga WSPA bore vs two yearly average annual rainfall
- Katunga WSPA use per Katunga WSPA bore vs annual summer rainfall
- Katunga WSPA use per Katunga WSPA bore vs annual irrigation rainfall

Figure 34:

- Katunga WSPA and Lower Murrumbidgee Groundwater Source use per Katunga WSPA bore vs annual rainfall
- Katunga WSPA and Lower Murrumbidgee Groundwater Source use per Katunga WSPA bore vs two yearly average annual rainfall
- Katunga WSPA and Lower Murrumbidgee Groundwater Source use per Katunga WSPA bore vs annual summer rainfall
- Katunga WSPA and Lower Murrumbidgee Groundwater Source use per Katunga WSPA bore vs annual irrigation rainfall

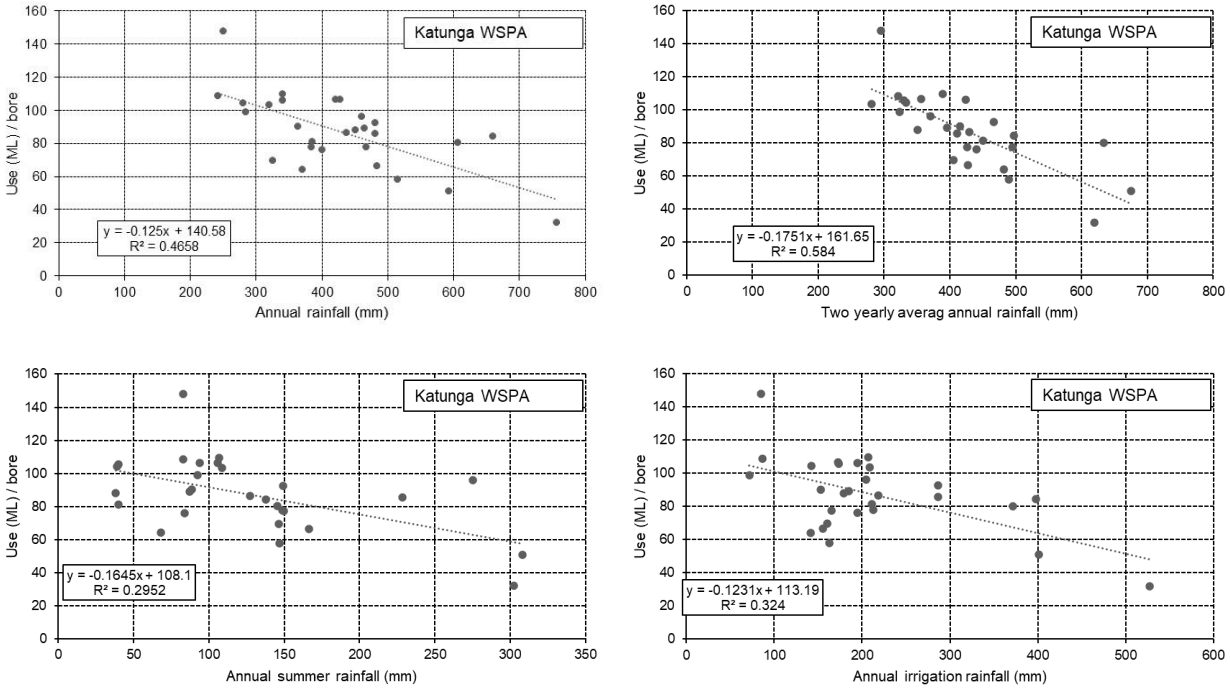


Figure 33 Katunga WSPA: Hindcast method 2 correlations (Katunga WSPA only)

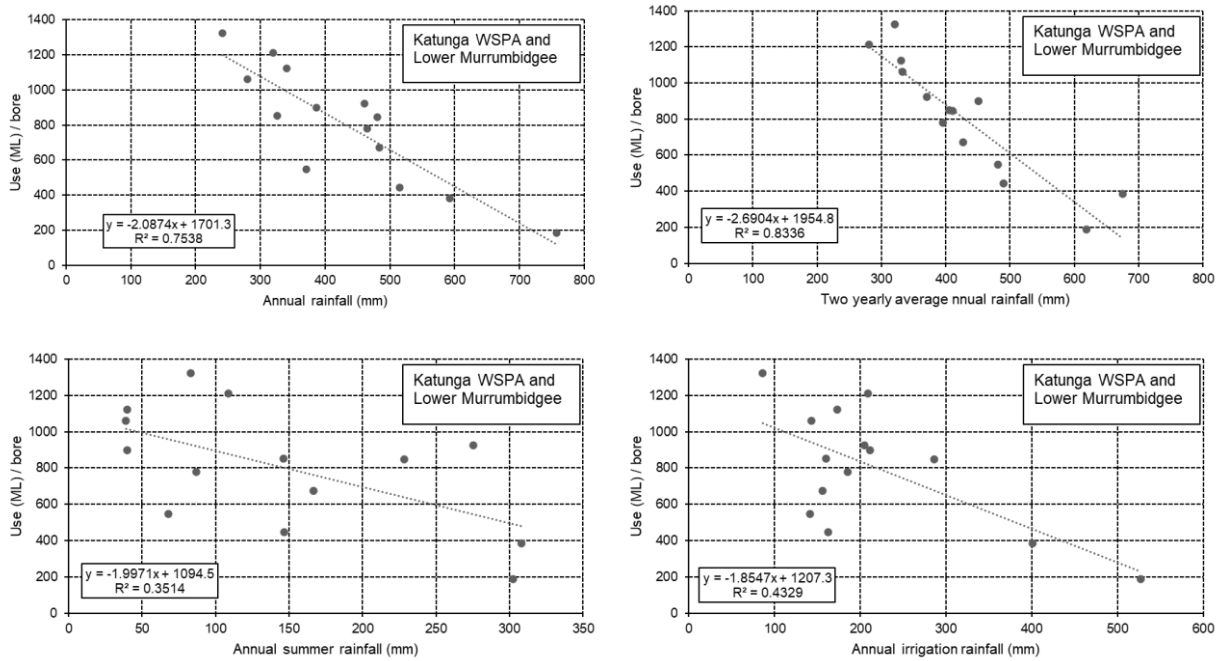


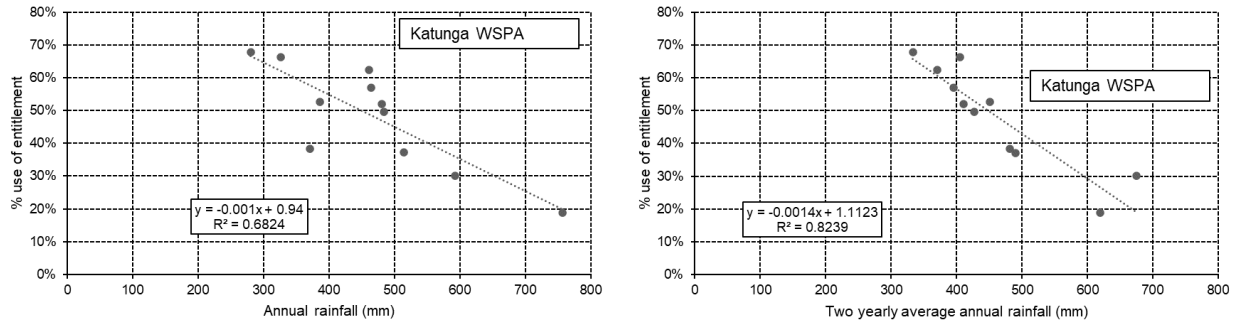
Figure 34 Katunga WSPA: Hindcast method 2 correlations (Katunga WSPA and Lower Murrumbidgee)

As shown in Figure 33 and similar to method H1, the goodness-of-fit represented by the R^2, increased in both instances where the extraction from the Lower Murrumbidgee Groundwater Source (external influence) was included. The best goodness-of-fit result was shown to be the correlation of the two yearly average annual rainfall with the combined groundwater extraction from Katunga WSPA and Lower Murrumbidgee Groundwater Source per bore. When applying hindcast method 1 to the modelling, the models of combined extraction of Katunga WSPA and externalities used the correlation with two yearly average annual rainfall and the model using only Katunga WSPA extraction used the correlation of two yearly average annual rainfall.

7.2.4.3 Hindcasting Method 3 (H3)

Four correlations were developed using method H3 as described below and shown in Figure 33:

- Percentage of entitlement vs annual rainfall
- Percentage of entitlement vs two yearly average annual rainfall
- Percentage of entitlement vs annual summer rainfall
- Percentage of entitlement vs annual irrigation rainfall



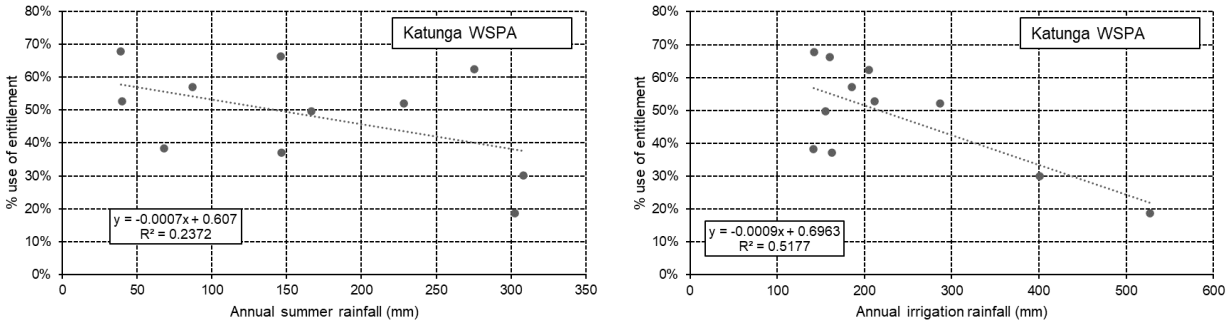


Figure 35 Katunga WSPA: Hindcast method 3 correlations

As shown in Figure 35 and similar to method H1 and H2, the best goodness-of-fit result was shown to be the correlation of the two yearly average annual rainfall with the combined groundwater extraction from Katunga WSPA and Lower Murrumbidgee Groundwater Source per bore. This correlation and the Katunga WSPA only extraction per bore with two yearly average annual rainfall were both modelled.

7.2.4.4 Comparison

A comparison of the three input datasets is shown in Figure 36 and Figure 37 for the hindcasting based on just Katunga WSPA groundwater use. Figure 36 shows a comparison of the three hindcasting methods against the recorded use only over the recorded use date and Figure 37 shows the hindcasted data back to 1973/1974. A comparison of the three input datasets for hindcasting based on the combined Katunga WSPA and Lower Murrumbidgee groundwater use is shown in Figure 38 and Figure 39. Figure 38 shows a comparison of the three hindcasting methods against the recorded use only over the recorded use date and Figure 39 shows the hindcasted data back to 1973/1974.

As shown in Figure 37 and Figure 39, groundwater use using method H3 does not decrease historically as there is no factor to account for the changing number of bores extracting over time and thus, results in a higher groundwater extraction estimate than the other two methods. Both sets of hindcasting results show that the smallest average variation of recorded use to estimated use occurs for method H2; thus, this hindcasting method is expected to provide a more probable estimated groundwater use than the other two methods for Katunga WSPA. However, all methods were trialled in the modelling.

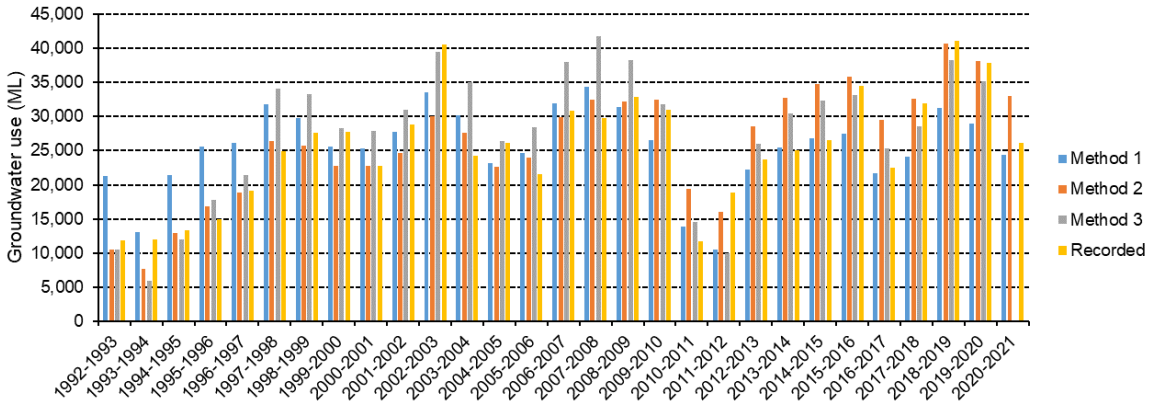


Figure 36 Katunga WSPA: Comparison of hindcasting over recorded use period – Katunga WSPA only extraction

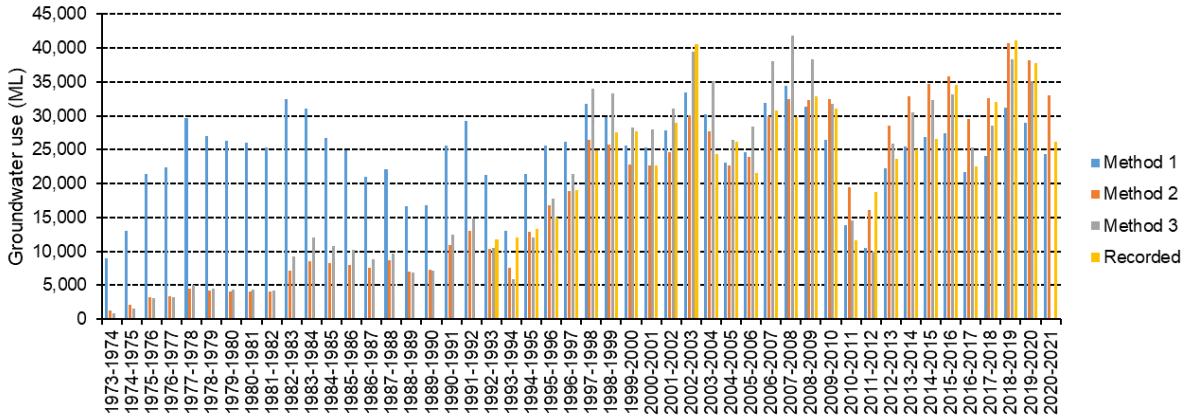


Figure 37 *Katunga WSPA: Comparison of hindcasting – Katunga WSPA only extraction*

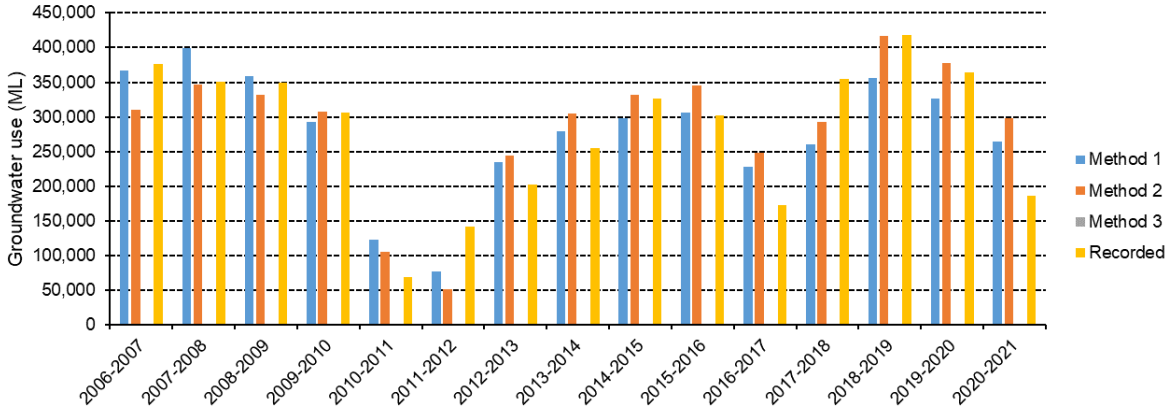


Figure 38 *Katunga WSPA: Comparison of hindcasting over recorded use period – Katunga WSPA and Lower Murrumbidgee extraction*

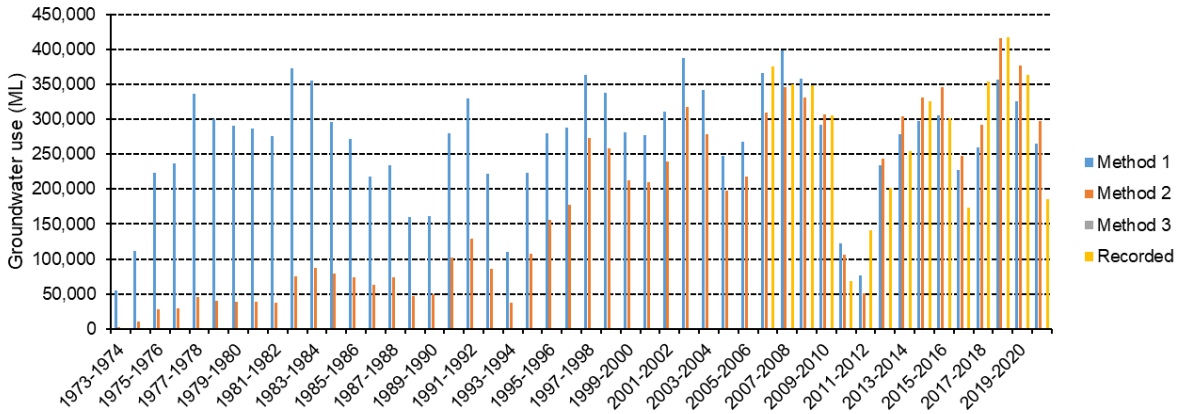


Figure 39 *Katunga WSPA: Comparison of hindcasting – Katunga WSPA and Lower Murrumbidgee extraction*

7.3 Modelling

7.3.1 Model inputs

A number of different models were run based on the various model inputs developed and combinations of these. Table 21 summarises these combinations of model inputs run for Katunga WSPA. Model runs highlighted blue indicate they were run with annual extraction and grey indicates they were run using two yearly average annual extraction.

Table 21 Katunga WSPA: summary of model inputs

Model input	Model runs																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Annual recovered levels for representative Suites (M_I_1 and M_I_2)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Annual extraction – Katunga WSPA only	✓																		
Two yearly average annual extraction – Katunga WSPA only		✓																	
Annual extraction – Katunga WSPA and Lower Murrumbidgee			✓																
Two yearly average annual extraction – Katunga WSPA and Lower Murrumbidgee				✓															
H1 annual extraction – Katunga WSPA only					✓														
H1 annual extraction – Katunga WSPA and Lower Murrumbidgee						✓													
H2 annual extraction – Katunga WSPA only							✓												
H2 annual extraction – Katunga WSPA and Lower Murrumbidgee								✓											
H3 annual extraction – Katunga WSPA only									✓										
H1 two yearly average annual extraction – Katunga WSPA only										✓									
H1 two yearly average annual extraction – Katunga WSPA and Lower Murrumbidgee											✓								

Model input	Model runs																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
H2 two yearly average annual extraction – Katunga WSPA only												✓							
H2 two yearly average annual extraction – Katunga WSPA and Lower Murrumbidgee													✓						
S1 annual extraction – Katunga WSPA only														✓					
S2 annual extraction – Katunga WSPA only															✓				
S3 annual extraction – Katunga WSPA only																✓			
S1 annual extraction and H1 annual extraction – Katunga WSPA only																	✓		
S2 annual extraction and H2 annual extraction – Katunga WSPA only																		✓	
S3 annual extraction and H3 annual extraction – Katunga WSPA only																			✓

7.3.2 Model calibration and uncertainty analysis

A statistical summary of the model output results for the runs described in Table 21 is presented in Table 22 for the selection of potential representative Suites for Katunga WSPA. The column heading for M_I_2 is highlighted blue to indicate that this Suite was selected as the most likely representative Suite based on the process outlined in section 7.2.1. The statistics and measures of uncertainty summarised include the average 95 PPU thickness (95PPU TH), percentage of observed levels within 95 PPU (%Obs in 95 PPU), R^2 and root mean square error (RMSE), number of annual recovered level observation points (No obs data points) and the range of observed annual recovered levels.

Suite M_I_1

A review of the results for Suite M_I_1 shows that model runs 1 and 4 (highlighted orange) show the best results when looking at the runs with the smallest 95PPU thickness, RMSE and R^2 of the 19 different model input combinations. However, model 4 only included 14 observation points and around half the observed drawdown from the recovered water level dataset and model 1 includes most of the drawdown range in the observed data set with the 28 data points. The hindcasted datasets include more observed water levels in the calibration and capture a greater range of water levels (more drawdown data), considering this, model 8 (highlighted green) becomes the preferred model run. The graphical model output for this run is shown in Figure 40.

Suite M_I_2

A review of the results and statistical summary for Suite M_I_2 shows that model runs 7 and 13 (highlighted green) show the best results when considering the four statistical measures and the number of observation points included in the calibration of the 19 different model input combinations; all three models had very similar results for each of the statistics and uncertainty measures. Model 13 includes a smaller amount of observed extraction data and there is a large difference between this model and the model without two-yearly data which indicates this model is highly sensitive when externalities are included. Given this model run 7 has been adopted. The graphical model output for model runs 7 and 13 are shown in Figure 41 and Figure 42 respectively.

Based on these results, modelling was progressed on the basis of adopting model 8 for Suite M_I_1 and model 7 for Suite M_I_2.

Table 22 Katunga WSPA: summary of model calibration outputs

Suite	Statistic	Model run																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
M_I_1	95PPU TH	7.82	8.71	8.62	6.75	NA	11.81	9.03	**8.19**	12.53	18.11	19.83	11.52	8.73	8.7	3.82	111.27	10.08	14.96	27.24
	%Obs in 95 PPU	96.43	100	100	100	15.0	100	100	**100**	65.96	100	100	70.21	100	100	90	100	97.83	97.83	100
	R^2	81.7	76.6	60.3	67.9	15	84.3	83.0	**86.8**	21.9	27.5	12.2	39.4	84.2	33.1	-214.4	-88.7	78.3	26.4	83.1
	RMSE	1.75	1.98	1.8	1.62	4.87	2.09	2.18	**1.92**	4.67	4.5	4.96	4.12	2.1	2.36	5.11	3.96	2.44	4.49	2.15
	No obs data points	28	28	14	14	47	47	47	**47**	47	47	47	47	47	9	9	9	45	45	45
	Range of observed levels	17.4	17.4	8.4	8.4	17.9	17.9	17.9	**17.9**	17.9	17.9	17.9	17.9	17.9	8.4	8.4	8.4	17.9	17.9	17.9
M_I_2	95PPU TH	4.49	4.66	5.05	4.7	6.99	5.74	**4.37**	7.58	4.58	6.77	5.98	5.58	3.82	5.97	NA	5.09	4.32	5.86	4.06
	%Obs in 95 PPU	96.43	96	100	100	97.87	95.74	**93.62**	93.62	93.62	97.87	95.74	95.74	93.62	30	0	100	93.48	45.65	15.22
	R^2	90.3	89.2	65.0	73.5	92.5	93.2	**94.7**	82.6	94.7	92.5	93.2	92.1	96.1	-209.3	39.8	43.7	95.1	89.5	95
	RMSE	0.94	0.99	1.16	1.01	1.22	1.16	**1.02**	1.86	1.03	1.22	1.16	1.25	0.88	2.91	1.28	1.24	0.97	1.42	0.97
	No obs data points	28	28	14	14	47	47	**47**	47	47	47	47	47	47	10	10	10	46	46	46
	Range of observed levels	11.6	11.6	5.5	5.5	14.2	14.2	**14.2**	14.2	14.2	14.2	14.2	14.2	14.2	5.3	5.3	5.3	14.2	14.2	14.2

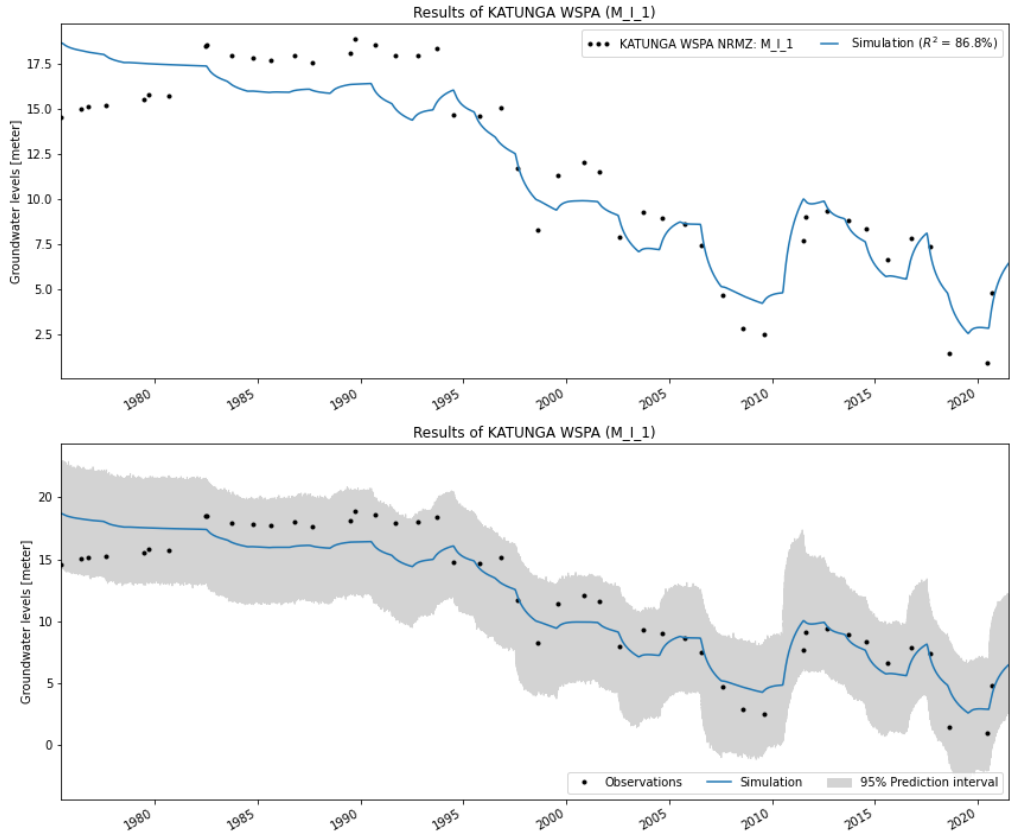


Figure 40 ***Katunga WSPA Suite M_I_1: model run 8 (Annual recorded extraction with externalities with hindcast method H2) output hydrographs***

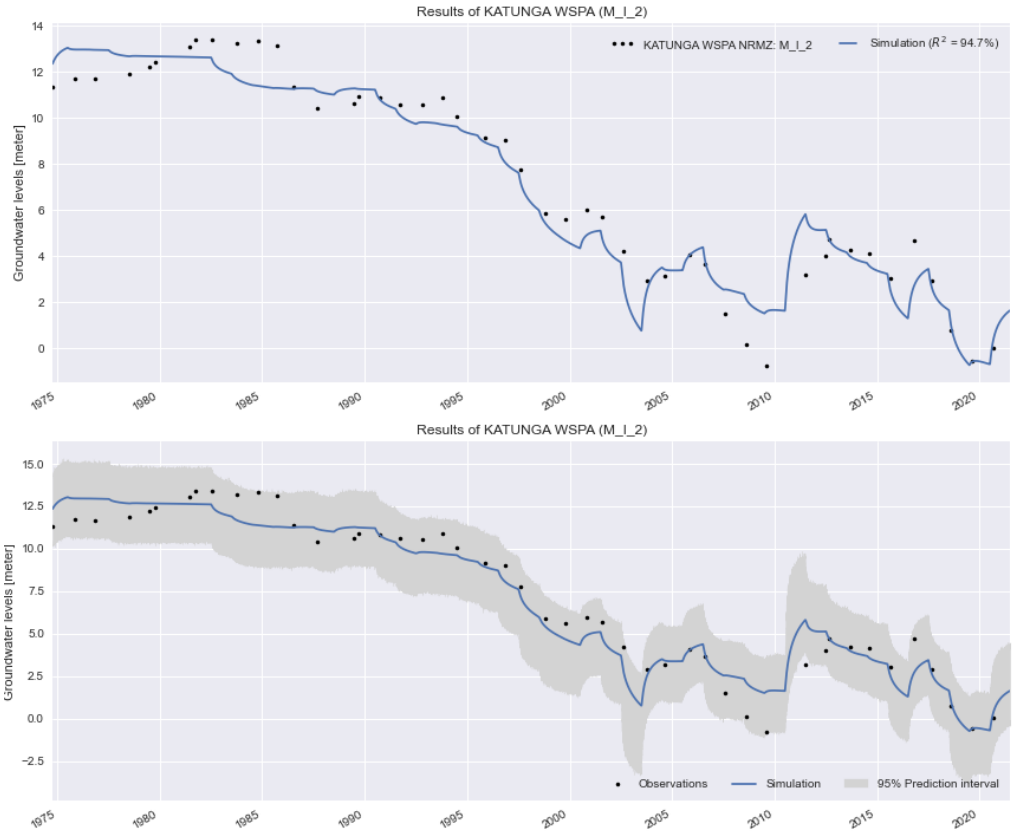


Figure 41 ***Katunga WSPA Suite M_I_2: model run 7 (Annual recorded extraction with hindcast method H2) output hydrographs***

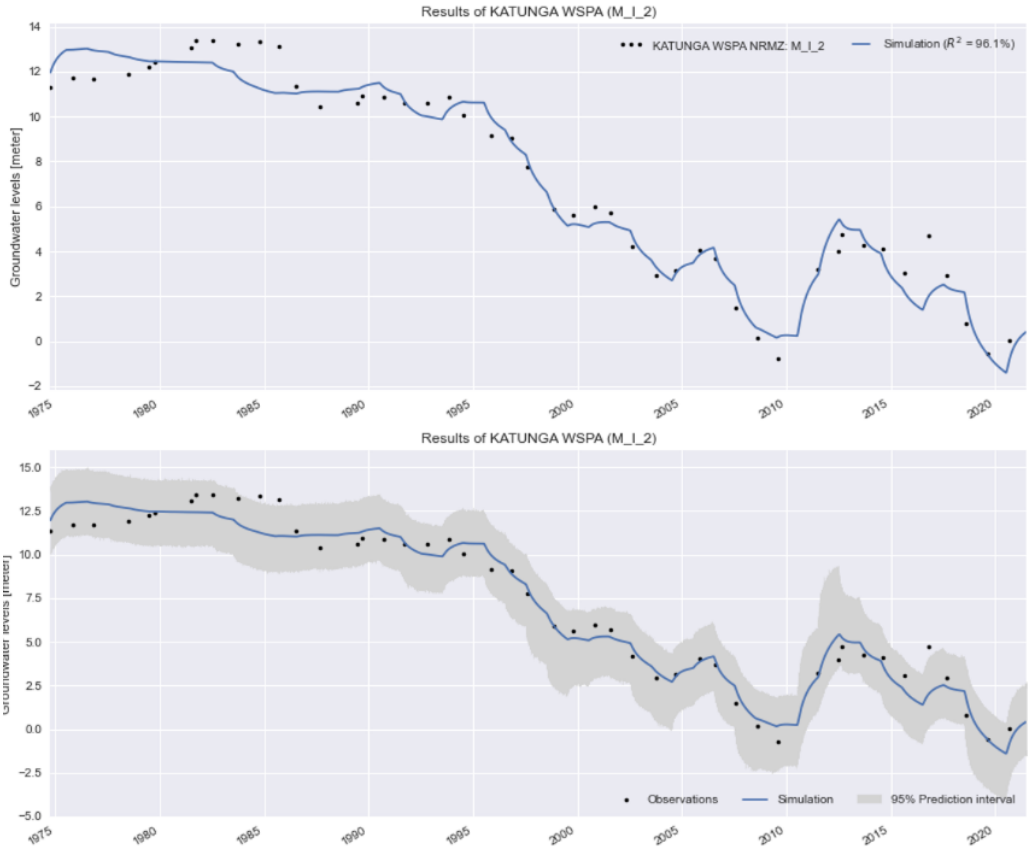


Figure 42 *Katunga WSPA Suite M_I_2: model run 13 (Two yearly annual average recorded extraction with externalities with hindcast method H2) output hydrographs*

7.4 Predictive modelling

7.4.1 Model inputs

The preferred model to run the predictive modelling for Katunga WSPA was model run 8 was run for Suite M_I_1 and model run 7 for Suite M_I_2. The key inputs for the model were the annual recovered levels and the annual extraction in Katunga WSPA. To conduct the forecasting for the 19 scenarios discussed in section 3.5.3, a few factors were required in the calculations; these factors are summarised in Table 23.

Table 23 *Katunga WSPA: forecast scenario inputs*

Input item	PCV	Licenced entitlement (based on 2020/21)	Existing use (based on 2020/2021)	Average use over recorded period (from VWA)	Maximum use over recorded period (from VWA, year 2018/19)
Value (ML/year)	60,577	60,203	26,133	27,785	41,104
Combined value (ML/year): Katunga WSPA and Lower Murrumbidgee Groundwater Source	333,828	333,828	186,225	278,037	418,033

The model run 8 was run for all 19 forecast scenarios on Suites M_I_1 and model run 7 for Suite M_I_2.

7.4.2 Predictive model uncertainty

The model output files of the predicted models can be found in the data package provided as part of Appendix E.

Markov Chain Monte Carlo (MCMC) predictions were undertaken on each of the forecasted scenarios for each of the two Suites. An example of one of the outputs is presented in Figure 43 for scenario 4. As shown in Figure 43, the uncertainty of the model prediction increases as the model predicts further into the future. Comparing with the graphical output for the same scenario, the MCMC realisations tend to fall within the 95% prediction interval bands as shown in Figure 44.

Uncertainty is also accounted for by using 19 forecast scenarios to develop a groundwater use to drawdown relationship (analogous to a Monte Carlo type simulation) where a range of possible outcomes are generated. It is noted however, that the forecast scenarios were not randomly generated, but rather based upon a series of estimated use behaviours.

It is noted that the model for Suite M_I_2 for forecast scenario 5 and thus the results for this forecasted model are not reported below.

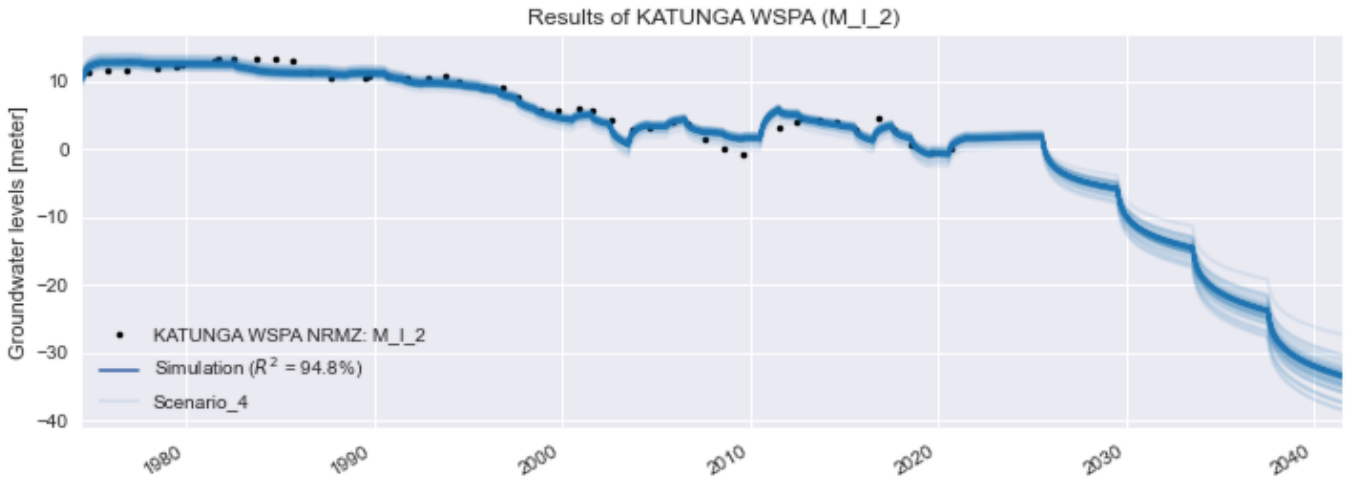


Figure 43 Katunga WSPA: Suite M_I_2 MCMC analysis for Forecast Scenario 4

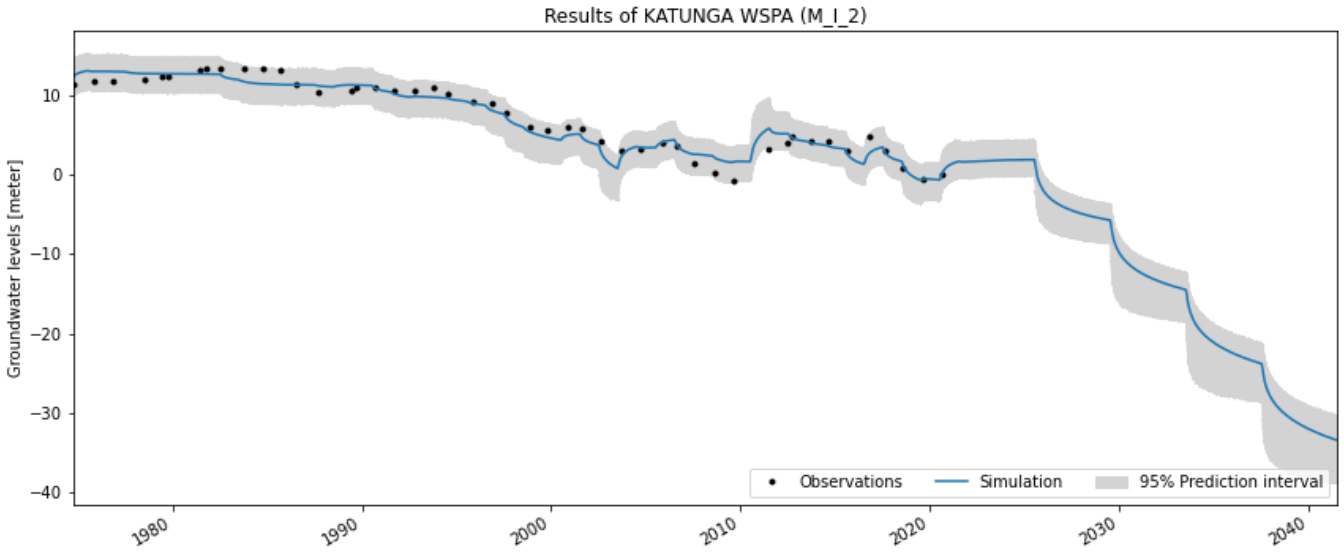


Figure 44 Katunga WSPA: Suite M_I_2 Forecast Scenario 4 with 95% prediction bands

7.4.3 Extraction vs drawdown

To calculate the drawdown based on the annual recovered levels simulated by the model, the pre-development conditions (pre commencement of extraction) need to be estimated. For many of the GMUs, the water level prior to groundwater development was unknown, due to:

- Uncertainty regarding the commencement of development in some GMUs
- The initiation of groundwater development preceding SOBN bore installation and temporal groundwater monitoring

Using the pre-development levels defined in section 7.2.2, the modelled water levels were converted into drawdowns (from this baseline pre-development level) for each of the 19 scenarios. This predevelopment condition is shown in Figure 45 for Suite M_I_2 hydrograph of annual recovered levels. In Figure 45:

- Actual annual groundwater use is represented by the blue column graph between 1992/1993 and 2020/2021
- Hindcasted groundwater use is represented by the orange columns between 1973/1974 and 1991/1992
- Forecasted use is represented by the grey columns after 2021/2022
- The annual recovered water level behaviour based on recorded data is represented by the red line graph, where the earliest data is taken to best reflect the pre-development levels
- In the case of Figure 45, the pre-development annual recovered levels are taken to be the maximum level (1981/1982) which equates to 13.41 m (the pre-development level for Suite M_I_1 is 18.52 m based on 1981/1982)

The modelled forecasted annual recovered levels are represented by the purple line in Figure 45.

The calibration annual recovered levels are represented by the black line in Figure 45.

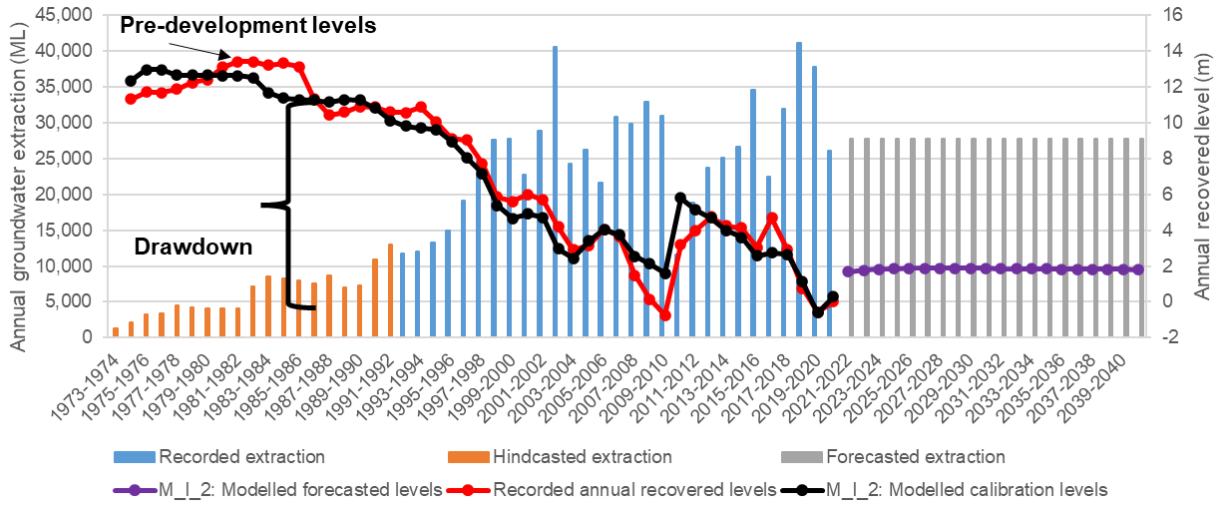


Figure 45 Estimating pre-pumping water levels (example from Suite M_I_2)

For Suite M_I_1, the volumes needed to be converted from a combined volume of Katunga WSPA and Lower Murrumbidgee Deep Groundwater Source to just a volume that represents Katunga WSPA. On average, Katunga WSPA extraction makes up 11% o of the combined volume based on the recorded datasets. As such 11% of the combined volume has been used in the use-drawdown relationships for Suite M_I_1.

For Suite M_I_1, the calculated drawdowns and volumes for each of the scenarios were plotted in individual graphs for each scenario, all scenarios together in the one graph (Figure 46) and a graph of the scenarios for specific time periods (Figure 47) to develop the volume to drawdown relationship. For each scenario, a linear regression was applied and the coefficient of determination (R^2) was calculated. A comparison of each of these graphs shows most R^2 values were similar with a few of the individual graphs having higher R^2 values. The same process was applied for Suite M_I_2 and again, most R^2 values were similar with a few of the individual graphs having higher R^2 values.

The use-drawdown for all the 19 forecast scenario drawdowns and volumes (both the recorded and forecasted volumes) over each year modelled (1975 to 2041) is shown in Figure 46 for Suite M_I_1 and Figure 48 for M_I_2. Note the abscissa range of the chart has been clipped and does not show forecast drawdowns for the higher use scenarios (more improbable). Reviewing these figures, the following is noted:

- There should be zero drawdown under zero use and therefore a line of best fit should pass through the origin (0,0) or close to it. Suite M_I_2 has an intersection very close to the origin with an intercept of 0.3 m, whereas Suite M_I_1 has a much higher intercept value of 1.7. This is due to the difference in the recorded annual recorded level to the level predicted by the model at the selected pre-development date.
- Average use is around 28,000 ML. Figure 46 and Figure 48 indicate that the model generally forecasts drawdown relatively close to the predicted line of best fit for use volumes between 30,000 ML and 40,000 ML.
- For the same annual use, different drawdowns can be obtained as Pastas predicts a water level for each year. For example, Figure 45 shows a scenario where groundwater use remains constant at around 28,000 ML/year over the next 20 years.
- The correlation for groundwater use and drawdown for Suite M_I_1 as shown in Figure 46 is poorer than that for Suite M_I_2
- The various forecast scenarios generally result in data plotting reasonably close together in a linear trend. The 19 forecast scenarios applied to populate the chart is analogous to a Monte Carlo type simulation where a range of possible outcomes are generated. It is noted however, that the forecast scenarios were not randomly generated, but rather based upon a series of estimated use behaviours.

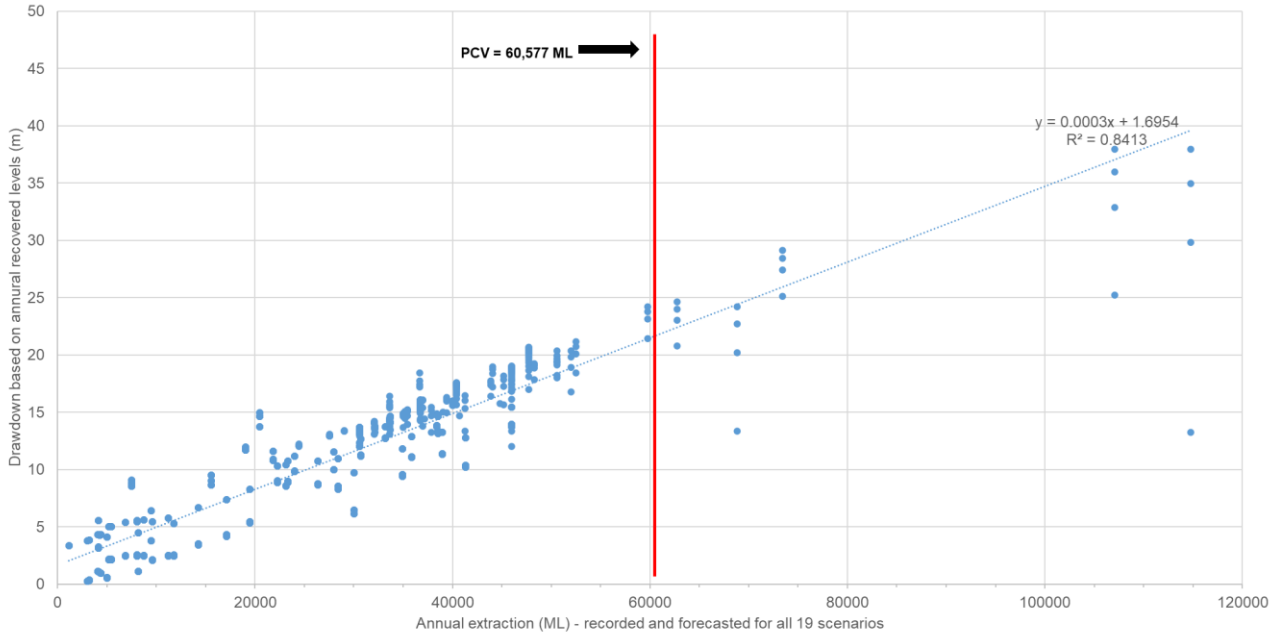


Figure 46 ***Katunga WSPA Suite M_I_1: Drawdown (on annual recovered levels) and GMU extraction volumes (recorded and forecasted <120,000 ML) for all data between 1975 to 2041 and all forecasted scenarios***

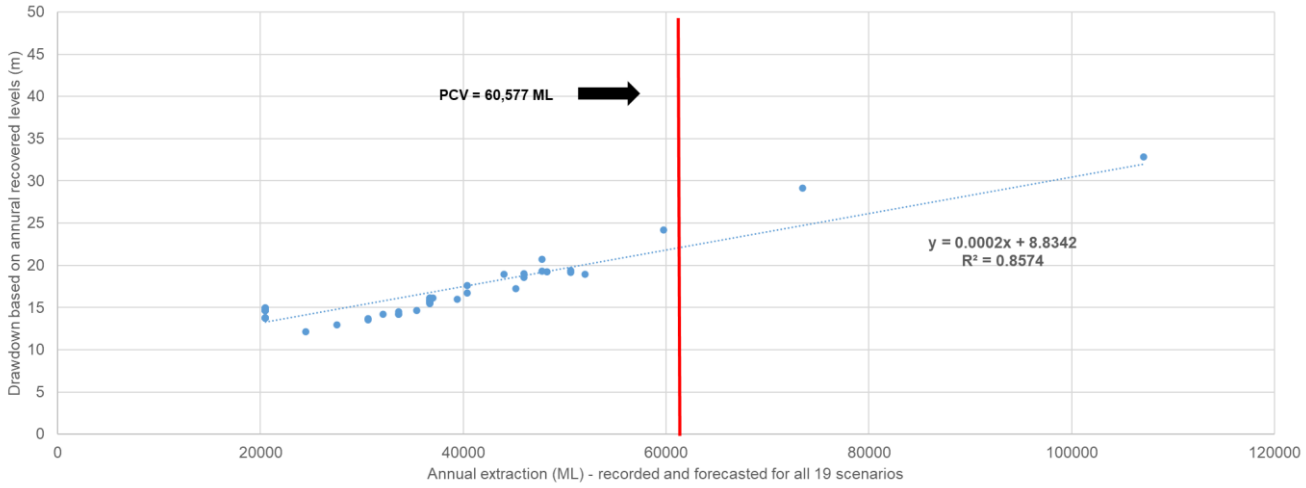
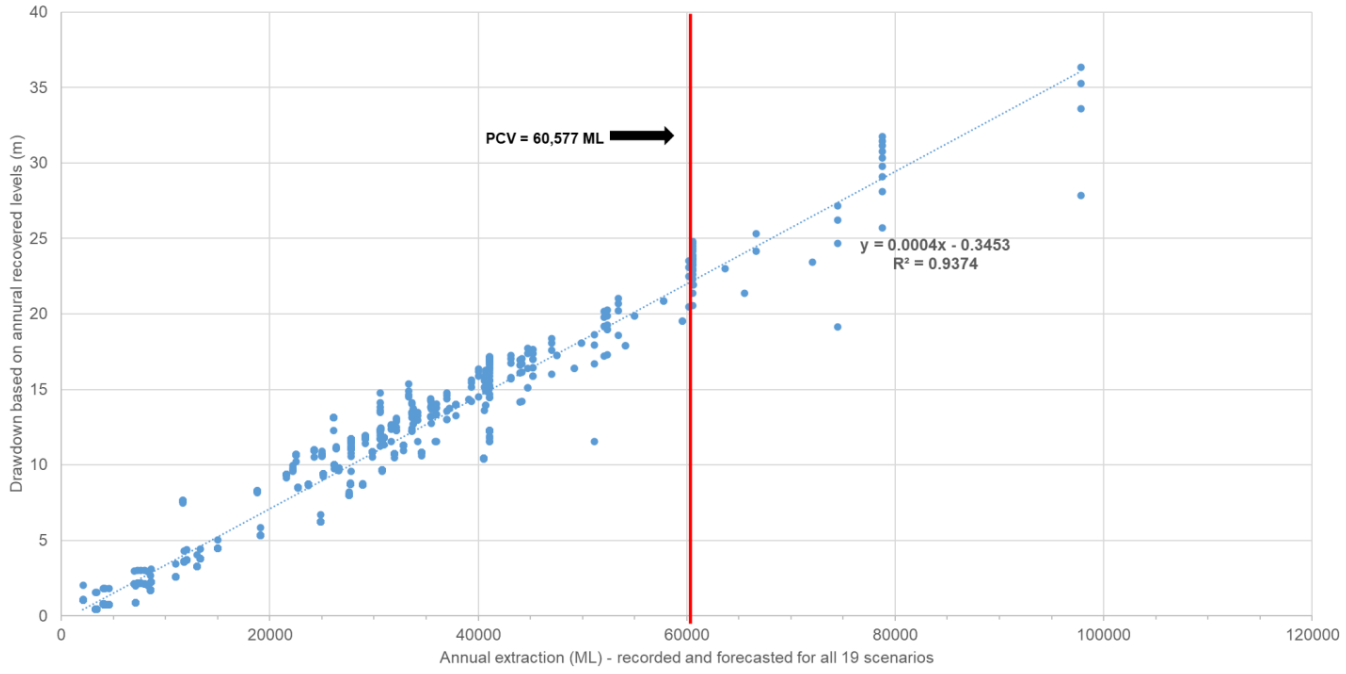


Figure 47 ***Katunga WSPA Suite M_I_1: Drawdown (on annual recovered levels) and GMU extraction volumes (recorded and forecasted <120,000 ML) for years 2020/2021, 2030/2031 and 2040/2041 for all forecasted scenarios***



–

Figure 48 ***Katunga WSPA Suite M_I_2: Drawdown (on annual recovered levels) and GMU extraction volumes (recorded and forecasted <120,000 ML) for all data between 1975 to 2041 and all forecasted scenarios***

7.5 Sustainability metrics

7.5.1 Application of metrics

Using the use - drawdown relationships developed through the previous step of forecasting aquifer response under a range of use scenarios, groundwater drawdown can be used to compare against groundwater resource sustainability metrics. The groundwater resource sustainability metrics applied to this study were developed by DEECA, as outlined in section 3.6.1.

The application of these metrics and the relationship developed between drawdown based on the Suite annual recovered levels and extraction volume for the whole GMU is shown in Table 24 for Katunga WSPA Suite M_I_1 and

Table 25 for Katunga WSPA Suite M_I_2 (noting Katunga WSPA has a current PCV of 60,577 ML/year). As part of the modelling, a 95% prediction interval band was applied to the modelling results. The relationship between drawdown and extraction volumes can also be interrogated at the lower and upper bands of the 95% prediction interval as shown in Table 24 and Figure 49 for Suite M_I_1, and

Table 25 and Figure 50 for Suite M_I_2.

As previously discussed, for Suite M_I_1, the predicted model adopted was based on the combined extraction from Katunga WSPA and Lower Murrumbidgee Groundwater Sources (deep aquifer). This was brought back to a Katunga WSPA only extraction for plotting the drawdown with extraction by taking 11% of the combined extraction (11% is the average portion of Katunga WSPA to the combined extraction based on recorded data). Table 24 shows the volume for Katunga WSPA to a given drawdown; the same table has been replicated for the combined use as shown in Table 26 (its noted that this is the actually usage used in the predictive model).

The two Katunga Suites M_I_1 and M_I_2 have a similar drawdown-use relationship, but Suite M_I_1 shows greater variability and uncertainty when comparing the drawdown to use relationships based on the 95% prediction interval bands. That is for example, the variation in drawdown based on the 95% prediction bands at a volume of 30,000 ML for the GMU is 6.4 to 17.8 m of drawdown for Suite M_I_1 and only 9.6 to 13.6 m of drawdown for Suite M_I_2 (reflected in the error bars of Figure 49 and Figure 50).

A comparison of volumes for the whole GMU at drawdown intervals provided by DEECA is shown in Table 26 for Suite M_I_1 and M_I_2. Note that the volumes under each of these suite headings are for the entire GMU.

Table 24 Relationship of Suite drawdown to GMU extraction for Katunga WSPA Suite M_I_1

Volume (ML/year) for whole of GMU	Based on model prediction of Suite M_I_1 annual recovered levels
	Drawdown over 20 years (m) (lower limit to upper limit based on 95% prediction interval band)
70,000	22.7 (18.4 - 33.8)
65,000	21.2 (16.9 - 31.8)
60,000	19.7 (15.4 - 29.8)
55,000	18.2 (13.9 - 27.8)
50,000	16.7 (12.4 - 25.8)
45,000	15.2 (10.9 - 23.8)
40,000	13.7 (9.4 - 21.8)
35,000	12.2 (7.9 - 19.8)
30,000	10.7 (6.4 - 17.8)
25,000	9.2 (4.9 - 15.8)
20,000	7.7 (3.4 - 13.8)
15,000	6.2 (1.9 - 11.8)
10,000	4.7 (0.4 - 9.8)
5,000	3.2 (-1.1 - 7.8)
0	1.7 (-2.6 - 5.8)

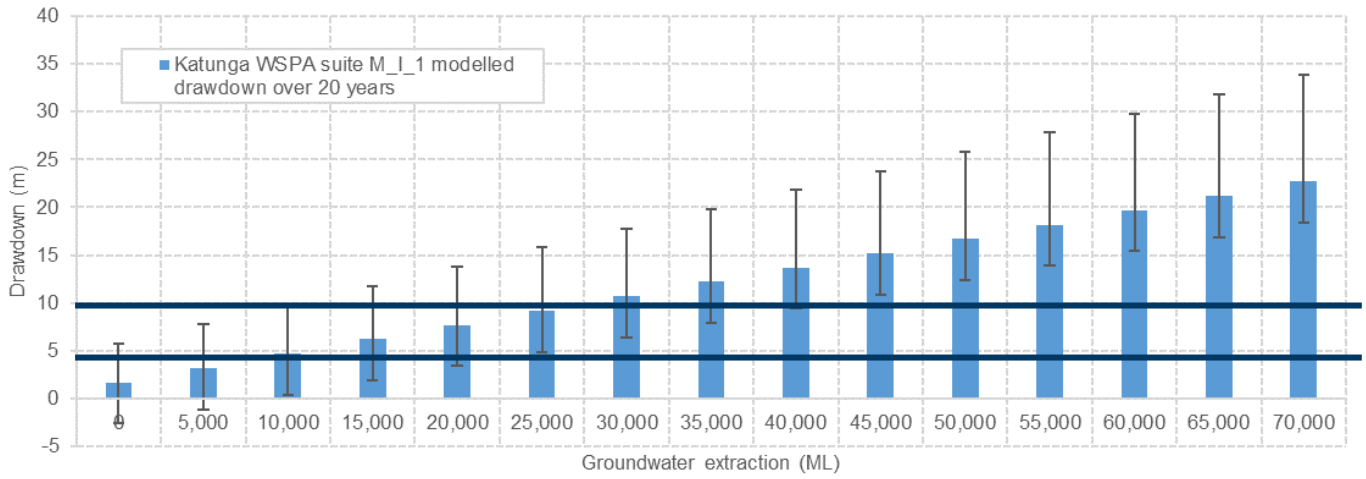


Figure 49 *Katunga WSPA Suite M_I_1: Relationship of Suite drawdown to GMU extraction. Error bars show results of drawdown using levels from model's 95% prediction intervals from pre-development levels (1981/1982)*

Table 25 *Relationship of Suite drawdown to GMU extraction for Katunga WSPA Suite M_I_2*

Volume (ML/year) for whole of GMU	Based on model prediction of Suite M_I_2 annual recovered levels
	Drawdown over 20 years (m) (lower limit to upper limit based on 95% prediction interval band)
70,000	27.7 (25.6 - 29.6)
65,000	25.7 (23.6 - 27.6)
60,000	23.7 (21.6 - 25.6)
55,000	21.7 (19.6 - 23.6)
50,000	19.7 (17.6 - 21.6)
45,000	17.7 (15.6 - 19.6)
40,000	15.7 (13.6 - 17.6)
35,000	13.7 (11.6 - 15.6)
30,000	11.7 (9.6 - 13.6)
25,000	9.7 (7.6 - 11.6)
20,000	7.7 (5.6 - 9.6)
15,000	5.7 (3.6 - 7.6)
10,000	3.7 (1.6 - 5.6)
5,000	1.7 (-0.4 - 3.6)
0	-0.3 (-2.4 - 1.6)

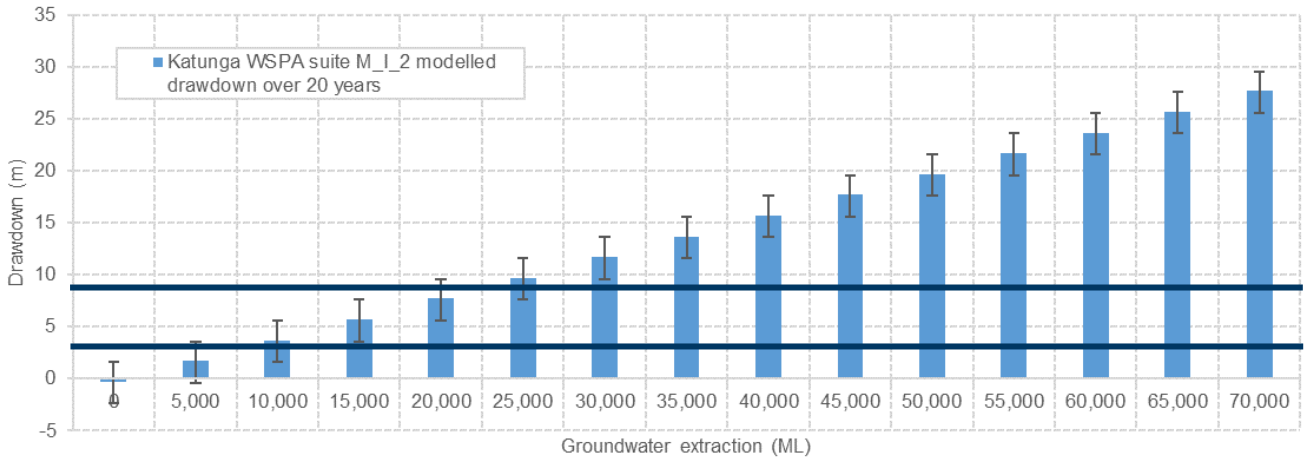


Figure 50 *Katunga WSPA Suite M_I_2: Relationship of Suite drawdown to GMUA extraction (with error bars showing results of drawdown using levels from model's 95% prediction intervals from pre-development levels (1981-1982)*

Table 26 *Relationship of Suite drawdown to GMU extraction for Katunga WSPA and Lower Murrumbidgee Groundwater Source, Suite M_I_1*

Volume (ML/year) for Katunga WSPA and Lower Murumbidgee Deep Groundwater	Based on model prediction of Suite M_I_1 annual recovered levels
	Drawdown over 20 years (m) (lower limit to upper limit based on 95% prediction interval band)
260,000	11.2 (6.5 - 17.9)
240,000	10.6 (5.9 - 17.1)
220,000	10 (5.3 - 16.3)
200,000	9.4 (4.7 - 15.5)
180,000	8.8 (4.1 - 14.7)
160,000	8.2 (3.5 - 13.9)
140,000	7.6 (2.9 - 13.1)
120,000	7 (2.3 - 12.3)
100,000	6.4 (1.7 - 11.5)
80,000	5.8 (1.1 - 10.7)
60,000	5.2 (0.5 - 9.9)
40,000	4.6 (-0.1 - 9.1)
20,000	4 (-0.7 - 8.3)
0	3.4 (-1.3 - 7.5)

Table 27 *Predicted GMU volumes for drawdown metrics*

Drawdown (m)	Predicted volumes for GMU based on Suite M_I_1 drawdowns (lower limit to upper limit)	Predicted volumes for GMU based on Suite M_I_2 drawdowns (lower limit to upper limit)
5	11,000 (-2,000 – 25,400)	13,400 (8,400 – 18,600)
10	27,900 (10,500 – 42,000)	25,900 (20,900 – 31,000)

	Volume (ML/year)	Drawdown over 20 years
	70,000	22.7 (18.4 - 33.8)
	65,000	21.2 (16.9 - 31.8)
PCV = 60,577	60,000	19.7 (15.4 - 29.8)
	55,000	18.2 (13.9 - 27.8)
	50,000	16.7 (12.4 - 25.8)
	45,000	15.2 (10.9 - 23.8)
	40,000	13.7 (9.4 - 21.8)
Av use = 27,785	35,000	12.2 (7.9 - 19.8)
	30,000	10.7 (6.4 - 17.8)
	25,000	9.2 (4.9 - 15.8)
	20,000	7.7 (3.4 - 13.8)
	15,000	6.2 (1.9 - 11.8)
	10,000	4.7 (0.4 - 9.8)
	5,000	3.2 (-1.1 - 7.8)
	0	1.7 (-2.6 - 5.8)

	Volume (ML/year)	Drawdown over 20 years
	70,000	27.7 (25.6 - 29.6)
	65,000	25.7 (23.6 - 27.6)
PCV = 60,577	60,000	23.7 (21.6 - 25.6)
	55,000	21.7 (19.6 - 23.6)
	50,000	19.7 (17.6 - 21.6)
	45,000	17.7 (15.6 - 19.6)
	40,000	15.7 (13.6 - 17.6)
Av use = 27,785	35,000	13.7 (11.6 - 15.6)
	30,000	11.7 (9.6 - 13.6)
	25,000	9.7 (7.6 - 11.6)
	20,000	7.7 (5.6 - 9.6)
	15,000	5.7 (3.6 - 7.6)
	10,000	3.7 (1.6 - 5.6)
	5,000	1.7 (-0.4 - 3.6)
	0	-0.3 (-2.4 - 1.6)

Legend

- Groundwater Management Units
- Middle Aquifer Suites
  - M_I_1
  - M_I_2
  - M_J_9
- Major town
- Rail
- Freeway & highway
- River
- Park

EDWARD RIVER
MURRAY RIVER
Newell Hwy
New South Wales
MULWALA CANAL
Murray Valley Hwy
Goulburn Valley Hwy
Katunga WSPA
M_I_2
M_I_1
M_J_9
YARRAWONGA
New South Wales

Paper Size ISO A3

0 2 4 6 8

Kilometres

Map Projection: Lambert Conformal Conic
Horizontal Datum: GDA 1994
Grid: GDA 1994 VICGRID94

N

GHD

DEECA
Sustainable Yields
Confined Aquifers

KATUNGA WSPA: KEY SUITES VOLUME VS DRAWDOWN

Project No. 31-12564066
Revision No. 0
Date 15/01/2024

FIGURE 51

Data source: DEECA, VicMap, 2022; DEECA, GMU locations, 2022; DEECA, extraction bore locations, 2022; GHD, aquifer suites, 2018; . Created by: cperyer

7.6 GMU summary

7.6.1 Findings

Katunga WSPA primarily relates to the Calivil Formation aquifer (UTAF) and groundwater is predominately extracted from this aquifer for irrigation purposes. The UTAF falls within the Middle Aquifer Suites, which at Katunga WSPA comprise M_I_1 (27%), M_I_2 (67%) and M_J_9 (0%), providing a total GMU coverage of 94%. The identified representative Suites are M_I_2 (most preferred) and M_I_1. The Suite hydrographs for the representative Suites show an overall decreasing trend along with seasonal fluctuation and thus recovered water levels, which were adopted for the assessment.

As identified through the conceptualisation, Katunga WSPA may be influenced by extraction occurring north of the GMU in NSW from the Lower Murrumbidgee Groundwater Sources (deep aquifer). Of the two hindcasting methods that look at both extraction datasets, the correlations developed to apply the hindcasting were improved when both datasets were considered rather than the Katunga WSPA dataset alone. However, the difference between the Katunga WSPA only and the combined Katunga WSPA and Lower Murrumbidgee Groundwater Sources model runs was minor, with the Katunga only extraction model runs generally showing a better result statistically for Suite M_I_2 but the combined extraction model runs giving a better result for Suite M_I_1.

Application of two yearly annual average extraction instead of annual average generally showed a poorer to similar model fit based on the statistical analysis across the model runs. The best match using the two yearly average annual extraction was model run 4 (two yearly average annual extraction for Katunga WSPA and Lower Murrumbidgee with annual recovered levels) for Suite M_I_1 and model run 13 for Suite M_I_2 (two yearly average annual extraction for Katunga WSPA and Lower Murrumbidgee Groundwater Source hindcasted using method H2 with annual recovered levels).

The application of spatial distribution produced a poorer model fit in comparison to the other non-hindcasted models. The quality of the result did not increase when spatial distribution methodology was combined with hindcasting methodology.

Based on an assessment of all model runs, model run 8 of Katunga WSPA and Lower Murrumbidgee Groundwater Sources annual recorded extraction with hindcast method H2 and model run 7 of Katunga WSPA annual recorded extraction with hindcast method H2 was adopted to undertake the predictive modelling for Suite M_I_1 and M_I_2 respectively.

The pre-development levels were defined for the two Suites are based on the maximum annual recorded levels in the early time series Suite data; this resulted in pre-developments levels of 18.52 m for Suite M_I_1 and 13.41 m for Suite M_I_2. The drawdowns were calculated based on these pre-development levels and the simulated levels from each of the 19 forecast scenarios.

The volumes estimated for a given drawdown for each Suite is shown below.

Drawdown (m)	Predicted volumes for GMU based on Suite M_I_1 drawdowns (lower limit to upper limit)	Predicted volumes for GMU based on Suite M_I_2 drawdowns (lower limit to upper limit)
5	11,000 (-2,000 – 25,400)	13,400 (8,400 – 18,600)
10	27,900 (10,500 – 42,000)	25,900 (20,900 – 31,000)

The models for both Suites M_I_2 and M_I_1 were assessed as having a “Good” model applicability rating using the criteria outlined in section 5.2. Both Suites would have had a higher rating if the RMSE was lower than 1, its noted that both Suites had an RMSE less than 2 m (with M_I_2 having an RMSE of 1.02).

Suite M_I_2 was selected as the most likely representative Suite for Katunga WSPA based on its coverage, the number of active SOBNs, and the location of Suite bores to extraction points.

7.6.2 Limitations

In addition to the limitations applicable to all 25 GMUs discussed in section 1.8, the following Katunga WSPA specific limitations have been identified:

- Groundwater use for Lower Murrumbidgee Groundwater Sources is not available on a groundwater use by bore basis and thus has not been incorporated into the spatial distribution modelling methodology
- The model results for Suite M_I_1 are based on combined extraction of Katunga WSPA and Lower Murrumbidgee Deep Groundwater Source. However, the extraction used in the adopted use-drawdown relationship is using Katunga WSPA extraction only. When extraction of Katunga WSPA and Lower Murrumbidgee Groundwater Sources are combined annually, on average, Katunga WSPA extraction makes up 11% of this thus 11% of the combined volume has been used in the final relationship to represent the Katunga WSPA only extraction.
- The licenced bore dataset provided by DEECA has 81% of bores assigned to Katunga WSPA with no depth data and thus couldn't be assigned to a VAF layer and in turn Suite. These bores were assigned to an aquifer through this study by GHD, in order to assist with the determination of the representative Suite. However, this data was not used in the model analysis.

7.6.3 Recommendations

In addition to the recommendations applicable to all 25 GMUs discussed in section 32, the following Katunga WSPA specific recommendations have been identified:

- The licenced bore dataset provided by DEECA has 81% of bores assigned to Katunga WSPA with no depth data and thus couldn't be assigned to a VAF layer and in turn Suite. It is recommended that DEECA obtains the relevant depth and aquifer monitored data for licenced bores within this GMU.

8. Corinella GMA

8.1 Conceptualisation

The hydrogeological conceptualisation elements relevant to this study are summarised in Table 28 and a map of the GMU is presented in Figure 52. It is noted that a significant volume of information was collated to provide hydrogeological conceptual understanding of the GMU. The information that is directly relevant to the modelling are in bold or colour coded within Table 28.

Table 28 Corinella GMA – Tabulated conceptualisation

GMU summary

Corinella GMA is situated on the southeast margin of the Tertiary Westernport Basin, covering an area of 110 km. Within this area, the GMA pertains to all formations below the surface, but was intended to primarily manage the groundwater resource of the Childers Formation (Lower Tertiary Aquifer, LTA). The PCV (2,550 ML/year) therefore primarily relates to confined aquifers, however, as this GMU is located along the coast, its anticipated that the aquifer if semi-confined to confined.

Groundwater the Corinella GMA is extracted predominately for commercial and industrial purposes, stock and domestic use, urban and high value horticulture use such as vegetable irrigation.

Hydrostratigraphy summary

Aquifer	Formation	Relevant Suites (% coverage of GMU)	% of GMU covered by Suites	Number of SON bores	Groundwater use	Approx. use volumes ML (2019/20)	Approx entitlement volumes ML (2019/20)	Understanding (Low, Medium, High)
Upper	Undifferentiated sediments (QA)	-	-	0	NA	0	0	Low
Middle	Brighton Group/Baxter Sandstone (UTAF)	-	-	0	Urban, irrigation, stock, domestic, dairy	34 (10)	267 (32)	Low
	Batesford Limestone (UMTA)	-	-	0	NA	0	0	Low
Lower	Childers Formation (LTA)	M_S_88 (90%)	90%	1	Urban, dairy, domestic, stock	5 (5)	262 (14)	Medium
	Mornington Volcanics (LTB)	-	-	0	NA	0	0	Low
Basement	Basement rocks	-	-	0	Domestic	0	136	Low

Note that volumes listed above are based on the DEECA provided licenced bore dataset with associated VAF layers. Bores have been assigned to a VAF layer based on bore depth where available. In some instances, bore depth is not available and has been reallocated where possible; the reassigned volumes are indicated within the brackets.

Note that volumes listed above include 5 ML of unassigned use due to unknown depths and 10 ML assigned to the UTQD, but this VAF layer doesn't occur in this GMU.

Characteristic and importance	Description	Degree of understanding
Intended aquifer		
Aquifer thickness within GMU (range, based on VAF)	Max: 229 m, Average: 61 m	High
Aquifer extent	Small, local	High
Likelihood of inter-aquifer flow	High	Low
Likelihood of groundwater – surface water interaction	Low	Low GHD (2020)
Representative Suite	**M_S_88**	**Medium. 60% of GMU extraction occurs within this Suite, which relates to the most relevant GMU aquifer**
Current hydrological condition of representative aquifer		
Representative Suite trend	Variable – consistent with long term average rainfall	High
Groundwater quality (average salinity based on WMIS and CDM Smith spatial segment with highest coverage)	4,993 mg/L (WMIS) <3,100 mg/L (CDM Smith 2022)	Low Based on WMIS Based on CDM Smith (2022)
Groundwater yield	0.5 – 5 L/s	Based on CDM Smith (2022)
Groundwater levels		
Temporal groundwater level data range	**1969 - 2021**	
Spatial clustering of licensed bores in relation to Suites	No	Based on DEECA density mapping and licenced bore data.
Groundwater use		
Licensed groundwater use	**60 ML**	**Low – aquifer not sufficiently stressed, i.e., Suite hydrographs not showing a significant stress period (Based on average historical VWA data over 15 years)**
Minimum historic groundwater use	**14 ML**	**High (Based on historical VWA data, year 2020/21**
Maximum historic groundwater use	**129 ML**	**High (Based on historical VWA data, year 2009/10)**
Entitlement (Groundwater allocation)	**662 ML**	**Low – aquifer not sufficiently stressed, i.e., Suite hydrographs not showing a significant stress period (Based on licenced volumes in 2020/21)**

Characteristic and importance	Description	Degree of understanding
Significant drivers of groundwater level variability (primary)	**Pumping for irrigation**	**Moderate**
Secondary drivers of groundwater level variability	Pumping for commercial and industrial	Moderate
Groundwater use profile	No clear distribution	Low
External Influence	None identified	
Groundwater values and risks		
Existing Environmental Values to be protected, relevant to this GMU	Potable water supply Licensed non-potable supply (irrigation, commercial, industrial) Unlicensed non-potable supply (domestic and stock)	
Risks to groundwater values	Direct risks: – Drawdown which may affect access to groundwater by existing users	Moderate
Indicators used to assess impacts to groundwater	– Measured drawdown using pre-determined metrics measured from a pre-determined level for the purpose of this modelling	Moderate

Legend

Extraction bores by aquifer
- UTAF (105)
- LTA (111)
- BSE (114)

No depth (assumed to be middle aquifer)

SOBN (by aquifer)
- UMTA
- LTA

LTB

Middle suite bore
- M_ID
- M_S_88

Middle aquifer suite
- M_S_3
- M_S_88

Groundwater Management Unit (GMU)

Town

Freeway & highway

Major road

Minor road

Stream

M_S_88

CORONET BAY

Bass Hwy

M_S_88

Corinella GMA

BASS

NEWHAVEN

SAN REMO

Anderson-Link-Rd

KILCUNDA

Bass Hwy

Paper Size ISO A3

0 0.55 1.1 1.65 2.2

Kilometers

N

Map Projection: Lambert Conformal Conic
Horizontal Datum: GDA 1994
Grid: GDA 1994 VICGRID94

GHD

DEECA
Sustainable yield review - confined aquifers

Corinella GMA
Site location and key features

Project No. **12564066**
Revision No. **0**
Date **15/01/2024**

Figure 52

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Print date: 15 Jan 2024 - 14:22

Data source: DELWP, VicMap, 2022; DELWP, GMUs, 2022; DELWP, SOBN, 2022; GHD, aquifer suites, 2018; DELWP, extraction bores, 2022 Created by: cperyer

8.2 Technical analysis

8.2.1 Hydrograph review and selection of representative Suites for further analysis

Suite hydrographs were generated for the confined Suites for Corinella GMA as shown in Figure 53. There is only one Suite hydrograph which shows seasonal fluctuations and hence recovered water levels.

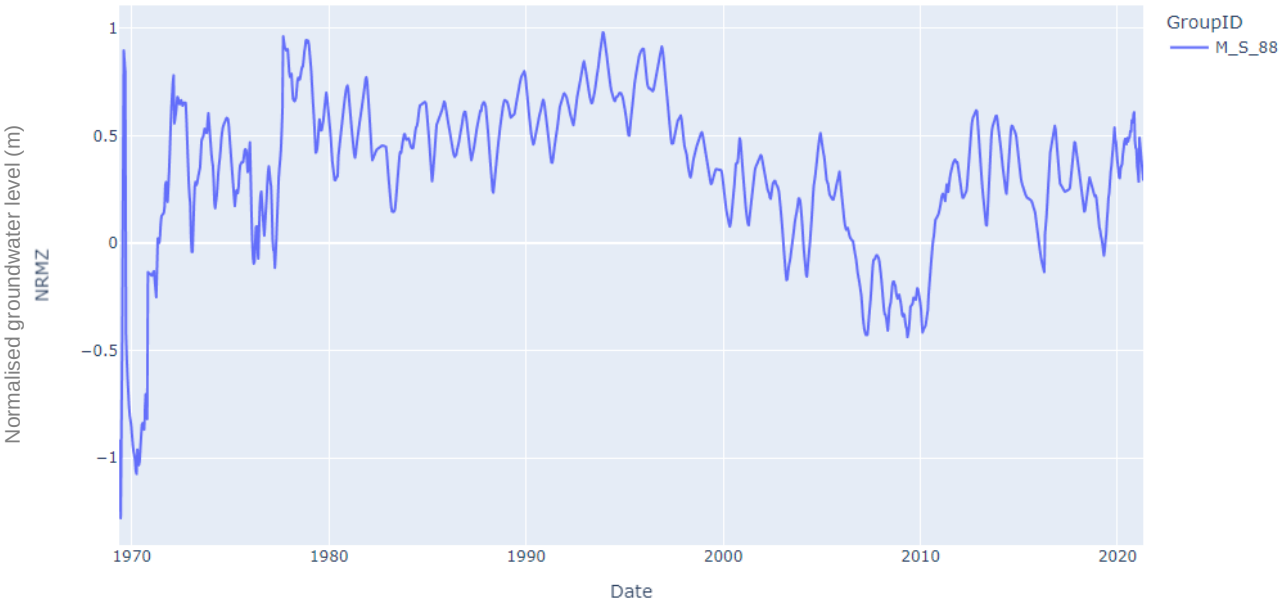


Figure 53 Corinella GMA Suite Hydrographs for all confined aquifers

The representative Suites analysed for this GMU was Suite M_S_88, which was selected following the methodology outlined in section 2.6.4 and summarised as follows:

- The greatest volume of extraction occurring within Suite M_S_88
- Suite M_S_88 pertains to the LTA which is the intended aquifer for this GMU (this occurrence is an exception to the rule as an M Suite is normally monitoring a middle aquifer but in this instance the M suite represents the Childers Formation)
- Suite M_S_88 covers 60%
- Suite M_S_88 has 1 active SOBN bore within the Suite area
- Suite bores for M_S_88 are not close to extraction points

The annual recovered Suite hydrograph for the representative Suite for Corinella GMA, M_S_88 is shown in Figure 54.

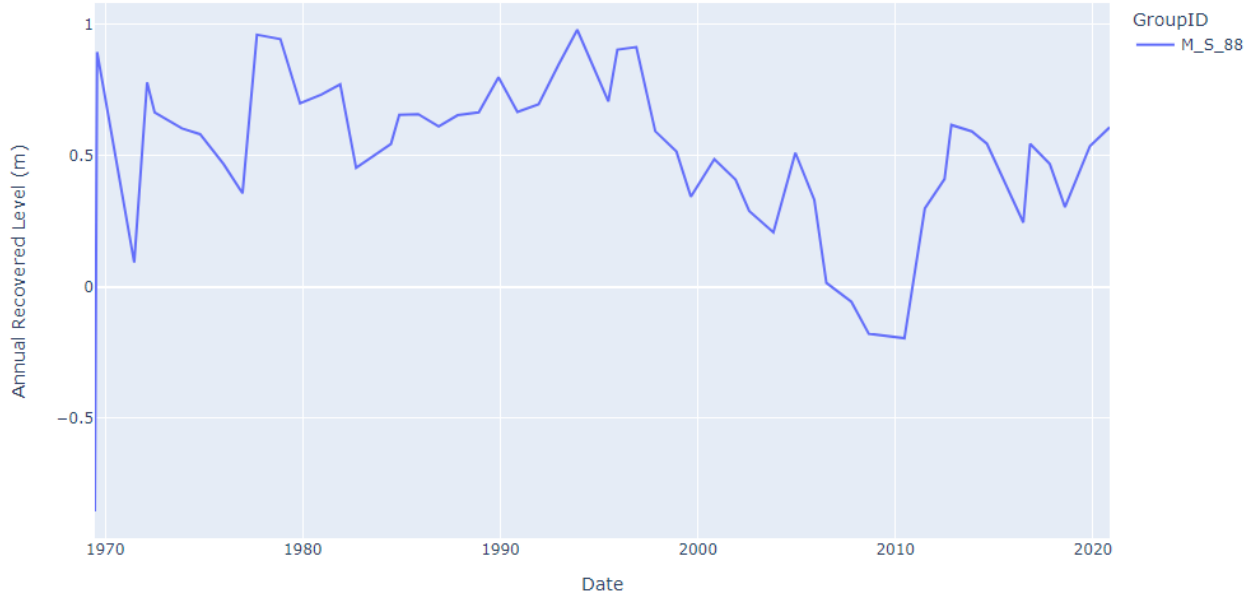


Figure 54 *Corinella GMA Annual Recovered Level Suite Hydrographs for representative Suite*

8.2.2 Pre-development level

To estimate the pre-development level conditions, GHD reviewed the Suite hydrographs of annual recovered levels and assumed that the early time data was the best representation of conditions prior to major development within Corinella GMA. This pre-2007 early time series data was adopted as the baseline of pre-development conditions.

The pre-development annual recovered levels are taken to be the average of the first 32 readings which equate to 0.6 m (refer further details in section 8.4.3).

8.2.3 Externalities

Through the conceptualisation, no external influence was identified for Corinella GMA.

8.2.4 Hindcasting

Groundwater use data for Corinella GMA is available from 2004/2005 to 2020/2021. Licenced groundwater extraction (excluding stock and domestic) for Corinella is thought to of commenced in 2006/2007. However, to run the models back to the defined pre-development levels, we need to include extraction data back to 1973/1974, the start of the annual recovered levels dataset. Given the hydrograph shown in Figure 54, it appears extraction was occurring prior to 2006/07, thus the hindcasting methodologies outlined in section 3.3.4.5 were applied to Corinella GMA. A summary of the hindcasting results is shown in the following sections.

8.2.4.1 Hindcasting Method 1 (H1)

Applying method H1, eight different correlations were developed as described below.

Figure 55:

- Annual rainfall vs annual groundwater extraction at Corinella GMA
- Two yearly average annual rainfall vs annual groundwater extraction at Corinella GMA
- Annual summer period rainfall vs annual groundwater extraction at Corinella GMA
- Annual irrigation period rainfall vs annual groundwater extraction at Corinella GMA

Figure 56:

- Annual rainfall vs annual irrigation groundwater extraction at Corinella GMA
- Two yearly average annual rainfall vs annual irrigation groundwater extraction at Corinella GMA
- Annual summer period rainfall vs annual irrigation groundwater extraction at Corinella GMA
- Annual irrigation period rainfall vs annual irrigation groundwater extraction at Corinella GMA

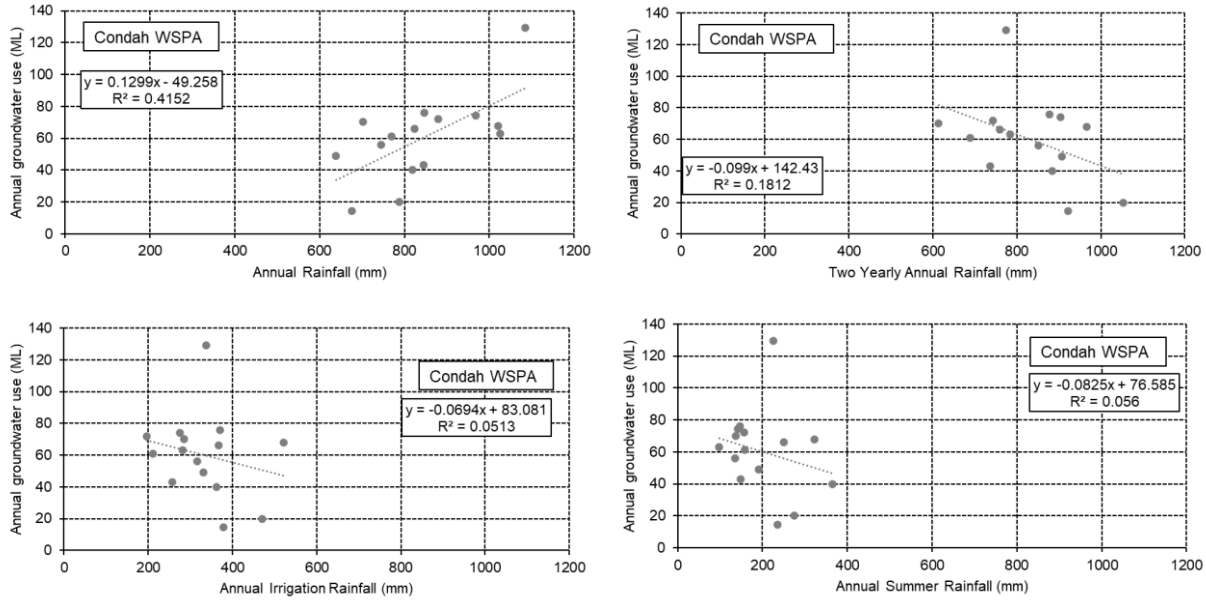


Figure 55 Corinella GMA: Hindcast method 1 correlations (Corinella GMA annual extraction)

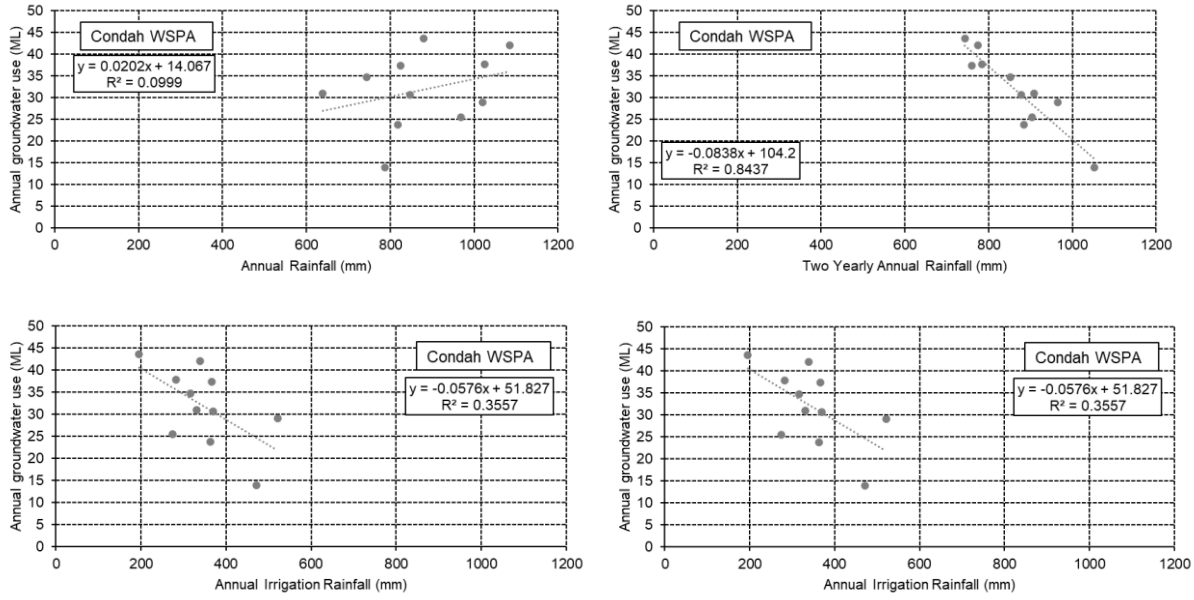


Figure 56 Corinella GMA: Hindcast method 1 correlations (Corinella GMA annual irrigation extraction)

Comparing the results of the correlations using annual irrigation against that of annual irrigation, generally the goodness-of-fit (R^2) increased when only considering extraction use for irrigation across all rainfall scenarios. The exception to this is when annual rainfall is used, the goodness-of-fit (R^2) decreases when annual irrigation use is used rather than total annual use. The best correlation achieved using hindcasted method H1 was the combination of two yearly annual average rainfall with annual groundwater use; this was the correlation adopted when applying hindcast method H1 for the modelling.

8.2.4.2 Hindcasting Method 2 (H2)

Applying method H2, four different correlations were developed as described below.

Figure 57:

- Annual rainfall vs annual groundwater extraction at Corinella GMA
- Two yearly average annual rainfall vs annual groundwater extraction at Corinella GMA
- Annual summer period rainfall vs annual groundwater extraction at Corinella GMA
- Annual irrigation period rainfall vs annual groundwater extraction at Corinella GMA

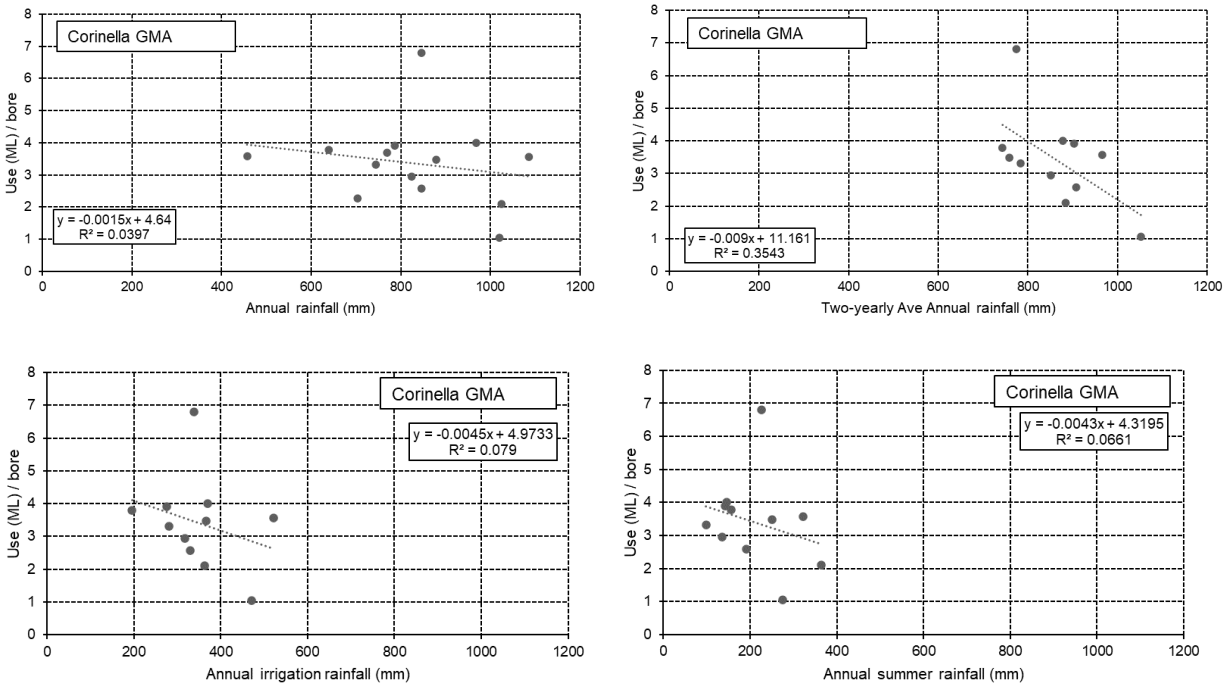


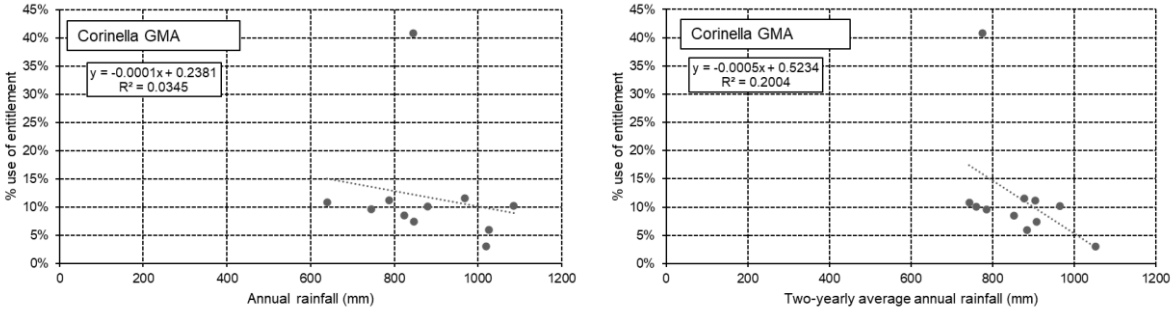
Figure 57 Corinella GMA: Hindcast method 2 correlations (Corinella GMA annual extraction)

Generally, the goodness-of-fit (R^2) was poor across all correlations developed under hindcast method H2. The best goodness-of-fit (R^2) achieved was for the two-yearly annual average with an R^2 of 0.35; this was the correlation adopted when applying hindcast method H2 for the modelling.

8.2.4.3 Hindcasting Method 3 (H3)

Four correlations were developed using method H3 as described below and shown in Figure 58:

- Percentage of entitlement vs annual rainfall
- Percentage of entitlement vs two yearly average annual rainfall
- Percentage of entitlement vs annual summer rainfall
- Percentage of entitlement vs annual irrigation rainfall



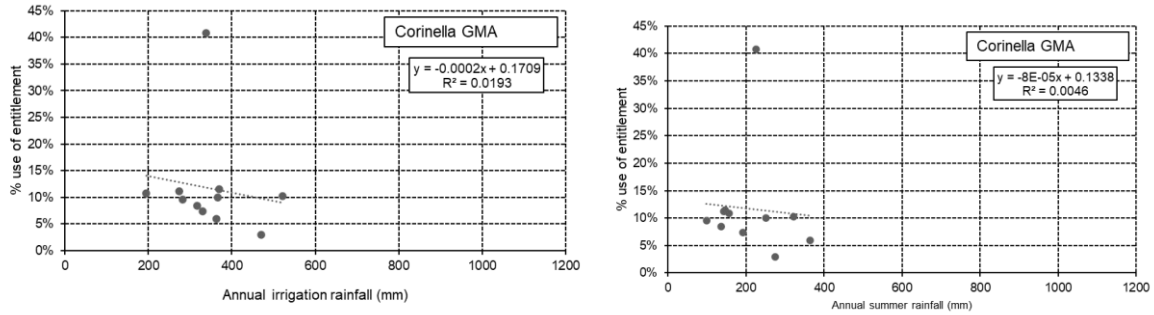


Figure 58 Corinella GMA: Hindcast method 3 correlations (Corinella GMA annual extraction)

Generally, the goodness-of-fit (R^2) was poor across all correlations developed under hindcast method H3. The best goodness-of-fit (R^2) achieved was for the two-yearly annual average with an R^2 of 0.2; this was the correlation adopted when applying hindcast method H3 for the modelling.

8.2.4.4 Comparison

A comparison of the three input datasets is shown in Figure 59 and Figure 60 for the hindcasting based on just Corinella GMA groundwater use. Figure 59 shows a comparison of the three hindcasting methods against the recorded use only over the recorded use date and Figure 60 shows the hindcasted data back to 1973/1974.

As shown in Figure 60, groundwater use using method H1 does not decrease historically as there is no factor to account for the changing number of bores extracting over time and thus, results in a higher groundwater extraction estimate than method H2. When looking at just the period of recorded data in Figure 59, method H1 has the closest estimate to the recorded extraction values. However, due to method H1 not decreasing in usages with time, it's likely that method H2 provides a better historic estimate prior to the recorded period.

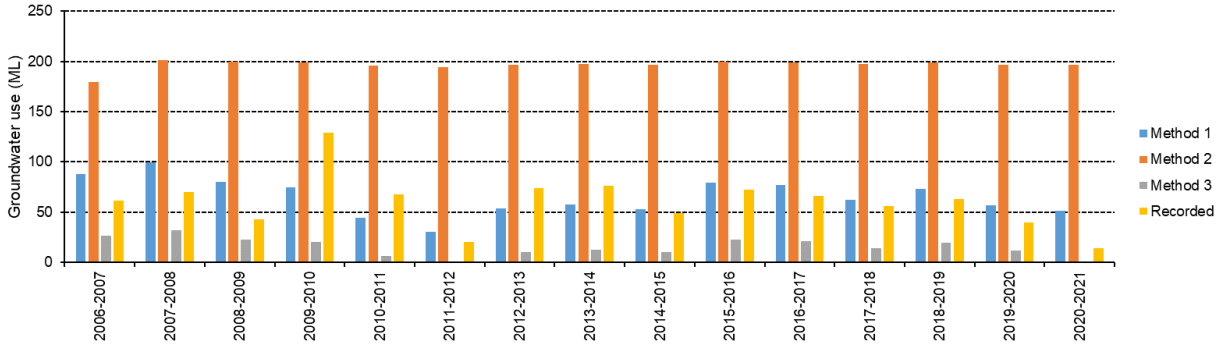


*Figure 59 Corinella GMA: Comparison of hindcasting over recorded use period – Corinella **GMA only extraction***

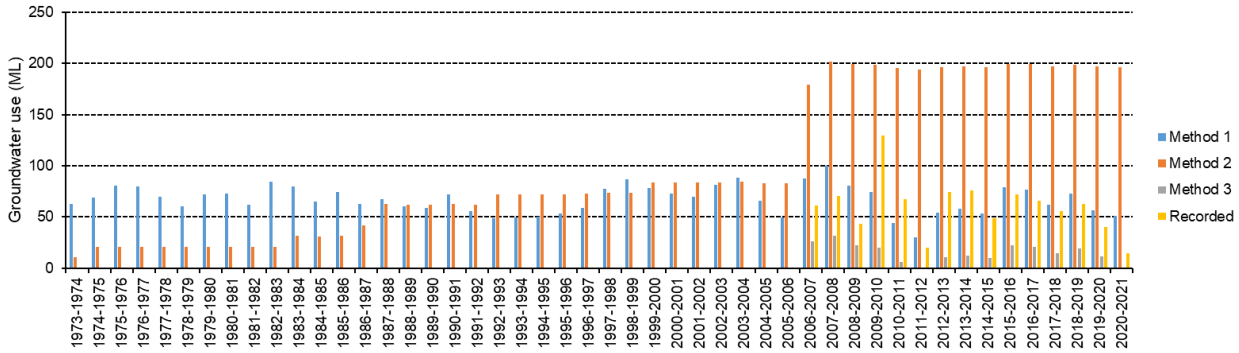


*Figure 60 Corinella GMA: Comparison of hindcasting – Corinella **GMA only extraction***

8.3 Modelling

8.3.1 Model inputs

A number of different models were run based on the various model inputs developed and combinations of these. Table 29 summarises these combinations of model inputs run for Corinella GMA. Model runs highlighted blue indicated they were run with annual extraction and grey indicates they were run using two yearly average annual extraction. It is noted that for Corinella, some additional model runs were undertaken with climate data; this is explained further in the section below.

Table 29 Corinella GMA: summary of model inputs

Model input	Model runs																			
	1	1c	2	3	4	5c	6	7c	8	9	10	11	12	13	14	15	16	17	18	19
Annual recovered levels for representative Suites (M_S_88)	✓	✓	✓			✓		✓							✓	✓	✓			
Annual extraction – Corinella GMA only	✓	✓																		
Annual climate data		✓				✓		✓												
Two yearly average annual extraction – Corinella GMA only			✓																	
Annual extraction – Corinella GMA and Externalities																				
Two yearly average annual extraction – Corinella GMA and Externalities																				
H1 annual extraction – Corinella GMA only						✓														
H1 annual extraction – Corinella GMA and Externalities																				
H2 annual extraction – Corinella GMA only								✓												
H2 annual extraction – Corinella GMA and Externalities																				
H3 annual extraction – Corinella GMA only																				
H1 two yearly average annual extraction – Corinella GMA only																				
H1 two yearly average annual extraction – Corinella GMA and Externalities																				
H2 two yearly average annual extraction – Corinella GMA only																				
H2 two yearly average annual extraction – Corinella GMA and Externalities																				
S1 annual extraction – Corinella GMA only															✓					

Model input	Model runs																			
	1	1c	2	3	4	5c	6	7c	8	9	10	11	12	13	14	15	16	17	18	19
S2 annual extraction – Corinella GMA only																✓				
S3 annual extraction – Corinella GMA only																	✓			
S1 annual extraction and H1 annual extraction – Corinella GMA only																				
S2 annual extraction and H2 annual extraction – Corinella GMA only																				
S3 annual extraction and H3 annual extraction – Corinella GMA only																				

8.3.2 Model calibration and uncertainty analysis

A statistical summary of the model output results for the runs described in Table 29 is presented in Table 30 for the selection of potential representative Suites for Corinella GMA. Suite M_S_88 was selected as the most likely representative Suite based on the process outlined in section 8.2.17.2.1. The statistics summarised include the average 95 PPU thickness (95PPU TH), percentage of observed levels within 95 PPU (%Obs in 95 PPU), R^2. root mean square error (RMSE), number of annual recovered level observation points (No obs data points) and the range of observed annual recovered levels.

Suite M_S_88

An initial review of the results and statistical summary for Suite M_S_88 showed that model run 1 (highlighted orange) showed the best results (by considering the other three statistical measures) of the original five different model input combinations tested (1,2,14,15 and 16). However, due to the relatively poor results by all five models, the model was run again but incorporating climate data which was found to improve the model results (as shown by the difference in model 1 and model 1c). As previously touched on, the models had to be run with hindcasting to incorporate the early time series data into the model when pre-development levels had been defined; thus hindcasted models with climate added were also run. These model runs are indicated with a 'c'. Based on the results of the additional model runs, model 7c has the best statistical results and has been adopted. The graphical model output for this run is shown in Figure 61.

Based on these results, modelling was progressed on the basis of adopting model 7c.

Table 30 Corinella GMA: summary of model outputs

Suite	Statistic	Model run							
		1	1c	2	5c	7c	14	15	16
M_S_88	95PPU TH	1.02	0.63	1.07	0.85	0.64	3.74	0.52	0.52
	%Obs in 95 PPU	92.86	100	100	97.87	93.62	90	100	100
	R^2	30.1	84.8	19.9	64.6	71.6	1.7	-1.4	-1.4
	RMSE	0.23	0.11	0.25	0.16	0.14	0.13	0.13	0.13
	No obs data points	14	14	14	47	47	10	10	10
	Range of observed levels	0.8	0.8	0.8	1.2	1.2	0.4	0.4	0.4

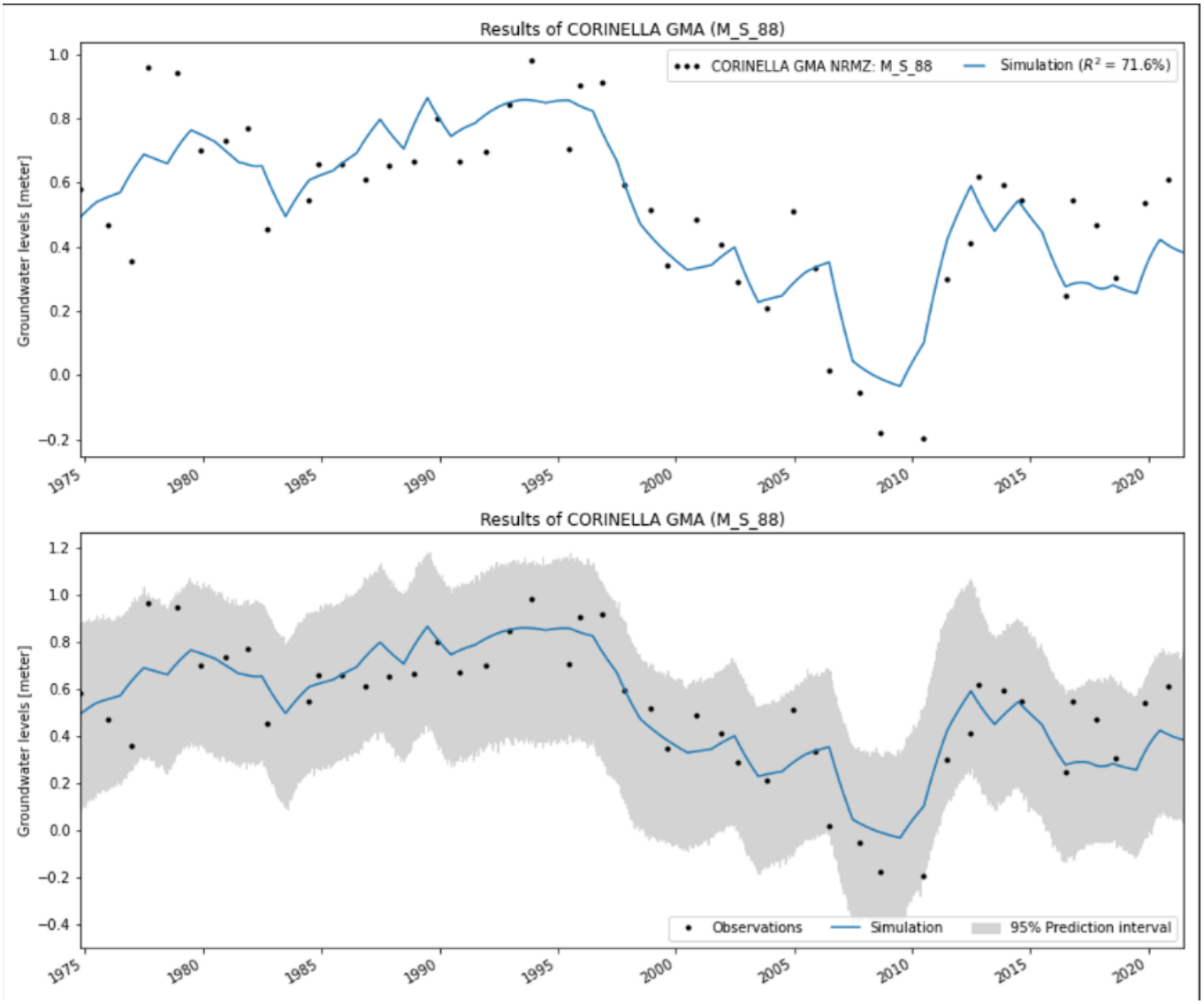


Figure 61 ***Corinella GMA Suite M_I_1: model run 7c (Corinella GMA annual extraction with hindcast method H2 and climate) output hydrographs***

8.4 Predictive modelling

8.4.1 Model inputs

The preferred model to run the predictive modelling for Corinella GMA was model run 7c for the representative Suite, thus the key inputs for the model were the annual recovered levels and the annual extraction in Corinella GMA. To conduct the forecasting for the 19 scenarios discussed in section 3.5.3, a few factors were required in the calculations, as summarised in Table 31.

Table 31 ***Corinella GMA: forecast scenario inputs***

Input item	PCV	Licenced entitlement (based on 2020/21)	Existing use (based on 2020/2021)	Average use over recorded period (from VWA)	Maximum use over recorded period (from VWA, year 2009/10)
Value (ML/year)	2,550	662	14	60	129

The model run 7c was run for all 19 forecast scenarios on Suite M_S_88.

8.4.2 Predictive model uncertainty

The model output files of the predicted models can be found in the data package provided in Appendix E.

Markov Chain Monte Carlo (MCMC) predictions were undertaken on each of the forecasted scenarios for each of the two Suites. An example of one of the outputs is presented in Figure 62 for scenario 3. As shown in Figure 62, the uncertainty of the model prediction increases as the model predicts further into the future. Comparing with the graphical output for the same scenario, the MCMC realisations tend to fall within the 95% prediction interval bands as shown in Figure 63.

Uncertainty is also accounted for by using 19 forecast scenarios to develop a groundwater use to drawdown relationship (analogous to a Monte Carlo type simulation) where a range of possible outcomes are generated. It is noted however, that the forecast scenarios were not randomly generated, but rather based upon a series of estimated use behaviours.

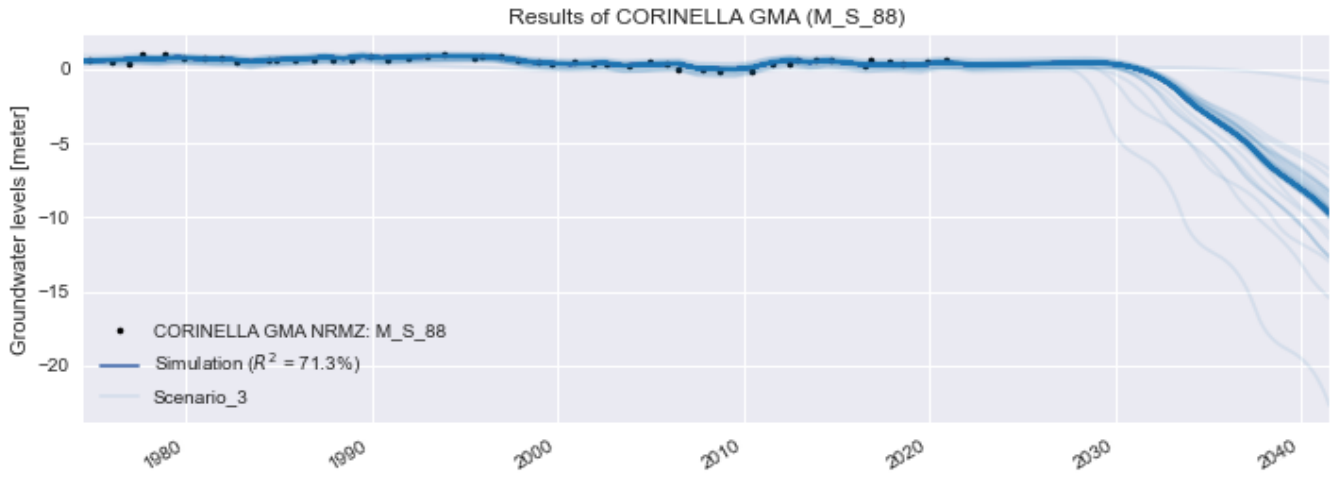


Figure 62 Corinella GMA: Suite M_S_88 MCMC analysis for Forecast Scenario 3

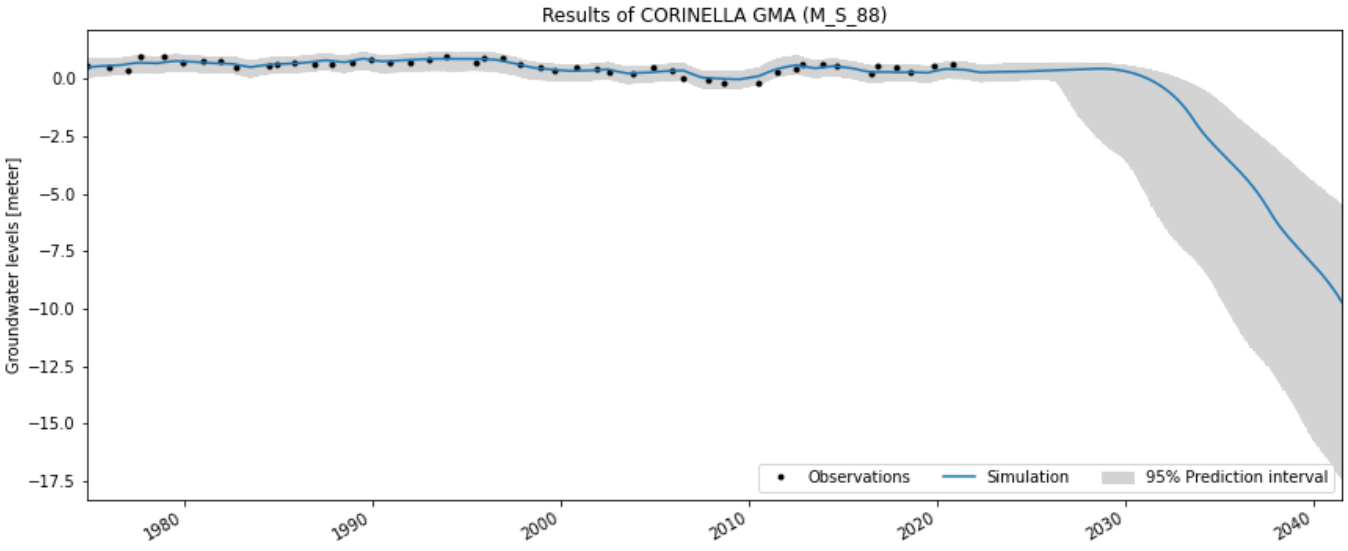


Figure 63 Corinella GMA: Suite M_S_88 Forecast Scenario 3 with 95% prediction bands

8.4.3 Extraction vs drawdown

To calculate the drawdown based on the annual recovered levels simulated by the model, the pre-development conditions (pre commencement of extraction) need to be estimated. At Corinella GMA, the water level prior to groundwater development was known since extraction commenced in 2007 and the Suite level hydrograph dates back to 1974.

Using the pre-development levels defined in section 8.2.2, the modelled water levels were converted into drawdowns (from this baseline pre-development level) for each of the 19 scenarios. This predevelopment condition is shown in Figure 64 for Suite M_S_88 hydrograph of annual recovered levels. In Figure 64:

- Actual annual groundwater use is represented by the blue column graph between 2007/2008 and 2020/2021
- Forecasted use is represented by the grey columns after 2021/2022
- The annual recovered water level behaviour based on recorded data is represented by the red line graph, whereby the earliest data is taken to best reflect the pre-development levels
- In the case of Figure 64, the pre-development annual recovered levels are taken to be the average of the first 32 readings which equate to 0.6 m
- The modelled forecasted annual recovered levels are represented by the purple line in Figure 64
- The calibration annual recovered levels are represented by the black line in Figure 64

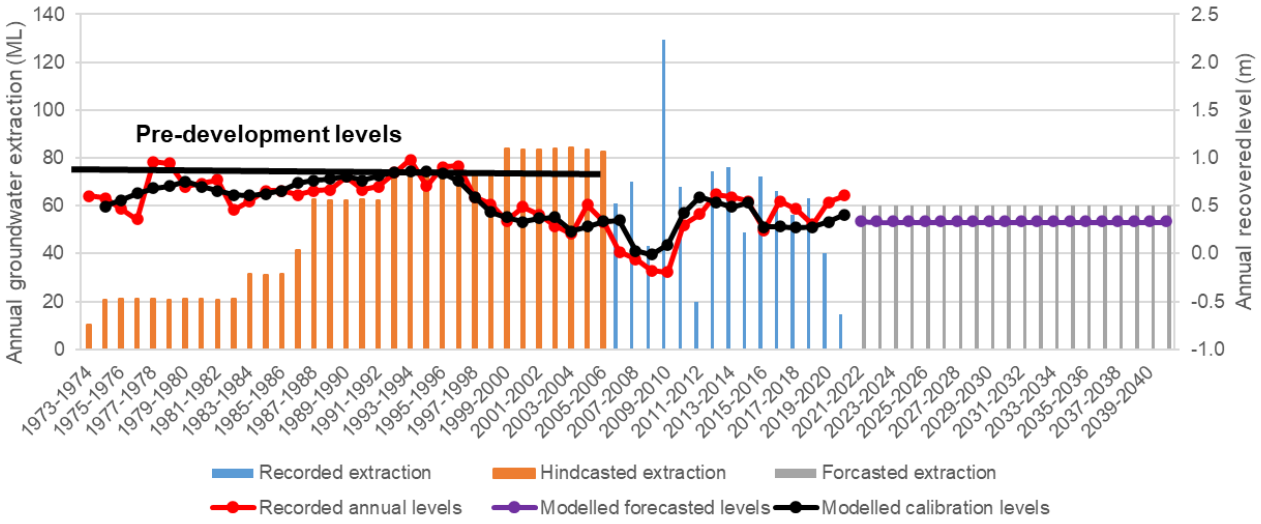


Figure 64 Estimating pre-pumping water levels (example from Suite M_S_88)

For Suite M_S_88, the calculated drawdowns and volumes for each of the scenarios were plotted in individual graphs for each scenario, all scenarios together in the one graph (Figure 65) and a graph of the scenarios for specific time periods (Figure 66) to develop the volume to drawdown relationship. For each scenario, a linear regression was applied and the coefficient of determination (R^2) was calculated. A comparison of each of these graphs shows no significant change in the coefficient of determination between Figure 65 and Figure 66, however, there were differences between individual scenario runs.

The use-drawdown for all the 19 forecast scenario drawdowns and volumes (both the recorded and forecasted volumes) over each year modelled (1974 to 2041) is shown in Figure 65 for Suite M_S_88. Reviewing these figures, the following is noted:

- There should be zero drawdown under zero use and therefore a line of best fit should pass through or close to the origin (0,0)
- Average use is around 60 ML and maximum historic use is around 130 ML. Figure 65 indicates that the model generally forecasts drawdown close to the predicted line of best fit, when use is <500 ML
- For the same annual use, different drawdowns can be obtained as Pastas predicts a water level for each year. For example, Figure 64 shows a scenario where groundwater use remains constant at around 60 ML/year over the next 20 years

- The correlation for groundwater use and drawdown for Suite M_S_88 is moderate
- The various forecast scenarios generally result in data plotting reasonably close together in a linear trend. The 19 forecast scenarios applied to populate the chart is analogous to a Monte Carlo type simulation where a range of possible outcomes are generated. It is noted however, that the forecast scenarios were not randomly generated, but rather based upon a series of estimated use behaviours.

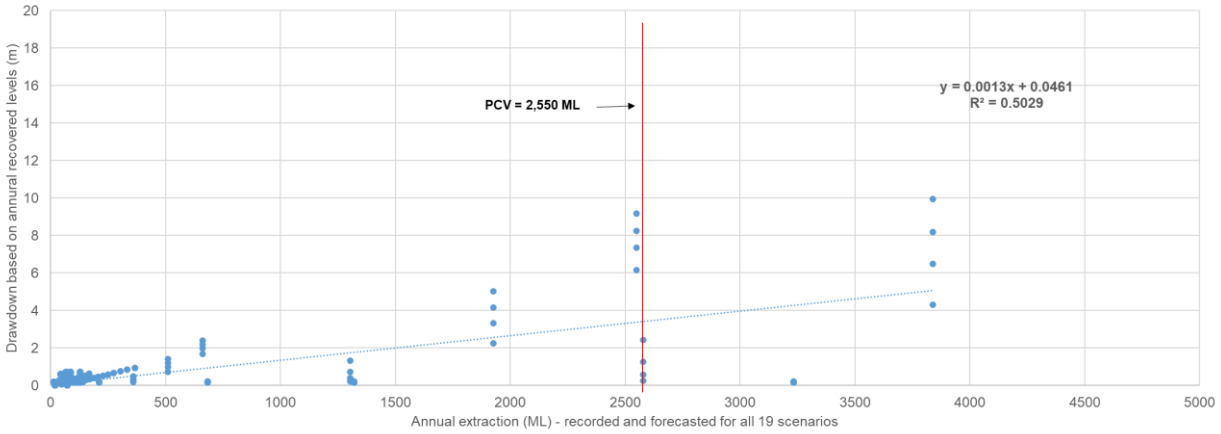


Figure 65 ***Corinella GMA Suite M_S_88: Drawdown (on annual recovered levels) and extraction volumes (recorded and forecasted <5,000 ML) for all data between 1974 to 2041 and all forecasted scenarios***

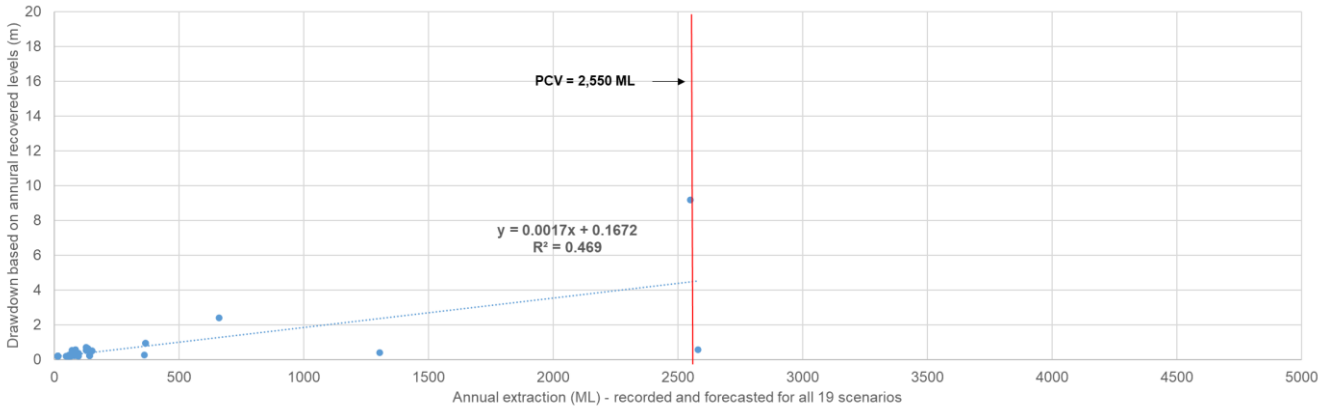


Figure 66 ***Corinella GMA Suite M_S_88: Drawdown (on annual recovered levels) and extraction volumes (recorded and forecasted <5,000 ML) for years 2020/2021, 2030/2031 and 2040/2041 for all forecasted scenarios***

8.5 Sustainability metrics

8.5.1 Application of metrics

Using the use - drawdown relationships developed through the previous step of forecasting aquifer response under a range of use scenarios, groundwater drawdown can be used to compare against metrics that define groundwater resource sustainability.

The application of these metrics and the relationship developed between drawdown based on the Suite annual recovered levels and extraction volume for the whole GMU, which is shown in Table 32 for Corinella GMA Suite M_S_88 (noting Corinella GMA has a current PCV of 2,550 ML/year). As part of the modelling, a 95% prediction interval band was applied to the modelling results. The relationship between drawdown and extraction volumes can also be interrogated at the lower and upper bands of the 95% prediction interval as shown in Table 32 and Figure 67 for Suite M_S_88.

A comparison of volumes at drawdown intervals provided by DEECA is shown in Table 33 for Suite M_S_88. Note that the volumes under each of these suite headings are for the entire GMU.

Table 32 Relationship of Suite drawdown to GMU extraction for Corinella GMA Suite M_S_88

Volume (ML/year) for whole of GMU	Based on model prediction of Suite M_S_88 annual recovered levels
	Drawdown over 20 years (m) (lower limit to upper limit based on 95% prediction interval band)
8,000	10.4 (5.4 - 34.6)
7,500	9.8 (5 - 32.4)
7,000	9.1 (4.7 - 30.3)
6,500	8.5 (4.3 - 28.1)
6,000	7.8 (4 - 26)
5,500	7.2 (3.6 - 23.8)
5,000	6.5 (3.3 - 21.7)
4,500	5.9 (2.9 - 19.5)
4,000	5.2 (2.6 - 17.4)
3,500	4.6 (2.2 - 15.2)
3,000	3.9 (1.9 - 13.1)
2,500	3.3 (1.5 - 10.9)
2,000	2.6 (1.2 - 8.8)
1,500	2 (0.8 - 6.6)
1,000	1.3 (0.5 - 4.5)
500	0.7 (0.1 - 2.3)
0	0 (-0.2 - 0.2)

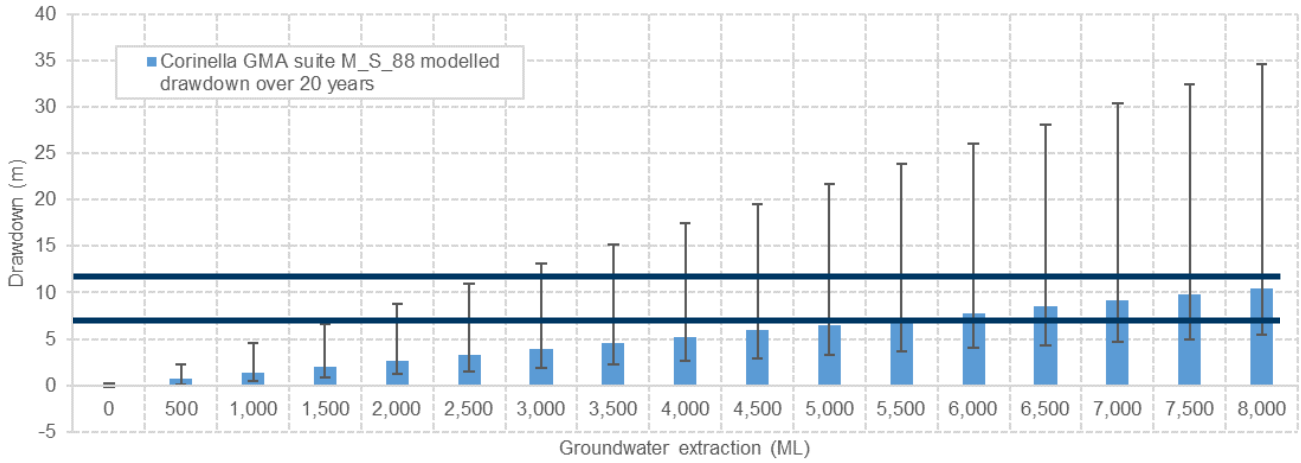
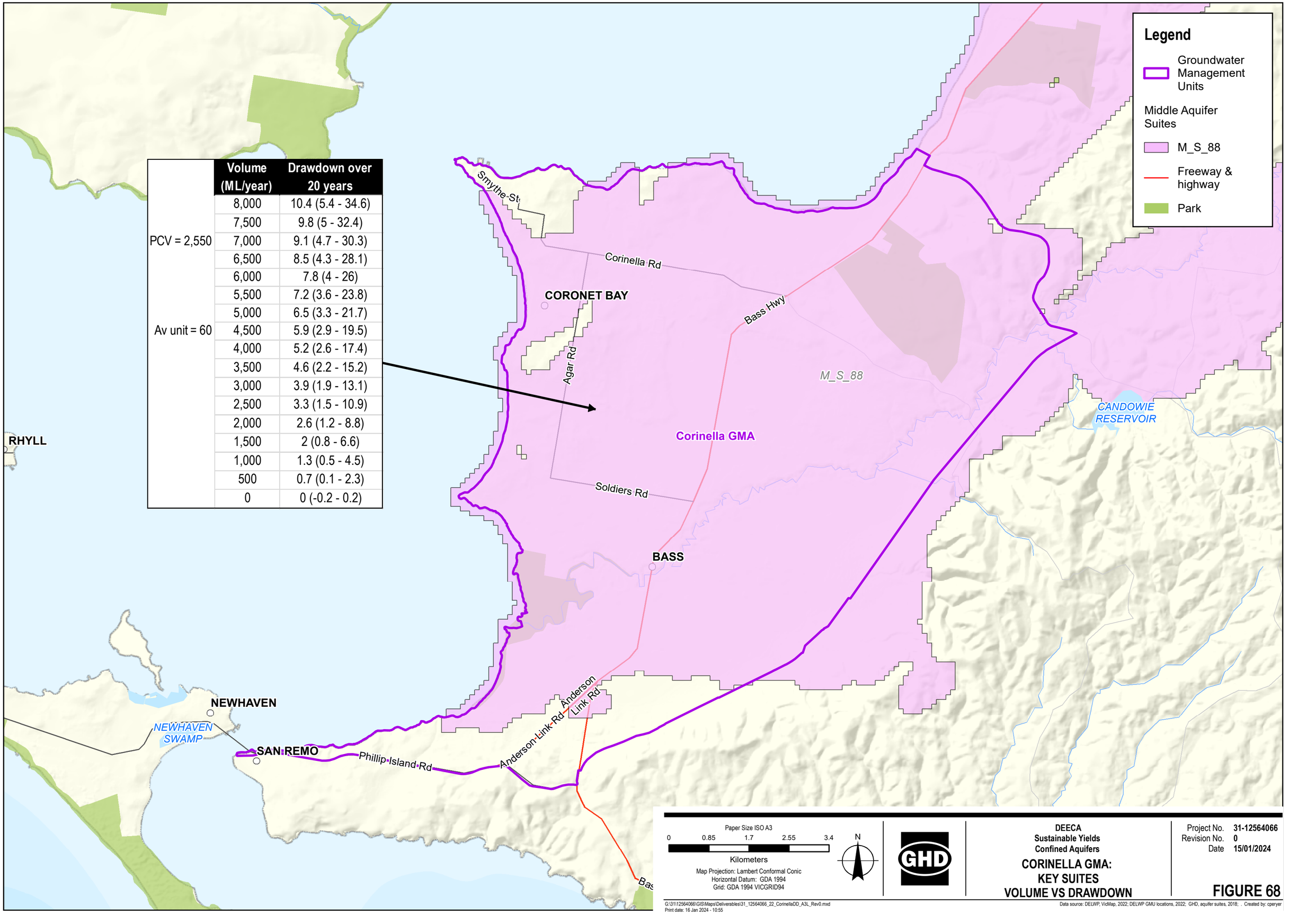


Figure 67 Corinella GMA Suite M_S_88: Relationship of drawdown to extraction (with error bars showing results of drawdown using levels from model's 95% prediction intervals)

Table 33 Predicted GMU volumes for drawdown metrics

Drawdown (m)	Predicted volumes for GMU based on Suite M_S_88 drawdowns (lower limit to upper limit)
5	3,800 (1,100 – 7,400)
10	7,700 (2,300 – 14,600)

	Volume (ML/year)	Drawdown over 20 years
	8,000	10.4 (5.4 - 34.6)
	7,500	9.8 (5 - 32.4)
PCV = 2,550	7,000	9.1 (4.7 - 30.3)
	6,500	8.5 (4.3 - 28.1)
	6,000	7.8 (4 - 26)
	5,500	7.2 (3.6 - 23.8)
	5,000	6.5 (3.3 - 21.7)
Av unit = 60	4,500	5.9 (2.9 - 19.5)
	4,000	5.2 (2.6 - 17.4)
	3,500	4.6 (2.2 - 15.2)
	3,000	3.9 (1.9 - 13.1)
	2,500	3.3 (1.5 - 10.9)
	2,000	2.6 (1.2 - 8.8)
	1,500	2 (0.8 - 6.6)
	1,000	1.3 (0.5 - 4.5)
	500	0.7 (0.1 - 2.3)
	0	0 (-0.2 - 0.2)



Paper Size ISO A3

0 0.85 1.7 2.55 3.4

Kilometers

Map Projection: Lambert Conformal Conic
Horizontal Datum: GDA 1994
Grid: GDA 1994 VICGRID94

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DEECA
Sustainable Yields
Confined Aquifers

CORINELLA GMA: KEY SUITES VOLUME VS DRAWDOWN

Project No. 31-12564066
Revision No. 0
Date 15/01/2024

FIGURE 68

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Print date: 16 Jan 2024 - 10:55

Data source: DELWP, VicMap, 2022; DELWP GMU locations, 2022; GHD, aquifer suites, 2018; . Created by: cperyer

8.6 GMU summary

8.6.1 Findings

Corinella GMA primarily relates to the Childers Formation aquifer (LTA) and groundwater is predominately extracted from this aquifer for irrigation purposes. The LTA falls within the Middle Aquifer Suites, which at Corinella GMA comprises M_S_88 (this is an exception to the normal rule an L suite would normally represent the LTA), which provides a total coverage of 90%. The Suite hydrograph for the representative Suite (M_S_88) shows a variable trend that is consistent with long term average rainfall.

Application of two yearly annual average extraction instead of annual average generally showed similar to slightly poorer model fit based on the statistical analysis across the model runs. The application of spatial distribution produced a poorer model fit than the model run using just the annual recorded groundwater usage for the whole GMU). However, due to the relatively poor results by all five models, the model of using annual extraction was run again but incorporating climate data which was found to improve the model results. Now that the model was improved, the models had to be run with hindcasting to incorporate the early time series data into the model when pre-development levels had been defined; thus, hindcasted models with climate added were also run. In undertaking the hindcasting, the models results improved again.

Based on an assessment of all model runs, the model run 7c of Corinella GMA only annual extraction hindcasted using hindcast method H2 with the annual recovered levels and climate was adopted to undertake the predictive modelling for Suite M_S_88. It is noted that this model run had the highest R^2 of 71.6.

The pre-development levels were defined for the representative Suite based on the early time series Suite data for the annual recovered levels; this resulted in a pre-development level of 0.6 m for Suite M_S_88. The drawdowns were calculated based on this pre-development level and the simulated levels from each of the 19 forecast scenarios.

The volumes estimated for a given drawdown for each Suite is shown below.

Drawdown (m)	Predicted volumes for GMU based on Suite M_S_88 drawdowns (lower limit to upper limit)
5	3,800 (1,100 – 7,400)
10	7,700 (2,300 – 14,600)

The model for Suite M_S_88 was assessed as having a “Moderate” model applicability rating using the criteria outlined in section 5.2. Due to the limited range in calibration volumes, the greater the proposed extraction rates beyond the calibration range leads to a greater potential for drawdown forecast errors.

8.6.2 Limitations

In addition to the limitations applicable to all 25 GMUs discussed in section 1.9, the following Corinella GMA specific limitations have been identified:

- The licenced bore dataset provided by DEECA has 9% of bores assigned to Corinella GMA with no depth data and not assigned to a VAF layer and in turn Suite. These bores were assigned to an aquifer by GHD for this study, in order to assist with the determination of the representative Suite. However, this data was not used in the model analysis.
- Licenced extraction is thought to of started in 2006/2007, however the extraction dataset needs to extend back to the predevelopment levels. The hydrograph also indicates that extraction is occuring back to 1996/1997.
- Model Calibration was between 0-150 ML/year groundwater extraction range. The greater the proposed extraction rates beyond this calibration range the more potential for drawdown forecast errors. The greater the proposed extraction rates beyond this calibration range the more potential for drawdown forecast errors. In this GMU, drawdown prediction for extraction volumes up to 50 times the calibration range are being made to meet the 10m drawdown metric.
- Further checks and potential re-calibration may be required as rates increase for the GMUs.

8.6.3 Recommendations

In addition to the recommendations applicable to all 25 GMUs discussed in section 32, the following Corinella GMA specific recommendations have been identified:

- To address the above bore depth data limitation, it is recommended that DEECA obtains the relevant depth and aquifer monitored data for licenced bores within this GMU

9. Cut Paw Paw GMA

9.1 Conceptualisation

The hydrogeological conceptualisation elements relevant to this study are summarised in Table 34 and a map of the GMU is presented in Figure 69. It is noted that a significant volume of information was collated to inform the hydrogeological conceptual understanding of the GMU. The information that is directly relevant to the modelling is shown in bold or colour coded within Table 34.

Table 34 Cut Paw Paw GMA – Tabulated conceptualisation

GMU summary

Cut Paw Paw GMA covers an area of 57 km^2 on the northwestern margin of Port Phillip Bay. The GMU is bounded by Princes Highway and Buckley Street to the north, Port Phillip Bay (specifically Altona Bay) to the south, Maribyrnong and Yarra Rivers to the east and Laverton Creek to the west.

Cut Paw Paw GMA pertains to all formations below the surface, but was intended to primarily manage the groundwater resources of the Werribee Formation (Lower Tertiary Aquifer, LTA). The PCV (3,650 ML/year) therefore primarily relates to confined aquifers.

Groundwater in this GMU has been extracted predominately for irrigation, industrial and commercial purposes, typically from the LTA.

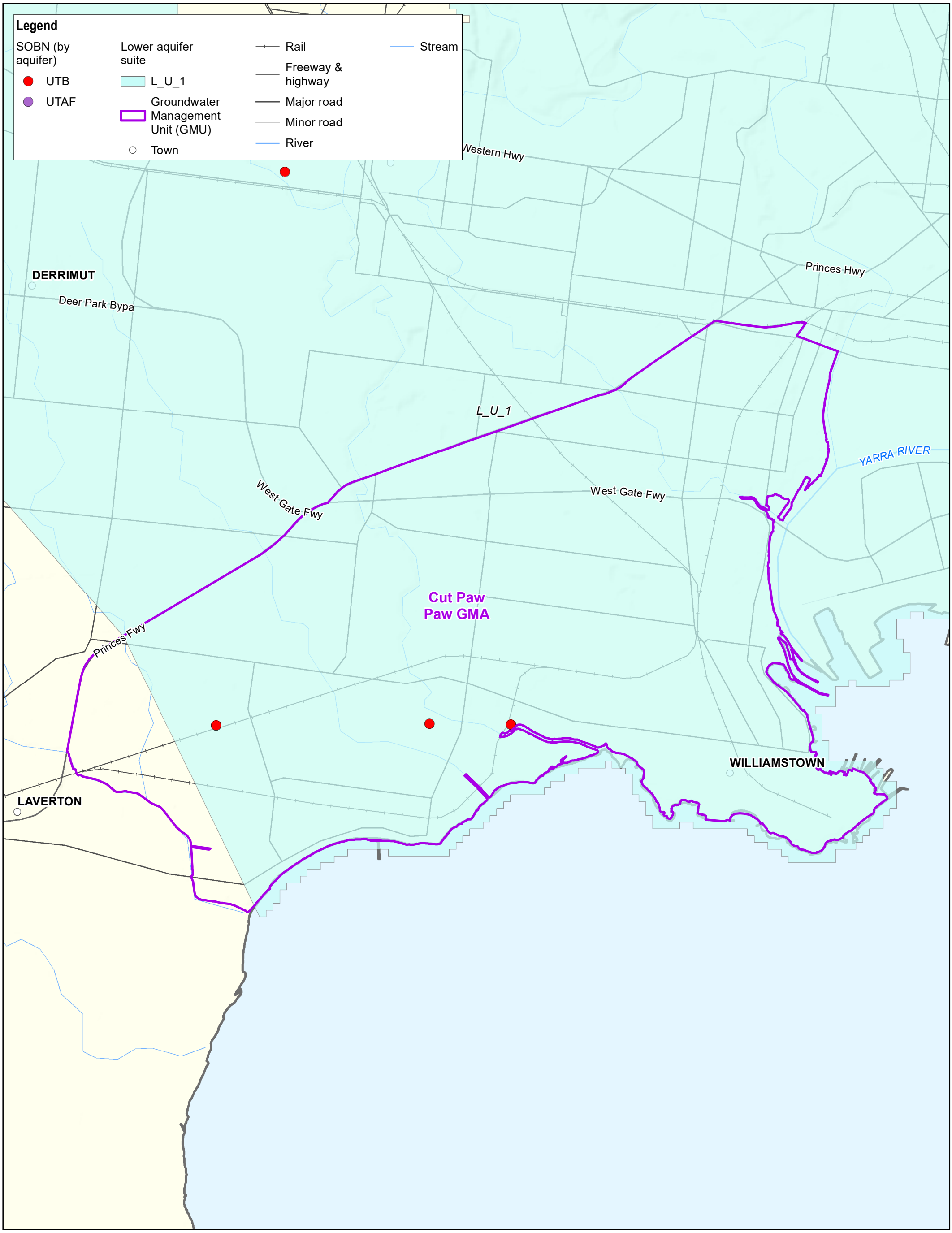
Hydrostratigraphy summary

Aquifer	Formation	Relevant Suites (% coverage of GMU)	% of GMU covered by Suites	Number of SON bores	Groundwater use	Use volumes ML (2019/20)	Entitlement volumes ML (2019/20)	Understanding (Low, Medium, High)
Upper	QA	-	-	0	Unknown	0	0	Low
	Newer Volcanics (UTB)	U_AP_2 (86%)	86%	0	NA	NA	12	Low
Middle	Brighton Group/Baxter Formation (UTAF)	M_U_2 (37%), U_AR_1 (12%)	49%	0	Unknown	0	0	Low
	Fyansford Formation (UMTD)	-	-	0	Unknown	0	0	Low
Lower	Werribee Formation (LTA)	L_U_1 (93%)	93%	0	Irrigation	0	511	Low
	Mornington Volcanics (LTB)	-	-	0	NA	NA	NA	Low
Basement	Basement (BSE)	-	-	0	Dewatering	0	0	Low

Note that volumes listed above are based on the DEECA provided licenced bore dataset with associated VAF layers. Bores have been assigned to a VAF layer based on bore depth, where this data was available.

Characteristic & importance	Description	Degree of understanding
Intended aquifer		
Aquifer thickness within GMU (range, based on VAF)	Max: 93 m, Average: 65 m	High
Aquifer extent	Regional, extensive	High
Likelihood of inter-aquifer flow	Low	Low
Likelihood of groundwater – surface water interaction	Low	Low GHD (2020)
Representative Suite	**L_U_1**	**High. 100% of GMU extraction occurs within this Suite, which relates to the most relevant GMU aquifer**
Current hydrological condition of representative aquifer		
Representative Suite trend	Declining	High
Groundwater quality (average salinity based on CDM Smith spatial segment(s) with highest coverage)	3,101- 5,400 mg/L	Low Based on CDM Smith (2022)
Groundwater yield	0.5 - 5 L/s	Low Based on CDM Smith (2022)
Groundwater levels		
Temporal groundwater level data range	**1974 - 2021**	
Spatial clustering of licensed bores in relation to Suites	**No, only 1 active licenced bore**	**Based on DEECA density mapping and licenced bore data**
Groundwater use		
Licensed groundwater use	**99 ML**	**High (Based on average historical VWA data over 14 years)**
Minimum historic groundwater use	**12 ML**	**High (Based on historical VWA data, year 2015/16)**
Maximum historic groundwater use	**424 ML**	**High (Based on historical VWA data, year 2013/14)**
Entitlement (Groundwater allocation)	**523 ML**	**High (Based on licenced volumes in 2020/21)**
Significant drivers of groundwater level variability (primary)	**Pumping for irrigation**	**Moderate**
Secondary drivers of groundwater level variability	**Pumping for commercial and industrial**	**Moderate**
Groundwater use profile	**Influenced by seasonality**	**Low**
External Influence	**None identified**	

Groundwater values and risks		
Existing Environmental Values to be protected, relevant to this GMU	Potable water supply Licensed non-potable supply (irrigation, commercial, industrial) Unlicensed non-potable supply (domestic and stock)	
Risks to groundwater values	Direct risks: – Drawdown which may affect access to groundwater by existing users	Moderate
Indicators used to assess impacts to groundwater	– Measured drawdown using pre-determined metrics measured from a pre-determined level for the purpose of this modelling	Moderate



Paper Size ISO A3

0 0.35 0.7 1.05 1.4

Kilometers

Map Projection: Lambert Conformal Conic
Horizontal Datum: GDA 1994
Grid: GDA 1994 VICGRID94

N

GHD

DEECA
Sustainable yield review - confined aquifers

Cut Cut Paw GMA
Site location and key features

Project No. **12564066**
Revision No. **0**
Date **15/01/2024**

Figure 69

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Data source: DELWP, VicMap, 2022; DELWP, GMUs, 2022; DELWP, SOBN, 2022; GHD, aquifer suites, 2018; DELWP, extraction bores, 2022 Created by: cperyer

9.2 Technical analysis

9.2.1 Hydrograph review and selection of representative Suites for further analysis

Suite hydrographs were generated for the confined Suites for Cut Paw Paw GMA as shown in Figure 70. Generally, the Suite hydrographs show the seasonal fluctuations and hence recovered water levels.

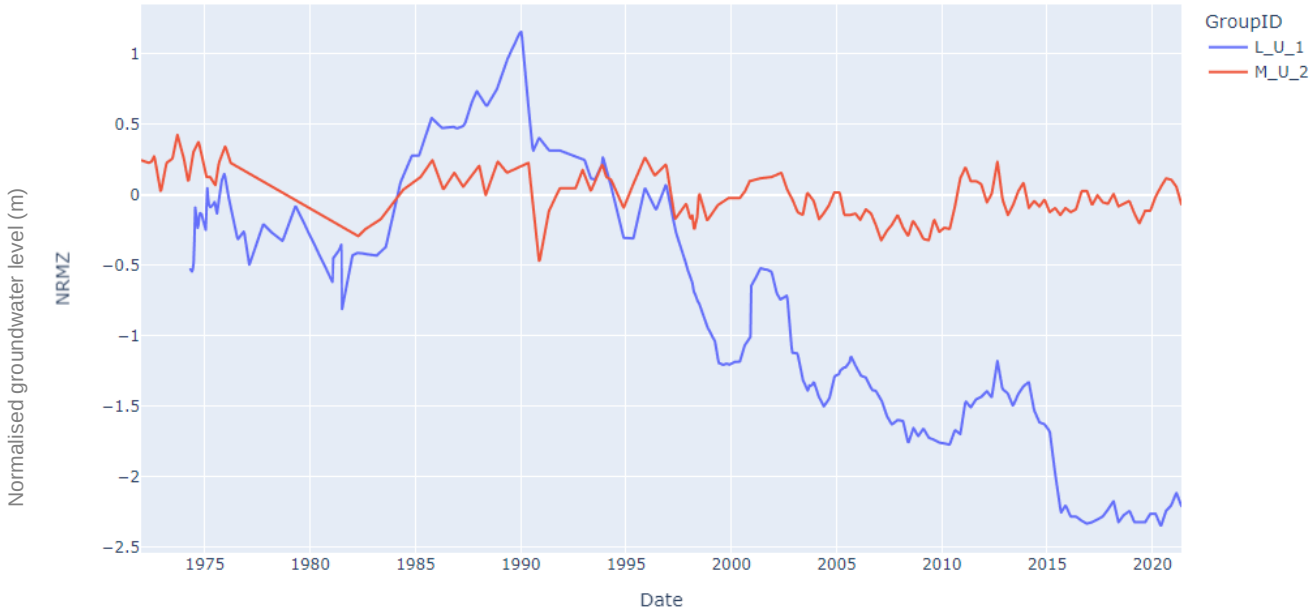


Figure 70 Cut Paw Paw GMA Suite Hydrographs for all confined aquifers

The representative Suite analysed for this GMU was Suite L_U_1, which was selected following the methodology outlined in section 2.6.4 and summarised as follows:

- The greatest volume of extraction occurring within the Lower Aquifer
- The Lower Aquifer pertains to the LTA which is the intended aquifer for this GMU
- Suite L_U_1 covers 93% of the GMU
- Suites L_U_1, U_AP_2 and M_U_2 don't have any active SOBN bores within the Suite areas
- Suite bores for L_U_1 are not close to extraction points within the GMU

The annual recovered Suite hydrograph for the representative Suite for Cut Paw Paw GMA, L_U_1. is shown in Figure 71.

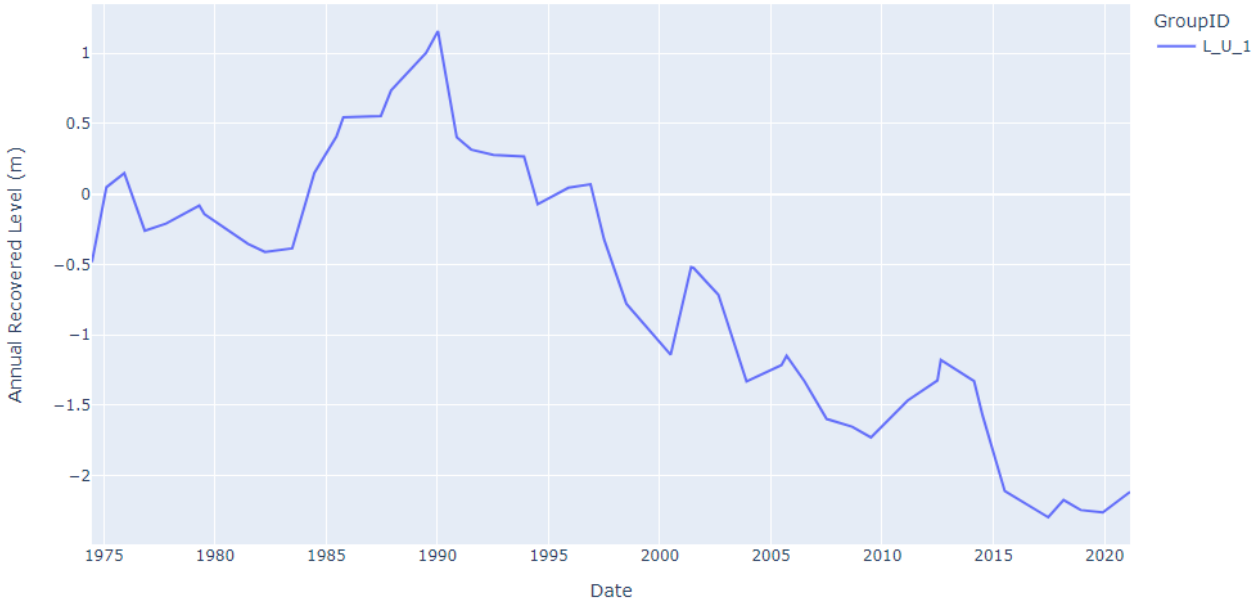


Figure 71 *Cut Paw Paw GMA Annual Recovered Level Suite Hydrographs for the representative Suite*

9.2.2 Pre-development level

To estimate the pre-development level conditions, GHD reviewed the Suite hydrographs of annual recovered levels and assumed that the maximum levels in the early time series data was the best representation of conditions prior to major development within Cut Paw Paw WSPA. This the maximum levels in the early time series data was adopted as the baseline of pre-development conditions.

The pre-development annual recovered levels are taken to be the maximum level in the early time series data which equates to 1.16 m for Suite L_U_1 in the year 1989/1990 (refer further details in section 9.4.3).

9.2.3 Externalities

Through the conceptualisation, no potential external influence was identified for Cut Paw Paw GMA.

9.2.4 Hindcasting

Groundwater use data for Cut Paw Paw GMA is available from 2004/2005 to 2020/2021. The hindcasting methodologies outlined in section 3.3.4.5 were applied to Cut Paw Paw GMA, as summarised below.

9.2.4.1 Hindcasting Method 1 (H1)

Applying method H1, four different correlations were developed as described below.

Figure 72:

- Annual rainfall vs annual groundwater extraction at Cut Paw Paw GMA
- Two yearly average annual rainfall vs annual groundwater extraction at Cut Paw Paw GMA
- Annual summer period rainfall vs annual groundwater extraction at Cut Paw Paw GMA
- Annual irrigation period rainfall vs annual groundwater extraction at Cut Paw Paw GMA

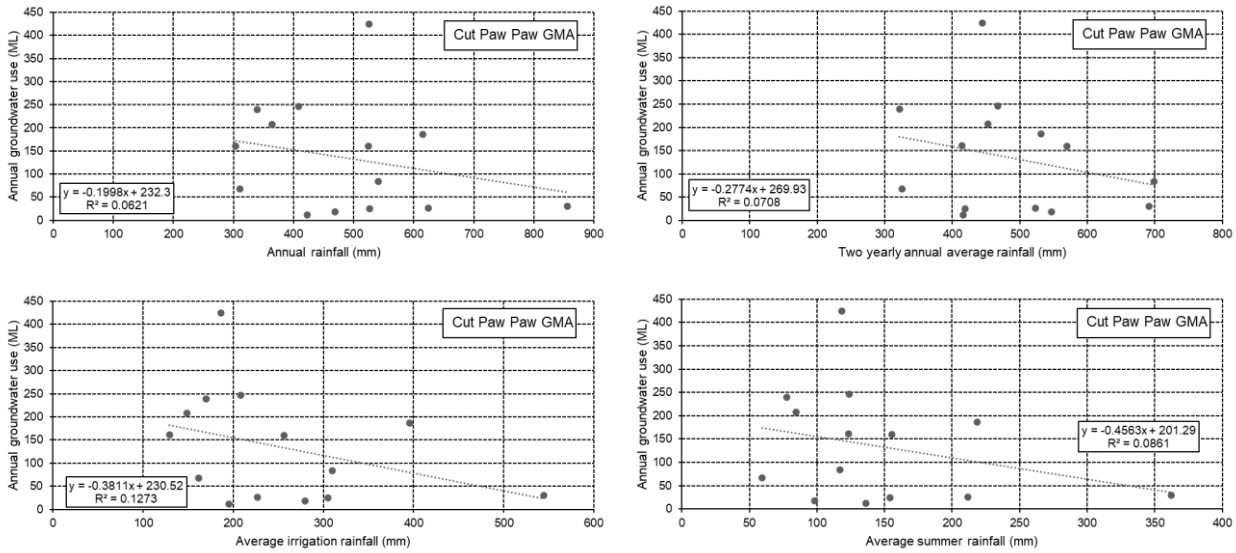


Figure 72 Cut Paw Paw GMA: Hindcast method 1 correlations (Cut Paw Paw GMA only)

As shown in Figure 72, the goodness-of-fit is relatively poor across all correlations tested. Nearly all extraction is from irrigation within Cut Paw Paw GMA. Therefore, correlations based only on irrigation usage were not developed as this did not significantly change the use values. The best goodness-of-fit result was shown to be the correlation of the annual irrigation rainfall with annual groundwater extraction; this was the correlation modelled for this method.

9.2.4.2 Hindcasting Method 2 (H2)

Four correlations were developed using method H2 for as described below and shown in Figure 73:

- Cut Paw Paw GMA use per Cut Paw Paw GMA bore vs annual rainfall
- Cut Paw Paw GMA use per Cut Paw Paw GMA bore vs two yearly average annual rainfall
- Cut Paw Paw GMA use per Cut Paw Paw GMA bore vs annual summer period rainfall
- Cut Paw Paw GMA use per Cut Paw Paw GMA bore vs annual irrigation period rainfall

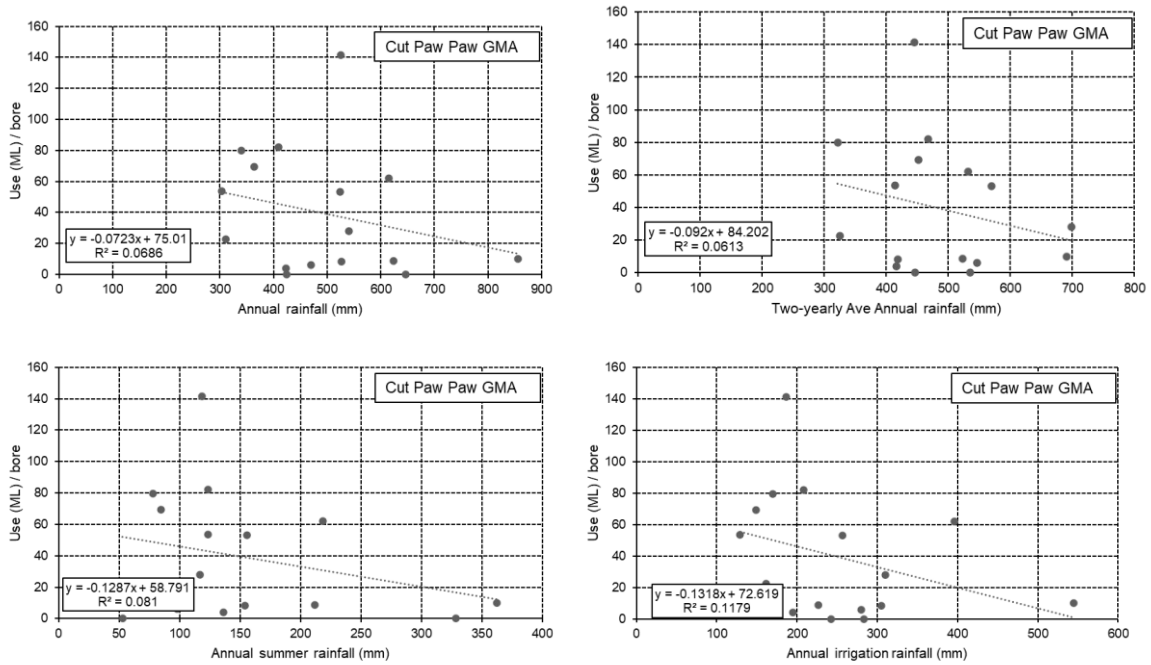


Figure 73 Cut Paw Paw GMA: Hindcast method 2 correlations (Cut Paw Paw GMA only)

As shown in Figure 73 and similar to method H1, the goodness-of-fit represented by the R^2 increased slightly when annual irrigation rainfall was adopted. It is noted that the goodness-of-fit is quite poor for Cut Paw Paw GMA using this method. The Cut Paw Paw GMA only extraction per bore (with annual irrigation rainfall) was modelled.

9.2.4.3 Hindcasting Method 3 (H3)

Four correlations were developed using method H3 as described below and shown in Figure 74:

- Percentage of entitlement vs annual rainfall
- Percentage of entitlement vs two yearly average annual rainfall
- Percentage of entitlement vs annual summer period rainfall
- Percentage of entitlement vs annual irrigation period rainfall

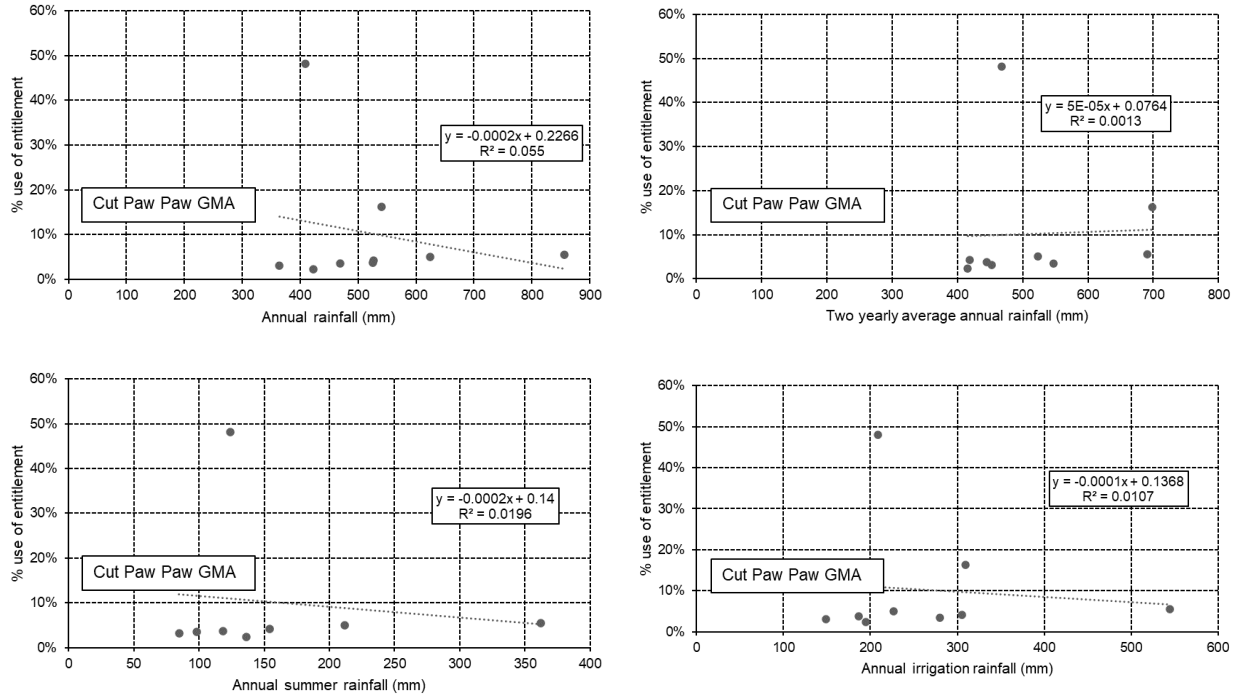


Figure 74 Cut Paw Paw GMA: Hindcast method 3 correlations

As shown in Figure 74, the best goodness-of-fit result was shown to be the correlation with the annual rainfall; this is the correlation that was modelled for hindcast method 3. It is noted that there is only minor variation between the four different correlations.

9.2.4.4 Comparison

A comparison of the three input datasets is shown in Figure 75 and Figure 76 for the hindcasting based on Cut Paw Paw GMA groundwater use. Figure 75 shows a comparison of the three hindcasting methods against the recorded use only, over the recorded use date and Figure 76 shows the hindcasted data back to 1971/1972.

As you can see from Figure 76, groundwater use using method 1 does not decrease historically as there is no factor to account for the changing number of bores extracting over time and thus provides a higher groundwater extraction estimate than the other two methods. The hindcasting results show that the smallest average variation of recorded use to estimated use occurs for method 2. This hindcasting method is expected to provide a more probable estimated groundwater use than the other two methods for Cut Paw Paw GMA.

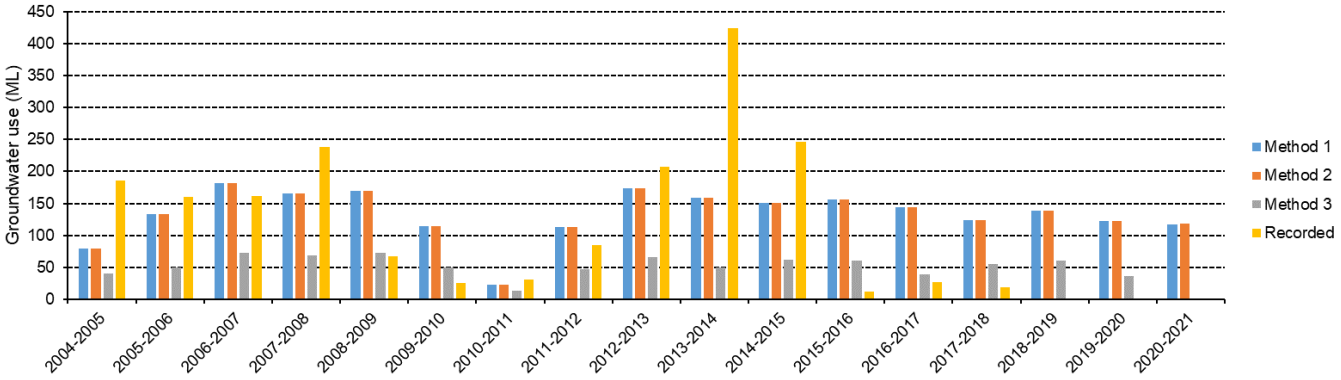


Figure 75 *Cut Paw Paw GMA: Comparison of hindcasting over recorded use period – Cut Paw Paw GMA only extraction*

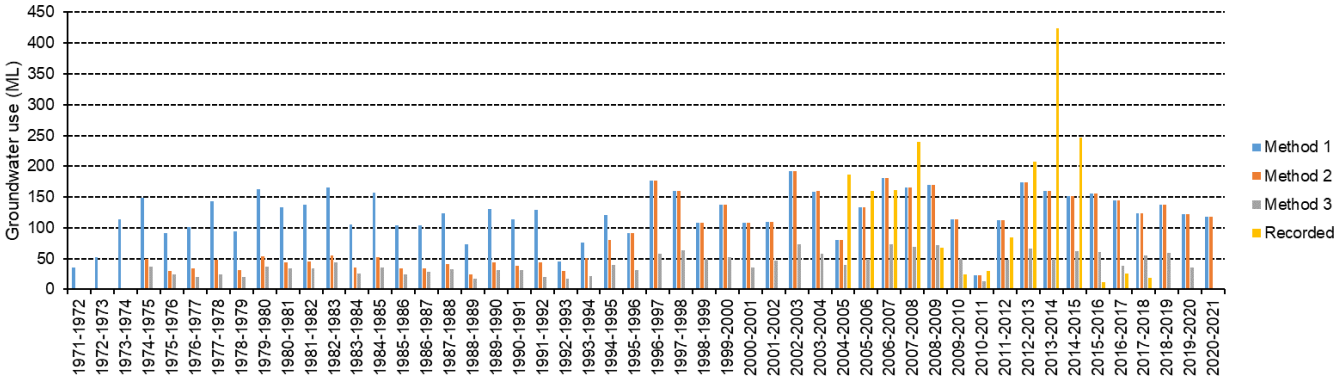


Figure 76 *Cut Paw Paw GMA: Comparison of hindcasting – Cut Paw Paw GMA only extraction*

9.3 Modelling

9.3.1 Model inputs

A number of different models were run based on the various model inputs developed and combinations of these. Table 35 summarises these combinations of model inputs run for Cut Paw Paw GMA. Model runs highlighted blue were run with annual extraction and those in grey were run using two yearly average annual extraction. It is noted that no spatial distribution methods could be run due to no Suite bores for L_U_1 occurring within Cut Paw Paw GMA. It is noted that for Cut Paw Paw WSPA, some additional model runs were undertaken with climate data; this is explained further in the section below.

Table 35 Cut Paw Paw GMA: summary of model inputs

Model input	Model runs																			
	1	2	3	4	5	6	7	7c	8	9	10	11	12	13	14	15	16	17	18	19
Annual recovered levels for representative Suites (L_U_1)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Annual extraction – Cut Paw Paw GMA only	✓																			
Annual climate data										✓										
Two yearly average annual extraction – Cut Paw Paw GMA only		✓																		
Annual extraction – Cut Paw Paw GMA and Externalities			✓																	
Two yearly average annual extraction – Cut Paw Paw GMA and Externalities				✓																
H1 annual extraction – Cut Paw Paw GMA only					✓															
H1 annual extraction – Cut Paw Paw GMA and Externalities						✓														
H2 annual extraction – Cut Paw Paw GMA only							✓	✓												
H2 annual extraction – Cut Paw Paw GMA and Externalities									✓											
H3 annual extraction – Cut Paw Paw GMA only										✓										
H1 two yearly average annual extraction – Cut Paw Paw GMA only											✓									
H1 two yearly average annual extraction – Cut Paw Paw GMA and Externalities												✓								
H2 two yearly average annual extraction – Cut Paw Paw GMA only													✓							
H2 two yearly average annual extraction – Cut Paw Paw GMA and Externalities														✓						

Model input	Model runs																			
	1	2	3	4	5	6	7	7c	8	9	10	11	12	13	14	15	16	17	18	19
S1 annual extraction – Cut Paw Paw GMA only															✓					
S2 annual extraction – Cut Paw Paw GMA only																✓				
S3 annual extraction – Cut Paw Paw GMA only																	✓			
S1 annual extraction and H1 annual extraction – Cut Paw Paw GMA only																		✓		
S2 annual extraction and H2 annual extraction – Cut Paw Paw GMA only																			✓	
S3 annual extraction and H3 annual extraction – Cut Paw Paw GMA only																				✓

9.3.2 Model calibration and uncertainty analysis

A statistical summary of the model output results for the runs described in Table 35 is presented in Table 36 for the representative Suite for Cut Paw Paw GMA. Suite L_U_1 was selected as the most likely representative Suite based on the process outlined in section 9.2.17.2.1. The statistics summarised include the average 95 PPU thickness (95PPU TH), percentage of observed levels within 95 PPU (%Obs in 95 PPU), R^2 and root mean square error (RMSE), number of annual recovered level observation points (No obs data points) and the range of observed annual recovered levels.

Suite L_U_1

A review of the results and statistical summary for Suite L_U_1 shows that model runs 1 and 2 (highlighted orange) show the best results (by looking for the runs with the smallest 95PPU thickness and then considering the other three statistical measures) of the 19 different model input combinations. As previously touched on, the models had to be run with hindcasting to incorporate the early time series data into the model when pre-development levels had been defined; thus the best hindcast model result (model 7) was run again with climate to try and improve the results (model run 7c). Table 36 shows that the model of 7c with the climate data (highlighted green) are an improvement of the initial model run of 7 without climate. The graphical model output for these runs is shown in Figure 77 and Figure 78 for model runs 7 and 7c respectively.

Given the results, model 7c was selected as the preferred model to undertake the predictive modelling.

Table 36 Cut Paw Paw GMA: summary of model outputs

Suite	Statistic	Model run							
		1	2	5	7	7c	9	10	12
L_U_1	95PPU TH	1.64	1.61	2.94	2.24	2.05	2.34	2.72	2.15
	%Obs in 95 PPU	93.75	93.75	93.75	93.75	95.83	95.83	93.75	93.75
	R^2	66.3	66.5	71.0	76.4	83.9	72.8	72.0	76.2
	RMSE	0.24	0.24	0.49	0.45	0.38	0.49	0.48	0.46
	No obs data points	16	16	48	48	48	48	48	48
	Range of observed levels	1.1	1.1	3.5	3.5	3.5	3.5	3.5	3.5

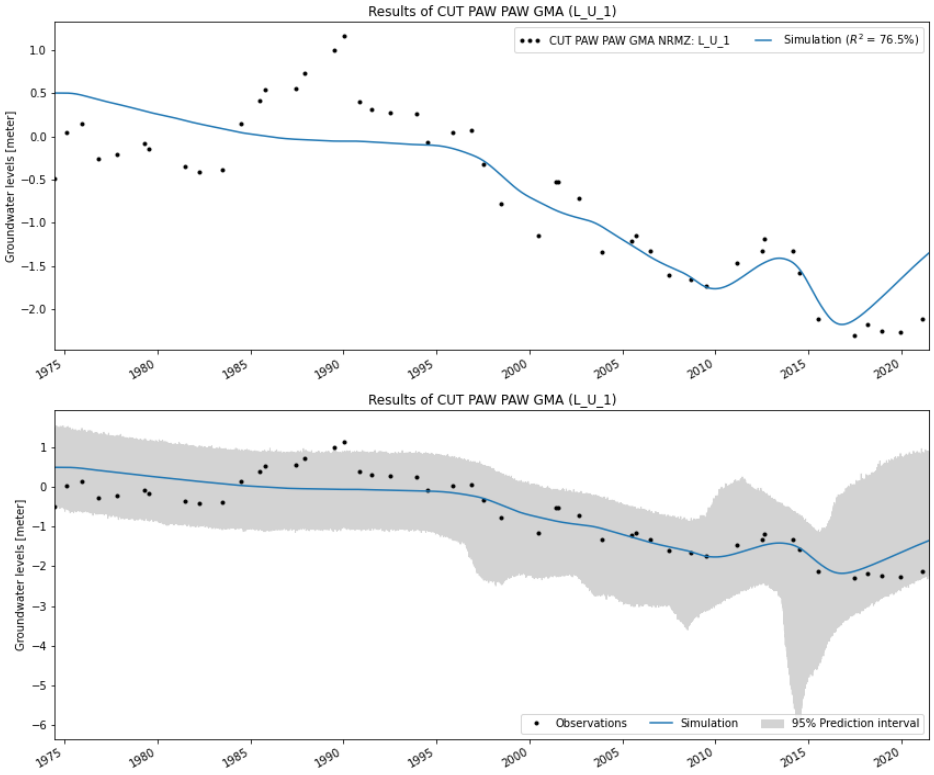


Figure 77 *Cut Paw Paw GMA Suite L_U_1: model run 1 (annual extraction using hindcast method H2 for Cut Paw Paw GMA) output hydrographs*

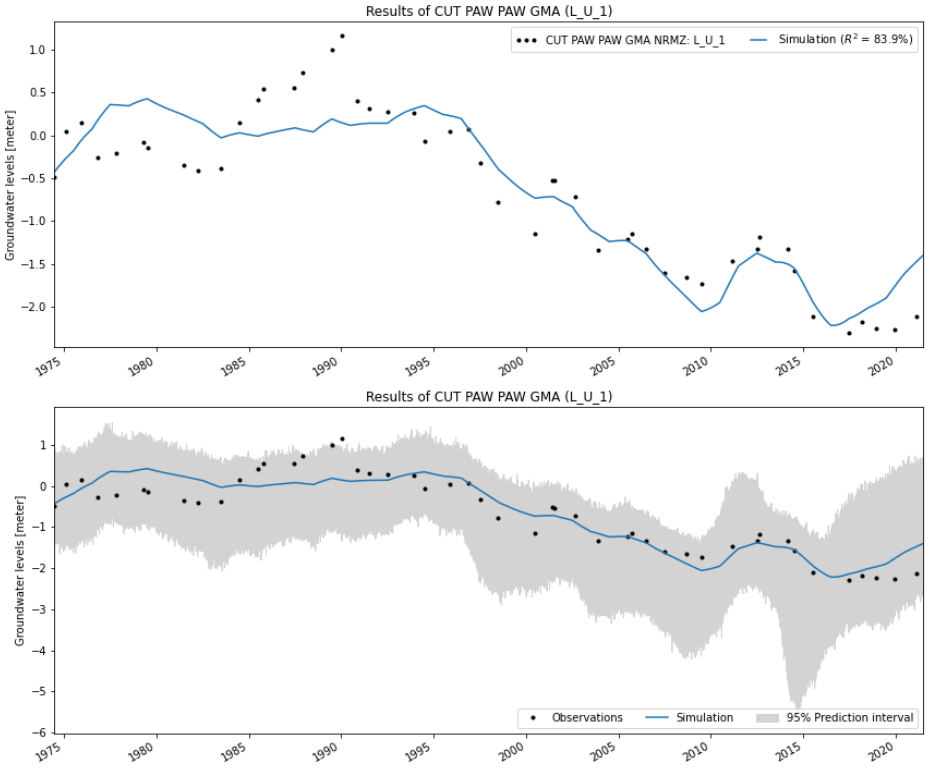


Figure 78 *Cut Paw Paw GMA Suite L_U_1: model run 7c (annual extraction using hindcast method H2 with climate for Cut Paw Paw GMA) output hydrographs*

9.4 Predictive modelling

9.4.1 Model inputs

The preferred model to run the predictive modelling for Cut Paw Paw GMA was model run 7c for the representative Suite, thus the key inputs for the model were the annual recovered levels and the annual extraction in Cut Paw Paw GMA. To conduct the forecasting for the 19 scenarios discussed in section 3.5.3, a few factors were required in the calculations, as summarised in Table 37.

Table 37 Cut Paw Paw GMA: forecast scenario inputs

Input item	PCV	Licenced entitlement (based on 2020/21)	Existing use (based on 2020/2021)	Average use over recorded period (from VWA)	Maximum use over recorded period (from VWA, year 2013/14)
Value (ML)	3,650	523	0	99	424

9.4.2 Predictive model uncertainty

The model output files of the predicted models are provided in Appendix E.

Markov Chain Monte Carlo (MCMC) predictions were undertaken on each of the forecasted scenarios for each of the two Suites. An example of one of the outputs is presented in Figure 79 for scenario 4. This shows that uncertainty in model prediction increases as the model predicts further into the future. Comparing with the graphical output for the same scenario, the MCMC realisations generally fall within the 95% prediction interval bands as shown in Figure 80. It's noted that for scenario 4 shown, the volumes used in the forecast scenario are can be up to 17 times greater than the calibration volumes. It is assumed that this has impacted the uncertainty analysis, resulting in large prediction intervals and variations in the MCMC realisations.

Uncertainty is also accounted for by using 19 forecast scenarios to develop a groundwater use to drawdown relationship (analogous to a Monte Carlo type simulation) where a range of possible outcomes are generated. It is noted however, that the forecast scenarios were not randomly generated, but rather based upon a series of estimated use behaviours.

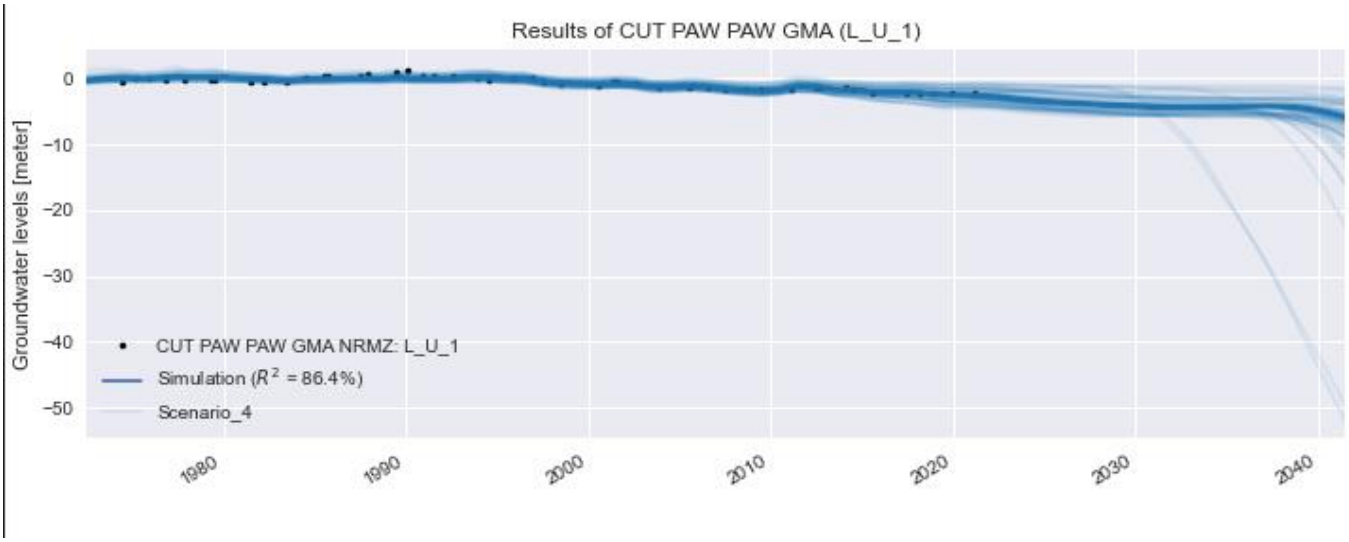


Figure 79 Cut Paw Paw GMA: Suite L_U_1 MCMC analysis for Forecast Scenario 4

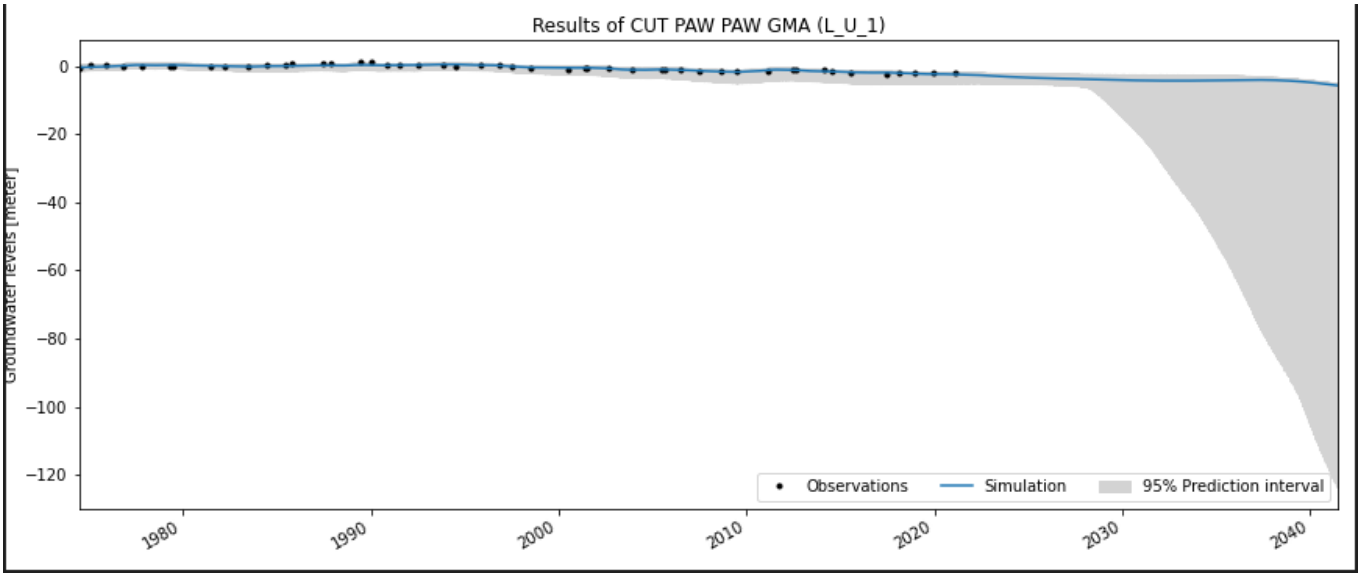


Figure 80 *Cut Paw Paw GMA: Suite L_U_1 Forecast Scenario 4 with 95% prediction bands*

9.4.3 Extraction vs drawdown

To calculate drawdown based on the annual recovered levels simulated by the model, the pre-development conditions (pre commencement of extraction) need to be estimated. For Cut Paw Paw GMA the water level prior to groundwater development was unknown, due to:

- Uncertainty regarding the commencement of development
- Groundwater development preceding SOBN bore installation and temporal groundwater monitoring

Using the pre-development levels defined in section 9.2.2, the modelled water levels were converted into drawdowns (from this baseline pre-development level) for each of the 19 scenarios. This predevelopment condition is shown in Figure 81 for Suite L_U_1 hydrograph of annual recovered levels. In Figure 81:

- Actual annual groundwater use is represented by the blue column graph between 2004/2005 and 2020/2021
- Hindcasted groundwater use is represented by the orange columns between 1974/1975 and 2004/2005
- Forecasted use is represented by the grey columns after 2021/2022
- The modelled forecasted annual recovered levels are represented by the purple line in Figure 81
- The calibration annual recovered levels are represented by the black line in Figure 81
- The annual recovered water level behaviour based on recorded data is represented by the red line graph, whereby the earliest data is taken to best reflect the pre-development levels
- In Figure 81, the pre-development annual recovered levels are taken to be the maximum level in the early time series data which equates to 1.16 m in 1989/1990

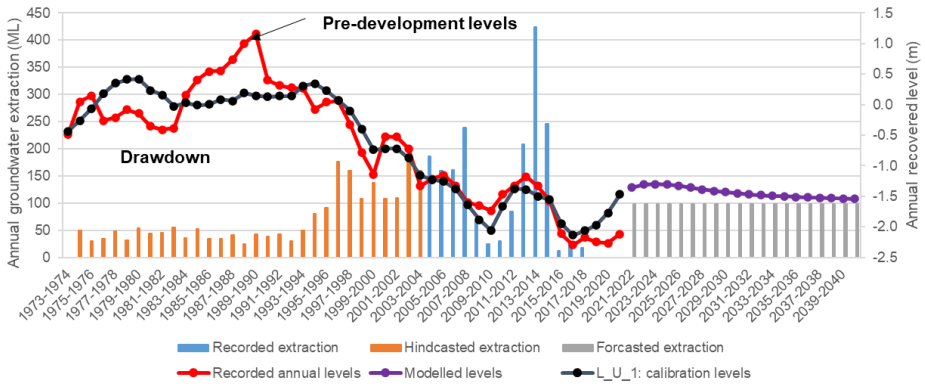


Figure 81 *Estimating pre-pumping water levels (example from Suite L_U_1)*

For Suite L_U_1, the calculated drawdowns and volumes for each of the scenarios were plotted in individual graphs for each scenario, all scenarios together in the one graph (Figure 82) and a graph of the scenarios for specific time periods (Figure 83) to develop the volume to drawdown relationship. For each scenario, a linear regression was applied and the coefficient of determination (R^2) was calculated. A comparison of each of these graphs shows no significant change in the coefficient of determination between Figure 82 and Figure 83, however, there were differences between individual scenario runs.

The use-drawdown for all the 19 forecast scenario drawdowns and volumes (both the recorded and forecasted volumes) over each year modelled (1974 to 2041) is shown in Figure 82 for Suite L_U_1. Note the abscissa range of the chart has been clipped and does not show forecast drawdowns for the higher use scenarios (more improbable). Reviewing these figures, the following is noted:

- There should be zero drawdown under zero use and therefore a line of best fit should pass through or close to the origin (0,0). In the instance of Cut Paw Paw WSPA, the limited calibration data at higher volumes has likely results in poor estimates at higher volumes and hence skews the slope of the line and intercept.
- Average use is around 100 ML. Figure 82 indicates that the model will generally forecast drawdown above the predicted line of best fit for use volumes between 0 ML and 500 ML
- For the same annual use, different drawdowns can be obtained as Pastas predicts a water level for each year. For example, Figure 81 shows a scenario where groundwater use remains constant at around 100 ML/year over the next 20 years.
- The correlation for groundwater use and drawdown for Suite L_U_1 is relatively poor as shown in Figure 82
- The various forecast scenarios generally result in data plotting reasonably close together in a linear trend. The 19 forecast scenarios applied to populate the chart is analogous to a Monte Carlo type simulation where a range of possible outcomes are generated. It is noted however, that the forecast scenarios were not randomly generated, but rather based upon a series of estimated use behaviours.

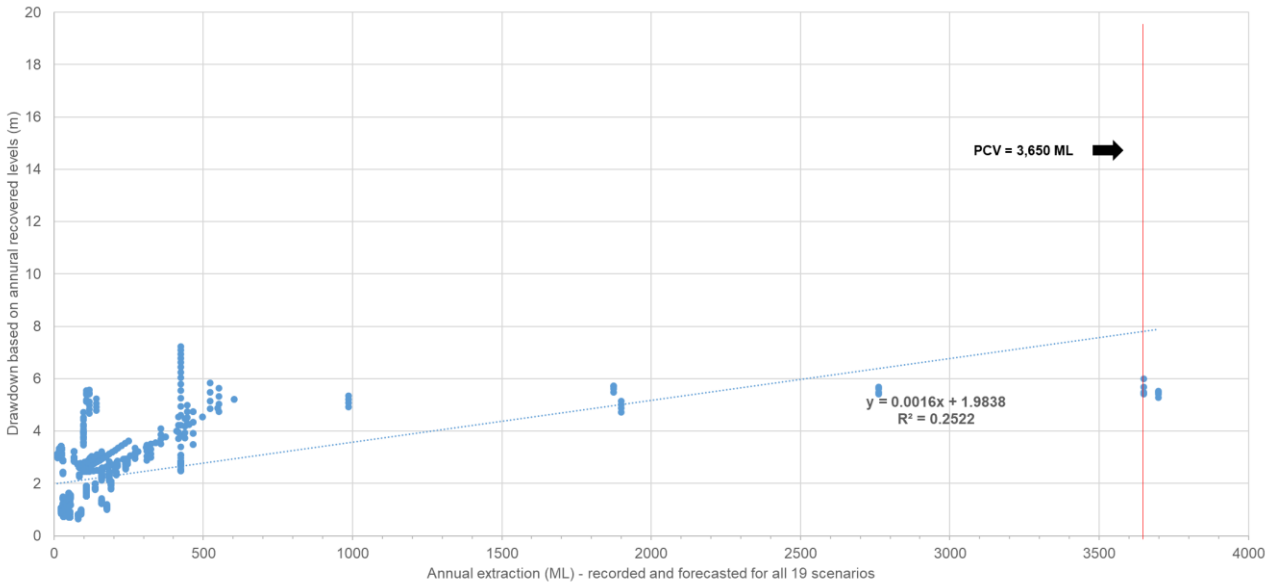


Figure 82 ***Cut Paw Paw GMA Suite L_U_1: Drawdown (on annual recovered levels) and extraction volumes (recorded and forecasted <3,700 ML) for all data between 1974 to 2041 and all forecasted scenarios***

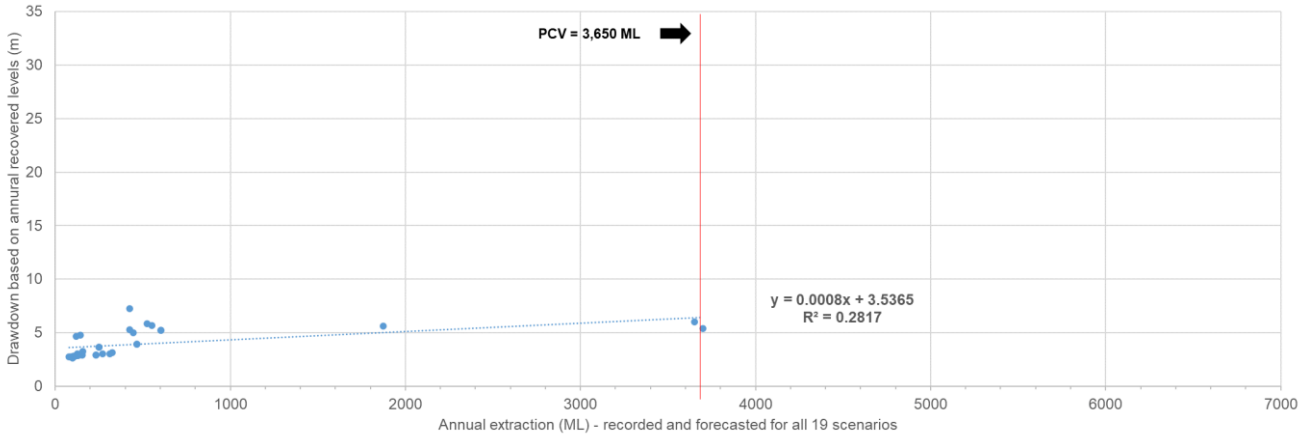


Figure 83 ***Cut Paw Paw GMA Suite L_U_1: Drawdown (on annual recovered levels) and extraction volumes (recorded and forecasted <3,700 ML) for years 2020/2021, 2030/2031 and 2040/2041 for all forecasted scenarios***

9.5 Sustainability metrics

9.5.1 Application of metrics

Using the use - drawdown relationships developed through the previous step of forecasting aquifer response under a range of use scenarios, groundwater drawdown can be used to compare against metrics that define groundwater resource sustainability.

The application of these metrics and the relationship developed between drawdown based on the Suite annual recovered levels and extraction volume for the whole GMU, which is shown in Table 38 for Cut Paw Paw GMA Suite L_U_1 (noting Cut Paw Paw GMA has a PCV of 3,650 ML/year). As part of the modelling, a 95% prediction interval band was applied to the modelling results. The relationship between drawdown and extraction volumes can also be interrogated at the lower and upper bands of the 95% prediction interval as shown in Table 38 and Figure 84 for Suite L_U_1.

A comparison of volumes at drawdown intervals provided by DEECA is shown in Table 39 for Suite L_U_1.

Table 38 Relationship of Suite drawdown to GMU extraction for Cut Paw Paw GMA Suite L_U_1

Volume (ML/year) for whole of GMU	Based on model prediction of Suite M_S_88 annual recovered levels
	Drawdown over 20 years (m) (lower limit to upper limit based on 95% prediction interval band)
7,000	13.2 (10.3 - 53.8)
6,500	12.4 (9.6 - 50.2)
6,000	11.6 (9 - 46.5)
5,500	10.8 (8.3 - 42.9)
5,000	10 (7.7 - 39.2)
4,500	9.2 (7 - 35.6)
4,000	8.4 (6.4 - 31.9)
3,500	7.6 (5.7 - 28.3)
3,000	6.8 (5.1 - 24.6)
2,500	6 (4.4 - 21)
2,000	5.2 (3.8 - 17.3)
1,500	4.4 (3.1 - 13.7)
1,000	3.6 (2.5 - 10)
500	2.8 (1.8 - 6.4)
0	2 (1.2 - 2.7)

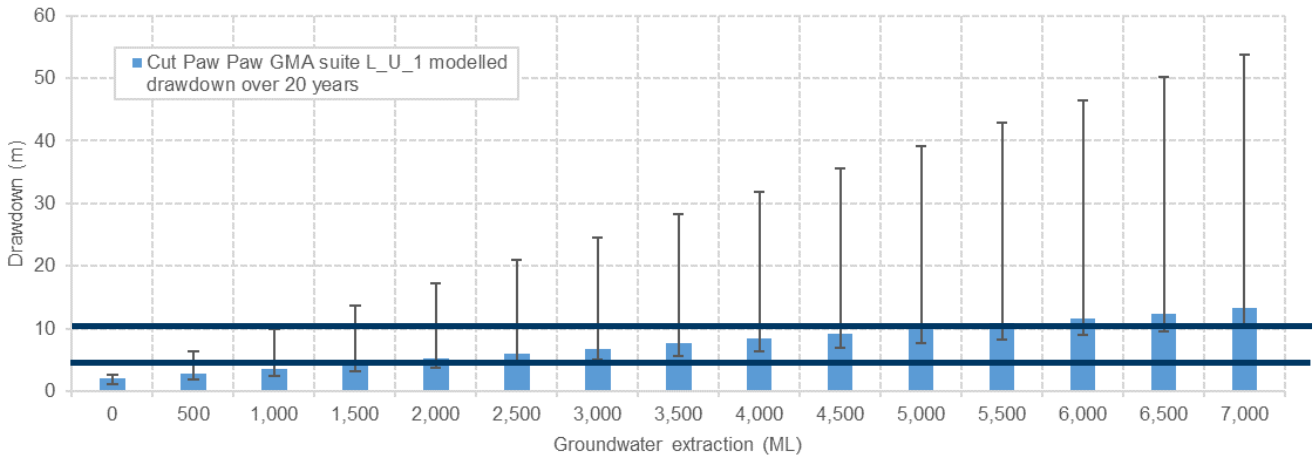


Figure 84 Cut Paw Paw GMA Suite L_U_1: Relationship of Suite drawdown to GMU extraction (with error bars showing results of drawdown using levels from model's 95% prediction intervals)

Table 39 Predicted GMU volumes for drawdown metrics

Drawdown (m)	Predicted volumes for GMU based on Suite L_U_1 (lower limit to upper limit)
5	1,900 (300 – 2,900)
10	5,000 (1,000 – 6,800)

	Volume (ML/year)	Drawdown over 20 years
PCV = 3,650	7,000	13.2 (10.3 - 53.8)
	6,500	12.4 (9.6 - 50.2)
	6,000	11.6 (9 - 46.5)
	5,500	10.8 (8.3 - 42.9)
	5,000	10 (7.7 - 39.2)
	4,500	9.2 (7 - 35.6)
	4,000	8.4 (6.4 - 31.9)
Av unit = 99	3,500	7.6 (5.7 - 28.3)
	3,000	6.8 (5.1 - 24.6)
	2,500	6 (4.4 - 21)
	2,000	5.2 (3.8 - 17.3)
	1,500	4.4 (3.1 - 13.7)
	1,000	3.6 (2.5 - 10)
	500	2.8 (1.8 - 6.4)
	0	2 (1.2 - 2.7)

Legend

- Groundwater Management Units
- Lower Aquifer Suites
  - L_U_1
- Rail
- Freeway & highway
- Park

DERRIMUT
Deer Park Bypa
SUNSHINE
Princes Hwy
Citylink
L_U_1
West Gate Fwy
West Gate Fwy
YARRA RIVER
YARRA RIVER
PORT MELBOURNE
Cut Paw Paw GMA
CHERRY LAKE
WILLIAMSTOWN
LAVERTON
Princes Fwy
Princes Fwy

Paper Size ISO A3
0 0.5 1 1.5 2
Kilometers
Map Projection: Lambert Conformal Conic
Horizontal Datum: GDA 1994
Grid: GDA 1994 VICGRID94

N

GHD

DEECA
Sustainable Yields
Confined Aquifers

CUT PAW PAW GMA:
KEY SUITES
VOLUME VS DRAWDOWN

Project No. 31-12564066
Revision No. 0
Date 15/01/2024

FIGURE 85

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Print date: 16 Jan 2024 - 11:00

Data source: DELWP, VicMap, 2022; DELWP GMU locations, 2022; GHD, aquifer suites, 2018; . Created by: cperyer

9.6 GMU summary

9.6.1 Findings

Cut Paw Paw GMA primarily relates to the Werribee Formation aquifer (LTA) and groundwater is predominately extracted from this aquifer for irrigation purposes. The LTA falls within the Lower Aquifer Suites, which at Cut Paw Paw GMA is L_U_1 providing a total coverage of 93% and which is identified as the representative Suite. The Suite hydrographs for the representative Suite shows an overall decreasing trend along with seasonal fluctuation and thus recovered water levels, which were adopted for the assessment.

Application of two yearly annual average extraction instead of annual average extraction generally showed a similar to slightly poorer model fit based on the statistical analysis across the model runs. The application of hindcasting methods did improve the R^2 results, but did not improve the other statistical measures. Spatial distribution methods could not be applied for Cut Paw Paw GMA because there were no Suite bores available for Suite L_U_1. Applying climate to the best hindcasted model (which was using hindcast method H2), improved the model results.

Based on an assessment of all model runs, the model run 7c of Cut Paw Paw GMA only annual extraction hindcasted using hindcast method H2 with the annual recovered levels and climate was adopted to undertake the predictive modelling for Suite L_U_1.

The pre-development levels were defined for the representative Suite based on the early time series Suite data for the annual recovered levels. This resulted in a pre-development level of 1.16 m for Suite L_U_1. The drawdowns were calculated based on this pre-development level and the simulated levels from each of the 19 forecast scenarios.

The volumes estimated for a given drawdown for each Suite is shown below.

Drawdown (m)	Predicted volumes for GMU based on Suite L_U_1 (lower limit to upper limit)
5	1,900 (300 – 2,900)
10	5,000 (1,000 – 6,800)

The model for Suite L_U_1 was assessed as having a “Moderate” model applicability rating using the criteria outlined in section 5.2. Due to the limited range in calibration volumes, the greater the proposed extraction rates beyond the calibration range leads to a greater potential for drawdown forecast errors.

9.6.2 Limitations

In addition to the limitations applicable to all the 25 GMUs discussed in section 1.8, the following Cut Paw Paw GMA specific limitations have been identified:

- Spatial use data is available for Cut Paw Paw GMA but no spatial distribution methods could be run due to no Suite bores for L_U_1 occurring within the Cut Paw Paw GMA
- Model Calibration was between approximately 50-450 ML/year groundwater extraction range (well below the current PCV of 3,650 ML/year)
- The greater the proposed extraction rates beyond this calibration range the more potential for drawdown forecast errors. In this GMU prediction for extraction volumes up to 10 times the calibration range are being made to meet the 10m drawdown metric.
- Further checks and potential re-calibration may be required as extraction rates increase for this GMU

9.6.3 Recommendations

No additional recommendations were identified for Cut Paw Paw GMA.

10. Frankston GMA

10.1 Conceptualisation

The hydrogeological conceptualisation elements relevant to this study are summarised in Table 40 and a map of the GMU is presented in Figure 86. It is noted that a significant volume of information was collated to provide hydrogeological conceptual understanding of the GMU. The information that is directly relevant to the modelling are in bold or colour coded within Table 40.

Table 40 Frankston GMA – Tabulated conceptualisation

GMU summary

Frankston GMA is situated in the south-eastern suburbs of Melbourne on the eastern margin of Port Phillip Bay, covering an area of 140 km^2. The northern boundary of the GMA coincides with Patterson River/Eumemmerring Creek, the east bound by Cranbourne and Lyndhurst, the west by the Port Phillip coastline, and the south extends from Frankston to the intersection of Frankston-Cranbourne Road and the Cranbourne/Lyndhurst boundary.

Frankston GMA pertains to all formations below the surface but was primarily intended to manage the groundwater resource of the Brighton Group Aquifer (Upper Tertiary Aquifer – fluvial, UTAF). However, it was recognised that there was a degree of hydraulic connection with the underlying aquifer systems and therefore the GMA also includes the underlying Older Volcanics, Werribee Formation and Palaeozoic basement although they are utilised to a lesser extent. The PCV (3,200 ML/year) therefore relates to both the unconfined and confined aquifers.

Groundwater in this GMU is extracted predominately for stock and domestic purposes and agriculture including grazing, turf farms and market gardens (RMCG, 2008).

Hydrostratigraphy summary

Aquifer	Formation	Relevant Suites (% coverage of GMU)	% of GMU covered by Suites	Number of SON bores	Groundwater use	Use volumes ML (2019/20)	Entitlement volumes ML (2019/20)	Understanding (Low, Medium, High)
Upper	Undifferentiated sediments (QA)	U_AN_2 (0.2%) U_S_88 (0.7%)	0.2%	0	NA	0		Low
Middle	Brighton Group/Baxter Formation (UTAF)	M_S_88 (3%), M_T_3 (43%)	46%	2	Commercial, irrigation, domestic, stock	0	5	Medium
	Fyansford Formation (UMTD)	-	-	0	Commercial, domestic, stock	8	49	Low
Lower	Werribee Formation (LTA)	L_U_1 (78%)	78%	0	Commercial, industrial, irrigation	626 (60)	1,584 (63)	Medium
	Mornington Volcanics (LTB)	L_S_2 (1%)	1%	0	Industrial, irrigation	0	0	Low
Basement	Basement rocks	B_T_2 (0.3%)	0.3%	0	Commercial, domestic, dairy, irrigation, stock, industrial	53	574	Low

Note that volumes listed above are based on the DEECA provided licenced bore dataset with associated VAF layers. Bores have been assigned to a VAF layer based on bore depth where available. In some instances, bore depth is not available and has been reallocated where possible, with reassigned volumes are indicated within the brackets.

Note that volumes listed above include 60 ML of unassigned use due to unknown depths

Characteristic and importance	Description	Degree of understanding
Intended aquifer (UTAF highlighted blue above)		
Aquifer thickness within GMU (range, based on VAF)	Max: 53 m, Average: 17 m	High
Aquifer extent	Small, local	High
Likelihood of inter-aquifer flow	Medium	Low
Likelihood of groundwater – surface water interaction	Medium	Low GHD (2020)
Representative Suite	**L_U_1**	**High. 100% of GMU extraction occurs within this Suite (91% if including the reassignment of extraction).**
Current hydrological condition of representative aquifer		
Representative Suite trend	Declining	High
Groundwater quality (average salinity based on WMIS and CDM Smith spatial segment(s) with highest coverage)	1,769 mg/L (WMIS) 1,200 – 5,400 mg/L (CDM Smith, 2022)	Moderate Based on WMIS Based on CDM Smith (2022)
Groundwater yield	0.5 – 5 L/s	Low Based on CDM Smith (2022)
Groundwater levels		
Temporal groundwater level data range	**1973-2021**	
Spatial clustering of licensed bores in relation to Suites	No	Based on DEECA density mapping and licenced bore data.
Groundwater use		
Licensed groundwater use	**230 ML**	**High (Based on average historical VWA data over 15 years)**
Minimum historic groundwater use	**50 ML**	**High (Based on historical VWA data, year 2014/15)**
Maximum historic groundwater use	**686 ML**	**High (Based on historical VWA data, year 2019/20)**
Entitlement (Groundwater allocation)	**2,212 ML**	**High (Based on licenced volumes in 2020/21)**
Significant drivers of groundwater level variability (primary)	**Pumping for irrigation**	**Moderate**
Secondary drivers of groundwater level variability	**Pumping for stock or domestic use**	**Moderate**

Groundwater use profile	**Seasonal (~Oct-Apr irrigation season)**	**Low**
External Influence	**None identified**	
Groundwater values and risks		
Existing Environmental Values to be protected, relevant to this GMU	Potable water supply Licensed non-potable supply (irrigation, commercial, industrial) Unlicensed non-potable supply (domestic and stock)	
Risks to groundwater values	Direct risks: – Drawdown which may affect access to groundwater by existing users – Drawdown may affect seawater intrusion	Moderate
Indicators used to assess impacts to groundwater	– Measured drawdown using pre-determined metrics measured from a pre-determined level for the purpose of this modelling	Moderate

Legend

Extraction bores by aquifer
- UTAF (105)
- UMTD (108)
- LTA (111)
- LTBA (112)

BSE (114) (but assumed to be LTA or UTAF)

No depth (assumed to be lower aquifer)

SOBN (by aquifer)
- UTAF

Lower suite bore
- L_U_1

Lower aquifer suite
- L_S_2
- L_U_1

Groundwater Management Unit (GMU)

- Town
- Rail
- Freeway & highway
- Major road
- Stream

Monash Fwy
Princes Hwy
South Gippsland Fwy
South Gippsland Hwy
Mornington Peninsula Fwy
CHELSEA
L_U_1
Eastlink
Frankston Fwy
Frankston GMA
Dandenong Valley Hwy
Western Port Hwy
CRANBOURNE
L_S_2
Nepean Hwy
LANGWARRIN
FRANKSTON
Moorooduc Hwy

Paper Size ISO A3

0 0.4 0.8 1.2 1.6

Kilometers

Map Projection: Lambert Conformal Conic
Horizontal Datum: GDA 1994
Grid: GDA 1994 VICGRID94

N

GHD

DEECA
Sustainable yield review - confined aquifers

Frankston GMA
Site location and key features

Project No. **12564066**
Revision No. **0**
Date **15/01/2024**

Figure 86

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Print date: 15 Jan 2024 - 13:24

Data source: DELWP, VicMap, 2022; DELWP, GMUs, 2022; DELWP, SOBN, 2022; GHD, aquifer suites, 2018; DELWP, extraction bores, 2022 Created by: cperyer

10.2 Technical analysis

10.2.1 Hydrograph review and selection of representative Suites for further analysis

Suite hydrographs were generated for the confined Suites for Frankston GMA as shown in Figure 87. Generally, the Suite hydrographs show the seasonal fluctuations and hence recovered water levels. There is variability in the trends observed between these Suites, for example L_S_2 shows much lower levels prior to 1990 and B_T_2 shows a different trend to the other Suites post 2010.

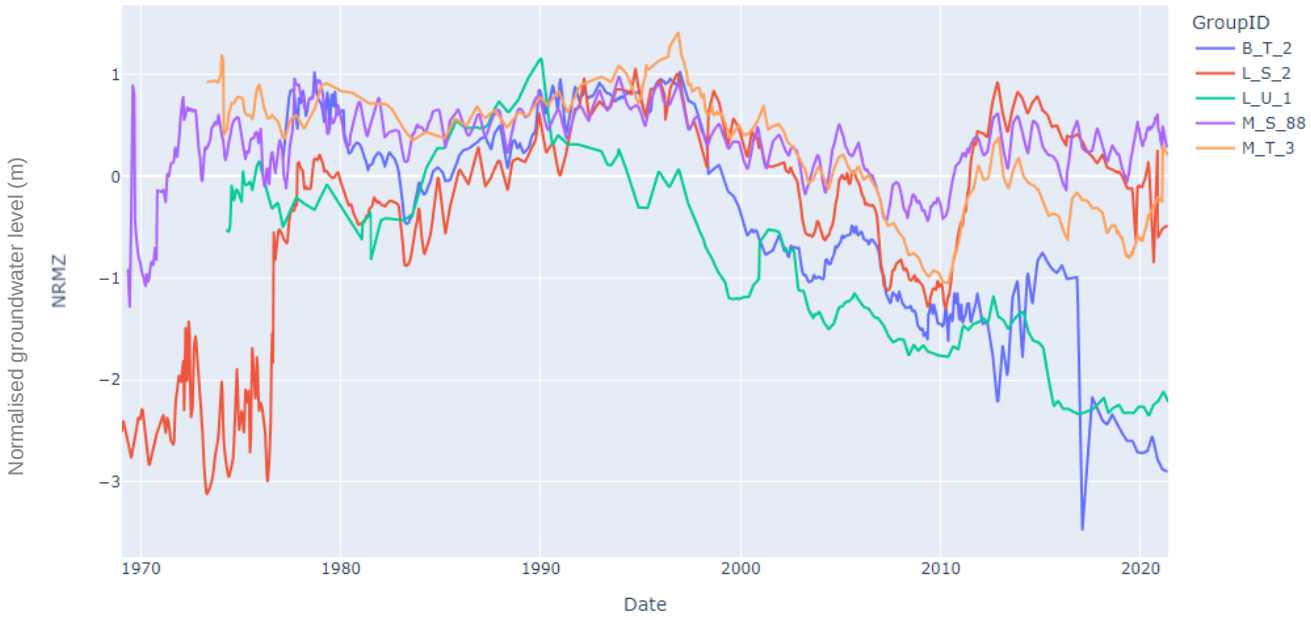


Figure 87 Frankston GMA Suite Hydrographs for all confined aquifers

The Representative Suites analysed for this GMU were Suites L_U_1 and M_T_3. The Representative Suites were selected based on the methodology outlined in section 2.6.4 which identified Suite L_U_1 as the most representative followed by M_T_3. The process is summarised as follows:

- The greatest volume of extraction occurring within the Lower Aquifer
- The Lower Aquifer pertains to the LTA, but the intended aquifer for this GMU is the UTAF which correlates to Suite M_T_3
- Suite L_U_1 covers 78% of the GMU and M_T_3 covers 43% of the GMU
- Suite L_U_1 doesn't have any active SOBN bores within the Suite area, Suite M_T_3 has one active SOBN bore within the Suite area

The one Suite bore for L_U_1 within the GMU is close to an extraction point.

The annual recovered Suite hydrograph for the representative Suites for Frankston GMA, L_U_1 and M_T_3 is shown in Figure 88.

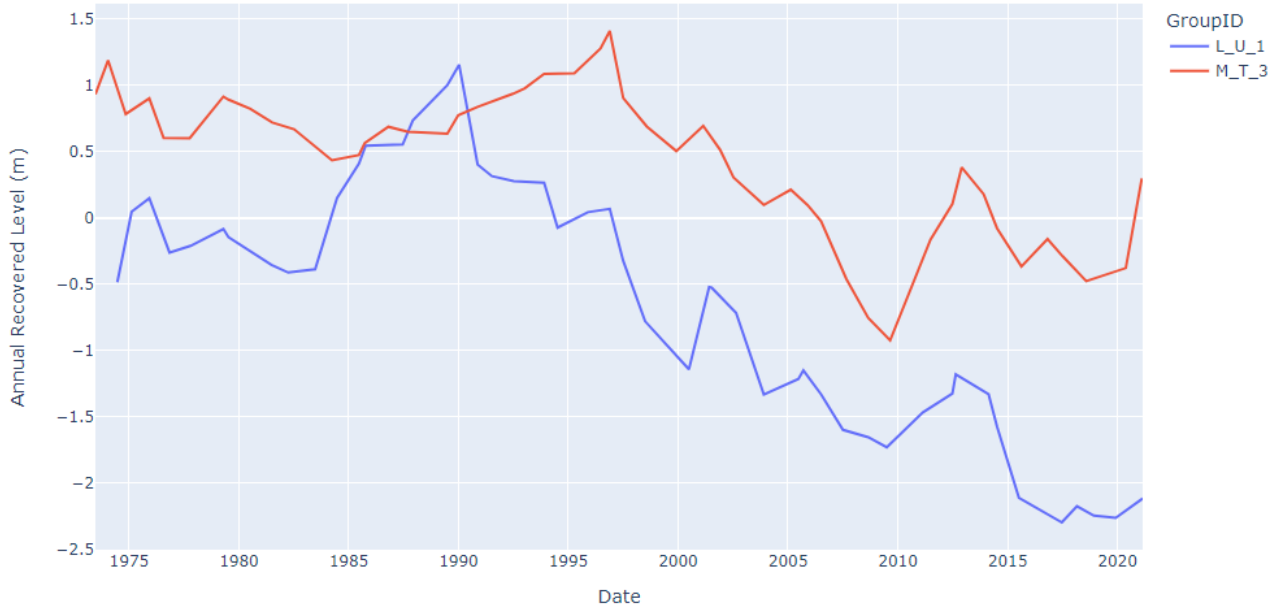


Figure 88 Frankston GMA Annual Recovered Level Suite Hydrographs for the representative Suites

10.2.2 Pre-development level

To estimate the pre-development level conditions, GHD reviewed the Suite hydrographs of annual recovered levels and assumed that the maximum levels in the early time series data was the best representation of conditions prior to major development within Frankston GMA. Thus, the maximum levels in the early time series data was adopted as the baseline of pre-development conditions.

The pre-development annual recovered levels are taken to be the maximum level in the early time series data which equates to 1.16 m for Suite L_U_1 in the year 1989/1990 and 1.41 m for Suite M_T_3 in the year 1996/1997(refer further details in section 10.4.3).

10.2.3 Externalities

Through the conceptualisation, there were no external influences inferred for Frankston GMA.

10.2.4 Hindcasting

Groundwater use data for Frankston GMA is available from 2004/2005 to 2020/2021. The hindcasting methodologies outlined in section 3.3.4.5 were applied to Frankston GMA. A summary of the hindcasting results is shown below.

10.2.4.1 Hindcasting Method 1 (H1)

Applying method H1, four different correlations were developed as described below.

Figure 89:

- Annual rainfall vs annual groundwater extraction at Frankston GMA
- Two yearly average annual rainfall vs annual groundwater extraction at Frankston GMA
- Annual summer period rainfall vs annual groundwater extraction at Frankston GMA
- Annual irrigation period rainfall vs annual groundwater extraction at Frankston GMA

Figure 90:

- Annual rainfall vs annual irrigation groundwater extraction at Frankston GMA
- Two yearly average annual rainfall vs annual irrigation groundwater extraction at Frankston GMA
- Annual summer period rainfall vs annual groundwater irrigation extraction at Frankston GMA
- Annual irrigation period rainfall vs annual groundwater irrigation extraction at Frankston GMA

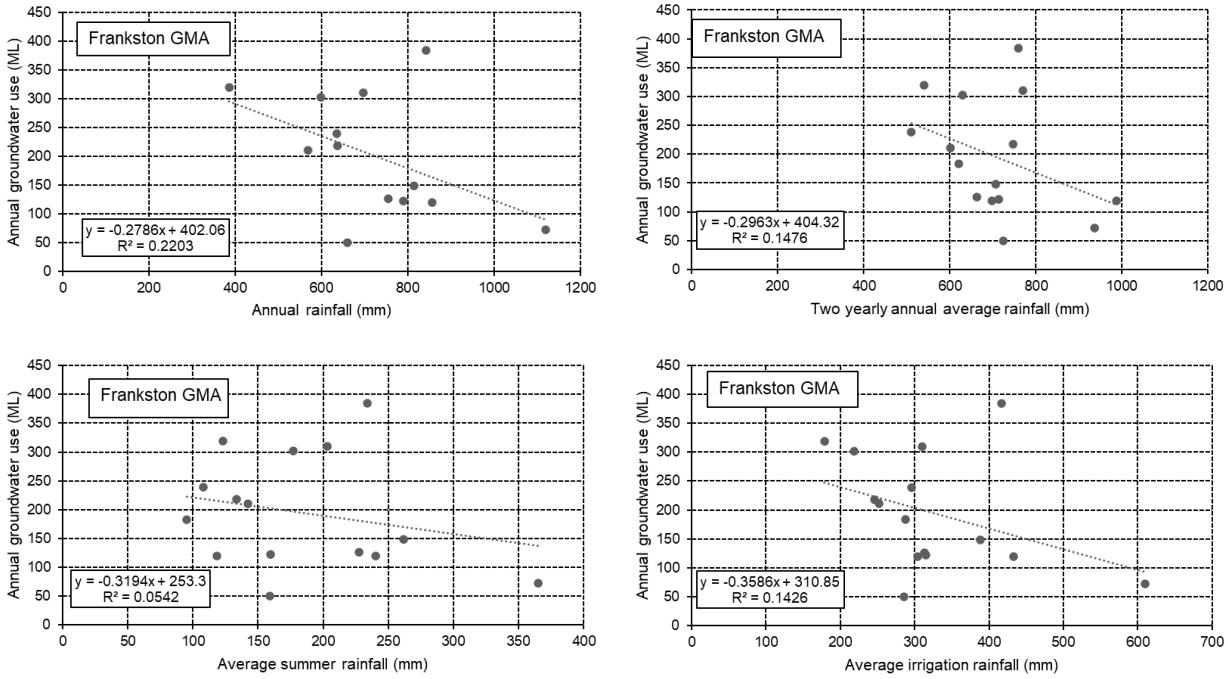


Figure 89 Frankston GMA: Hindcast method 1 correlations (Frankston GMA annual use)

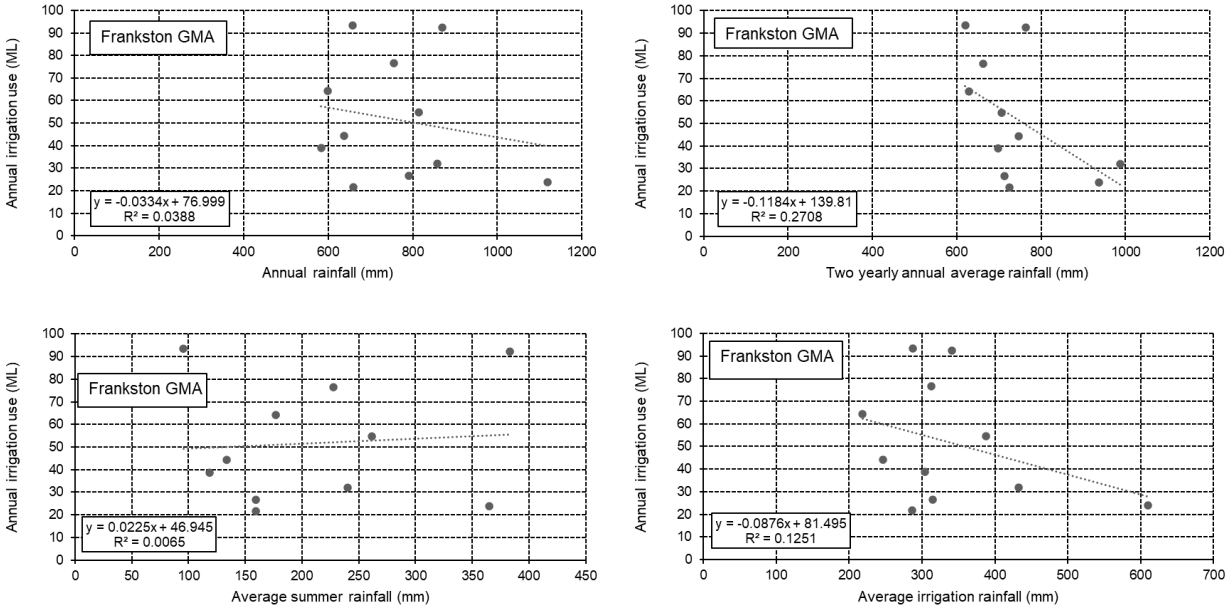


Figure 90 Frankston GMA: Hindcast method 1 correlations (Frankston GMA annual irrigation use)

As shown in Figure 89 and Figure 90, the goodness-of-fit is relatively poor across most correlations tested ($R^2 < 0.2$). The highest correlation achieved was the combination of annual irrigation groundwater use with two-yearly average rainfall for Frankston GMA; this was the correlation modelled for hindcast method H1.

10.2.4.2 Hindcasting Method 2 (H2)

Four correlations were developed using method H2 as described below and shown in Figure 91:

- Frankston GMA use per Frankston GMA bore vs annual rainfall
- Frankston GMA use per Frankston GMA bore vs two yearly average annual rainfall
- Frankston GMA use per Frankston GMA bore vs annual summer period rainfall
- Frankston GMA use per Frankston GMA bore vs annual irrigation period rainfall

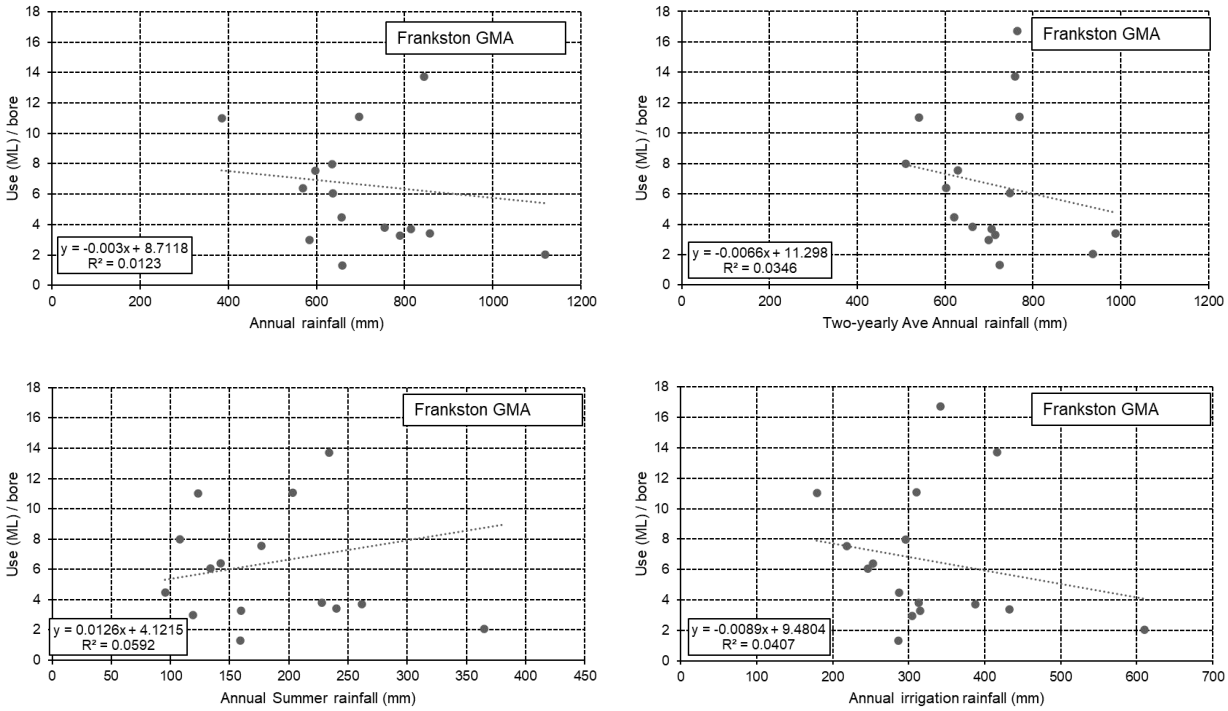


Figure 91 Frankston GMA: Hindcast method 2 correlations (Frankston GMA only)

As shown in Figure 91, the goodness-of-fit, represented by the R^2, increased slightly when annual summer rainfall was adopted. It is noted that the goodness-of-fit is quite poor for Frankston GMA using this method. As such, the Frankston GMA only extraction per bore (with annual irrigation rainfall) was modelled for hindcast method H2.

10.2.4.3 Hindcasting Method 3 (H3)

Four correlations were developed using method H3 as described below and shown in Figure 92:

- Percentage of entitlement vs annual rainfall
- Percentage of entitlement vs two yearly average annual rainfall
- Percentage of entitlement vs annual summer period rainfall
- Percentage of entitlement vs annual irrigation period rainfall

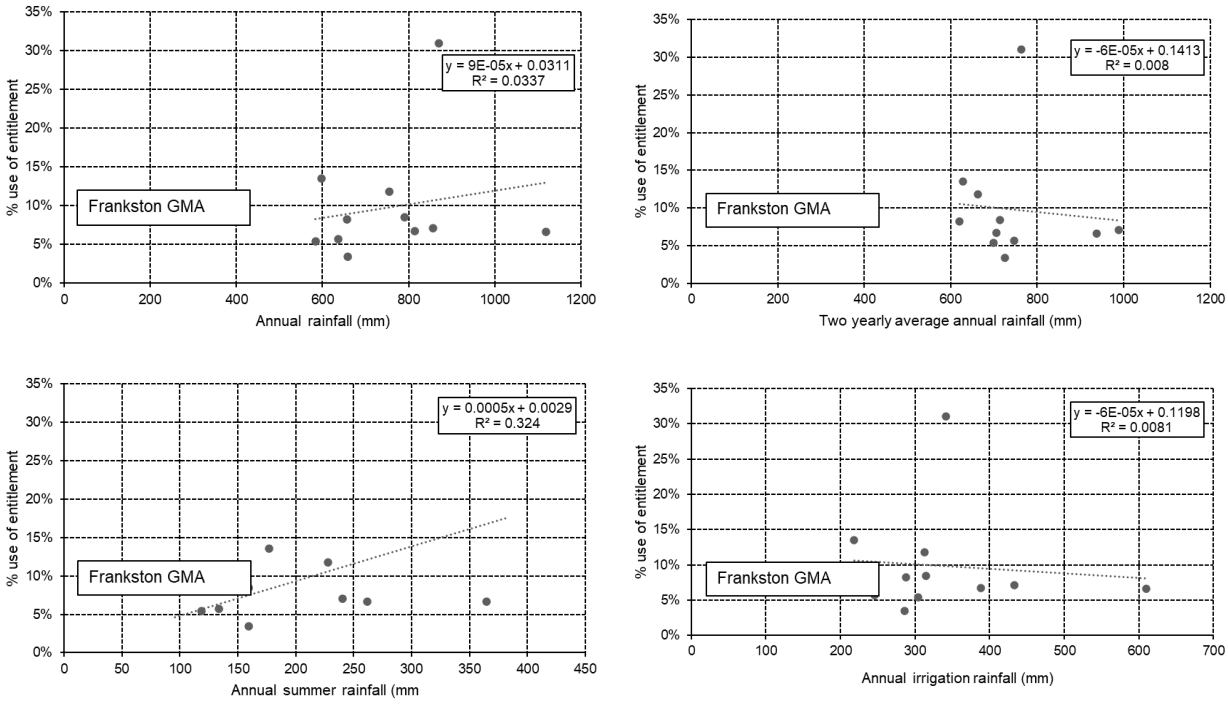


Figure 92 Frankston GMA: Hindcast method 3 correlations

As shown in Figure 92, the best goodness-of-fit result was shown to be the correlation with the annual summer rainfall; this is the correlation that was modelled for hindcast method 3. It is noted that there is only minor variation between the three other correlations.

10.2.4.4 Comparison

A comparison of the three input datasets is shown in Figure 93 and Figure 94 for the hindcasting based on Frankston GMA groundwater use. Figure 93 shows a comparison of the three hindcasting methods against the recorded use only, over the recorded use date, while Figure 94 shows the hindcasted data back to 1968/1969.

As you can see from Figure 94, groundwater use using method 1 does not decrease historically as there is no factor to account for the changing number of bores extracting over time, resulting in a higher groundwater extraction estimate than the other two methods. The hindcasting results show that the smallest average variation of recorded use to estimated use occurs for method 1. Thus, this hindcasting method is expected to provide a more probable estimated groundwater use than the other two methods, for most of the historic data period. It is noted however, that this method may over estimate in the earliest years of extraction.

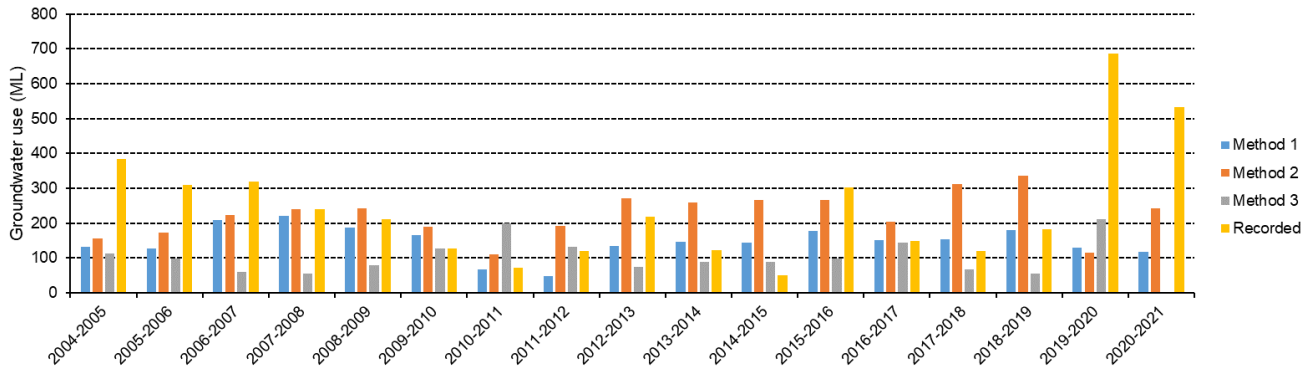


Figure 93 Frankston GMA: Comparison of hindcasting over recorded use period – Frankston GMA only extraction

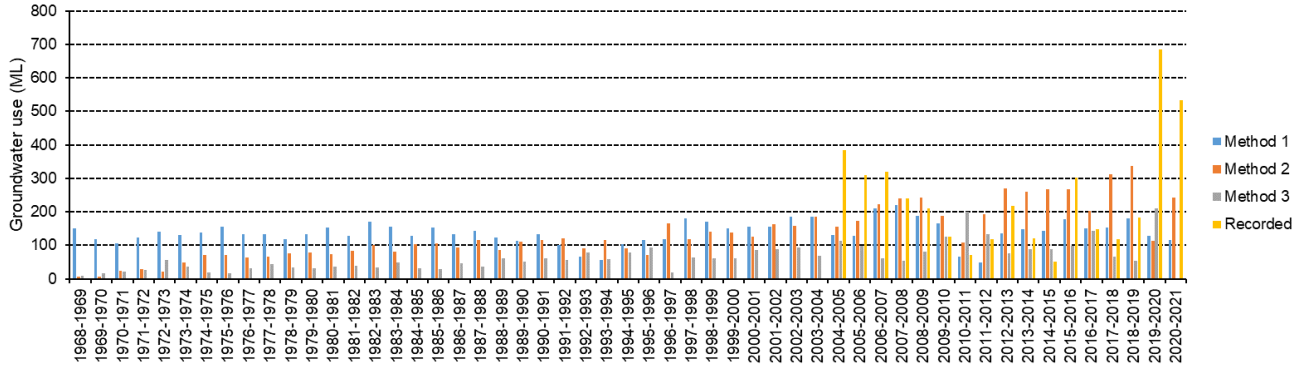


Figure 94 ***Frankston GMA: Comparison of hindcasting – Frankston GMA only extraction***

10.3 Modelling

10.3.1 Model inputs

A number of different models were run based on the various model inputs developed and combinations of these, as summarised in Table 41. Model runs highlighted blue were run with annual extraction and those highlighted grey were run using two yearly average annual extraction. It is noted that for Frankston GMA, some additional model runs were undertaken with climate data; this is explained further in the section below.

Table 41 Frankston GMA: summary of model inputs

Model input	Model runs																					
	1	2	3	4	5	6	7	8	9	9c	10	11	12	13	14	15	16	17	17c	18	18c	19
Annual recovered levels for representative Suites (L_U_1 and M_T_3)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Annual extraction – Frankston GMA only	✓																					
Annual climate data										✓									✓		✓	
Two yearly average annual extraction – Frankston GMA only		✓																				
Annual extraction – Frankston GMA and Externalities			✓																			
Two yearly average annual extraction – Frankston GMA and Externalities				✓																		
H1 annual extraction – Frankston GMA only					✓																	
H1 annual extraction – Frankston GMA and Externalities						✓																
H2 annual extraction – Frankston GMA only							✓															
H2 annual extraction – Frankston GMA and Externalities								✓														
H3 annual extraction – Frankston GMA only									✓	✓												
H1 two yearly average annual extraction – Frankston GMA only											✓											
H1 two yearly average annual extraction – Frankston GMA and Externalities												✓										
H2 two yearly average annual extraction – Frankston GMA only													✓									

Model input	Model runs																				
	1	2	3	4	5	6	7	8	9	9c	10	11	12	13	14	15	16	17	17c	18	18c	19
H2 two yearly average annual extraction – Frankston GMA and Externalities														✓								
S1 annual extraction – Frankston GMA only															✓							
S2 annual extraction – Frankston GMA only																✓						
S3 annual extraction – Frankston GMA only																	✓					
S1 annual extraction and H1 annual extraction – Frankston GMA only																		✓	✓			
S2 annual extraction and H2 annual extraction – Frankston GMA only																				✓	✓	
S3 annual extraction and H3 annual extraction – Frankston GMA only																						✓

10.3.2 Model calibration and uncertainty analysis

A statistical summary of the model output results for the runs described in Table 41 is presented in Table 42 for the selection of potential representative Suites for Frankston GMA. The column heading for L_U_1 is highlighted blue to indicate that this Suite was selected as the most likely representative Suite based on the process outlined in section 10.2.1. The statistics summarised include the average 95 PPU thickness (95PPU TH), percentage of observed levels within 95 PPU (%Obs in 95 PPU), R^2 and root mean square error (RMSE), number of annual recovered level observation points (No obs data points) and the range of observed annual recovered levels.

Suite L_U_1

A review of the results and statistical summary for Suite L_U_1 shows that model run 14 (highlighted orange) has the best results when firstly considering the smaller 95PPU band thickness compared to the other three statistical measures. However, this model contains limited data points and does not incorporate the early time series data/the defined pre-development level. The hindcasted version of model 14 is model 17 which shows slightly poorer results than model run 14. To see if the model 17 results could be improved the model was run with climate (model run 17c); this did improve the results across all statistical measures except the percentage of observations within the 95% prediction interval. Given the above, model run 17c (highlighted green) is the preferred model run for predictive modelling of Suite L_U_1 for Frankston GMA. The model outputs for model run 17c is shown in Figure 95.

Suite M_T_3

A review of the results and statistical summary for Suite M_T_3 shows that model run 9 (highlighted orange) initially provides the best model results when considering the R2, RMSE and the 95PPU thickness. However, as the model results were not excellent, model 9 was run again but with climate added in as shown by model run 9c (highlighted green). This showed that adding climate improved the results across all four statistical measures, the model outputs for model run 9c is shown in Figure 96.

Given the results, model run 9c is the preferred model run for predictive modelling of Suite M_T_3 for Frankston GMA.

Table 42 *Frankston GMA: summary of model outputs*

Suite	Statistic	Model run															
		1	2	5	7	9	9c	10	12	14	15	16	17	17c	18	18c	19
L_U_1	95PPU TH	1.77	1.98	2.61	6.89	3.09	6.18	2.92	2.56	1.07	3.67	0.9	2.41	1.9	2.75	3.21	2.75
	%Obs in 95 PPU	100	100	93.75	95.83	89.58	93.75	93.75	91.67	100	100	100	93.62	93.62	63.83	68.09	63.83
	R^2	32.6	35.9	71.8	79.3	38.5	84.6	46.5	83.5	87.0	77.1	74.0	80.6	89.2	48.8	53.7	48.8
	RMSE	0.33	0.34	0.48	0.42	0.71	0.37	0.67	0.37	0.16	0.21	0.22	0.41	0.3	0.66	0.63	0.66
	No obs data points	16	16	48	48	48	48	48	48	10	10	10	47	47	47	47	47
	Range of observed levels	1.1	1.1	3.5	3.5	3.5	3.5	3.5	3.5	1.1	1.1	1.1	3.5	3.5	3.5	3.5	3.5
M_T_3	95PPU TH	1.03	1.01	1.78	1.64	1.28	0.68	1.77	1.61	1.31	1.25	4.55	2.12	1.34	2.42	NA	2.42
	%Obs in 95 PPU	87.5	87.5	97.96	93.88	93.88	95.92	97.96	91.84	90	100	100	95.83	100	100	0	100
	R^2	61.6	60.1	36.0	52.0	72.2	88.7	37.2	51.6	-49.4	-91.4	25.8	64.7	89.5	28.1	23.1	28.1
	RMSE	0.29	0.28	0.44	0.39	0.3	0.18	0.43	0.39	0.32	0.4	0.23	0.32	0.18	0.46	0.48	0.46
	No obs data points	16	16	49	49	49	49	49	49	10	10	10	48	48	48	48	48
	Range of observed levels	1.3	1.3	2.3	2.3	2.3	2.3	2.3	2.3	0.9	0.9	0.9	2.3	2.3	2.3	2.3	2.3

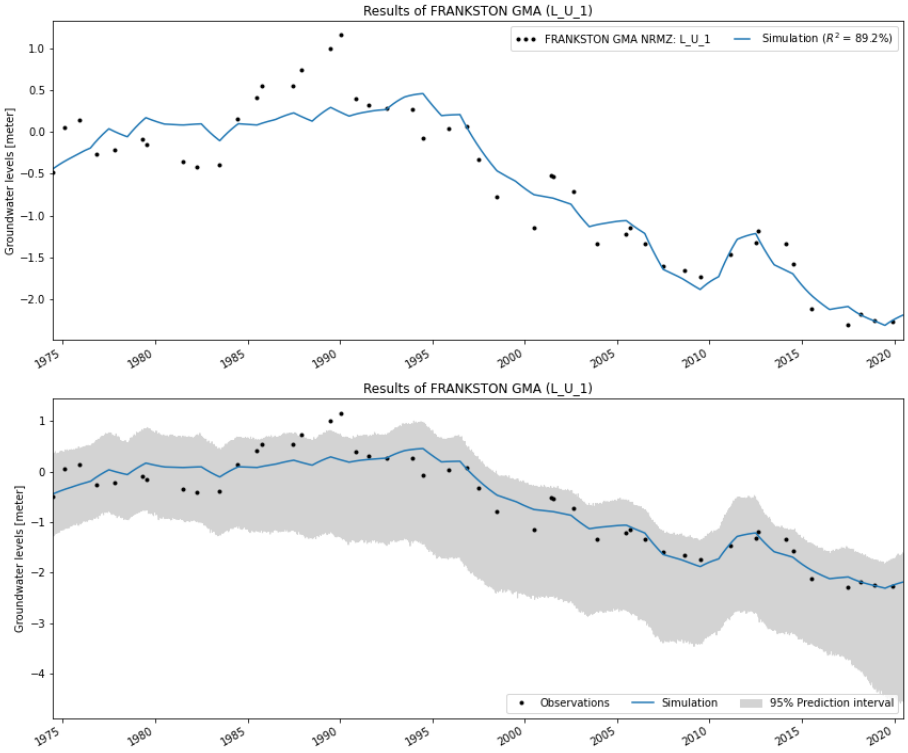


Figure 95 ***Frankston GMA Suite L_U_1: model run 17c (Frankston GMA annual extraction using hindcast method H3 and spatial distribution method S1 and climate) output hydrographs***

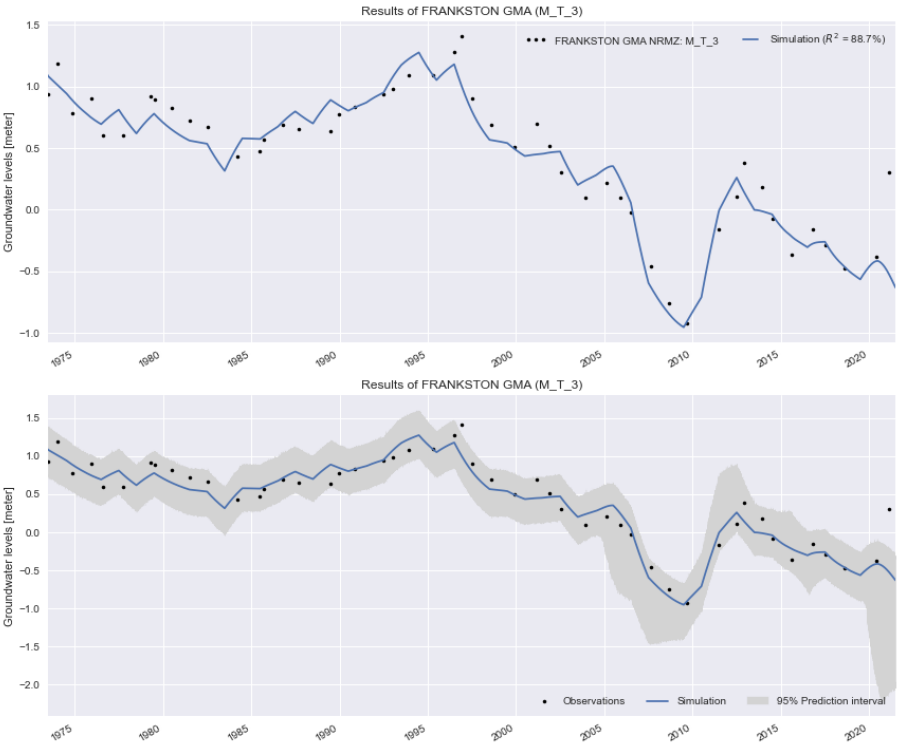


Figure 96 ***Frankston GMA Suite M_T_3: model run 9c (Frankston GMA annual extraction using hindcast method H3 and climate) output hydrographs***

10.4 Predictive modelling

10.4.1 Model inputs

The preferred model to run the predictive modelling for Frankston GMA was model run 17c for Suite L_U_1 and model run 9c for Suite M_T_3. The key inputs for the models were the annual recovered levels, annual climate data and either annual extraction using spatial distribution method S1 and/or hindcast method 3. To conduct the forecasting for the 19 scenarios discussed in section 3.5, a few factors were required in the calculations; these factors are summarised in Table 43.

Table 43 Frankston GMA: forecast scenario inputs

Input item	PCV	Licenced entitlement (based on 2020/21)	Existing use (based on 2020/2021)	Average use over recorded period (from VWA)	Maximum use over recorded period (from VWA, year 2019/20)
Value (ML/year)	3,200	2,212	534	230	686

10.4.2 Predictive model uncertainty

The model output files of the predicted models can be found in the data package provided as part of Appendix E.

MCMC predictions were undertaken on each of the forecasted scenarios for each of the two Suites. An example of one of the outputs is presented in Figure 97 for scenario 4 for Suite L_U_1. As shown in Figure 97, the uncertainty of the model prediction increases as the model predicts further into the future. Comparing with the graphical output for the same scenario, the MCMC realisations tend to fall within the 95% prediction interval bands as shown in Figure 98.

An example of one of the outputs is presented in Figure 99 for scenario 4 for Suite M_T_3. As shown in Figure 99, the uncertainty of the model prediction increases as the model predicts further into the future. Comparing with the graphical output for the same scenario, some of the MCMC realisations fall outside the 95% prediction interval bands as shown in Figure 100, however, most fall within this band.

It's noted that for scenario 4 shown, the volumes used in the forecast scenario can be up to 9 times greater than the calibration volumes. It is assumed that this has impacted the uncertainty analysis, resulting in large prediction intervals and variations in the MCMC realisations.

Uncertainty is also accounted for by using 19 forecast scenarios to develop a groundwater use to drawdown relationship (analogous to a Monte Carlo type simulation) where a range of possible outcomes are generated. It is noted however, that the forecast scenarios were not randomly generated, but rather based upon a series of estimated use behaviours.

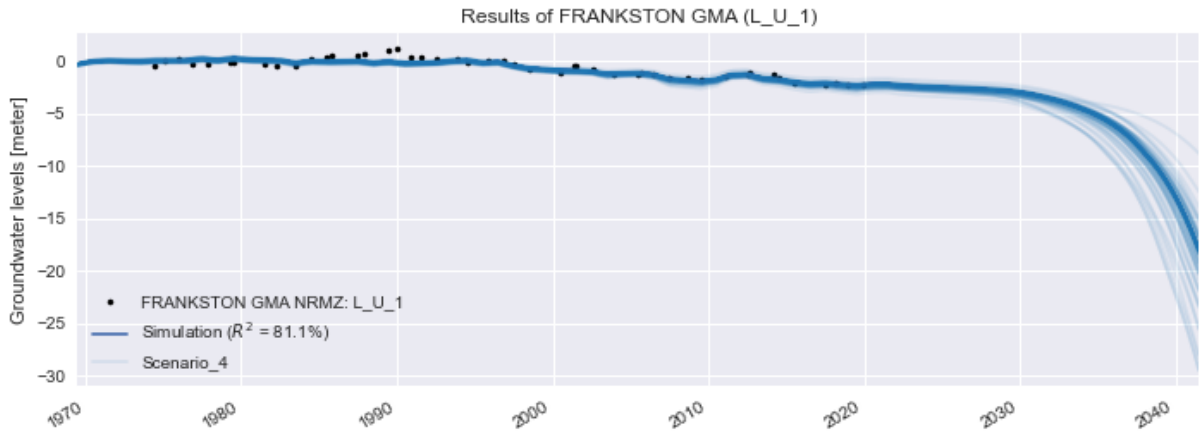


Figure 97 Frankston GMA: Suite L_U_1 MCMC analysis for Forecast Scenario 4

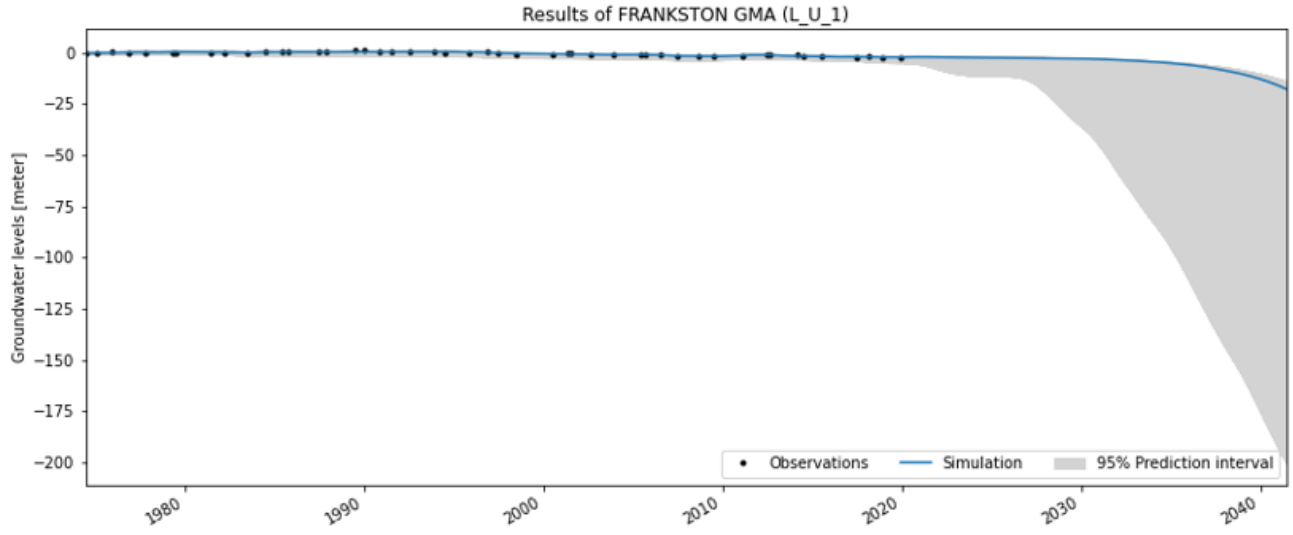


Figure 98 *Frankston GMA: Suite L_U_1 Forecast Scenario 4 with 95% prediction bands*

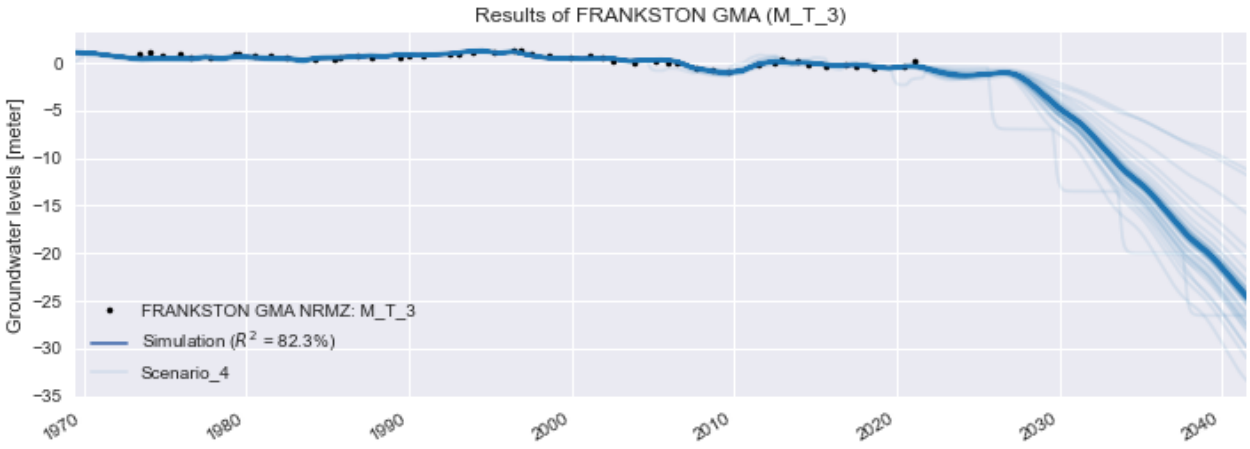


Figure 99 *Frankston GMA: Suite M_T_3 MCMC analysis for Forecast Scenario 4*

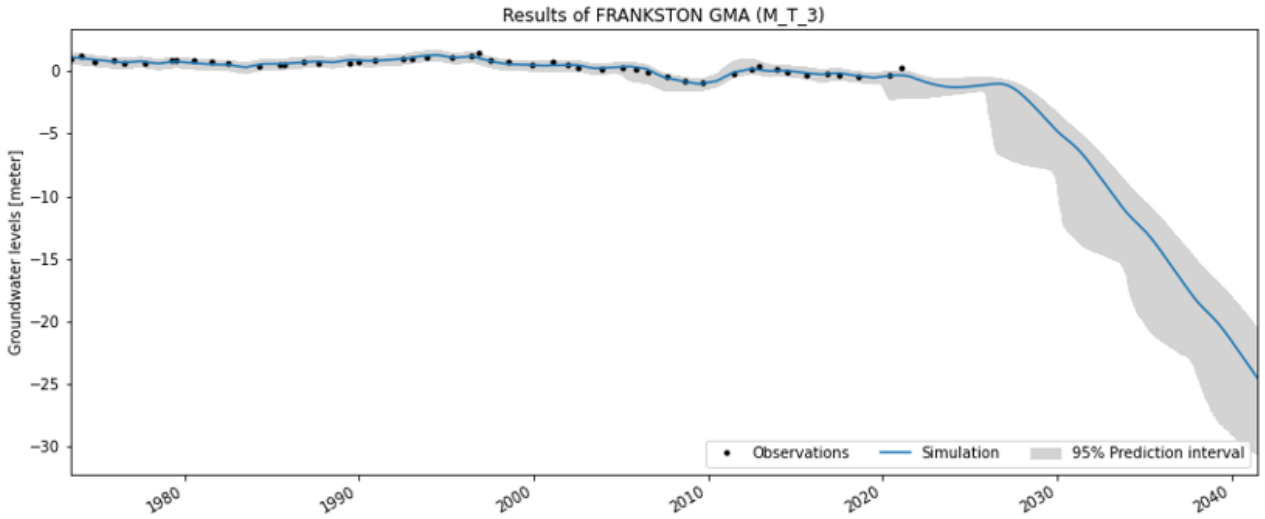


Figure 100 *Frankston GMA: Suite M_T_3 Forecast Scenario 4 with 95% prediction bands*

10.4.3 Extraction vs drawdown

To calculate the drawdown based on the annual recovered levels simulated by the model, the pre-development conditions (pre commencement of extraction) need to be estimated. For Frankston GMA, the water level prior to groundwater development was unknown, due to:

- Uncertainty regarding the commencement of development in some GMUs
- The initiation of groundwater development preceding SOBN bore installation and temporal groundwater monitoring

Using the pre-development levels defined in section 10.2.2, the modelled water levels were converted into drawdowns (from this baseline pre-development level) for each of the 19 scenarios. This predevelopment condition is shown in Figure 101 for Suite L_U_1 hydrograph of annual recovered levels. In Figure 101:

- Actual annual groundwater use is represented by the blue column graph between 2009/2010 and 2020/2021
- Hindcasted groundwater use is represented by the orange columns between 1972/1973 and 2009/2010
- Forecasted use is represented by the grey columns after 2021/2022
- The annual recovered water level behaviour based on recorded data is represented by the red line graph, where by the maximum level is taken to best reflect the pre-development levels
- In the case of Figure 101, the pre-development annual recovered levels are taken to be the reading in 1989/1990 of 1.16 m

The modelled forecasted annual recovered levels (from scenario 1) are represented by the purple line in Figure 101.

The calibration annual recovered levels are represented by the black line in Figure 101.

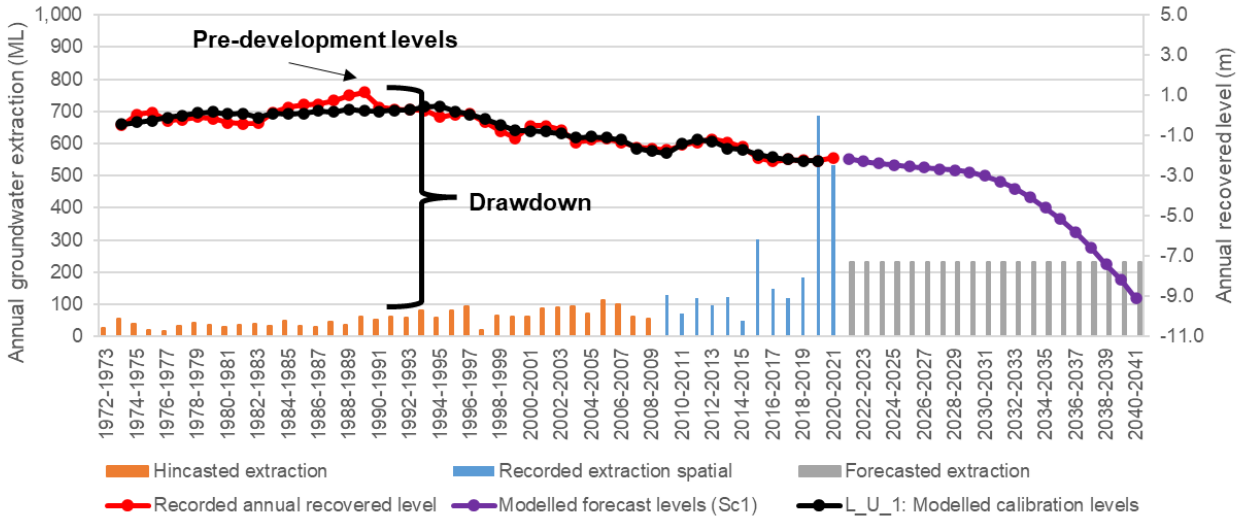
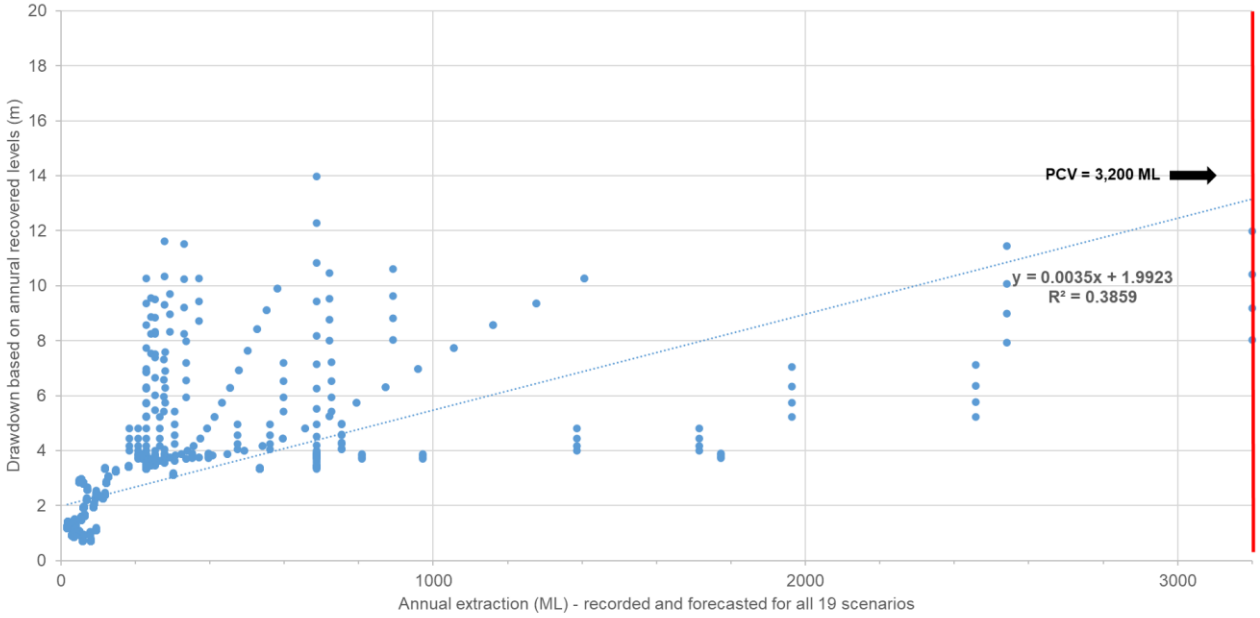


Figure 101 Estimating pre-pumping water levels (example from Suite L_U_1)

For Suite L_U_1, the calculated drawdowns and volumes for each of the scenarios were plotted in individual graphs for each scenario, all scenarios together in the one graph (Figure 102) and a graph of the scenarios for specific time periods (Figure 103) to develop the volume to drawdown relationship. For each scenario, a linear regression was applied and the coefficient of determination (R^2) was calculated. A comparison of each of these graphs shows variations in the coefficient of determination and slope of the linear line (as can be seen between Figure 102 and Figure 103). The same process was applied for Suite M_T_3 and again, there were variations in the coefficient of determination and slope of the linear line between the graphs. As such, the relationship developed using all scenarios was adopted as it best captures this variation between forecast scenarios.

The use-drawdown for all the 19 forecast scenario drawdowns and volumes (both the recorded and forecasted volumes over each year modelled is shown in Figure 102 for Suite L_U_1 (1974 to 2041) and Figure 104 for Suite M_T_3 (1973 to 2041). Note the abscissa range of the chart has been clipped and does not show forecast drawdowns for the higher use scenarios (more improbable volumes of higher then the PCV). Reviewing these figures, the following is noted:

- There should be zero drawdown under zero use and therefore a line of best fit should pass through the origin (0,0) or close to it
- Average use is around 230 ML, Figure 102 indicates that where use is below 1,000 ML, the model forecast drawdown tends to occur above the predicted line of best fit and for Figure 104, the model forecast drawdown tends to occur relatively close to the predicted line of best fit
- For the same annual use, different drawdowns can be obtained as Pastas predicts a water level for each year. For example, Figure 101 shows a scenario where groundwater use remains constant at around 230 ML/year over the next 20 years.
- The correlation for groundwater use and drawdown for Suite L_U_1 is poor as shown in Figure 102; this correlation improves for Suite M_T_3 as shown in Figure 104
- The various forecast scenarios generally result in data plotting reasonably close together in a linear trend. The 19 forecast scenarios applied to populate the chart is analogous to a Monte Carlo type simulation where a range of possible outcomes are generated. It is noted however, that the forecast scenarios were not randomly generated, but rather based upon a series of estimated use behaviours.



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Figure 102 ***Frankston GMA Suite L_U_1: Drawdown (on annual recovered levels) and extraction volumes (recorded and forecasted <3,200 ML) for all data between 1974 to 2041 and all forecasted scenarios***

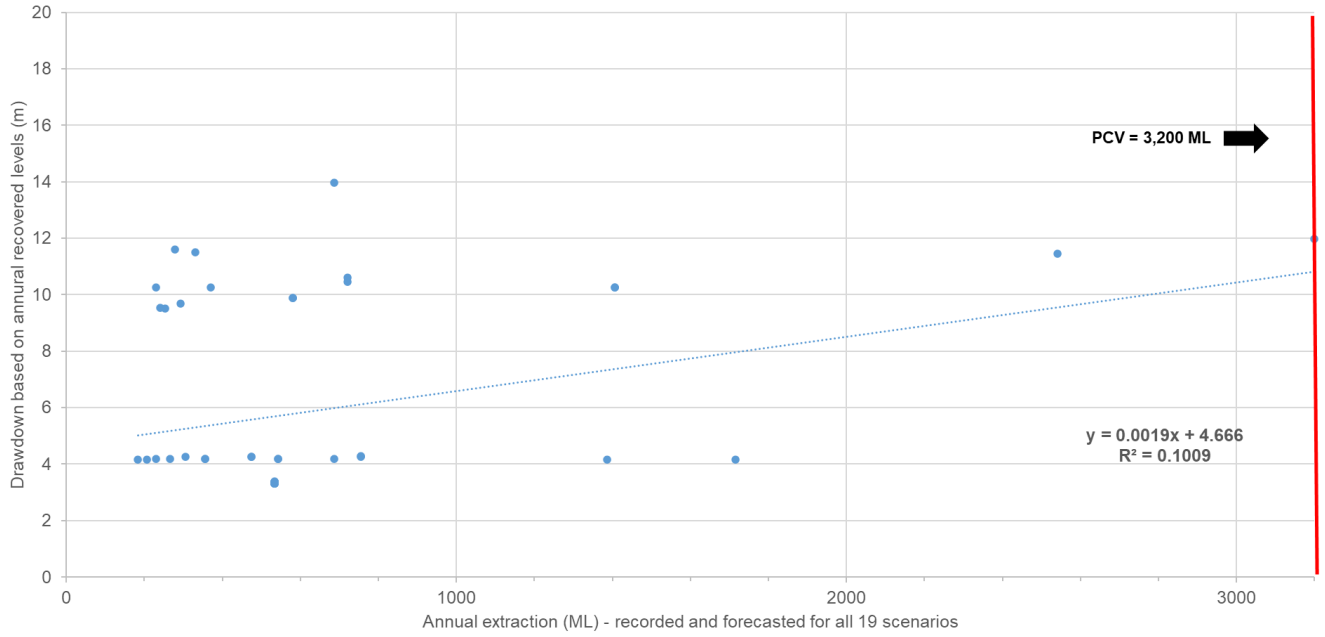


Figure 103 *Frankston GMA Suite L_U_1: Drawdown (on annual recovered levels) and extraction volumes (recorded and forecasted <3,200 ML) for years 2020/2021, 2030/2031 and 2040/2041 for all forecasted scenarios*

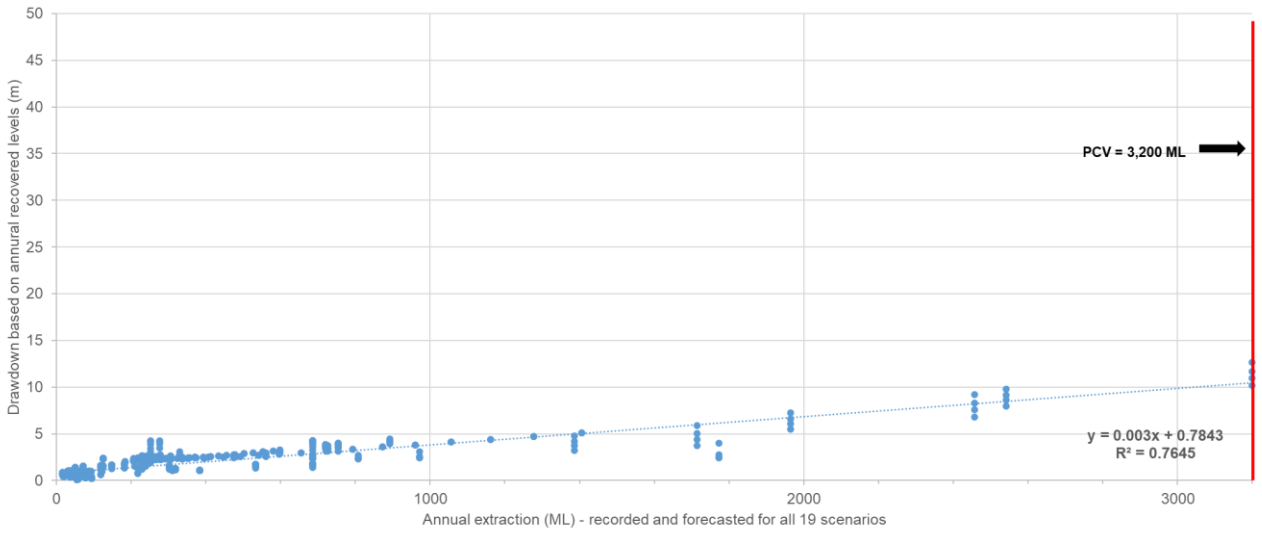


Figure 104 *Frankston GMA Suite M_T_3: Drawdown (on annual recovered levels) and extraction volumes (recorded and forecasted <3,200 ML) for all data between 1973 to 2041 and all forecasted scenarios*

10.5 Sustainability metrics

10.5.1 Application of metrics

Using the use - drawdown relationships developed through the previous step of forecasting aquifer response under a range of use scenarios, groundwater drawdown can be used to compare against metrics that define groundwater resource sustainability.

The application of these metrics and the relationship developed between drawdown based on the Suite annual recovered levels and extraction volume for the whole GMU, which is shown in Table 44 for Frankston GMA Suite L_U_1 and Table 45 for Frankston GMA Suite M_T_3 (noting Frankston GMA has a current PCV of 3,200 ML/year). As part of the modelling, a 95% prediction interval band was applied to the modelling results. The drawdowns based on these intervals are shown in Table 44 and Figure 105 for Suite L_U_1, and Table 45 and Figure 106 for Suite M_T_3.

In comparing the two Frankston GMA Suites L_U_1 and M_T_3, Suite L_U_1 shows higher drawdowns for a given volume than Suite M_T_3. Suite L_U_1 also shows a greater variation in drawdowns based on the 95% prediction intervals applied to a given volume.

A comparison of volumes for the whole of GMU at drawdown intervals provided by DEECA is shown in

Table 46 for Suite L_U_1 and M_T_3. A drawdown of 5 m is predicted to occur at volumes of 900 ML (with a possible range of 100 – 1,100 ML) using Suite L_U_1 and 1,400 ML (with a possible range of 900 – 1,700 ML) using Suite M_T_3. A drawdown of 10 m is predicted to occur at volumes of 2,300 ML (with a possible range of 300 – 2,700 ML) using Suite L_U_1 and 3,100 ML (with a possible range of 2,100 – 3,600 ML) using Suite M_T_3.

Table 44 Relationship of Suite drawdown to GMU extraction for Frankston GMA Suite L_U_1

Volume (ML/year) for whole of GMU	Based on model prediction of Suite L_U_1 annual recovered levels
	Drawdown over 20 years (m) (lower limit to upper limit based on 95% prediction interval band)
7,500	28.2 (24.8 - 163.8)
7,000	26.5 (23.2 - 153.1)
6,500	24.7 (21.7 - 142.3)
6,000	23 (20.1 - 131.6)
5,500	21.2 (18.6 - 120.8)
5,000	19.5 (17 - 110.1)
4,500	17.7 (15.5 - 99.3)
4,000	16 (13.9 - 88.6)
3,500	14.2 (12.4 - 77.8)
3,000	12.5 (10.8 - 67.1)
2,500	10.7 (9.3 - 56.3)
2,000	9 (7.7 - 45.6)
1,500	7.2 (6.2 - 34.8)
1,000	5.5 (4.6 - 24.1)
500	3.7 (3.1 - 13.3)
0	2 (1.5 - 2.6)

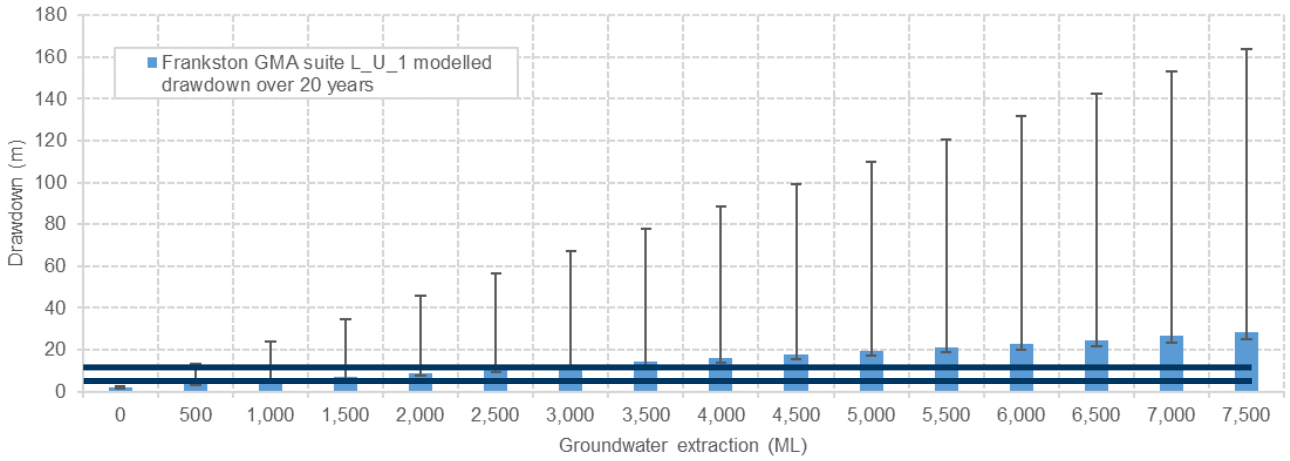


Figure 105 ***Frankston GMA Suite L_U_1: Relationship of Suite drawdown to GMU extraction (with error bars showing results of drawdown using levels from model's 95% prediction intervals, lowest limit only)***

Table 45 ***Relationship of Suite drawdown to GMU extraction for Frankston GMA Suite M_T_3***

Volume (ML/year) for whole of GMU	Based on model prediction f Suite M_T_3 annual recovered levels
	Drawdown over 20 years (m) (lower limit to upper limit based on 95% prediction interval band)
7,500	23.3 (20.6 - 32.6)
7,000	21.8 (19.3 - 30.5)
6,500	20.3 (17.9 - 28.4)
6,000	18.8 (16.6 - 26.3)
5,500	17.3 (15.2 - 24.2)
5,000	15.8 (13.9 - 22.1)
4,500	14.3 (12.5 - 20)
4,000	12.8 (11.2 - 17.9)
3,500	11.3 (9.8 - 15.8)
3,000	9.8 (8.5 - 13.7)
2,500	8.3 (7.1 - 11.6)
2,000	6.8 (5.8 - 9.5)
1,500	5.3 (4.4 - 7.4)
1,000	3.8 (3.1 - 5.3)
500	2.3 (1.7 - 3.2)
0	0.8 (0.4 - 1.1)

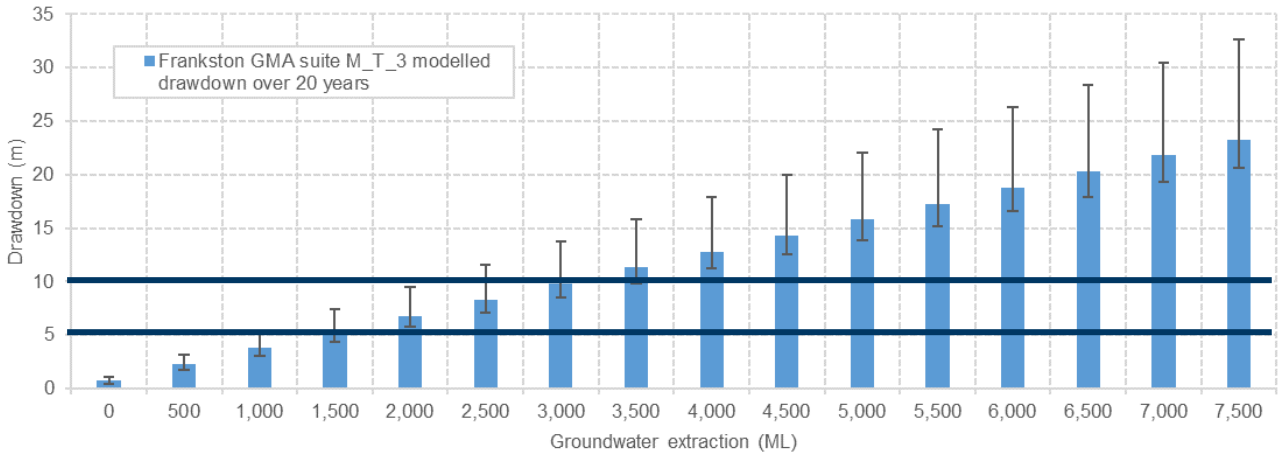


Figure 106 ***Frankston GMA Suite M_T_3: Relationship of Suite drawdown to GMU extraction (with error bars showing results of drawdown using levels from model's 95% prediction intervals, lower limit only)***

Table 46 ***Predicted GMU volumes for drawdown metrics***

Drawdown (m)	Predicted volumes for GMU based on Suite L_U_1 drawdowns (lower limit to upper limit)	Predicted volumes for GMU based on Suite M_T_3 drawdowns (lower limit to upper limit)
5	900 (100 – 1,100)	1,400 (900 – 1,700)
10	2,300 (300 – 2,700)	3,100 (2,100 – 3,600)

	Volume (ML/year)	Drawdown over 20 years
PCV = 3,200	7,500	23.3 (20.6 - 32.6)
	7,000	21.8 (19.3 - 30.5)
	6,500	20.3 (17.9 - 28.4)
	6,000	18.8 (16.6 - 26.3)
	5,500	17.3 (15.2 - 24.2)
	5,000	15.8 (13.9 - 22.1)
	4,500	14.3 (12.5 - 20)
Av unit = 230	4,000	12.8 (11.2 - 17.9)
	3,500	11.3 (9.8 - 15.8)
	3,000	9.8 (8.5 - 13.7)
	2,500	8.3 (7.1 - 11.6)
	2,000	6.8 (5.8 - 9.5)
	1,500	5.3 (4.4 - 7.4)
	1,000	3.8 (3.1 - 5.3)
	500	2.3 (1.7 - 3.2)
	0	0.8 (0.4 - 1.1)

Legend

Groundwater Management Units

Middle Aquifer Suites

- M_S_2
- M_S_88
- M_T_1
- M_T_2
- M_T_3

- Rail
- Freeway & highway
- Major road
- Minor road
- Park
- Stream
- Town

	Volume (ML/year)	Drawdown over 20 years
PCV = 3,200	7,500	28.2 (24.8 - 163.8)
	7,000	26.5 (23.2 - 153.1)
	6,500	24.7 (21.7 - 142.3)
	6,000	23 (20.1 - 131.6)
	5,500	21.2 (18.6 - 120.8)
	5,000	19.5 (17 - 110.1)
	4,500	17.7 (15.5 - 99.3)
Av unit = 230	4,000	16 (13.9 - 88.6)
	3,500	14.2 (12.4 - 77.8)
	3,000	12.5 (10.8 - 67.1)
	2,500	10.7 (9.3 - 56.3)
	2,000	9 (7.7 - 45.6)
	1,500	7.2 (6.2 - 34.8)
	1,000	5.5 (4.6 - 24.1)
	500	3.7 (3.1 - 13.3)
	0	2 (1.5 - 2.6)

Legend

Groundwater Management Units

Lower Aquifer Suites

- L_S_2
- L_S_88
- L_U_1

- Rail
- Park
- Freeway & highway
- Major road
- Minor road
- Stream
- Town

SPRINGVALE
CHELSEA
CRANBOURNE
FRANKSTON
LANGWARRIN
BERWICK SPRINGS
FRANKSTON RESERVOIR
Frankston GMA
M_T_2
M_T_3
M_S_2
M_S_88
M_T_1
L_U_1
L_S_2
Princes Hwy
Monash Fwy
South Gippsland Fwy
Mornington Peninsula Fwy
Eastlink
Frankston Fwy
Dandenong Valley Hwy
Western Port Hwy
Nepean Hwy
Moorooduc Hwy
South Gippsland Hwy

Paper Size ISO A3

0 1 2 3 4 Kilometers

Map Projection: Lambert Conformal Conic
Horizontal Datum: GDA 1994
Grid: GDA 1994 VICGRID94

N

GHD

DEECA
Sustainable Yields
Confined Aquifers

FRANKSTON GMA: KEY SUITES VOLUME VS DRAWDOWN

Project No. 31-12564066
Revision No. 0
Date 15/01/2024

FIGURE 107

Data source: DEECA, VicMap, 2022; DEECA GMU locations, 2022; GHD, aquifer suites, 2018; . Created by: cperyer

10.6 GMU summary

10.6.1 Findings

Frankston GMA primarily relates to the Brighton Group aquifer (UTAF), however there is a degree of connection with the underlying aquifers. Bore use data suggests that extraction predominately occurs from the Werribee Formation (LTA) and groundwater is predominately extracted from this aquifer for stock and domestic purposes. The UTAF and LTA falls within the middle and lower aquifer Suites, the middle aquifer Suites that cover Frankston GMA are M_S_88 (3%), M_T_3 (43%) and the lower Suites are L_U_1 (78%). The identified representative Suites are L_U_1 (most preferred) and M_T_3. The Suite hydrographs for the representative Suites show an overall decreasing trend along with seasonal fluctuation and thus recovered water levels, which were adopted for the assessment.

Application of two yearly annual average extraction instead of annual generally showed a similar model fit based on the statistical analysis across the model runs for Suite M_T_3. For Suite L_U_1, the two yearly average generally showed poorer results than the annual extraction (except hindcast method H2). The best match using the two yearly average annual extraction was model run 2 (two yearly average annual extraction for Frankston GMA) for both Suites.

The application of spatial distribution produced an improved model fit (statistically) for Suite L_U_1 when using spatial methods 1 and 3 compared to the annual recorded groundwater usage for the whole GMU. For Suite M_T_3, applying spatial methods produced a poorer model fit. The quality of the result did not increase when spatial distribution methodology was combined with hindcasting methodology.

For the best hindcasted model results, climate was applied which improved the statistical measures. Based on this, model run 17c of annual extraction with spatial distribution method S1 and hindcast method H3 with climate was adopted for the predictive modelling for Suite L_U_1 and model run 9c of annual extraction within hindcast method H3 and climate for Suite M_T_3 was adopted for the predictive modelling.

The pre-development levels were defined for the two representative Suites based on the maximum annual recovered levels prior to the main period of drawdown; this resulted in pre-development levels of 1.16 m for Suite L_U_1 and 1.41 m for Suite M_T_3. The drawdowns were calculated based on these pre-development levels and the simulated levels from each of the 19 forecast scenarios.

The volumes estimated for a given drawdown for each Suite is shown below.

Drawdown (m)	Predicted volumes for GMU based on Suite L_U_1 drawdowns (lower limit to upper limit)	Predicted volumes for GMU based on Suite M_T_3 drawdowns (lower limit to upper limit)
5	900 (100 – 1,100)	1,400 (900 – 1,700)
10	2,300 (300 – 2,700)	3,100 (2,100 – 3,600)

The model for Suite L_U_1 was assessed as having a “Moderate” model applicability rating and Suite M_T_3 was assessed as having an “Excellent” rating using the criteria outlined in section 5.2. It’s noted that the use-drawdown graph for Suite L_U_1 shows that the same use year on year an increase in drawdown is observed; this may be the influence of climate in the model. For both Suites, due to the limited range in calibration volumes, the greater the proposed extraction rates beyond the calibration range leads to a greater potential for drawdown forecast errors.

10.6.2 Limitations

In addition to the limitations applicable to all the 25 GMUs discussed in section 1.8, the following Frankston GMA specific limitations have been identified:

- The licenced bore dataset provided by DEECA has 15% of bores assigned to Frankston GMA with no depth data and thus couldn’t be assigned to a VAF layer and in turn Suite. These bores were assigned to an aquifer in order to assist with the determination of the representative Suite. However, this data was not used in the model analysis.

- The spatial dataset used for the modelling is only available to the year 2019/2020. To account for this, annual recorded data from Victorian Water Accounts for the year 2020/2021 has been assigned to bores based on the method described in section 3.5.
- For L_U_1, model calibration was between approximately 50-700 ML/year groundwater extraction range (well below the current PCV of 3,200 ML/year, around 20% of the PCV)
- The greater the proposed extraction rates beyond this calibration range the more potential for drawdown forecast errors. In this GMU drawdown prediction for extraction volumes up to 3 times the calibration range, are being made to meet the 10m drawdown metric.
- Use-drawdown graphs have been cut off to current PCV due to such low usage (2xPCV is very extreme for this GMU)
- Suite dataset L_U_1 has a groundwater level change of around 3 m and is the same dataset used for Cut Paw Paw GMA. (i.e., this suite represents the LTA across a large areal extent)
- The use-drawdown graph for Suite L_U_1 shows that for the same year on year use an increase in drawdown is observed (i.e., the drawdown does not stabilise). This may be the influence of climate in the model.

10.6.3 Recommendations

In addition to the recommendations applicable to all the 25 GMUs discussed in section 32 the following Frankston GMA specific recommendations have been identified:

- The licenced bore dataset provided by DEECA has 15% of bores assigned to Frankston GMA with no depth data and thus couldn't be assigned to a VAF layer and in turn Suite. It is recommended that DEECA obtains the relevant depth and aquifer monitored data for licenced bores within this GMU.

11. Koo Wee Rup WSPA

11.1 Conceptualisation

The hydrogeological conceptualisation elements relevant to this study are summarised in Table 47 and a map of the GMU is presented in Figure 108. It is noted that a significant volume of information was collated to inform the hydrogeological conceptual understanding of the GMU. The information that is directly relevant to the modelling are in bold or colour coded within Table 47.

Table 47 Koo Wee Rup WSPA – Tabulated conceptualisation

GMU summary

Koo Wee Rup WSPA is situated in southern Victoria within the Westernport Basin, which is partly bound by Westernport Bay as shown in Figure 8. Koo Wee Rup WSPA covers an area of 1,114 km^2 and within this area, the WSPA pertains to all formations below the surface with a PCV of 12,915 ML/year. Koo Wee Rup WSPA has areas of intensive groundwater use for irrigation.

The GMU pertains to all formations below the surface but was intended to primarily manage groundwater resources of the Tertiary Westernport Group which comprises the Baxter, Sherwood and Yallock Formations (UTAF, UMTA). The GMU therefore primarily relates to confined aquifers.

The Westernport Basin has been studied extensively, owing partly to significant use of groundwater resources, and the potential for saltwater instruction effects. Groundwater in this GMU is predominately used for irrigation and dairy purposes, however urban, industrial, stock and domestic are also prevalent.

Koo Wee Rup WSPA is managed by SRW and occurs within the Central Groundwater Basin.

Hydrostratigraphy summary

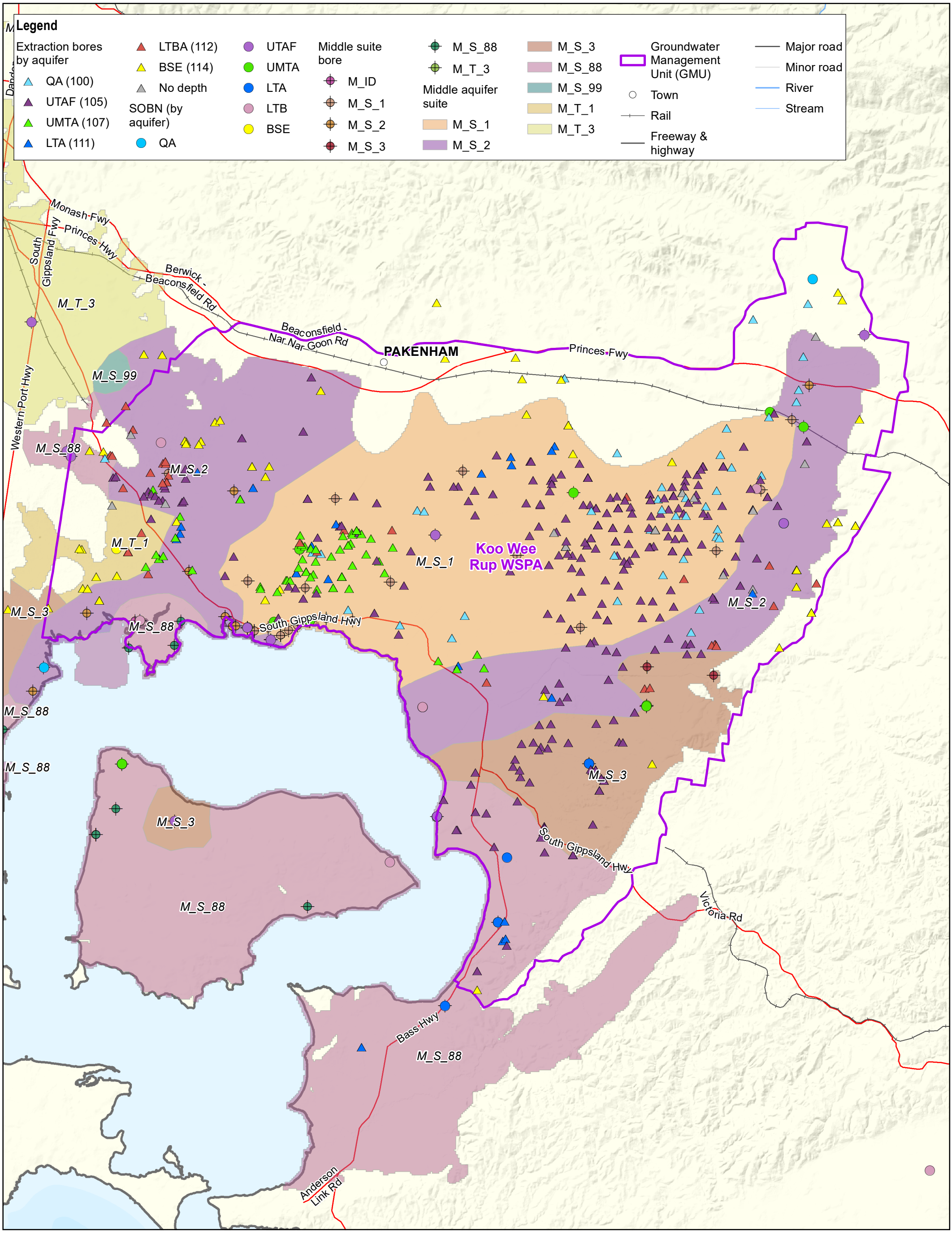
Aquifer	Formation	Relevant Suites (% coverage of GMU)	% of GMU covered by Suites	Number of SON bores	Groundwater use	Use volumes ML (2019/20)	Entitlement volumes ML (2019/20)	Understanding (Low, Medium, High)
Upper	Undifferentiated sediments (QA)	U_AL_1(18%), U_AL_2 (50%) U_AL_3 (5%), U_AN_2 (0.8%) U_AL_99 (3%) U_S_88 (0%)	76%	3	Industrial, irrigation, stock, domestic, dairy	37	385	Medium
Middle	Brighton Group/Baxter Formation (UTAF)	M_S_1 (33%), M_S_2 (26%), M_S_3 (9%), M_S_88 (8%), M_T_1 (2%)	77%	8	Commercial, irrigation, industrial, stock, domestic, dairy	2,321	7,433	Medium
	Batesford Limestone/Sherwood Formation/Yallock Formation (UMTA)	M_S_1 (33%), M_S_2 (26%), M_S_3 (9%), M_S_88 (8%), M_T_1 (2%)	77%	13	Industrial, irrigation, domestic, stock, dairy	123	817	Medium
Lower	Childers Formation (LTA)	-	-	3	Urban, commercial, industrial, irrigation, domestic, stock, diary	125	813	Low
	Mornington Volcanics (LTBA)	L_S_1 (32%), L_S_2 (29%), L_S_88 (5%) L_U_1 (0.1%)	65%	9	Commercial, industrial, irrigation, domestic, stock, dairy	20	251	Low
Basement	Basement rocks (BSE)	B_T_1 (11%), B_T_2 (55%)	65%	1	Urban, industrial, commercial, irrigation, domestic, tock, dairy	134	1,517	Low

Note that volumes listed above are based on the DEECA provided licenced bore dataset with associated VAF layers. Bores have been assigned to a VAF layer based on bore depth where available. In some instances, bore depth is not available and has been reallocated where possible, the reassigned volumes are indicated within the brackets.

Note that volumes listed above do not include 153 ML of unassigned use due to unknown depths (which is 1,359 ML of entitlements). 2 ML assigned to UTQD has been re-assigned to the QA.

Characteristic & importance	Description	Degree of understanding
Intended aquifer (UTAF and UMTA highlighted blue above)		
Aquifer thickness within GMU (range, based on VAF)	Max: 170.3 m, Average: 74.9 m	High
Aquifer extent	UTAF: Small, local UMTA: Small, local	High
Likelihood of inter-aquifer flow	High	High
Likelihood of groundwater – surface water interaction	Medium	Moderate
Representative Suite	**M_S_1**	**Medium. 33% of GMU extraction occurs within this Suite, which relates to the most relevant GMU aquifer (WSPA Zone 7)**
Current hydrological condition of representative aquifer		
Representative Suite trend	Variable – consistent with long term average rainfall	Moderate – trend is reflective of WSPA Zone 7. Suites M_S_1 (WSPA Zone 2B) and M_S_2 (WSPA Zone 2A and 6) also show similar trends
Groundwater quality (average salinity based on WMIS and CDM Smith spatial segment(s) with highest coverage)	3,346 mg/L 601 – 3,100 mg/L	Moderate – data quite variable Based on WMIS and CDM Smith (2022)
Groundwater yield	0.5 – 5 L/s (based on referenced data; should be much higher based on GHD experience)	Low Based on CDM Smith (2022)
Groundwater levels		
Temporal groundwater level data range	**1970 to 2021**	**High**
Spatial clustering of licensed bores in relation to Suites	**Yes, both M_S_1 and U_AL_2**	**Based on DEECA density mapping and licenced bore data.**
Groundwater use		
Licensed groundwater use	**3,610 ML**	**High (Based on average historical VWA data over 17 years of data)**

Characteristic & importance	Description	Degree of understanding
Minimum historic groundwater use	**6,452 ML**	**High (Based on historical VWA data, year 2006/07)**
Maximum historic groundwater use	**1,924 ML**	**High (Based on historical VWA data, year 2011/12)**
Entitlement (Groundwater allocation)	**12,575 ML**	**High (Based on licenced volumes in 2020/21)**
Significant drivers of groundwater level variability (primary)	**Pumping for irrigation & dairy**	**High**
Secondary drivers of groundwater level variability	Commercial/industrial and urban water supplies	High
Groundwater use profile	Influenced by seasonality	High
External influence	**None identified**	
Groundwater values and risks		
Existing Environmental Values to be protected, relevant to this GMU	Potable water supply Licensed non-potable supply (irrigation, commercial, industrial) Unlicensed non-potable supply (domestic and stock)	
Risks to groundwater values	Direct risks: Drawdown which may affect access to groundwater by existing users Drawdown which may affect seawater instruction	
Indicators used to assess impacts to groundwater	Measured drawdown using pre-determined metrics measured from a pre-determined level for the purpose of this modelling	



Paper Size ISO A3

0 1.5 3 4.5 6

Kilometers

Map Projection: Lambert Conformal Conic
Horizontal Datum: GDA 1994
Grid: GDA 1994 VICGRID94

N

GHD

DEECA
Sustainable yield review - confined aquifers

Koo Wee Rup WSPA
Site location and key features

Project No. **12564066**
Revision No. **0**
Date **16/01/2024**

Figure 108

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Print date: 16 Jan 2024 - 12:51

Data source: DELWP, VicMap, 2022; DELWP, GMUs, 2022; DELWP, SOBN, 2022; GHD, aquifer suites, 2018; DELWP, extraction bores, 2022 Created by: cperyer

11.2 Technical analysis

11.2.1 Hydrograph review and selection of representative Suites for further analysis

Suite hydrographs were generated for the confined Suites for Koo Wee Rup WSPA as shown in Figure 109. The Suite hydrographs show the seasonal fluctuations and hence recovered water levels. All Suite hydrographs shown in Figure 109 do not exhibit a strong increasing or decreasing trend over time.

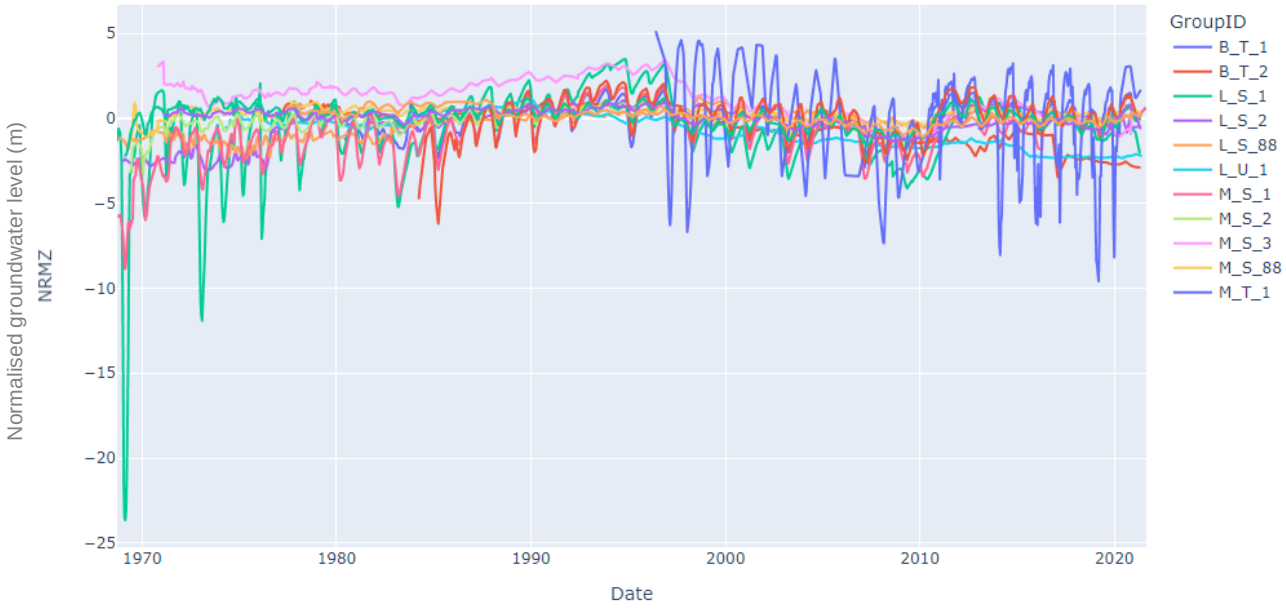


Figure 109 Koo Wee Rup WSPA Suite Hydrographs for all confined aquifers

The representative Suites analysed for this GMU were Suites M_S_1, M_S_2 and M_S_3. The Representative Suites were selected based on the methodology outlined in section 2.6.4 which identified Suite M_S_1 as the most representative followed by M_S_3 then M_S_2. The process is summarised as follows:

- The greatest volume of extraction occurring within the middle aquifer
- The middle aquifer pertains to the UTAF and UMTA which are the intended aquifers for this GMU
- Suite M_S_1 covers 33% of the GMU, M_S_2 covers 26% and M_S_3 covers 9% of the GMU
- Suite M_S_1 has 5 active SOBN bores within the Suite area, M_S_2 has 3 SOBN bores within the Suite area and M_S_3 has 3 SOBN bores within the Suite area
- Suite bores for M_S_1, M_S_2 and M_S_3 are located close to extraction points

The annual recovered Suite hydrograph for the representative Suites for Koo Wee Rup WSPA, M_S_1, M_S_2 and M_S_3 is shown in Figure 110.

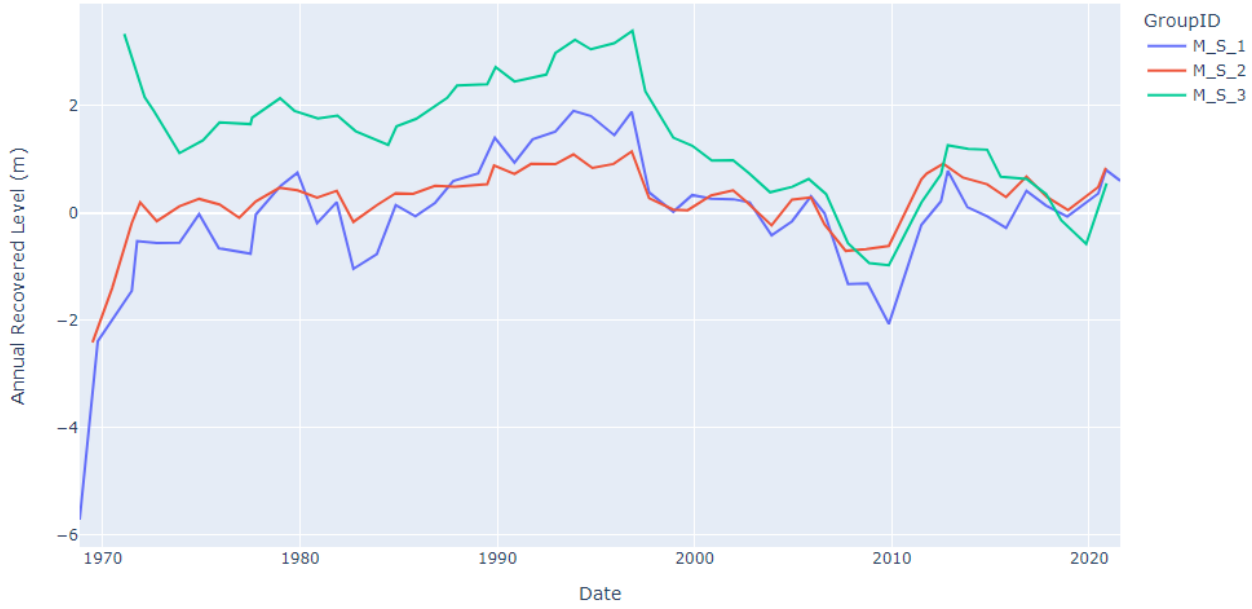


Figure 110 Koo Wee Rup WSPA Annual Recovered Level Suite Hydrograph for representative Suites

11.2.2 Pre-development level

To estimate the pre-development level conditions, GHD reviewed the Suite hydrographs of annual recovered levels and assumed that the maximum levels in the early time series data was the best representation of conditions prior to major development within Koo Wee Rup WSPA for Suites M_S_1 and M_S_2. For Suite M_S_3 the earliest time series data point for the annual recovered levels was the second highest level and occurs prior to extraction, thus this was assumed this was representative of pre-development levels for this Suite.

The pre-development annual recovered levels are taken to be the maximum level in the early time series data for Suite M_S_1 and M_S_2 which equates to 1.88 m for Suite M_S_1 in the year 1996/1997 and 1.14 m for Suite M_S_2 in the year 1996/1997. The pre-development annual recovered levels are taken to be the earliest time series data for Suite M_S_3 which is 3.33 m in the year 1970/1971 (refer further details in section 11.4.3).

11.2.3 Externalities

Through the conceptualisation, no external influence was identified for Koo Wee Rup WSPA.

11.2.4 Hindcasting

Groundwater use data for Koo Wee Rup WSPA is available from 1974/1975 to 2020/2021. As groundwater data is available for the extraction period, no hindcasting is needed when running models without spatial distribution. However, as the spatial distribution extraction dataset only dates back to 2009/2010 this needs to be hindcasted back to 1974/1975 for model runs incorporating both spatial distribution and hindcasting. As hindcasting methods H1 and H2 are not applicable to spatial distribution methods, only hindcasting method H3 was applied for Koo Wee Rup WSPA. The hindcasting methodology for method H3 outlined in section 3.3.4.5 was applied to Koo Wee Rup WSPA. A summary of the hindcasting results is shown below.

11.2.4.1 Hindcasting Method 3 (H3)

As Koo Wee Rup WSPA only extraction does not require hindcasting when considering extraction on an annual basis, this method hasn't been applied to obtain a historic extraction value on a GMU basis. However, when taking into account spatial distribution, the extraction dataset commenced in 2009/2010 and thus hindcasting is needed. In this respect, the hindcasting method was applied to hindcast use value back on a bore-by-bore basis.

Four correlations were developed using method H3 as described below and shown in Figure 111:

- Percentage of entitlement vs annual rainfall
- Percentage of entitlement vs two yearly average annual rainfall
- Percentage of entitlement vs annual summer period rainfall
- Percentage of entitlement vs annual irrigation period rainfall

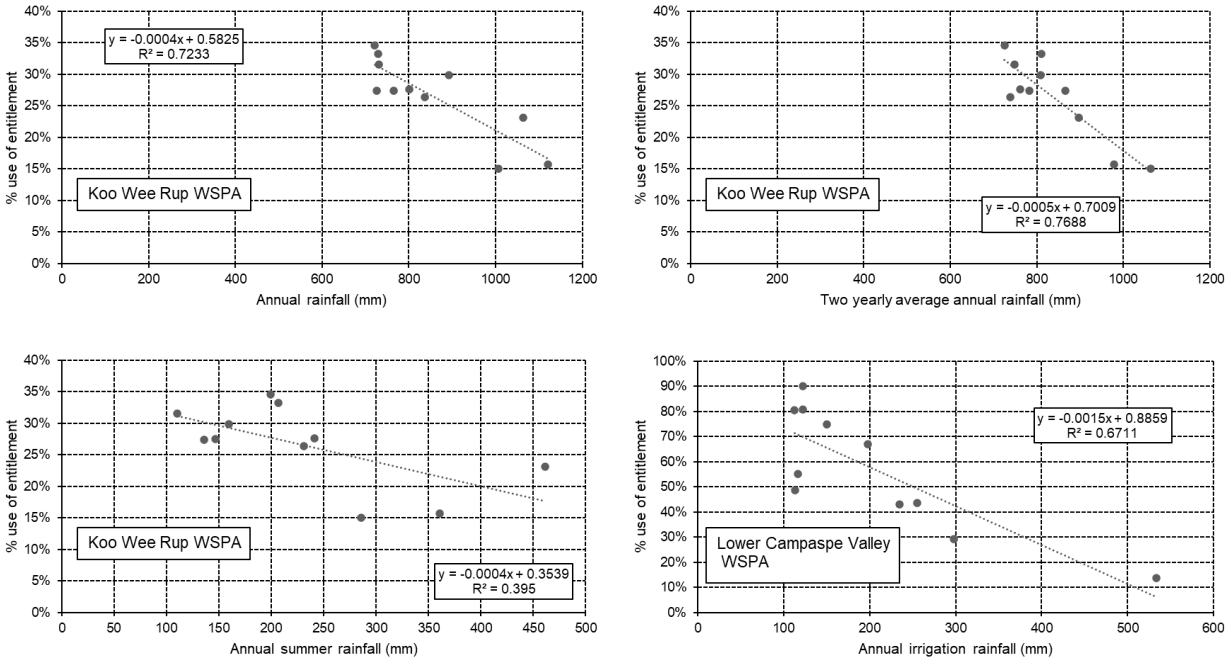


Figure 111 Koo Wee Rup WSPA: Hindcast method 3 correlations

The best goodness-of-fit result was shown to be the correlation of the two yearly average annual rainfall; this correlation was used for the H3 modelling combined with spatial distribution methods.

11.2.4.2 Comparison

A comparison of the hindcasting and the recorded datasets is shown in Figure 112 back to 1974/1975. There are years when the hindcasting method produces a relatively good estimate with a variation from the recorded of around 20 ML. However, prior to 1994, the hindcasting method estimate underestimates groundwater use.

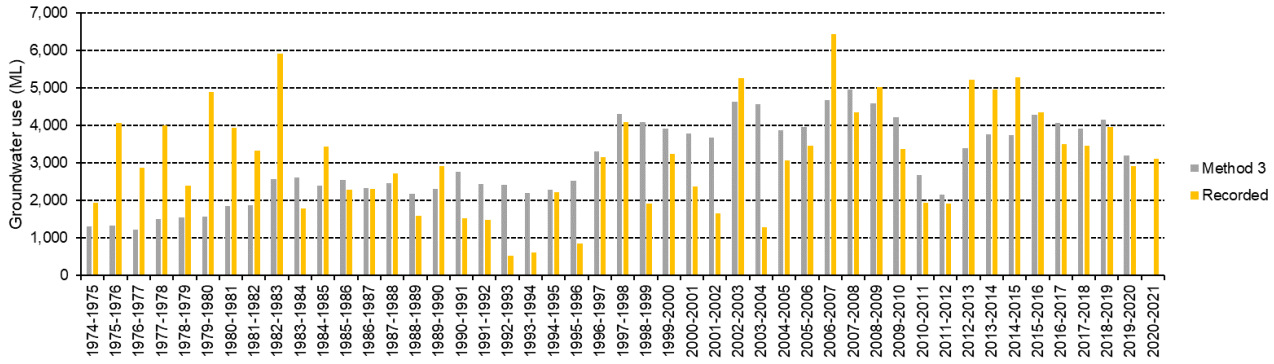


Figure 112 Koo Wee Rup WSPA: Comparison of hindcasting over recorded use period – Koo Wee Rup WSPA only extraction

11.3 Modelling

11.3.1 Model inputs

A number of different models were run based on the various model inputs developed and combinations of these. Table 48 summarises these combinations of model inputs run for Koo Wee Rup WSPA. Model runs highlighted blue indicate they were run with annual extraction and grey indicates they were run using two yearly average annual extraction.

Table 48 Koo Wee Rup WSPA: summary of model inputs

Model input	Model runs																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Annual recovered levels for representative Suites (M_S_1, M_S_2 and M_S_3)	✓	✓												✓	✓	✓			✓
Annual extraction – Koo Wee Rup WSPA only	✓																		
Two yearly average annual extraction – Koo Wee Rup WSPA only		✓																	
Annual extraction – Koo Wee Rup WSPA and Externalities																			
Two yearly average annual extraction – Koo Wee Rup WSPA and Externalities																			
H1 annual extraction – Koo Wee Rup WSPA only																			
H1 annual extraction – Koo Wee Rup WSPA and Externalities																			
H2 annual extraction – Koo Wee Rup WSPA only																			
H2 annual extraction – Koo Wee Rup WSPA and Externalities																			
H3 annual extraction – Koo Wee Rup WSPA only																			
H1 two yearly average annual extraction – Koo Wee Rup WSPA only																			
H1 two yearly average annual extraction – Koo Wee Rup WSPA and Externalities																			
H2 two yearly average annual extraction – Koo Wee Rup WSPA only																			
H2 two yearly average annual extraction – Koo Wee Rup WSPA and Externalities																			
S1 annual extraction – Koo Wee Rup WSPA only														✓					
S2 annual extraction – Koo Wee Rup WSPA only															✓				

Model input	Model runs																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
S3 annual extraction – Koo Wee Rup WSPA only																✓			
S1 annual extraction and H1 annual extraction – Koo Wee Rup WSPA only																			
S2 annual extraction and H2 annual extraction – Koo Wee Rup WSPA only																			
S3 annual extraction and H3 annual extraction – Koo Wee Rup WSPA only																			✓

11.3.2 Model calibration and uncertainty analysis

A statistical summary of the model output results for the runs described in Table 48 is presented in Table 49 for the selection of potential representative Suites for Koo Wee Rup WSPA. The column heading for M_S_1 is highlighted blue to indicate that this Suite was selected as the most likely representative Suite as discussed in section 11.2.1. The statistics summarised include four key statistical measures pf the average 95 PPU thickness (95PPU TH), percentage of observed levels within 95 PPU (%Obs in 95 PPU), R^2 and root mean square error (RMSE) as well as the number of annual recovered level observation points (No obs data points) and the range of observed annual recovered levels.

Suite M_S_1

A review of the results and statistical summary for Suite M_S_1 shows that model runs 1 and 2 (highlighted green) show the best results (when considering all four statistical measures) of the six different model input combinations. Model 1 tends to underestimate high recovered levels (see Figure 113) and model 2 tends to underestimate low recovered levels. In reviewing all statistical measures, most variables were similar except for the number of observations within the 95% prediction band given the thickness of the band did not change significantly between model 1 and model 2; thus model 1 was selected as the preferred model to progress to predictive modelling.

Suite M_S_2

A review of the results and statistical summary for Suite M_S_2 shows that model run 14 (highlighted orange) shows the best results (when considering all four key statistical measures) of the six different model input combinations. However, this dataset covers only a small subset of the total annual recovered level data (10 out of a potential 46 data points). Given that model 1 is a much longer dataset which incorporates the period of defined pre-development and has reasonable similar results to model 14. The graphical model output for model run 1 is shown in Figure 114. The model run 1 results show low values for the 95PPU thickness and RMSE which are preferrable but with a relatively low R^2, which indicates a low model correlation with the observed data. However, this is the best result for the Suite and thus model 1 was progressed to predictive modelling.

Suite M_S_3

A review of the results and statistical summary for Suite M_S_3 shows that model run 15 (highlighted orange) shows the best results (when considering all four key statistical measures) of the six different model input combinations. However, this dataset covers only a small subset of the total annual recovered level data (10 out of a potential 46 data points). Model run 1, 2 and 19 all include more than 40 observation points in their models and incorporate the period of defined pre-development; all these models have similar results. Given the other two Suites in Koo Wee Rup WSPA use model run 1 and the limited differences between model run 1, 2 and 19; model 1 is the preferred model to progress to predictive modelling. The graphical model output for this run is shown in Figure 115.

Given the results, modelling was progressed on the basis of adopting model run 1 for Suite M_S_1, Suite M_S_2 and Suite M_S_3.

Table 49 Koo Wee Rup WSPA: summary of model outputs

Suite	Statistic	Model run					
		1	2	14	15	16	19
M_S_1	95PPU TH	2.3	2.18	1.09	1.3	nan	7.52
	%Obs in 95 PPU	97.83	95.65	90	90	0	100
	R^2	56.6	59.3	-0.8	-17.1	-17.1	-413
	RMSE	0.55	0.53	0.31	0.33	0.33	1.9
	No obs data points	46	46	10	10	10	45
	Range of observed levels	4.0	4.0	1.1	1.1	1.1	4.0
M_S_2	95PPU TH	1.35	1.37	0.82	nan	4337.77	2.49
	%Obs in 95 PPU	95.65	95.65	100	0	80	93.33
	R^2	43.4	44.4	54.8	22.3	58.1	-688.2
	RMSE	0.32	0.32	0.16	0.21	0.16	1.21
	No obs data points	46	46	10	10	10	45
	Range of observed levels	1.9	1.9	0.9	0.9	0.9	1.9
M_S_3	95PPU TH	3.74	3.52	3.07	1.32	28.06	3.57
	%Obs in 95 PPU	100	100	100	90	100	93.33
	R^2	32.6	41	73.2	68.6	72.6	27.2
	RMSE	0.9	0.84	0.3	0.32	0.3	0.94
	No obs data points	46	46	10	10	10	45
	Range of observed levels	4.4	4.4	1.8	1.8	1.8	4.4

Notes:
The term ‘nan’ indicates a non-applicable metric, as the 95% prediction interval bands could not be estimated and thus the thickness could not be calculated

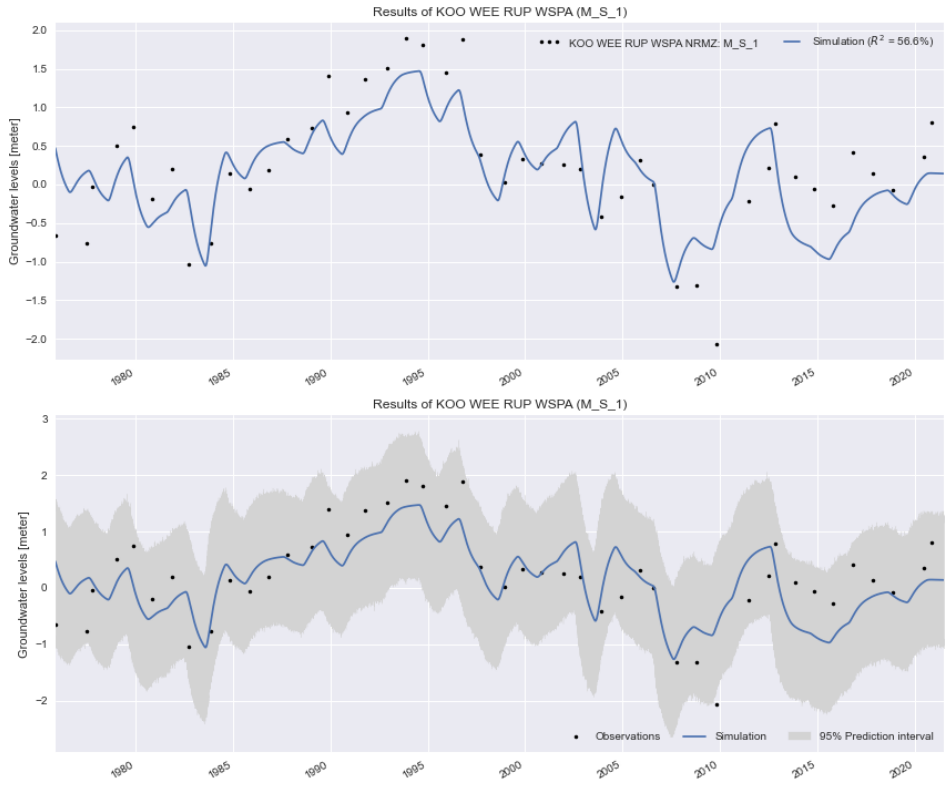


Figure 113 ***Koo Wee Rup WSPA Suite M_S_1: model run 1 (Koo Wee Rup WSPA annual extraction) output hydrographs***

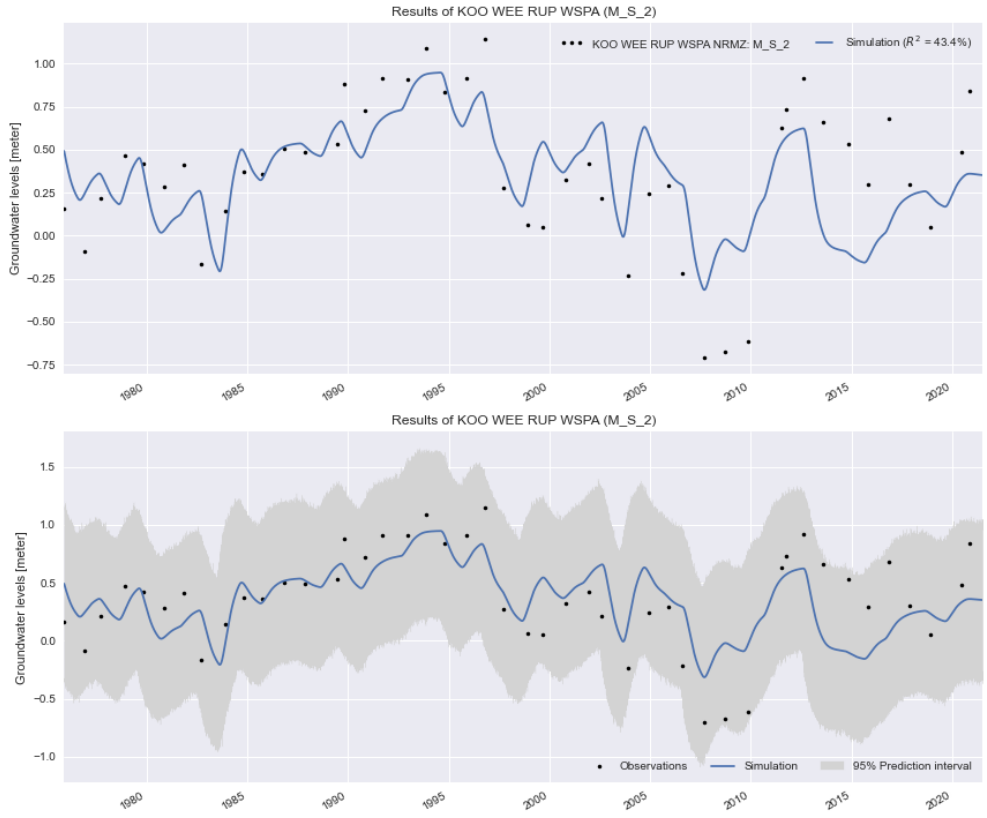


Figure 114 ***Koo Wee Rup WSPA Suite M_S_2: model run 1 (Koo Wee Rup WSPA annual extraction) output hydrographs***

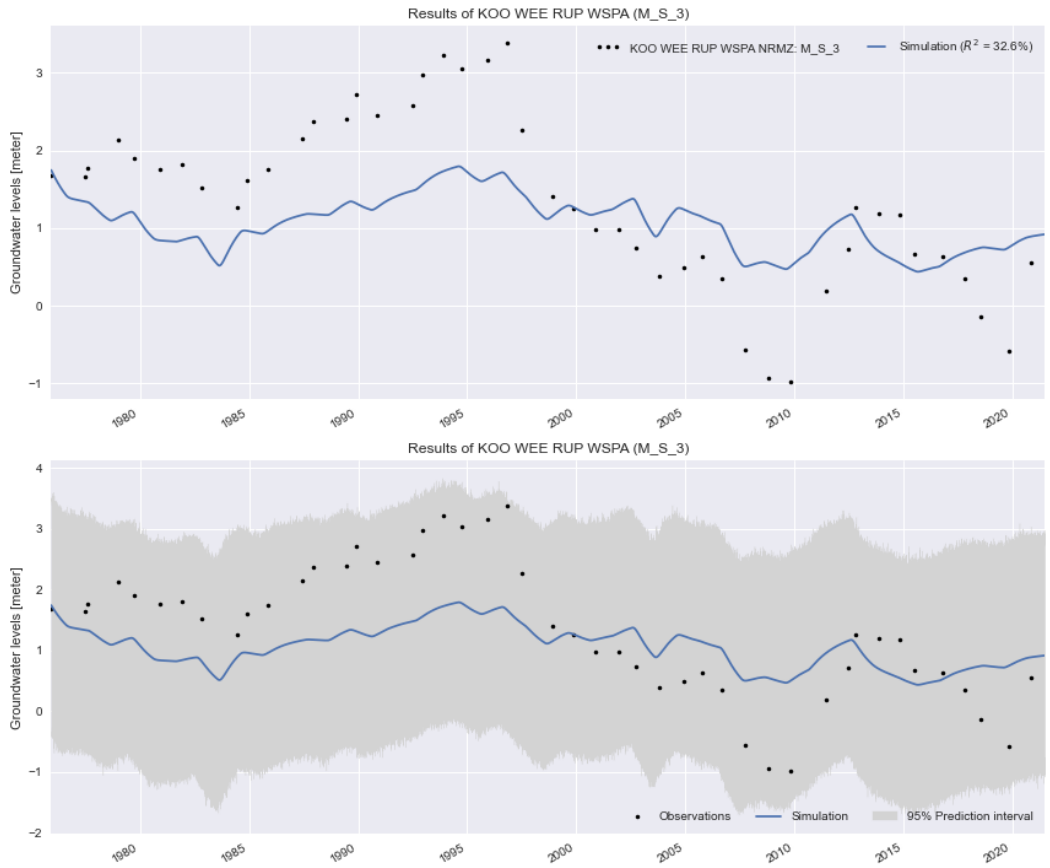


Figure 115 *Koo Wee Rup WSPA Suite M_S_3: model run 1 (Koo Wee Rup WSPA annual extraction) output hydrographs*

11.4 Predictive modelling

11.4.1 Model inputs

The preferred model to run the predictive modelling for Koo Wee Rup WSPA was model run 1 for Suite M_S_1, Suite M_S_2 and Suite M_S_3. To conduct the forecasting for the 19 scenarios discussed in section 3.5, a few factors were required in the calculations; these factors are summarised in Table 50.

Table 50 *Koo Wee Rup WSPA: forecast scenario inputs*

Input item	PCV	Licenced entitlement (based on 2020/21)	Existing use (based on 2020/2021)	Average use over recorded period (from VWA)	Maximum use over recorded period (from VWA, year 2006/07)
Value (ML/year)	12,915	12,566	3,123	3,610	6,452

11.4.2 Predictive model uncertainty

The model output files of the predicted models can be found in the data package provided as part of Appendix E.

MCMC predictions were undertaken on each of the forecasted scenarios for each of the three Suites. An example of one of the outputs is presented in Figure 116 for scenario 4. As shown in Figure 116, the uncertainty of the model prediction increases as the model predicts further into the future. Comparing with the graphical output for the same scenario, the MCMC realisations tend to fall within the 95% prediction interval bands but there are some that lie outside of these bands as shown in Figure 117.

Uncertainty is also accounted for by using 19 forecast scenarios to develop a groundwater use to drawdown relationship (analogous to a Monte Carlo type simulation) where a range of possible outcomes are generated. It is noted however, that the forecast scenarios were not randomly generated, but rather based upon a series of estimated use behaviours.

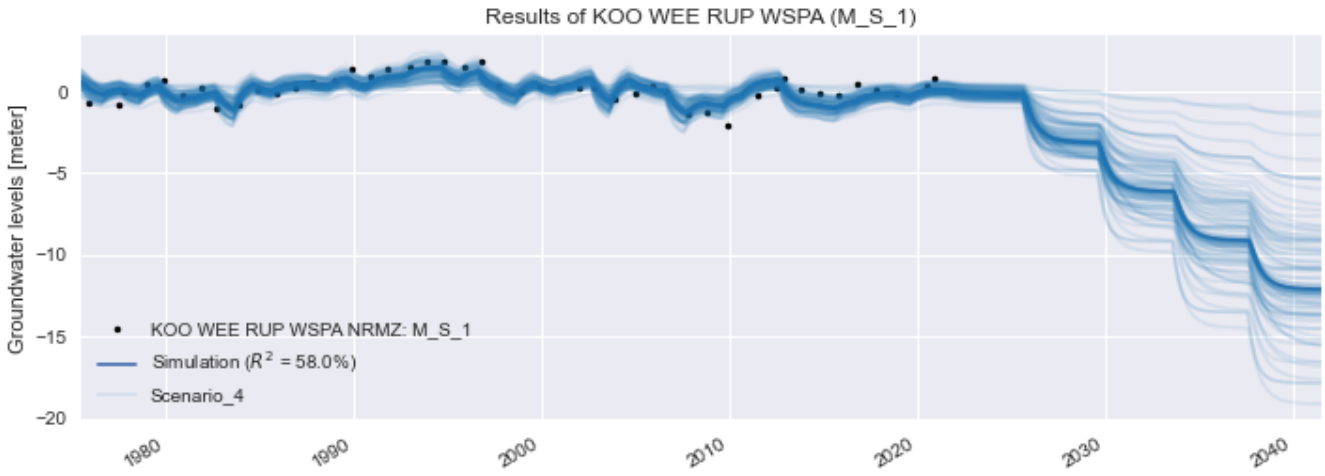


Figure 116 *Koo Wee Rup WSPA: Suite M_S_1 MCMC analysis for Forecast Scenario 4*

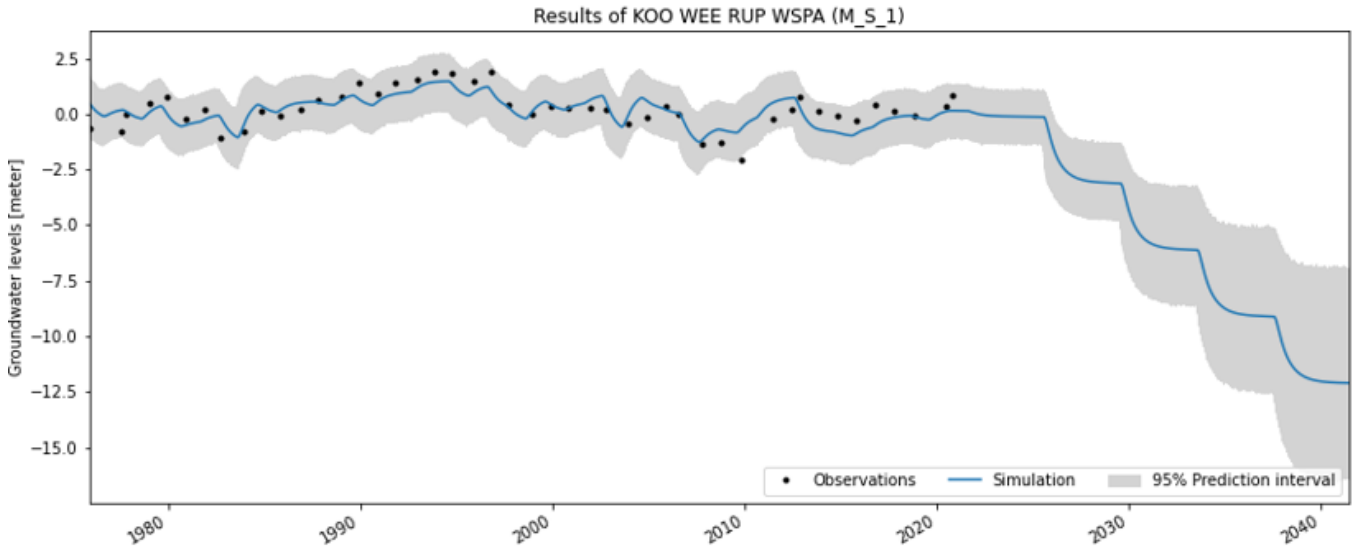


Figure 117 *Koo Wee Rup WSPA: Suite M_S_1 Forecast Scenario 4 with 95% prediction bands*

11.4.3 Extraction vs drawdown

To calculate the drawdown based on the annual recovered levels simulated by the model, the pre-development conditions (pre commencement of extraction) need to be estimated. For Koo Wee Rup WSPA, historic groundwater use is available back to 1974/1975 which aligns with an early period of development in the GMU.

Using the pre-development levels defined in section 11.2.2, the modelled water levels were converted into drawdowns (from this baseline pre-development level) for each of the 19 scenarios. This predevelopment condition is shown in Figure 118 for Suite M_S_1 hydrograph of annual recovered levels. In Figure 118:

- Actual annual groundwater use is represented by the blue column graph between 1974/1975 and 2020/2021
- Forecasted use is represented by the grey columns after 2021/2022
- In the case of Figure 118, the pre-development annual recovered levels are taken to be the maximum reading before the period of drawdown which occurred in 1996/1997 and was 1.9 m
- The modelled forecasted annual recovered levels are represented by the purple line in Figure 118.
- The calibration annual recovered levels are represented by the black line in Figure 118.

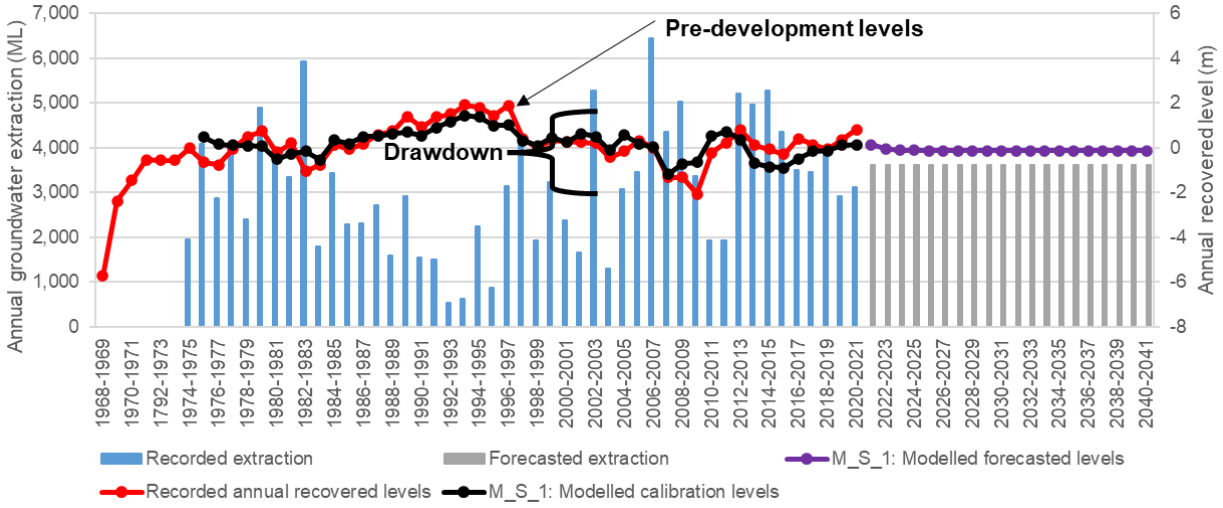


Figure 118 Estimating pre-pumping water levels (example from Suite M_S_1)

For Suite M_S_1, the calculated drawdowns and volumes for each of the scenarios were plotted in individual graphs for each scenario, all scenarios together in the one graph (Figure 119) and a graph of the scenarios for specific time periods (Figure 120) to develop the volume to drawdown relationship. For each scenario, a linear regression was applied and the coefficient of determination (R^2) was calculated. A comparison of each of these graphs shows there is variations in the coefficient of determination between different scenarios, but the slope of the linear regression only varied by 0.0001. The same process was applied for Suite M_S_2 and M_S_3 and again, there was variations in the coefficient of determination between the graphs but the slope of the linear regression generally only varied by 0.0001. As such, the relationship developed using all scenarios was adopted as it best captures this variation between forecast scenarios.

The use-drawdown for all the 19 forecast scenario drawdowns and volumes (both the recorded and forecasted volumes) over each year modelled is shown in Figure 119 for Suite M_S_1 (1976 to 2041), Figure 121 for Suite M_S_2 (1976 to 2041) and Figure 122 for Suite M_S_3 (1976 to 2041). Note the abscissa range of the chart has been clipped and does not show forecast drawdowns for the higher use scenarios (more improbable volumes such as two times the PCV).

Reviewing these figures, the following is noted:

- There should be zero drawdown under zero use and therefore a line of best fit should pass through the origin (0,0) or close to it. Suite M_S_1 and M_I_2 have a y-intercept close to the origin while suite M_S_3 has a much larger y-intercept
- Average use is around 3,000 ML to 4,000 ML, Figure 119, Figure 121 and Figure 122 indicate that where volumes of groundwater use is in this range, the model forecast drawdown tends to occur close to the predicted line of best fit
- For the same annual use, different drawdowns can be obtained as Pastas predicts a water level for each year. For example, Figure 118 shows a scenario where groundwater use remains constant at around 3,600 ML/year over the next 20 years.
- The correlation for groundwater use and drawdown for Suite M_S_1, M_S_2 and M_S_3 is excellent as shown in Figure 119, Figure 121 and Figure 122 respectively
- The various forecast scenarios generally result in data plotting reasonably close together in a linear trend. The 19 forecast scenarios applied to populate the chart is analogous to a Monte Carlo type simulation where a range of possible outcomes are generated. It is noted however, that the forecast scenarios were not randomly generated, but rather based upon a series of estimated use behaviours.

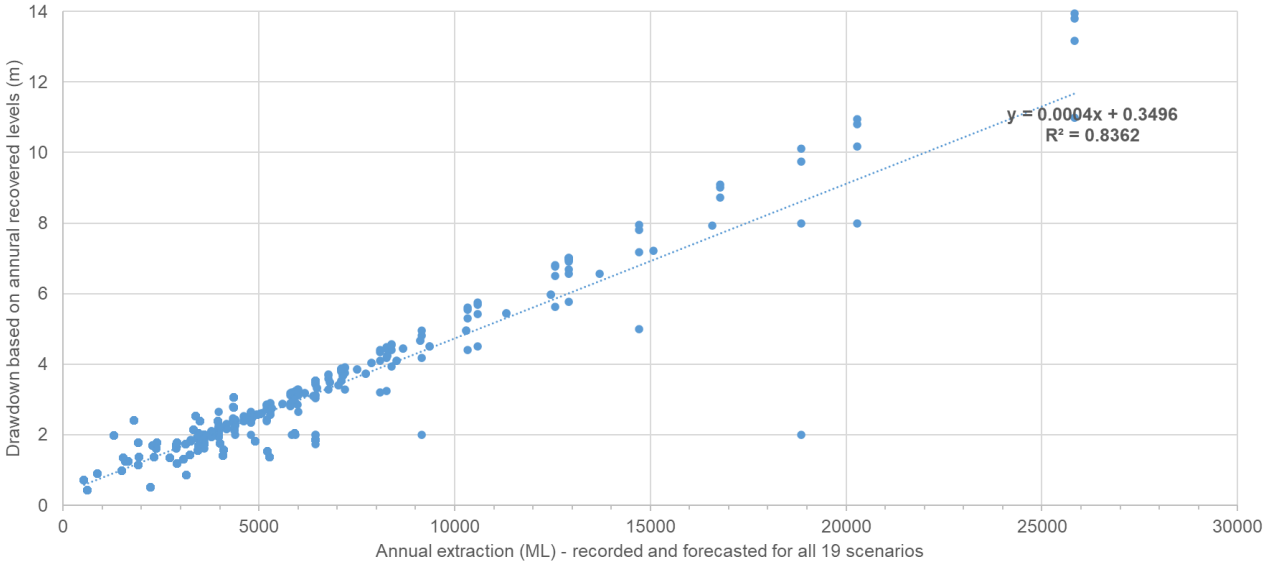


Figure 119 *Koo Wee Rup WSPA Suite M_S_1: Drawdown (on annual recovered levels) and extraction volumes (recorded and forecasted <30,000 ML) for all data between 1976 to 2041 and all forecasted scenarios*

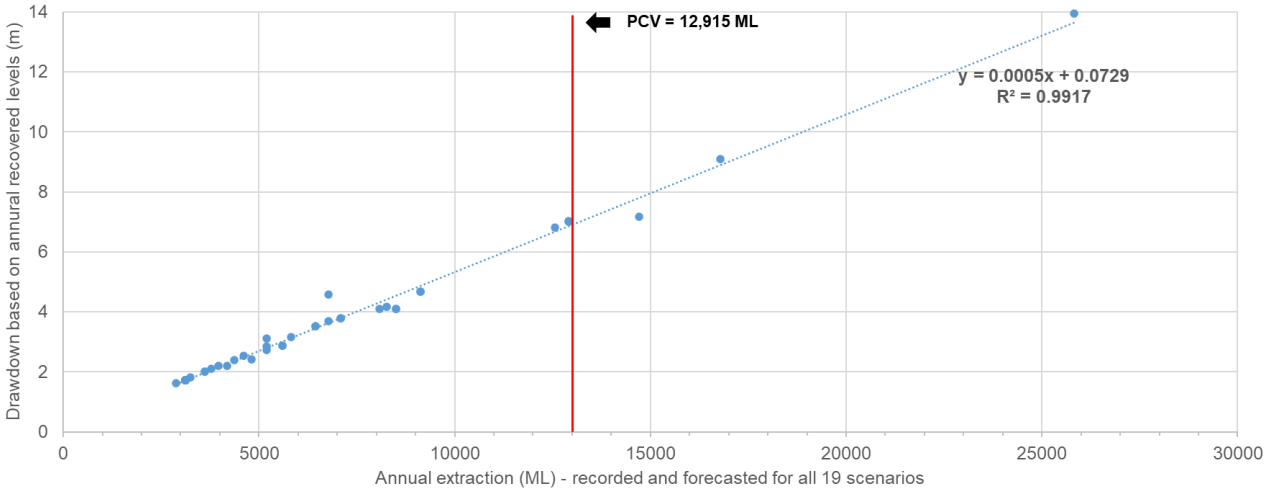


Figure 120 *Koo Wee Rup WSPA Suite M_S_1: Drawdown (on annual recovered levels) and extraction volumes (recorded and forecasted <30,000 ML) for years 2020/2021, 2030/2031 and 2040/2041 for all forecasted scenarios*

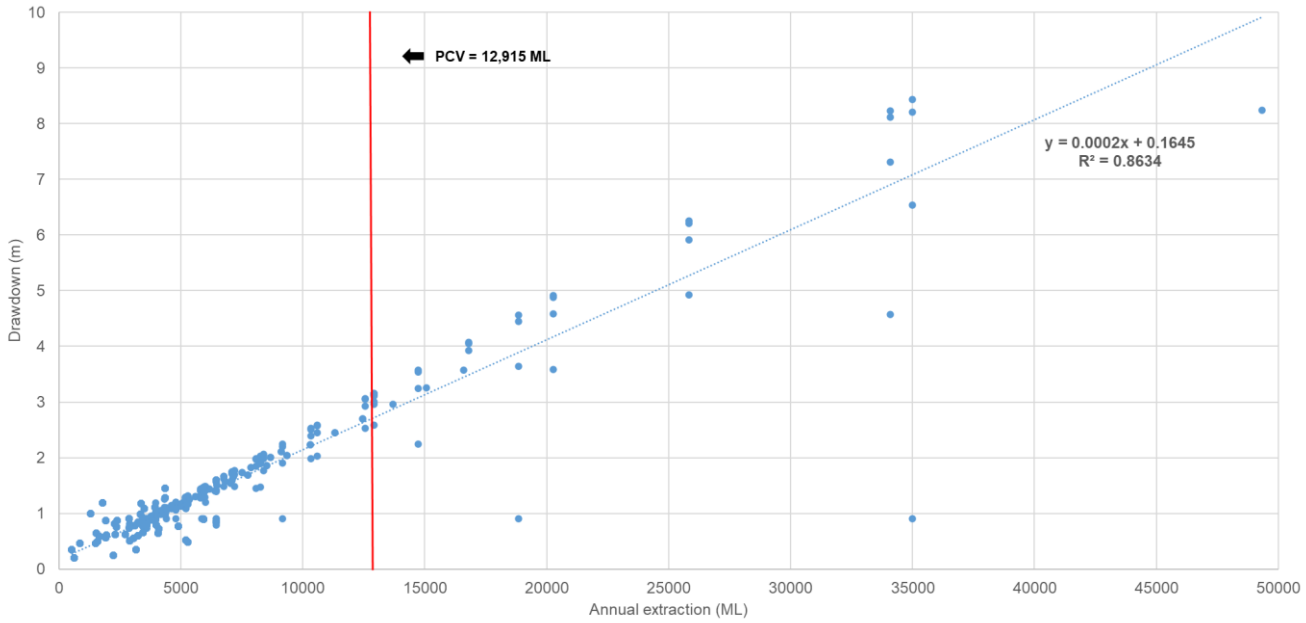


Figure 121 *Koo Wee Rup WSPA Suite M_S_2: Drawdown (on annual recovered levels) and extraction volumes (recorded and forecasted <30,000 ML) for all data between 1976 to 2041 and all forecasted scenarios*

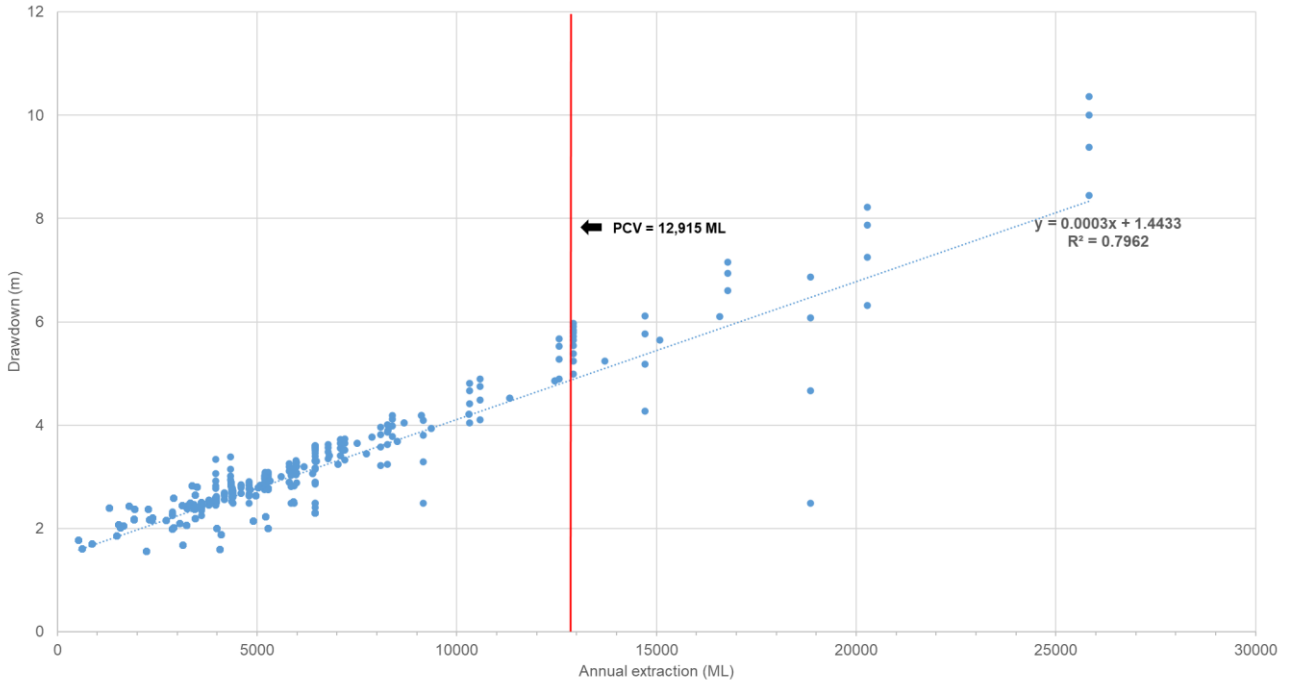


Figure 122 *Koo Wee Rup WSPA Suite M_S_3: Drawdown (on annual recovered levels) and extraction volumes (recorded and forecasted <30,000 ML) for all data between 1976 to 2041 and all forecasted scenarios*

11.5 Sustainability metrics

11.5.1 Application of metrics

Using the use - drawdown relationships developed through the previous step of forecasting aquifer response under a range of use scenarios, groundwater drawdown can be used to compare against metrics that define groundwater resource sustainability.

The application of these metrics and the relationship developed between drawdown based on the Suite annual recovered levels and extraction volume for the whole GMU, which is shown in Table 51 for Koo Wee Rup WSPA Suite M_S_1, Table 52 for Koo Wee Rup WSPA Suite M_I_2 and Table 53 for Koo Wee Rup WSPA Suite M_S_3 (noting Koo Wee Rup WSPA has a current PCV of 12,915 ML/year). As part of the modelling, a 95% prediction interval band was applied to the modelling results. The relationship between drawdown and extraction volumes can also be interrogated at the lower and upper bands of the 95% prediction interval as shown in Table 51 and Figure 123 for Suite M_S_1, Table 52 and Figure 124 for Suite M_S_2 and Table 53 and Figure 125 for Suite M_S_3. Figure 126 shows graphically and spatially by Suite the drawdowns associated with extraction rates.

In comparing the three selected Suites for Koo Wee Rup WSPA, Suite M_S_2 requires almost double the volume to be extracted from the GMU than Suites M_S_1 and M_S_3 to achieve the same level of drawdown. All three Suites show a greater range in the 95% prediction interval estimates as volumes increase.

A comparison of whole of GMU volumes at drawdown intervals provided by DEECA is shown in Table 54 for Suite M_S_1, M_S_2 and M_S_3. Based on Suite M_S_1, 5 m of drawdown is predicted to occur at a groundwater extraction volume of 11,600 ML which could range from 7,500 ML to 18,400 ML based on the 95% prediction intervals. For Suite M_S_2, 5 m of drawdown is predicted to occur at a groundwater extraction volume of 24,200 ML which could range from 21,700 ML to 53,300 ML based on the 95% prediction intervals. For Suite M_S_3, 5 m of drawdown is predicted to occur at a groundwater extraction volume of 11,900 ML which could range from 6,800 ML to 25,600 ML based on the 95% prediction intervals.

Based on Suite M_S_1, 10 m of drawdown is predicted to occur at a groundwater extraction volume of 24,100 ML which could range from 17,500 ML to 35,000 ML based on the 95% prediction intervals. For Suite M_S_2, 10 m of drawdown is predicted to occur at a groundwater extraction volume of 49,200 ML which could range from 46,700 ML to 103,300 ML based on the 95% prediction intervals. For Suite M_S_3, 10 m of drawdown is predicted to occur at a groundwater extraction volume of 28,500 ML which could range from 23,500 ML to 50,600 ML based on the 95% prediction intervals.

Table 51 Relationship of Suite drawdown to GMU extraction for Koo Wee Rup WSPA Suite M_S_1

Volume (ML/year) for whole of GMU	Based on model prediction of Suite M_S_1 annual recovered levels
	Drawdown over 20 years (m) (lower limit to upper limit based on 95% prediction interval band)
30,000	12.3 (8.5 - 16.2)
28,000	11.5 (7.9 - 15.2)
26,000	10.7 (7.3 - 14.2)
24,000	9.9 (6.7 - 13.2)
22,000	9.1 (6.1 - 12.2)
20,000	8.3 (5.5 - 11.2)
18,000	7.5 (4.9 - 10.2)
16,000	6.7 (4.3 - 9.2)
14,000	5.9 (3.7 - 8.2)
12,000	5.1 (3.1 - 7.2)
10,000	4.3 (2.5 - 6.2)
8,000	3.5 (1.9 - 5.2)

Volume (ML/year) for whole of GMU	Based on model prediction of Suite M_S_1 annual recovered levels
	Drawdown over 20 years (m) (lower limit to upper limit based on 95% prediction interval band)
6,000	2.7 (1.3 - 4.2)
4,000	1.9 (0.7 - 3.2)
2,000	1.1 (0.1 - 2.2)
0	0.3 (-0.5 - 1.2)

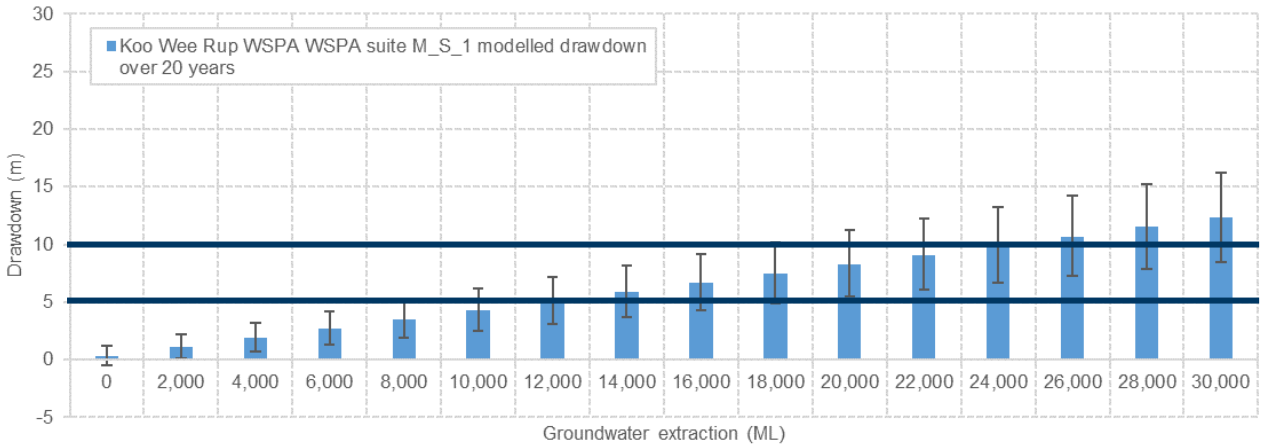


Figure 123 *Koo Wee Rup WSPA Suite M_S_1: Relationship of Suite drawdown to GMU extraction (with error bars showing results of drawdown using levels from model's 95% prediction intervals)*

Table 52 *Relationship of Suite drawdown to **GMU** extraction for Koo Wee Rup WSPA Suite M_S_2*

Volume (ML/year)	Based on model prediction of Suite M_S_2 annual recovered levels
	Drawdown over 20 years (m) (lower limit to upper limit based on 95% prediction interval band)
50,000	10.2 (4.7 - 10.7)
48,000	9.8 (4.5 - 10.3)
46,000	9.4 (4.3 - 9.9)
44,000	9 (4.1 - 9.5)
42,000	8.6 (3.9 - 9.1)
40,000	8.2 (3.7 - 8.7)
38,000	7.8 (3.5 - 8.3)
36,000	7.4 (3.3 - 7.9)
34,000	7 (3.1 - 7.5)
32,000	6.6 (2.9 - 7.1)
30,000	6.2 (2.7 - 6.7)
28,000	5.8 (2.5 - 6.3)
26,000	5.4 (2.3 - 5.9)
24,000	5 (2.1 - 5.5)
22,000	4.6 (1.9 - 5.1)

Volume (ML/year)	Based on model prediction of Suite M_S_2 annual recovered levels
	Drawdown over 20 years (m) (lower limit to upper limit based on 95% prediction interval band)
20,000	4.2 (1.7 - 4.7)
18,000	3.8 (1.5 - 4.3)
16,000	3.4 (1.3 - 3.9)
14,000	3 (1.1 - 3.5)
12,000	2.6 (0.9 - 3.1)
10,000	2.2 (0.7 - 2.7)
8,000	1.8 (0.5 - 2.3)
6,000	1.4 (0.3 - 1.9)
4,000	1 (0.1 - 1.5)
2,000	0.6 (-0.1 - 1.1)
0	0.2 (-0.3 - 0.7)

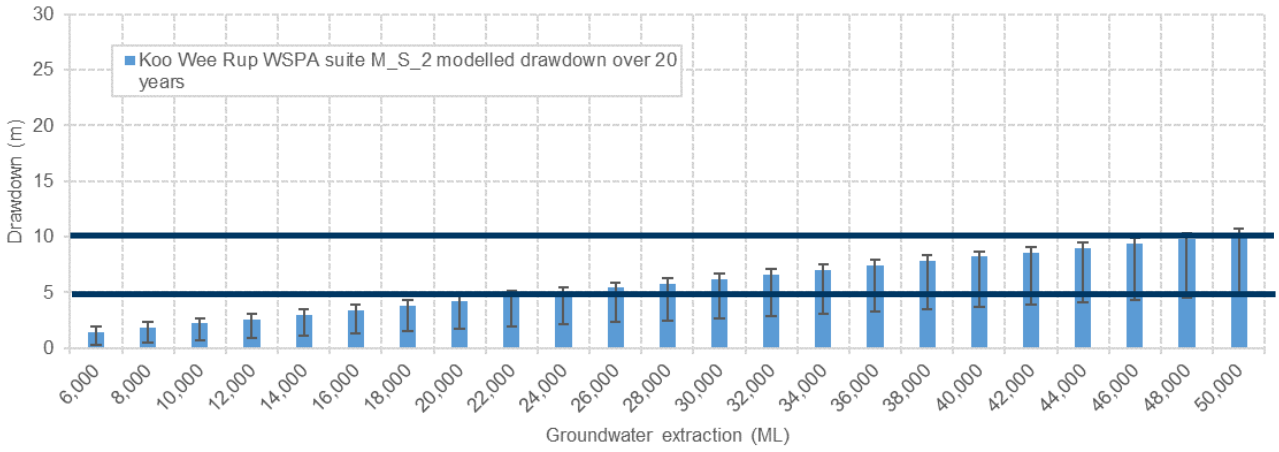


Figure 124 *Koo Wee Rup WSPA Suite M_S_2: Relationship of Suite drawdown toGMU extraction (with error bars showing results of drawdown using levels from model's 95% prediction intervals)*

Table 53 *Relationship of Suite drawdown to GMU extraction for Koo Wee Rup WSPA Suite M_S_3*

Volume (ML/year) for whole of GMU	Based on model prediction of Suite M_S_3 annual recovered levels
	Drawdown over 20 years (m) (lower limit to upper limit based on 95% prediction interval band)
30,000	10.4 (5.9 - 12)
28,000	9.8 (5.5 - 11.4)
26,000	9.2 (5.1 - 10.8)
24,000	8.6 (4.7 - 10.2)
22,000	8 (4.3 - 9.6)
20,000	7.4 (3.9 - 9)
18,000	6.8 (3.5 - 8.4)
16,000	6.2 (3.1 - 7.8)

Volume (ML/year) for whole of GMU	Based on model prediction of Suite M_S_3 annual recovered levels
	Drawdown over 20 years (m) (lower limit to upper limit based on 95% prediction interval band)
14,000	5.6 (2.7 - 7.2)
12,000	5 (2.3 - 6.6)
10,000	4.4 (1.9 - 6)
8,000	3.8 (1.5 - 5.4)
6,000	3.2 (1.1 - 4.8)
4,000	2.6 (0.7 - 4.2)
2,000	2 (0.3 - 3.6)
0	1.4 (-0.1 - 3)

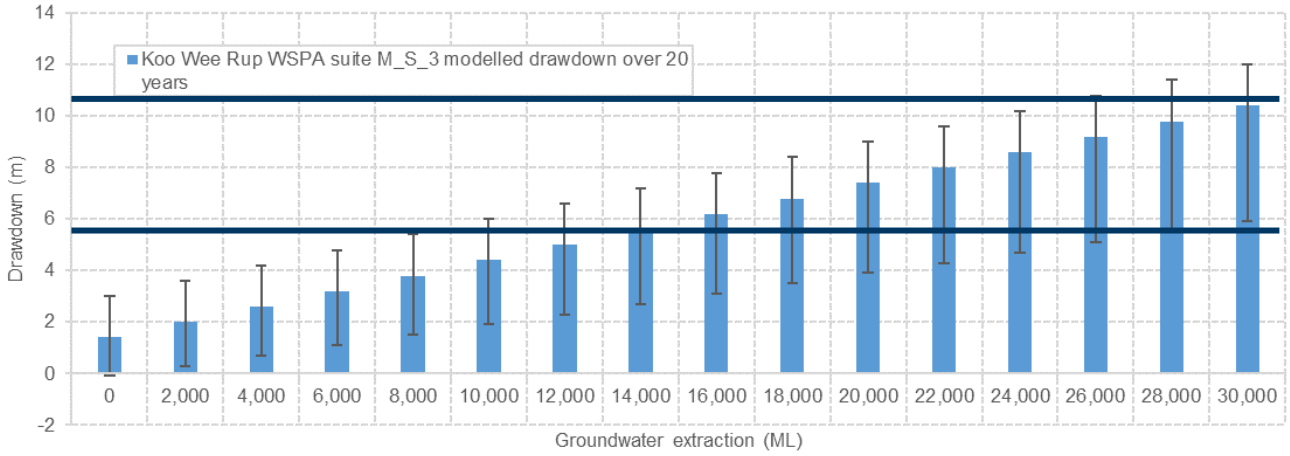
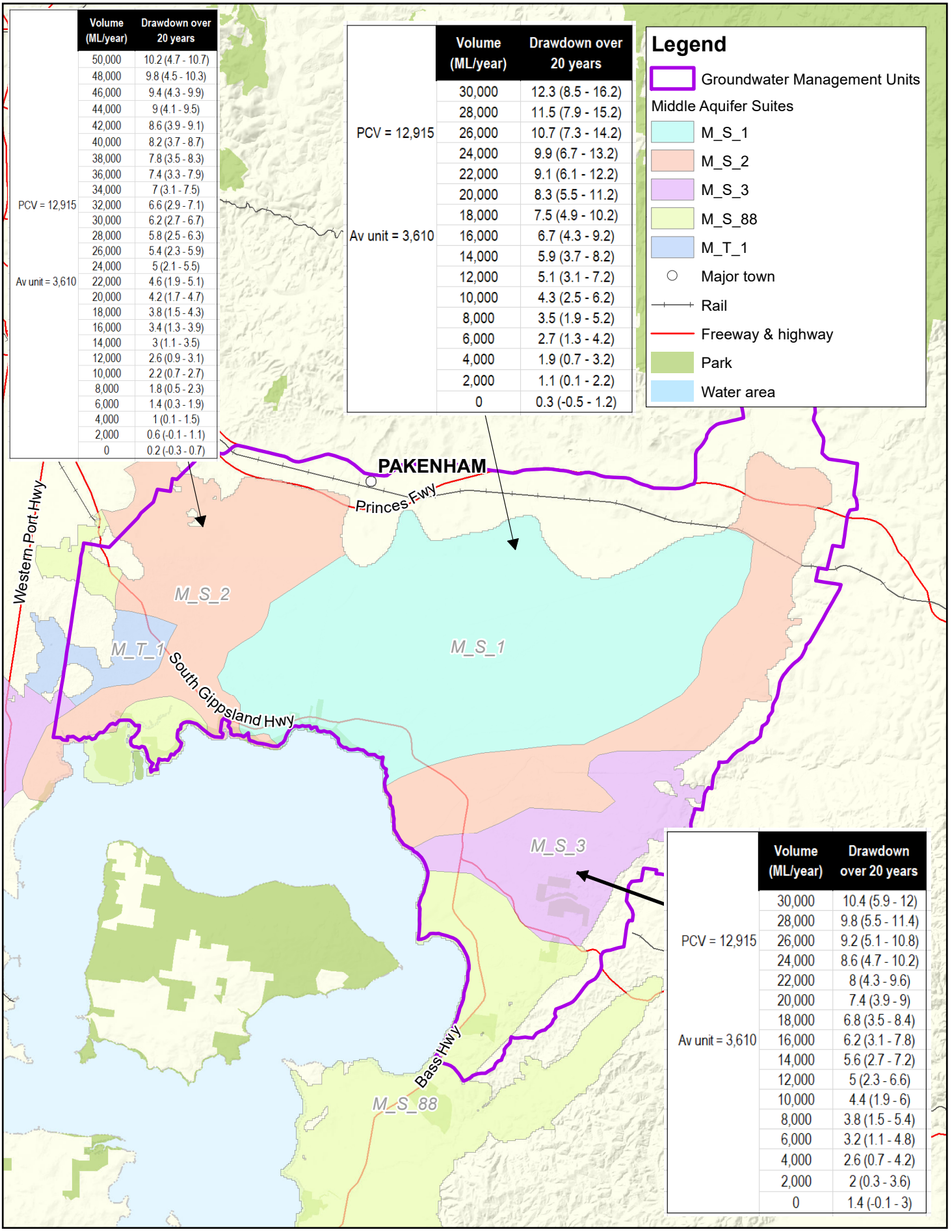


Figure 125 *Koo Wee Rup WSPA Suite M_S_3: Relationship of Suite drawdown to GMU extraction (with error bars showing results of drawdown using levels from model's 95% prediction intervals)*

Table 54 *Predicted GMU volumes for drawdown metrics*

Drawdown (m)	P Predicted volumes for GMU based on Suite M_S_1 drawdowns (lower limit to upper limit)	Predicted volumes for GMU based on Suite M_S_2 drawdowns (lower limit to upper limit)	Predicted volumes for GMU based on Suite M_S_3 drawdown (lower limit to upper limit)
5	11,600 (7,500 – 18,400)	24,200 (21,700 – 53,300)	11,900 (6,800 – 25,600)
10	24,100 (17,500 – 35,000)	49,200 (46,700 – 103,300)	28,500 (23,500 – 50,600)



	Volume (ML/year)	Drawdown over 20 years
	50,000	10.2 (4.7 - 10.7)
	48,000	9.8 (4.5 - 10.3)
	46,000	9.4 (4.3 - 9.9)
	44,000	9 (4.1 - 9.5)
	42,000	8.6 (3.9 - 9.1)
	40,000	8.2 (3.7 - 8.7)
	38,000	7.8 (3.5 - 8.3)
	36,000	7.4 (3.3 - 7.9)
	34,000	7 (3.1 - 7.5)
PCV = 12,915	32,000	6.6 (2.9 - 7.1)
	30,000	6.2 (2.7 - 6.7)
	28,000	5.8 (2.5 - 6.3)
	26,000	5.4 (2.3 - 5.9)
	24,000	5 (2.1 - 5.5)
Av unit = 3,610	22,000	4.6 (1.9 - 5.1)
	20,000	4.2 (1.7 - 4.7)
	18,000	3.8 (1.5 - 4.3)
	16,000	3.4 (1.3 - 3.9)
	14,000	3 (1.1 - 3.5)
	12,000	2.6 (0.9 - 3.1)
	10,000	2.2 (0.7 - 2.7)
	8,000	1.8 (0.5 - 2.3)
	6,000	1.4 (0.3 - 1.9)
	4,000	1 (0.1 - 1.5)
	2,000	0.6 (-0.1 - 1.1)
	0	0.2 (-0.3 - 0.7)

	Volume (ML/year)	Drawdown over 20 years
	30,000	12.3 (8.5 - 16.2)
	28,000	11.5 (7.9 - 15.2)
PCV = 12,915	26,000	10.7 (7.3 - 14.2)
	24,000	9.9 (6.7 - 13.2)
	22,000	9.1 (6.1 - 12.2)
	20,000	8.3 (5.5 - 11.2)
	18,000	7.5 (4.9 - 10.2)
Av unit = 3,610	16,000	6.7 (4.3 - 9.2)
	14,000	5.9 (3.7 - 8.2)
	12,000	5.1 (3.1 - 7.2)
	10,000	4.3 (2.5 - 6.2)
	8,000	3.5 (1.9 - 5.2)
	6,000	2.7 (1.3 - 4.2)
	4,000	1.9 (0.7 - 3.2)
	2,000	1.1 (0.1 - 2.2)
	0	0.3 (-0.5 - 1.2)

	Volume (ML/year)	Drawdown over 20 years
	30,000	10.4 (5.9 - 12)
	28,000	9.8 (5.5 - 11.4)
PCV = 12,915	26,000	9.2 (5.1 - 10.8)
	24,000	8.6 (4.7 - 10.2)
	22,000	8 (4.3 - 9.6)
	20,000	7.4 (3.9 - 9)
	18,000	6.8 (3.5 - 8.4)
Av unit = 3,610	16,000	6.2 (3.1 - 7.8)
	14,000	5.6 (2.7 - 7.2)
	12,000	5 (2.3 - 6.6)
	10,000	4.4 (1.9 - 6)
	8,000	3.8 (1.5 - 5.4)
	6,000	3.2 (1.1 - 4.8)
	4,000	2.6 (0.7 - 4.2)
	2,000	2 (0.3 - 3.6)
	0	1.4 (-0.1 - 3)

Paper Size ISO A3

0 2 4 6 8

Kilometers

Map Projection: Lambert Conformal Conic
Horizontal Datum: GDA 1994
Grid: GDA 1994 VICGRID94

N

GHD

DEECA
Sustainable Yields
Confined Aquifers

Project No. **31-12564066**
Revision No. **0**
Date **15/01/2024**

KOO WEE RUP WSPA: KEY SUITES VOLUME VS DRAWDOWN

FIGURE 126

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Print date: 16 Jan 2024 - 12:20

Data source: DELWP, VicMap, 2022; DELWP GMU locations, 2022; SKM, suite obs bore locations, 2013; DELWP, extraction bore locations, 2022; GHD, aquifer suites, 2018. Created by: cperyer

11.6 GMU summary

11.6.1 Findings

Koo Wee Rup WSPA primarily relates to the Brighton Group/Baxter Formation Aquifers (UTAF) and the Batesford Limestone/Sherwood Formation/Yallock Formation (UMTA). Within Koo Wee Rup WSPA, groundwater is predominately extracted from these aquifers for irrigation and dairy purposes. The UTAF and UMTA fall within the middle aquifer Suites, which at Koo Wee Rup WSPA are Suite M_S_1 (33%), Suite M_S_2 (26%), Suite M_S_3 (9%), Suite M_S_88 (8%) and Suite M_T_1 (2%), providing a total coverage of 78%. The identified representative Suites are Suite M_S_1 (most preferred), Suite M_S_2 and Suite M_S_3. The Suite hydrographs for the representative Suites do not show an increasing or decreasing trend, but do exhibit seasonal fluctuations and thus recovered water levels, which were adopted for the assessment. No external influences were identified for Koo Wee Rup WSPA as part of the conceptualisation.

Application of two yearly annual average extraction, instead of annual average, generally showed similar results across the Suites based on the statistical analysis across the model runs. The application of spatial distribution produced poorer model fit statistics than the model run using just the annual recorded groundwater usage for Suite M_S_1, but variably improved the model fit statistics for Suites M_S_2 and M_S_3 depending on the type of spatial distribution methodology applied. However, the spatial distribution methodology uses a reduced dataset and does not incorporate the time of pre-development.

Based on an assessment of all model runs, the model run 1 was selected for all three for Suites of annual extraction with the annual recovered levels was adopted for predictive modelling.

The pre-development levels were defined for the representative Suites based on either the early time series Suite data for the annual recovered levels (Suite M_S_3) or the maximum levels prior to the commencement of the main drawdown period (Suite M_S_1 and M_S_2). This resulted in pre-development levels of 1.9 m for Suite M_S_1, 1.1 m for Suite M_S_2 and 3.3 m for Suite M_S_3. The drawdowns were calculated based on these pre-development levels and the simulated levels from each of the 19 forecast scenarios.

The models for Suites M_S_1 and M_S_2 were assessed as having a “Good” model applicability rating and Suite M_S_3 was assessed as having a “Moderate” rating using the criteria outlined in section 5.2. Suite M_S_1 was considered the most representative for Koo Wee Rup WSPA.

The volumes estimated for a given drawdown for each Suite is shown below.

Drawdown (m)	P Predicted volumes for GMU based on Suite M_S_1 drawdowns (lower limit to upper limit)	Predicted volumes for GMU based on Suite M_S_2 drawdowns (lower limit to upper limit)	Predicted volumes for GMU based on Suite M_S_3 drawdown (lower limit to upper limit)
5	11,600 (7,500 – 18,400)	24,200 (21,700 – 53,300)	11,900 (6,800 – 25,600)
10	24,100 (17,500 – 35,000)	49,200 (46,700 – 103,300)	28,500 (23,500 – 50,600)

11.6.2 Limitations

In addition to the limitations applicable to all the 25 GMUs discussed in section 1.8, the following Koo Wee Rup WSPA specific limitations have been identified:

- The licenced bore dataset provided by DEECA has 7% of bores assigned to Koo Wee Rup WSPA with no depth data and thus couldn’t be assigned to a VAF layer and in turn Suite. These bores were assigned to an aquifer in order to assist with the determination of the representative Suite. However, this data was not used in the model analysis.
- The spatial dataset used for the modelling is only available to the year 2019/2020. To account for this, annual recorded data from Victorian Water Accounts for the year 2020/2021 has been assigned to bores based on the method described in section 3.5.
- Model calibration for Suite M_S_1 was completed using a groundwater extraction range of approximately 600-6,500 ML/year (below the current PCV of 12,915 ML/year, or around 50% of the PCV)

- The greater the proposed extraction rates beyond this calibration range the more potential for drawdown forecast errors. In this GMU drawdown prediction for extraction volumes up to 4 times the calibration range are being made to meet the 10m drawdown metric.
- Further checks and potential re-calibration may be required as extraction rates increase for this GMU
- Suite M_S_3 does not capture full range of drawdown and thus has a larger intercept. However, this is not preferred Suite.

11.6.3 Recommendations

In addition to the recommendations applicable to all the 25 GMUs discussed in section 32, the following Koo Wee Rup WSPA specific recommendations have been identified:

- The licenced bore dataset provided by DEECA has 7% of bores assigned to Koo Wee Rup WSPA with no depth data and thus couldn't be assigned to a VAF layer and in turn Suite. It is recommended that DEECA obtains the relevant depth and aquifer monitored data for licenced bores within this GMU.

12. Moorabbin GMA

12.1 Conceptualisation

The hydrogeological conceptualisation elements relevant to this study are summarised in Table 55 and a map of the GMU is presented in

Figure 127. It is noted that a significant volume of information was collated to inform the hydrogeological conceptual understanding of the GMU. The information that is directly relevant to the modelling are in bold or colour coded within Table 55.

Table 55 Moorabbin GMA – Tabulated conceptualisation

GMU summary

The Moorabbin GMA is situated on the eastern side of Port Phillip Bay, covering an area of approximately 130 km^2. The GMA is bound in the north by the Princess Highway, Clayton Road/Boundary Road in the east and Port Phillip Bay in the south and west.

Moorabbin GMA pertains to all formations below the ground surface, but was intended to primarily manage groundwater resources of the Brighton Group (Upper Tertiary Aquifer – fluvial, UTAF) and the sands within the Fyansford Formation (Upper-Mid Tertiary Aquitard, UMTD). The PCV (2,700 ML/year) primarily relates to unconfined aquifers, however, it is recognised that there was a degree of hydraulic connection with the underlying aquifer systems and now all aquifers are considered (with deeper formation utilised to a lesser extent).

Groundwater in the Moorabbin GMA is extracted predominately for golf course irrigation, stock and domestic purposes and market gardens.

Hydrostratigraphy summary

Aquifer	Formation	Relevant Suites (% coverage of GMU)	% of GMU covered by Suites	Number of SON bores	Groundwater use	Use volumes ML (2019/20)	Entitlement volumes ML (2019/20)	Understanding (Low, Medium, High)
Upper	Undifferentiated sediments (QA)	-	-	0	NA	0	0	Low
Middle	Brighton Group/Baxter Sandstone (UTAF)	M_T_1 (1%), M_T_2 (7%), M_T_3 (92%)	100%	6	Irrigation, dewatering, domestic, stock	479	1,557	Moderate
	Fyansford Formation (UMTD)	-	-	1	Irrigation, domestic, stock	0	0	Low
Lower	Werribee Formation (LTA)	L_U_1 (45%)	45%	0	Irrigation	73	176	Low
	Mornington Volcanics (LTB)	-	-	0	Irrigation	0	0	Low
Basement	Basement rocks (BSE)	-	-	0	Irrigation, commercial, industrial, domestic, stock	184	1,306	Low

Note that volumes listed above are based on the DEECA provided licenced bore dataset with associated VAF layers. Bores have been assigned to a VAF layer based on bore depth where available. In some instances, bore depth is not available and has been reallocated where possible, the reassigned volumes are indicated within the brackets.

Note that volumes listed above do not include 79 ML of unassigned use due to unknown depths (241 ML of entitlement).

Characteristic and importance	Description	Degree of understanding
Intended aquifer		
Aquifer thickness within GMU (range, based on VAF)	Max: 46 m, Average: 19 m	High
Aquifer extent	Small, local	High
Likelihood of inter-aquifer flow	High	Low
Likelihood of groundwater – surface water interaction	Low	Low
Representative Suite	**M_T_3**	**Low. 39% of GMU extraction occurs within this aquifer, which relates to the most relevant GMU aquifer. This Suite covers 92% of the GMU.** **Likely issue with bore data since 52% of extraction does not occur within defined/relevant Suites**
Current hydrological condition of representative aquifer		
Representative Suite trend	Decreasing – consistent with long term average rainfall	High GHD (2018)
Groundwater quality (average salinity based on WMIS and CDM Smith spatial segment(s) with highest coverage)	2,049 mg/L (WMIS) 1,201 – 3,100 mg/L (CDM Smith (2022)	Moderate Based on WMIS and CDM Smith (2022)
Groundwater yield	0.5 L/s to over 10 L/s	Low. Based on CDM Smith (2022) and GHD experience
Groundwater levels		
Temporal groundwater level data range	**1973-2021**	**High**
Spatial clustering of licensed bores in relation to Suites	No	Based on DEECA density mapping and licenced bore data.
Groundwater use		
Licensed groundwater use	**1,096 ML**	**High (Based on average historical VWA data over 15 years)**
Minimum historic groundwater use	545 ML	High (Based on historical VWA data, year 2010/11)
Maximum historic groundwater use	**1,987 ML**	**High (Based on historical VWA data, year 2006/07)**
Entitlement (Groundwater allocation)	**2,624 ML**	**High (Based on licenced volumes in 2020/21)**
Significant drivers of groundwater level variability (primary)	**Pumping for irrigation**	**Moderate**
Secondary drivers of groundwater level variability	Pumping for stock or domestic use	Moderate
Groundwater use profile	Seasonal (~Oct-Apr irrigation season)	Low
External Influence	**None identified**	

Characteristic and importance	Description	Degree of understanding
Groundwater values and risks		
Existing Environmental Values to be protected, relevant to this GMU	Potable water supply Licensed non-potable supply (irrigation, commercial, industrial Unlicensed non-potable supply (domestic and stock)	
Risks to groundwater values	Direct risks: – Drawdown which may affect access to groundwater by existing users – Saltwater intrusion	
Indicators used to assess impacts to groundwater	– Measured drawdown using pre-determined metrics measured from a pre-determined level for the purpose of this modelling	

Legend

Extraction bores by aquifer
- UTAF (105)
- UMTD (108)
- LTA (111)
- LTBA (112)

BSE (114) (but assumed to be LTA)

No depth (assumed to be middle aquifer)

SOBN (by aquifer)
- UTAF
- UMTD

Middle suite bore
- M_ID
- M_T_1
- M_T_2
- M_T_3

Middle aquifer suite
- M_T_1
- M_T_2
- M_T_3

Lower aquifer suite
- L_U_1

Groundwater Management Unit (GMU)

Town

Rail

Freeway & highway

Major road

Minor road

River

Stream

Burwood Hwy

Burwood Hwy

ST KILDA

Princes Hwy

M_T_3

Monash Fwy

OAKLEIGH

North Rd

BRIGHTON

Wellington Rd

Moorabbin GMA

MOORABBIN

M_T_2

SANDRINGHAM

M_T_1

L_U_1

Nepean Hwy

MORDIALLOC

Paper Size ISO A3

0 0.4 0.8 1.2 1.6

Kilometers

Map Projection: Lambert Conformal Conic
Horizontal Datum: GDA 1994
Grid: GDA 1994 VICGRID94

N

GHD

DEECA
Sustainable yield review - confined aquifers

Moorabbin GMA
Site location and key features

Project No. **12564066**
Revision No. **0**
Date **16/01/2024**

Figure 127

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Print date: 16 Jan 2024 - 12:40

Data source: DELWP, VicMap, 2022; DELWP, GMUs, 2022; DELWP, SOBN, 2022; GHD, aquifer suites, 2018; DELWP, extraction bores, 2022 Created by: cperyer

12.2 Technical analysis

12.2.1 Hydrograph review and selection of representative Suites for further analysis

Suite hydrographs were generated for the relevant Suites for Moorabbin GMA as shown in Figure 128. Generally, the hydrographs for Suite M_T_1 and Suite M_T_2 show a trend of seasonal fluctuation and thus annual recovered levels, with Suite M_T_1 showing fluctuations in the order of 10 m. The hydrographs for Suite M_T_3 and Suite L_U_1 show less seasonal variability.

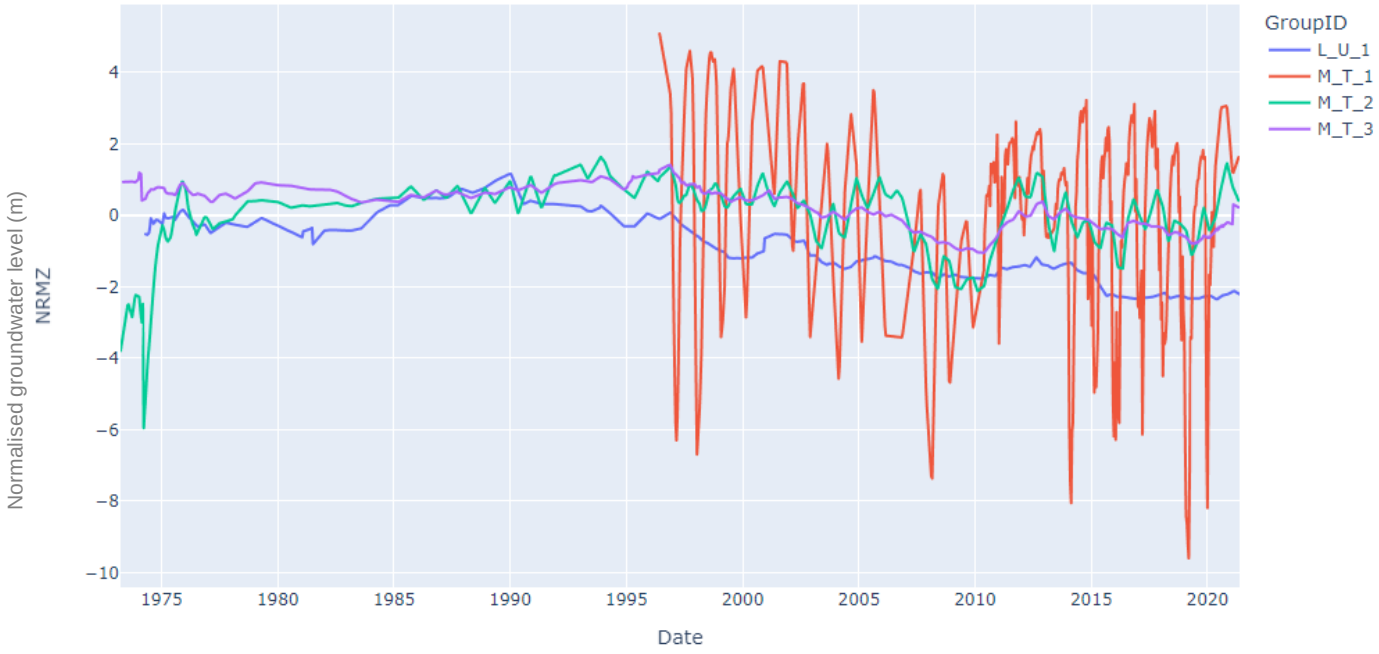


Figure 128 Moorabbin GMA Suite Hydrographs for all confined aquifers

The representative Suites analysed for this GMU were Suites M_T_2 and M_T_3. The Representative Suites were selected based on the methodology outlined in section 2.6.4 which identified Suite M_T_3 as the most representative followed by M_T_2. The process is summarised as follows:

- The greatest volume of extraction occurring within the Middle Aquifer
- The Middle Aquifer pertains to the UTAF, which is the intended aquifer of the GMU
- Suite M_T_1 covers 1% of the GMU, Suite M_T_2 covers 7% of the GMU and Suite M_T_3 covers 92% of the GMU providing a total coverage of 100%
- Suite M_T_2 has four active SOBN bores and Suite M_T_3 has one active SOBN bore and Suite M_T_1 has two active SOBN bores
- Suite M_T_1 bores are close to extraction points and one bore for Suite M_T_2 is close to an extraction point

The annual recovered Suite hydrographs for the representative Suites for Moorabbin GMA are M_T_2 and M_T_3 and are shown in Figure 129.

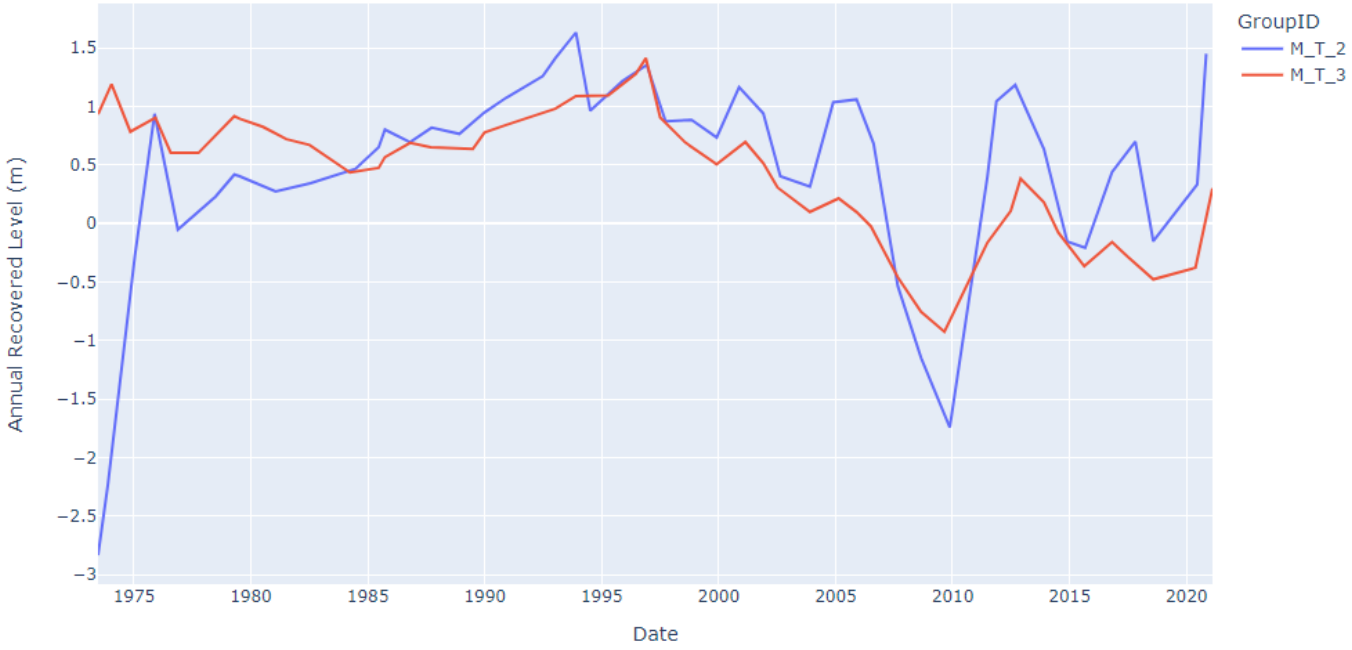


Figure 129 Moorabbin GMA Annual Recovered Level Suite Hydrographs for representative Suites

12.2.2 Pre-development level

To estimate the pre-development level conditions, GHD reviewed the Suite hydrographs of annual recovered levels and assumed that the maximum levels in the early time series data was the best representation of conditions prior to major development within Moorabbin GMA for Suite M_T_2. For Suite M_T_3 the second earliest time series data point for the annual recovered levels was one of the highest recorded annual recovered levels and occurs during a period of low extraction, thus this was assumed this was representative of pre-development levels for this Suite.

The pre-development annual recovered levels are taken to be the maximum level in the early time series data for Suite M_T_2 which equates to 1.63 m in the year 1993/1994. The pre-development annual recovered levels are taken to be the second earliest time series data for Suite M_T_3 which is 1.19 m in the year 1973/1974(refer further details in section 12.4.3).

12.2.3 Externalities

Through the conceptualisation, no external influence was identified for Moorabbin GMA.

12.2.4 Hindcasting

Groundwater use data for Moorabbin GMA is available from 2006/2007 to 2020/2021. The hindcasting methodologies outlined in section 3.3.4.5 were applied to Moorabbin GMA. A summary of the hindcasting results is shown in the following sections.

12.2.4.1 Hindcasting Method 1 (H1)

Applying method H1, four different correlations were developed using the annual groundwater extraction as described below and shown in Figure 130:

- Annual rainfall vs annual groundwater extraction at Moorabbin GMA
- Two yearly average annual rainfall vs annual groundwater extraction at Moorabbin GMA
- Annual summer period rainfall vs annual groundwater extraction at Moorabbin GMA
- Annual irrigation period rainfall vs annual groundwater extraction at Moorabbin GMA

Another four correlations were developed based on annual irrigation extraction as described below and shown in Figure 131:

- Annual rainfall vs annual irrigation groundwater extraction at Moorabbin GMA
- Two yearly average annual rainfall vs annual irrigation groundwater extraction at Moorabbin GMA
- Annual summer period rainfall vs annual irrigation groundwater extraction at Moorabbin GMA
- Annual irrigation period rainfall vs annual irrigation groundwater extraction at Moorabbin GMA

As shown in Figure 130, the goodness-of-fit represented by the R^2 is greatest for the annual summer rainfall with annual irrigation groundwater use. When only irrigation groundwater extraction is considered, the goodness-of-fit of groundwater use generally increased. The annual summer rainfall with annual irrigation groundwater use has been adopted for hindcast method H1.

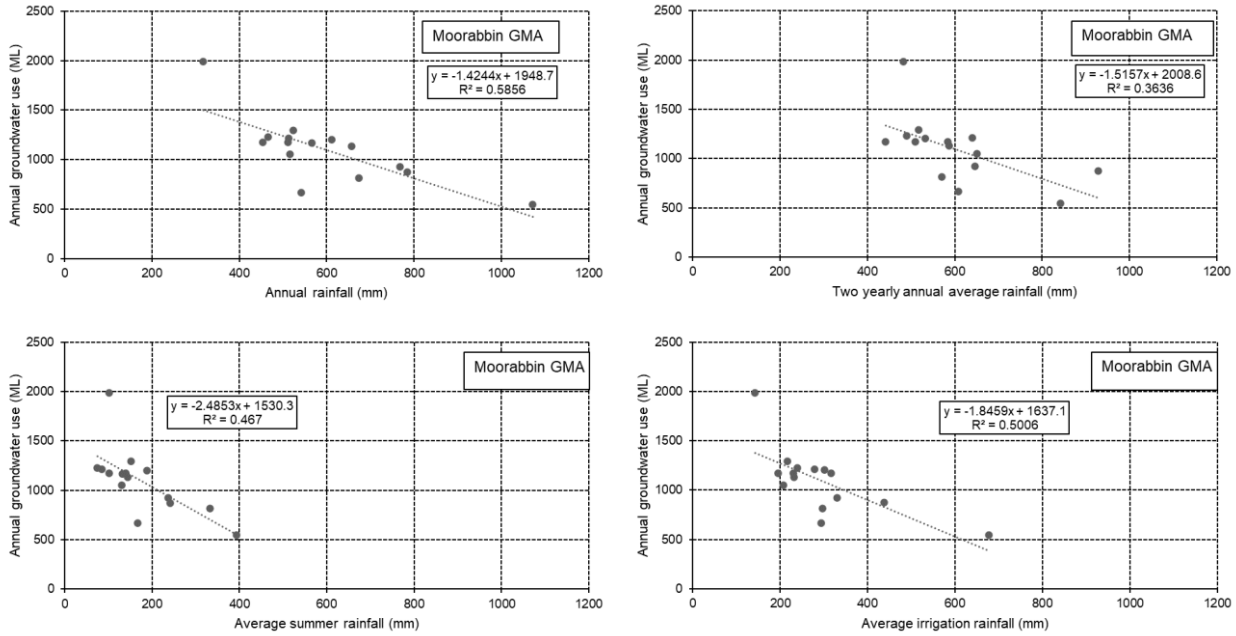


Figure 130 Moorabbin GMA: Hindcast method 1 correlations (Moorabbin GMA annual extraction)

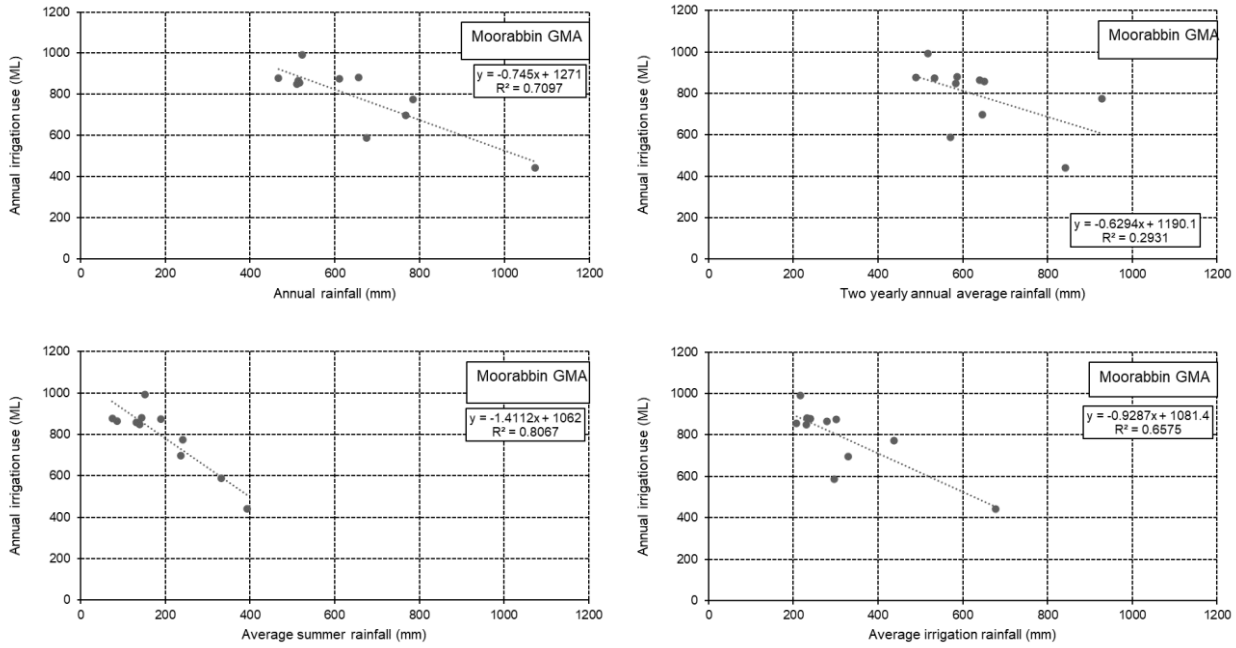


Figure 131 Moorabbin GMA: Hindcast method 1 correlations (Moorabbin GMA annual irrigation extraction)

12.2.4.2 Hindcasting Method 2 (H2)

Similar to method H1, four correlations were developed using method H2 as described below and shown in Figure 132:

- Moorabbin GMA use per Moorabbin GMA bore vs annual rainfall
- Moorabbin GMA use per Moorabbin GMA bore vs two yearly average annual rainfall
- Moorabbin GMA use per Moorabbin GMA bore vs annual summer period rainfall
- Moorabbin GMA use per Moorabbin GMA bore vs annual irrigation period rainfall

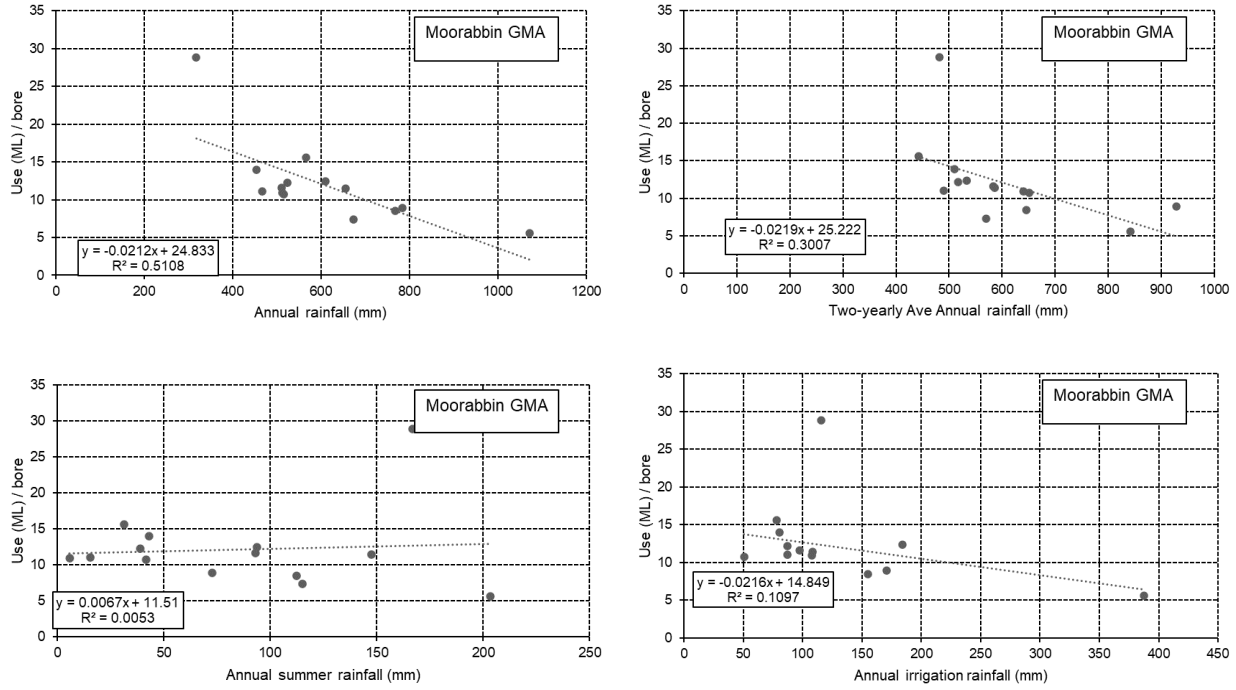


Figure 132 Moorabbin GMA: Hindcast method 2 correlations

As shown in Figure 132, the goodness-of-fit represented by the R^2 is greatest for annual rainfall with the use by bore. The correlation decreased significantly when rainfall was reduced to a smaller period over the year. The annual rainfall has been adopted for hindcast method H2.

12.2.4.3 Hindcasting Method 3 (H3)

Four correlations were developed using method H3 as described below and shown in Figure 133:

- Percentage of entitlement vs annual rainfall
- Percentage of entitlement vs two yearly average annual rainfall
- Percentage of entitlement vs annual summer period rainfall
- Percentage of entitlement vs annual irrigation period rainfall

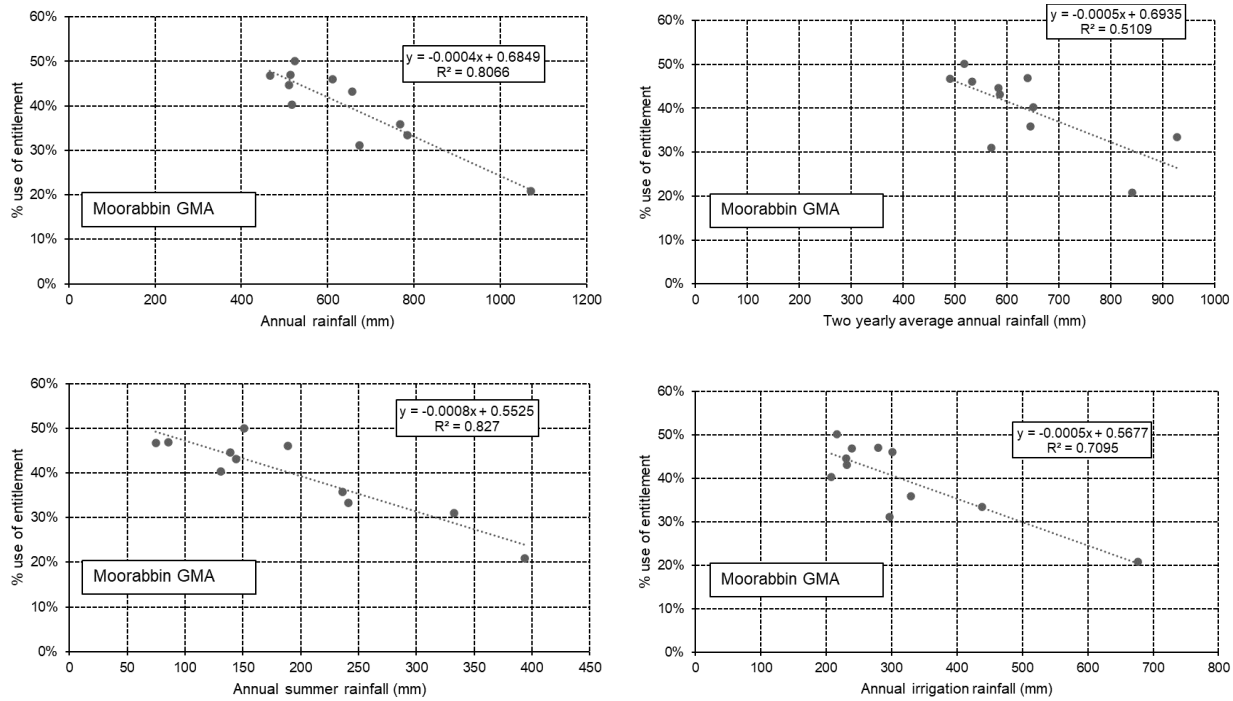


Figure 133 Moorabbin GMA: Hindcast method 3 correlations

As shown in Figure 133 and similar to method 1, the best goodness-of-fit result was shown to be the correlation with annual summer rainfall, however, this is closely followed by the annual rainfall. The correlation of annual summer rainfall was adopted for hindcast method H3.

12.2.4.4 Comparison

A comparison of the three input datasets is shown in Figure 134 and Figure 135 for the hindcasting based on Moorabbin GMA groundwater use. Figure 134 shows a comparison of the three hindcasting methods against the recorded use only over the recorded use date, while Figure 135 shows the hindcasted data back to 1973/1974.

As shown in Figure 135, groundwater use using method 1 does not decrease historically as there is no factor to account for the changing number of bores extracting over time. The hindcasting results show that the smallest average variation of recorded use to estimated use occurs for method 1; however, this is likely to overestimate when looking at historical extraction. Method 3 shows the second closest estimates to the recorded use and given that this method takes into account the decreasing number of bores into the past, this hindcasting method is expected to provide a more probable estimated groundwater use than the other two methods for Moorabbin GMA.

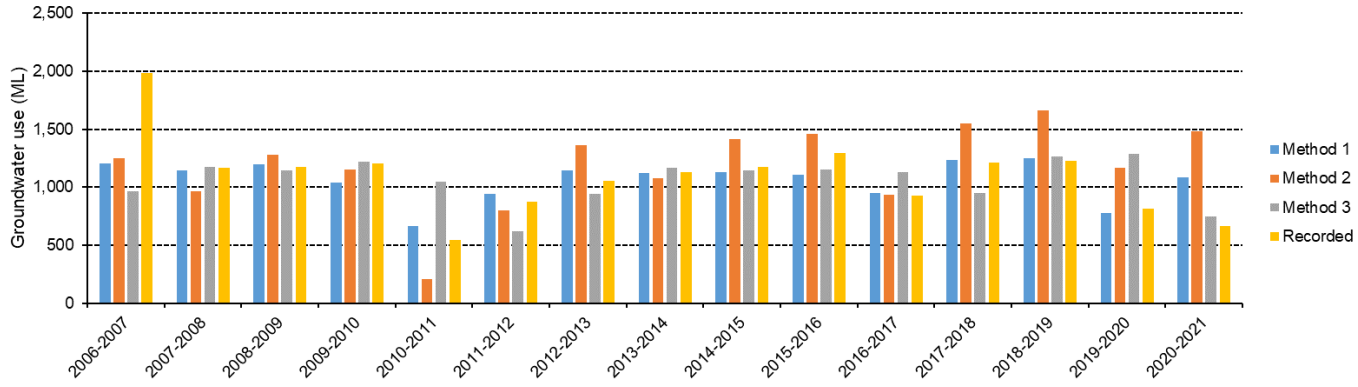


Figure 134 Moorabbin GMA: Comparison of hindcasting over recorded use period

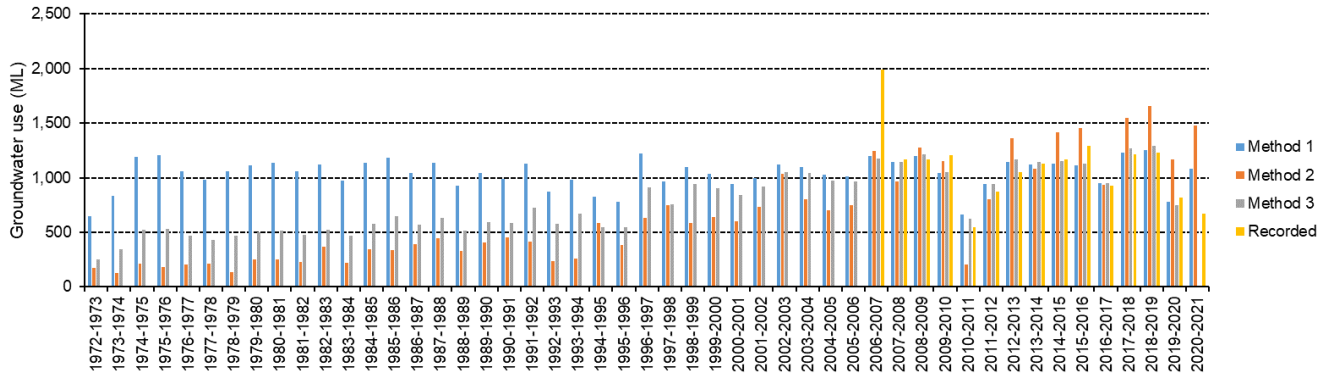


Figure 135 Moorabbin GMA: Comparison of hindcasting

12.3 Modelling

12.3.1 Model inputs

A number of different models were run based on the various model inputs developed and combinations of these. Table 56 summarises these combinations of model inputs run for Moorabbin GMA. Model runs highlighted blue indicate they were run with annual extraction and grey indicates they were run using two yearly average annual extraction.

Table 56 Moorabbin GMA: summary of model inputs

Model input	Model runs																			
	1	2	3	4	5	6	7	8	9	10	11	12	12c	13	14	15	16	17	18	19
Annual recovered levels for representative Suites (M_T_2 and M_T_3)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Annual extraction – Moorabbin GMA only	✓																			
Annual climate data													✓							
Two yearly average annual extraction – Moorabbin GMA only		✓																		
Annual extraction – Moorabbin GMA and Externalities			✓																	
Two yearly average annual extraction – Moorabbin GMA and Externalities				✓																
H1 annual extraction – Moorabbin GMA only					✓															
H1 annual extraction – Moorabbin GMA and Externalities						✓														
H2 annual extraction – Moorabbin GMA only							✓													
H2 annual extraction – Moorabbin GMA and Externalities								✓												
H3 annual extraction – Moorabbin GMA only									✓											
H1 two yearly average annual extraction – Moorabbin GMA only										✓										
H1 two yearly average annual extraction – Moorabbin GMA and Externalities											✓									

Model input	Model runs																		
	1	2	3	4	5	6	7	8	9	10	11	12	12c	13	14	15	16	17	18	19
H2 two yearly average annual extraction – Moorabbin GMA only												✓	✓							
H2 two yearly average annual extraction – Moorabbin GMA and Externalities														✓						
S1 annual extraction – Moorabbin GMA only															✓					
S2 annual extraction – Moorabbin GMA only																✓				
S3 annual extraction – Moorabbin GMA only																	✓			
S1 annual extraction and H1 annual extraction – Moorabbin GMA only																		✓		
S2 annual extraction and H2 annual extraction – Moorabbin GMA only																			✓	
S3 annual extraction and H3 annual extraction – Moorabbin GMA only																				✓

12.3.2 Model calibration and uncertainty analysis

A statistical summary of the model output results for the runs described in Table 56 is presented in Table 57 for the selection of potential representative Suites for Moorabbin GMA. The column heading for M_T_3 is highlighted blue to indicate that this Suite was selected as the most likely representative Suite based on the process outlined in section 12.2.1. The statistics summarised include four key statistical measures pf the average 95 PPU thickness (95PPU TH), percentage of observed levels within 95 PPU (%Obs in 95 PPU), R^2 and root mean square error (RMSE) as well as the number of annual recovered level observation points (No obs data points) and the range of observed annual recovered levels.

Suite M_T_2

A review of the results and statistical summary for Suite M_T_2 shows that model runs 2, 14 and 16 (highlighted orange) had the best results when firstly considering the smaller 95PPU band thickness compared to the other three statistical measures. However, these models contain limited data points and does not incorporate the early time series data/the defined pre-development level. One of the hindcasted version of model 2 is model 12 which showed poorer results than model run 2 (model 11 was also considered but the hindcast method H1 tended to overestimate historical extraction). To see if the model 12 results could be improved the model was run with climate (model run 12c); this did improve the results across all statistical measures. Given the above, model run 12c (highlighted green) is the preferred model run for predictive modelling of Suite M_T_2 for Moorabbin GMA. The graphical model output for this model run is shown in Figure 136.

Suite M_T_3

A review of the results and statistical summary for Suite M_T_3 shows that model run 12 and 14 (highlighted orange) had the best results when firstly considering the smaller 95PPU band thickness compared to the other three statistical measures. However, model run 14 contains limited data points and does not incorporate the early time series data/the defined pre-development level. To see if the model 12 results could be improved, the model was run with climate (model run 12c); this did improve the results across most statistical measures. Given the above, model run 12c (highlighted green) is the preferred model run for predictive modelling of Suite M_T_3 for Moorabbin GMA. The graphical model output for model run 12c is shown in Figure 137.

Given the results, modelling was progressed on the basis of adopting model run 12c for Suite M_T_2 and Suite M_T_3.

Table 57 Moorabbin GMA: summary of model outputs

Suite	Statistic	Model run													
		1	2	5	7	9	10	12	12c	14	15	16	17	18	19
M_T_2	95PPU TH	3.03	2.29	2.86	2.8	2.98	2.76	2.76	2.49	1.63	2.41	1.49	2.87	2.99	2.99
	%Obs in 95 PPU	100	92.86	95.83	95.83	95.83	95.83	95.83	97.92	100	100	100	93.62	95.74	95.74
	R^2	39.2	66.3	10.4	12.2	4.3	20.3	11.8	52.8	40.6	42.7	45.3	7.0	-10.5	-10.5
	RMSE	0.67	0.5	0.71	0.71	0.74	0.67	0.71	0.52	0.36	0.36	0.36	0.72	0.79	0.79
	No obs data points	14	14	48	48	48	48	48	48	10	10	10	47	47	47
	Range of observed levels	3.2	3.2	3.9	3.9	3.9	3.9	3.9	3.9	1.4	1.4	1.4	3.9	3.9	3.9
M_T_3	95PPU TH	1.33	1.1	1.94	1.18	1.21	1.59	1.04	0.57	0.87	NA	4.33	1.49	1.64	1.64
	%Obs in 95 PPU	92.86	100	97.92	95.83	95.83	97.92	95.83	93.75	100	0	100	97.87	36.17	36.17
	R^2	7.1	54.4	36.4	76.2	74.6	49.8	78.1	89.1	59.3	61.5	61.4	60.0	56.3	56.3
	RMSE	0.34	0.25	0.43	0.27	0.27	0.39	0.26	0.18	0.16	0.15	0.15	0.34	0.35	0.35
	No obs data points	14	14	48	48	48	48	48	48	10	10	10	47	47	47
	Range of observed levels	1.3	1.3	2.3	2.3	2.3	2.3	2.3	2.3	0.9	0.9	0.9	2.3	2.3	2.3

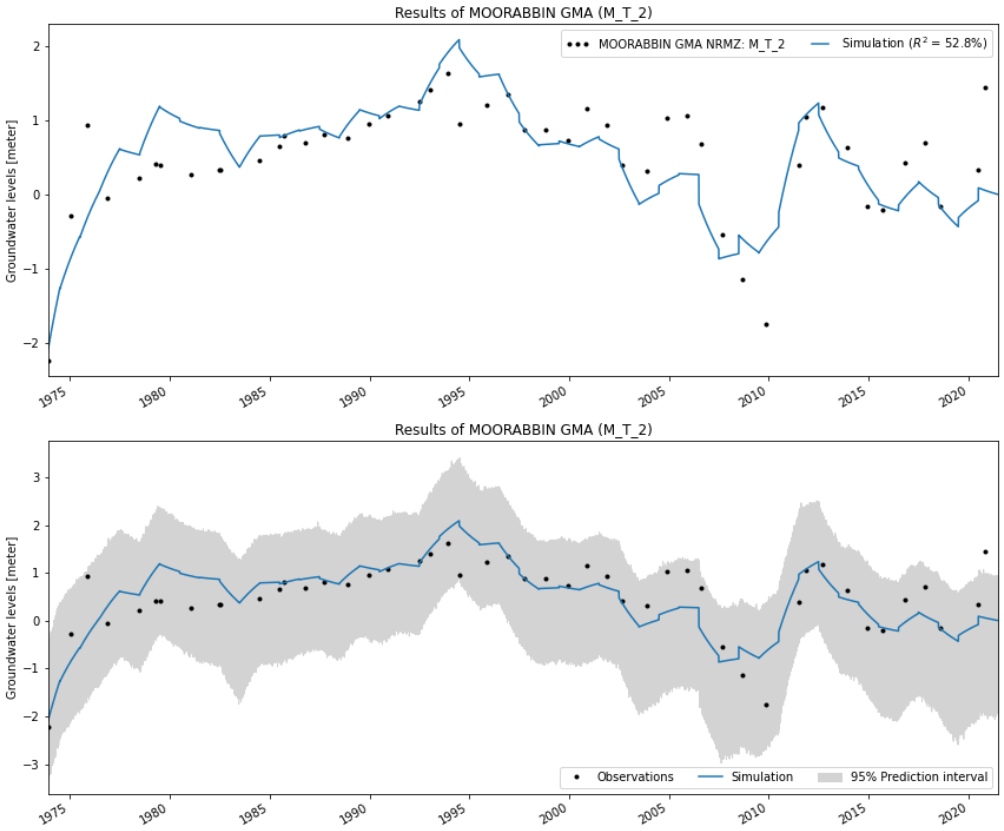


Figure 136 ***Moorabbin GMA Suite M_T_2: model run 12c (Moorabbin GMA two yearly average annual extraction with hindcast method H2 and climate) output hydrographs***

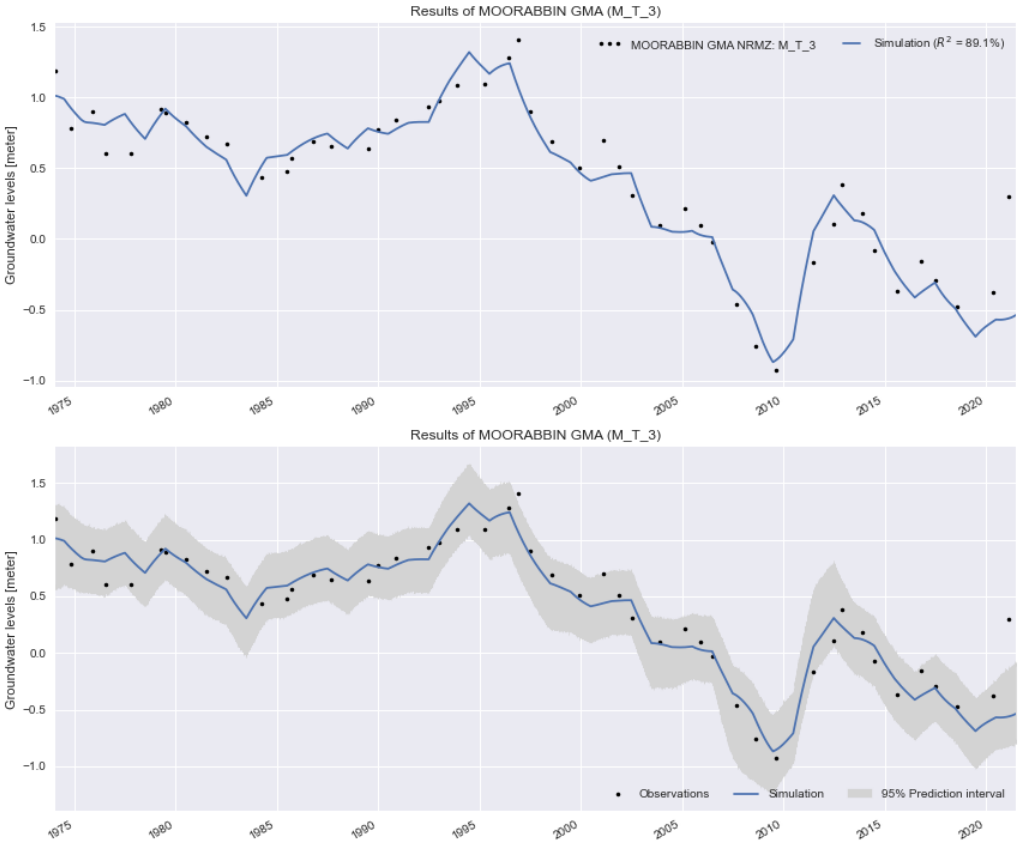


Figure 137 ***Moorabbin GMA Suite M_T_3: model run 12c (Moorabbin GMA two yearly average annual extraction with hindcast method H2 and climate) output hydrographs***

12.4 Predictive modelling

12.4.1 Model inputs

The preferred model to run the predictive modelling for Moorabbin GMA was model run 12c for Suite M_T_2 and Suite M_T_3. To conduct the forecasting for the 19 scenarios discussed in section 3.5.3, a few factors were required in the calculations; these factors are summarised in Table 58.

Table 58 Moorabbin GMA: forecast scenario inputs

Input item	PCV	Licenced entitlement (based on 2020/21)	Existing use (based on 2020/2021)	Average use over recorded period (from VWA)	Maximum use over recorded period (from VWA, year 2006/07)
Value (ML/year)	2,700	2,624	667	1,096	1,987

12.4.2 Predictive model uncertainty

The model output files of the predicted models can be found in the data package provided as part of Appendix E.

MCMC predictions were undertaken on each of the forecasted scenarios for each of the two Suites. An example of one of the outputs is presented in Figure 138 for scenario 13. As shown in Figure 138, the uncertainty of the model prediction increases as the model predicts further into the future. Comparing with the graphical output for the same scenario, the majority of MCMC realisations tend to fall within the 95% prediction interval bands as shown in Figure 139.

Uncertainty is also accounted for by using 19 forecast scenarios to develop a groundwater use to drawdown relationship (analogous to a Monte Carlo type simulation) where a range of possible outcomes are generated. It is noted however, that the forecast scenarios were not randomly generated, but rather based upon a series of estimated use behaviours.

It is noted that forecast scenario 4, 7 and 14 for Suite M_T_2 were not able to produce 95% prediction interval limit data thus these scenarios are not included in the assessment.

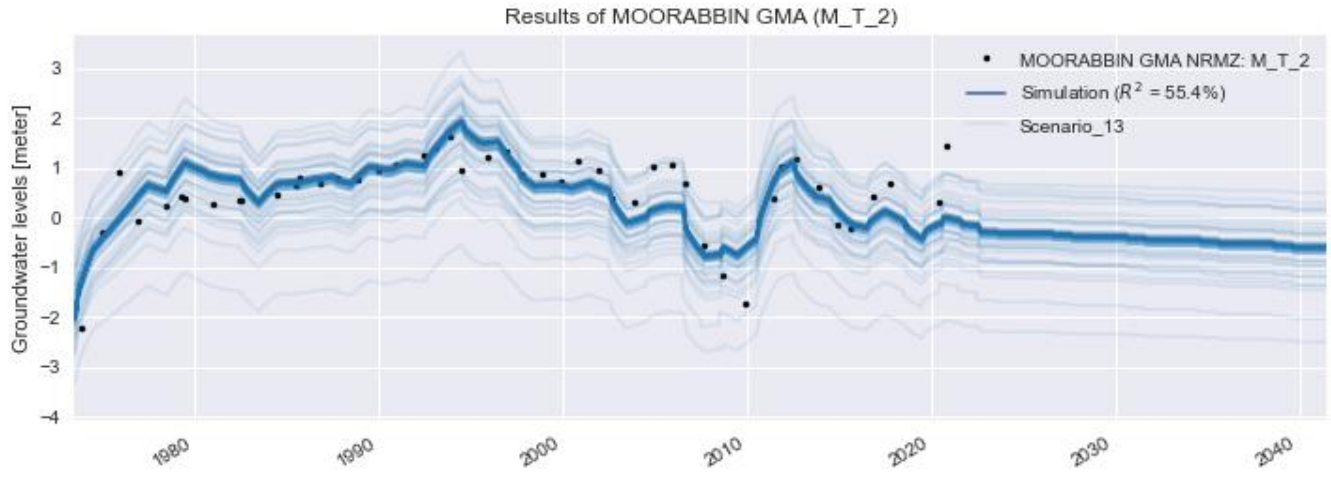


Figure 138 Moorabbin GMA: Suite M_T_2 MCMC analysis for Forecast Scenario 13

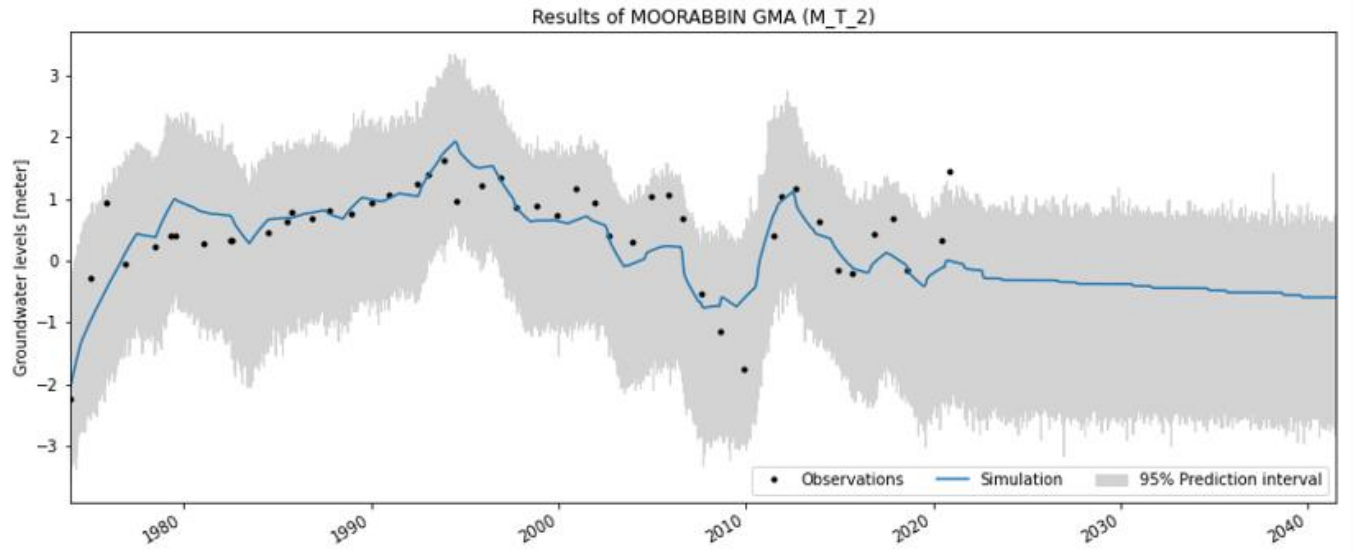


Figure 139 Moorabbin GMA: Suite M_T_2 Forecast Scenario 13 with 95% prediction bands

12.4.3 Extraction vs drawdown

To calculate the drawdown based on the annual recovered levels simulated by the model, the pre-development conditions (pre commencement of extraction) need to be estimated. For Moorabbin GMA, the water level prior to groundwater development was unknown, due to:

- Uncertainty regarding the commencement of development in some GMUs
- The initiation of groundwater development preceding SOBN bore installation and temporal groundwater monitoring

Using the pre-development levels defined in section 12.2.2, the modelled water levels were converted into drawdowns (from this baseline pre-development level) for each of the 19 scenarios. This predevelopment condition is shown in Figure 140 for Suite M_T_2 hydrograph of annual recovered levels. In Figure 140:

- Actual annual groundwater use is represented by the blue column graph between 2006/2007 and 2020/2021
- Hindcasted groundwater use (using method H2) is represented by the orange columns between 1973/1974 to 2006/2007
- Forecasted use is represented by the grey columns after 2021/2022
- The annual recovered water level behaviour based on recorded data is represented by the red line graph, where the earliest data is taken to best reflect the pre-development levels
- The pre-development annual recovered levels are taken to be the maximum annual recovered level in 1993/1994 which equates to 1.63 m
- The modelled forecasted annual recovered levels are represented by the purple line in Figure 140
- The calibration annual recovered levels are represented by the black line in Figure 140

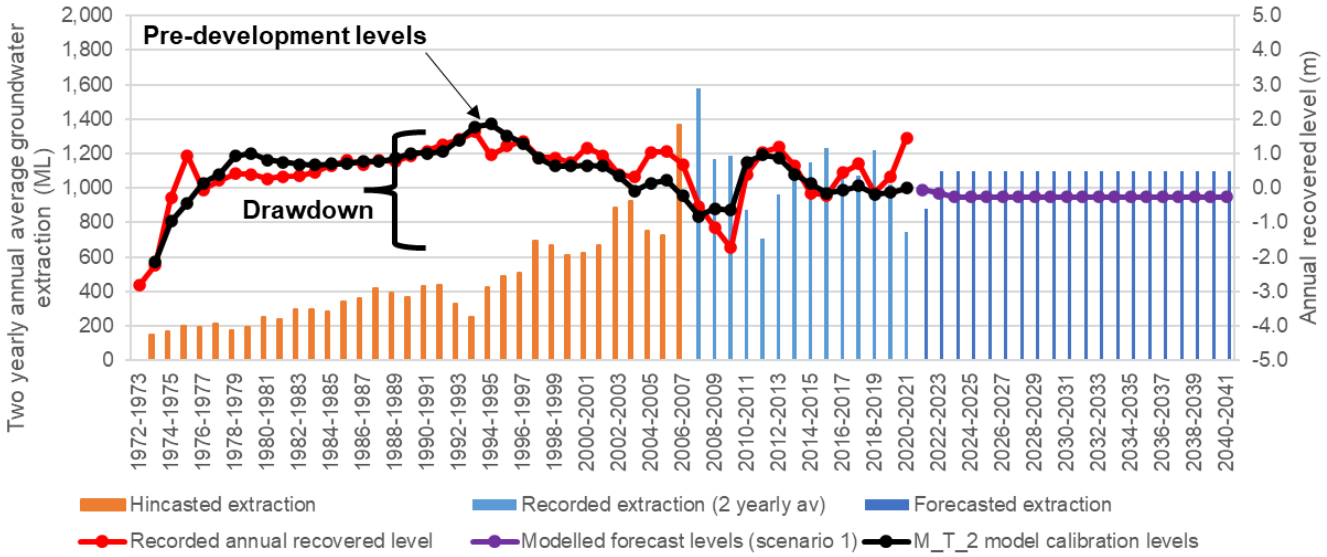


Figure 140 Estimating pre-pumping water levels (example from Suite M_T_2)

For Suite M_T_2, the calculated drawdowns and volumes for each of the scenarios were plotted in individual graphs for each scenario, all scenarios together in the one graph (Figure 141) and a graph of the scenarios for specific time periods (Figure 142) to develop the volume to drawdown relationship. For each scenario, a linear regression was applied and the coefficient of determination (R^2) was calculated. A comparison of each of these graphs shows there was variations in the coefficient of determination between different scenarios and variations of up to 0.0004 in the slope of the linear regression. The same process was applied for Suite M_T_3 and again, there were variations in the coefficient of determination between different scenarios and variations of the slope of the linear regression. As such, the relationship developed using all scenarios was adopted as it best captures this variation between forecast scenarios.

The use-drawdown for all the 19 forecast scenario drawdowns and volumes (both the recorded and forecasted volumes) over each year modelled is shown in Figure 141 for Suite M_T_2 (1974 to 2041) and Figure 143 for M_T_3 (1974 to 2041). Note the abscissa range of the chart has been clipped and does not show forecast drawdowns for the higher use scenarios (more improbable usages of two times the PCV). Reviewing these figures, the following is noted:

- There should be zero drawdown under zero use and therefore a line of best fit should pass through the origin (0,0) or close to it
- Average use is around 1,100 ML. Figure 141 for Suite M_T_2 and Figure 143 for Suite M_T_3 indicates that where use is around this volume the model forecast drawdown tends to occur slightly above the predicted line of best fit
- For the same annual use or two yearly annual average use, different drawdowns can be obtained as Pastas predicts a water level for each year. For example, Figure 140 shows a scenario where groundwater use remains constant at around 1,100 ML/year over the next 20 years.
- The correlation in terms of R^2 for groundwater use and drawdown for Suite M_T_2 is poor as shown in Figure 141 and is excellent for Suite M_T_3 as shown in Figure 143
- The various forecast scenarios generally result in data plotting reasonably close together in a linear trend. The 19 forecast scenarios applied to populate the chart is analogous to a Monte Carlo type simulation where a range of possible outcomes are generated. It is noted however, that the forecast scenarios were not randomly generated, but rather based upon a series of estimated use behaviours.

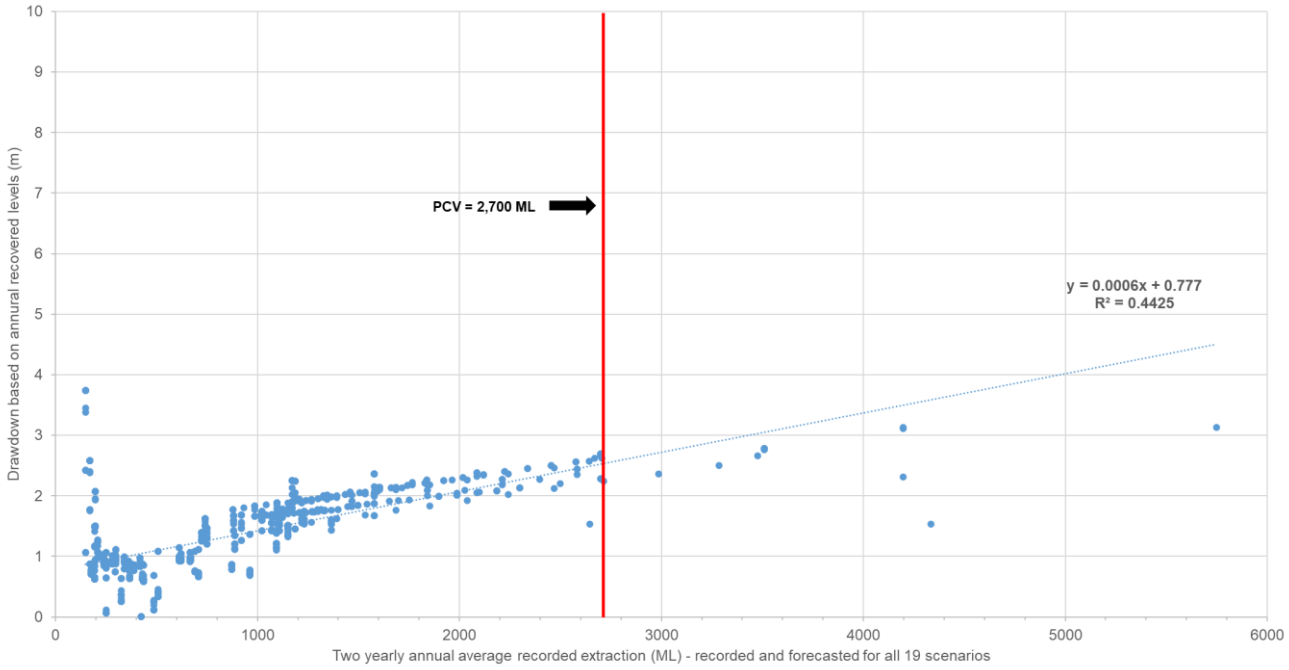


Figure 141 *Moorabbin GMA Suite M_T_2: Drawdown (on annual recovered levels) and extraction volumes (recorded and forecasted <6,000 ML) for all data between 1974 to 2041 and all forecasted scenarios*

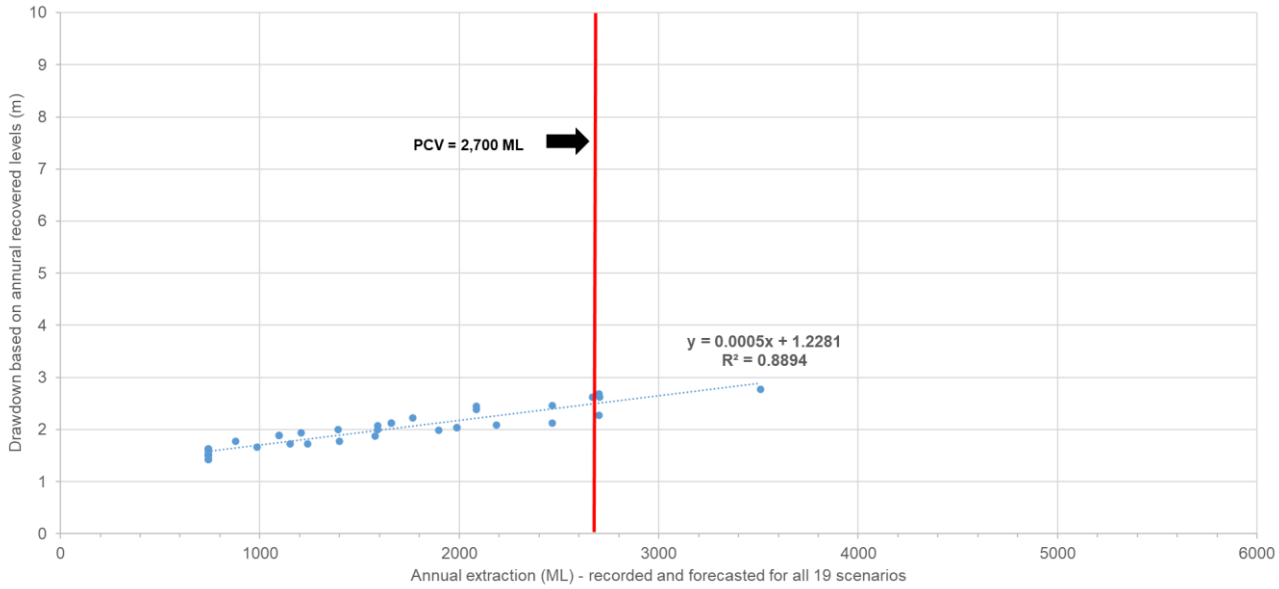


Figure 142 *Moorabbin GMA Suite M_T_2: Drawdown (on annual recovered levels) and extraction volumes (recorded and forecasted <6,000 ML) for years 2020/2021, 2030/2031 and 2040/2041 for all forecasted scenarios*

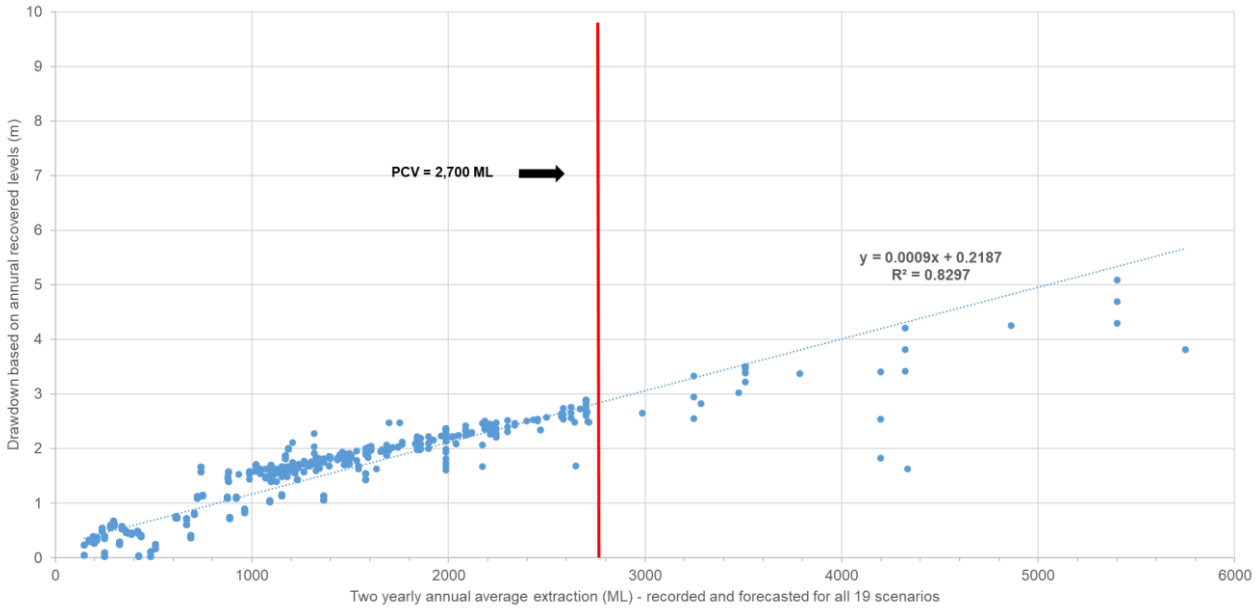


Figure 143 ***Moorabbin GMA Suite M_T_3: Drawdown (on annual recovered levels) and extraction volumes (recorded and forecasted <6,000 ML) for all data between 1974 to 2041 and all forecasted scenarios***

12.5 Sustainability metrics

12.5.1 Application of metrics

Using the use - drawdown relationships developed through the previous step of forecasting aquifer response under a range of use scenarios, groundwater drawdown can be used to compare against groundwater resource sustainability metrics.

The application of these metrics and the relationship developed between drawdown based on the Suite annual recovered levels and extraction volume for the whole GMU, which is shown in Table 59 for Moorabbin GMA Suite M_T_2 and Table 60 for Moorabbin GMA Suite M_T_3 (noting Moorabbin GMA has a current PCV of 2,700 ML/year). As part of the modelling, a 95% prediction interval band was applied to the modelling results. The relationship between drawdown and extraction volumes can also be interrogated at the lower and upper bands of the 95% prediction interval as shown in Table 59 and Figure 144 for Suite M_T_2, and Table 60 and Figure 145 for Suite M_T_3.

Suite M_T_2 generally shows greater variability and uncertainty when comparing the drawdown to use relationships based on the 95% prediction interval bands. For example, the variation in drawdown based on the 95% prediction bands at a volume of 3,000 ML is 0.9 to 3.7 m of drawdown for Suite M_T_2 and only 2.5 to 3.5 m of drawdown at Suite M_T_3 (reflected in the error bars of Figure 144 and Figure 145).

A comparison of volumes at drawdown intervals provided by DEECA is shown in

Table 61 for Suite M_T_2 and Suite M_T_3. Based on the relationships developed, 5 m of drawdown is predicted to occur based on an extraction volume of 7,000 ML (but could vary from 5,200 to 16,800 ML) based on Suite M_T_2 and 5,300 ML (but could vary from 4,500 to 5,700 ML) based on Suite M_T_3. Based on the relationships developed, 10 m of drawdown is predicted to occur based on an extraction volume of 15,400 ML (but could vary from 13,500 to 33,500 ML) based on Suite M_T_2 and 10,900 ML (but could vary from 9,500 to 11,300 ML) based on Suite M_T_3.

*Table 59 Relationship of Suite drawdown to **GMU** extraction for Moorabbin GMA Suite M_T_2*

Volume (ML/year) for whole of GMU based on two yearly annual average	Based on model prediction of Suite M_T_2 annual recovered levels
	Drawdown over 20 years (m) (lower limit to upper limit based on 95% prediction interval band)
16,000	10.4 (4.8 - 11.5)
15,000	9.8 (4.5 - 10.9)
14,000	9.2 (4.2 - 10.3)
13,000	8.6 (3.9 - 9.7)
12,000	8 (3.6 - 9.1)
11,000	7.4 (3.3 - 8.5)
10,000	6.8 (3 - 7.9)
9,000	6.2 (2.7 - 7.3)
8,000	5.6 (2.4 - 6.7)
7,000	5 (2.1 - 6.1)
6,000	4.4 (1.8 - 5.5)
5,000	3.8 (1.5 - 4.9)
4,000	3.2 (1.2 - 4.3)
3,000	2.6 (0.9 - 3.7)
2,000	2 (0.6 - 3.1)
1,000	1.4 (0.3 - 2.5)
0	0.8 (0 - 1.9)

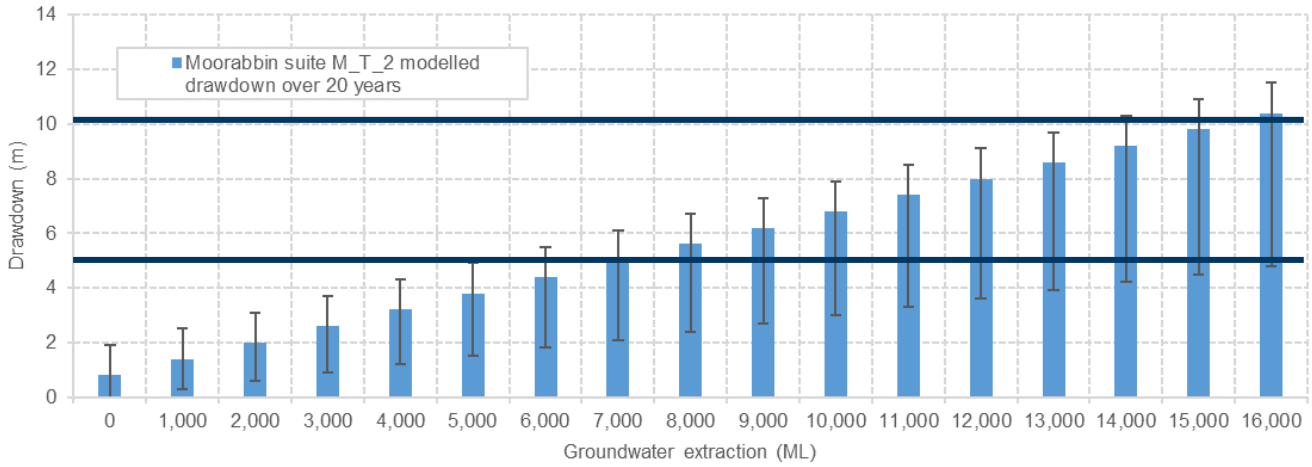


Figure 144 Moorabbin GMA Suite M_T_2: Relationship of Suite drawdown to GMU extraction (with error bars showing results of drawdown using levels from model's 95% prediction intervals)

Table 60 Relationship of Suite drawdown to GMU extraction for Moorabbin GMA Suite M_T_3

Volume (ML/year) for whole of GMU based on two yearly annual average	Based on model prediction of Suite M_T_3 annual recovered levels
	Drawdown over 20 years (m) (lower limit to upper limit based on 95% prediction interval band)
11,000	10.1 (9.7 - 11.5)
10,000	9.2 (8.8 - 10.5)
9,000	8.3 (7.9 - 9.5)
8,000	7.4 (7 - 8.5)
7,000	6.5 (6.1 - 7.5)
6,000	5.6 (5.2 - 6.5)
5,000	4.7 (4.3 - 5.5)
4,000	3.8 (3.4 - 4.5)
3,000	2.9 (2.5 - 3.5)
2,000	2 (1.6 - 2.5)
1,000	1.1 (0.7 - 1.5)
0	0.2 (-0.2 - 0.5)

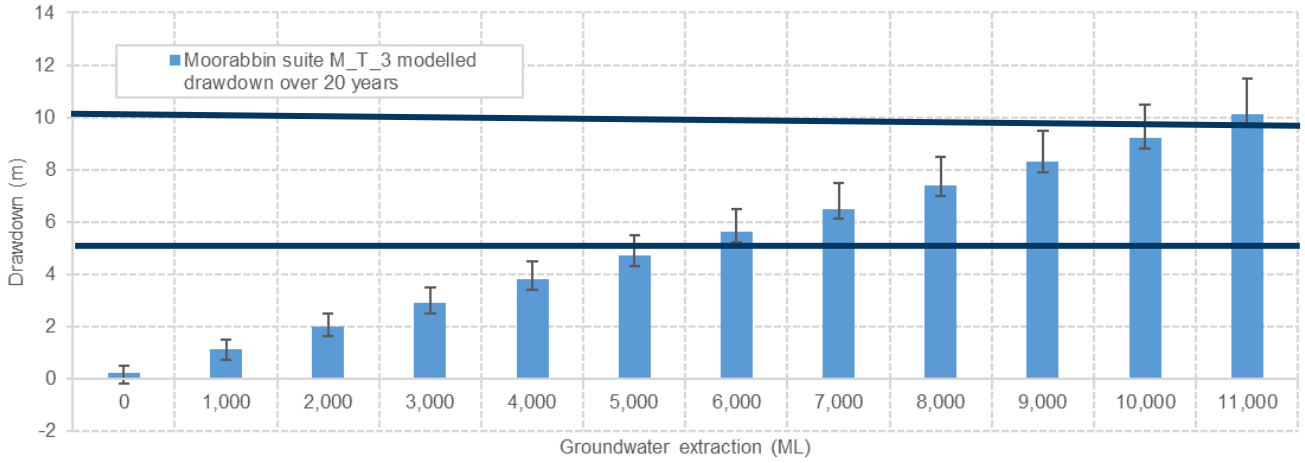
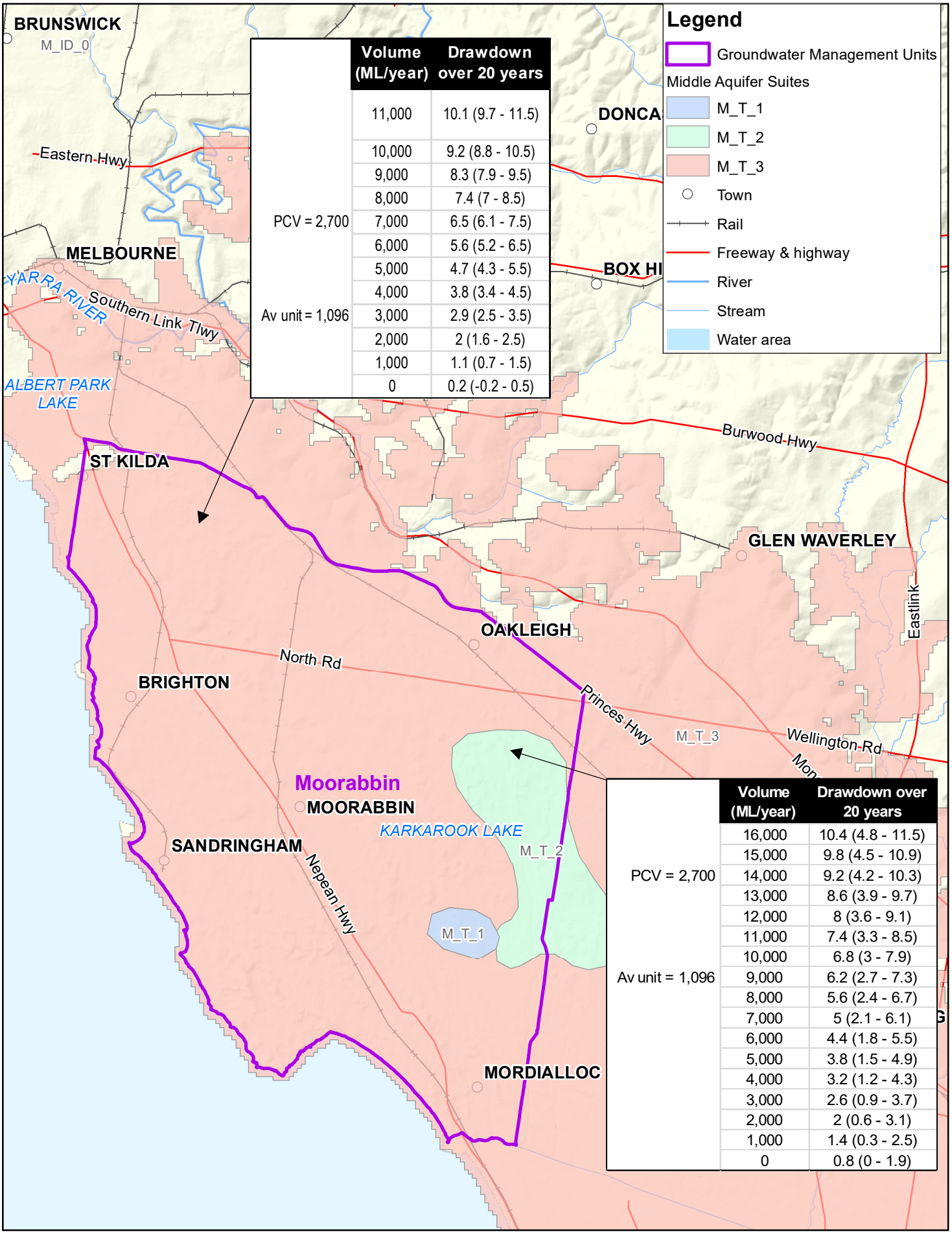


Figure 145 Moorabbin GMA Suite M_T_3: Relationship of Suite drawdown to GMU two yearly annual average extraction (with error bars showing results of drawdown using levels from model's 95% prediction intervals)

Table 61 Predicted GMU volumes for drawdown metrics

Drawdown (m)	Predicted two yearly average annual volumes for GMU based on Suite M_T_2 drawdowns (lower limit to upper limit)	Predicted two yearly average annual volumes for GMU based on Suite M_T_3 drawdowns (lower limit to upper limit)
5	7,000 (5,200 – 16,800)	5,300 (4,500 – 5,700)
10	15,400 (13,500 – 33,500)	10,900 (9,500 – 11,300)



	Volume (ML/year)	Drawdown over 20 years
PCV = 2,700	11,000	10.1 (9.7 - 11.5)
	10,000	9.2 (8.8 - 10.5)
	9,000	8.3 (7.9 - 9.5)
	8,000	7.4 (7 - 8.5)
	7,000	6.5 (6.1 - 7.5)
	6,000	5.6 (5.2 - 6.5)
	5,000	4.7 (4.3 - 5.5)
	4,000	3.8 (3.4 - 4.5)
Av unit = 1,096	3,000	2.9 (2.5 - 3.5)
	2,000	2 (1.6 - 2.5)
	1,000	1.1 (0.7 - 1.5)
	0	0.2 (-0.2 - 0.5)

	Volume (ML/year)	Drawdown over 20 years
PCV = 2,700	16,000	10.4 (4.8 - 11.5)
	15,000	9.8 (4.5 - 10.9)
	14,000	9.2 (4.2 - 10.3)
	13,000	8.6 (3.9 - 9.7)
	12,000	8 (3.6 - 9.1)
	11,000	7.4 (3.3 - 8.5)
	10,000	6.8 (3 - 7.9)
Av unit = 1,096	9,000	6.2 (2.7 - 7.3)
	8,000	5.6 (2.4 - 6.7)
	7,000	5 (2.1 - 6.1)
	6,000	4.4 (1.8 - 5.5)
	5,000	3.8 (1.5 - 4.9)
	4,000	3.2 (1.2 - 4.3)
	3,000	2.6 (0.9 - 3.7)
	2,000	2 (0.6 - 3.1)
	1,000	1.4 (0.3 - 2.5)
	0	0.8 (0 - 1.9)

Paper Size ISO A3

0 0.85 1.7 2.55 3.4

Kilometers

Map Projection: Lambert Conformal Conic
Horizontal Datum: GDA 1994
Grid: GDA 1994 VICGRID94

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GHD

DEECA
Sustainable Yields
Confined Aquifers

Project No. 31-12564066
Revision No. 0
Date 15/01/2024

MOORABBIN GMA: KEY SUITES VOLUME VS DRAWDOWN

FIGURE 146

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Print date: 06 Feb 2024 - 09:13

Data source: DELWP, VicMap, 2022; DELWP GMU locations, 2022; GHD, aquifer suites, 2018 Created by: bsmyth

12.6 GMU summary

12.6.1 Findings

Moorabbin GMA primarily relates to the Brighton Group aquifer (UTAF) and groundwater is predominately extracted from this aquifer for golf course irrigation and stock and domestic purposes. The UTAF falls within the Middle Aquifer Suites, which at Moorabbin GMA comprise Suites M_T_1 (1%), M_T_2 (7%) and M_T_3 (92%), providing a total GMU coverage of 100%. The identified representative Suites are M_T_2 and M_T_3 (most preferred). The Suite hydrographs for the representative Suites show seasonal fluctuations and thus recovered water levels, which were adopted for the assessment.

Application of two yearly annual average extraction, rather than annual extraction, generally showed an improved model fit based on the statistical analysis across the model runs. The application of only spatial distribution produced a slightly improved model compared to annual extraction and most of the two yearly annual average extraction runs; the spatial distribution datasets had a smaller input dataset and do not cover the pre-development period. It is noted that the quality of the model results decreased when spatial distribution methodology was combined with hindcasting methodology.

Based on an assessment of all model runs, the model run 12c of two yearly annual average extraction with hindcast method H2 and climate was adopted to undertake the predictive modelling for Suite M_T_2 and Suite M_T_3. It was found that adding climate to the hindcasted dataset improved the model results.

The pre-development levels were defined for the two representative Suites, based on the maximum annual recovered levels for Suite M_T_2 and the maximum annual recovered level in the early time series data for Suite M_T_3. This resulted in pre-development levels of 1.63 m for Suite M_T_2 and 1.19 m for Suite M_T_3. The drawdowns were calculated based on these pre-development levels and the simulated levels from each of the 19 forecast scenarios.

The volumes estimated for a given drawdown for each Suite is shown below.

Drawdown (m)	Predicted two yearly average annual volumes for GMU based on Suite M_T_2 drawdowns (lower limit to upper limit)	Predicted two yearly average annual volumes for GMU based on Suite M_T_3 drawdowns (lower limit to upper limit)
5	7,000 (5,200 – 16,800)	5,300 (4,500 – 5,700)
10	15,400 (13,500 – 33,500)	10,900 (9,500 – 11,300)

The model for Suite M_T_3 was assessed as having an “Excellent” model applicability rating and Suite M_T_2 was assessed as having a “Moderate” rating using the criteria outlined in section 5.2. For both Suites, due to the limited range in calibration volumes, the greater the proposed extraction rates beyond the calibration range leads to a greater potential for drawdown forecast errors.

Given its coverage and that most of the extraction from the Middle Aquifer is likely to come from Suite M_T_3 and that Suite M_T_2 failed to successfully run forecast scenario 4, 7 and 14, Suite M_T_3 is considered to be the most representative Suite for Moorabbin GMA.

12.6.2 Limitations

In addition to the limitations applicable to all 25 GMUs discussed in section 1.8, the following Moorabbin GMA specific limitations have been identified:

- The licenced bore dataset provided by DEECA has 10% of bores assigned to Moorabbin GMA with no depth data and thus couldn’t be assigned to a VAF layer and in turn Suite. These bores were assigned to an aquifer through this study by GHD, in order to assist with the determination of the representative Suite. However, this data was not used in the model analysis.
- The spatial dataset used for the modelling is only available to the year 2019/2020. To account for this, annual recorded data from Victorian Water Accounts for the year 2020/2021 has been assigned to bores based on the method described in section 3.5.

- The predictive models for Suite M_T_2 failed to compute correctly for forecast scenario 4, 7 and 14. As such, the results from these forecast scenarios have been excluded from the assessment for this Suite.
- The correlation developed is based on a two yearly average annual groundwater use
- Model calibration was between 0-1,600 ML/year groundwater extraction range. The greater the proposed extraction rates beyond this calibration range the more potential for drawdown forecast errors.
- In this GMU prediction for extraction volumes up to 6 times the calibration range are being made to meet the 10m drawdown metric (M_T_3). Further checks and potential re-calibration may be required as rates increase for the GMUs.

12.6.3 Recommendations

In addition to the recommendations applicable to all 25 GMUs discussed in section 32, the following Moorabbin GMA specific recommendations have been identified:

- The licenced bore dataset provided by DEECA has 10% of bores assigned to Moorabbin GMA with no depth data and thus couldn't be assigned to a VAF layer and in turn Suite. It is recommended that DEECA obtains the relevant depth and aquifer monitored data for licenced bores within this GMU.

13. Murrayville GMA

13.1 Conceptualisation

The hydrogeological conceptualisation elements relevant to this study are summarised in Table 62 and a map of the GMU is presented in Figure 147. It is noted that a significant volume of information was collated to inform the hydrogeological conceptual understanding of the GMU. The information that is directly relevant to the modelling are in bold or colour coded within Table 62.

Table 62 Murrayville GMA – Tabulated conceptualisation

GMU summary

Murrayville GMA is situated in western Victoria and is bounded by the Victoria – South Australia (SA) border as shown in Figure 147. Murrayville GMA covers an area of 1,918 km^2. The GMA incorporates the bulk of extraction bores in the Murrayville-Tutye area.

The GMA pertains to all formations below the surface, but was intended primarily to manage the groundwater resource of the Murray Group Limestone (UMTA). The GMA has a PCV of 11,005 ML/year which primarily relates to the confined UMTA. Groundwater in the GMA is typically extracted for stock and domestic, town supply and irrigation purposes.

Part of Murrayville GMA is within the Victoria – South Australian Border Zone, which incorporates an area 20 km either side of the Victoria – South Australia border.

A report by the Department of Water, Land and Biodiversity Conservation (2006) indicated that observed drawdowns occurred in the border zone in 2006, with the centre of drawdown occurring in SA and extending into Victoria. However, the report concluded that water extractions in SA do not affect groundwater inflows into Murrayville GMA from the south, and does not impede the development of groundwater in Victoria.

Murrayville GMA is managed by GWMW and occurs within the Wimmera Groundwater Basin.

Hydrostratigraphy summary

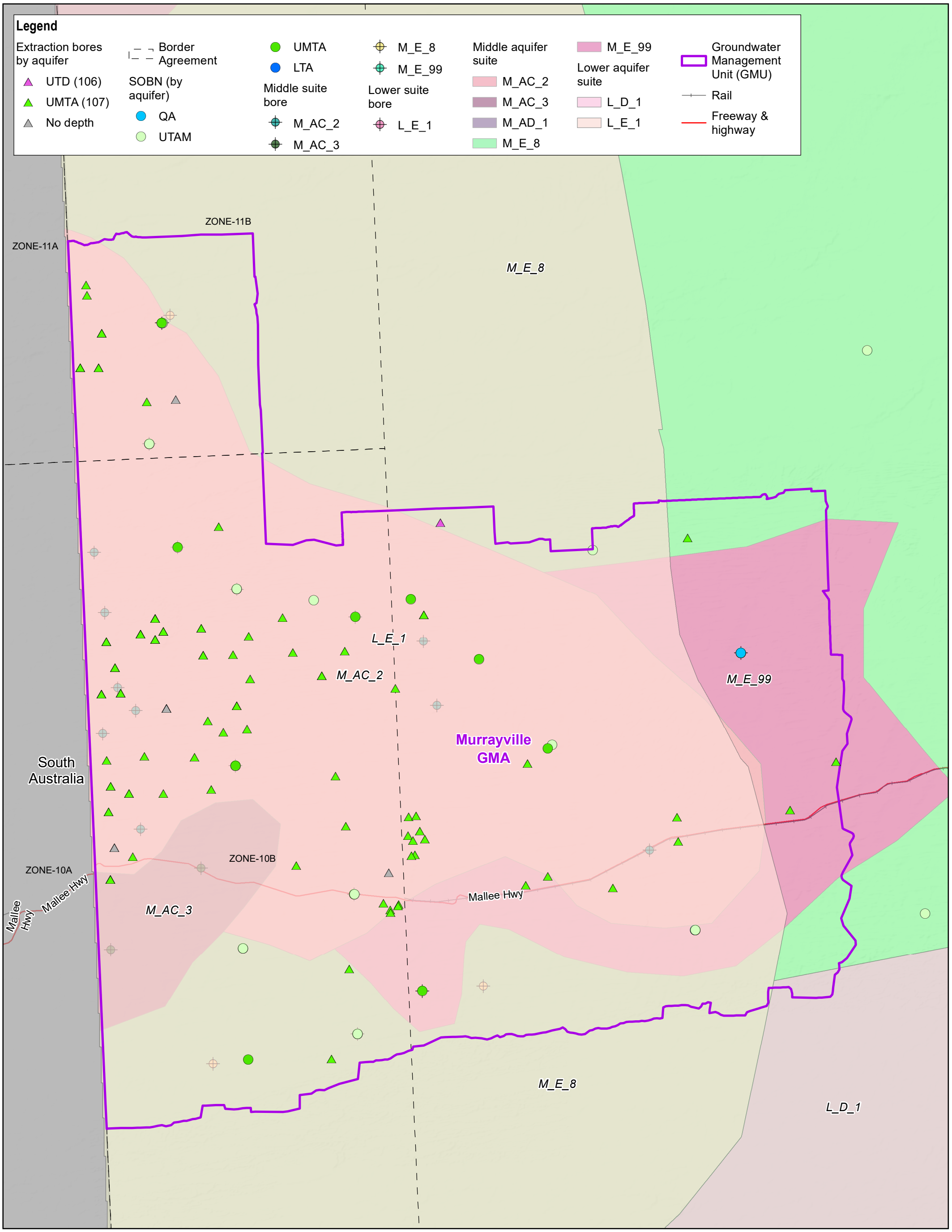
Aquifer	Formation	Relevant Suites (% coverage of GMU)	% of GMU covered by Suites	Number of SON bores	Groundwater use	Use volumes ML (2019/20)	Entitlement volumes ML (2019/20)	Understanding (Low, Medium, High)
Upper	Loxton-Parilla Sand (UTAM)	U_BI_8 (87%)	87%	5	NA	0		Medium
	Bookpurnong Beds (UTD)	-	-	0	Stock	0	0	Low
Middle	Murray Group (Duddo Limestone) (UMTA)	M_AC_2 (56%), M_AC_3 (5%), M_E_99 (18%) M_E_8 (22%)	100%	14	Urban, industrial, irrigation, domestic, stock, dairy	4,909	9,285	High
Lower	Etrick Marl (LMTD)	-	-	0	NA	0	0	Low
	Renmark Group (LTA)	L_E_1 (88%), L_D_1 (0.3%)	88%	1	Irrigation	0	0	Medium
Basement	Basement rocks (BSE)	-	-	0	NA	0	0	Low

Note that volumes listed above are based on the DEECA provided licenced bore dataset with associated VAF layers. Bores have been assigned to a VAF layer based on bore depth where available.

Note that volumes listed above do not include 377 ML of unassigned use due to unknown depths (470 ML of entitlement)

Characteristic and importance	Description	Degree of understanding
Intended aquifer		
Aquifer thickness within GMU (range, based on VAF)	Max: 179.9 m, Average: 132.1 m	High
Aquifer extent	Regional, extensive	High
Likelihood of inter-aquifer flow	Low	High
Likelihood of groundwater – surface water interaction	Low	High
Representative Suite	**M_AC_2**	**High. 87% of GMU extraction occurs within this Suite, which relates to the most relevant GMU aquifer.**
Current hydrological condition of representative aquifer		
Representative Suite trend	Decreasing	High
Groundwater quality (average salinity based on WMIS and CDM Smith spatial segment(s) with highest coverage)	1,844 mg/L (WMIS) Variable across GMU (CDM Smith (2022))	Moderate – data is variable Based on WMIS and CDM Smith (2022)
Groundwater yield	>5 L/s	Low Based on CDM Smith (2022)
Groundwater levels		
Temporal groundwater level data range	**1967 to 2021**	**High** **Based on M_AC_2**
Spatial clustering of licensed bores in relation to Suites	**Yes, M_AC_2**	**Based on DEECA density mapping and licenced bore data.**
Groundwater use		
Licensed groundwater use	**5,408 ML**	**High (Based on average historical VWA data over 17 years)**
Minimum historic groundwater use	2,866 ML	High (Based on historical VWA data, year 2005/06)
Maximum historic groundwater use	**8,331 ML**	**High (Based on historical VWA data, year 2017/18)**
Entitlement (Groundwater allocation)	**9,755 ML**	**High (Based on licenced volumes in 2020/21)**
Significant drivers of groundwater level variability (primary)	**Pumping for irrigation**	**High**
Secondary drivers of groundwater level variability	Pumping for stock or domestic use	Moderate
Groundwater use profile	Influenced by seasonality and agricultural practices	High
External influence	**Mallee Prescribed Wells Area**	

Characteristic and importance	Description	Degree of understanding
Groundwater values and risks		
Existing Environmental Values to be protected, relevant to this GMU	Potable water supply Licensed non-potable supply (irrigation, commercial, industrial) Unlicensed non-potable supply (domestic and stock)	
Risks to groundwater values	Direct risks: Drawdown which may affect access to groundwater by existing users	Moderate
Indicators used to assess impacts to groundwater	Measured drawdown using pre-determined metrics measured from a pre-determined level for the purpose of this modelling	Moderate



Paper Size ISO A3

0 1.5 3 4.5 6

Kilometers

Map Projection: Lambert Conformal Conic
Horizontal Datum: GDA 1994
Grid: GDA 1994 VICGRID94

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GHD

DEECA
Sustainable yield review - confined aquifers

Murrayville GMA
Site location and key features

Project No. **12564066**
Revision No. **0**
Date **16/01/2024**

Figure 147

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Print date: 16 Jan 2024 - 12:54

Data source: DELWP, VicMap, 2022; DELWP, GMUs, 2022; DELWP, SOBN, 2022; GHD, aquifer suites, 2018; DELWP, extraction bores, 2022; DWLBC, border agreements, 1998 Created by: cperyer

13.2 Technical analysis

13.2.1 Hydrograph review and selection of representative Suites for further analysis

Suite hydrographs were generated for the confined Suites for Murrayville GMA as shown in Figure 148. The Suite hydrographs show the seasonal fluctuations for Suites M_AC_2 and M_AC_3 and hence recovered water levels. Suites L_D_1, L_E_1, M_E_8 and M_E_99 show some minor fluctuations. All Suite hydrographs shown in Figure 148 exhibit a general decreasing trend. Suite M_AC_2 shows a different water level response prior to 1997 which may be related to the commencement of groundwater extraction in 1996. The data for Suite M_AC_3 only extends to 2016, which is likely to impact the suitability of this Suite as a representative Suite if the Suite bores are no longer monitored.

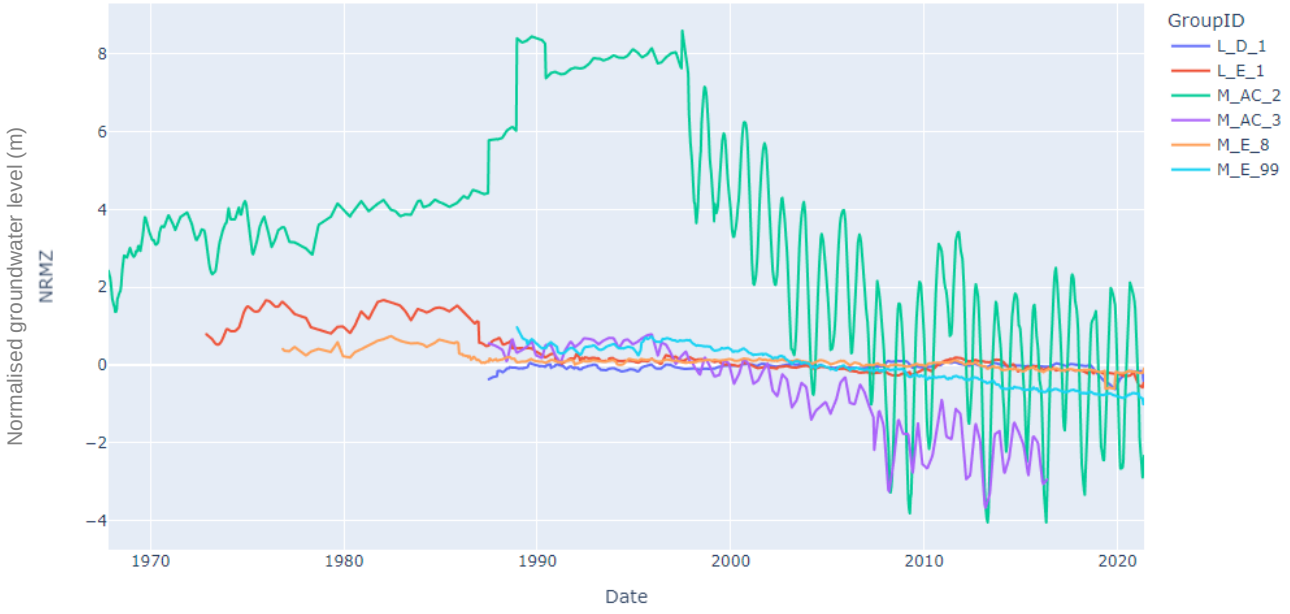


Figure 148 Murrayville GMA Suite Hydrographs for all confined aquifers

The representative Suite analysed for this GMU was Suite M_AC_2. The representative Suite was selected following the methodology outlined in section 2.6.4 and summarised as follows:

- The greatest volume of extraction occurring within the Middle Aquifer
- The Middle Aquifer pertains to the UMTA which is the intended aquifer for this GMU
- Suite M_AC_2 covers 56% of the GMU, M_AC_3 covers 5%, M_E_8 covers 22% and M_E_99 covers 18%
- Within the GMU, Suite M_AC_2 has six active SOBN bores, M_AC_3 has zero, M_E_8 has one and M_E_99 has one
- Suite bores for M_AC_2 are close to extraction points

The annual recovered Suite hydrographs for the representative Suites for Murrayville GMA M_AC_2 is shown in Figure 149.

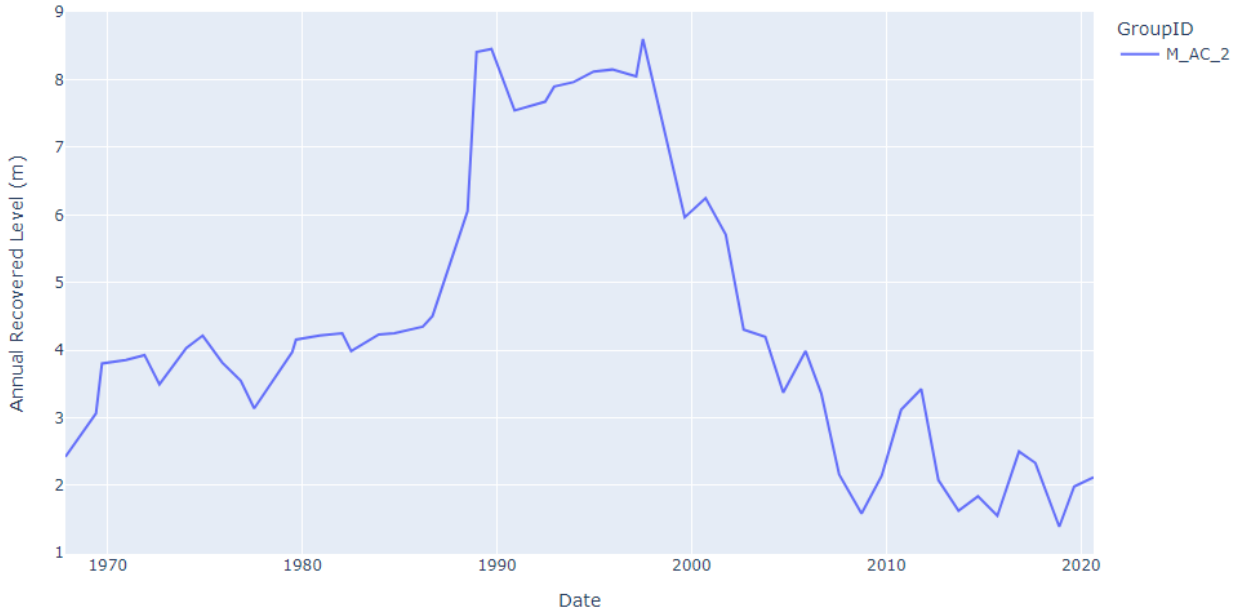


Figure 149 Murrayville GMA Annual Recovered Level Suite Hydrographs for representative Suites

13.2.2 Pre-development level

To estimate the pre-development level conditions, GHD reviewed the Suite hydrographs of annual recovered levels and assumed that the maximum levels in the early time series data was the best representation of conditions prior to major development within Murrayville GMA for Suite M_AC_2.

The pre-development annual recovered levels are taken to be the maximum level in the early time series data which equates to 8.60 m for Suite M_AC_2 in the year 1997/1998 (refer further details in section 13.4.3).

13.2.3 Externalities

As identified through the conceptualisation, Murrayville GMA may be influenced by extraction occurring in the Mallee Prescribed Wells Area (PWA) in SA. To test the influence of this extraction, data obtained from the Mallee PWA was incorporated into the model.

Figure 150 shows the Murrayville GMA annual groundwater extraction volumes, the Mallee PWA extraction volumes and the combined volumes. Note that where extraction does not occur in both Murrayville GMA and Mallee PWA, that year of data cannot be incorporated into the model without hindcasting. It is noted that the Murrayville GMA extraction only makes up around 14% of the combined extraction.

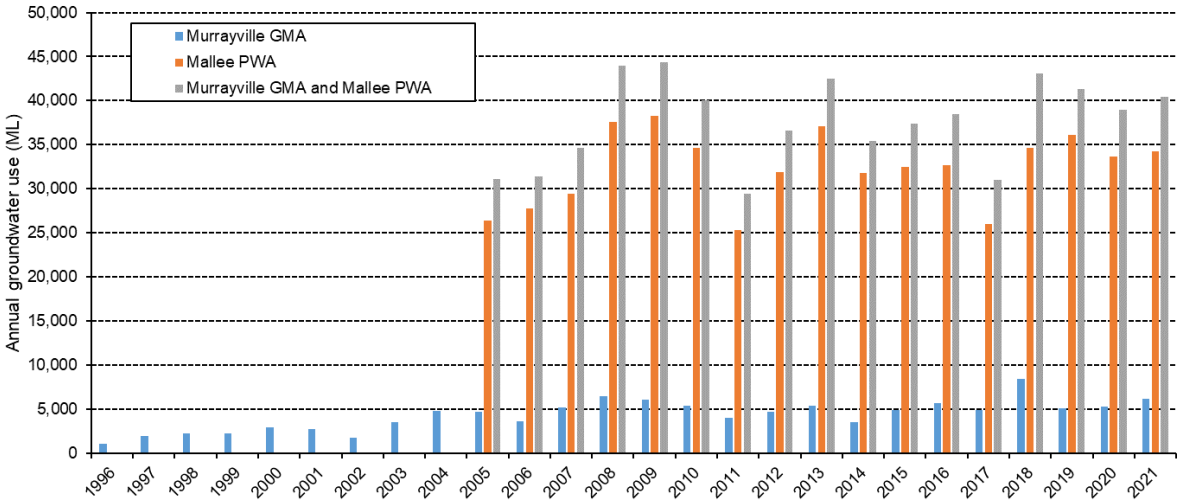


Figure 150 Murrayville GMA and Mallee PWA groundwater use

13.2.4 Hindcasting

Groundwater use data for Murrayville GMA is available between 1995/1996 and 2020/2021 and combined groundwater use for Murrayville GMA and Mallee PWA is available from 2004/2005 to 2020/2021. The hindcasting methodologies outlined in section 3.3.4.5 were applied to Murrayville GMA for only the combined extraction data of Murrayville GMA and Mallee PWA. A summary of the hindcasting results is provided in the following section.

13.2.4.1 Hindcasting Method 1 (H1)

Applying method H1, four different correlations were developed as described below and shown in Figure 151:

- Annual rainfall vs annual combined extraction at Murrayville GMA and Mallee PWA (external influence)
- Two yearly average annual rainfall vs annual combined extraction at Murrayville GMA and Mallee PWA (external influence)
- Annual summer period rainfall vs annual combined extraction at Murrayville GMA and Mallee PWA (external influence)
- Annual irrigation period rainfall vs annual combined extraction at Murrayville GMA and Mallee PWA (external influence)

As shown in Figure 151, the best goodness-of-fit result was shown to be the correlation of the annual rainfall with the combined annual groundwater extraction from Murrayville GMA and Mallee PWA. Thus, this was the correlation modelled for hindcast method H1.

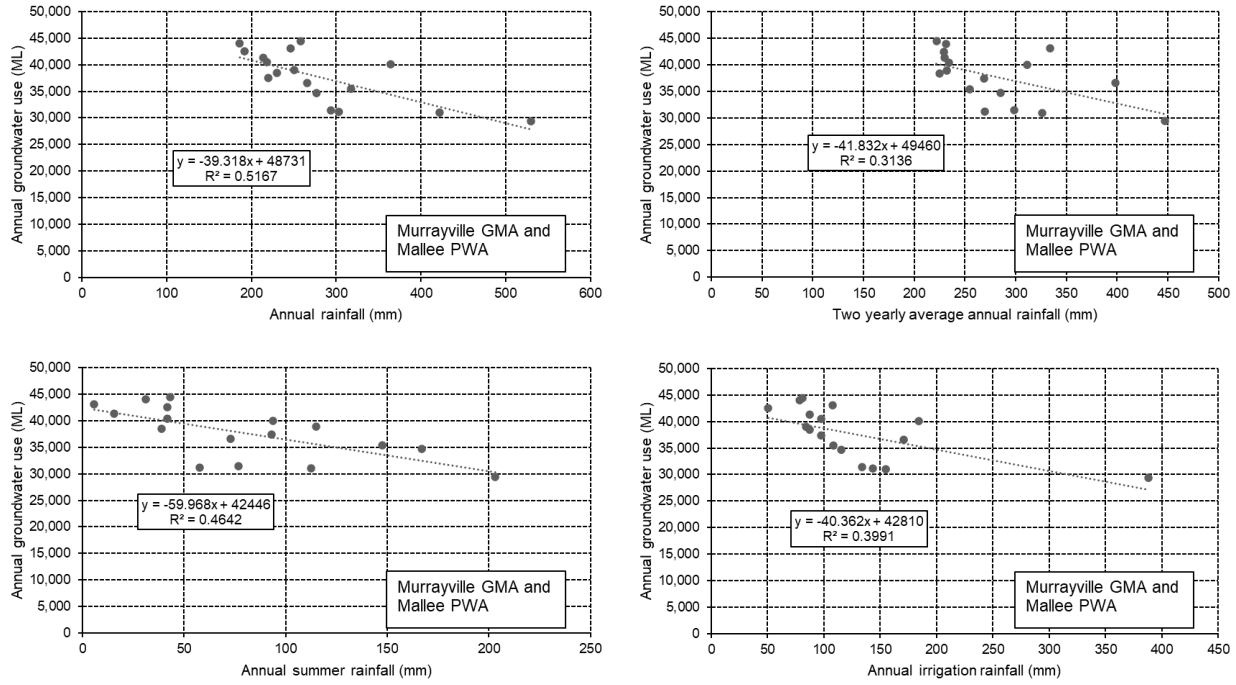


Figure 151 ***Murrayville GMA: Hindcast method 1 correlations (Murrayville GMA and Mallee PWA and annual groundwater use)***

13.2.4.2 Hindcasting Method 2 (H2)

Four correlations were developed using method H2 as described below and shown in Figure 152:

- Murrayville GMA and Mallee PWA use per Murrayville GMA bore vs annual rainfall
- Murrayville GMA and Mallee PWA use per Murrayville GMA bore vs two yearly average annual rainfall
- Murrayville GMA and Mallee PWA use per Murrayville GMA bore vs annual summer period rainfall
- Murrayville GMA and Mallee PWA use per Murrayville GMA bore vs annual irrigation period rainfall

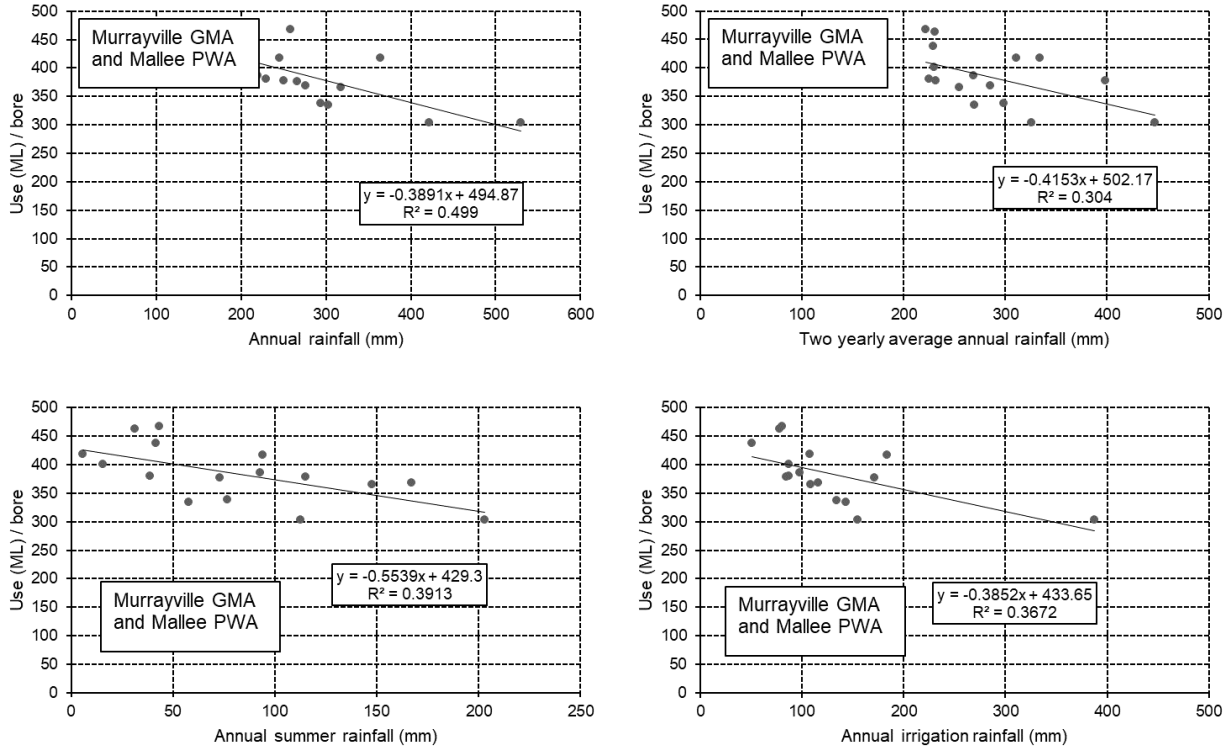


Figure 152 Murrayville GMA: Hindcast method 2 correlations

As shown in Figure 152 and similar to method H1, the best goodness-of-fit result was shown to be the correlation of the annual rainfall and combined Murrayville GMA and Mallee PWA use per bore. This was the correlation adopted for the hindcast method H2 modelling.

13.2.4.3 Hindcasting Method 3 (H3)

Hindcast method three cannot be applied when incorporating the external influence Mallee PWA due to the spatial entitlement data required. As Murrayville GMA only extraction does not require hindcasting, this method hasn't been considered as an input into the model on its own, however it is incorporated when taking into account spatial distribution as the extraction dataset commenced in 2009/2010 and thus hindcasting is required. In this respect, the hindcasting method was applied to the hindcasted use value on a bore by bore basis. Four correlations were developed using method H3 as described below and shown in Figure 153:

- Percentage of entitlement vs annual rainfall
- Percentage of entitlement vs two yearly average annual rainfall
- Percentage of entitlement vs annual summer period rainfall
- Percentage of entitlement vs annual irrigation period rainfall

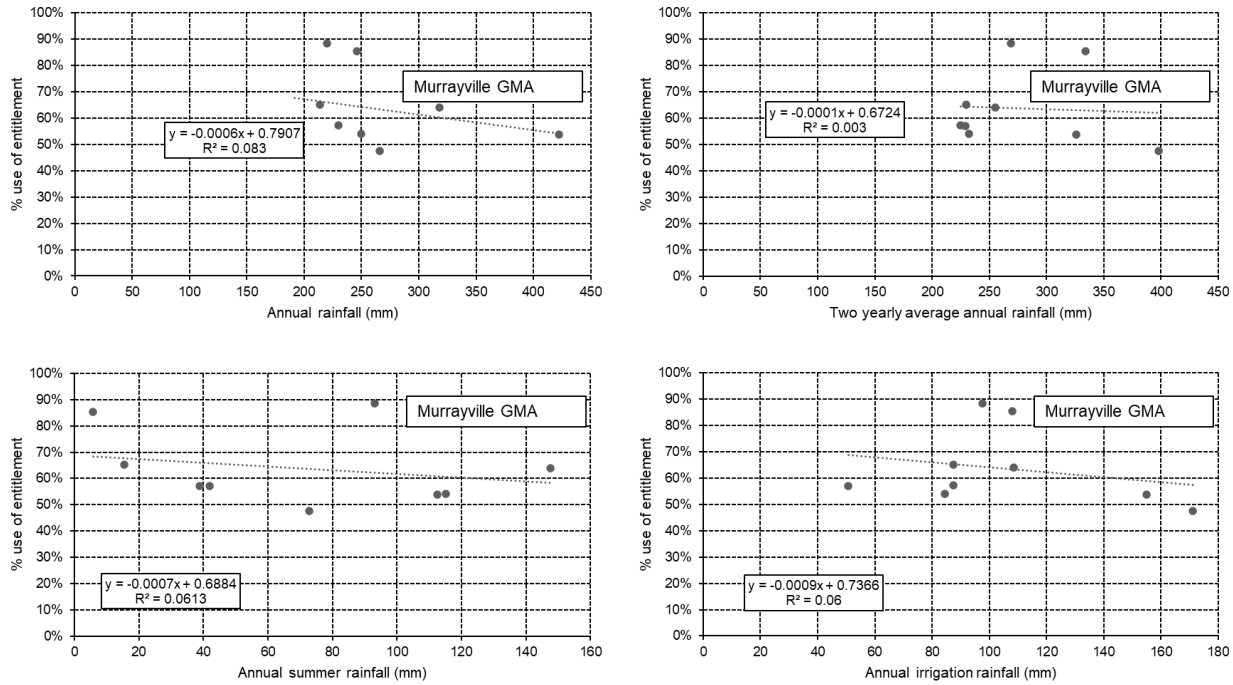


Figure 153 Murrayville GMA: Hindcast method 3 correlations

As shown in Figure 153 and similar to method H1 and H2, the best goodness-of-fit result for Murrayville GMA only extraction was very poor. From the four correlations developed, the relationship between annual rainfall and percentage use of entitlement was the best (albeit still a very poor fit). Due to the very poor fit, hindcast method H3 was not progressed due to high uncertainty in the input data and likely low confidence in resultant model data.

13.2.4.4 Comparison

A comparison of the three input datasets for hindcasting based on the combined Murrayville GMA and Mallee PWA groundwater use is shown in Figure 154 and Figure 155. Figure 154 shows a comparison of the three hindcasting methods against the recorded use only over the recorded use date and Figure 155 shows the hindcasted data back to 1995/1996.

As shown in Figure 155, groundwater use using method 1 does not decrease historically as there is no factor to account for the changing number of bores extracting over time and thus provides a higher groundwater extraction estimate than the method H2. The hindcasting results show that the smallest average variation of recorded use to estimated use occurs for method H1. This hindcasting method is expected to provide a more probable estimated groundwater use than the other method for Murrayville GMA over the period 2004/2005, but as it doesn't account for reduction in usage prior to this period due to the number of extraction bores, method H2 is likely to provide a better estimate prior to 2004/2005.

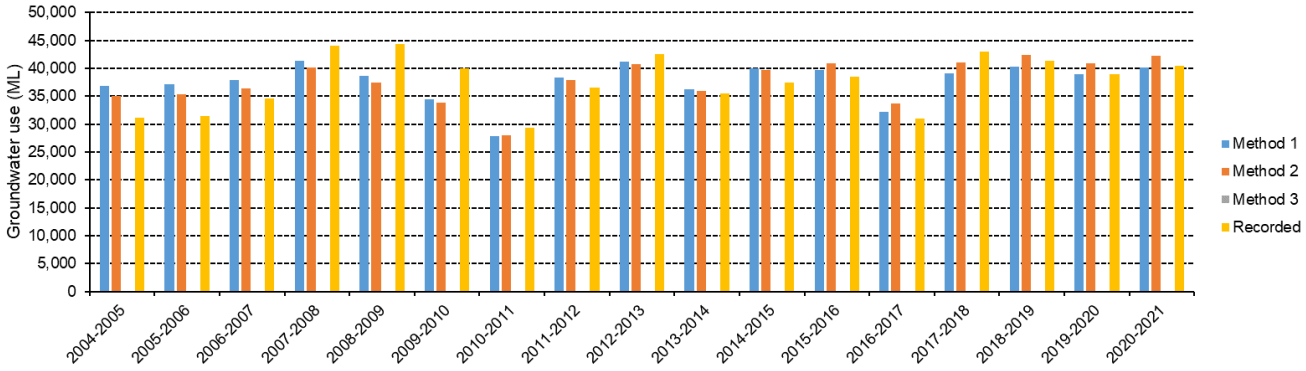


Figure 154 Murrayville GMA: Comparison of hindcasting over recorded use period – Murrayville GMA and Mallee PWA

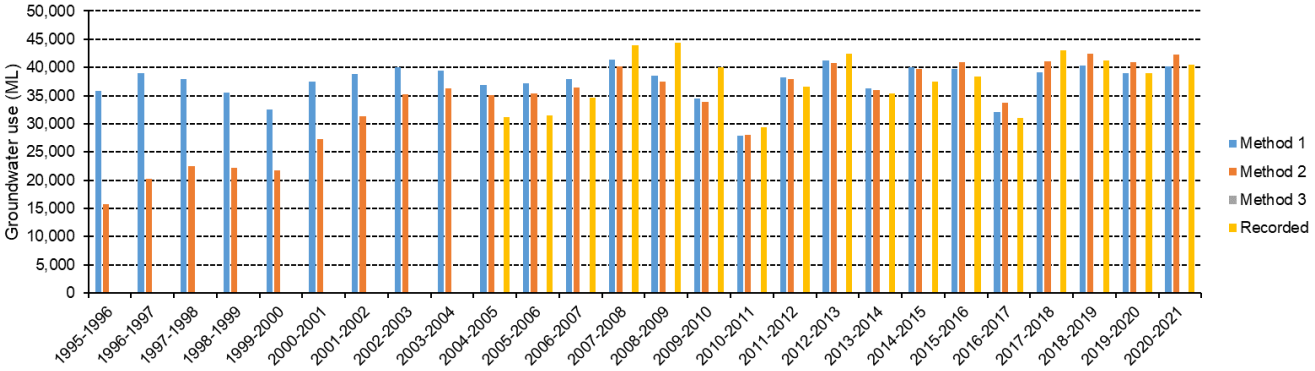


Figure 155 Murrayville GMA: Comparison of hindcasting – Murrayville GMA and Mallee PWA

13.3 Modelling

13.3.1 Model inputs

A number of different models were run based on the various model inputs developed and combinations of these. Table 63 summarises the combinations of model inputs run for Murrayville GMA. Model runs highlighted blue indicate they were run with annual extraction and grey indicates they were run using two yearly average annual extraction.

Table 63 Murrayville GMA: summary of model inputs

Model input	Model runs																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Annual recovered levels for representative Suites (M_AC_2)	✓	✓	✓	✓		✓		✓			✓		✓	✓	✓	✓			
Annual extraction – Murrayville GMA only	✓																		
Two yearly average annual extraction – Murrayville GMA only		✓																	
Annual extraction – Murrayville GMA and Mallee PWA			✓																
Two yearly average annual extraction – Murrayville GMA and Mallee PWA				✓															
H1 annual extraction – Murrayville GMA only																			
H1 annual extraction – Murrayville GMA and Mallee PWA						✓													
H2 annual extraction – Murrayville GMA only																			
H2 annual extraction – Murrayville GMA and Mallee PWA								✓											
H3 annual extraction – Murrayville GMA only																			
H1 two yearly average annual extraction – Murrayville GMA only																			
H1 two yearly average annual extraction – Murrayville GMA and Mallee PWA											✓								

Model input	Model runs																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
H2 two yearly average annual extraction – Murrayville GMA only																			
H2 two yearly average annual extraction – Murrayville GMA and Mallee PWA													✓						
S1 annual extraction – Murrayville GMA only														✓					
S2 annual extraction – Murrayville GMA only															✓				
S3 annual extraction – Murrayville GMA only																✓			
S1 annual extraction and H1 annual extraction – Murrayville GMA only																			
S2 annual extraction and H2 annual extraction – Murrayville GMA only																			
S3 annual extraction and H3 annual extraction – Murrayville GMA only																			

13.3.2 Model calibration and uncertainty analysis

A statistical summary of the model output results for the runs described in Table 63 is presented in Table 64 for the selection of potential representative Suites for Murrayville GMA. The column heading for M_AC_2 is highlighted blue to indicate that this Suite was selected as the most likely representative Suite based on the process outlined in section 13.2.1. The statistics summarised include four key statistical measures pf the average 95 PPU thickness (95PPU TH), percentage of observed levels within 95 PPU (%Obs in 95 PPU), R^2 and root mean square error (RMSE) as well as the number of annual recovered level observation points (No obs data points) and the range of observed annual recovered levels.

Suite M_AC_2

A review of the results and statistical summary for Suite M_AC_2 shows that model run 8 (highlighted green) shows the best result of the 11 different model input combinations. Model run 8 has the highest R^2 and percentage of observations within the 95% prediction interval bands. Although it doesn't have the smallest 95PPU thickness and RMSE (like model run 3), it includes a greater number of observations points. The graphical model output for this run is shown in Figure 156.

Model run 8 was selected for predictive modelling.

Table 64 Murrayville GMA: summary of model outputs

Suite	Statistic	Model run																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
M_AC_2	95PPU TH	3.34		1.75	nan		3.2		2.07			3.18		2.09	2.25	1.92	1.81	3.27	3.79	2.36
	%Obs in 95 PPU	100		93.75	0		96		100			100		96	100	100	100	100	12.5	100
	R^2	87.5		74.2	71.5		92.7		95.7			93		95.5	48	46.4	52.3	90.3	90.4	92.2
	RMSE	0.74		0.38	0.39		0.57		0.44			0.55		0.45	0.46	0.47	0.44	0.66	0.66	0.59
	No obs data points	25		16	25		25		25			24		24	25	16	16	25	25	25
	Range of observed levels	7.2		2.6	7.2		7.2		7.2			7.2		7.2	7.2	2.6	2.6	7.2	7.2	7.2

Notes:
The term ‘nan’ indicates a non-applicable metric, as the 95% prediction interval bands could not be estimated and thus the thickness could not be calculated

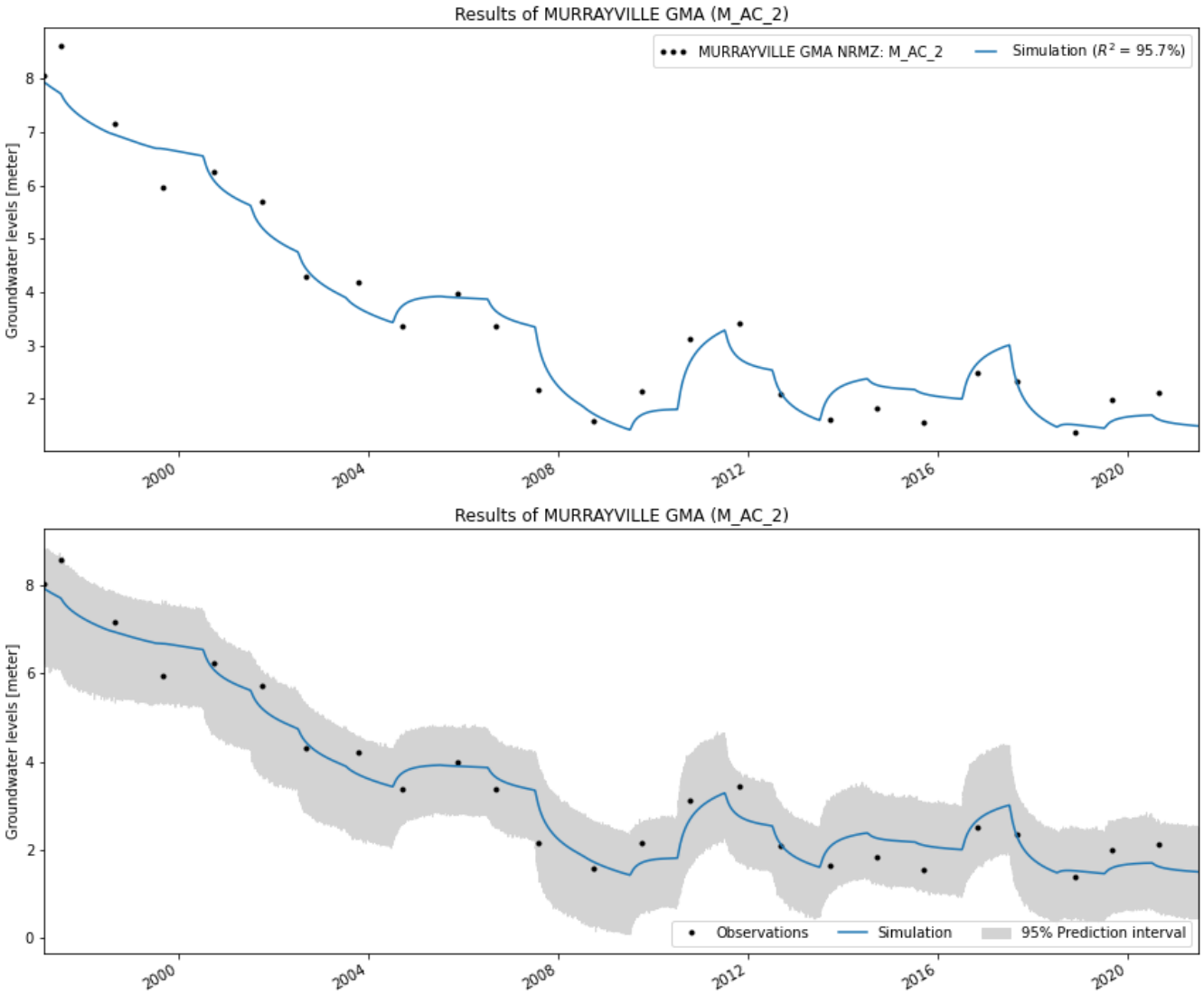


Figure 156 ***Murrayville GMA Suite M_AC_2: model run 3 (Murrayville GMA and Mallee PWA annual extraction with hindcast method H2) output hydrographs***

13.4 Predictive modelling

13.4.1 Model inputs

The preferred model to run the predictive modelling for Murrayville GMA was model run 8 for the representative Suite. The key inputs for the model were the annual recovered levels and the annual extraction in Murrayville GMA and Mallee PWA using hindcast method H2. To conduct the forecasting for the 19 scenarios discussed in section 3.5.3 a few factors were required in the calculations, as summarised in Table 65.

Table 65 Murrayville GMA and Mallee PWA combined: forecast scenario inputs

Input item	PCV	Licenced cap/entitlement	Existing use (based on 2020/2021)	Average use over recorded period (from GWMW and SA DEW)	Maximum use over recorded period (from GWMW and SA DEW, year 2008/09)
Combined Value (ML/year)	72,305	71,055	40,446	37,655	44,400

The model run 8 was run for all 19 forecast scenarios on Suite M_AC_2.

13.4.2 Predictive modelling uncertainty

The model output files of the predicted models can be found in the data package provided in Appendix E.

MCMC predictions were undertaken on each of the forecasted scenarios for each of the two Suites. An example of one of the outputs is presented in Figure 157 for scenario 8. As shown in Figure 157, uncertainty of the model prediction increased as the model predicts further into the future. Comparing with the graphical output for the same scenario, the MCMC realisations tend to fall within the 95% prediction interval bands as shown in Figure 158.

Uncertainty is also accounted for by using 19 forecast scenarios to develop a groundwater use to drawdown relationship (analogous to a Monte Carlo type simulation) where a range of possible outcomes are generated. It is noted however, that the forecast scenarios were not randomly generated, but rather based upon a series of estimated use behaviours.

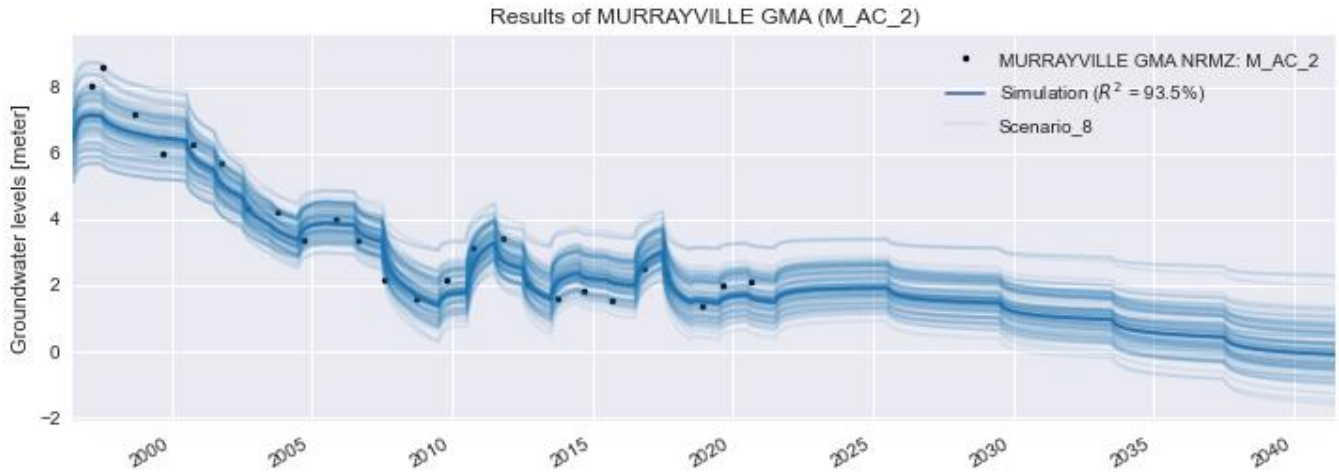


Figure 157 Murrayville GMA: Suite M_AC_2 MCMC analysis for Forecast Scenario 8

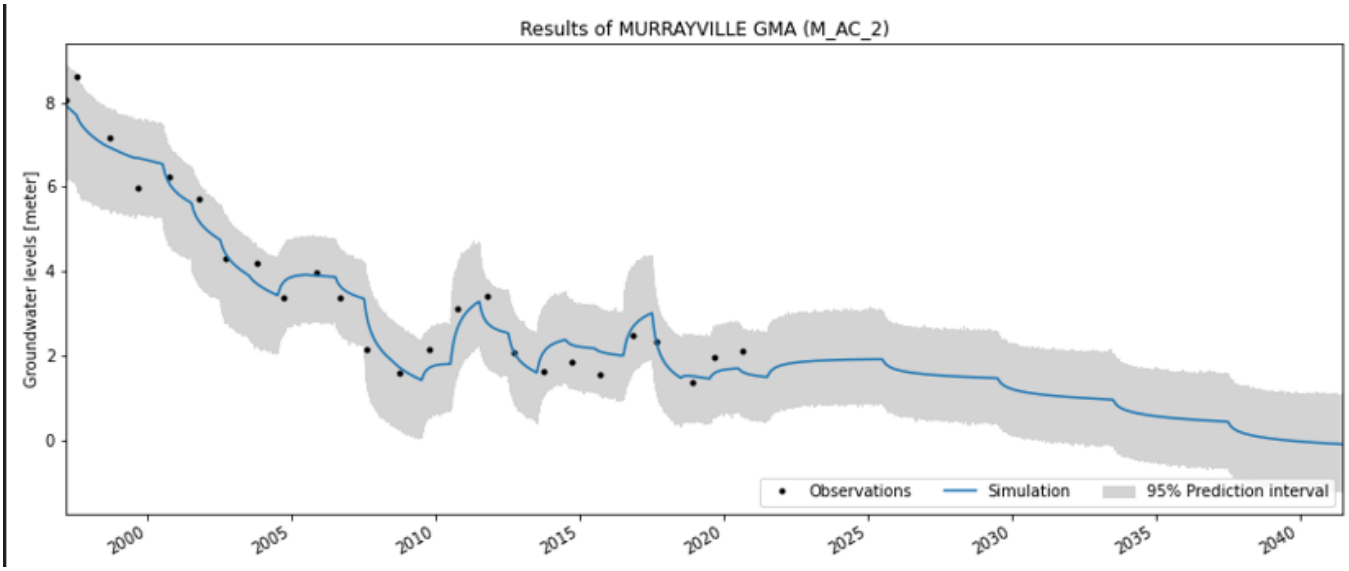


Figure 158 Murrayville GMA: Suite M_AC_2 Forecast Scenario 8 with 95% prediction bands

13.4.3 Extraction vs drawdown

Using the pre-development levels defined in section 13.2.2, the modelled water levels were converted into drawdowns (from this baseline pre-development level) for each of the 19 scenarios. This predevelopment condition is shown as annual recovered levels in Figure 159 for Suite M_AC_2. In Figure 159:

- Actual annual groundwater use for Murrayville GMA and Mallee PWA is represented by the blue column graph between 2004/2005 and 2020/2021
- Hindcasted groundwater use is represented by the orange columns between 1995/1996 and 2003/2004
- Forecasted use is represented by the grey columns after 2021/2022
- Annual recovered water level behaviour based on recorded data is represented by the red line graph, whereby the earliest data is taken to best reflect the pre-development levels
- In this case the pre-development annual recovered levels are taken to be the maximum level of the early time-series data which equates to around 8.6 m in 1997/1998
- Forecasted annual recovered levels are represented by the purple line in Figure 159
- The calibration annual recovered levels are represented by the black line in Figure 159

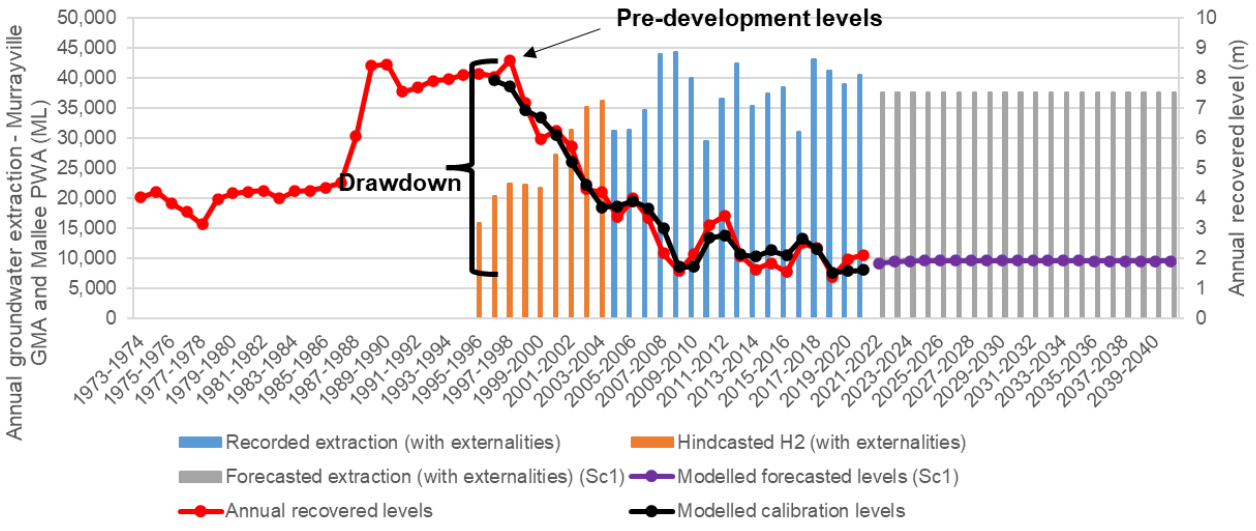


Figure 159 Estimating pre-pumping water levels (example from Suite M_AC_2)

For Suite M_AC_2, the volumes needed to be converted from a combined volume of Murrayville GMA and Mallee PWA to just a volume that represents Murrayville GMA. On average, Murrayville GMA extraction makes up 14% o of the combined volume based on the recorded datasets. As such 14% of the combined volume has been used in the use-drawdown relationships for Suite M_AC_2 when representing Murrayville GMA only extraction.

For Suite M_AC_2 using only Murrayville GMA extraction, calculated drawdowns and volumes for each of the scenarios were plotted in individual graphs for each scenario, all scenarios together in the one graph (Figure 160) and a graph of the scenarios for specific time periods (Figure 161) to develop the volume to drawdown relationship. For each scenario, a linear regression was applied and the coefficient of determination (R^2) was calculated. A comparison of each of these graphs shows no significant change in the coefficient of determination between Figure 160 and Figure 161, however, there were differences between individual scenario runs. As such, the relationship developed using all scenarios was adopted as it best captures this variation between forecast scenarios.

Also included is the plot of use-drawdown using the combined Murrayville GMA and Mallee PWA extraction as shown in Figure 162. Comparing Figure 160 and Figure 162, it shows there is not much different in the R2 but there is a change in the slope of the line of best fit as well as the intercept value.

Use-drawdown for all the 19 forecast scenario drawdowns and volumes (both the recorded and forecasted volumes) over each year modelled (1997 to 2041) is shown in Figure 160 for Suite M_AC_2. Note the abscissa range of the chart has been clipped and does not show forecast drawdowns for the higher use scenarios (more improbable). Reviewing these figures, the following is noted:

- There should be zero drawdown under zero use and therefore a line of best fit should pass through the origin (0,0) or close to it. In this instance, the difference between the modelled level and observed annual recovered level constributed to the intercept value.
- Average use is around 5,408 ML for Murrayville; Figure 160 indicates at these volumes the forecast model drawdown will lie relatively close to the predicted line of best fit
- For the same annual use, different drawdowns can be obtained as Pastas predicts a water level for each year. For example, Figure 159 shows a scenario where combined groundwater use in Murrayville GMA and Mallee PWA remains constant at around 38,000 ML/year over the next 20 years.
- The correlation for groundwater use and drawdown for Suite M_AC_2 is excellent as shown in Figure 160

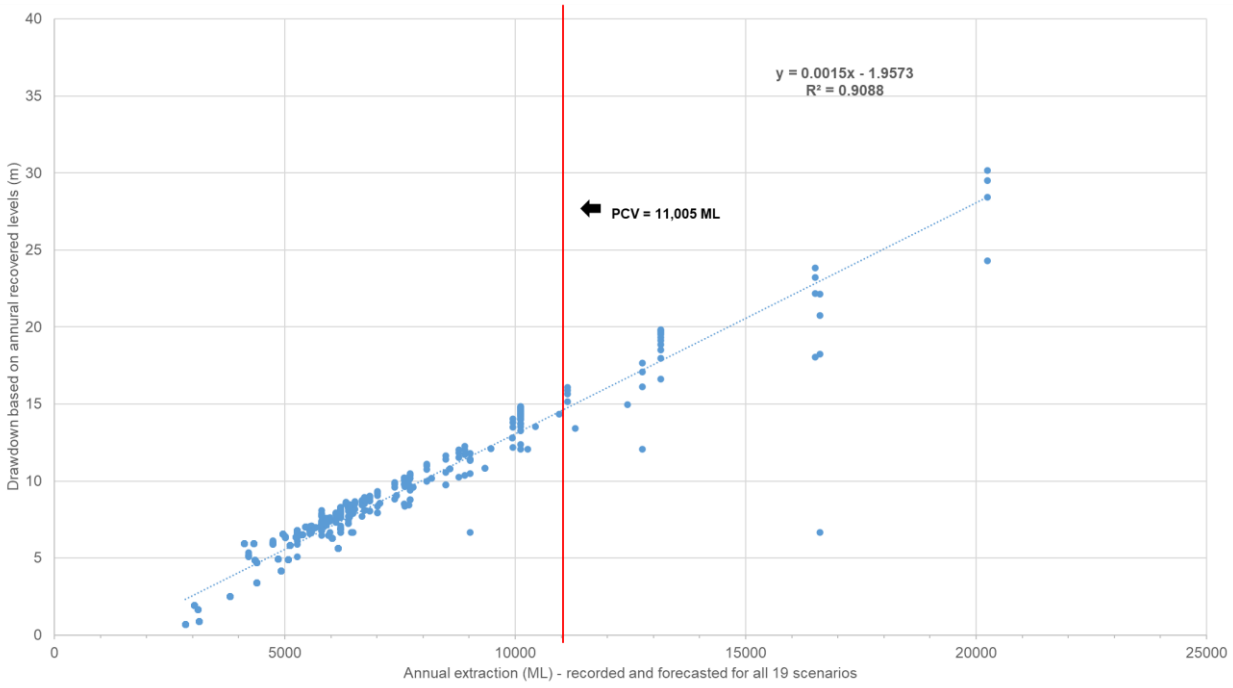


Figure 160 ***Murrayville GMA Suite M_AC_2: Drawdown (on annual recovered levels) and extraction volumes (recorded and forecasted <22,000 ML Murrayville GMA) for all data between 1997 to 2041 and all forecasted scenarios***

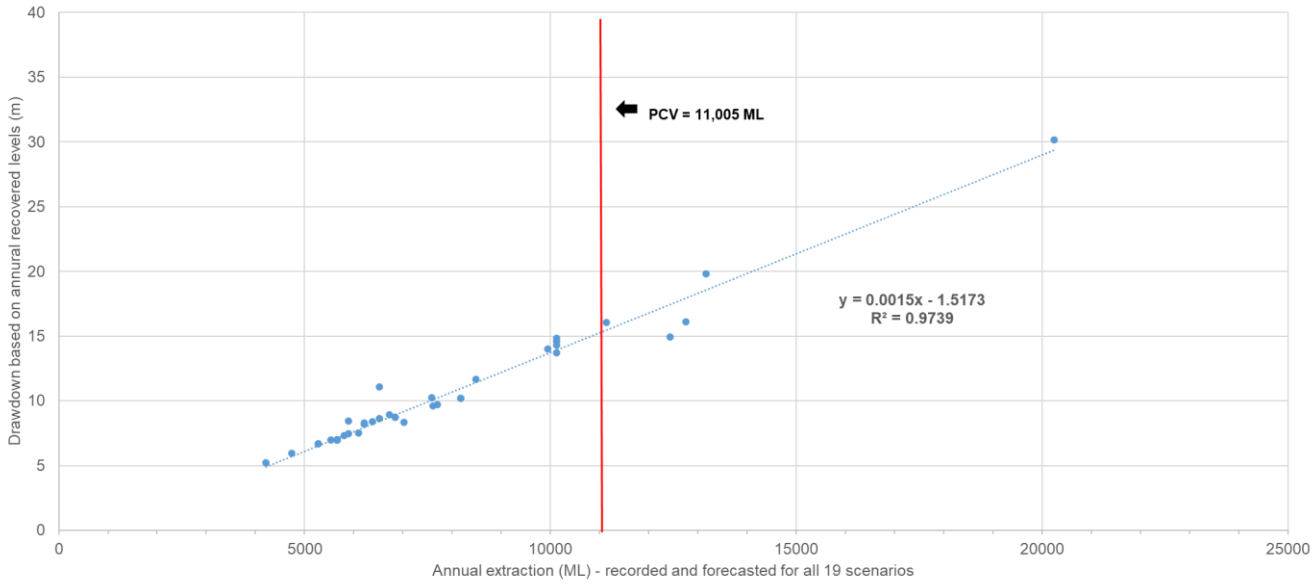


Figure 161 *Murrayville GMA Suite M_AC_2: Drawdown (on annual recovered levels) and extraction volumes (recorded and forecasted <22,000 ML Murrayville GMA) for years 2020/2021, 2030/2031 and 2040/2041 for all forecasted scenarios*

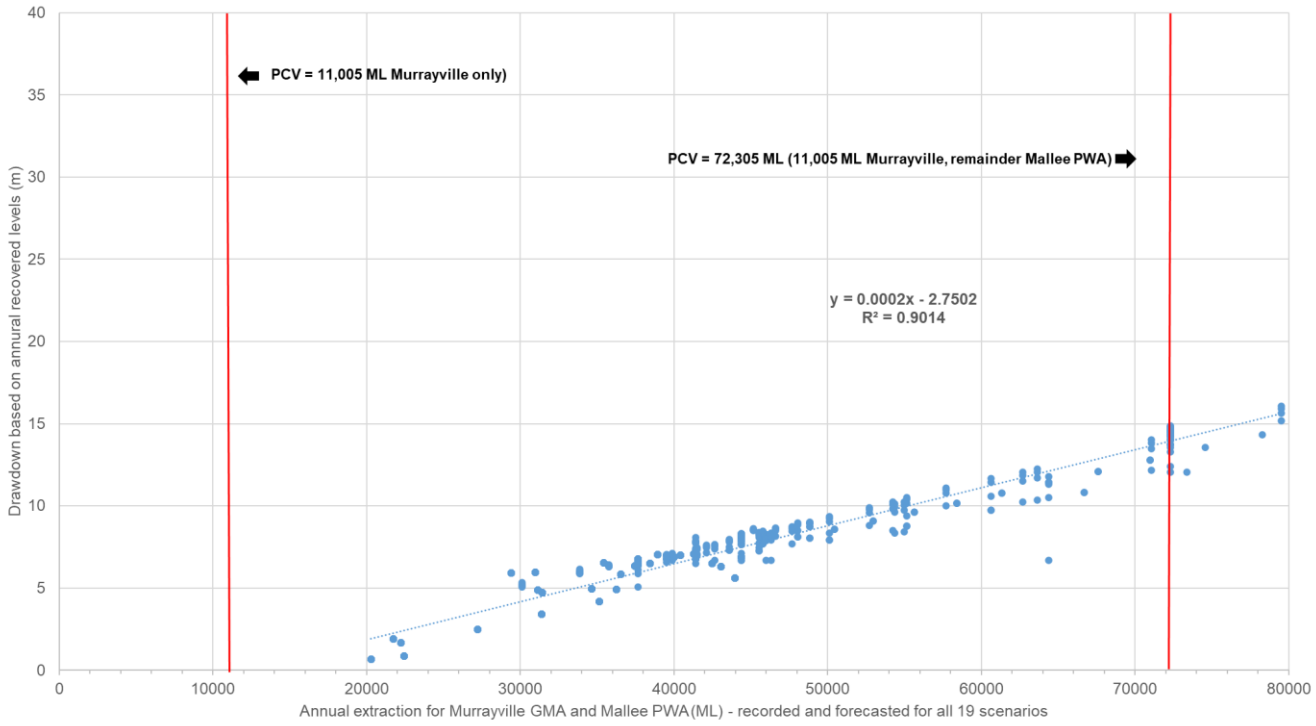


Figure 162 *Murrayville GMA Suite M_AC_2: Drawdown (on annual recovered levels) and extraction volumes (recorded and forecasted <80,000 ML for Murrayville GMA and Mallee PWA) for all data between 2005 to 2041*

13.5 Sustainability metrics

13.5.1 Application of metrics

Using the use - drawdown relationships developed through the previous step of forecasting aquifer response under a range of use scenarios, groundwater drawdown can be used to compare against groundwater resource sustainability metrics. The groundwater resource sustainability metrics applied to this study were developed by DEECA, as outlined in section 3.6.1.

The application of these metrics and the relationship developed between drawdown based on the Suite annual recovered levels and extraction volume for the whole GMU, which is shown in Table 66 for Murrayville GMA Suite M_AC_2 (noting Murrayville GMA has a current PCV of 11,005 ML). As part of the modelling, a 95% prediction interval band was applied to the modelling results. The relationship between drawdown and extraction volumes can also be interrogated at the lower and upper bands of the 95% prediction interval as shown in the bracketed values in Table 66 and in Figure 163. Figure 164 shows graphically and spatially by Suite the drawdowns associated with extraction rates.

As previously discussed, for Suite M_AC_2, the predicted model adopted was based on the combined extraction from Murrayville GMA and Mallee PWA. This was brought back to a Murrayville GMA only extraction for plotting the drawdown with extraction by taking 14% of the combined extraction (14% is the average portion of Murrayville GMA to the combined extraction based on recorded data). Table 66 shows the volume for Murrayville GMA to a given drawdown; the same table has been replicated for the combined use as shown in Table 67 (It is noted that this is the actually usage used in the predictive model).

A comparison of volumes at drawdown intervals provided by DEECA is shown in Table 68 for Suite M_AC_2. Based on the relationships developed, 5 m of drawdown is predicted to occur based on an extraction volume of 4,600 ML (but could vary from 4,100 to 5,200 ML) and 10 m of drawdown is predicted to occur based on an extraction volume of 8,000 ML (but could vary from 7,200 to 8,800 ML) based on Suite M_AC_2.

Table 66 *Relationship of Suite drawdown to GMU extraction for Murrayville GMA Suite M_AC_2*

Volume – whole of Murrayville GMA only (ML/year)	Based on model prediction of Suite M_AC_2 annual recovered levels
	Drawdown over 20 years
22,000	31 (28.5 - 33.6)
20,000	28 (25.7 - 30.4)
18,000	25 (22.9 - 27.2)
16,000	22 (20.1 - 24)
14,000	19 (17.3 - 20.8)
12,000	16 (14.5 - 17.6)
10,000	13 (11.7 - 14.4)
8,000	10 (8.9 - 11.2)
6,000	7 (6.1 - 8)
4,000	4 (3.3 - 4.8)
2,000	1 (0.5 - 1.6)
0	-2 (-2.3 - -1.6)

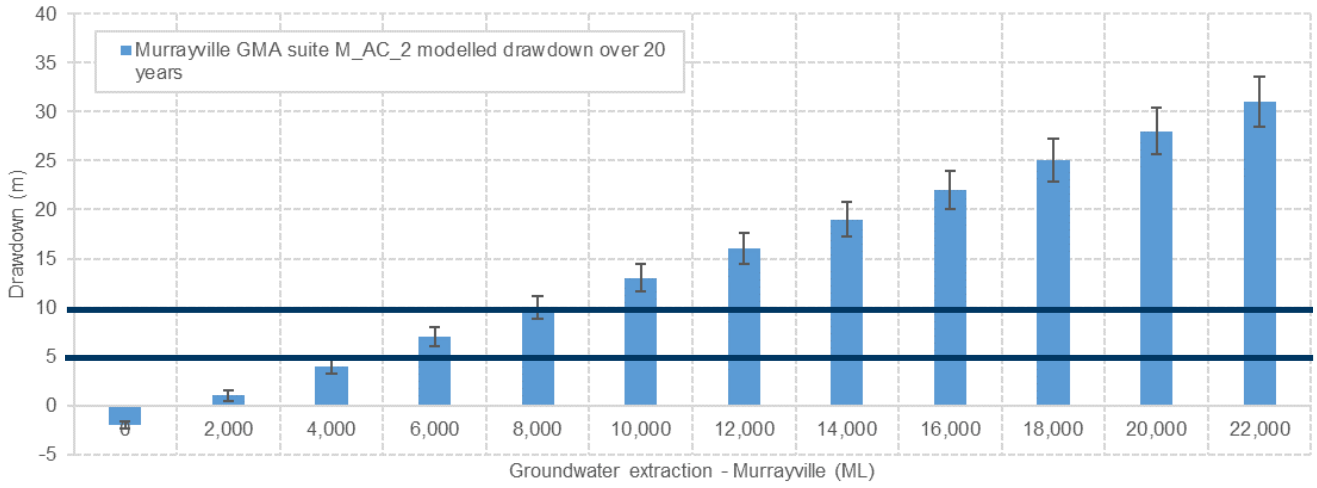


Figure 163 ***Murrayville GMA Suite M_AC_2: Relationship of Suite drawdown to extraction from Murrayville GMA (with error bars showing results of drawdown using levels from model's 95% prediction intervals)***

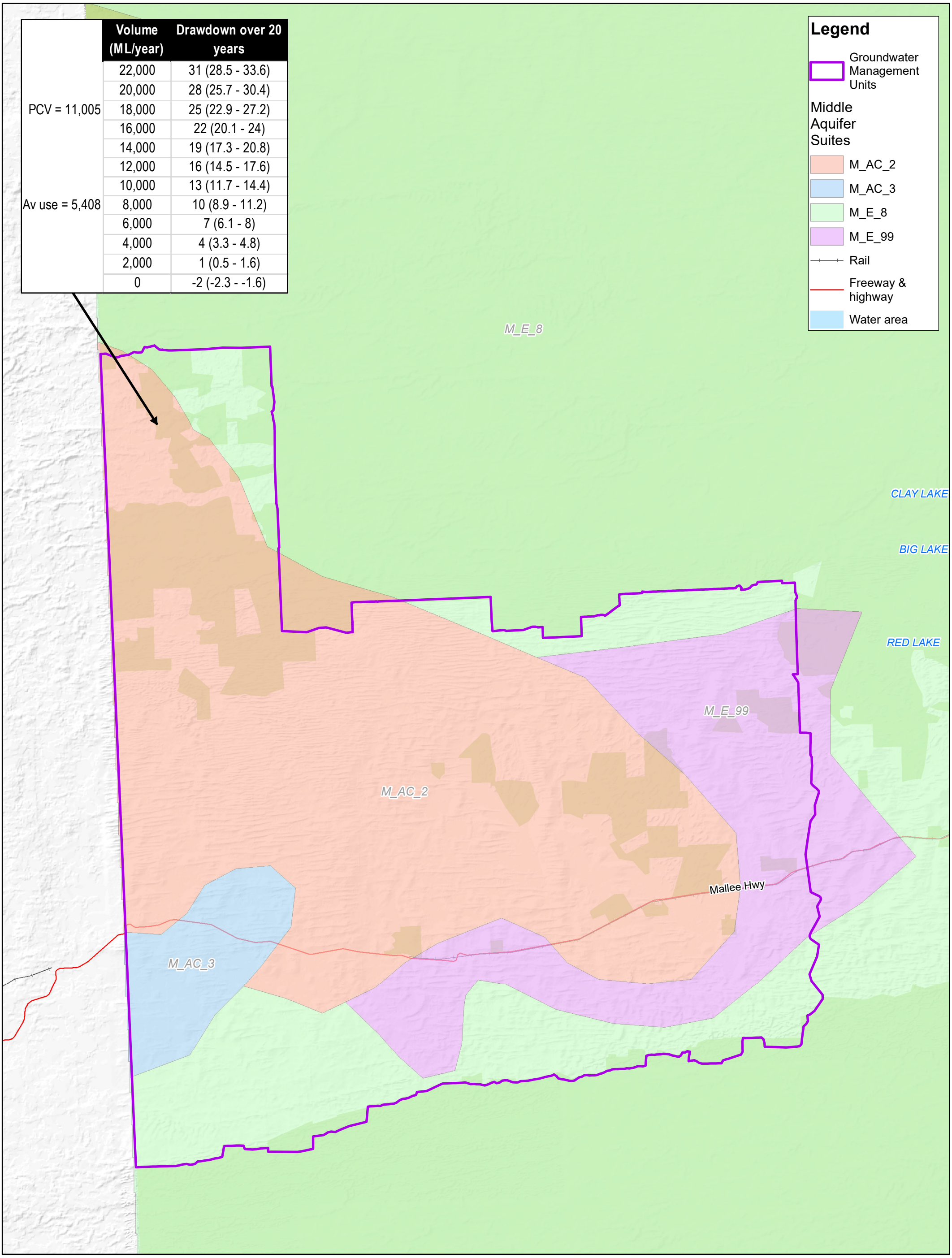
Table 67 Relationship of Suite drawdown to GMU extraction for Murrayville GMA and Mallee PWA for Suite M_AC_2

Volume – Murrayville GMA whole of GMU and Mallee PWA (ML/year)	Based on model prediction of Suite M_AC_2 annual recovered levels
	Drawdown over 20 years
70,000	11.2 (10.7 - 12.2)
65,000	10.2 (9.7 - 11.2)
60,000	9.2 (8.7 - 10.2)
55,000	8.2 (7.7 - 9.2)
50,000	7.2 (6.7 - 8.2)
45,000	6.2 (5.7 - 7.2)
40,000	5.2 (4.7 - 6.2)
35,000	4.2 (3.7 - 5.2)
30,000	3.2 (2.7 - 4.2)
25,000	2.2 (1.7 - 3.2)
20,000	1.2 (0.7 - 2.2)
15,000	0.2 (-0.3 - 1.2)
10,000	-0.8 (-1.3 - 0.2)
5,000	-1.8 (-2.3 - -0.8)
0	-2.8 (-3.3 - -1.8)

Table 68 Predicted volumes for drawdown metrics

Drawdown (m)	Predicted volumes for Murrayville GMA based on Suite M_AC_2 (lower limit to upper limit) (ML)
5	4,600 (4,100 – 5,200)
10	8,000 (7,200 – 8,800)

	Volume (ML/year)	Drawdown over 20 years
	22,000	31 (28.5 - 33.6)
	20,000	28 (25.7 - 30.4)
PCV = 11,005	18,000	25 (22.9 - 27.2)
	16,000	22 (20.1 - 24)
	14,000	19 (17.3 - 20.8)
	12,000	16 (14.5 - 17.6)
	10,000	13 (11.7 - 14.4)
Av use = 5,408	8,000	10 (8.9 - 11.2)
	6,000	7 (6.1 - 8)
	4,000	4 (3.3 - 4.8)
	2,000	1 (0.5 - 1.6)
	0	-2 (-2.3 - -1.6)



Paper Size ISO A3

0 4 8 12 16

Kilometers

DEECA
Sustainable Yields
Confined Aquifers

MURRAYVILLE GMA: KEY SUITES VOLUME VS DRAWDOWN

Project No. **31-12564066**
Revision No. **0**
Date **15/01/2024**

FIGURE 164

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Print date: 16 Jan 2024 - 09:22

Data source: DELWP, VicMap, 2022; DELWP GMU locations, 2022; SKM, suite obs bore locations, 2013; DELWP, extraction bore locations, 2022; GHD, aquifer suites, 2018; Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.
Created by: cperyer

13.6 GMU summary

13.6.1 Findings

Murrayville GMA primarily relates to the Murray Group Limestone (UMTA) and groundwater is predominately extracted from this aquifer for irrigation purposes. The UMTA falls within the Middle Aquifer Suites, which comprise M_AC_2 (56%), M_AC_3 (5%), M_E_99 (18%) and M_E_8 (22%) in Murrayville GMA, providing a total coverage of 100%. The identified representative Suite is M_AC_2. The Suite hydrograph for the representative Suite shows an overall decreasing trend along with seasonal fluctuation and thus recovered water levels, which were adopted for the assessment.

As identified through the conceptualisation, Murrayville GMA may be influenced by extraction occurring west of the GMU in SA from the Mallee PWA. Extraction occurring from the Mallee PWA makes up around 86% of the total extraction when the two datasets are combined. Comparing the Murrayville GMA only model run with the combined Murrayville GMA and Mallee PWA, the combined extraction model run showed a better goodness-of-fit. Based on these results, it was considered that this external influence should be included in the predictive modelling.

Application of two yearly annual average extraction, instead of annual average, generally showed a poorer model fit based on the statistical analysis across the model runs without hindcasting and in one case, the model failed to run. When hindcasting methods were applied with the two-yearly average, the model results were similar. The best match using the two yearly average annual extraction was model run 13 for Suite M_AC_2, which comprised two yearly average annual extraction for Murrayville GMA and Mallee PWA with hindcast method 2 applied and annual recovered levels.

The application of spatial distribution produced a poorer model fit than the model run using only the annual recorded groundwater usage for Murrayville GMA and Mallee PWA. The quality of the result (improved statistical measures) did not increase when spatial distribution methodology was combined with hindcasting methodology.

Based on an assessment of all model runs, the model run 8 of Murrayville GMA and Mallee PWA annual extraction using hindcast method H2 with the annual recovered levels was adopted to undertake the predictive modelling for Suite M_AC_2. The pre-development levels were defined for the representative Suite based on the maximum levels in the early time series data for annual recovered levels; this resulted in a pre-development level of 8.6 m for Suite M_AC_2. The drawdowns were calculated based on these pre-development levels and the simulated levels from each of the 19 forecast scenarios.

The volumes estimated for a given drawdown for each Suite is shown below.

Drawdown (m)	Predicted volumes for Murrayville GMA based on Suite M_AC_2 (lower limit to upper limit) (ML)
5	4,600 (4,100 – 5,200)
10	8,000 (7,200 – 8,800)

The model for Suite M_AC_2 was assessed as having an “Excellent” model applicability rating using the criteria outlined in section 5.2. The model is based on a combined extraction regime from both Murrayville GMA and Mallee PWA but this was brought back to a Murrayville GMA use based on the average proportion of Murrayville GMA extraction in the combined use dataset. The resultant relationship of use-drawdown makes sense given the historical extraction and observed drawdowns.

13.6.2 Limitations

In addition to the limitations applicable to all 25 GMUs discussed in section 1.8, the following Murrayville GMA specific limitations have been identified:

- Groundwater use for Mallee PWA was not incorporated into the spatial distribution modelling methodology
- Groundwater extraction data is not available from the period of commencement of licenced groundwater extraction in the GMU
- The spatial use dataset is missing recorded groundwater use data for Murrayville GMA for two years of data (2009/10 and 2010/11)
- The licenced bore dataset provided by DEECA has 8% of bores assigned to Murrayville GMA with no depth data, which were not assigned to a VAF layer and in turn Suite. These bores were assigned to an aquifer and Suite by GHD for this study, based on the primary aquifer that extraction occurs from for this GMU.
- The results have the modelled levels using Murrayville GMA and Mallee PWA extractions, but the volumes stated are Murrayville GMA only in the use-drawdown graphs. When extraction of Murrayville GMA and Mallee PWA are combined annually, on average, Murrayville GMA extraction makes up 14% of this thus 14% of the combined volume has been used in the final relationship.

13.6.3 Recommendations

In addition to the recommendations applicable to all 25 GMUs discussed in section 32, the following Murrayville GMA specific recommendations have been identified:

- To address the above bore depth data limitation, it is recommended that DEECA obtains the relevant depth and aquifer monitored data for licenced bores within this GMU
- The missing groundwater use information for the spatial dataset for years 2009/10 and 2010/11 should be identified and incorporated

14. West Wimmera GMA

14.1 Conceptualisation

The hydrogeological conceptualisation elements relevant to this study are summarised in Table 69 and a map of the GMU is presented in Figure 165. It is noted that a significant volume of information was collated to inform the hydrogeological conceptual understanding of the GMU. The information that is directly relevant to the modelling are in bold or colour coded within Table 69.

Table 69 West Wimmera GMA – Tabulated conceptualisation

GMU summary

West Wimmera GMA is situated in western Victoria, bordered in the north by the Murrayville GMA, the east by the Wimmera River, Lankoop and Harrow in the south and the South Australian border in the west; it covers an area of approximately 17,251 km^2. The GMA covers four surface water drainage divisions – the Mallee, Wimmera-Avon, Millicent Coast and the Glenelg. The Little Desert National Park and Big Desert Wilderness Area occur within this GMA.

West Wimmera GMA pertains to all formations below the ground surface, but was intended to primarily manage the groundwater resource of the shallow Pliocene Sands Aquifer (Upper Tertiary Aquifer, UTAM), the Tertiary Limestone Aquifer (Upper-Mid Tertiary Aquifer, UMTA) and the deeper Tertiary confined sand aquifer (Lower Tertiary Aquifer, LTA). It is noted that the Tertiary Limestone Aquifer (UMTA) is the most significant aquifer in the region and most of the groundwater extracted within the West Wimmera GMA is from this aquifer. The Tertiary Limestone Aquifer is generally unconfined, becoming partially confined by the overlying Bookpurnong Beds to the north and east. A number of sink holes and karstic features occur in the south-west of the area which recharge this aquifer (GWMWater 2011).

West Wimmera GMA has six sub-zones, each with a different basis for establishment (GWMWater 2011):

– Big Desert Zone: the land is not for commercial or agricultural development as comprises the Big Desert and adjacent conservation zones
– Gymbowen Zone: yield of aquifer in this zone reduces from west (adjacent Neuarpur) to east
– Little Desert Zone: the land is not for commercial or agricultural development as comprises the Little Desert National Park and adjacent public land
– Neaurpur Zone: the area is a zone of intense use and declining groundwater levels
– Northern Zone: this area has stable groundwater levels
– Southern Zone: the aquifer is lower yielding than the adjacent Neuarpur

The PCV for West Wimmera GMA (57,409 ML/year) relates to both unconfined and confined aquifers and is determined as the sum of the PCVs of the six sub-zones. Sub-zones and sub-zone PCVs are set for either the Tertiary Limestone Aquifer or the Tertiary confined sands aquifer, as shown in Table 70.

Table 70 Summary of PCV limits for West Wimmera GMA (adapted from PCV Order 2013)

Zone	Sub-zone	Pliocene Sands Aquifer PCV (ML)	Tertiary Limestone Aquifer PCV (ML)	Tertiary Confined Sands Aquifer PCV (ML)	Total PCV (ML)	
					Sub-zone	Zone
Big Desert		0	25	0		**25**
Gymbowen		50	2,000	200		**2,200**
Little Desert		0	25	0		**25**
Neuarpur	Sub-zone 1	0	20,700	200	20,900	**25,150**
	Sub-zone 1	0	4,050	200	4,250	
Northern		50	22,390	500		**22,940**
Southern	Apsley	0	2,901	200	3,101	**7,019**
	Langkoop	0	2,000	100	2,100	
	Ullswater	50	888	100	1,038	
	Edenhope	50	680	50	780	
Total			**55,659**	**1,550**		**57,409**

West Wimmera GMA is subject to seasonal allocation restrictions. In 2018/19 the seasonal allocation was 100% for all zones except for Neuarpur Sub-Zone 1, which was restricted to 80% of entitlement volume. Similar restrictions were in place in previous years.

Groundwater in the GMA is predominately used for irrigation, urban water supply and stock and domestic. Commercial use also occurs including that for feedlots, piggeries and poultry (GWMWater 2011[5]). Extraction for irrigation purposes occurs primarily in an area within 40 km from the South Australia border due to the higher yield and better quality of groundwater in that area (GWMWater 2011). Types of irrigation crops that utilise groundwater within this GMA include potatoes, onions, carrots and olive trees (GHD 2020).

A compilation of the views and values of Traditional Owners has been prepared for this region, which takes into account culture-based values of water. Aboriginal values and objectives should be considered in future Victorian water management and planning in this region (DEECA 2019).

Hydrostratigraphy summary

Aquifer	Formation	Relevant Suites (% coverage of GMU)	% of GMU covered by Suites	Number of SON bores	Groundwater use	Use volumes ML (2019/20)	Entitlement volumes ML (2019/20)	Understanding (Low, Medium, High)
Upper	Woorinen Formation (QA)	-	-	0	NA	0	0	Low
	Shepparton Formation (UTQA)	-	-	1	NA	0	0	Low
	Loxton – Parilla Sand (UTAM)	U_BA_9 (0.3%), U_BC_88 (15%), U_BF_99 (11%), U_BI_8 (62%), U_E_1 (8%), U_H_9 (0.4%), U_J_2 (2%), U_J_4 (0.3%)	100%	23	Irrigation, stock	65	630	High
Middle	Bookpurnong Beds (UTD)	-	-	0	Irrigation, industrial, domestic, stock	0	0	Low
	Murray Group Limestone/Duddo Limestone (UMTA)	M_AD_1 (3%), M_AE_1 (1%), M_AF_1 (1%), M_E_1 (5%), M_E_8 (87%), M_E_99 (1%) M_J_2(1%)	98%	57	Urban, industrial, commercial, irrigation, stock, domestic	20,911 (179)	44,616 (1,744)	High
	UMTD	-	-	1	Urban, irrigation, domestic, stock	0	0	Low

[5] GWMWater 2011, West Wimmera Groundwater Management Strategy, June 2011

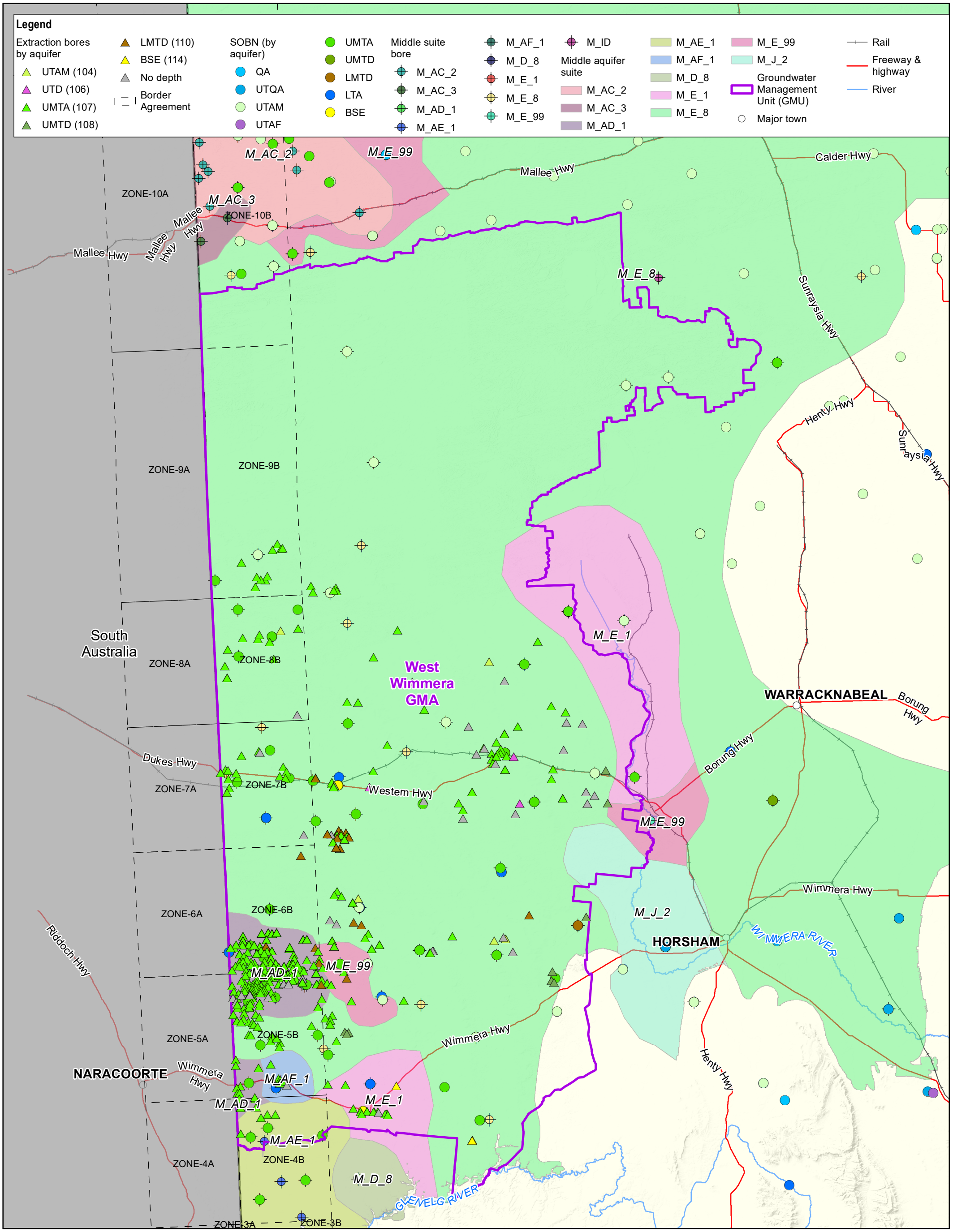
Lower	Etrick Marl (LMTD)	-	-	1	Irrigation	0	0	Low
	Renmark Group (LTA)	L_AE_1 (7%), L_AF_1 (5%), L_D_1 (70%), L_D_2 (2%), L_E_1 (14%),	98%	19	Irrigation	0 (2,247)	0 (4,843)	High
Basement	Basement rocks	B_B_8 (30%)	30%	2	Urban	0	0	Low

Note that volumes listed above are based on the DEECA provided licenced bore dataset with associated VAF layers. Bores have been assigned to a VAF layer based on bore depth where available. It is noted that 76 ML has been reassigned from UTD to UMTA, 103 ML has been reassigned from UMTD to UMTA, 2177ML has been reassigned from LMTD to the LTA and 70ML has been reassigned from the Basement to LTA (as indicated by the values in brackets); this is based on feedback from GWMW and that the aquitards are unlikely to have extraction from them.

Note that volumes listed above do not include 1,297 ML of unassigned use due to unknown depths (3,545 ML of entitlement).

Characteristic and importance	Description	Degree of understanding
Intended aquifer		
Aquifer thickness within GMU (range, based on VAF)	UTAM Min: 0 m, Max: 142 m, Average: 43 m UMTA Min: 0 m, Max: 175 m, Average: 91 m UTAF Min: 0 m, Max: 278 m, Average: 91 m	High
Aquifer extent	UTAM: Regional, extensive UMTA: Regional, extensive LTA: Regional, extensive	High
Likelihood of inter-aquifer flow	Low	Low
Likelihood of groundwater – surface water interaction	Low	Low
Representative Suite	**M_AD_1**	**Medium. 56% of GMU extraction occurs within this Suite, which relates to the most relevant GMU aquifer.**
Current hydrological condition of representative aquifer		
Representative Suite trend	Decreasing	High
Groundwater quality (average salinity based on WMIS and CDM Smith spatial segment(s) with highest coverage)	Variable spatially	Low Based on VAF 107 CDM Smith (2022)
Groundwater yield	Variable spatially	Low Based on VAF 107 CDM Smith (2022)

Characteristic and importance	Description	Degree of understanding
Groundwater levels		
Temporal groundwater level data range	**1976-2021**	
Spatial clustering of licensed bores in relation to Suites	**Yes, M_AD_1**	**Based on DEECA density mapping and licenced bore data.**
Groundwater use		
Licensed groundwater use	22,033 ML	High (Based on average historical VWA data over 10 years)
Minimum historic groundwater use	15,601 ML	High (Based on historical VWA data, year 2011/12)
Maximum historic groundwater use	**27,310 ML**	**High (Based on historical VWA data, year 2017/18)**
Entitlement (Groundwater allocation)	**53,358 ML**	**High (Based on licenced volumes in 2020/21)**
Significant drivers of groundwater level variability (primary)	Pumping for irrigation	Moderate
Secondary drivers of groundwater level variability	Pumping for town water supply	Moderate
Groundwater use profile	Seasonal (~Oct-Apr irrigation season)	Low
External Influence	**Border zone extraction (zones 4A to 10A)**	
Groundwater values and risks		
Existing Environmental Values to be protected, relevant to this GMU	Potable water supply Licensed non-potable supply (irrigation, commercial, industrial) Unlicensed non-potable supply (domestic and stock)	
Risks to groundwater values	Direct risks: – Drawdown which may affect access to groundwater by existing users	Moderate
Indicators used to assess impacts to groundwater	– Measured drawdown using pre-determined metrics measured from a pre-determined level for the purpose of this modelling	Moderate



Paper Size ISO A3

0 5.5 11 16.5 22

Kilometers

Map Projection: Lambert Conformal Conic
Horizontal Datum: GDA 1994
Grid: GDA 1994 VICGRID94

N

GHD

DEECA
Sustainable yield review - confined aquifers

West Wimmera GMA
Site location and key features

Project No. **12564066**
Revision No. **0**
Date **16/01/2024**

Figure 165

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Print date: 16 Jan 2024 - 12:49

Data source: DELWP, VicMap, 2022; DELWP, GMUs, 2022; DELWP, SOBN, 2022; GHD, aquifer suites, 2018; DELWP, extraction bores, 2022; DWLBC, border agreements, 1998 Created by: cperyer

14.2 Technical analysis

14.2.1 Hydrograph review and selection of representative Suites for further analysis

Suite hydrographs were generated for the relevant Suites for West Wimmera GMA as shown in Figure 166, Figure 167 and Figure 168. Generally, the Suite hydrographs show the seasonal fluctuations and hence recovered water levels with all Suites generally showing a declining trend with time. Suites B_B_8 and L_AE_1 both show an increase in levels in recent times.

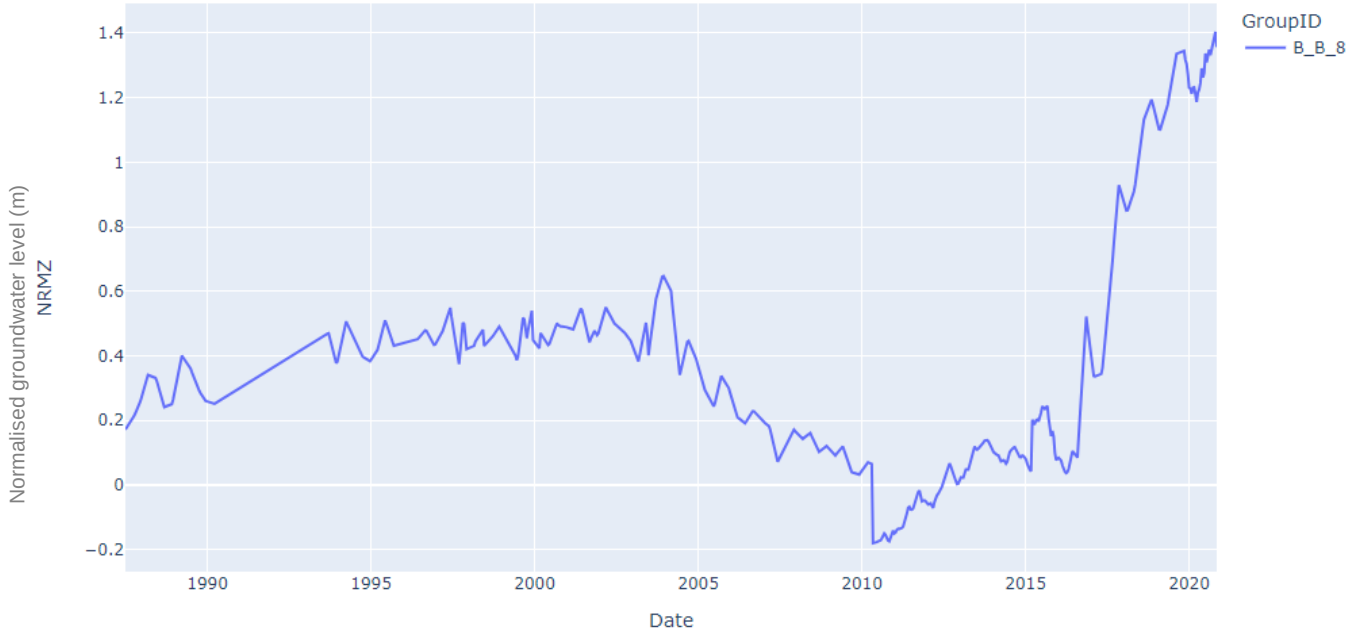


Figure 166 *West Wimmera GMA Suite Hydrographs for all confined Basement aquifers*

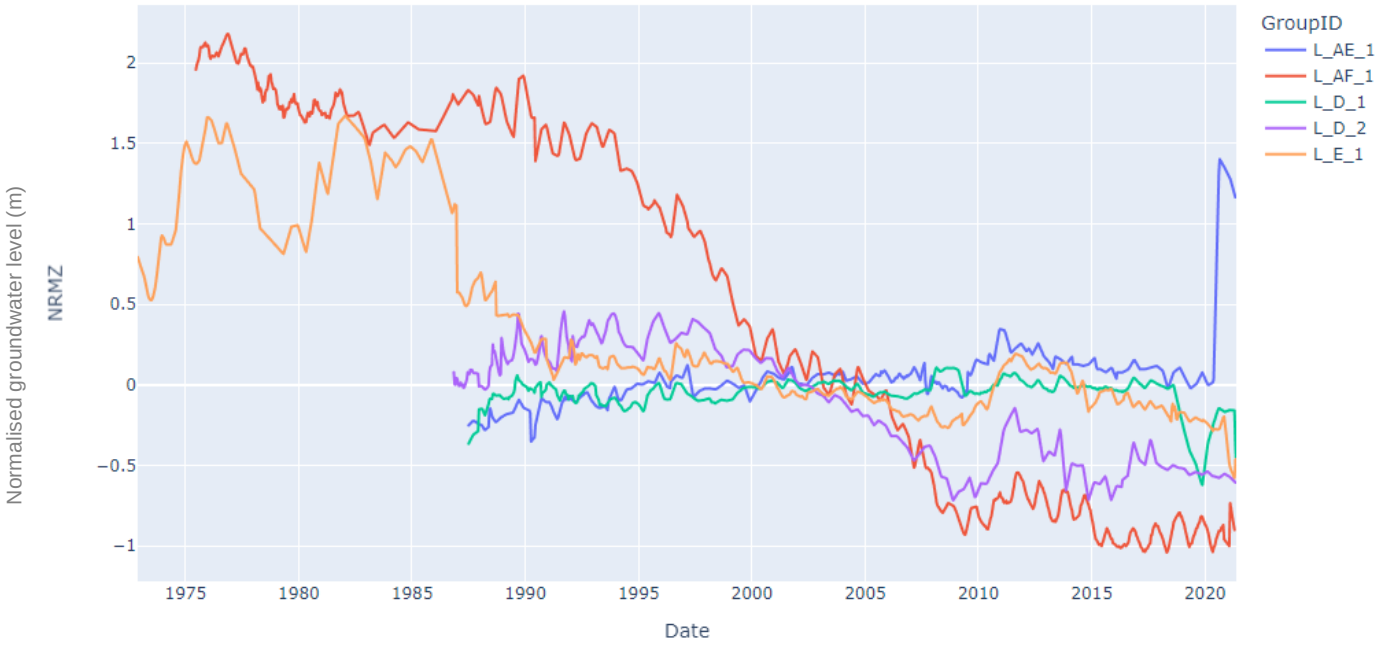


Figure 167 *West Wimmera GMA Suite Hydrographs for all confined Lower aquifers*

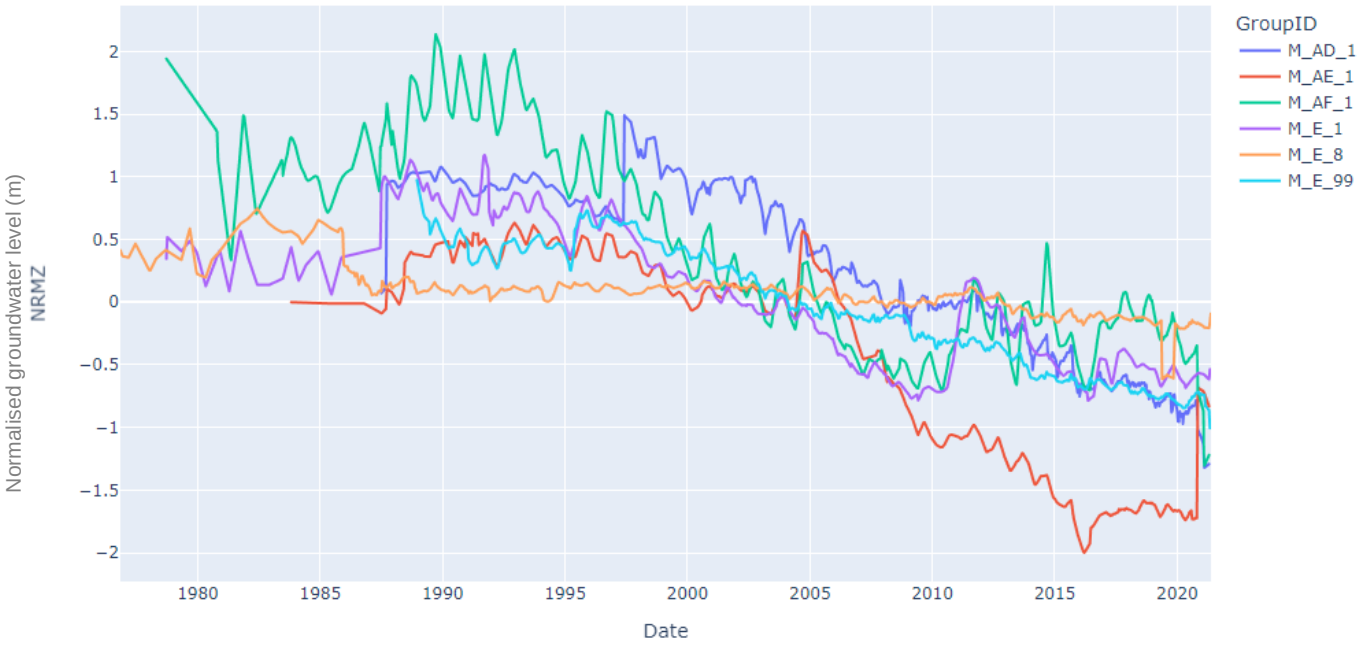


Figure 168 *West Wimmera GMA Suite Hydrographs for all confined Middle aquifers*

The representative Suites analysed for this GMU were Suites M_AD_1 and M_E_8. The Representative Suites were selected based on the methodology outlined in section 2.6.4 which identified Suite M_AD_1 as the most representative followed by M_E_8. The process is summarised as follows:

- The greatest volume of extraction occurring within the Middle Aquifer
- The Middle Aquifer pertains to the UMTA which is one of the intended aquifers for this GMU
- Suite M_AD_1 covers 3% of the GMU with 56% of the GMU extraction occurring within it and Suite M_E_8 covers 87% of the GMU with 24% of GMU extraction occurring within it
- Suite M_AD_1 has 10 active SOBN bores and Suite M_E_8 has 27 active SOBN bores
- Suite bores for M_AD_1 and M_E_8 are all close to extraction points

The annual recovered Suite hydrographs for the representative Suites M_AD_1 and M_E_8 for West Wimmera GMA are shown in Figure 169.

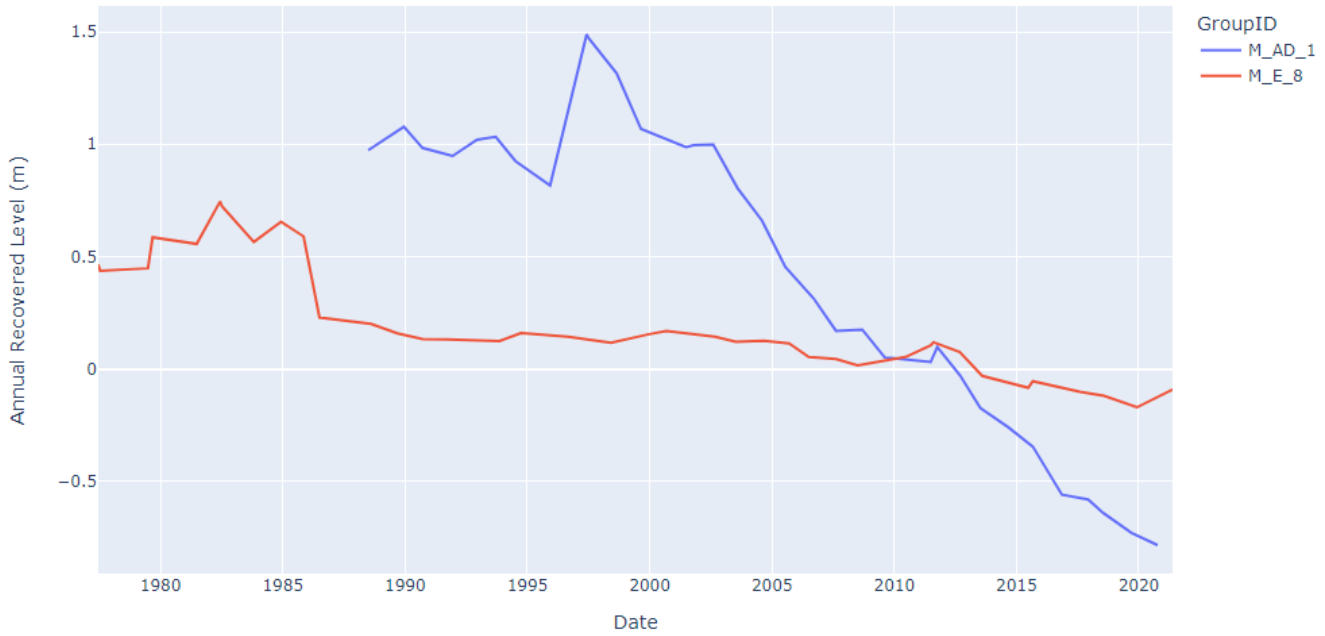


Figure 169 West Wimmera GMA Annual Recovered Level Suite Hydrographs for representative Suites

14.2.2 Pre-development level

To estimate the pre-development level conditions, GHD reviewed the Suite hydrographs of annual recovered levels and assumed that the early time data was the best representation of conditions prior to major development within West Wimmera GMA. This early time series data was adopted as the baseline of pre-development conditions.

The pre-development annual recovered levels are taken to be the average of the first 8 readings for Suite M_AD_1 which equates to 1.00 m and the average of the first ten readings for Suite M_E_8 which equates to 0.58 m (refer further details in section 14.4.3).

14.2.3 Externalities

As identified through the conceptualisation, West Wimmera GMA may be influenced by extraction occurring in the Border Zones in South Australia (zones 4A to 10A). To test the influence of this extraction, data obtained for border zones 4A to 10A for the Tertiary Limestone Aquifer and incorporated into the model.

Figure 150 shows the West Wimmera GMA annual groundwater extraction volumes, the border zones 4A to 10A combined extraction volumes and the combined volumes from West Wimmera and the border zone. Note that where extraction does not occur in both West Wimmera GMA and the border zones, that year of data cannot be incorporated into the model without hindcasting. It is noted that the West Wimmera GMA extraction only makes up around 26% of the combined extraction.

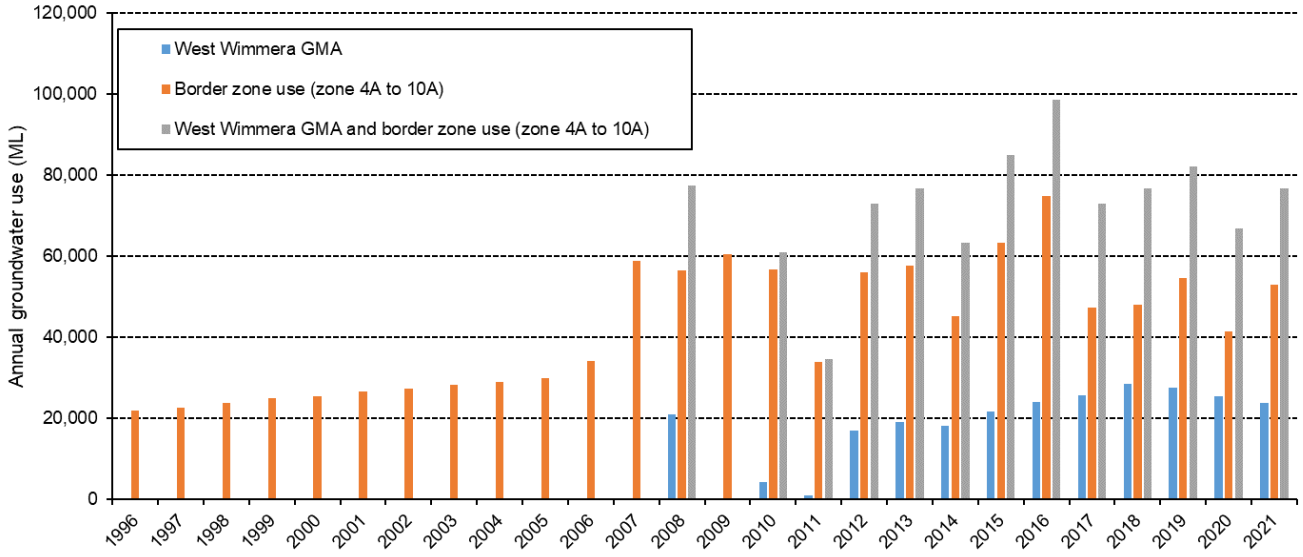


Figure 170 *West Wimmera GMA and border zones 4A to 10A groundwater use*

14.2.4 Hindcasting

Groundwater use data for West Wimmera GMA is available from 207/2008 to 2020/2021. The hindcasting methodologies outlined in section 3.3.4.5 were applied to West Wimmera GMA. A summary of the hindcasting results is shown in the following sections.

14.2.4.1 Hindcasting Method 1 (H1)

Applying method H1, twelve different correlations were developed as described below in Figure 171:

- Annual rainfall vs annual groundwater extraction at West Wimmera GMA
- Two yearly average annual rainfall vs annual groundwater extraction at West Wimmera GMA
- Annual summer period rainfall vs annual groundwater extraction at West Wimmera GMA
- Annual irrigation period rainfall vs annual groundwater extraction at West Wimmera GMA

Applying the method using annual irrigation extraction at West Wimmera GMA as shown in Figure 172:

- Annual rainfall vs annual irrigation groundwater extraction at West Wimmera GMA
- Two yearly average annual rainfall vs annual irrigation groundwater extraction at West Wimmera GMA
- Annual summer period rainfall vs annual irrigation groundwater extraction at West Wimmera GMA
- Annual irrigation period rainfall vs annual irrigation groundwater extraction at West Wimmera GMA

Applying the method for combined extraction at West Wimmera GMA and border zones 4A to 10A as shown in Figure 173:

- Annual rainfall vs annual groundwater extraction at West Wimmera GMA and border zones 4A to 10A
- Two yearly average annual rainfall vs annual groundwater extraction at West Wimmera GMA and border zones 4A to 10A
- Annual summer period rainfall vs annual groundwater extraction at West Wimmera GMA and border zones 4A to 10A
- Annual irrigation period rainfall vs annual groundwater extraction at West Wimmera GMA and border zones 4A to 10A

As shown in Figure 171, the goodness-of-fit represented by the R^2 is greatest for annual irrigation rainfall with annual groundwater use. The correlation decreased when groundwater extraction for irrigation purposes was adopted as shown in Figure 172 but remained similar when extraction from the border zones was also considered. Given this, the annual irrigation rainfall with annual groundwater use was adopted for hindcast method H1 for when considered only West Wimmera GMA extraction and when considering the combined extraction.

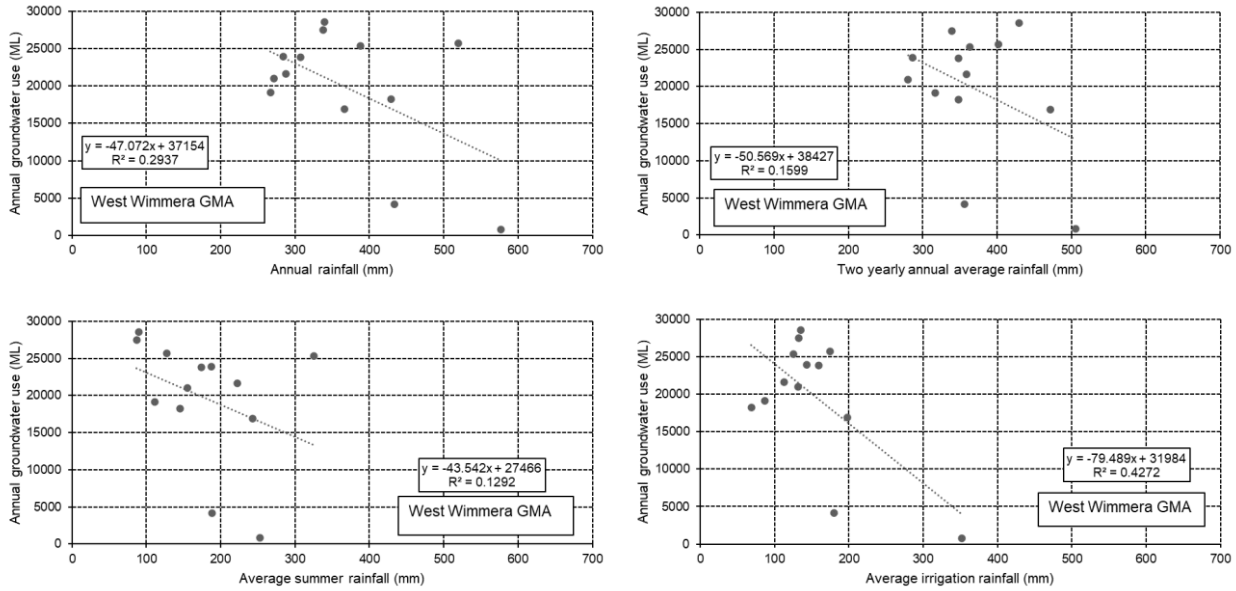


Figure 171 West Wimmera GMA: Hindcast method 1 correlations (West Wimmera GMA annual extraction)

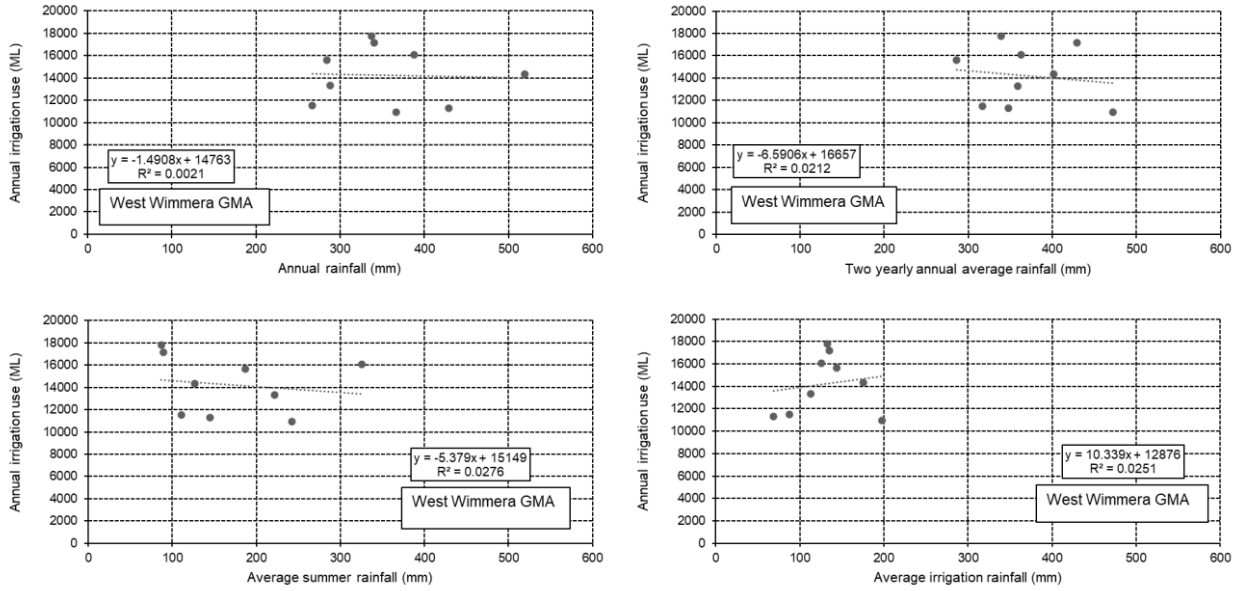


Figure 172 West Wimmera GMA: Hindcast method 1 correlations (West Wimmera GMA annual irrigation extraction)

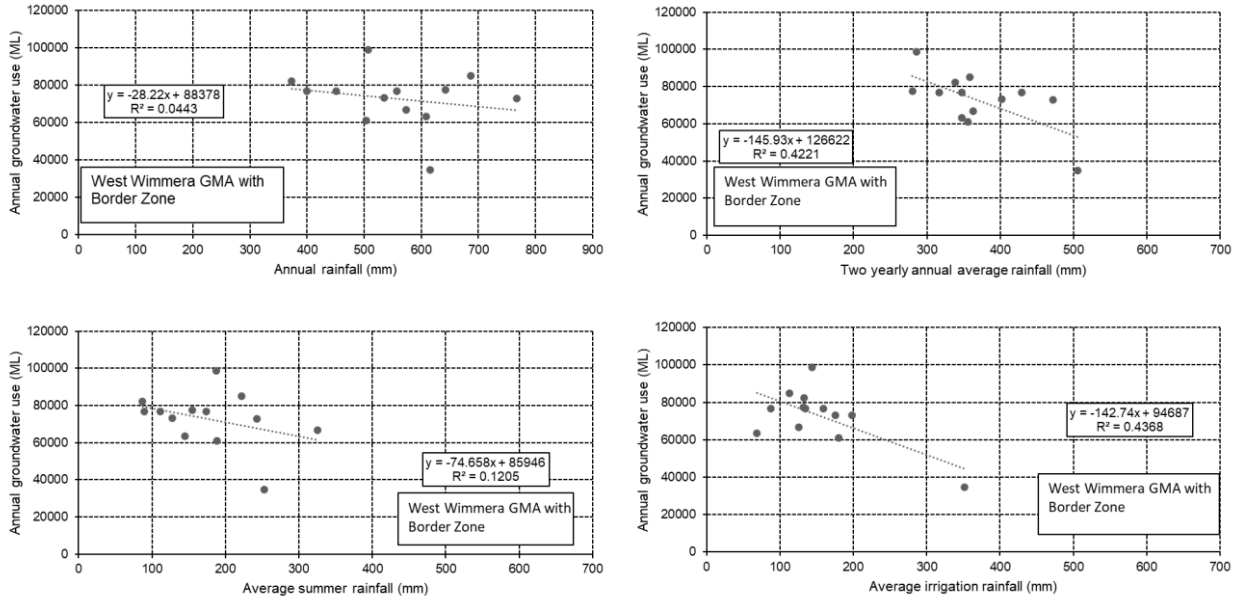


Figure 173 ***West Wimmera GMA: Hindcast method 1 correlations (West Wimmera GMA and border zone 4A and 10A extraction) annual irrigation extraction)***

14.2.4.2 Hindcasting Method 2 (H2)

Similar to method H1, four correlations were developed using method H2 and West Wimmera GMA extractions as described below and shown in Figure 174:

- West Wimmera GMA use per West Wimmera GMA bore vs annual rainfall
- West Wimmera GMA use per West Wimmera GMA bore vs two yearly average annual rainfall
- West Wimmera GMA use per West Wimmera GMA bore vs annual summer period rainfall
- West Wimmera GMA use per West Wimmera GMA bore vs annual irrigation period rainfall

Four correlations were developed using method H2 and the combined West Wimmera GMA and border zone 4A to 10A extractions as described below and shown in Figure 175:

- West Wimmera GMA and border zone zones 4A to 10A use per West Wimmera GMA bore vs annual rainfall
- West Wimmera GMA and border zone zones 4A to 10A use per West Wimmera GMA bore vs two yearly average annual rainfall
- West Wimmera GMA and border zone zones 4A to 10A use per West Wimmera GMA bore vs annual summer period rainfall
- West Wimmera GMA and border zone zones 4A to 10A use per West Wimmera GMA bore vs annual irrigation period rainfall

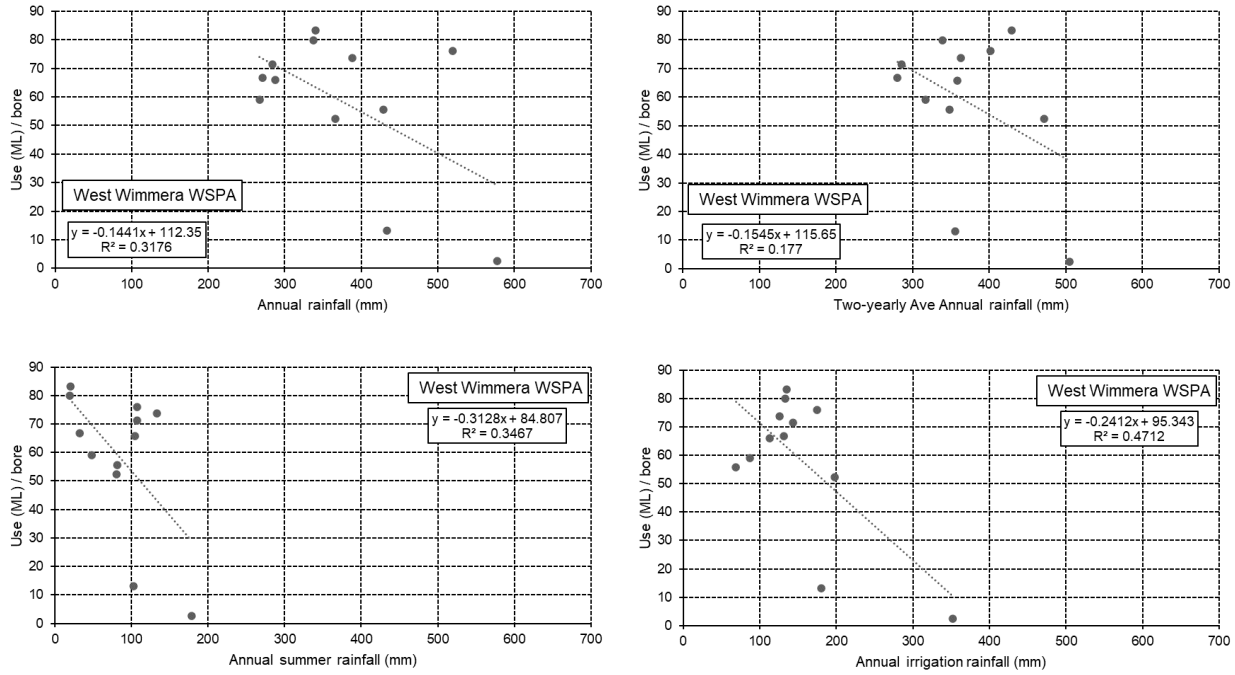


Figure 174 West Wimmera GMA: Hindcast method 2 correlations (West Wimmera GMA extraction)

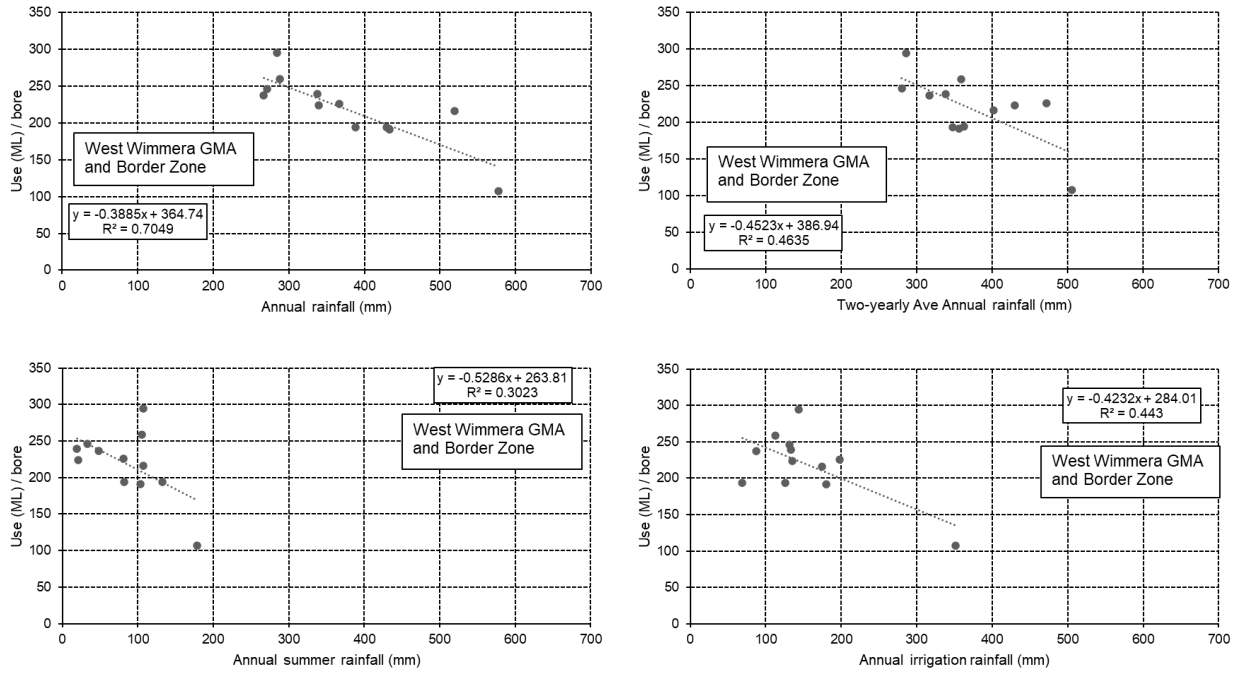


Figure 175 West Wimmera GMA: Hindcast method 2 correlations (combined West Wimmera GMA and border zone 4A to 10A extraction)

As shown in Figure 174, the goodness-of-fit represented by the R^2 is greatest for annual irrigation rainfall. The correlation decreased significantly when rainfall was set to two yearly average annual. When the combined extraction of West Wimmera GMA and border zones 4A to 10A is used in the correlations, the correlation using annual rainfall has the highest R^2. Thus, the correlation with annual irrigation rainfall was modelled for hindcast method H2 when considering only West Wimmera GMA extraction, but when the combined extraction is considered, the correlation of annual rainfall was modelled for hindcast method H2.

14.2.4.3 Hindcasting Method 3 (H3)

Four correlations were developed using method H3 as described below and shown in Figure 176:

- Percentage of entitlement vs annual rainfall
- Percentage of entitlement vs two yearly average annual rainfall
- Percentage of entitlement vs annual summer period rainfall
- Percentage of entitlement vs annual irrigation period rainfall

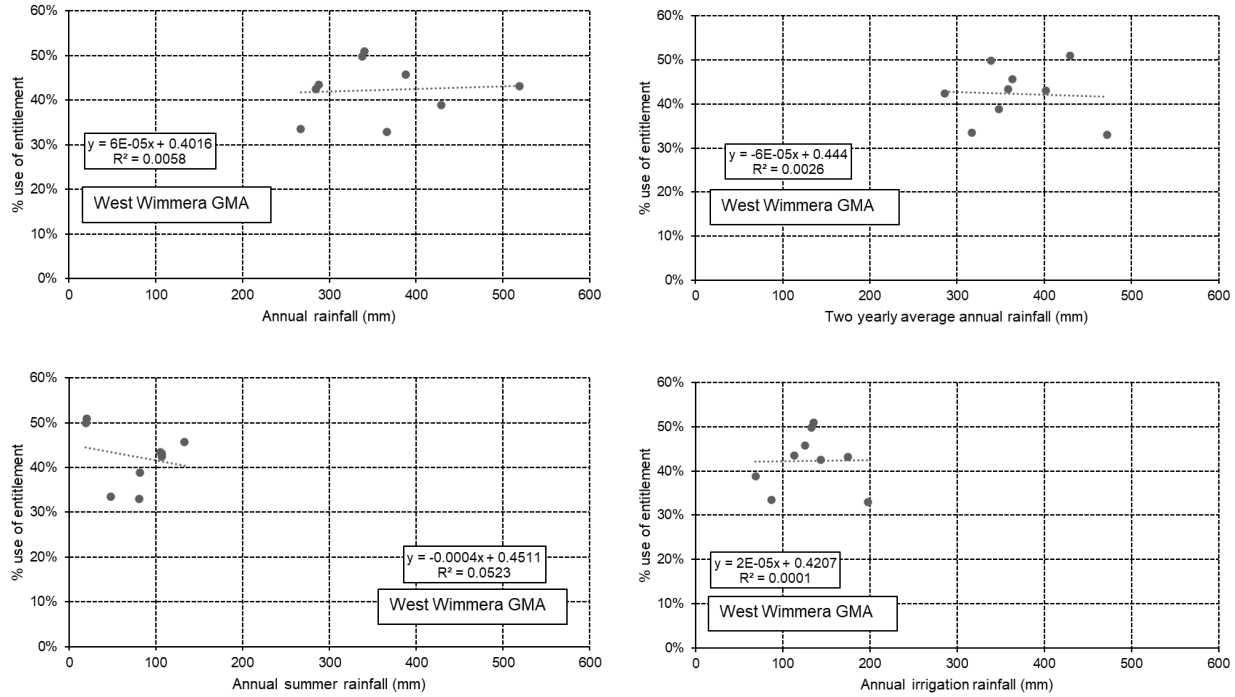


Figure 176 West Wimmera GMA: Hindcast method 3 correlations

As shown in Figure 176, the goodness-of-fit was low across all four correlations. The highest R^2 was shown to be the correlation with the annual summer rainfall. Thus, this is the correlation modelled for hindcast method H3.

14.2.4.4 Comparison

A comparison of the three input datasets is shown in Figure 177 and Figure 178 for the hindcasting based on West Wimmera GMA groundwater use. Figure 177 shows a comparison of the three hindcasting methods against the recorded use only over the recorded use date and Figure 178 shows the hindcasted data back to 1972/1973.

As shown in Figure 178, groundwater use using method H1 does not decrease historically as there is no factor to account for the changing number of bores extracting over time and thus, results in a higher groundwater extraction estimate than the other two methods. The hindcasting results show that the smallest average variation of recorded use to estimated use occurs for method H2. Thus, this hindcasting method is expected to provide a more probable estimated groundwater use than the other two methods for West Wimmera GMA.

A comparison of the three input datasets is shown in Figure 179 and Figure 180 for the hindcasting based on the combined West Wimmera GMA and border zone 4A to 10A groundwater use. Figure 179 shows a comparison of the three hindcasting methods against the recorded use only over the recorded use date and Figure 180 shows the hindcasted data back to 1972/1973.

As shown in Figure 180, groundwater use using method H2 does not decrease historically as there is no factor to account for the changing number of bores extracting over time and thus, results in a higher groundwater extraction estimate than the other two methods. The hindcasting results show that the smallest average variation of recorded use to estimated use occurs for method H2. Thus, this hindcasting method is expected to provide a more probable estimated groundwater use than the other two methods for the combined West Wimmera GMA and border zone extraction.

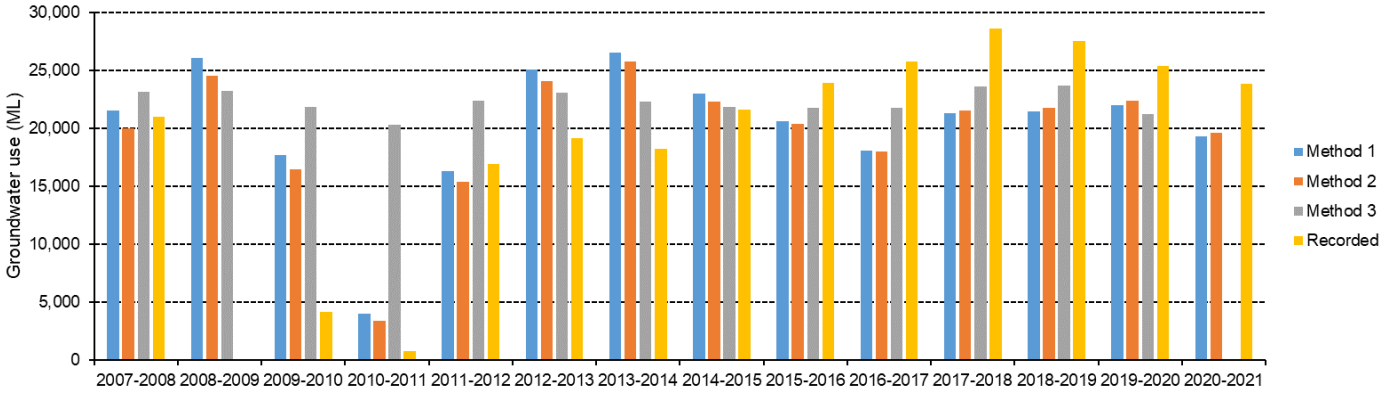


Figure 177 *West Wimmera GMA: Comparison of hindcasting over recorded use period (West Wimmera GMA extraction only)*

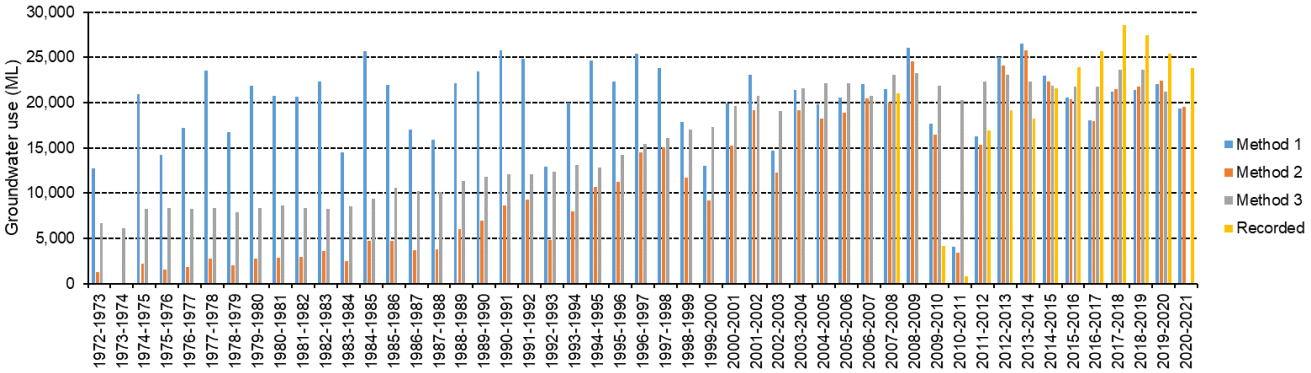


Figure 178 *West Wimmera GMA: Comparison of hindcasting (West Wimmera GMA extraction only)*

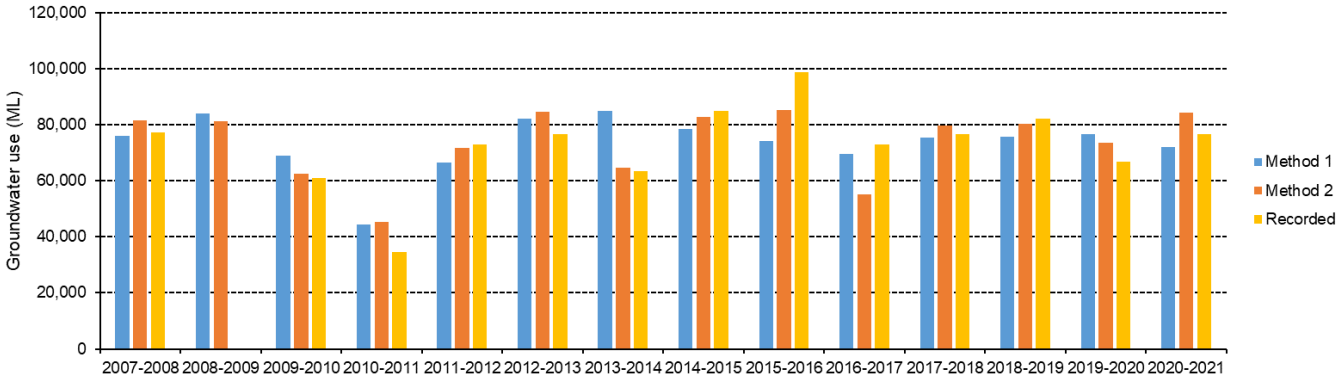


Figure 179 *West Wimmera GMA: Comparison of hindcasting over recorded use period (West Wimmera GMA and border zone 4A to 10A)*

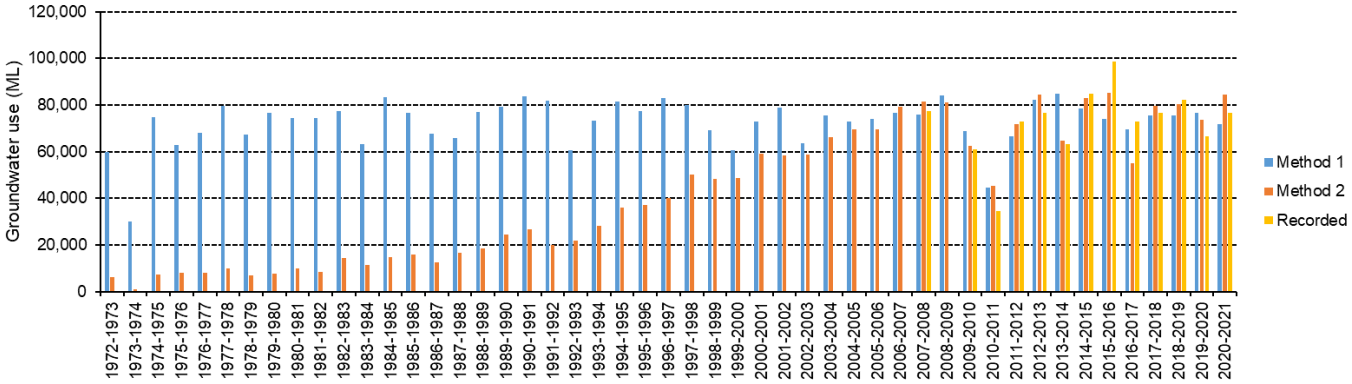


Figure 180 *West Wimmera GMA: Comparison of hindcasting (West Wimmera GMA and border zone 4A to 10A)*

14.3 Modelling

14.3.1 Model inputs

A number of different models were run based on the various model inputs developed and combinations of these. Table 71 summarises these combinations of model inputs run for West Wimmera GMA. Model runs highlighted blue indicate they were run with annual extraction and grey indicates they were run using two yearly average annual extraction.

Table 71 West Wimmera GMA: summary of model inputs

Model input	Model runs																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Annual recovered levels for representative Suites (M_AD_1 and M_E_8)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Annual extraction – West Wimmera GMA only	✓																		
Two yearly average annual extraction – West Wimmera GMA only		✓																	
Annual extraction – West Wimmera GMA and Externalities			✓																
Two yearly average annual extraction – West Wimmera GMA and Externalities				✓															
H1 annual extraction – West Wimmera GMA only					✓														
H1 annual extraction – West Wimmera GMA and Externalities						✓													
H2 annual extraction – West Wimmera GMA only							✓												
H2 annual extraction – West Wimmera GMA and Externalities								✓											
H3 annual extraction – West Wimmera GMA only									✓										
H1 two yearly average annual extraction – West Wimmera GMA only										✓									
H1 two yearly average annual extraction – West Wimmera GMA and Externalities											✓								

Model input	Model runs																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
H2 two yearly average annual extraction – West Wimmera GMA only												✓							
H2 two yearly average annual extraction – West Wimmera GMA and Externalities													✓						
S1 annual extraction – West Wimmera GMA only														✓					
S2 annual extraction – West Wimmera GMA only															✓				
S3 annual extraction – West Wimmera GMA only																✓			
S1 annual extraction and H1 annual extraction – West Wimmera GMA only																	✓		
S2 annual extraction and H2 annual extraction – West Wimmera GMA only																		✓	
S3 annual extraction and H3 annual extraction – West Wimmera GMA only																			✓

14.3.2 Model calibration and uncertainty analysis

A statistical summary of the model output results for the runs described in Table 71 is presented in Table 72 for the selection of potential representative Suites for West Wimmera GMA. The column heading for M_AD_1 is highlighted blue to indicate that this Suite was selected as the most likely representative Suite based on the process outlined in section 14.2.1. The statistics summarised include four key statistical measures pf the average 95 PPU thickness (95PPU TH), percentage of observed levels within 95 PPU (%Obs in 95 PPU), R^2 and root mean square error (RMSE) as well as the number of annual recovered level observation points (No obs data points) and the range of observed annual recovered levels.

Suite M_AD_1

A review of the results and statistical summary for M_AD_1 shows that model runs 1, 15 and 16 (highlighted orange) had the best results when considering the four measures which reflect the accuracy and precision of the model of the 19 different model input combinations. However, these models only include 10 to 11 observation points and do not cover the period of pre-development. Given this, the best result based on the statistics presented and with a longer observation record included was model run 7 in terms of R^2 and RMSE, as well as having a low 95PPU thickness. The graphical model output for this model run is shown in Figure 181. Given the statistical results, model run 7 has been adopted for the predictive modelling.

Suite M_E_8

A review of the results and statistical summary for Suite M_E_8 shows that model run 1, 14 and 16 (highlighted orange) had the best results when considering the four measures which reflect the accuracy and precision of the model of the 19 different model input combinations. The results from these three models were very similar with the main differentiator being that model run 14 has the lowest RMSE, highest R^2 value and equal smallest 95PPU thickness and equal highest percentage of observation points within the 95PPU band. However, these models only include 10 to 11 observation points and do not cover the period of pre-development. Given this, the best model result in terms of statistics using hindcasting was model run 6, closely followed by model run 7 with the main difference between the two the R^2. Model run 6 uses hindcast method H1 which was found to have a poor correlation when using externalities and also overestimates extraction historically, given this, model run 7 which utilises hindcast method H2 has been adopted. The graphical model output for this model run is shown in Figure 182.

Modelling was progressed on the basis of adopting model run 7 for Suite M_AD_1 and for Suite M_E_8.

Table 72 West Wimmera GMA: summary of model outputs

Suite	Statistic	Model run																		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
M_AD_1	95PPU TH	0.3	0.27	0.62	0.64	1.76	1.76	1.19	1.16	2.6	2.1	1.95	1.22	1.2	0.37	0.14	0.11	1.2	1.02	1.02
	%Obs in 95 PPU	100	100	100	63.64	91.18	91.18	91.18	91.18	97.06	91.18	91.18	91.18	91.18	100	100	100	90.91	93.94	93.94
	R^2	99.0	98.9	99.1	96.7	94.7	94.6	95.3	94.8	52.6	94.0	94.3	95.3	94.7	99.1	98.6	99.1	94.7	94.5	94.5
	RMSE	0.03	0.03	0.03	0.05	0.16	0.16	0.15	0.15	0.46	0.17	0.16	0.15	0.16	0.03	0.03	0.03	0.15	0.15	0.15
	No Obs	11	11	11	11	34	34	34	34	34	34	34	34	34	10	10	10	33	33	33
	No obs data points	11	11	11	11	34	34	34	34	34	34	34	34	34	10	10	10	33	33	33
	Range of observed levels	0.9	0.9	0.9	0.9	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	0.8	0.8	0.8	2.2	2.2	2.2
M_E_8	95PPU TH	0.07	0.08	0.21	0.23	0.75	0.54	0.54	0.62	0.61	0.56	0.54	0.61	0.62	0.07	NA	0.08	0.62	0.66	0.66
	%Obs in 95 PPU	90.91	100	100	100	91.11	91.11	93.33	93.33	91.11	93.33	91.11	93.33	93.33	100	0	100	90.91	29.55	29.55
	R^2	98.4	97.8	91.0	91.0	74.2	79.6	69.8	67.5	68.1	68.8	78.1	67.9	66.3	98.7	93.5	95.7	67.5	68.2	68.2
	RMSE	0.02	0.02	0.03	0.03	0.12	0.1	0.13	0.13	0.13	0.11	0.11	0.13	0.13	0.01	0.02	0.02	0.13	0.13	0.13
	No Obs	10	10	10	10	44	44	44	44	44	44	44	44	44	10	10	10	44	44	44
	No obs data points	11	11	11	11	45	45	45	45	45	45	45	45	45	10	10	10	44	44	44
	Range of observed levels	0.3	0.3	0.3	0.3	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.3	0.3	0.3	0.9	0.9	0.9

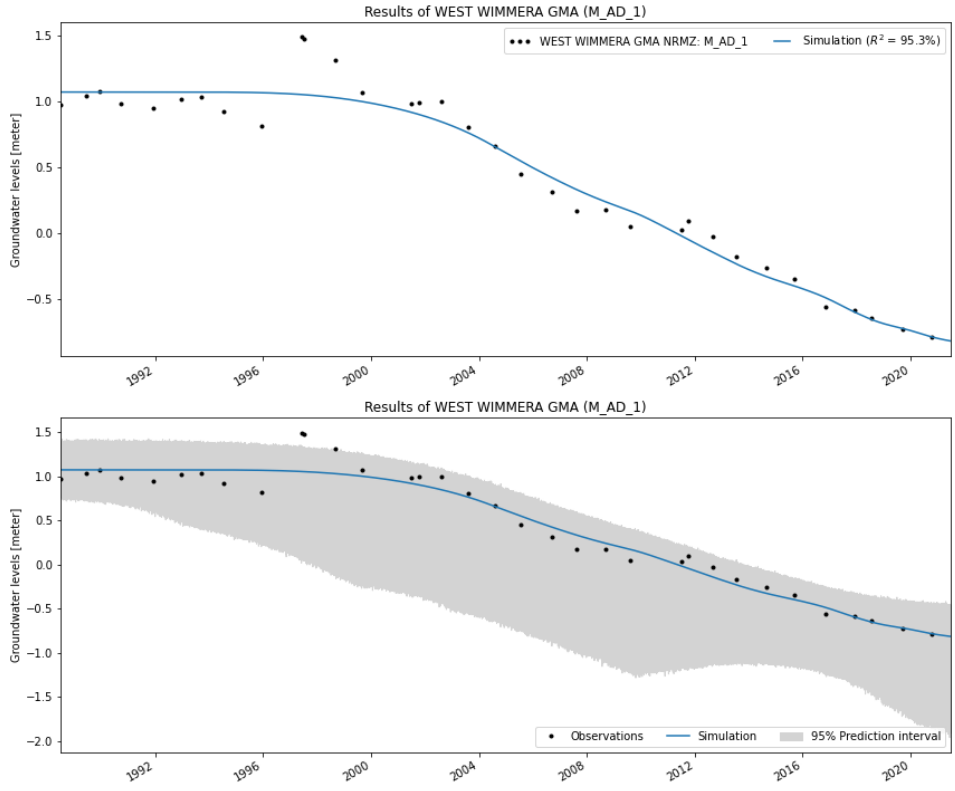


Figure 181 *West Wimmera GMA Suite M_AD_1: model run 7 (West Wimmera GMA annual extraction with hindcast method H2) output hydrographs*

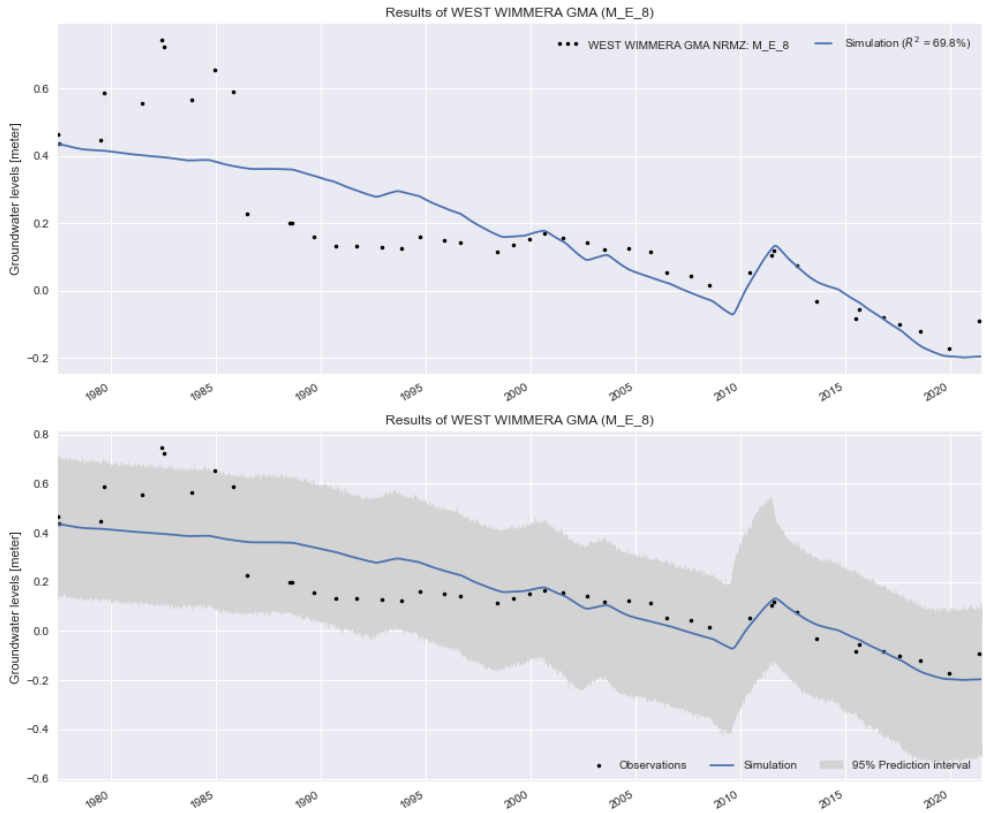


Figure 182 *West Wimmera GMA Suite M_E_8: model run 7 (West Wimmera GMA annual extraction with hindcast method H2) output hydrographs*

14.4 Predictive modelling

14.4.1 Model inputs

The preferred model to run the predictive modelling for West Wimmera GMA was model run 7 for the two selected Suites. To conduct the forecasting for the 19 scenarios discussed in section 3.5.3, a few factors were required in the calculations; these factors are summarised in Table 73.

Table 73 West Wimmera GMA: forecast scenario inputs

Input item	PCV	Licenced entitlement (based on 2020/21)	Existing use (based on 2020/2021)	Average use over recorded period (from VWA)	Maximum use over recorded period (from VWA, year 2017/18)
Value (ML/year)	57,409	53,358	23,843	22,033	27,310

14.4.2 Predictive model uncertainty

The model output files of the predicted models can be found in the data package provided as part of Appendix E.

MCMC predictions were undertaken on each of the forecasted scenarios for each of the two Suites. An example of one of the outputs is presented in Figure 183 for scenario 3. As shown in Figure 183, the uncertainty of the model prediction increases as the model predicts further into the future. Comparing with the graphical output for the same scenario, there are some MCMC realisations that fall outside the 95% prediction interval bands into the forecasted period as shown in Figure 184.

Uncertainty is also accounted for by using 19 forecast scenarios to develop a groundwater use to drawdown relationship (analogous to a Monte Carlo type simulation) where a range of possible outcomes are generated. It is noted however, that the forecast scenarios were not randomly generated, but rather based upon a series of estimated use behaviours.

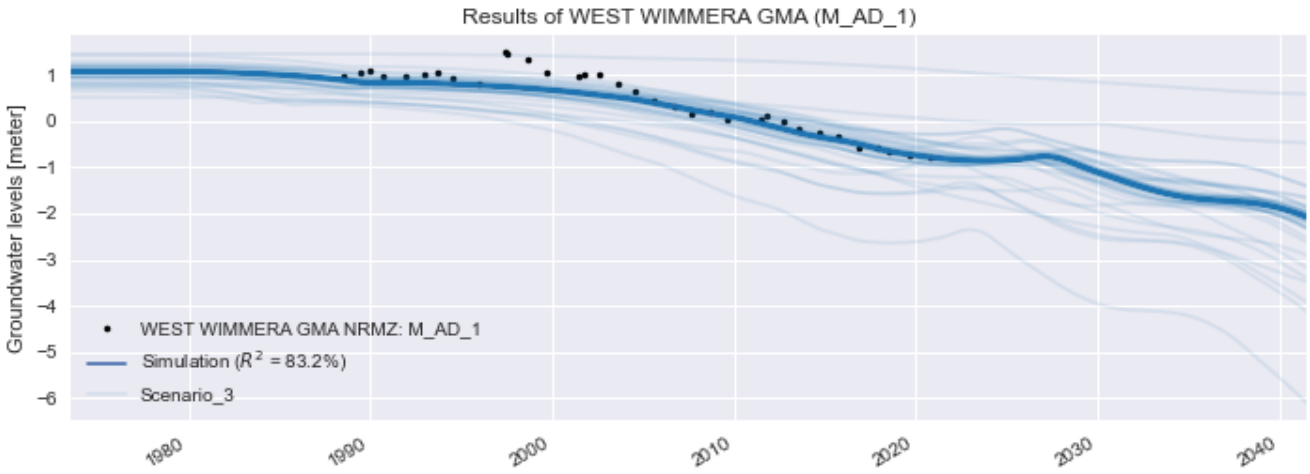


Figure 183 West Wimmera GMA: Suite M_AD_1 MCMC analysis for Forecast Scenario 14

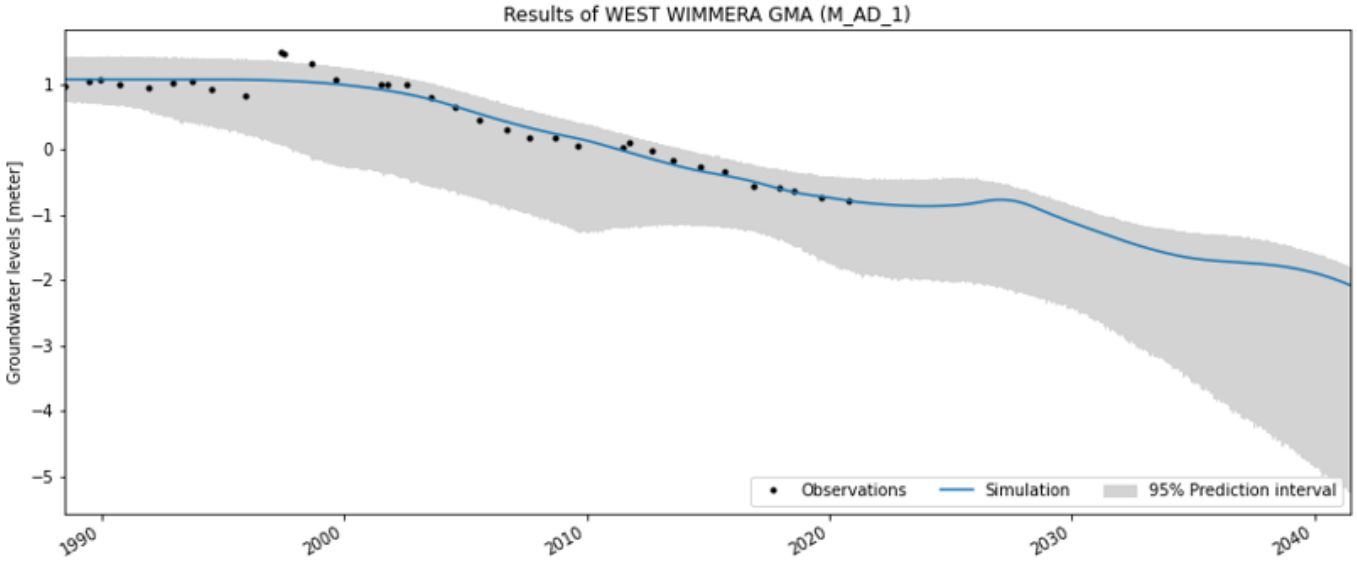


Figure 184 West Wimmera GMA: Suite M_AD_1 Forecast Scenario 14 with 95% prediction bands

14.4.3 Extraction vs drawdown

To calculate the drawdown based on the annual recovered levels simulated by the model, the pre-development conditions (pre commencement of extraction) need to be estimated. For West Wimmera GMA, the water level prior to groundwater development was unknown, due to:

- Uncertainty regarding the commencement of development in some GMUs
- The initiation of groundwater development preceding SOBN bore installation and temporal groundwater monitoring

Using the pre-development levels defined in section 14.2.2, the modelled water levels were converted into drawdowns (from this baseline pre-development level) for each of the 19 scenarios. This predevelopment condition is shown in Figure 185 for Suite M_AD_1 hydrograph of annual recovered levels. In Figure 185:

- Actual annual groundwater use is represented by the blue column graph between 2009/2010 and 2020/2021, and the year 2007/2008
- Hindcasted groundwater use is represented by the orange columns between 1973/1974 to 2007/2008 and the year 2008/2009
- Forecasted use is represented by the grey columns after 2021/2022
- The annual recovered water level behaviour based on recorded data is represented by the red line graph, where the earliest data is taken to best reflect the pre-development levels
- The pre-development annual recovered levels are taken to be the average of the first eight readings which equate to 1.00 m

The modelled forecasted annual recovered levels are represented by the purple line in Figure 185.

The calibration annual recovered levels are represented by the black line in Figure 185.

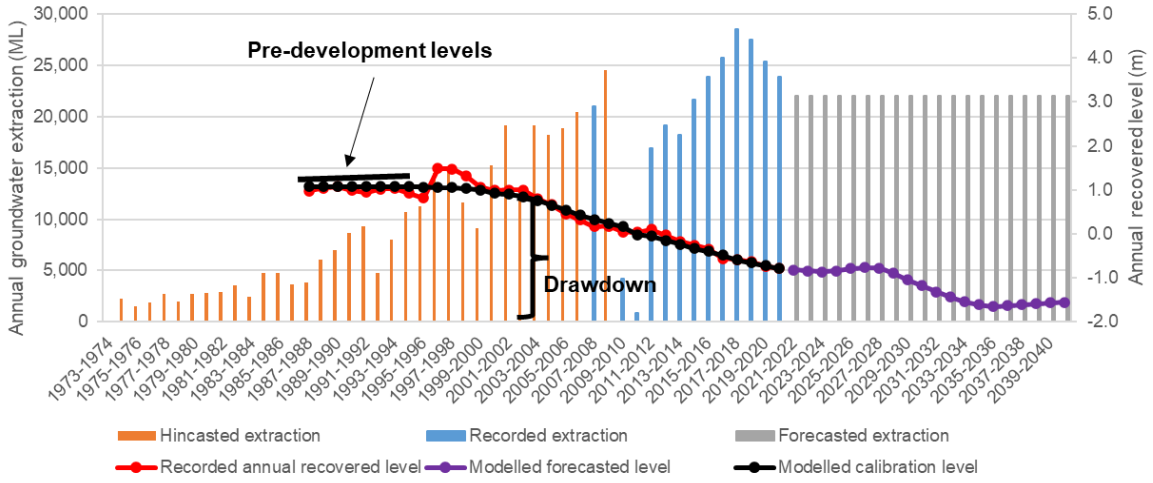


Figure 185 Estimating pre-pumping water levels (example from Suite M_AD_1)

For Suite M_AD_1, the calculated drawdowns and volumes for each of the scenarios were plotted in individual graphs for each scenario, all scenarios together in the one graph (Figure 186) and a graph of the scenarios for specific time periods (Figure 187) to develop the volume to drawdown relationship. For each scenario, a linear regression was applied and the coefficient of determination (R^2) was calculated. A comparison of each of these graphs shows there was variations in the coefficient of determination between different scenarios and slight variations of in the slope of the linear regression. The same process was applied for Suite M_E_8 and again, there was variations in the coefficient of determination between different scenarios but consistency in the slope of the linear regression. As such, the relationship developed using all scenarios was adopted as it best captures this variation between forecast scenarios.

The use-drawdown for all the 19 forecast scenario drawdowns and volumes (both the recorded and forecasted volumes) over each year modelled is shown in Figure 186 for Suite M_AD_1 and Figure 188 for Suite M_E_8. Note the abscissa range of the chart has been clipped and does not show forecast drawdowns for the higher use scenarios (more improbable volumes of two times the PCV). Reviewing these figures, the following is noted:

- There should be zero drawdown under zero use and therefore a line of best fit should pass through the origin (0,0) or close to it
- Average use is around 22,000 ML. Figure 186 for Suite M_AD_1 indicates that at average use the model forecast drawdown tends to plot close to the predicted line of best fit. Similarly, in Figure 188 for Suite M_E_8 this indicates that at the average use the model forecast drawdown tends to occur close to the predicted line of best fit.
- For the same annual use, different drawdowns can be obtained as Pastas predicts a water level for each year. For example, Figure 185 shows a scenario where groundwater use remains constant at around 22,000 ML/year over the next 20 years.
- The correlation in terms of R^2 for groundwater use and drawdown for Suite M_AD_1 is moderate and for Suite M_E_8 is excellent as shown in Figure 186 and Figure 188 respectively. The line of best fit for Suite M_E_8 tends to fit the data better as shown in Figure 188.
- The various forecast scenarios generally result in data plotting reasonably close together in a linear trend. The 19 forecast scenarios applied to populate the chart is analogous to a Monte Carlo type simulation where a range of possible outcomes are generated. It is noted however, that the forecast scenarios were not randomly generated, but rather based upon a series of estimated use behaviours.

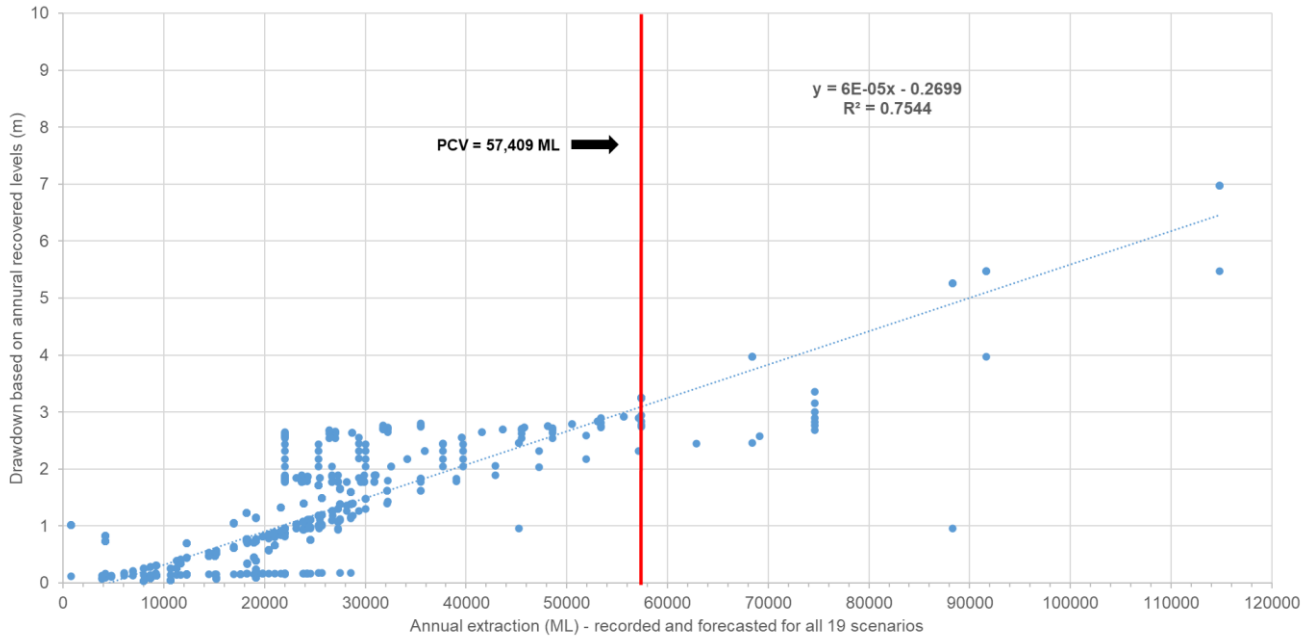


Figure 186 *West Wimmera GMA Suite M_AD_1: Drawdown (on annual recovered levels) and extraction volumes (recorded and forecasted <120,000 ML) for all data between 1988 to 2041 and all forecasted scenarios*

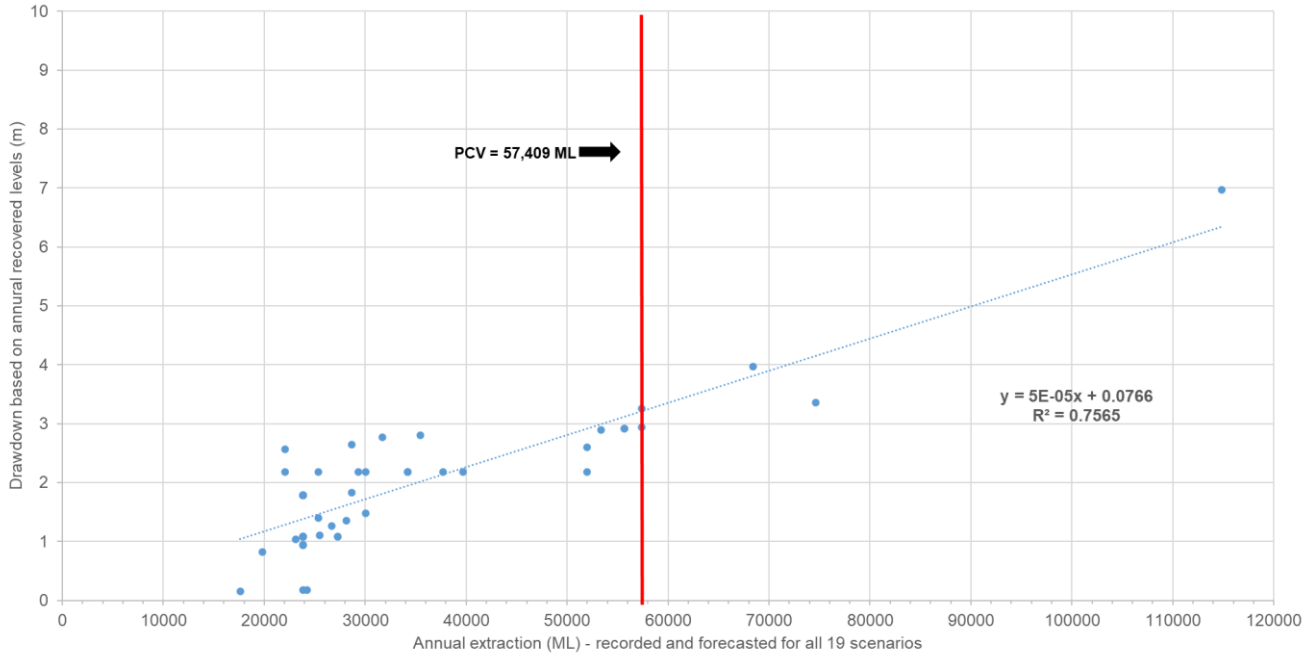


Figure 187 *West Wimmera GMA Suite M_AD_1: Drawdown (on annual recovered levels) and extraction volumes (recorded and forecasted <120,000 ML) for years 2020/2021, 2030/2031 and 2040/2041 for all forecasted scenarios*

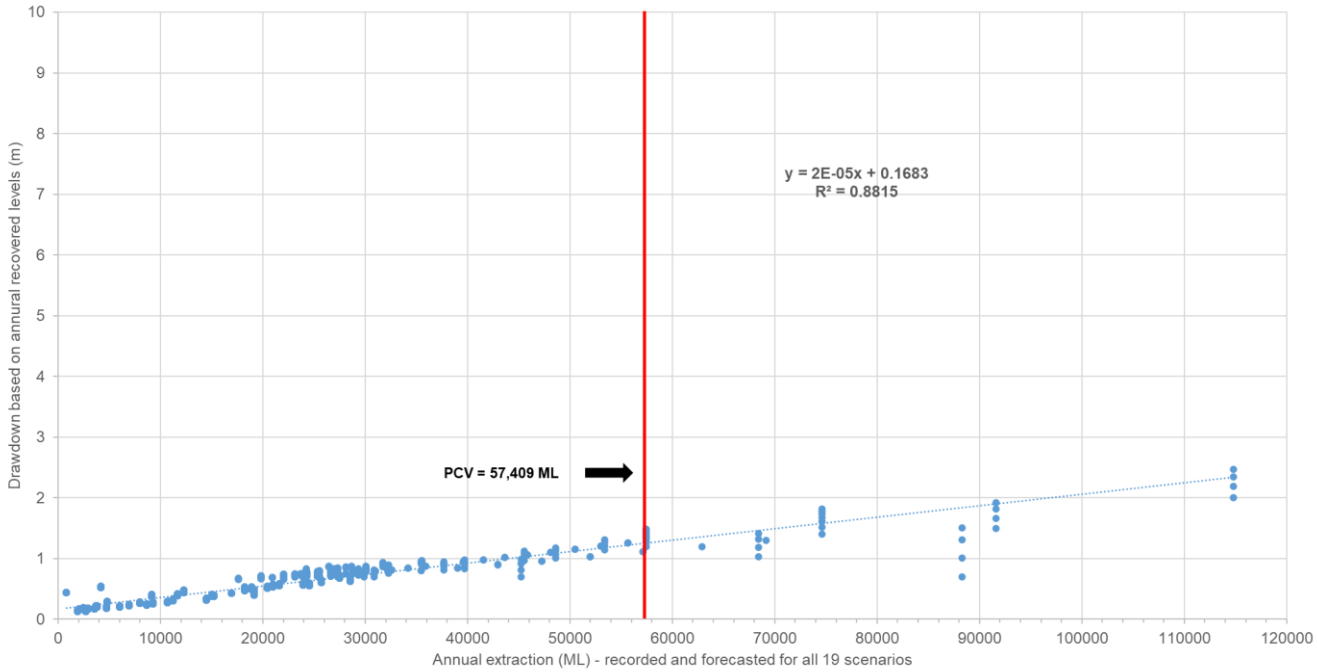


Figure 188 ***West Wimmera GMA Suite M_E_8: Drawdown (on annual recovered levels) and extraction volumes (recorded and forecasted <120,000 ML) for all data between 1977 to 2041 and all forecasted scenarios***

14.5 Sustainability metrics

14.5.1 Application of metrics

Using the use - drawdown relationships developed through the previous step of forecasting aquifer response under a range of use scenarios, groundwater drawdown can be used to compare against groundwater resource sustainability metrics.

The application of these metrics and the relationship developed between drawdown based on the Suite annual recovered levels and extraction volume for the whole GMU, which is shown in Table 74 for West Wimmera GMA Suite M_AD_1 and Table 75 for West Wimmera GMA Suite M_E_8 (noting West Wimmera GMA has a current PCV of 57,409 ML/year). As part of the modelling, a 95% prediction interval band was applied to the modelling results. The relationship between drawdown and extraction volumes can also be interrogated at the lower and upper bands of the 95% prediction interval as shown in Table 74 and Figure 189 for Suite M_AD_1, and Table 75 and Figure 190 for Suite M_E_8.

The two West Wimmera GMA Suites M_AD_1 and M_E_8 have different drawdown-use relationships which shows that a greater volume of water needs to be extracted for an estimated 5 m of drawdown to occur for Suite M_E_8 than Suite M_AD_1. A comparison of volumes at drawdown intervals provided by DEECA is shown in Table 76 for Suite M_AD_1 and M_E_8. Based on the relationships developed, 5 m of drawdown is predicted to occur with 87,800 ML (which could range from 65,500 to 116,900 ML) of use based on Suite M_AD_1 and 241,600 ML (which could range from 154,000 to 505,600 ML) of based on Suite M_E_8. Whereas, 10 m of drawdown is predicted to occur with 171,200 ML (which could range from 137,100 to 216,900 ML) of use based on Suite M_AD_1 and 491,600 ML (which could range from 320,700 to 1,005,600 ML) of based on Suite M_E_8.

Table 74 Relationship of Suite drawdown to GMU extraction for West Wimmera GMA Suite M_AD_1

Volume (ML/year) for whole of GMU	Based on model prediction of Suite M_AD_1 annual recovered levels
	Drawdown over 20 years (m) (lower limit to upper limit based on 95% prediction interval band)
180,000	10.5 (8.2 - 13)
170,000	9.9 (7.7 - 12.3)
160,000	9.3 (7.2 - 11.6)
150,000	8.7 (6.7 - 10.9)
140,000	8.1 (6.2 - 10.2)
130,000	7.5 (5.7 - 9.5)
120,000	6.9 (5.2 - 8.8)
110,000	6.3 (4.7 - 8.1)
100,000	5.7 (4.2 - 7.4)
90,000	5.1 (3.7 - 6.7)
80,000	4.5 (3.2 - 6)
70,000	3.9 (2.7 - 5.3)
60,000	3.3 (2.2 - 4.6)
50,000	2.7 (1.7 - 3.9)
40,000	2.1 (1.2 - 3.2)
30,000	1.5 (0.7 - 2.5)
20,000	0.9 (0.2 - 1.8)
10,000	0.3 (-0.3 - 1.1)
0	-0.3 (-0.8 - 0.4)

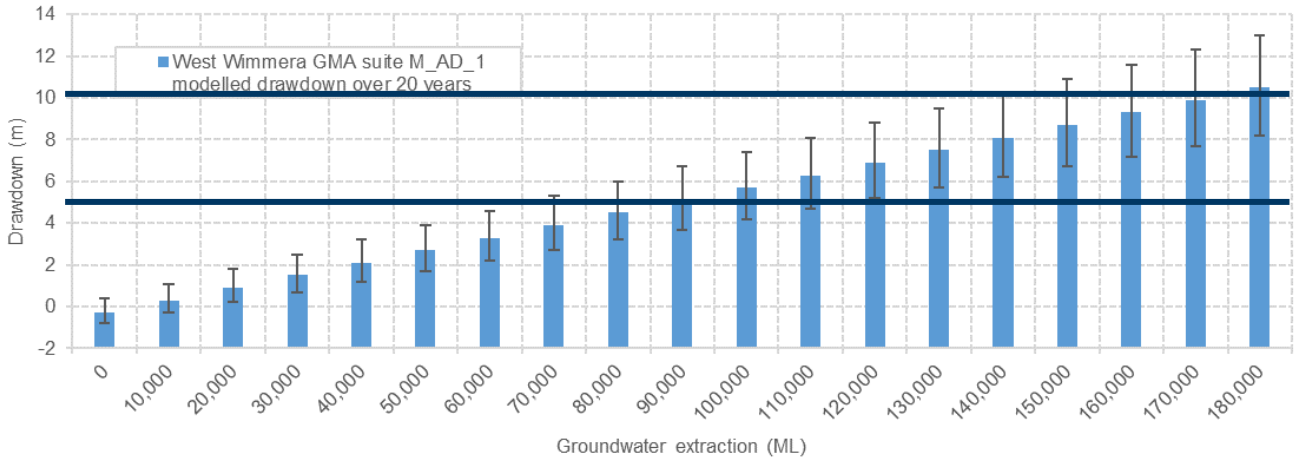


Figure 189 West Wimmera GMA Suite M_AD_1: Relationship of Suite drawdown to GMU extraction (with error bars showing results of drawdown using levels from model's 95% prediction intervals)

Table 75 Relationship of Suite drawdown to GMU extraction for West Wimmera GMA Suite M_E_8

Volume (ML/year) for whole of GMU	Based on model prediction of Suite M_E_8 annual recovered levels
	Drawdown over 20 years (m) (lower limit to upper limit based on 95% prediction interval band)
150,000	3.2 (1.4 - 4.9)
140,000	3 (1.3 - 4.6)
130,000	2.8 (1.2 - 4.3)
120,000	2.6 (1.1 - 4)
110,000	2.4 (1 - 3.7)
100,000	2.2 (0.9 - 3.4)
90,000	2 (0.8 - 3.1)
80,000	1.8 (0.7 - 2.8)
70,000	1.6 (0.6 - 2.5)
60,000	1.4 (0.5 - 2.2)
50,000	1.2 (0.4 - 1.9)
40,000	1 (0.3 - 1.6)
30,000	0.8 (0.2 - 1.3)
20,000	0.6 (0.1 - 1)
10,000	0.4 (0 - 0.7)
0	0.2 (-0.1 - 0.4)

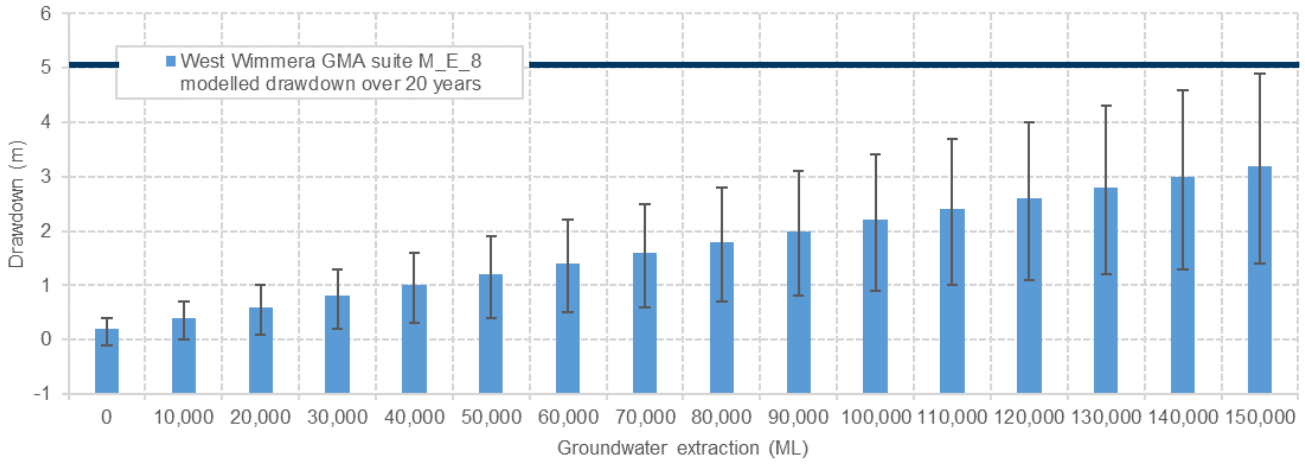


Figure 190 West Wimmera GMA Suite M_E_8: Relationship of Suite drawdown to GMU extraction (with error bars showing results of drawdown using levels from model's 95% prediction intervals)

Table 76 Predicted volumes for drawdown metrics

Drawdown (m)	Predicted volumes for GMU based on Suite M_AD_1 drawdowns (lower limit to upper limit)	Predicted volumes for GMU based on Suite M_E_8 drawdowns (lower limit to upper limit)
5	87,800 (65,600 – 116,900)	241,600 (154,000 – 505,600)
10	171,200 (137,100 – 216,900)	491,600 (320,700 – 1,005,600)

	Volume (ML/year)	Drawdown over 20 years
	150,000	3.2 (1.4 - 4.9)
	140,000	3 (1.3 - 4.6)
PCV = 57,409	130,000	2.8 (1.2 - 4.3)
	120,000	2.6 (1.1 - 4)
	110,000	2.4 (1 - 3.7)
	100,000	2.2 (0.9 - 3.4)
	90,000	2 (0.8 - 3.1)
Av unit = 22,033	80,000	1.8 (0.7 - 2.8)
	70,000	1.6 (0.6 - 2.5)
	60,000	1.4 (0.5 - 2.2)
	50,000	1.2 (0.4 - 1.9)
	40,000	1 (0.3 - 1.6)
	30,000	0.8 (0.2 - 1.3)
	20,000	0.6 (0.1 - 1)
	10,000	0.4 (0 - 0.7)
	0	0.2 (-0.1 - 0.4)

	Volume (ML/year)	Drawdown over 20 years
	180,000	10.5 (8.2 - 13)
	170,000	9.9 (7.7 - 12.3)
	160,000	9.3 (7.2 - 11.6)
PCV = 57,409	150,000	8.7 (6.7 - 10.9)
	140,000	8.1 (6.2 - 10.2)
	130,000	7.5 (5.7 - 9.5)
	120,000	6.9 (5.2 - 8.8)
	110,000	6.3 (4.7 - 8.1)
Av unit = 22,033	100,000	5.7 (4.2 - 7.4)
	90,000	5.1 (3.7 - 6.7)
	80,000	4.5 (3.2 - 6)
	70,000	3.9 (2.7 - 5.3)
	60,000	3.3 (2.2 - 4.6)
	50,000	2.7 (1.7 - 3.9)
	40,000	2.1 (1.2 - 3.2)
	30,000	1.5 (0.7 - 2.5)
	20,000	0.9 (0.2 - 1.8)
	10,000	0.3 (-0.3 - 1.1)
	0	-0.3 (-0.8 - 0.4)

Legend

- Groundwater Management Units
- Middle Aquifer Suites
  - M_AC_2
  - M_AC_3
  - M_AD_1
  - M_AE_1
  - M_AF_1
  - M_E_1
  - M_E_8
  - M_E_99
  - M_F_4
  - M_G_8
  - M_J_2
- Major town
- Rail
- Freeway & highway
- River
- Park

Paper Size ISO A3

0 6.5 13 19.5 26

Kilometers

Map Projection: Lambert Conformal Conic
Horizontal Datum: GDA 1994
Grid: GDA 1994 VICGRID94

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GHD

DEECA
Sustainable Yields
Confined Aquifers

WEST WIMMERA GMA: KEY SUITES VOLUME VS DRAWDOWN

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FIGURE 191

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Data source: DELWP, VicMap, 2022; DELWP GMU locations, 2022; GHD, aquifer suites, 2018; . Created by: cperyer

14.6 GMU summary

14.6.1 Findings

West Wimmera GMA primarily relates the shallow Pliocene Sands Aquifer (UTAM), the Tertiary Limestone Aquifer (UMTA) and the deeper Tertiary confined sand aquifer (LTA). Most extraction from West Wimmera GMA comes from the UMTA which is a semi-confined aquifer. Groundwater in the GMA is predominately used for irrigation, urban water supply and stock and domestic purposes. The UMTA falls within the Middle Aquifer Suites, which at West Wimmera GMA comprise Suites M_AD_1 (3%), M_AE_1 (1%), M_AF_1 (1%), M_E_1 (5%), M_E_8 (87%), M_E_99 (1%) and M_J_2 (1%), providing a total GMU coverage of 99%. The identified representative Suites are M_AD_1 (most preferred) and M_E_8. The Suite hydrographs for the representative Suites show an overall decreasing trend along with seasonal fluctuation and thus recovered water levels, which were adopted for the assessment.

As identified through the conceptualisation, West Wimmera GMA may be influenced by extraction occurring in the Border Zones in South Australia (zones 4A to 10A). To test the influence of this extraction, data obtained for border zones 4A to 10A for the Tertiary Limestone Aquifer and incorporated into the modelling.

Application of two yearly annual average extraction, instead of annual extraction, generally showed a slightly poorer model fit based on the statistical analysis across the model runs (the exception was when hindcast method 1 was applied to Suite M_E_8).

When hindcasting was applied, hindcast method H2 produced the best model results statistically and hindcast method H3 produced the poorest result of the hindcast methods. The application of spatial distribution generally produced similar results to the model run using only annual extraction. However, the quality of the result decreased when spatial distribution methodology was combined with hindcasting methodology.

Incorporating externalities into the modelling generally did not improve the model fit in comparison to the equivalent models without externalities (i.e., model with annual extraction and hindcast method H2 with West Wimmera only extraction compared to the model with annual extraction and hindcast method H2 with combined West Wimmera and border zone extraction).

Based on an assessment of all model runs, the model run 7 of annual extraction with the annual recovered levels was adopted to undertake the predictive modelling for both Suite M_AD_1 and M_E_8.

The pre-development levels were defined for the two representative Suites based on the early time data was the prior to major development within West Wimmera GMA. resulted in pre-developments levels of 1.00 m for Suite M_AD_1 and 0.58 m for Suite M_E_8. The drawdowns were calculated based on these pre-development levels and the simulated levels from each of the 19 forecast scenarios.

The volumes estimated for a given drawdown for each Suite is shown below.

Drawdown (m)	Predicted volumes for GMU based on Suite M_AD_1 drawdowns (lower limit to upper limit)	Predicted volumes for GMU based on Suite M_E_8 drawdowns (lower limit to upper limit)
5	87,800 (65,600 – 116,900)	241,600 (154,000 – 505,600)
10	171,200 (137,100 – 216,900)	491,600 (320,700 – 1,005,600)

The models for Suites M_AD_1 and M_E_8 were assessed as having an “Excellent” model applicability rating using the criteria outlined in section 5.2. For both Suites, due to the limited range in calibration volumes, the greater the proposed extraction rates beyond the calibration range leads to a greater potential for drawdown forecast errors.

Given that most of the extraction from the Middle Aquifer is likely to come from Suite M_AD_1 and that volumes seem unreasonably large for drawdowns of 5 m for Suite M_T_2; Suite M_AD_1 is considered to be the most representative Suite for West Wimmera GMA.

14.6.2 Limitations

In addition to the limitations applicable to all 25 GMUs discussed in section 1.8, the following West Wimmera GMA specific limitations have been identified:

- The licenced bore dataset provided by DEECA has 4% of bores assigned to West Wimmera GMA with no depth data and thus couldn't be assigned to a VAF layer and in turn Suite. These bores were assigned to an aquifer through this study by GHD, in order to assist with the determination of the representative Suite. However, this data was not used in the model analysis.
- For M_AD_1:
  - M_AD_1 preferred suite is only 3% of the area
  - Model calibration for suite M_AD_1 was completed using a groundwater extraction range of approximately 1000-30,000 ML/year
  - The greater the proposed extraction rates beyond this calibration range the more potential for drawdown forecast errors. In this GMU, drawdown prediction for extraction volumes up to 6 times the calibration range are being made to meet the 10 m drawdown metric.
- For M_E_8:
  - Model calibration for suite M_E_8 was completed using a groundwater extraction range of approximately 1,000-30,000 ML/year
  - The greater the proposed extraction rates beyond this calibration range the more potential for drawdown forecast errors. In this GMU, drawdown prediction for extraction volumes up to 16 times the calibration range are being made to meet the 10 m drawdown metric.
- Further checks and potential re-calibration may be required as extraction rates increase for this GMU

14.6.3 Recommendations

In addition to the recommendations applicable to all 25 GMUs discussed in section 32, the following West Wimmera GMA specific recommendations have been identified:

- The licenced bore dataset provided by DEECA has 4% of bores assigned to West Wimmera GMA with no depth data and thus couldn't be assigned to a VAF layer and in turn Suite. It is recommended that DEECA obtains the relevant depth and aquifer monitored data for licenced bores within this GMU.
- DEECA should obtain the extraction data for extraction bores within South Australia and incorporate this data to the modelling