Barwon Downs Hydrogeological Studies 2016-17

Barwon Water

Numerical Model - Calibration and Historical Impacts

| DRAFT

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Jacobs Group (Australia) Pty Limited
ABN 37 001 024 095
Floor 11, 452 Flinders Street
Melbourne VIC 3000
PO Box 312, Flinders Lane
Melbourne VIC 8009 Australia
T +61 3 8668 3000
F +61 3 8668 3001
www.jacobs.com

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Contents

Executive Summary

KEY FINDINGS

- The groundwater model has attained the highest ranking in confidence level classification in accordance with the Australian Groundwater Modelling Guidelines (Barnett et al., 2012). It is considered to be fit-for-purpose to assess future groundwater behaviour and impacts that may occur from groundwater extraction at a regional scale.
- The revised groundwater model is well calibrated at both a regional scale and local scale, and is now a more reliable representation of the hydrogeological setting and the rivers and creeks that interact with groundwater.
- The model was used to simulate historical impacts by separating groundwater extraction from natural climate fluctuations.
- The model indicates that operation of the borefield over the past 30 years is most likely responsible for two thirds of the reduction of base flow into Boundary Creek. The dry climate experienced during the same period accounts for the remaining third.
- This suggests that the lower sections of Boundary Creek would likely have no flow periods during summer regardless of groundwater pumping; however pumping has increased the frequency and duration of no flow periods in lower reaches of Boundary Creek.
- No other rivers or creeks have been impacted as significantly as Boundary Creek by the operation of the bore field. Operation of the borefield has likely resulted in a minor reduction in base flow in a small section of the Gellibrand River. Dry climate conditions have caused a greater reduction in base flow than the historical borefield operation.
- Shallow aquifers across most of the study area have not been significantly influenced by operation of the bore field which suggests that there is very little impact to vegetation outside the Boundary Creek catchment.
- Further technical studies are in progress to assess the future impact of a range of alternative borefield operating regimes on flows in Boundary Creek to maintain current ecological values in the lower part of the catchment, and measures to address the issue of acid water release from Yeodene Swamp into Boundary Creek. The outcomes of these studies will support Barwon Water's licence application.

BACKGROUND

The Barwon Downs borefield is operated under licence from Southern Rural Water and provides a drought resilient water source for greater Geelong. At the height of the worst drought on record (2006-10), the borefield provided up to 70 per cent of Geelong's drinking water. This licence is due for renewal in mid-2019.

Using groundwater has, in the past, generated community concern about impact to the local environment. To address these concerns, Barwon Water has carried out a program of technical studies and increased monitoring activities.

The outcomes of this program have been used to update the groundwater model. This has improved the model's ability to accurately predict impacts of pumping, allowing Barwon Water to better address community concerns.

This report presents the findings of the program to develop and calibrate a numerical groundwater model that can be used as a key tool in assessing possible effects of borefield operation.

OBJECTIVES

The objectives of developing an updated groundwater model were to:

- improve the existing groundwater model ability to assess future impacts related to groundwater pumping from the Barwon Downs borefield, and
- develop a tool to simulate impacts that would have happened naturally due to climate influences against impacts caused by groundwater pumping over the past 30 years.

APPROACH

To ensure that Barwon Water's licence application is supported by strong science, a program of technical studies and an enhanced monitoring program was implemented. This information was used to update and calibrate the groundwater model in accordance with the Australian Groundwater Modelling Guidelines (Barnett *et al.,* 2012).

The Barwon Downs groundwater model has evolved since its original development in the 1990s and has been expanded and updated over time as needed. The new model builds on earlier model versions, yet is a significant improvement so that it can be used with confidence to assess impacts associated with groundwater extraction. The Guidelines promote a continual refinement and improvement approach to developing a groundwater model, and this approach is accepted as the benchmark of industry best practice. It involves the following stages:

1. Planning,
2. Development of a conceptual model,
3. Model design,
4. Model construction, and
5. Model calibration.

The calibrated model was used to determine the historical impact of the borefield, including drawdown and changes to the surface water groundwater interaction at Boundary Creek and other rivers.

SUMMARY OF FINDINGS

<u>Model update and calibration</u>

Improvements made to the model produced a more reliable representation of the groundwater system at both the regional and local scale. Significant effort was made to improve the model for the Boundary Creek catchment due to the complex hydrogeology and groundwater surface interaction in that area.

The following improvements were made to the groundwater model:

- Additional two layers were added, and the extent and thickness of key formations were revised using information collected from new monitoring bores,
- A review of the local hydrogeology around the Colac and Bambra Faults highlighted very little groundwater flow across the faults. This information was incorporated into the model,
- Average recharge rates of 5 per cent of rainfall where the Lower Tertiary Aquifer (the aquifer Barwon Water extracts from) outcrops and less than 1 per cent of rainfall where the Mid Tertiary Aquitard outcrops were incorporated into the model based on recent field investigations,

- An improved understanding of how pumping in the Lower Tertiary Aquifer lowers the water table surrounding the borefield and how this affects the water levels in the formations above and below the Lower Tertiary Aquifer was incorporated into the model, and

- An improved understanding of groundwater surface water interactions was incorporated into the model.

The work has improved the ability of the model to match past behaviour of the aquifer which subsequently improves the confidence that the model can accurately predict potential future impacts of operating the Barwon Downs borefield.

The groundwater model has the highest ranking in confidence level classification and is considered to be fit-for-purpose for to assess future groundwater behaviour and impacts that may occur from groundwater extraction.

Historical impact assessment

The updated model was run over the period 1980 to 2016 with and without the Barwon Downs borefield operating to determine the historical impact. Key findings from the historical impact assessment are:

- Low rainfall climate conditions between 1980 and 2016 have caused a regional decline in groundwater levels across the study area.

- Operation of the Barwon Downs bore field over the same time period has caused further declines in groundwater levels across the study area. Declines in waterlevels are most noticeable in the aquifer being pumped (Lower Tertiary Aquifer) at the bore field, and less and less noticeable with distance from the bore field.

- Declines in water levels in the Lower Tertiary Aquifer only influences the water table in the shallow aquifer at the surface in some locations.

- Lowering of the water table in response to pumping is influenced by the thickness of the aquitards lie above the aquifer. The water table is expected to lower more noticeably where the aquitard material is thin and where the aquifer rises towards the ground surface.

Table 1 summarises likely historical impacts using the updated model assuming two different scenarios:

i. with groundwater pumping, and

ii. without groundwater pumping (allowing prediction of what likely impacts natural climate events would have caused).

Table 1-1 Summary of the impacts of the historical operation from the Barwon Downs borefield

Receptor	Assessment of historical impact
Regional groundwater levels	• Regional groundwater levels fluctuate naturally in response to climate variability and pumping. • Pumping from Barwon Downs has had more of an impact on groundwater levels compared to reduced recharge due to low rainfall. • Deeper groundwater levels are more influenced by pumping compared the shallow aquifer layers near the surface
Groundwater contribution to flow in Boundary Creek	• Boundary Creek was gaining water from groundwater and is now losing water to groundwater. • Climate conditions over the model timeframe could have caused a reduction in streamflow for short periods of time. • Operation of the bore field is most likely the primary cause of reduction in streamflow in Boundary Creek.

Receptor	Assessment of historical impact
Groundwater contribution to flow in Gellibrand River	• Groundwater naturally discharges to the Gellibrand River along much of the length of the River • The modeled area intersects only a small part of the Gellibrand River. • Climate conditions have caused more of reduction in a baseflow to the Gellibrand River than pumping from the bore field in this section of the River over the model time frame.
Vegetation and groundwater dependent ecosystems	• Vegetation and groundwater dependent ecosystems are reliant on groundwater in shallow aquifers in some areas. • Shallow aquifers across large areas of the study area have not been influenced by operation of the bore field. • Operation of the bore field has had caused declining groundwater levels in shallow aquifers in some parts of catchment, particularly where the Lower Tertiary Aquifer outcrops. • Overall operation of the bore field has cause an 8% decline in the overall evapotranspiration between 1980 and 2016.

CONCLUSIONS

Barwon Water used specialists from Jacobs to update the existing Barwon Downs groundwater model based on additional data and information collected as part of a broader investigation and monitoring program. These improvements increased the confidence in the model's predictive capabilities. The model has been used to assess the past effect of the operation of the borefield and is suitable for use to predict what impact future groundwater pumping will have on the environment and other users.

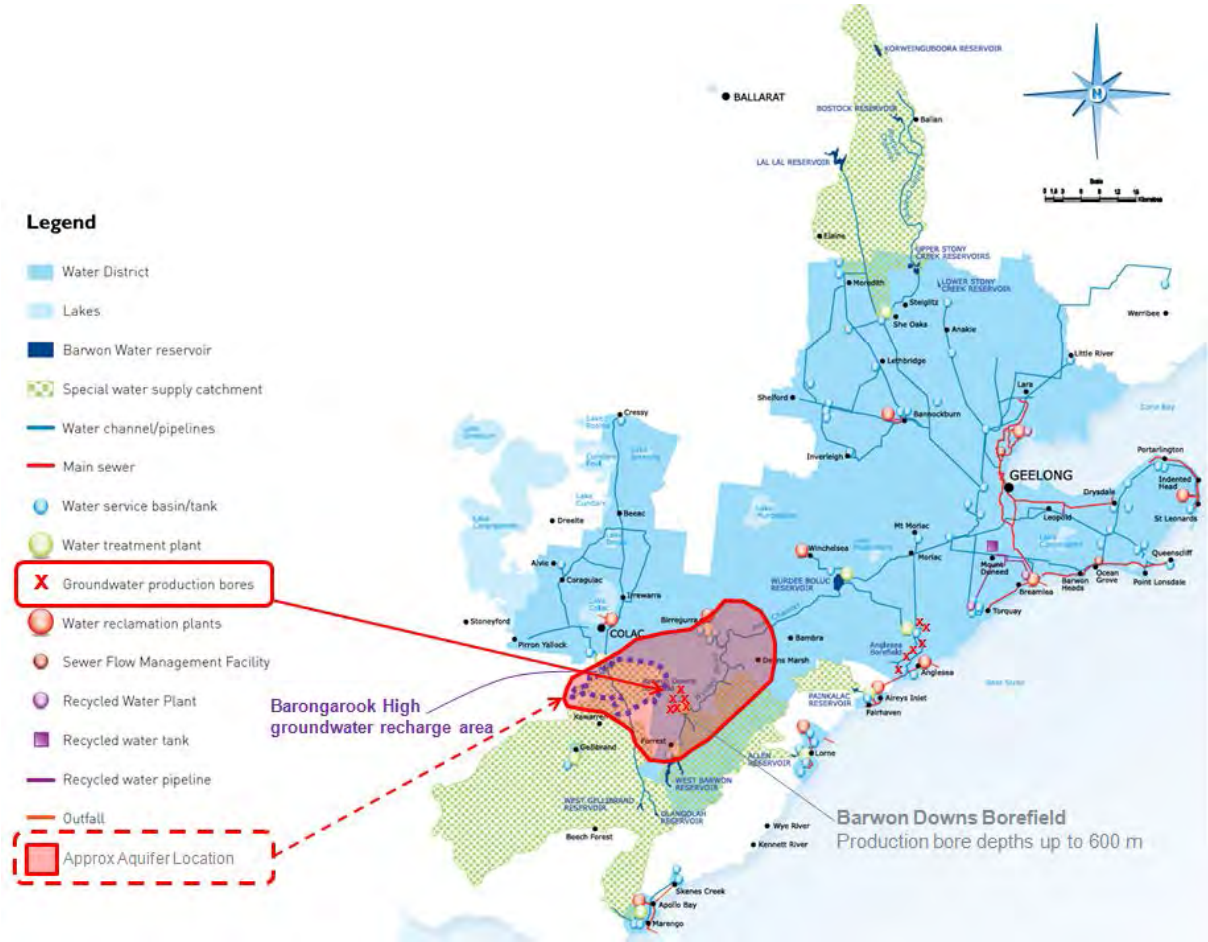
The groundwater model is considered a fit-for-purpose tool to assess the likely impacts of different groundwater extraction scenarios in support of the upcoming licence renewal.

1. Introduction

1.1 Barwon Downs region

The Barwon Downs bore field is located approximately 70 km south west of Geelong and 30 km south east of Colac (refer to Figure 1-1). The surrounding land is a mixture of agriculture and state forest. A substantial proportion of the study area has been farmed for over a century which has resulted in some parts of the landscape being highly modified compared to the surrounding natural environment.

Figure 1-1 Map of the Barwon Downs region including the aquifer extent and the primary groundwater recharge area



The regional groundwater system extends beneath two surface water catchments, the Barwon River catchment and the Otways Coast catchment.

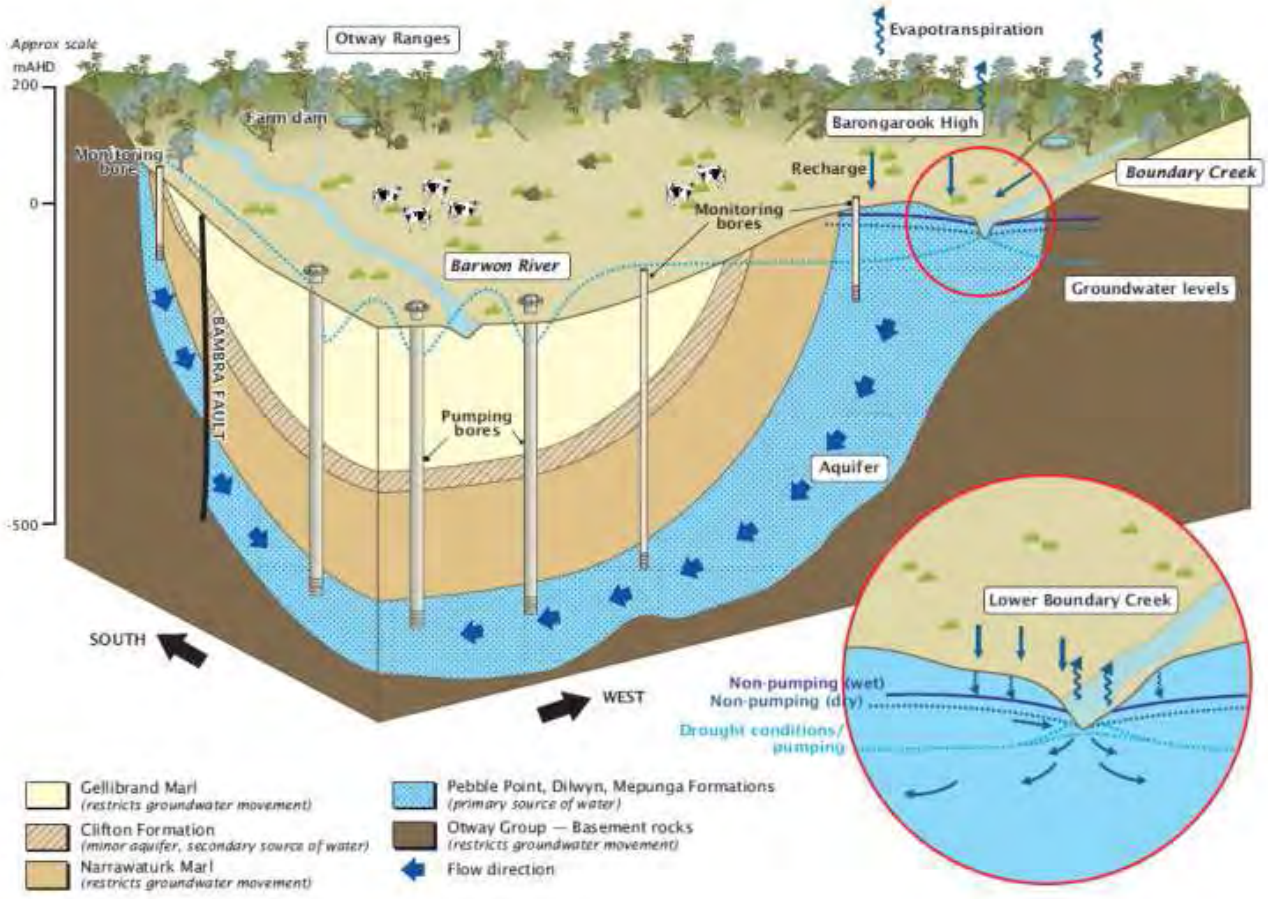
The Barwon River and its tributaries rise in the Otway Ranges and flow north through Forrest and Birregurra. The Barwon River West Branch and East Branch drain the southern half of the catchment and come together just upstream of the confluence with Boundary Creek. Boundary Creek flows east across the Barongarook High and joins the Barwon River around Yeodene.

The Otways Coast catchment is a large catchment with many rivers that flow towards the coast. The Gellibrand River is in the Otways Coast catchment and rises near Upper Gellibrand and flows in a westerly direction towards Gellibrand. The Gellibrand River discharges to the ocean at Princetown.

The borefield taps into an underground source of water, known as the Lower Tertiary Aquifer, with depths of up to 600 metres at the borefield. The aquifer covers an area of approximately 500 km^2 below the surface and is

connected to the surface in both the Barwon River catchment (Barongarook High) and the Otways Coast catchment near Gellibrand. Barongarook High is the main recharge area of the aquifer because of its unconfined nature.

Figure 1-2 Schematic of the Lower Tertiary Aquifer and where it outcrops at the surface



1.2 History of the Barwon Downs borefield

1.2.1 Borefield history

In response to the 1967-68 drought, when water supplies reached critical levels, the Geelong Waterworks and Sewerage Trust (now Barwon Water) began investigating groundwater resources as a means of supplementing surface water supplies used for the Geelong region. Investigations conducted in the Barwon Downs region revealed a significant groundwater resource with potential to meet this need.

In 1969 a trial production bore was built and tested close to the Wurdee Boluc inlet channel at Barwon Downs. With knowledge gained from these results another bore was built at nearby Gerangamete in 1977. A long term pump testing programme from 1987-1990 confirmed that the borefield should be centred on Gerangamete.

There are now six production bores in the borefield each between 500 and 600 metres deep. Pumps in each bore are capable of providing daily flows of up to 12 megalitres (ML) per day per bore. The pumped water is treated by an iron removal plant prior to transfer to Wurdee Buloc Reservoir. Total borefield production capacity is 55 ML per day.

1.2.2 Groundwater extraction

Barwon Water operates the borefield in times of extended dry periods. This has occurred only five times in the last 30 years. The borefield is a critical back up source for Barwon Water because it is buffered from climate variability due to the depth and large storage capacity of the aquifer, whereas surface water catchments are susceptible to seasonal fill patterns mostly driven by rainfall.

Although extraction occurs infrequently, large amounts of groundwater are drawn when needed to supplement surface water storages during drought. This is completed in compliance with the groundwater licence (refer to Section 1.3). This operational philosophy of intermittent pumping has been an effective way to provide customers with security of supply, especially in times of prolonged dry conditions.

To date, Barwon Water has extracted the following volumes from the aquifer:

- 3,652 ML from February to April in 1983 due to drought,
- 19,074 ML during a long term pump test in the late 1980s,
- 36,817 ML during the 1997 - 2001 drought,
- 52,684 ML during the 2006 – 2010 millennium drought, and
- 2,383 ML in 2016 to boost storages after a very dry summer.

Groundwater extraction has supplemented surface water supply by a total of 114,610 ML, equating to approximately 10 per cent of total water consumed over a 30 year period.

1.2.3 Licence history

The first licence was issued in 1975 but did not come into effect until 1982, as the bores were not brought into operation until the 1982-83 drought. This was the first time the borefield was used to supply water to Geelong. The licence issued by the State Rivers and Water Supply Commission (now Southern Rural Water) was to allow Barwon Water to operate four production bores based on the following conditions:

- Extraction for the purpose of urban water supply;
- Maximum daily extraction rate of 42.5 ML;
- Maximum annual extraction rate of 12,600 ML;
- Maximum ten-year extraction rate of 80,000 ML; and
- Periods of licence renewal of 15 years (1975 – 1990).

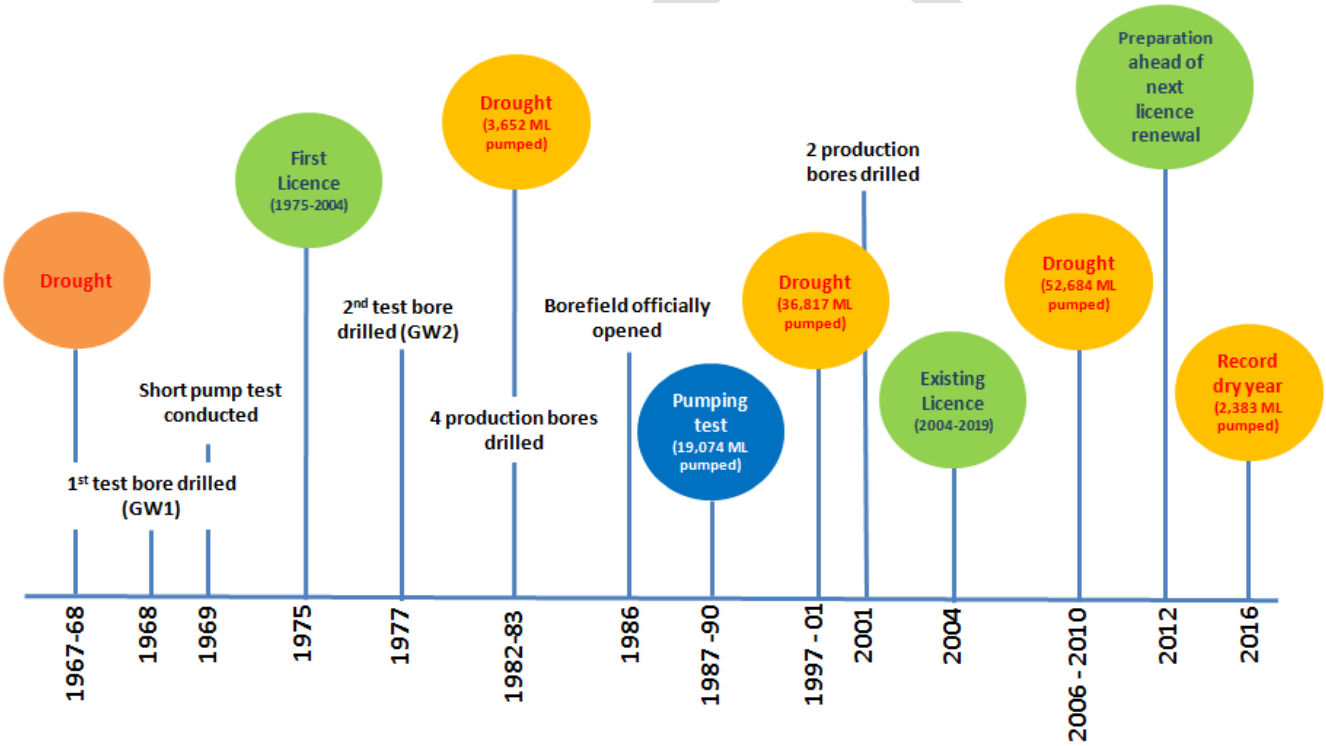
The licence was subsequently renewed for two periods of five years up to 2000. From 2000, the licence was temporarily extended three times for a total of four years to allow the licence renewal to take place through to 31 August 2004.

In 2002[1], Barwon Region Water Authority (now Barwon Water) applied to renew the Barwon Downs borefield licence for extraction of groundwater to meet urban water supply needs. The application proposed the following:

- Maximum daily extraction rate of 55 ML;
- Maximum annual extraction rate of 20,000 ML;
- Maximum ten-year extraction rate of 80,000 ML;
- Long term (100 year period) average extraction rate of 4,000 ML/year; and
- Licence renewal period of 15 years.

From 2004 to 2006, the licence was temporarily extended to allow for the licence renewal to take place. Licence conditions were drafted by the panel taking into consideration the findings of the technical groups and the submissions received. This licence is valid to 30 June 2019.

Figure 1-3 Timeline of events that surround the development and use of the Borefield



[1] *Note: Bulk Entitlement was considered in 2002 so that the Upper Barwon System could be managed conjunctively. This was put aside as the view at the time was that the rights to groundwater should continue to be contained in a licence and subject to regular review.*

1.3 Current groundwater licence

The Barwon Downs borefield is operated under licence from Southern Rural Water. This licence was granted in 2004 and is due for renewal by June, 2019.

This licence makes provision for extraction limits on a volumetric basis over a range of time scales. As part of the licence conditions, Barwon Water monitor groundwater levels and quality, subsidence, flow in Boundary Creek and Barwon River, as well as the protection of riparian vegetation, protection of stock and domestic use and the protection of flows in the Barwon River tributaries.

Reporting against these licence conditions is provided in an annual report to Southern Rural Water who administers and regulates groundwater licences on behalf of the Water Minister..

1.4 Strategic drivers for the Barwon Downs technical works monitoring program

Ahead of the upcoming 2019 licence renewal process, Barwon Water instigated a technical works monitoring program to improve the comprehensiveness of the current monitoring program to ensure the submission of a technically sound licence application.

Driving the need for this monitoring program is the reliance on the borefield to provide water security for Barwon Water customers, to address outstanding community issues particularly where the relationship between cause and effect is not yet fully understood, and to close out any known technical knowledge gaps.

1.4.1 Water security

The Barwon Downs borefield provides water for the regional communities of Geelong, the Surf Coast, the Bellarine Peninsula and part of the Golden Plains Shire.

A prolonged period of unprecedented drought (known as the Millennium drought) saw a sustained dry climate average from 1997 to 2011. In 1997, many of the region's water storages were close to capacity, however by January 1998, after high consumption and low catchment inflows, water restrictions were necessary to balance supply and demand in the Geelong area. This clearly highlighted that even by having large storages the region was susceptible to rapid changes.

In 2001, strong catchment inflows from healthy rainfall refilled storages, ending water restrictions in Geelong. Five years later, after a very dry year, strict water restrictions were again required with climate extremes exceeding the historical record. At the height of the Millennium drought, Geelong's water storages dropped to 14 per cent when catchment inflows were severely reduced. To meet demand during this time 52,684 ML was extracted from the borefield providing up to 70 per cent of Geelong's drinking water.

In 2010, improved rainfall restored storages and restrictions were again slowly lifted in the Geelong area. This allowed the Barwon Downs borefield to be switched off and to begin recharging. Without the use of the borefield during this time, residents and industry in Geelong, Bellarine Peninsula, Surf Coast and southern parts of the Golden Plains Shire would have run out of water.

The township of Colac will soon be connected to the Geelong system through construction of a pipeline between Colac and Geelong. This interconnection will also allow the borefield to supply Colac residents and will provide additional water security for the water supply system which is currently susceptible to seasonal fill patterns.

1.4.2 Community issues

Although Barwon Water is compliant with the monitoring program associated with the 2004 licence, it is accepted that this program is not comprehensive enough to address community interest about specific issues centered on potential environmental impacts in the local catchment.

Areas of community interest recently have included the:

- extent of stream flow reduction and any ecological impacts at various points along Boundary Creek,
- potential to increase existing acid sulphate soil risks in the Yeodene peat swamp,
- potential to increase the existing fire risk at the Yeodene peat swamp, and
- extraction limits and the current operational regime of the borefield, and whether they are sustainable under climate change projections.

A Community Reference Group was established in 2013 to provide community feedback and input into the technical works monitoring program.

1.4.3 Informing the licence renewal

To address community interest adequately and inform the licence renewal in 2019, Barwon Water commissioned a review of the existing monitoring program associated with the 2004 licence. This technical review recommended that a revised technical works monitoring program be developed with the following objectives:

- Better understand the environmental impacts of groundwater extraction;
- Estimate, and quantify where possible, the causes and relative contributions of groundwater variability (for example, groundwater extraction and drought) in contributing to environmental impacts; and
- Provide additional monitoring data and subsequent analysis required to support the licence renewal process.

1.5 Overview of the technical works monitoring program

1.5.1 Monitoring program development

The development of the technical works monitoring program is shown in Figure 1-4 and can be broken down into the following stages.

<u>Stage 1: Review of the existing monitoring program</u>

In 2012, Barwon Water initiated a review of the Barwon Downs monitoring program. The technical works monitoring program was developed in response to the:

- desire to address key community issues (see section 1.4.2), and
- 2008-09 flora study which recommended a long term vegetation and hydrogeological monitoring program be designed and implemented to better understand a range of factors such as groundwater extraction, drought and land use changes that were contributing to the drying of the catchment.

This review took into account both the social and technical issues that needed to be addressed to inform the licence renewal process in 2019 and was initiated early to allow sufficient time to establish a comprehensive monitoring program. A risk based approach was used to rank these issues, and control measures were developed to downgrade the residual risk ranking, which included activities such as additional monitoring and technical studies.

Stage 2: Technical works monitoring program scope refinement

In 2013, the scope of the technical works monitoring program was developed based on the recommendations of Stage 1. The Technical Works Monitoring Program was designed to improve the capacity to differentiate between groundwater extraction and climate effects on the groundwater system, predict water table and stream flow changes, and increase understanding of potential ecological impacts. Key improvement areas include:

- differentiating between groundwater extraction and climate effects on the regional groundwater system,
- understanding the potential risks of acid sulphate soils and whether that could change future extraction practices,
- assessing whether vegetation in areas dependent on groundwater will be at risk from water table decline, which could change future extraction practices,
- assessing flow requirements in Boundary Creek to determine if the current compensatory flow is effective,
- characterising groundwater dynamics in the aquitard to improve hydrogeological understanding of groundwater flow and quantity, and
- better understanding of groundwater and surface water interaction, particularly along Boundary Creek where groundwater contributes to base flow.

In the same year, the Barwon Downs Groundwater Community Reference Group was also formed by Barwon Water to ensure where possible, the monitoring program was adjusted and the scope refined, to take into consideration community issues and views. This was a critical contribution towards the broader licence renewal strategy as it raised confidence that the right monitoring data would be captured to specifically target key areas of community concern.

Stage 3: Construction of additional monitoring assets

During 2014-15, the following construction works were completed:

- 33 new groundwater monitoring bores drilled, including the replacement of one existing bore,
- 3 existing bores refurbished,
- 4 new potential acid sulphate soils monitoring bores were installed,
- 32 data loggers and two barometric loggers installed in new and existing bores,
- 1 new stream flow gauges installed, and
- 2 existing stream flow gauges replaced refurbished and reinstated.

Stage 4: Ongoing monitoring

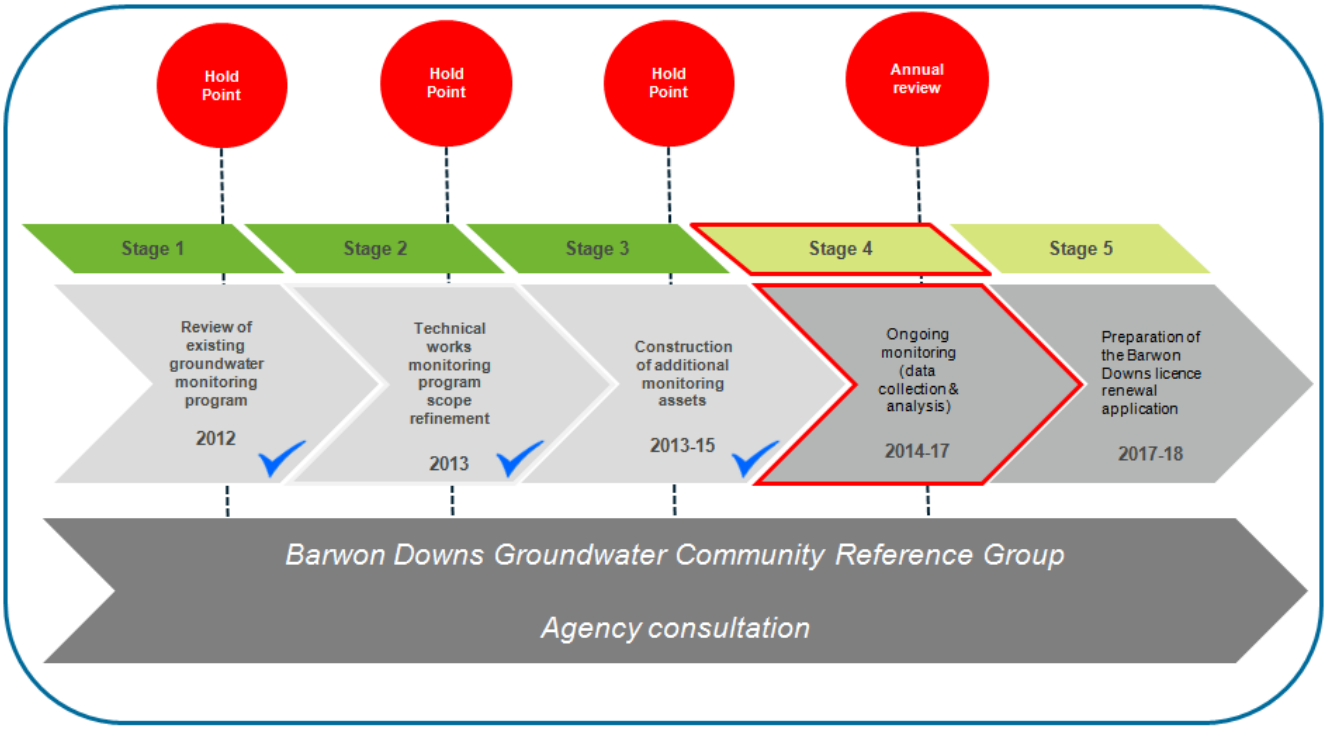
The technical works monitoring program is now in a phase of data collection and preliminary analysis. The intention of this stage is to update the conceptual understanding of the hydrogeology in the Barwon Downs region. This will be based on data collected from additional and existing monitoring assets and the outcomes of a range of investigative technical studies, all of which will be used to update and calibrate the groundwater model.

Preparation will also begin at this stage to form a comprehensive licence application.

Stage 5: Preparation for licence renewal submission

Prior to 2019, Barwon Water will need to formally submit a licence renewal application to Southern Rural Water. This will initiate a groundwater resource assessment process as set out under the Water Act.

Figure 1-4 Development of the technical works monitoring program



1.5.2 The inter-relationships of the technical works monitoring program

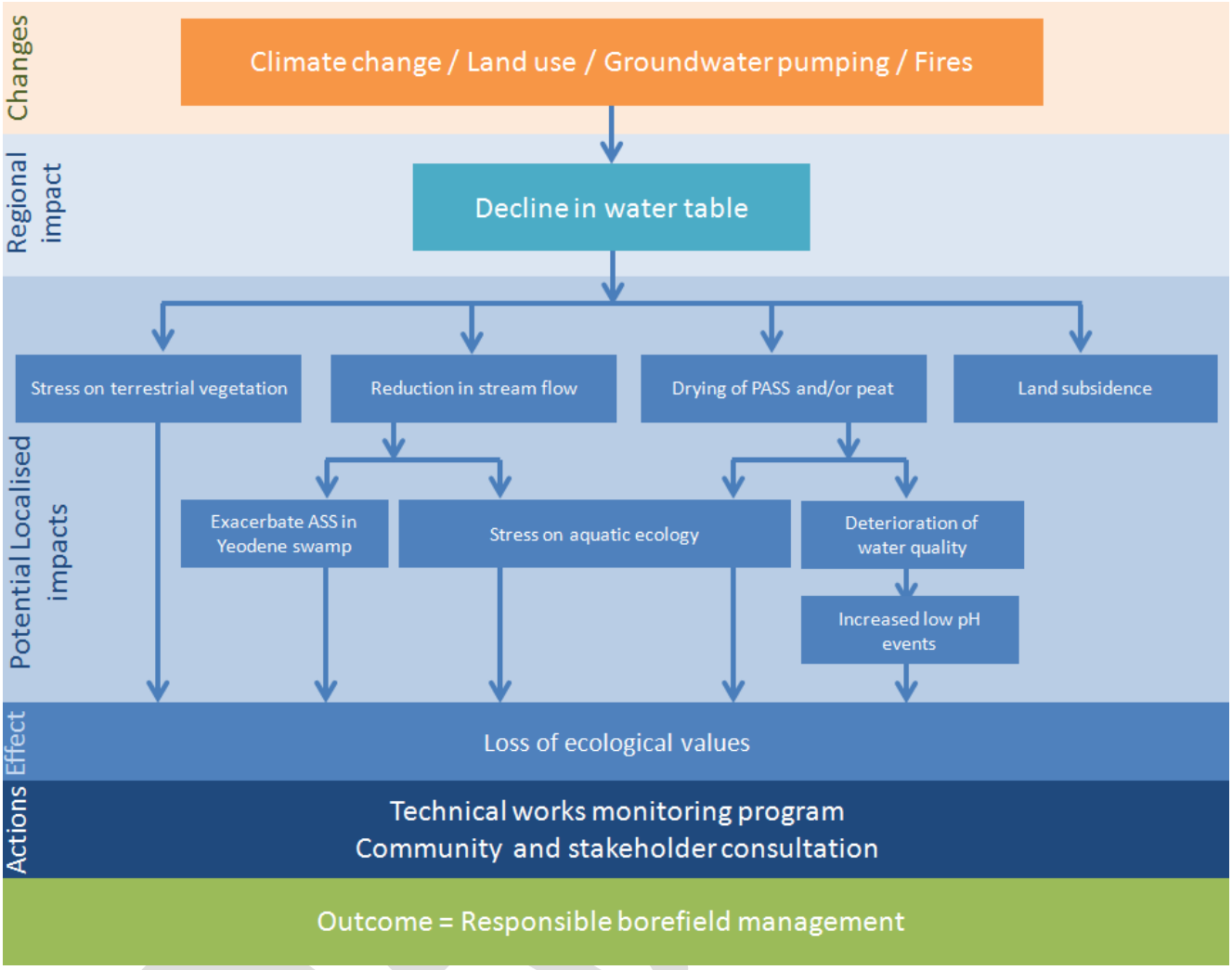
The technical works monitoring program is a complex, multi-disciplinary project due to the overlapping nature of the various components of the program as shown in Figure 1-5.

Changes in climate, land use practices and groundwater pumping will alter water availability throughout the catchment, including stream flow and groundwater levels. Many receptors are sensitive to changes in groundwater levels and stream flows, particularly those that are dependent on groundwater. Ultimately this can lead to the loss of ecological values (refer to Figure 1-5).

For example, a decline in groundwater level beneath a stream can cause a reduction in stream flow, which in turn can impact the habitat of aquatic ecology in the stream. Declining groundwater levels or reduced stream flow also has the potential to impact riparian vegetation and potential groundwater dependent activities.

The technical works monitoring program is designed to address knowledge gaps to better understand potential impacts from the borefield. The program is underpinned by scientific rigor using multiple lines of evidence-based techniques to establish the relationship between cause and effect for potential impacts caused by groundwater extraction.

Figure 1-5 Potential impacts in the catchment from changes in the catchment



1.6 This report

This report documents the update (including the expansion, building and calibration) of the revised groundwater model and the assessment of the likely historical impacts both with and without the operation of the Barwon Downs borefield.

The key objective is to update the existing model building on earlier model versions that can be used with confidence to assess historic and future impacts associated with groundwater extraction from the Barwon Downs borefield. These impacts are likely to include:

- **Declining groundwater levels**. The model will be required to determine whether the extraction of groundwater from the borefield can be sustained over a period of decades into the future.
- **Baseflow impacts**. The model will predict changes in groundwater discharge to rivers and creeks and also changes in river seepage to groundwater that may occur in the future as a result of borefield operations.
- **Impacts on groundwater dependent ecosystems (GDEs).** Impacts on GDEs can be assessed through the estimation of drawdown that is likely to occur at key locations adjacent to or within important GDEs. The model will also be used to predict the change in groundwater discharge fluxes through evapotranspiration under the assumption that evapotranspiration represents the extraction of groundwater by groundwater dependent vegetation.

- **Acid sulfate soils.** Predicted drawdown in shallow soils that are susceptible to acid sulfate generation will be determined by the model.

2. Conceptual understanding of the groundwater system

2.1 Chapter Overview

The purpose of this chapter is to describe the conceptual understanding of how water flows into and out of the groundwater system. The hydrogeological conceptual understanding has improved significantly over the years as a result of the information collected during the Technical Works Monitoring Program. The refined hydrogeological conceptualisation forms the basis for the groundwater model and allows the model to be calibrated with more certainty.

The Barwon Downs groundwater system has several different layers which are described in detail in the following sections. Water flows into the system from many different sources. The main types of water source are recharge from rainfall, aquifer throughflow and seepage from rivers. Similarly there are several mechanisms where water can leave the groundwater system including evaporation, seepage to rivers, aquifer throughflow and pumping.

Table 2-1 provides a summary of the key features of the Barwon Downs groundwater system and more detail is provided in the following sections.

Table 2-1 Overview of the conceptual understanding of the Barwon Downs groundwater system

Feature	Description	Significance of improvements
Stratigraphy	• The definition of the different layers in the groundwater system. • Consists of seven important layers.	• Findings were used to help refine the stratigraphic conceptualisation of the geological valley (the graben) • Improved definition resulted in revisions to unit thicknesses/extents and recognition of the Pember Mudstone as a continuous layer.
Faults	• Two faults are located on the edges of the groundwater system – Colac and Bambra Faults. • These faults control the movement of water into the groundwater system.	• Technical studies confirm that the faults allow limited amounts of water into the groundwater system.
Recharge from rainfall	• Recharge from rainfall is the primary means of water getting into the groundwater system.	• Field estimates indicated the recharge rate is approximately 10% of annual rainfall, which is lower than previous estimates. • Field estimates provide the most reliable estimate for the model.
Groundwater discharge	Groundwater discharges from the groundwater system in three ways: • evaportranspiration • horizontal flow (throughflow) • vertical flow (between layers).	• Additional monitoring data has provided more information and improved confidence in the horizontal and vertical flow processes in the groundwater system.
Aquifer drawdown	• Drawdown occurs when groundwater levels decline in response stresses on the aquifer, such as less recharge from rainfall or pumping.	Additional monitoring data has highlighted that different aquifers in the groundwater system respond differently to pumping: • Drawdown from pumping is most significant in the deeper layers of the Lower Tertiary Aquifer. • Less drawdown in shallower layers in the Lower Tertiary Aquifer. • Less drawdown in overlying aquitard and the watertable aquifer.

2.2 Review of stratigraphy

The stratigraphy of the Barwon Downs Graben includes a series of sedimentary units overlying Basement. These units have been deposited in a series of transgressive and regressive cycles and include the Pebble Point Formation, Pember Mudstone, Dilwyn Formation, Mepunga Formation, Narrawaturk Marl, Clifton Formation, Gellibrand Marl and Quaternary Alluvium.

Previous versions of the numerical model (SKM, 2001 and 2011) included five layers. In these previous versions, the Bedrock and the Pember Mudstone were not included. The confining nature of the Pember Mudstone was represented as a low vertical hydraulic conductivity assigned to the Dilwyn and the Pebble Point Formations.

In 2016, Jacobs reviewed the structure and thicknesses of each formation to update the numerical model. The key findings from the review include:

- Low permeability zones in the shallow aquifer at the Barongarook High are stratigraphically consistent with the Pember Mudstone in the deeper parts of the graben.
- Steep dipping beds are present at the interface between the graben and the Barongarook High (refer Figure 2-3). Review of existing and new bore logs support the presence of continuous, steep dipping beds and not fault driven discontinuous beds. This was supported by the occurrence of basement at greater depths in some stratigraphic logs closer to the centre of the graben.
- Revisions to the extent and thickness of the Lower Tertiary Aquifer (LTA) include:
    - Reduced extent/thickness of the LTA north of the Colac Fault.
    - Increased thickness of the Pebble Point Formation in the southwest of the graben
    - Removal of the Dilwyn Formation around Tulloh and Burtons Lookout.
- Minor revisions to the Mid-Tertiary Aquitard (MTD) including a general increase in the thickness of the Narrawaturk Marl and an increase in the extent of the Gellibrand Marl in the southwest of the model.

A brief description of these nine layers including the basement is provided in Table 2-2. Due to the relatively small spatial extent of the Quaternary Alluvium, this unit has been excluded from the numerical model.

Table 2-2 Stratigraphy of the Barwon Downs Graben and relationship to model layers in the groundwater model

System	Geological Unit	Description	Type	Model layer
Minor surficial sediments	Quaternary Alluvium	Sands, silts and gravels.	**Aquifer (minor)**	incorporated into layer 1
Mid Tertiary Aquitard (MTD)	Gellibrand Marl	Calcareous silty clay and clayey silt. Fossiliferous.	**Aquitard**	1
	Clifton Formation	Calcarenite with marine fossils and minor quartz and limonite sands	**Aquifer (minor)**	2
	Narrawaturk Marl	Calcareous mudstone with thin carbonaceous beds, sand beds and fossiliferous beds	**Aquitard**	3
Lower Tertiary Aquifer (LTA)	Mepunga Formation	Medium to coarse grained quartz sand with some carbonaceous clays and silt layers	**Aquifer**	4
	Dilwyn Formation	Carbonaceous, sandy clays and silts, with some quartz sand and silty sand beds, and minor gravel. Coal and carbonaceous clays also occur in this unit.	**Aquifer**	
	Pember Mudstone	Clays, silts and fine grained sand with carbonaceous, micaceous and pyritic horizons.	**Aquitard (minor)**	5
	Pebble Point Formation	Fine-grained sand with carbonaceous silt and quartz pebble beds. This unit is an equivalent to the Moomowroong Sand Member, Wiridjil Gravels that occur in the Gellibrand sub-basin to the south west of the study area.	**Aquifer (minor)**	6
Bedrock (BSE)		Sandstone, siltstone and mudstone with feldspar and quartz grains, well-bedded and consolidated.	Aquitard	7

2.3 Faults

Faults are hydrogeologically important to the Barwon Downs Graben as they cause discontinuities and partially bound the principal hydrogeological units. The most important faults are the Colac Fault and Bambra Fault. The Colac Fault restricts the extent of groundwater flow to the north. The Bambra Fault causes aquifer units to be upthrown on the southeast side of the fault, resulting in aquifer outcrop and termination of the Dilwyn Formation south east of the Fault.

Faults are generally found on the steeply dipping sides of the graben. The Colac Fault was previously used to define the northern groundwater model boundary (SKM, 2001 and SKM, 2011). Recent work indicates that there is a continuation of stratigraphic units across the fault, suggesting that it may not necessarily act as a groundwater flow boundary (Jacobs, 2015a). However, a further assessment of drawdown responses found that there was limited connectivity across the Colac Fault. This indicates that the fault acts as a boundary that significantly reduces the migration of groundwater responses to the north of the fault.

The Bambra Fault, or Bambra Fault zone, is characterised by a number of sub-parallel faults that have resulted in the upward displacement of stratigraphy to the southeast of the fault. In a recent review of borefield related groundwater responses in the Lower Tertiary Aquifer, Jacobs (2015a) found that the Bambra Fault was best represented by a 95% reduction in aquifer transmissivity to the southeast of the fault. The apparent loss of transmissivity to the southeast of the fault is due to the combined effects of aquifer thinning and displacement related disruption to aquifer continuity. The section of the Bambra Fault located further to the southwest is likely to have an even lower apparent transmissivity and could potentially be represented as a no-flow boundary in a numerical model.

2.4 Groundwater recharge and discharge

Figure 2-3 shows that the LTA, consisting of the Pebble Point, Dilwyn and Mepunga Formations, is the major aquifer in the region. The aquifer has various recharge and discharge processes. Recharge processes include rainfall infiltration, downward leakage from overlying formations and leakage from some rivers where the aquifer outcrops at the surface. Discharge processes include evapotranspiration from vegetation, aquifer throughflow to the north and south of the graben, upward leakage to the overlying formation and discharge to some rivers.

When an aquifer is in equilibrium, recharge to the aquifer will be similar to the discharge from the aquifer and groundwater level fluctuations will be stable. If there is more recharge than discharge, for example during periods of above average rainfall, the storage in the aquifer will increase and groundwater levels will rise. If there is more discharge from an aquifer, such as pumping or higher evapotranspiration, water is removed from storage and groundwater levels will decline. All groundwater systems respond constantly to variable climate conditions so fluctuations in groundwater levels are normal.

2.4.1 Recharge from rainfall

The key recharge process for the LTA is recharge from rainfall. Recharge from rivers is discussed in Section 3.

Recharge to groundwater occurs through rainfall infiltration to the shallowest aquifer across the entire study area. It is expected that the most significant recharge will occur at those locations where surface sediments are coarse grained and/or more permeable. In the catchment area this generally corresponds with the major aquifer units outcrop (as shown in Figure 2-2). Less recharge is expected across the remainder of the model domain where the low permeability Gellibrand Marl outcrops at the surface.

Previous studies have provided some estimate of groundwater recharge to the LTA; however these often incorporate little or no field data and provide a broad range of recharge estimates. Blake (1974) estimated recharge using a recharge rate of 5% of rainfall, but it is unclear what the percentage was based on. It is expected that a generalised “rule of thumb” was used. Lakey and Leonard (1984) used flow net and baseflow analysis to estimate a recharge rate of 14% of rainfall for the Barongarook High. More recent work conducted by Atkinson *et al.* (2014) focussed on using groundwater hydrographs to estimate recharge to the LTA in the Gellibrand River catchment. These recharge estimates were between 11% and 32% of rainfall, however as the study focussed on recharge processes around the rivers, these estimates are not considered to be representative of the recharge in the aquifer outcrop area, which is the focus for this work.

Numerical modelling of the Barwon Downs Graben by SKM (2001) was undertaken and calibration was achieved incorporating a recharge rate of 20% of rainfall to the LTA at the Barongarook High, 8% for the LTA south of the Bambra Fault and 3% for the other sediments (mainly Gellibrand Marl). Subsequent modelling by SKM (2011) included further spatial subdivision of these areas into five different zones of recharge, representing 0.2%, 3.0%, 5.2%, 23.5% and 28.3% of rainfall.

The recharge rates for the outcropping aquifer areas and in areas where the Gellibrand Marl is found at the ground surface have been estimated by Jacobs (2016b) using both analytical studies and modelling including:

- Isotope analysis,
- Chloride mass balance, and
- 1-D unsaturated zone modelling.

This assessment concluded that groundwater recharge rates to the outcropping LTA over the last 50 years is most likely to be at a rate equivalent to between 9% and 11% of annual rainfall. However, recharge in some areas (defined as preferential recharge zones) may be as high as 26% of the annual average rainfall. Additionally, it was found that historical recharge rates over the last 100 to 1000s of years may be considerably lower, representing around 5% of the modern annual average rainfall.

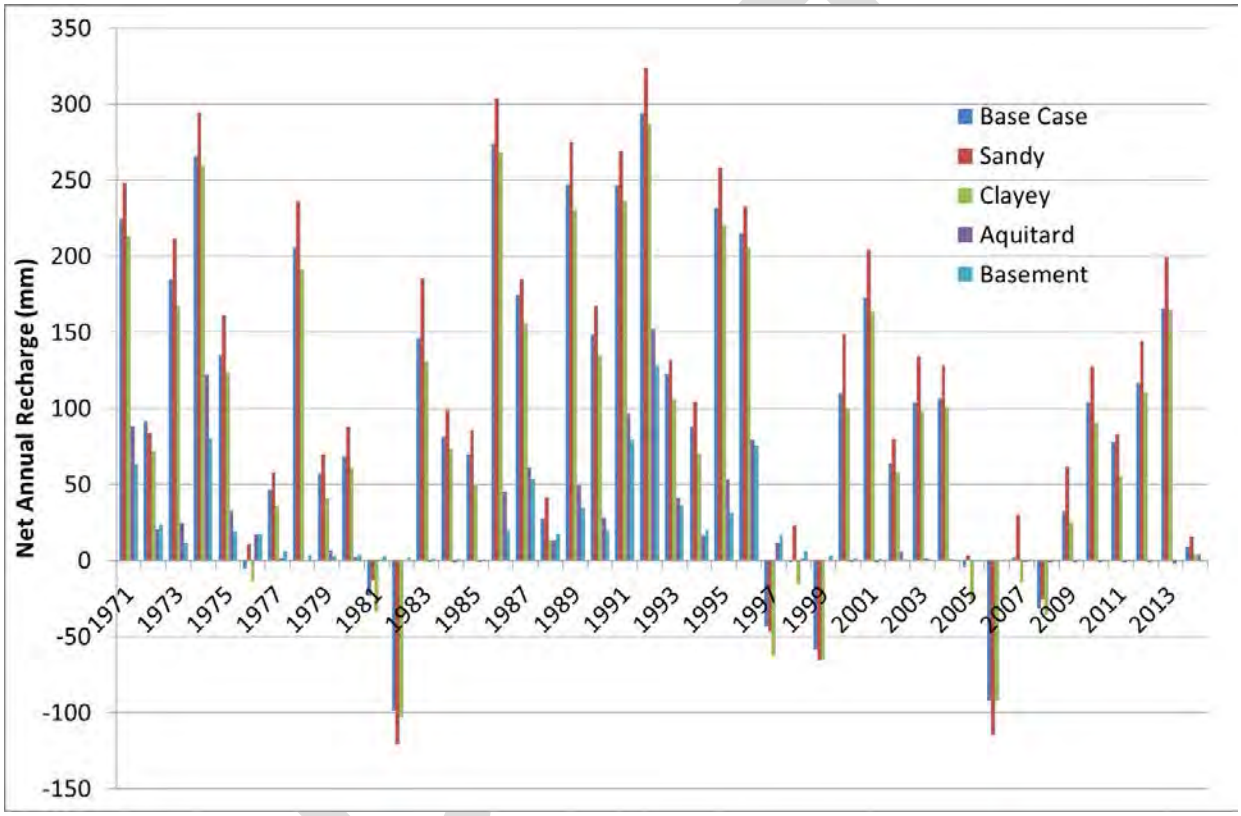
To support the isotope and chloride based estimates of recharge a one dimensional unsaturated zone model was developed. This model was used to simulate recharge in a number of different soil profiles. The main

advantage of the model is that it can provide more detailed estimates of the month to month and year to year variability than the overall average figures from chemical tracers.

The unsaturated zone model used the MIKE-SHE software and simulated recharge (and discharge) from a standard soil column. Soil types in the column were estimated based on samples from other studies in the Technical Works Monitoring Program and rainfall used in the recharge model is based on records from the Barwon Downs Gauge. Evaporation included in the model is based on the daily pan evaporation at Wurdee Boluc and occurs evenly over 24 hours.

The modelling found that there is significant variability in recharge from year to year. The simulated annual recharge for the five soil profiles types is shown in Figure 2-6. The key conclusion from this work is that in any year the recharge can vary (according to rainfall) and that in low rainfall periods when the borefield is likely to be used, it is also likely that there is low recharge and that water use by vegetation is indicated to cause overall discharge in some years.

Figure 2-1 Estimated recharge rates for the period 1971 to 2014.



2.4.2 Discharge Processes

The key discharge process in the Barwon Downs Graben is evapotranspiration, aquifer throughflow, leakage to overlying layers and groundwater pumping. Discharge to rivers is discussed in Section 4.5.

Evapotranspiration

The combination of direct evaporation and transpiration of water by vegetation (collectively known as evapotranspiration or ET) is one of the major water losses from the Barwon Downs Graben. In the previous version of the groundwater numerical model, the maximum ET rate was defined as 2,000 mm/year (SKM, 2011). No additional work has been undertaken in recent years as part of the Technical Works Monitoring Program to improve the estimates of ET as the estimates in the previous groundwater model were considered to be appropriate.

Aquifer throughflow

Groundwater levels at the Barongarook High are currently >240 m AHD and this drives groundwater flow to the east and towards the Gerangamete Flats and south towards Gellibrand (Figure 2-7). Groundwater flow within the graben discharges to the south west (towards Gellibrand) and north east (towards Bambra).

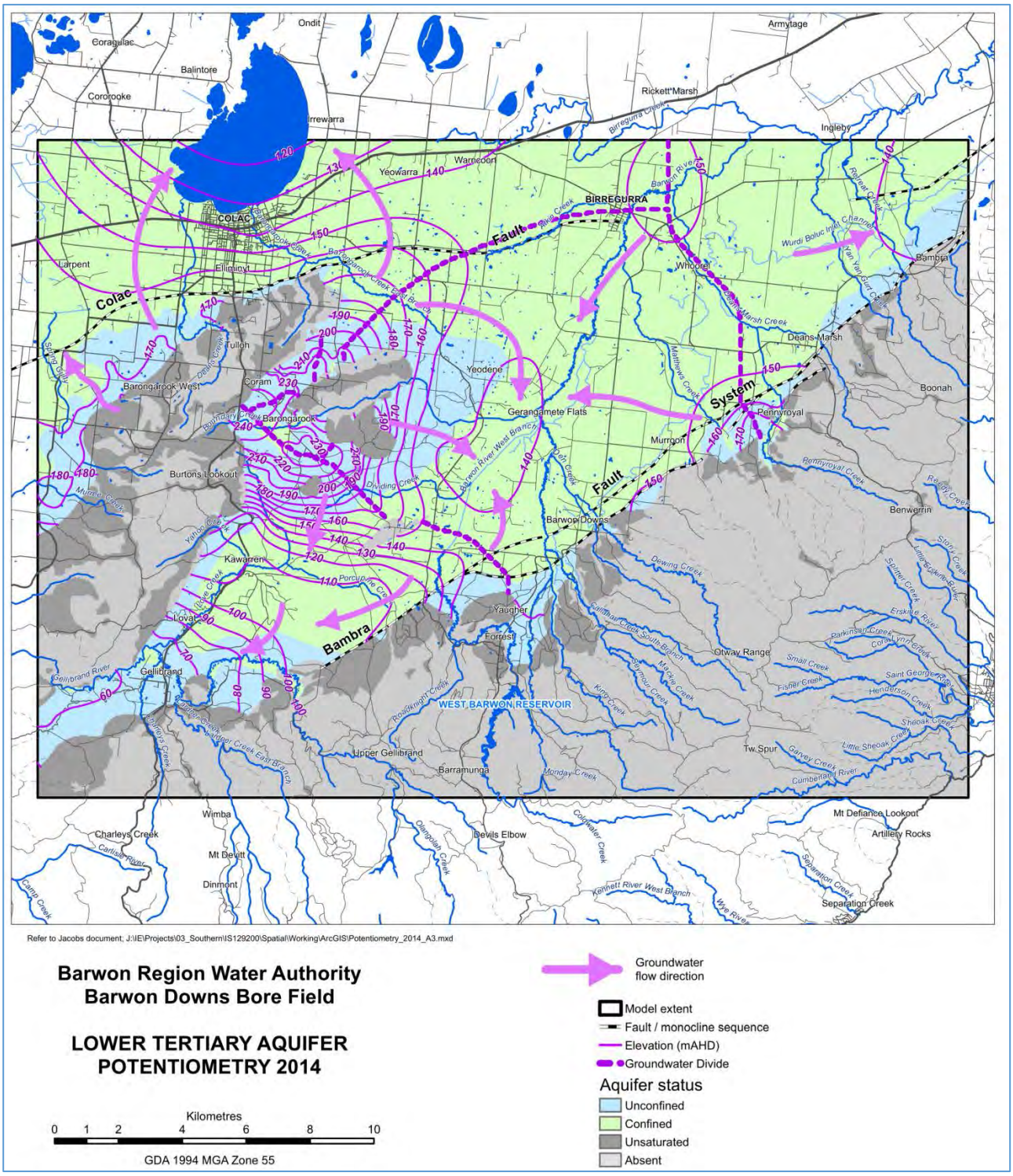
Since borefield operation began in 1982, groundwater levels in the Lower Tertiary Aquifer (LTA) system have changed over time. The changes are principally a result of drawdown centred in the borefield as a result of groundwater extraction, but also represent climatic impacts over time (i.e. periods of reduced rainfall recharge). The current (2014) groundwater levels/flow directions in the LTA are shown in Figure 2-7.

The highest groundwater levels in the LTA were observed on the Barongarook High where the Basement and the LTA outcrop. Groundwater flow from the high was predominantly east towards the Gerangamete Flats and to the south towards Gellibrand. These major flow paths are separated by an east-west trending groundwater divide. Groundwater flow to the north was also apparent, facilitated in part by the basement ridge through the Barongarook High which acts as a geological divide from the rest of the Barwon Downs Graben. Groundwater flow from the Gerangamete Flats occurred in a north-east direction towards Deans Marsh (Figure 2-2).

While these trends have remained broadly similar over time, at the peak of borefield extraction, drawdown in the borefield reversed groundwater flow directions in some areas. For example, groundwater flow near Deans Marsh is currently north east (as it was in 1987), however at the height of borefield operation, groundwater flow was south west – towards the borefield.

Additionally, rapid recovery in the centre of the borefield immediately after extraction facilitated groundwater flow from the graben to the south west, in areas where flow would have previously been north east. Changing groundwater flow directions will change the aquifers natural recharge and discharge zones. For example, groundwater that previously discharged to surface water can be reversed so that the surface water feature becomes a recharging zone for the aquifer. Alternatively groundwater may have discharged out of the Barwon Downs graben historically, while parts of the graben now act as a recharge area.

Figure 2-2 Groundwater flow direction in the LTA in 2014



Vertical flow processes

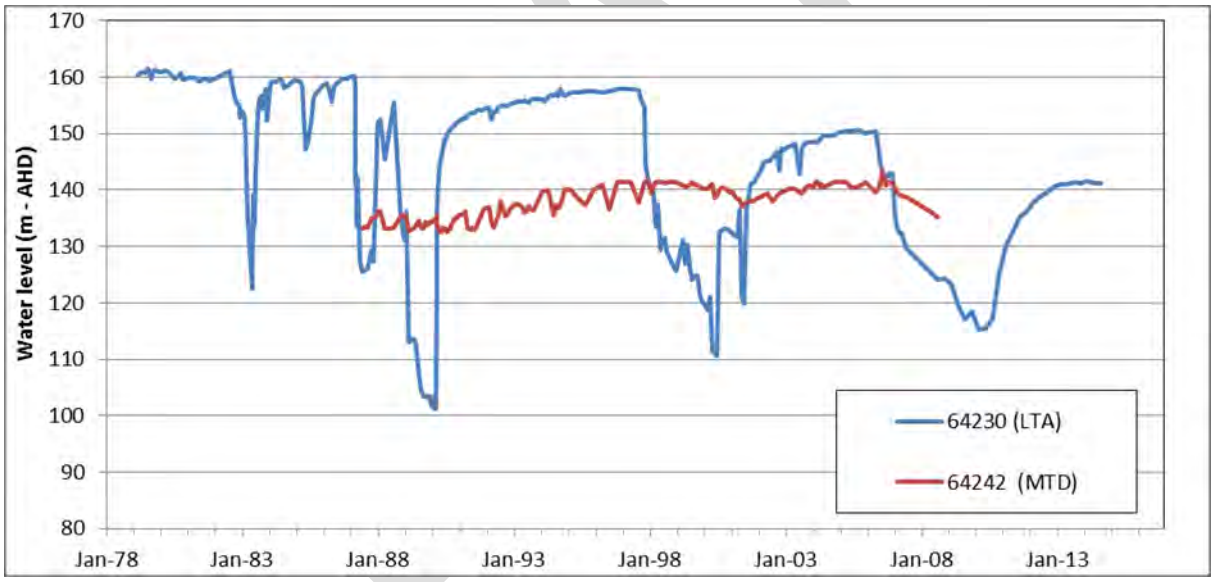
Previous assessments of hydraulic gradients between aquifers and aquitards in the Barwon Downs Graben have been limited. It is generally understood that upward hydraulic gradients exist between the Dilwyn and Pebble Point aquifers and the overlying Narrawaturk Marl aquitard through the central portion of the graben. This facilitates upward leakage from the aquifers into the overlying aquitard and is a key discharge process for the aquifer.

SKM (2008) suggested that while the potential for leakage between the LTA and MTD is apparent and that future drawdown in the MTD could occur, inadequate monitoring and characterisation of the MTD prevented definitive commentary on the matter. It was also postulated that perched water tables are likely to be present throughout the Barongarook High (where the LTA outcrops). However, the location cannot be reliably predicted due to the absence of shallow monitoring bores.

As part of recent investigations between 2014 and 2016, bores were constructed in the Gellibrand Marl above the LTA (Jacobs, 2016c). Groundwater monitoring in these bores indicates upward hydraulic gradients from the LTA to the Gellibrand Marl, consistent with those observed by Witebsky (1995) Shallow monitoring bores located throughout the Barongarook High as part of the same program identified perched, shallow groundwater systems in a number of areas around the north east side of the Barongarook High.

While historical assessments indicate upward leakage from the LTA, there is potential for this to reverse under continuing extraction. Continued monitoring of groundwater levels has identified this in some areas, where groundwater levels in the LTA have fallen below the overlying MTD for periods of time (see Figure 2-8).

Figure 2-3 Bore hydrographs in LTA and MTD near the borefield



2.5 Aquifer Drawdown

Groundwater levels fluctuate in response to climate conditions and groundwater extraction. When the borefield is operational, the drawdown cone spreads in the shape of a symmetrical elongated ellipse along the axis of the graben from northeast to southwest. The cone of depression is generally steep which reflects the low regional transmissivity of the aquifer (Witebsky, 1995).

Figure 2-9 shows two hydrographs for the LTA in the centre of the study area near Seven Bridges Road. In the deeper LTA where the groundwater is extracted there is a strong response to pumping whereas shallower bores in the LTA show a subdued response to pumping.

Figure 2-10 shows hydrographs from the MTD and the alluvial aquifer. The alluvial aquifer shows strong seasonal trends while the aquitard bore does not respond strongly to seasonal effects. The alluvial aquifers are typically more permeable and the watertable is shallower which means responses to rainfall recharge and evapo-transpiration are rapid. The MTD is significantly less permeable which means recharge via rainfall is takes longer.

As shown in Figure 2-11, drawdown in the Lower Tertiary Aquifer (LTA) from the Barwon Downs borefield has propagated in an elongated drawdown cone that extends north east and south west within the Graben. An investigation by Jacobs (2016a) confirmed that drawdown extends to Kawarren area. However there are others bores located closer to the borefield (between the borefield and the Kawarren area) that have reported negligible drawdown. The absence of drawdown is likely to be related to zones of reduced hydraulic conductivity in localised areas and the development of this conceptual understanding was incorporated into the numerical model.

Drawdown in the LTA is less than predicted throughout areas of the Barongarook High, including Yeodene (Big) Swamp and a number of drainage lines to the east of the high. This is consistent with stratigraphic variability in the LTA as suggested by SKM (2008) and represents an improved conceptual understanding of the system for incorporation into the numerical model. A number of shallow bores throughout these areas has also helped to identify the presence of minor perched aquifer systems at the high.

Figure 2-4 Examples of groundwater level trends at different depths in the LTA

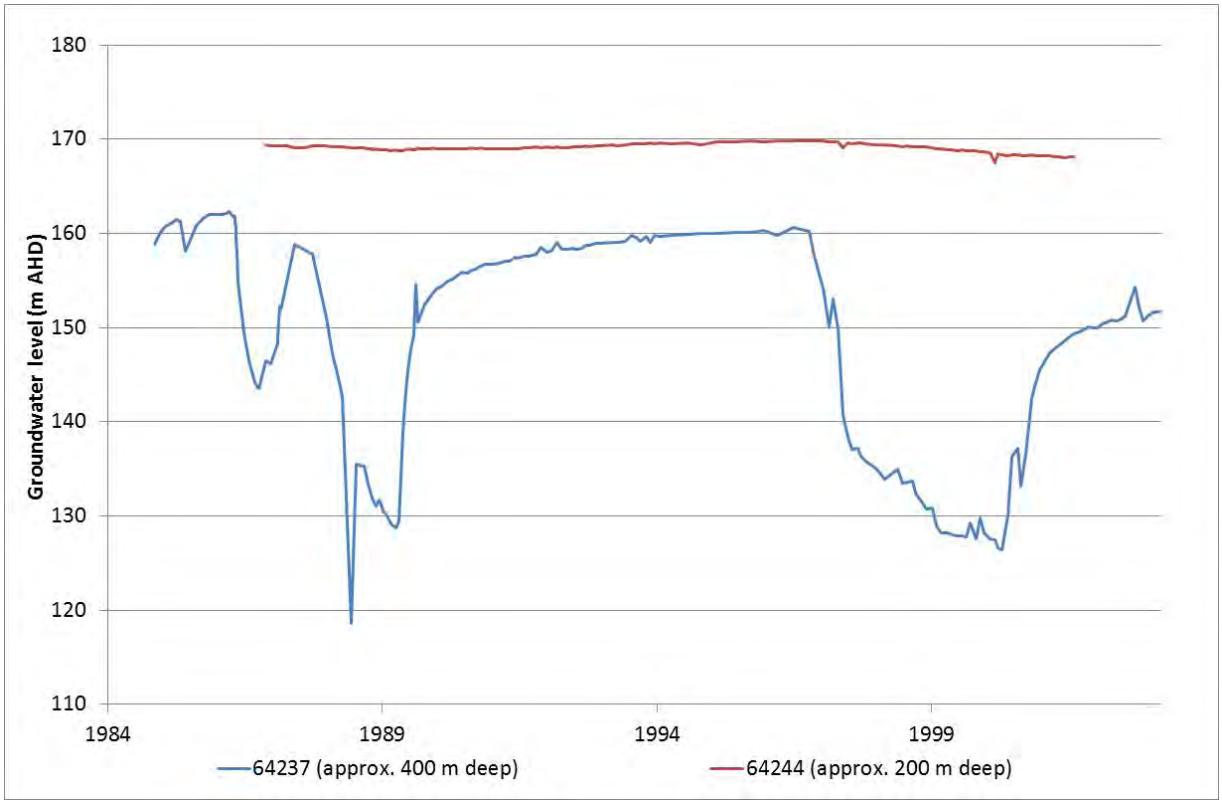


Figure 2-5 Examples of groundwater level trends in the Alluvial aquifer and the MTD (Aquitard)

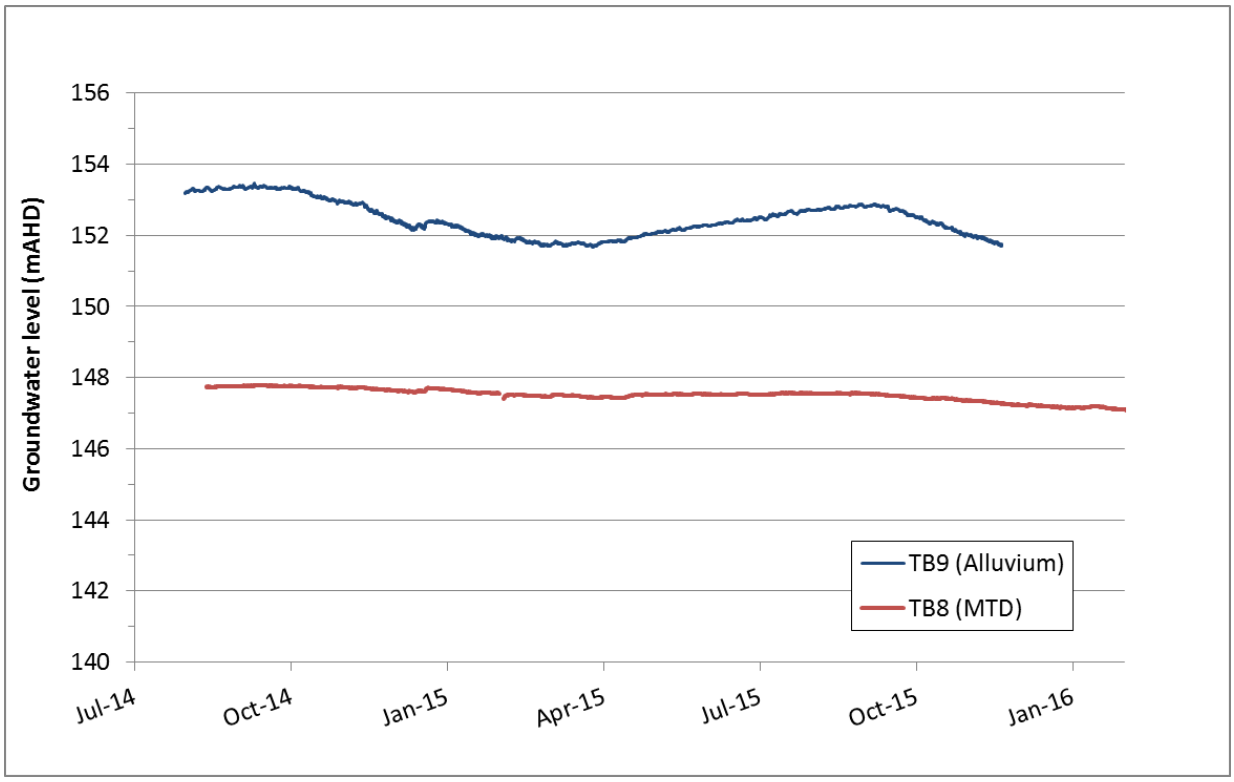
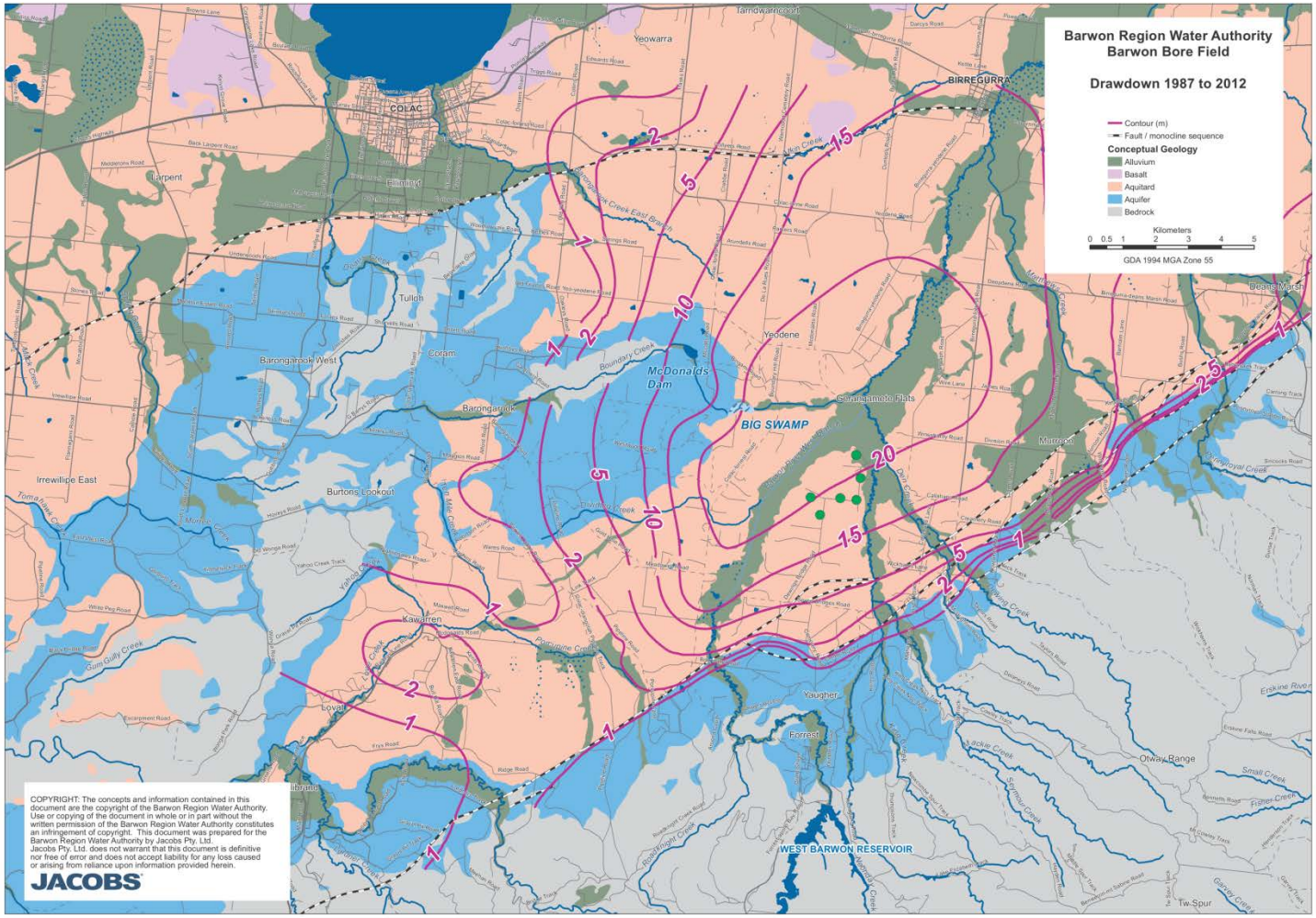


Figure 2-6 Drawdown in the LTA (1987-2012) (Jacobs, 2015b)



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3. Conceptual understanding of groundwater - surface water interactions

3.1 Chapter Overview

This chapter describes the current understanding of the interaction of groundwater and surface water in the study area. The major river systems in the study area are the Barwon Catchment and the Gellibrand Catchment. The interaction between these rivers and the groundwater system, particularly the Lower Tertiary Aquifer (LTA), varies significantly spatially and temporarily. This chapter describes our understanding of where groundwater discharges to rivers and where rivers recharge the groundwater system and how these interactions have changed over time.

The exchange of water between the groundwater system and the rivers is a key feature of the groundwater model and therefore a sound understanding of where rivers are gaining and losing is required. An overview of the interaction between groundwater and surface water is provided in Table 3-1 and more detail is provided in the following sections.

Table 3-1 Overview of groundwater surface water interaction

River	Summary of groundwater surface water interaction
Gellibrand River Catchment	
Gellibrand River	• Key discharge feature for the LTA aquifer. Groundwater provides a significant baseflow to river (i.e. gaining river).
Porcupine Creek	• Gaining river in headwaters where there are springs from the LTA • Losing river downstream where the creek flows over the MTD
Ten Mile, Yahoo, Love Creeks	• Springs from the MTD provide baseflow to these creeks (i.e. gaining rivers)
Barwon River Catchment	
Barwon East and West Branches	• Flows over the MTD through centre of the valley (the geological graben) and is thought to be marginally gaining. • Flow regulated in the West Barwon River by the operation of the West Barwon Dam
Barwon River	• Headwaters for most tributaries rise in Otways near the Bambra Fault and LTA likely to provide baseflow in these areas (gaining in headwaters)
Dividing Creek	• Drains surface water runoff with limited interaction with groundwater (most likely a losing river)
Boundary Creek (Reaches 1, 2 and 3)	• Reach 1 is gaining slightly as it flows over Basement rock • Reach 2 flows over LTA where groundwater levels have been influenced by pumping from Barwon Downs bore field. Creek was gaining in this location, but since 2000, the creek is now losing • Reach 3 is highly complex but is most likely gaining through most of the past

3.2 Gellibrand River Catchment

The Gellibrand River is located in the south of the study area and the key tributaries relevant to this study are Porcupine Creek, Ten Mile Creek, Yahoo Creek and Love Creek. Near the south western boundary of the groundwater model, the LTA outcrops along the Gellibrand River and the river is gaining in this area (SKM, 2012). This is a key discharge zone for the LTA.

Porcupine Creek flows over outcropping MTA and Clifton Formation which is a minor aquifer. There are several springs that provide base flow to headwaters of the creek. The creek is therefore gaining in the upper reaches and then becomes losing as it approaches the confluence of Ten Mile Creek (SKM, 2012).

SKM (2012) confirmed that there are several springs along Ten Mile Creek, Yahoo Creek and Love Creek. These springs flow from the MTD, which is supported by an upward gradient from the underlying LTA (SKM, 2012). Importantly these springs are not interpreted to be the result of flow out of the LTA, rather the underlying high LTA pressures preclude deep drainage and support the formation of springs. These springs provide baseflow to Ten Mile Creek and Yahoo Creek.

3.3 Barwon River Catchment

3.3.1 Overview of groundwater surface water interactions across catchment

The majority of tributaries of the **Barwon River** rise in the Otway Ranges to the south. These tributaries flow over the Basement and then the LTA in the vicinity of the Bambra Fault zone. The LTA is likely to provide base flow to these tributaries east of the Bambra fault zone, however no field studies have been undertaken to confirm this. The significance of the groundwater surface water interaction on the south east side of the fault zone is considered to be low as work done to date indicates a low degree of connection across the fault zone.

Two tributaries of the Barwon River rise on the Barongarook High – Dividing Creek and Boundary Creek. Some reaches along both creeks flow over the LTA and these areas have the most potential for groundwater surface water interactions.

Boundary Creek, flows across the Barongarook High over a mixture of LTA, Basement and Quaternary Alluvium. Given the number of receptors and community interest in the part of the catchment, there has been a significant amount of work done recently to understand the hydrogeology. The groundwater surface water interactions along Boundary Creek are discussed in detail below.

There are no stream flow gauges on **Dividing Creek,** because the creek does not flow all year round**.** Based on available information, the creek drains rainfall runoff and groundwater from the LTA does not provide a baseflow to creek. The creek is thought to recharge the LTA in the upper reaches.

The **Barwon East and West** branches, key tributaries of the Barwon River, typically flow in the MTD through the centre of the graben. The Barwon West Branch is regulated by the West Barwon Reservoir but it likely to be gaining slightly as it flows over the MTD, where some (deeper) bores are known to be artesian.

3.3.2 Boundary Creek

<u>Local hydrogeology and groundwater surface water interactions</u>

A long section along Boundary Creek is showed in Figure 2-13 and the surficial hydrogeology is shown in Figure 2-14. These figures which shows where the LTA, MTD, bedrock and alluvial sediments outcrop at the surface.

The **LTA** outcrops in the upper part of the catchment (Reach 1) and for a 2 to 3 km section downstream of McDonalds Dam (Reach 2). Due to the relatively high permeability of these sediments, the contribution to baseflow is higher than in other sections of Boundary Creek. Downstream of the dam, Boundary Creek was historically gaining along this reach. During the Millennium drought, groundwater levels declined in this part of

the catchment in response to the combined impact of drought and pumping from Barwon Downs borefield. This is discussed in more detail in the following section.

The creek is incised into outcropping **bedrock** for a distance of around 5 km in Reach 1 upstream of McDonalds Dam. A bore transect installed in 2014 confirms that Boundary Creek receives baseflow from the bedrock through this area. The bedrock has lower permeability than the LTA so the relative contribution of baseflow will be lower than for the LTA. Witebsky (1995) and field investigations indicate that indirect discharge from springs at the bedrock-aquifer interface and then overland flow to the creek also contribute to baseflow.

For the final 4 km of Reach 3, Boundary Creek overlies the **MTD**. A shallow bore installed in the aquitard, near Boundary Creek at Colac Forest Rd in 2014, indicates that groundwater levels in the aquitard are approximately at creek level, with a slight gradient towards the creek. The contribution of baseflow (from groundwater) to Boundary Creek will be significantly smaller than from the LTA, due to the lower permeability of the aquitard. This section of the creek has been dry for long periods in recent years, so baseflow contributions are likely to be minimal.

Alluvial material overlies the sediments in a number of places along Boundary Creek. Alluvial material can form important local aquifers, however the extent of alluvium on Boundary Creek is relatively small and the underlying material (LTA, MTD or bedrock) is expected to be the main control on discharge to the creek. The most significant alluvial deposit on Boundary Creek is at Yeodene (Big) Swamp. The role of groundwater in supporting the swamp is not well understood and will be the subject of further investigations in 2017.

<u>Changes in groundwater levels and groundwater surface water interactions over time</u>

The Barwon Downs borefield was used to augment Geelong water supply over three time periods – early 1987 to early 1990; late 1997 to mid 2001 and early 2006 to mid 2010. Over this time, groundwater levels in the LTA declined in response below average rainfall conditions and extraction from Barwon Downs. The impacts on groundwater levels are compounded as Barwon Downs is only utilised when there has been insufficient rainfall and subsequent runoff into the storages, which also means less recharge for the aquifer. The drawdown in the LTA aquifer between 1987 and 2012 is shown in Figure 2-11.

Upstream of the bedrock outcrop (upstream of Bushby's Lane), Figure 2-11 shows that drawdown does not extend to this part of the catchment and groundwater levels have not changed as a result of groundwater extraction from Barwon Downs. Around the bedrock outcrop area, drawdown in the LTA ranges between 10 m in the eastern part of the area to less than 1 m at the western end. Any decline in water levels in the bedrock aquifer is not known as there are no long term monitoring bores in the location. Two bores were installed recently in 2014 to fill this data gap (UBCk1 and UBCk2) and the groundwater levels in these bores are higher than the creek level which indicates that the creek is gaining at this location. The impact of changes in LTA water levels on springs at bedrock – LTA interface and subsequent overland flow to Boundary Creek is not well understood.

The groundwater levels in the **LTA downstream of McDonalds Dam** are monitored by Bore 109130. This bore is located about 50 metres from the creek and the hydrograph for this bore is shown in Figure 2-15. Bore 109130 is a shallow bore (17.5 m deep) monitoring the unconfined (outcrop) LTA. This shows that groundwater levels in the LTA have declined in response to pumping from Barwon Downs and below average rainfall conditions.

Figure 3-1 Long section along Boundary Creek

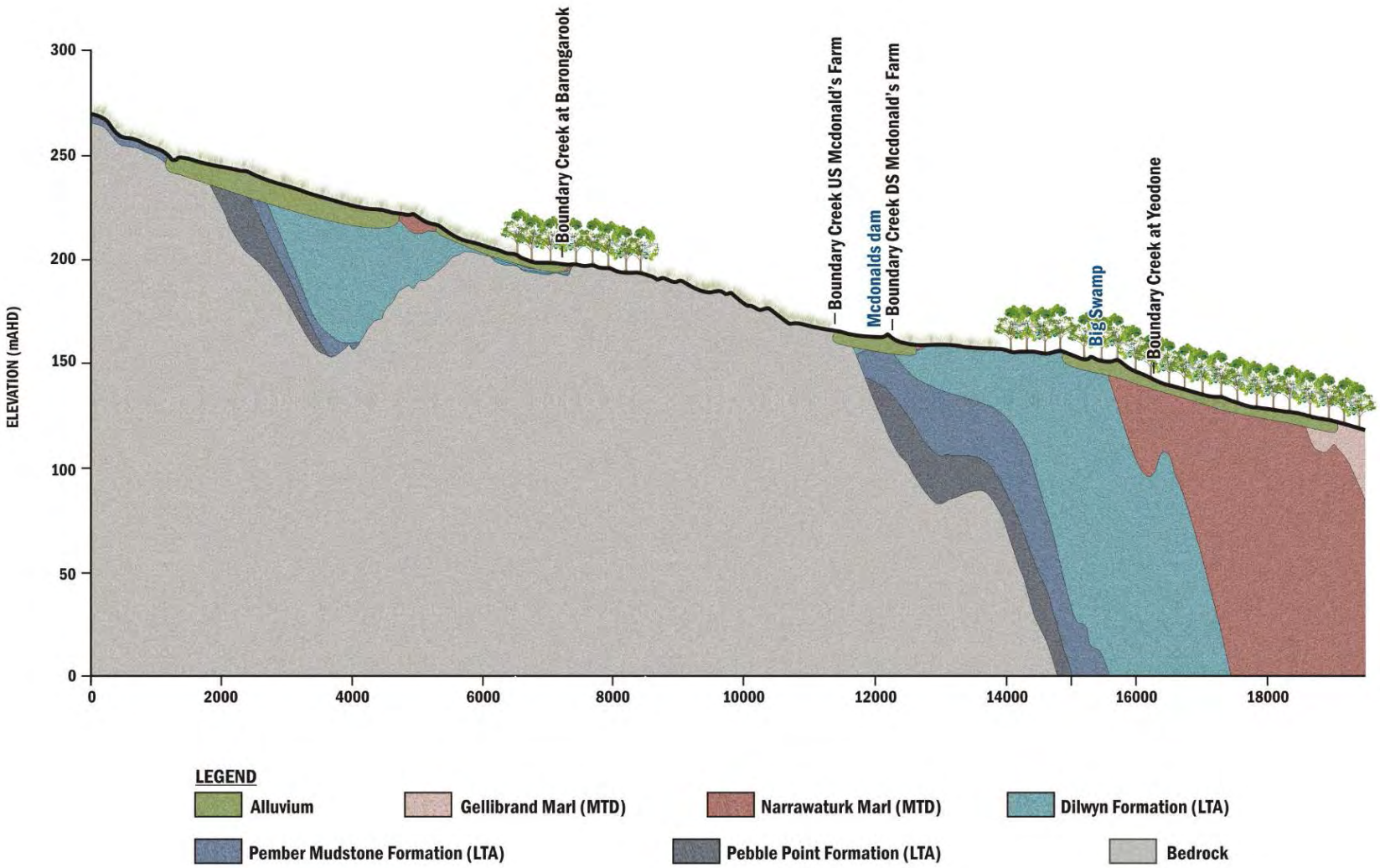

Figure 3-2 Surface hydrogeology in the Boundary Creek area

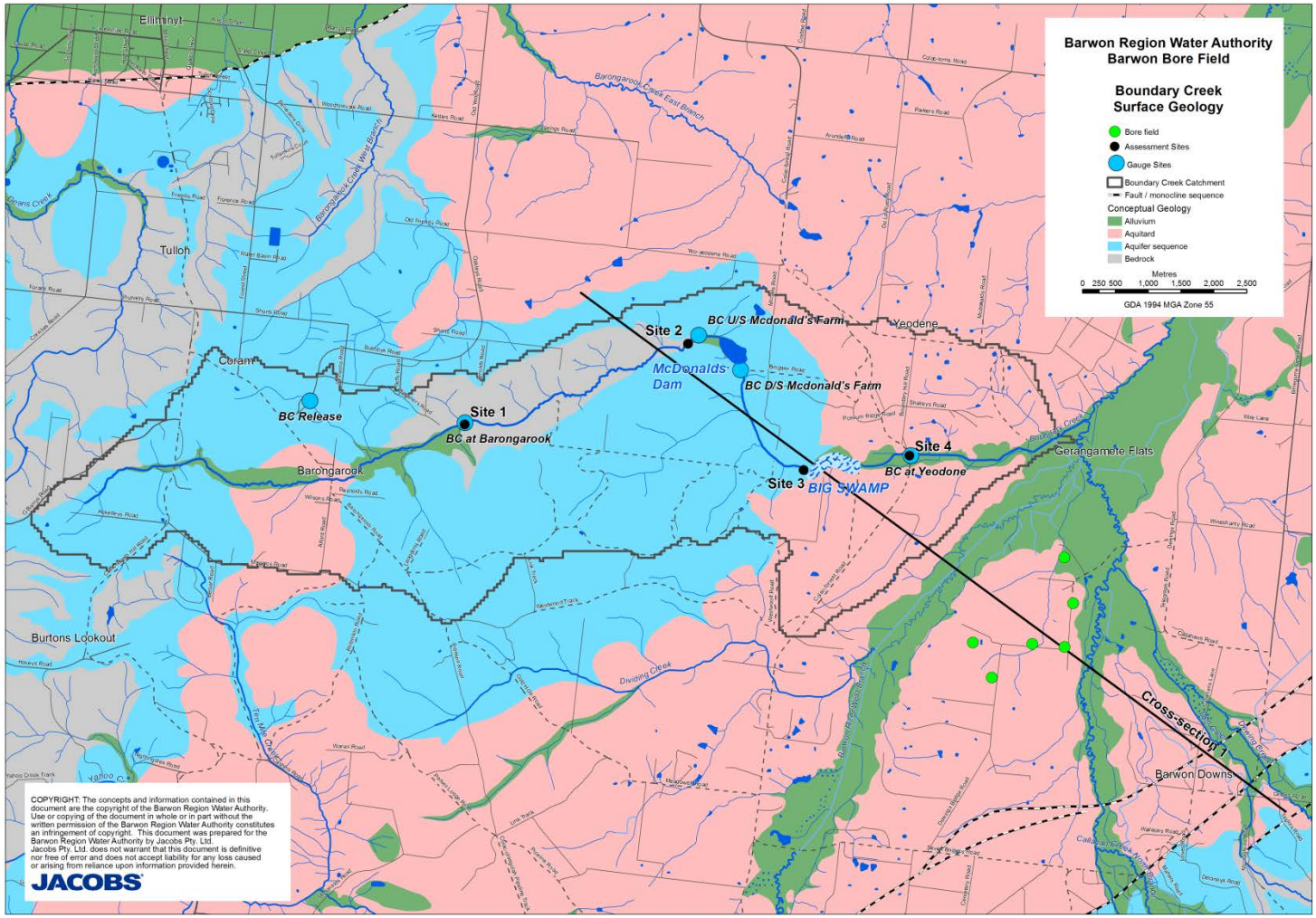

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Figure 3-3 Boundary Creek catchment showing the reaches

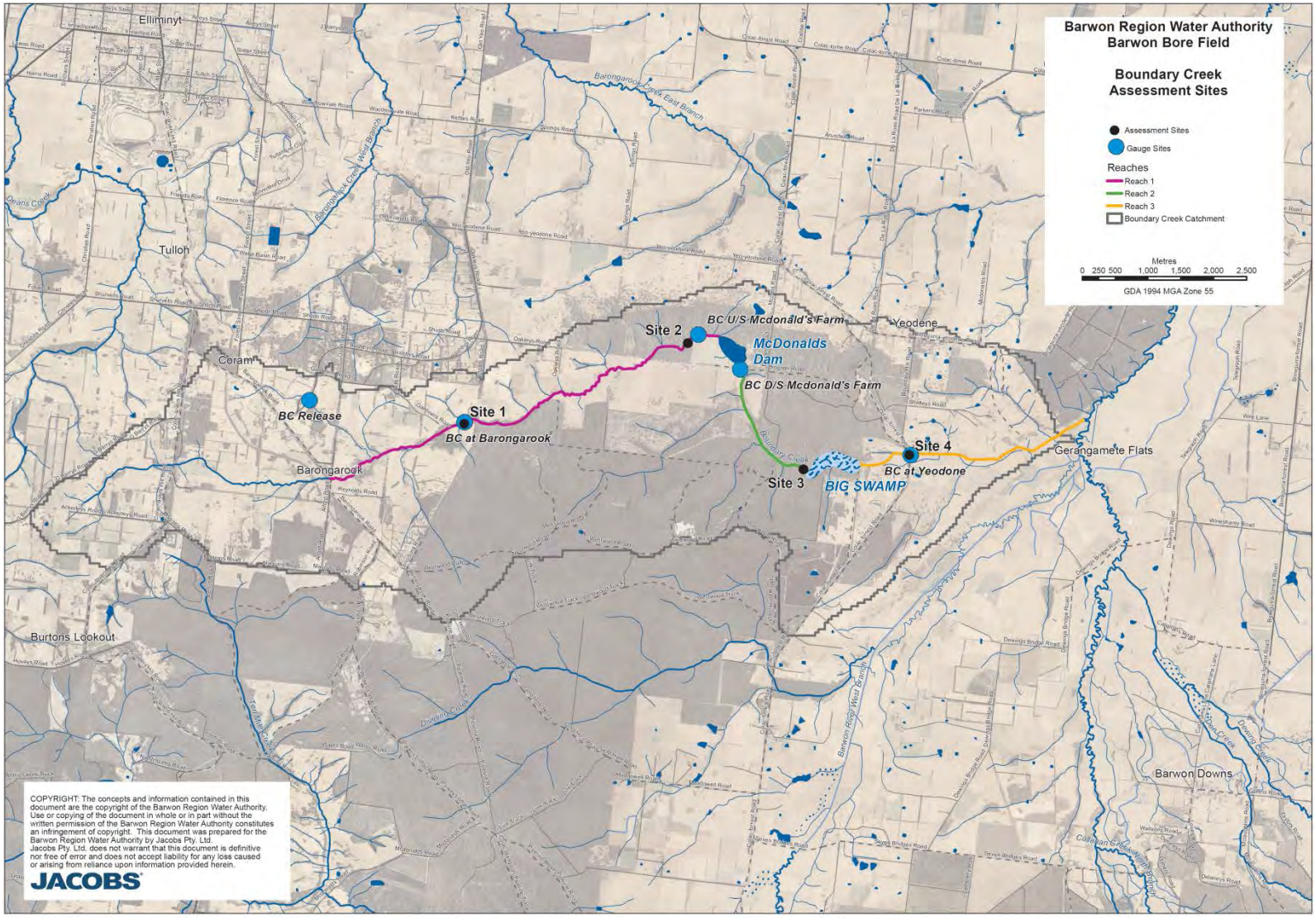


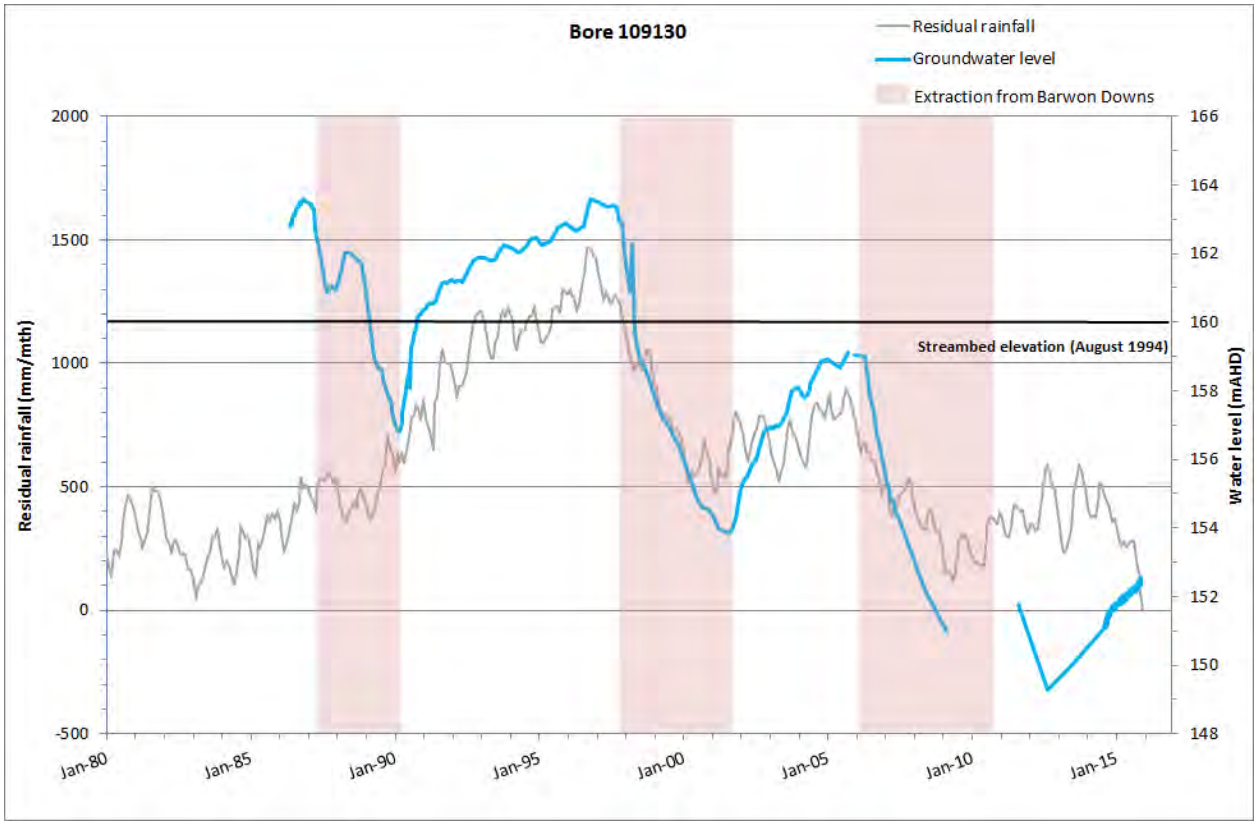
Figure 2-15 shows the groundwater levels in bore 109130, together with residual rainfall and the periods of groundwater extraction from Barwon Downs borefield. The residual rainfall is from Forest State Forest gauge and shows the trend in rainfall. Periods of above average rainfall are represented as rising trends and periods of below average rainfall are shown as declining trends. If the trend is steady, the rainfall is average. Key observations are outlined below:

- The residual rainfall trend shows above average rainfall conditions between 1983 and 1998.
- Between 1998 and 2010 rainfall was generally been below average, typical of the Millennium Drought, with some wetter periods in the mid 2000s. The borefield was used during this period.
- Average rainfall conditions prevailed until 2015, since then, rainfall has been significantly below average, represented by the sharp decline in the residual rainfall plot.

Groundwater level fluctuations in Bore 109130 appear to be influenced by the combine effect of below average rainfall and groundwater pumping from Barwon Downs borefield. Groundwater levels declined significantly during the late 1980s in response to pumping, in contrast to average rainfall conditions. Groundwater levels recovered when pumping ceased and then declined again, this time more significantly, in response to the combined influence of the Millennium Drought and pumping from Barwon Downs. Groundwater levels again recovered after pumping ceased in 2003 and rainfall conditions returned to average. However the groundwater levels did not reach pre-pumping levels before declining again in response to less rainfall and pumping. In recent times, groundwater levels have risen, as the aquifer recovers.

Groundwater levels in Bore 109130 were above the elevation of the streambed prior to 1998 and since then, groundwater levels have been below the base of the stream. In other words, prior to 1998 Boundary Creek was gaining and it is now losing along this reach. It is important to note that the impact of declining groundwater levels on streamflow has not been quantified. The operation of McDonalds dam also impacts streamflow in this reach.

Figure 3-4 Hydrograph of Bore 109130



3.3.3 Yeodene Swamp

Two monitoring bores were re-instated (109140 and 109143) between McDonalds Dam and Yeodene (Big) Swamp that had not been monitored since the late 1980s. TB2b was installed approximately 500 m upstream of the swamp and the groundwater levels have declined in that bore and the bore is currently dry.

There are two distinct areas between McDonalds Dam and Yeodene (Big) Swamp. The upper (approximate) third of this reach downstream of the dam is comprised of a well defined channel in open farmland, and there is very limited alluvium. Further downstream the creek flows through the 'damplands', which are a series of small braided channels. The damplands are supported by a localised perched aquifer in the alluvial sediments that is fed by rainfall and surface water flows. The groundwater in the LTA at this location is more than 3 m below the surface in the valley floor, which suggests that the LTA does not contribute baseflow to this creek at this location under current conditions.

At **Yeodene (Big) Swamp** three groundwater monitoring bores at the one location (targeting different depths) were installed in 2014/15 (Jacobs, 2016c). The bores monitor three different hydrogeological units beneath Yeodene (Big) Swamp – the shallow alluvial aquifer (TB1a), the underlying aquitard (TB1b) and the LTA (TB1c). The groundwater level in these bores since 2014 is shown in Figure 2-16. The hydrograph shows how groundwater levels in each unit change over time in response to rainfall recharge, climate conditions and other influences like groundwater extraction.

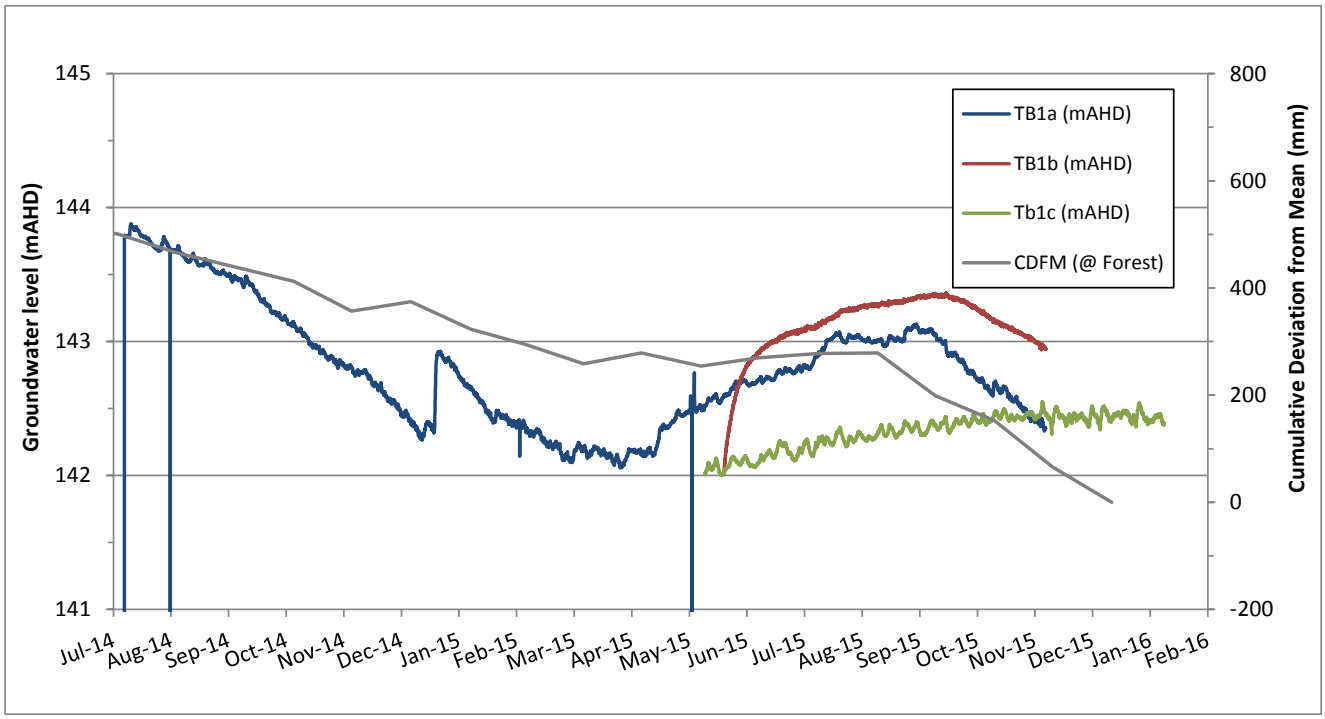
Since 2014, groundwater levels in the shallow alluvial aquifer (TB1a) have declined slightly in response to below average rainfall conditions. The rainfall at the Forest rainfall gauge is also shown on the hydrograph and the declining trend in the cumulative departure from the mean demonstrates that rainfall has been below average over this time period. Groundwater levels in the aquitard took some time to recover after the bore was constructed (until August 2015), and the water level in this unit also appears to decline in response to below average rainfall conditions (from September 2015).

Groundwater levels in the LTA show a rising trend in response to the aquifer recovering from groundwater extraction from Barwon Downs which ceased in 2010. Figure 2-16 shows that the drawdown in the LTA was around 20 m in this area of the aquifer and while groundwater levels have recovered since 2010, the water level remains lower than pre-pumping levels. It is most likely that there was historically an upward gradient from the LTA through the aquitard to the alluvial aquifer at Yeodene (Big) Swamp. An upward gradient still exists from the aquitard to the alluvial aquifer, which demonstrates that these units have been buffered somewhat from the drawdown measured in the LTA. Available information suggests that Yeodene (Big) Swamp is a groundwater discharge site.

The groundwater level in the alluvial aquifer at this location is above the base of the creek, indicating the creek is gaining along this reach. The lithological logs for Bores TB1a and TB2c indicate that there is a perched aquifer in the alluvial deposits which is hydraulically buffered from the underlying regional LTA aquifer.

There has been no historical groundwater level monitoring in the aquitard downstream of Yeodene (Big) Swamp. A recently installed bore at Colac-Forrest Rd indicates groundwater levels are approximately at Creek level, which suggests that there has not been a significant decline in groundwater level in the aquitard through this area.

Figure 3-5 Hydrograph of bores TB1a, TB1b and TB1c



3.3.4 Summary of Boundary Creek

In summary, upstream of the Barongarook gauge (Reach 1), Boundary Creek flows over a mixture of outcropping LTA, alluvial aquifer and outcropping bedrock. Groundwater levels in this part of the catchment have not been influenced significantly by groundwater extraction from the Barwon Downs borefield. This suggests that the nature of groundwater surface water interaction has also not changed significantly over time.

Between the Barongarook gauge and the gauge upstream of McDonalds Dam (Reach 1), Boundary Creek flows over outcropping bedrock. Two bores recentlyChap installed in the basement aquifer show that groundwater levels are higher than the stream bed which indicates that the creek is gaining in this part of the catchment.

Downstream of McDonalds Dam (Reach 2) groundwater levels have been heavily influenced by extraction from the borefield with drawdown in the LTA ranging between 15 and 20 metres below pre-pumping groundwater levels. The water levels in bore 109130 suggest that the creek was historically gaining in this location and is now losing. This section includes the Damplands and Yeodene (Big) Swamp. The extent of drawdown in shallow alluvial systems in response to LTA drawdown in this area is variable and is discussed further below.

The damplands shallow alluvial aquifer is thought to be supported by rainfall and surface water flow in Boundary Creek. It is likely that groundwater in the LTA historically provided baseflow to the alluvial aquifer and in turn to Boundary Creek in the Damplands. In contrast there is a thick alluvial aquifer at Yeodene (Big) Swamp, which is underlain by MTD and while it is likely the alluvial aquifer at this location has been buffered by declining groundwater levels in the LTA, the alluvial aquifer has received less streamflow from upstream in recent years.

Downstream of Yeodene (Big) Swamp (Reach 3) the watertable lies within the shallow alluvial aquifer and is close to the surface. Nested bores show there is an upward gradient from the underlying aquitard to alluvial aquifer which indicates that groundwater levels in the aquitard have been buffered from the drawdowns observed in the LTA. The alluvial aquifer here is of limited extent and hence groundwater surface water interaction is effectively controlled by the MTD Groundwater surface water interaction in this part of the catchment is thought to be gaining as demonstrated by the levels in the shallow aquifer. Due to the low permeability of the MTD, groundwater baseflow to the creek here is typically less than summer evaporation rates.

4. Barwon Downs Groundwater Model

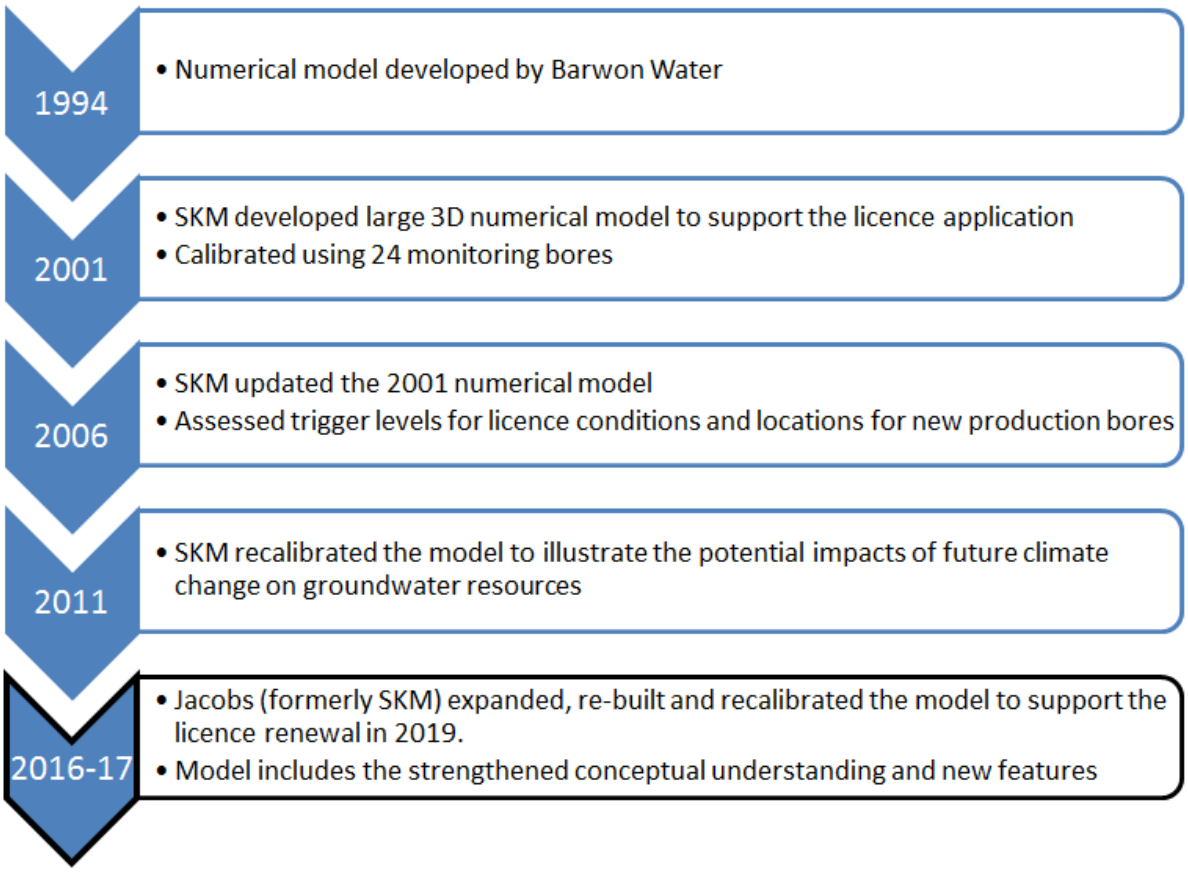
4.1 Chapter Overview

This chapter outlines the progressive improvements of the groundwater model for Barwon Downs. This approach is consistent with The Australian Groundwater Modelling Guidelines (Barnett *et al.,* 2012), which promote an iterative approach to the development of a groundwater model that involves on-going data collection, model updates to include newly acquired data and model validation or recalibration to ensure that the model is consistent with all available data.

4.2 History of the Barwon Downs groundwater model

An overview of the development and calibration of the numerical models of the Barwon Downs Graben is shown in Figure 4-1.

Figure 4-1 Overview of the development and calibration of numerical models of the Barwon Downs Graben



Groundwater modelling of the Barwon Downs Graben was initially undertaken by Barwon Water (Barrow *et al.*, 1994).

In 2001, Jacobs (then SKM) carried out an extensive groundwater modelling study, to support Barwon Water's groundwater licence application. This resulted in the development and calibration of a large three dimensional groundwater model of the Barwon Downs Graben (SKM, 2001). The model was calibrated by matching predicted groundwater levels to observed levels in a set of 24 monitoring bores spread throughout the Graben.

The groundwater model was again updated in 2006 with the aim of assessing appropriate trigger levels to be used in the groundwater licence conditions and to determine appropriate locations for new production bores.

The work included re-calibration of the groundwater model by comparing model estimates to observed groundwater behaviour over the period 1979 to 2006 (SKM, 2007).

The model was again re-calibrated in 2011 during an investigation to understand the potential impacts of future climate change on the groundwater resources of the Graben (SKM, 2011).

In 2016-17, the model was expanded, re-built and re-calibrated to support the upcoming renewal of the groundwater extraction licence for the borefield due in 2019. The update of the model includes new features and a significant improvement in the conceptual understanding, including:

- Re-evaluation of bore logs to develop a revised geological model,
- Additional groundwater monitoring bores,
- Field based estimates of hydraulic parameters, and
- Groundwater recharge estimates (based on multiple lines of evidence including isotope analysis, chloride mass balance and one dimensional unsaturated zone modelling).

The revised groundwater model has a much broader focus than previous work that had concentrated primarily on undertaking a resource assessment to determine the availability of groundwater.

5. Model Design

5.1 Chapter Overview

This chapter describes the design and re-building phase of the Barwon Downs groundwater model. The model design is consistent with The Australian Groundwater Modelling Guidelines (Barnett *et al.,* 2012).

The objectives of the groundwater model and the confidence classification were defined at the outset, as these provide the foundation for the model design. This chapter also outlines the software used and the key features of the groundwater model.

An overview of each model feature is provided in Table 5-1 and more detail is provided in the following sections.

Table 5-1 Overview of the key features of the design of the groundwater model

Feature	Description
Modelling objectives	• Update and improve the model calibration to improve the confidence with which future impacts can be predicted • Assess the impacts of the historical operation of the bore field.
Modelling approach	• The approach to groundwater model development is consistent with industry best practice as outlined in Barnett et al., 2012.
Confidence level classification	• This model is defined to have a high Confidence Level Classification in consideration of the risks to both the environmental assets and the development in question. • There is sufficient information to support the qualitative and quantitative criteria that define a high Confidence Level Classification
Software	• The model has been converted into a new software package (Modflow USG), which supports a new grid structure
Grid structure	• The grid structure has been refined in an effort to provide a better representation of groundwater interactions with surface waters (in particular Boundary Creek and Gellibrand River) and the influence of pumping.
Model area	• The model area has been expanded to include the Gellibrand River and incorporates the recent advances in the hydrogeological conceptualisation.
Recharge	• Average recharge rates of 5 per cent of rainfall where the Lower Tertiary Aquifer (the aquifer Barwon Water extracts from) outcrops and less than 1 per cent of rainfall where the Mid Tertiary Aquitard outcrops were selected based on field methods
Evapotranspiration	• Consistent with previous models, evapotranspiration occurs when the saturation zone is within 2 meters of the surface. No evaporation occurs from the unsaturated zone.
Model Boundaries	• The model boundaries at the Colac and Bambra Faults have been revised to reflect the improved conceptualisation.
River groundwater interaction	• The interaction between groundwater and surface water has been refined based on the refined conceptualisation outlined in Chapter 3.
Groundwater extraction from Barwon Downs	• Complete pumping records are included in the updated model.

5.2 Modelling Objectives

The groundwater modelling described in this report is a continuation of the model development that originally started in 2001 and that has included a number of subsequent upgrades and refinements. The overall objective of the modelling is to quantify both historic and potential future impacts of groundwater extraction from the Barwon Downs Borefield including groundwater drawdown, changes in river baseflow caused by borefield operation and changes in water availability for groundwater dependent ecosystems.

The current modelling effort is primarily aimed at:

1. Updating and improving model calibration in order to increase the confidence with which the future impacts can be predicted.

2. Preparing a detailed assessment of the impacts that have occurred to date from historic operation of the borefield.

The model will then be used to predict future impacts associated with borefield operations under a number of different groundwater extraction (water demand) and future climate assumptions. The results of the predictive scenarios will be documented in a separate stand alone report.

5.3 Modelling Approach

The Australian Groundwater Modelling Guidelines (Barnett *et al.,* 2012) presents an approach to groundwater model development that has been accepted throughout the groundwater industry as a benchmark of industry best practice. The Guidelines promote an iterative approach to groundwater model development that involves on-going data collection, periodic model updates to include newly acquired data and model validation or recalibration to ensure that the model is consistent with all available data (see Figure 3-1). Previous groundwater modelling of the Barwon Downs Graben as reported in SKM, 2001, 2007 and 2011 has followed this process.

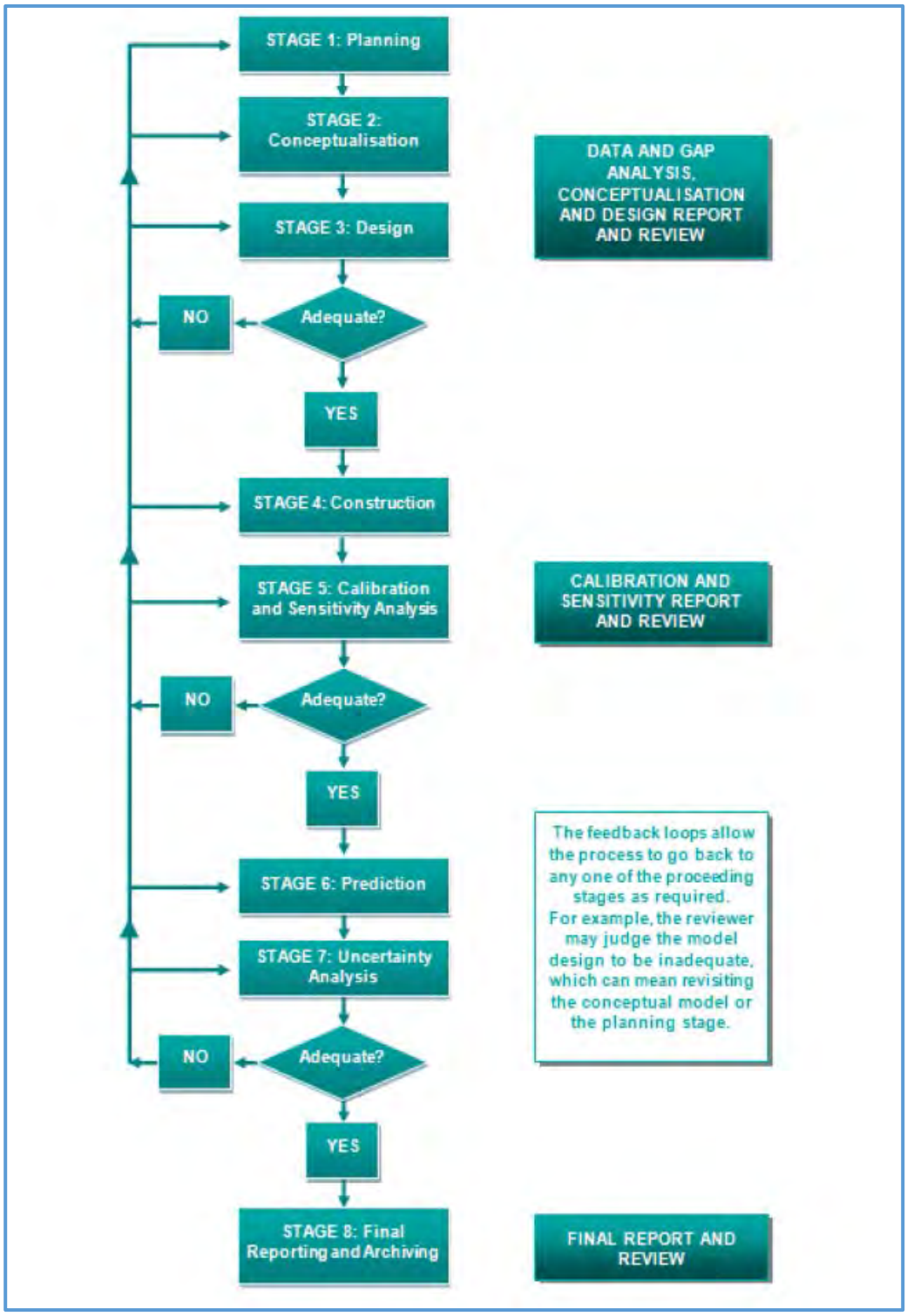
The hydrogeological conceptualisation forms the basis for the groundwater model. For Barwon Downs this conceptualisation has progressively evolved since the initial model development and the current conceptualisation is summarised in Section 2. The most recent advances in the conceptualisation have been made as a result of a number of field investigations and on-going data collection conducted as part of the Technical Works Monitoring Program. In this regard the latest conceptualisation provides an improved understanding of near surface impacts that have occurred in the past and that may occur in the future.

The model has been redesigned to incorporate the recent advances in the hydrogeological conceptualisation. It has been converted to a new software package (Modflow USG) and the model grid has been completely revised. These changes have been made in an effort to provide a better representation of groundwater interactions with surface waters (in particular Boundary Creek and Gellibrand River), groundwater flow in the basement and the interaction between the main aquifers.

Model calibration provides a means of demonstrating the model's ability to simulate groundwater responses by illustrating how well the model is able to replicate observed groundwater behaviour. The current modelling has updated the calibration by extending the model to 2016 and incorporating the most recent climate data, groundwater head measurements, river baseflow estimates and the groundwater extraction from the borefield. The model is now calibrated over the period 1980 to 2016.

Finally the calibration model has been interrogated to provide estimates of the impacts that have occurred since the start of groundwater extraction in the early 1980's. Future reports will describe the predictive scenarios that will assess the future groundwater response to various assumed levels of groundwater extraction and future climate assumptions. The predictive scenarios report will also describe uncertainty analysis that illustrates the potential variability in future predictions that may arise through uncertainty in the parameters and boundary conditions that influence groundwater behaviour.

Figure 5-1 : The modelling process (From Figure 1-2 of the Australian Groundwater Modelling Guidelines)



5.4 Confidence level classification

The Australian Groundwater Modelling Guidelines (Barnett *et al.,* 2012) introduces a Confidence Level Classification that provides a qualitative indication of the relative confidence with which model predictions can be made. The intention of the Classification is to facilitate a dialogue in non-technical language that helps to convey the modellers understanding of the reliability of model predictions. The Classification recognises the fact that high levels of confidence (involving significant investment in time and effort) are not required for all modelling projects. There is a similar recognition that in some cases the available hydrogeological data may not be sufficient to be able to develop a high confidence level model and that additional data collection and further calibration may be required before the desired Confidence Level Classification can be attained.

The Classification is important in that the determination of whether a model is “fit-for-purpose” depends, among other things, on the Confidence Level Classification identified as being appropriate for a given model and whether or not a reviewer considers that this Classification has been achieved.

The Guidelines, and the Confidence Level Classification in particular, are considered to provide a benchmark of industry best practice by the groundwater modelling community and environmental regulators. To this end, a model can be described as meeting industry best practice if;

1. A target Confidence Level Classification is defined that is consistent with the project objectives and is consistent with the risks to both environmental assets and to the development in question.

2. The model is developed in a manner that is consistent with qualitative and quantitative criteria that define the target Confidence Level Classification.

3. Where a model is unable to meet the target Confidence Level Classification, a plan to collect additional data and subsequent upgrading of the model (including re-calibration) is recommended.

The model described in this report is located in an area of relative high environmental values and the borefield development is the subject of intense community interest. It is clear that a **high Confidence Level Classification** (Class 3) target is warranted in this case. Furthermore the available data for this project is consistent with and should support the development of a Class 3 model. In particular, the relatively long history of groundwater extraction with associated monitoring of groundwater responses in an extensive network of monitoring bores has provided an excellent calibration data set that meets the Guideline criteria for a Class 3 model.

5.5 Software

Previous versions of the model used Modflow-96 (Harbaugh and MacDonald, 1996) and Modflow-2000 (Harbaugh and Bantar, 2000) numerical simulation codes.

Recently released Modflow USG (Unstructured Grids) software has been chosen for the current project. This software package is an attractive alternative for the Barwon Downs model as it provides a numerical framework that can be designed to incorporate a dense array of calculation nodes in areas of particular interest while maintaining a relatively sparse array of calculation nodes in areas of the model that are of lesser importance.

The Unstructured Grid approach has been adopted for the current investigation as an efficient means of providing detailed spatial resolution around important rivers and streams and around the borefield. This arrangement is particularly useful as it provides the spatial detail required to adequately simulate these features without requiring excessive numerical effort to solve the flow equations and to store the numerical results.

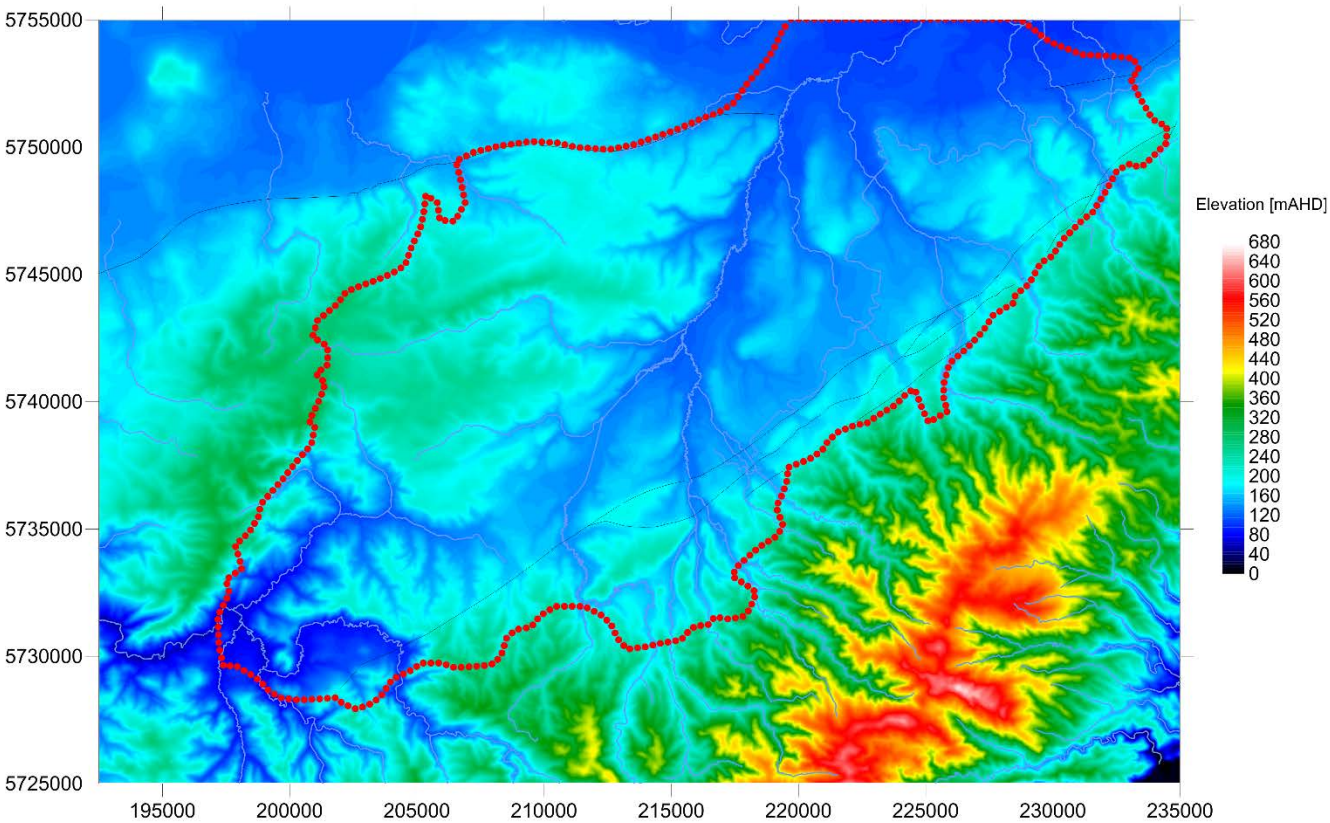
The development of the model has been undertaken with the Groundwater Vistas Version 6 Graphical User Interface. This utility provides a Windows based software platform that facilitates the definition of the model structure (the numerical grid and layers), the model boundary conditions and the various sinks and sources as required to simulate the physical processes that influence groundwater storage and movement within the model domain.

5.6 Model area

The model domain has been chosen to ensure that the aquifers of importance are fully represented within the model domain. The extent of the model domain is presented in Figure 3-3. The line of red dots shown in this figure illustrates the extent of the active model cells as defined by the full lateral extent of the Lower Tertiary Aquifer units (i.e., the Dilwyn and Pebble Point Formations). All areas in the model outside this line are inactive.

Figure 5-2 also shows the ground surface elevation used to define the top of the model.

Figure 5-2 : Model Domain



5.7 Grid structure

As described above the Modflow USG software code has been used and this has allowed a spatially variable numerical grid to be developed as shown in Figure 3-4. Increased spatial refinement has been added to the model in region of the borefield and the rivers where an accurate representation of groundwater gradients is required.

Each of the major hydrogeological units present at the site is represented as an individual model layer. The layers are summarised in Table 3-1.

The top and bottom of each layer has been defined in the model to match the contoured surfaces of the formation contacts that have been created from the stratigraphic interpretations described in Section 2.1. The resulting model layer thicknesses are shown in Appendix A.

Figure 5-3 : Numerical Grid

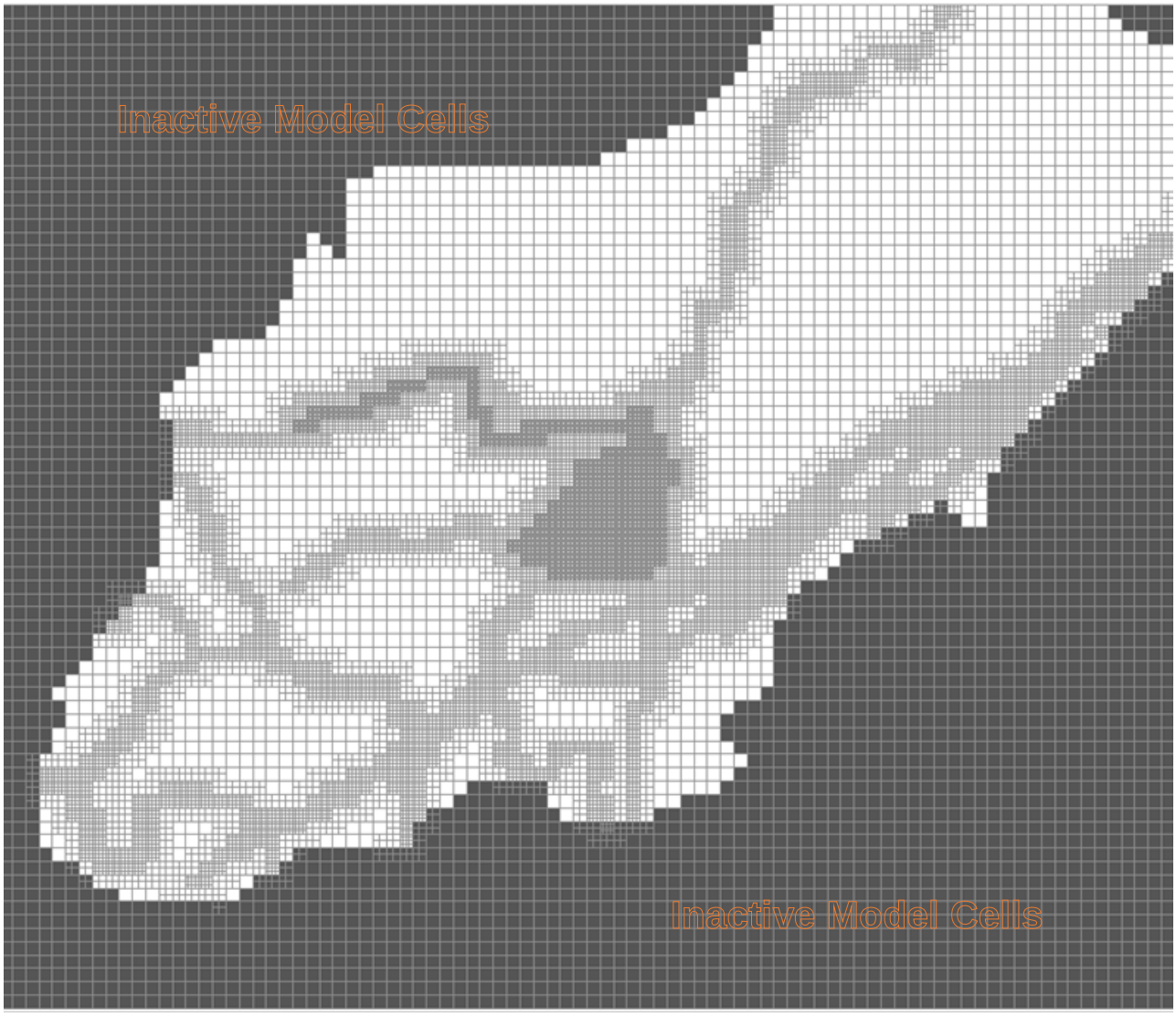


Table 5-2: Model layer structure

Model Layer	Hydrogeological Unit	Function
1	Gellibrand Marl	Aquitard
2	Clifton Formation	Minor Aquifer
3	Narrawaturk Marl	Aquitard
4	Dilwyn Formation	Major Aquifer
5	Pember Mudstone	Aquitard
6	Pebble Point Formation	Major Aquifer
7	Basement	Minor Aquifer

5.8 Recharge

Unsaturated zone modelling has been undertaken as described in Section 2.4.1. The modelling has produced estimates of the long term average recharge rates for various combinations of outcropping geology (soils), vegetation and depth to water table. The model has also produced time series estimates of recharge rates for the same combination of factors for the period of the transient calibration (January 1980 to May 2016).

Results of the unsaturated zone modelling were implemented in the numerical model as initial recharge time series estimates for the regions of aquitard outcrop and of Dilwyn Formation outcrop. Subsequent calibration involved the application of recharge multipliers to scale the recharge estimates as required to improve calibration. During this process different recharge multipliers were assumed for the Dilwyn Formation outcrop for the remainder of the area, being where the aquitards of the MLT and basement rocks outcrop. The recharge zones are shown in Figure 3-5 and the unscaled initial recharge estimates obtained from the unsaturated zone modelling are presented in Figure 3-6.

Figure 5-4 : Recharge zones

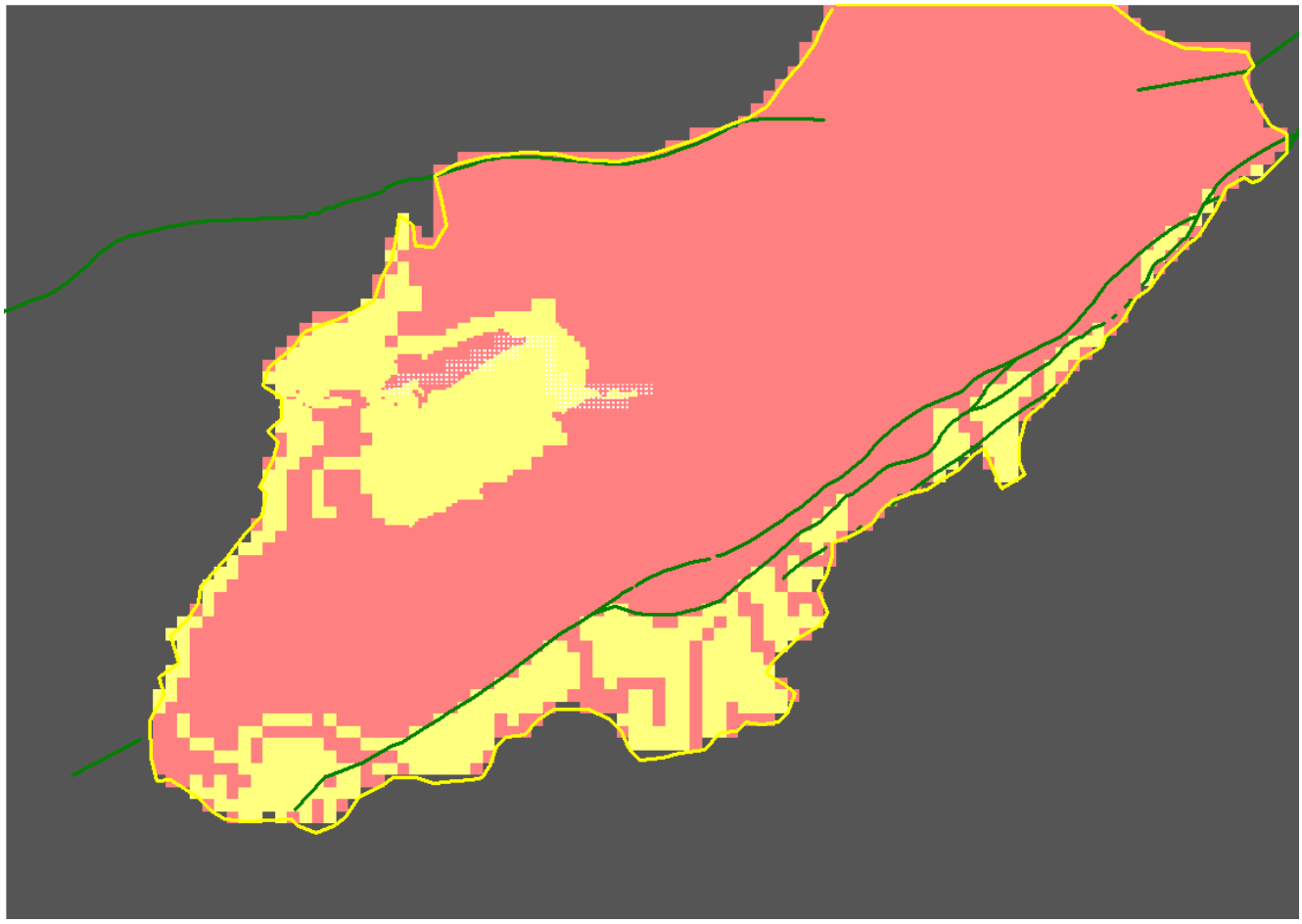
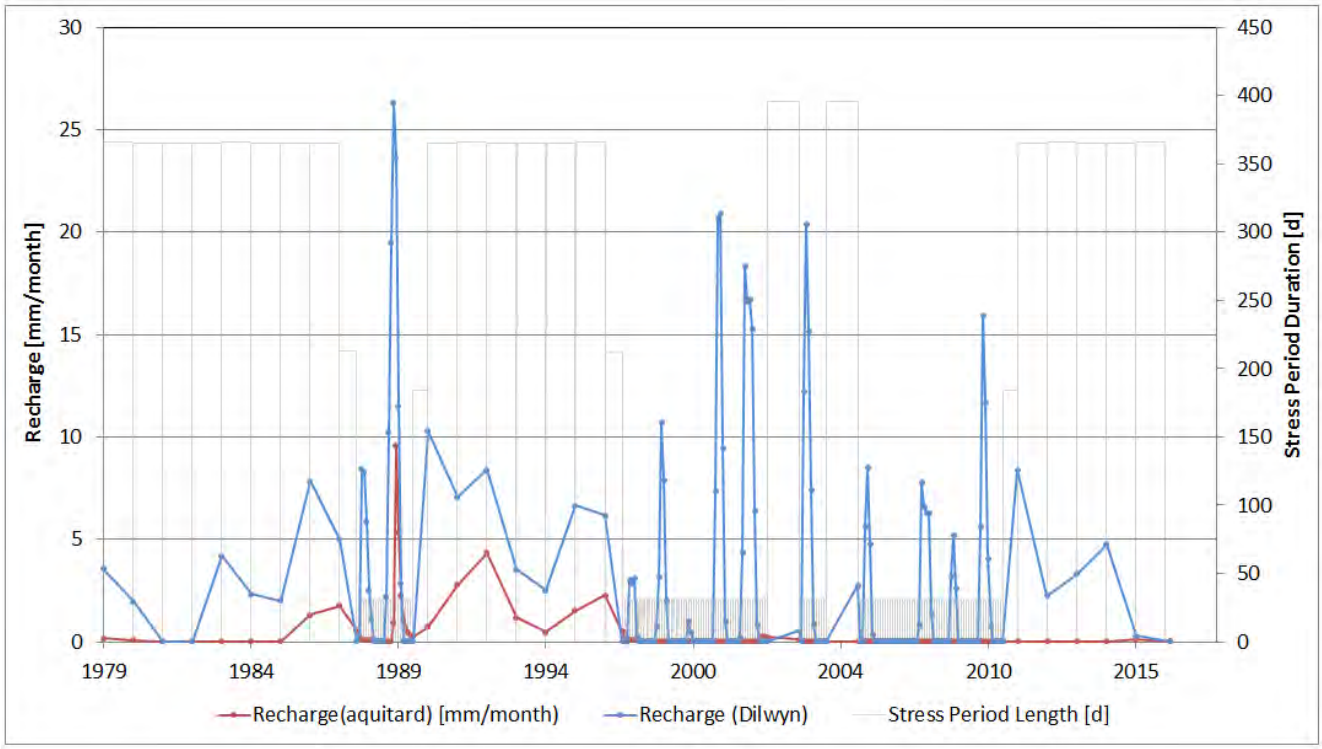


Figure 5-5 : Recharge time series estimates



5.9 Evapotranspiration

Evapotranspiration is included in the model to simulate the loss of groundwater in areas of shallow water table where groundwater is either exposed at the ground surface or is accessible to vegetation. It is noted that the model (and its representation of evapotranspiration) only considers water in the saturated zone and does not include water stored in the unsaturated zone above the watertable.

Evapotranspiration is modelled with the Modflow EVT Package in which a maximum evapotranspiration rate and an extinction depth are defined. In the EVT Package, the evapotranspiration rate varies linearly from the maximum defined rate when the water table is at the ground surface to zero when the water table is at the defined extinction depth (e.g. 2 m below ground surface being an effective spatially averaged root zone depth).

5.10 Model Boundaries

Specified head boundary conditions are used to facilitate the exchange of water on the edges of the model domain where the aquifers are conceptualised to interact with formations immediately outside the model domain. The Modflow General Head Boundary (GHB) Package has been used to allow the movement of water across the model domain. The direction of movement depends on the calculated groundwater head and the specified head on the boundary. Where the calculated head at the boundary is above the specified head, groundwater will flow out of the model domain. Where the calculated head at the boundary is less than the specified GHB head the model will calculate a flow into the model domain. The GHB has a conductance term that can be used to provide additional flow resistance and hence moderate the exchange of water with surrounding formations. The locations of the General Head Boundary Conditions are presented in Figure 3-7.

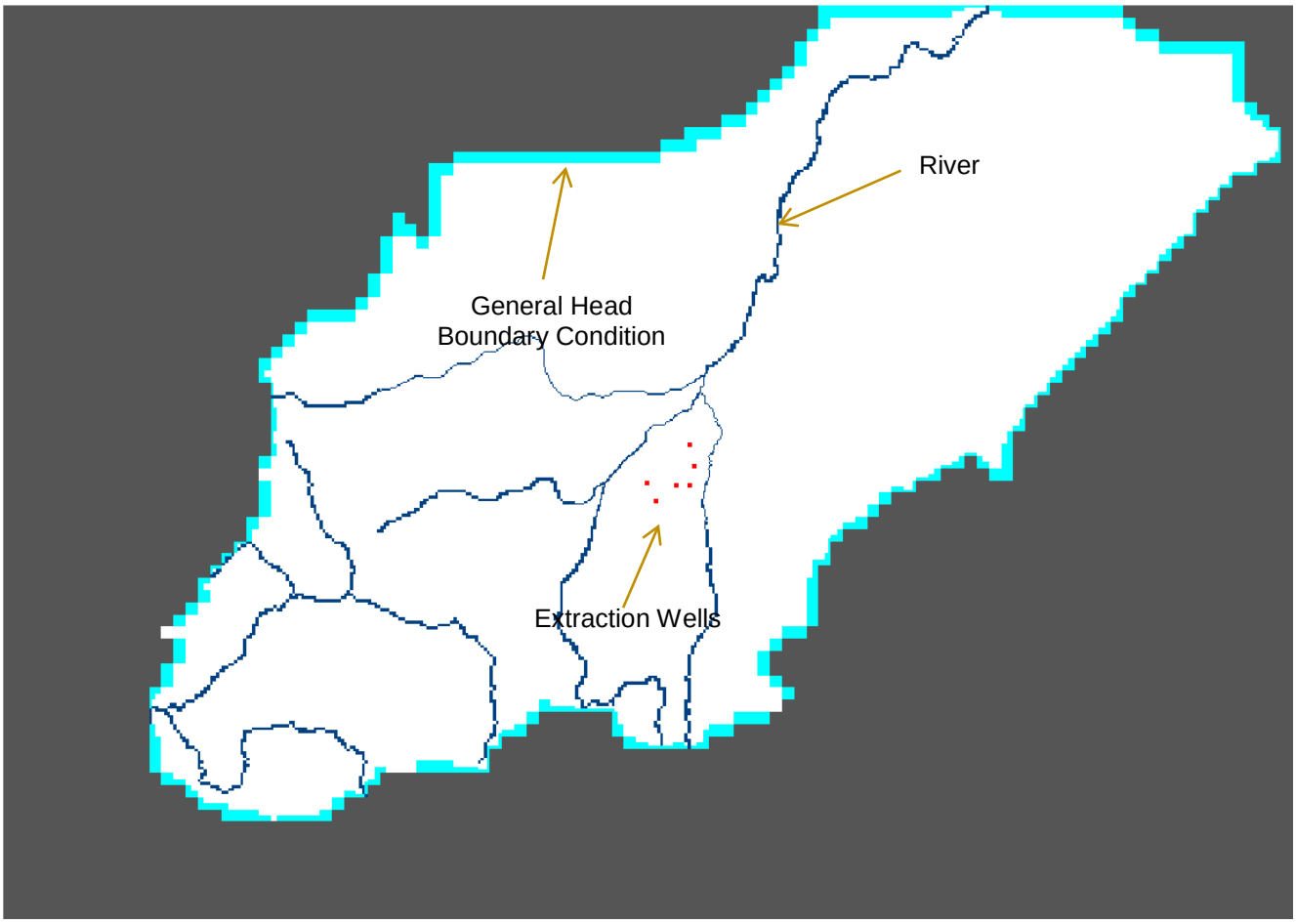
5.11 River groundwater interaction

Exchange of water between the aquifer and rivers and creeks is facilitated by the Modflow river (RIV) package which allows water to either discharge or recharge the groundwater system depending on the calculated groundwater head and the specified river stage. The Modflow RIV package includes a boundary conductance term which is a flow resistance term applied at the interface between the river and the aquifer. It can be used to moderate the exchange of groundwater with the river that might occur if the river bed has a low permeability.

Figure 3-7 shows the rivers included in the groundwater model. In all cases the river stage has been estimated to be 2 m below the ground surface (as defined by the 100m Digital Elevation Model) and the river bottom is specified to be 3 m below the ground surface. The river condition is specified in the model layer in which the defined river stage falls. In this regard Boundary Creek, the Gellibrand River, Porcupine Creek and Dividing Creek are considered of special importance as they cross areas where the aquifer units are outcropping and hence have the potential to directly recharge and drain the aquifer units. It should be noted that Figure 3-7 shows a composite of all model layers. The layer in which a particular river or reach of a river is included in the model depends on which model layer intersects with the specified river bed elevation.

Most rivers in the model domain are conceptualised as net gaining features in that they will accumulate baseflow as groundwater drains into the river bed in their natural, pre-development state. As groundwater heads decline in response to drought or to groundwater extraction, the river baseflow may decline and eventually rivers may convert from a net gaining to a net losing condition. If the estimated groundwater level at the river location falls below the specified river bottom elevation the river will no longer exchange water with the aquifer. In this state the rivers are conceptualised to be hydraulically separated from the aquifer system.

Figure 5-6 : Boundary conditions



5.12 Groundwater extraction from Barwon Downs borefield

The production bores are modelled using the Modflow WEL Package. The extraction rates for each of the bores in the model replicate the recorded pumping history for the individual wells. The locations of the production bores in the model domain are shown in Figure 3-7. Figure 3-8 shows the combined extraction rate from all production bores. The pumping rates recorded for each of the production bores are shown in Figure 3-9 (Bores GW-1 to GW-4) and Figure 3-10 (Bores GW-5 to GW-8).

Figure 5-7 : Combined borefield extraction for the Barwon Downs production wells.

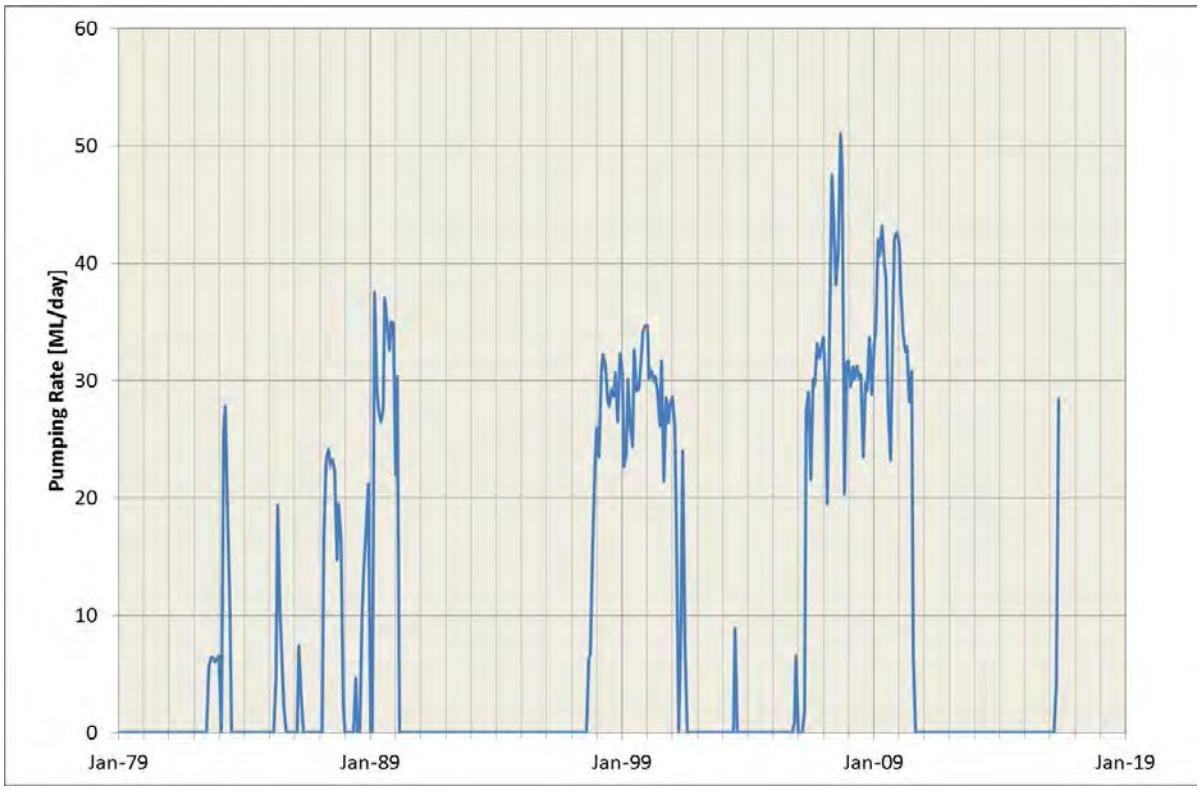


Figure 5-8 : Extraction rates for production wells GW-1 to GW-4

Figure 5-9 : Extraction rates for production wells GW-5 to GW-8

6. Calibration

6.1 Chapter overview

This chapter describes the process used to calibrate the groundwater model to ensure the simulated groundwater response adequately replicates observed groundwater behaviour. The current modelling has updated the previous calibration by extending the model to 2016 and incorporating the most recent climate data, groundwater level measurements, river baseflow estimates and the groundwater extraction from the borefield.

The calibration process is a staged process. The first stage involves calibrating the model to estimate pre-pumping conditions (also known as steady state). The pre-pumping, or steady state, conditions are used to start the second stage of the calibration process (transient calibration), which runs over a specified time period. In this case the transient calibration was over the period 1980 to 2016. The final stage uses a software package (PEST) that automatically adjusts the parameters to ensure the simulated responses match the observed responses.

The calibration acceptance criteria are defined at the start of the calibration process. Four acceptance criteria were defined:

- Acceptable match to pre-pumping groundwater levels
- Acceptable match to groundwater levels changes over time
- Groundwater surface water interactions consistent with conceptual understanding presented in Chapter 3
- Recharge estimates consistent with estimated recharge rates presented in Section 2.4.1

A summary of the calibration process is provided in Table 6-1 and more detail is provided in the following sections. The calibration results are presented in Chapter 7.

Table 6-1 Overview of the calibration process

Calibration process	Description
Method	Calibration method involves three stages: • Steady state calibration to estimate pre-pumping conditions (pre-1980) • Transient calibration to simulate groundwater responses between 1980 and 2016 • Parameterisation approach which automatically adjusts the parameters to get the best historical match.
Acceptance criteria	Four acceptance criteria defined for the calibration process relating to matching groundwater levels, groundwater surface water interaction and recharge rates.

6.2 Calibration Method

The model calibration has involved both steady state and transient calibrations in which the modelled heads and fluxes are compared to measured and inferred groundwater heads and fluxes. The steady state calibration is aimed at creating stable pre-pumping conditions that will be used as initial conditions (i.e. starting point) for the transient calibration model which runs from 1980 to 2016.

The steady state model produces a simulation of long term average groundwater conditions assuming no groundwater extraction and no seasonal fluctuations or long term trends in groundwater heads and fluxes. Calibration to steady state conditions ensures that the model is able to replicate the pre-pumping observed groundwater heads and fluxes but ignores all variability in climate and ignores the effects of the borefield operation.

Transient calibration is aimed at replicating the seasonal fluctuations and long term trends that have been observed in groundwater levels and fluxes. Of particular importance, the transient calibration is required to provide reliable representations of the changes in groundwater heads and fluxes that have resulted from historic operation of the borefield. The steady state and transient calibration models are run sequentially so that the steady state model heads provide the starting conditions for the transient calibration model. The process also helps to ensure that the model parameter values included in the calibrated model satisfy both steady state and transient calibration criteria.

The calibration acceptance criteria are summarised as:

- An acceptable representation of the pre-development steady state heads and associated potentiometric surface. In this case a target has been set at 5% scaled root mean square (RMS) error.
- An acceptable representation of the transient groundwater responses in observation bores. A target of 5% scaled RMS Error has been set.
- Predicted groundwater discharge to rivers that is consistent with measured river flows and with baseflow estimates.
- Recharge rates that are consistent with estimated recharge rates.

6.2.1 Steady State Calibration

Steady state calibration is undertaken to help constrain horizontal and vertical hydraulic conductivity values, recharge fluxes and river boundary condition conductance terms (i.e. flow resistance of the river bed). The process involved simulating pre-development steady state groundwater conditions and comparing the model predicted groundwater heads and fluxes to measured or inferred conditions. The model inputs were iteratively refined in order to improve the match between predicted and observed groundwater conditions.

The groundwater heads used as steady state calibration targets were selected as follows:

- Average pre-development heads were chosen for those bores that have records extending back to the early 1980's.
- For those bores that have records starting after 1982 (i.e. after the first period of groundwater extraction) but before the onset of the major groundwater extraction of 1987, a pre-development groundwater head was selected from a time when the observed groundwater heads were not impacted by borefield pumping.
- For those bores that have records starting after 1987 further interpretation was required to provide an estimated head that was not impacted by pumping. In some cases this involved an extrapolation backwards in time and in some cases also involved the use of long term groundwater head records in nearby bores to illustrate the level of drawdown that has occurred with time.

6.2.2 Transient calibration

Transient calibration models were run for the period 1980 to 2016. The borefield pumping operations undertaken during this period are included in the model and the total groundwater extraction assigned to the calibration model is presented in Figure 4-2. The figure also shows the stress period duration included in the transient calibration model. The stress periods have been chosen to provide monthly model inputs and outputs during periods of groundwater extraction and yearly discretisation for times when there is no groundwater extraction.

Recharge was included as a time series and applied to relevant zones across the top model layer. The initial recharge time series were obtained from the unsaturated zone modelling and are shown in Figure 3-6. During calibration the time series recharge rates for both the outcropping Dilwyn Formation and the outcropping aquitard formations (Gellibrand Marl, Narawaturk Marl and Basement) were adjusted through a multiplier parameter to help optimise the model's ability to match the observed groundwater responses.

The calibrated recharge multiplier (refer section 3.7) is 0.25 for both the area of aquifer outcrop and the area of aquitard outcrop. Note that the multiplier is applied to the time series of groundwater recharge estimated from unsaturated zone modelling as described in Section 2.4.1. The calibrated recharge over the aquifer outcrop corresponds to 4% of rainfall and 0.6% of rainfall over the aquitard for the period 1980-2014. The recharge rates are at the lower limit estimates of recent recharge and is consistent with long term recharge rates for the aquifer.

The model estimated heads were compared to observed groundwater heads in a total of 131 observation wells scattered throughout the model domain. The locations of all observation bores used for model calibration are presented in Figure 4-3 and the breakdown by layer in Table 4-1.

Table 6-2: Number of observation bore by model layer

Layer	Number of Observation Bores
1	15
2	3
3	19
4	67
5	2
6	18
7	7

Additional calibration targets related to the predicted baseflow/seepage in Reach 2 of Boundary Creek were included to help improve model reliability and confidence in the region where the creek crosses the outcrop of the Dilwyn Formation Aquifer. The targets were defined by calculating the flow difference between the stream gauges 233229A and 233228A at Yeodene. The number of targets (Figure 4-4) is limited by the period when both stream gauges time series are concurrent (i.e. post 2014). Moreover, rain periods were also removed, as the influence of runoff on streamflow cannot be represented in the model results. Evaporation on the river channel (evaporation from the Creek) is also not represented in the groundwater model and therefore the target is likely to include significant levels of uncertainty. For this reason, the baseflow/seepage target is treated as a *"soft"* or indicative target i.e., the calibration will only look at getting the model baseflow/seepage within reasonable proximity of the target.

Figure 6-1 : Groundwater extraction and stress periods.

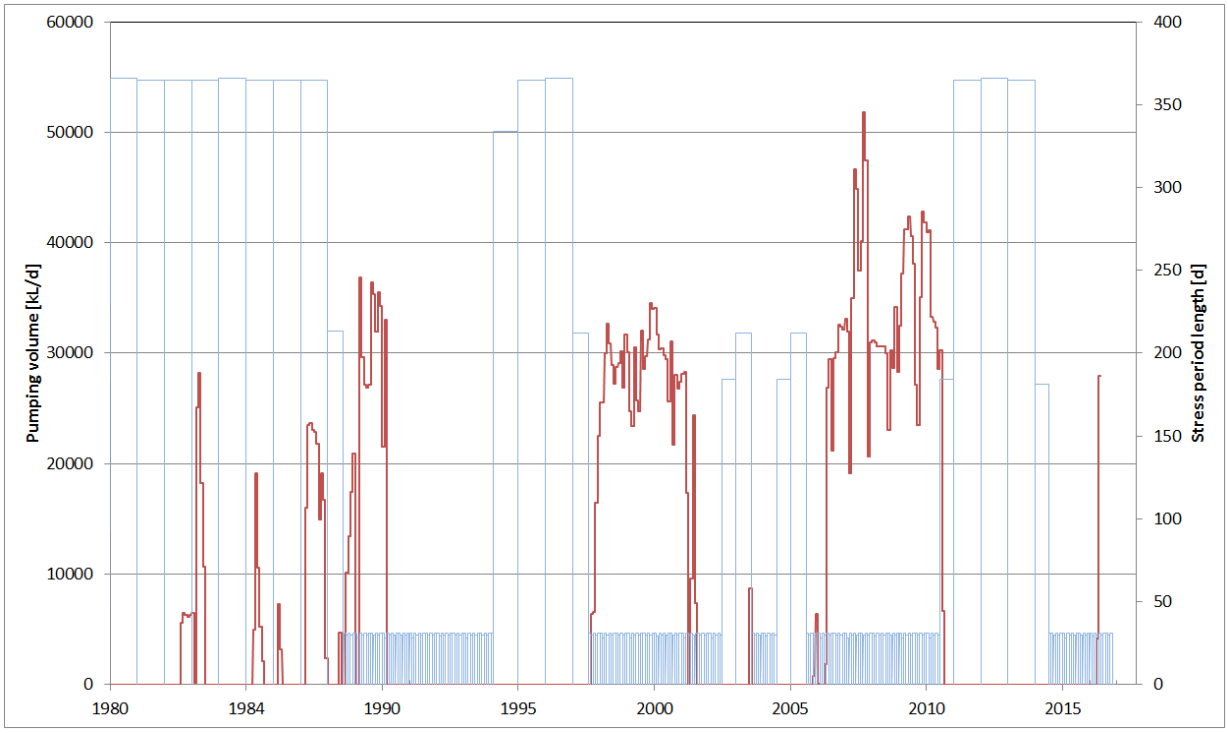


Figure 6-2 : Observation bores used as calibration targets

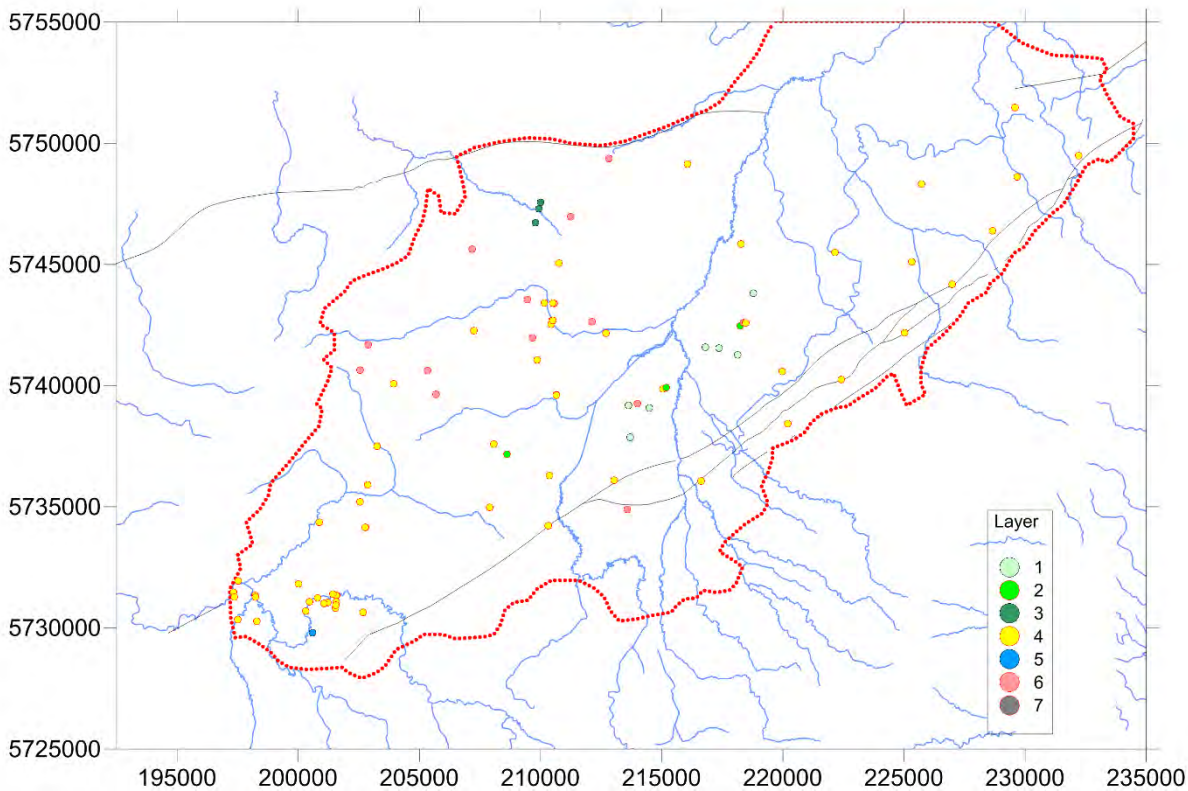
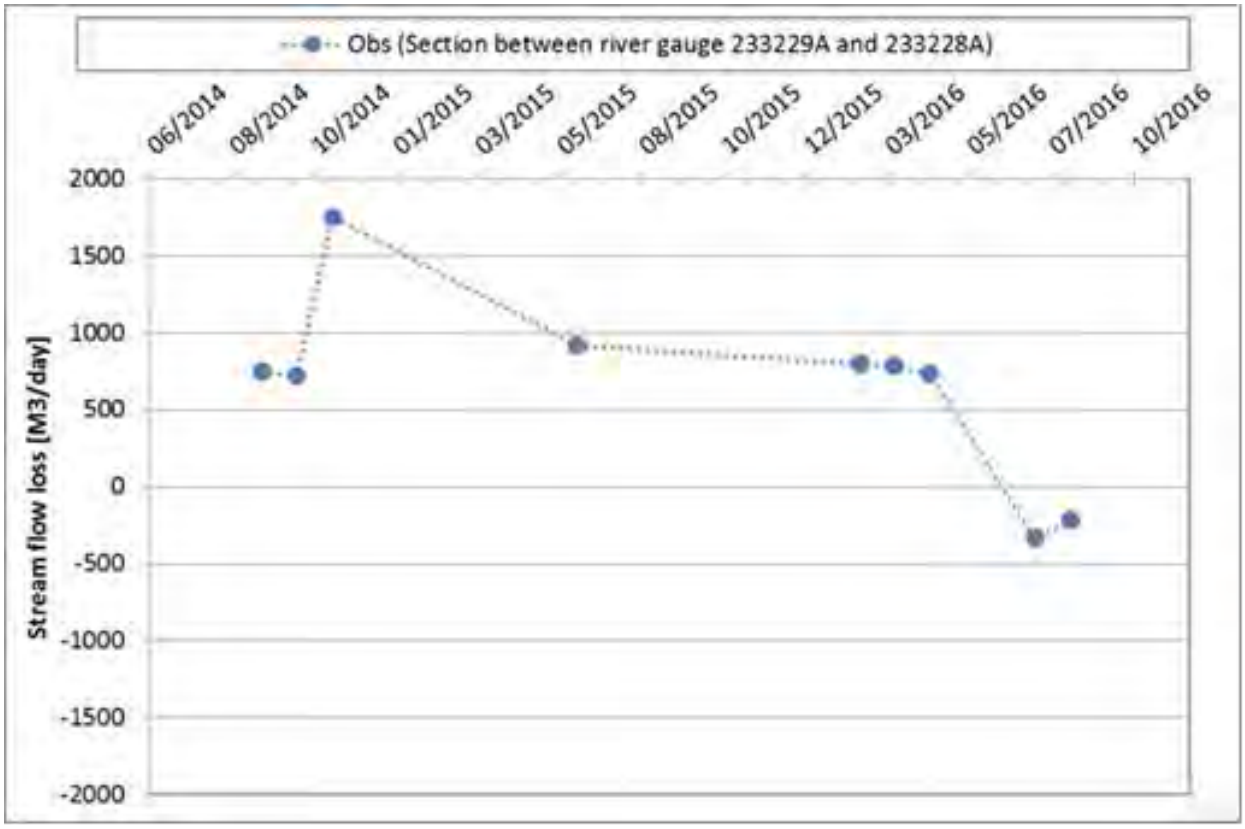


Figure 6-3 : Baseflow/Seepage target between rive gauge 233229A and 233228A at Yeodene



6.2.3 Parameterisation Approach

A mixture of both heterogeneous (spatially variable) and homogeneous (spatially constant within a defined area or zone) parameter fields were assigned to the model. Homogeneous or zonal parameter fields were assumed for recharge, maximum evapotranspiration rate and extinction depth, specific storage and river bed conductance. A single value for each of these parameters was assigned to spatial zones within the model domain.

For hydraulic conductivity (both horizontal and vertical) and specific yield, values were assumed to vary throughout the model domain. These heterogeneous parameter distributions were created using the PEST Pilot Points approach (Doherty, 2015). Pilot points are defined at locations distributed throughout the model domain. During calibration, values for hydraulic conductivity and specific yield are estimated at each pilot point in a manner that optimises the fit between observed and estimated calibration target data. The values assigned to all other locations are obtained by a spatial interpolation of the pilot point values. The locations of pilot points used in calibration are presented in Appendix B.

Calibration was conducted using the PEST software utilities (Doherty, 2015). Initial attempts to implement PEST were hampered by relatively long model run times due to the large number of model parameters and an apparent inability of PEST to find the global minimum objective function. As a result a calibration approach using both manual and automatic calibration methods was adopted. Parameter ranges considered by PEST in the calibration process are listed in Table 4-2.

Table 6-3: Pest parameters limits on pilot points by layer

		Kx	[m/d]	Kz	[m/d]	Sy	[]
Unit	**Layer**	**min**	**max**	**min**	**Max**	**min**	**max**
Gellibrand Marl	1	0.001	0.5	0.00001	0.01	0.001	0.15
Clifton Aquifer	2	0.01	50	0.001	9	0.01	0.15
Narawaturk Aquitard	3	0.00001	0.5	1E-06	0.005	0.001	0.15
Dilwyn Aquifer	4	0.01	50	0.001	9	0.01	0.15
Pember Aquitard	5	0.00001	0.5	0.00001	0.01	0.001	0.15
Pebble Point Aquifer	6	0.01	50	0.001	9	0.01	0.15
Basement	7	0.00001	0.5	0.00001	0.01	0.001	0.15

7. Calibration Results

7.1 Chapter Overview

This chapter presents the results of the calibration process described in the previous section. As discussed in Chapter 6, the calibration is assessed against the following criteria:

- Acceptable match to pre-pumping groundwater levels and to groundwater levels changes over time
- Groundwater surface water interactions consistent with conceptual understanding presented in Chapter 3
- Recharge estimates consistent with estimated recharge rates presented in Section 2.4.1

A summary of the calibration results is presented in Table 7-1

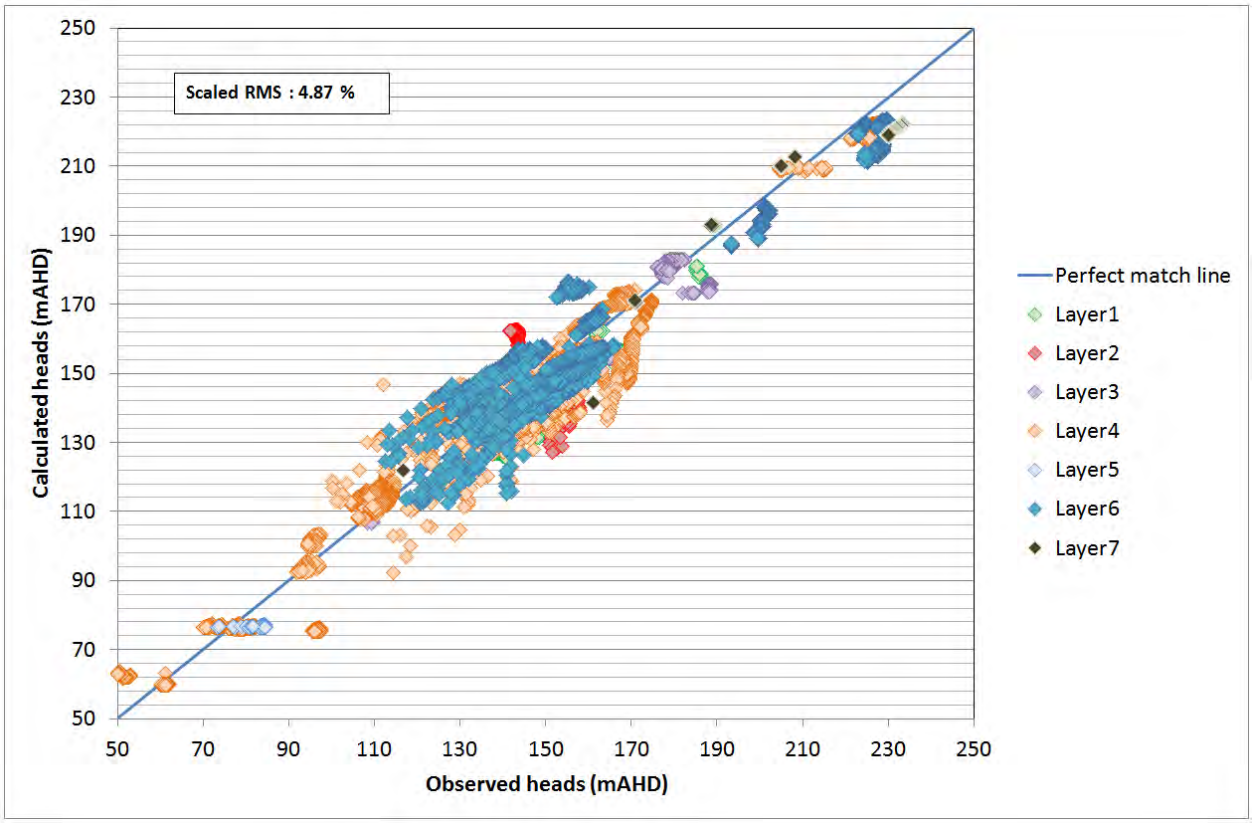
Table 7-1 Overview of the calibration results

Calibration criteria	Description
Groundwater levels (pre-pumping and over time)	• Acceptable representation of pre-pumping groundwater levels and groundwater level changes over time. • Model is able to replicate changing groundwater levels over time in all four sub-areas of the model (Central, Boundary Creek, Gellibrand River and Bambra Fault).
Groundwater surface water interaction	• Modelled fluxes to Boundary Creek are consistent with the conceptual understanding and baseflow estimates are acceptable. • Modelled fluxes to Gellibrand River are consistent with the conceptual understanding.
Recharge rates	• Recharge rates are lower than used in previous versions of the model, and are consistent with studies completed under the technical works monitoring program.

7.2 Groundwater levels

The comparison between the calibrated model predicted heads and the observed heads is shown in Figure 7-1. If the predicted heads perfectly matched the observed heads in every bore, all the points would fall on the perfect match line shown on the chart. The figure shows that the while there is some deviation from the perfect line match, the Scaled RMS Error is less than 5%, which meets the calibration criteria as defined above.

Figure 7-1 : Calibration scatter plot

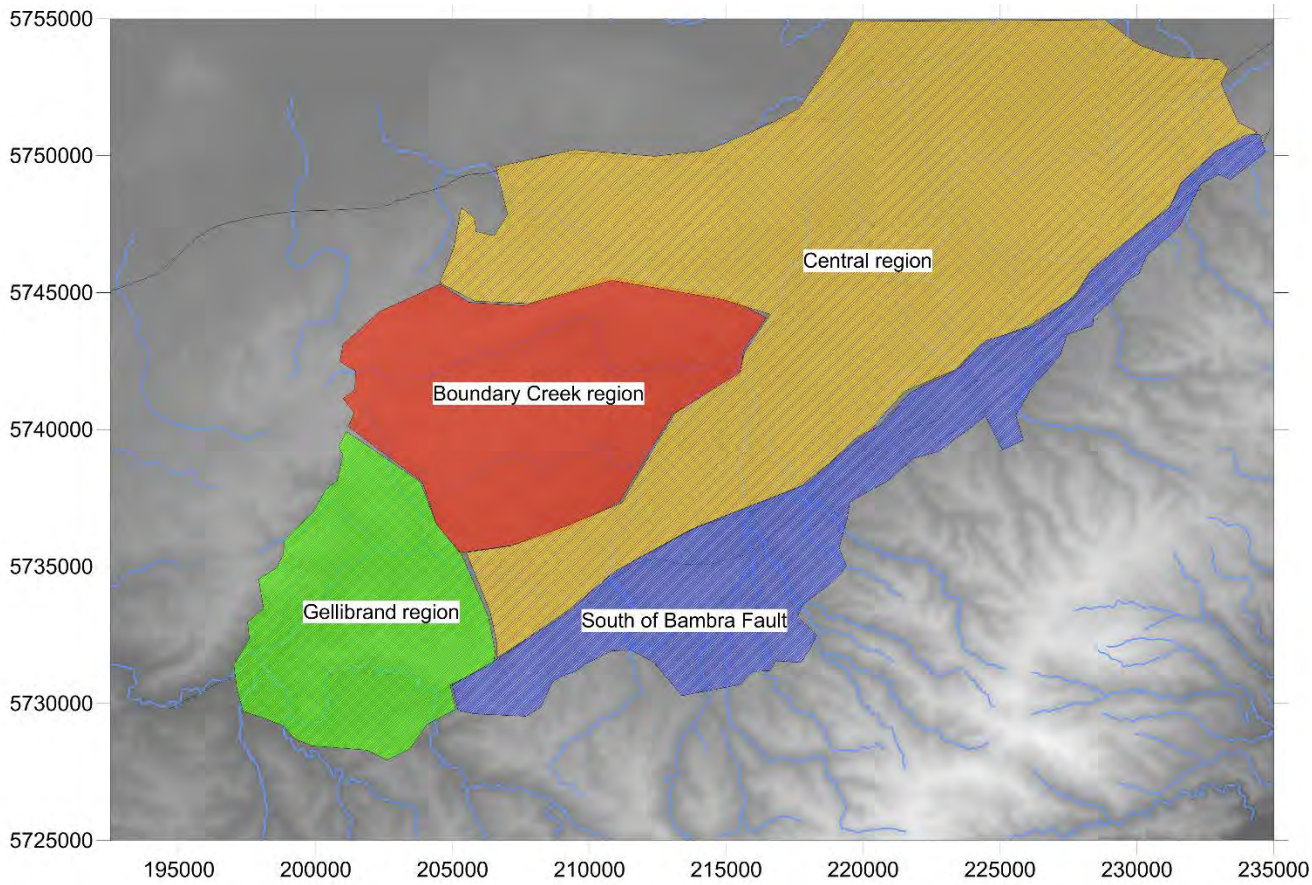


7.2.1 Calibration Hydrographs

To aid in the discussion of the calibration hydrographs, the model has been divided into four sub-areas – Central, Boundary Creek, Gellibrand and South of Bambra Fault as shown in Figure 7-2.

Calibration hydrographs for 82 bores located in different layers in each region are presented in Appendix D. A description of calibration results in each of the regions is discussed in the following sections.

Figure 7-2 : Calibration hydrograph sub-areas



Central Region

Drawdown propagates widely through the central region as the aquifers are generally deep and uniformly confined by the Narrawaturk Marl and Gellibrand Marl aquitards. Calibration hydrographs illustrate that the model has a reasonable level of calibration throughout the Dilwyn and Pebble Point Formations with a few exceptions. Some examples are presented in Figure 5-3 and are discussed below.

Bore 64230 is located in the Dilwyn Formation near the borefield and the model is able to accurately replicate the drawdown and recovery responses in this well. Further to the east, however, the model predicts a drawdown and recovery response in Bore 47773 where little or no response is observed. Apart from this bore the propagation of the groundwater responses through the central region is generally consistent with observations.

It is noted that although the heads in Bores 102867, 47775 and 109136 are underestimated by the model the drawdown and recovery responses are modelled quite well.

In the other model layers as shown in hydrographs included in Appendix D, it appears that the model has been reasonably well calibrated in the central region in the Narrawaturk Marl and Gellibrand Marl and less well calibrated in the Clifton Formation. This outcome is likely due to the fact that the Clifton Formation is of limited extent and thickness and its role in the hydrogeology of the graben is not well understood. With regard to the model calibration in the aquitard units (the Gellibrand and Narrawaturk Marls), the model is able to replicate heads and drawdown responses relatively well. The fact that the aquitards are relatively thick and are likely to include significant vertical head gradients makes the modelling of these units particularly difficult in a model in which they are represented as single individual layers with no vertical head gradients within each unit.

Boundary Creek Region

The Boundary Creek Region is centred on the Barongarook High and includes the aquifer outcrop areas where the aquifers are unconfined. In this area, all of the observation bores are measuring heads in the Dilwyn and Pebble Point Formations. Previous modelling of the Barwon Downs aquifer system has illustrated that calibration in the vicinity of the confined/unconfined aquifer transition area is difficult. As the drawdown response from borefield pumping propagates into the unconfined aquifer region, it is strongly suppressed by the water released from storage as the water table drops and water drains from the aquifer pores. The geometry of the aquifer and aquitard is very important in this area of the model to ensure the model can accurately replicate the hydraulic response as the aquifer transitions between confined and unconfined conditions. A further complexity in this part of the model domain is the fact that Boundary Creek exerts a reasonably significant impact on groundwater responses. The model's ability to reliably simulate the groundwater interactions with Boundary Creek requires the accurate definition of river stage through that part of the creek where it crosses the outcropping Dilwyn Formation. Calibration was improved following a careful refinement of the Digital Elevation Model (DEM) of the area that helped to improve estimates of the ground and creek elevations.

Calibration results for most locations in the Boundary Creek Region suggest a good model representation of the groundwater drawdown and recovery responses observed in observation wells. Some examples are provided in Figure 5-4.

While most sites indicate good model replication of the magnitude of the drawdown and recovery responses, Bore 109130 suggests that the model under-predicts the level of drawdown and recovery compared to the measured response. Elsewhere the model provides an excellent representation of the observed long term trends in groundwater level as well as the short term drawdown and recovery associated with periods of borefield operation. In terms of predicted groundwater levels, the model heads are consistently higher than those measured in Bore 64240 and are consistently lower than those measured in 109112. Elsewhere the modelled heads are very close to those measured in the observation wells.

The predicted fluxes into and out of Boundary Creek (shown in Figure 5-7) also show a good representation of the conceptual understanding of the groundwater surface water interactions in this region.

Figure 7-3 Example calibration hydrographs in the Central Region

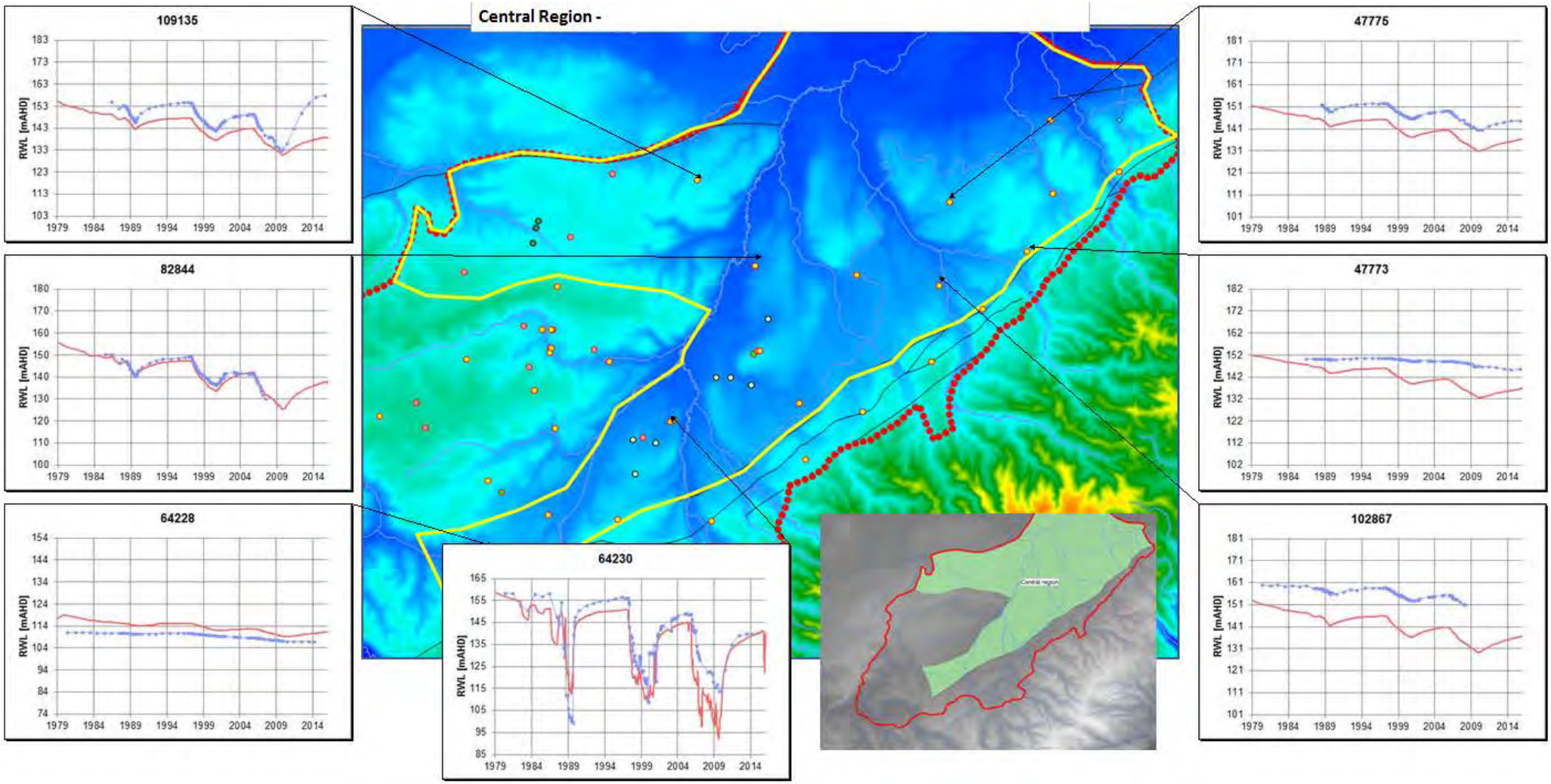
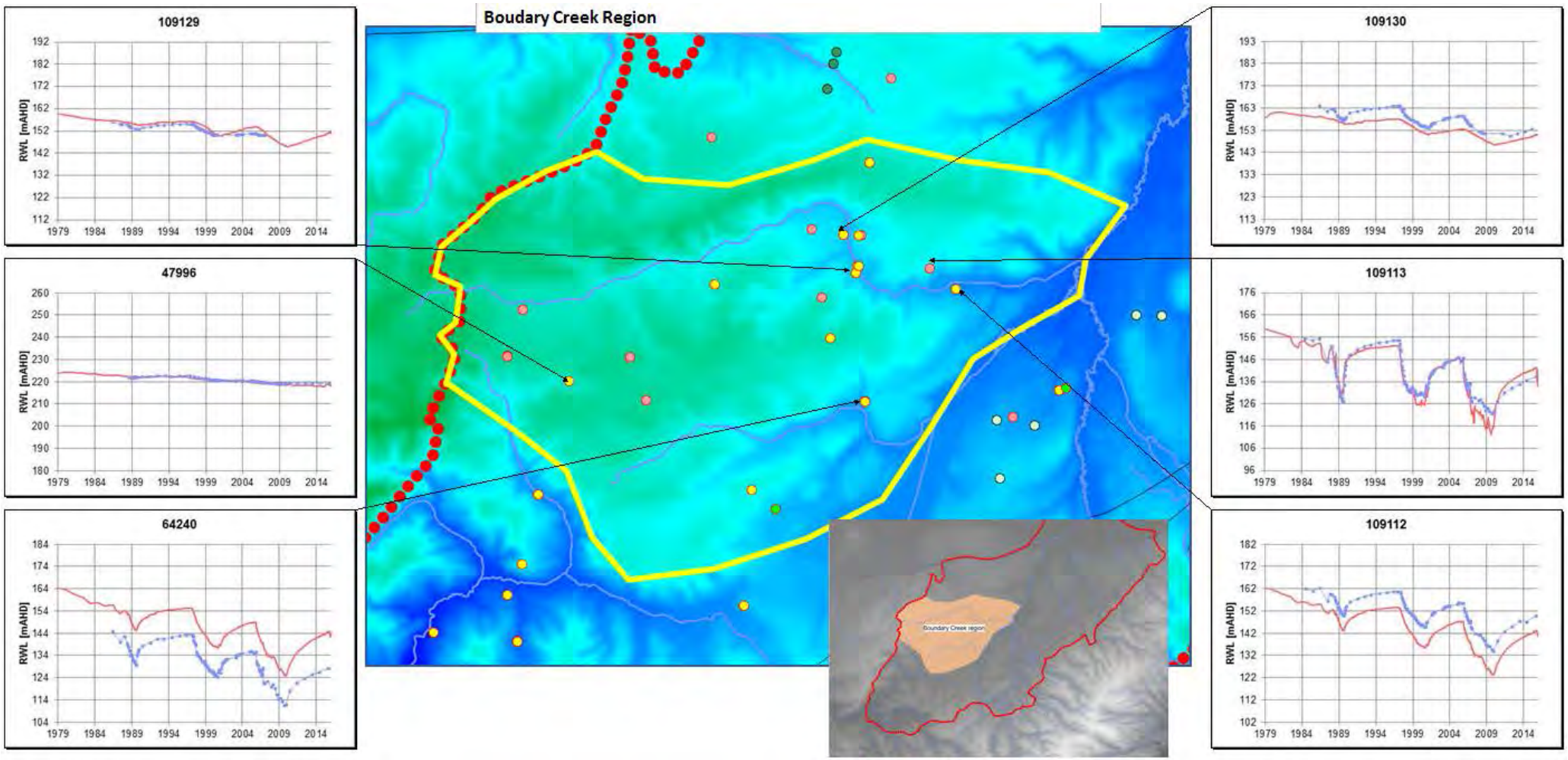


Figure 7-4 Example hydrographs in the Boundary Creek region



Gellibrand Region

The Gellibrand Region was not included in earlier versions of the model. It has a number of streams and rivers that are important features of the hydrogeology in this part of the graben. All observation bores included in the Gellibrand Region monitor heads in the Dilwyn and Pebble Point Formations. As seen in Appendix D, the calibration in this part of the model is generally very good. The modelled head responses and head values are in close agreement with observed responses and heads. This outcome provides confidence that the model is able to provide reliable predictions in this part of the model domain and that the model predicted interactions between groundwater and the various rivers and streams in this area are reasonably reliable.

South of Bambra Fault

The Bambra Fault has been shown to be an important feature that in parts disrupts the aquifer continuity through significant vertical displacement. Displacements have not only impacted the aquifer continuity, but have also resulted in the removal of overlying aquitards and have led to the outcropping of the aquifer sediments to the south of the fault. The interruption to the aquifer at the fault generally leads to suppression of drawdown and recovery responses arising from borefield pumping in those bores located to the south of the fault. Calibration has illustrated (refer to Appendix D) that generally the model is able to replicate this behaviour quite well, despite the fact that at some locations (e.g., Bores 48249 and 47771) the model predicts more drawdown than observed.

7.3 Groundwater surface water interaction

The net fluxes to each of the rivers and streams included in the model are presented in Figure 7-7 and Figure 7-8. The figure shows that the majority of rivers, except for Boundary Creek and Dividing Creek, are gaining flow from groundwater discharge (i.e., the predicted groundwater discharge fluxes exceed the predicted groundwater recharge fluxes for all times).

Boundary Creek has strong fluctuations in groundwater interaction with periods of net gain and net loss apparent over the calibration period. These fluctuations illustrate that Boundary Creek base flow is influenced by groundwater recharge processes and by groundwater extraction and associated drawdown.

Dividing Creek has a small but relatively constant net loss of flow to groundwater recharge, consistent with the conceptualisation.

Yahoo and Porcupine Creeks in the Gellibrand catchment also have a small net loss of flow to groundwater, but this is less significant than Boundary and Dividing Creeks.

Figure 7-5 : Net river fluxes in the Barwon River catchment [L/s]

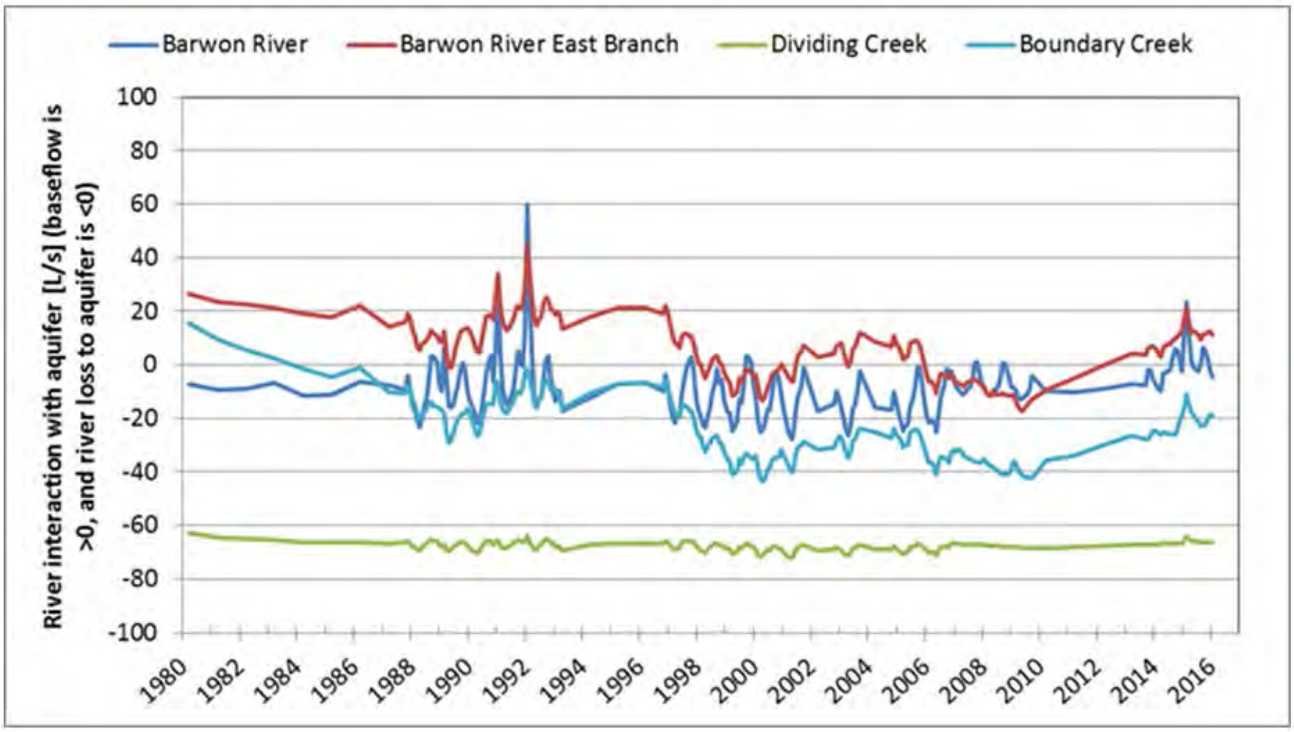
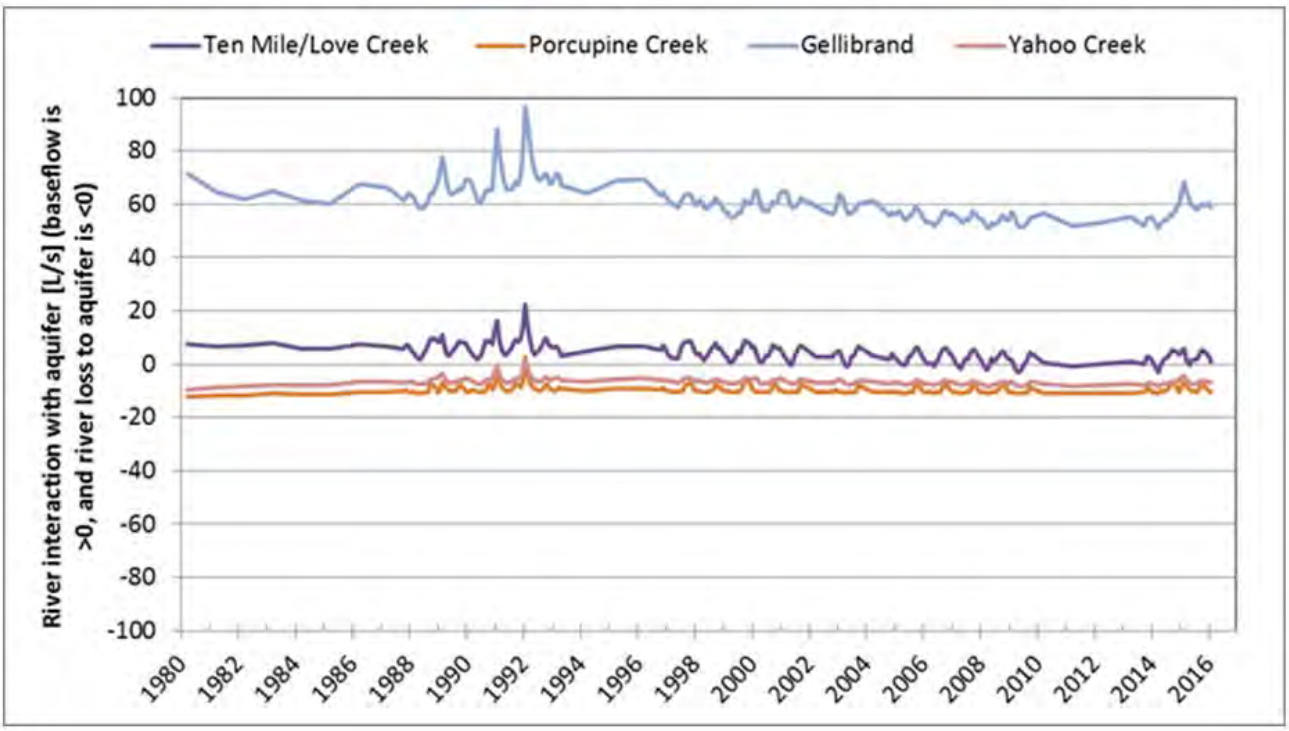


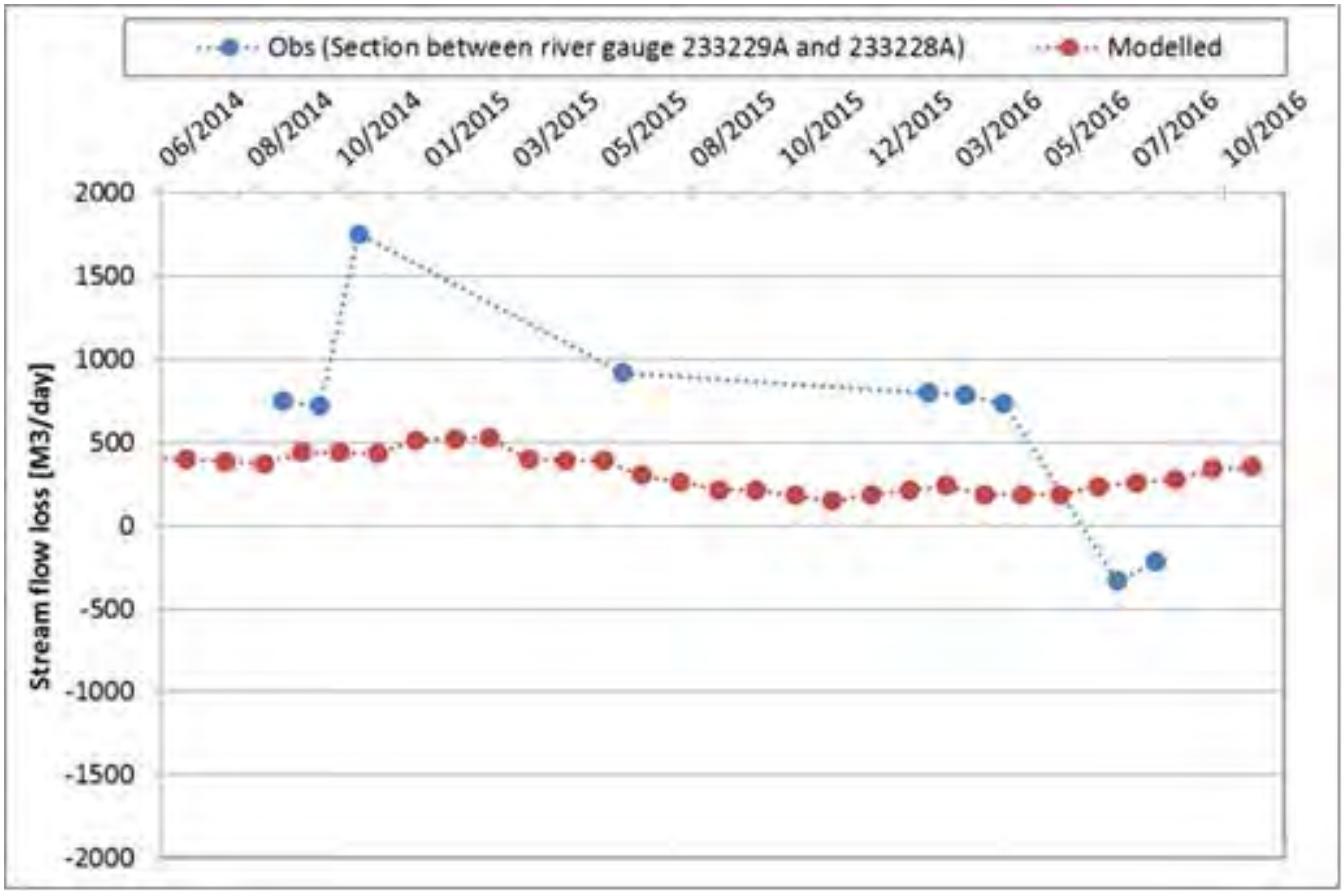
Figure 7-6 : Net river fluxes in the Gellibrand River catchment [L/s]



7.3.1 Boundary Creek baseflow/seepage

As described in chapter 4.2, the boundary creek baseflow/seepage was defined as a *"soft"* target to control to ensure the groundwater surface water interaction calculated by the model is consistent with observed flow in the boundary creek river. The calculated groundwater seepage is illustrated on Figure 5.5. The match is reasonable as the model does not account for the reduction of stream flow due to evapotranspiration and for runoff that can occur following rain events.

Figure 7-7 : Model groundwater seepage and flow reduction observed between 233229A and 233228A at Yeodene



7.4 Aquifer parameters

The hydraulic conductivity parameters (Kh and Kv) represent the capacity of an aquifer to transmit water horizontally and vertically. As each aquifer is not uniform, the hydraulic properties for each aquifer are not represented by a single value of Kh and Kv but by a field of hydraulic conductivities. The field of conductivity is obtained by interpolation of the calibrated Kh and Kv pilot points. The calibrated hydraulic conductivity distributions (horizontal and vertical) for all model layers are presented in Appendix C.

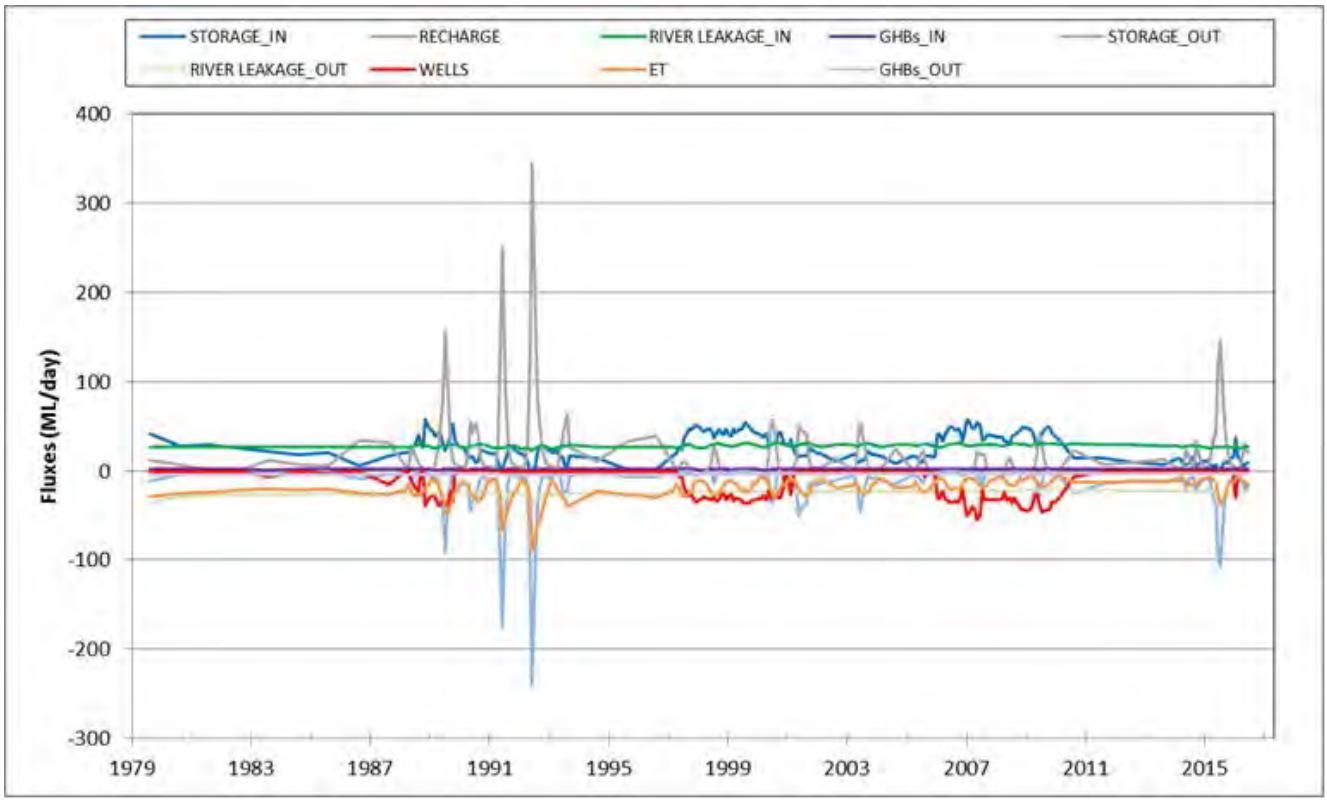
Similarly, the specific yield of outcropping layers was generated by interpolation of calibrated specific yield pilot points and the resulting distribution are represented in Appendix C. Specific storage was set at 5 E-06 m-1 for all layers.

7.5 Calibration model water budget

The calibration model water budget is illustrated in Figure 5-6. The principal inflows to the model include rainfall recharge and river seepage with significant *"storage in"* components at times of groundwater extraction from the borefield. The *"storage in"* flux represents the amount of water removed from storage in response to groundwater extraction. It is manifested in the model as drawdown in groundwater levels.

Evapotranspiration, groundwater discharge to rivers and *"storage out"* are the primary groundwater discharge fluxes in the model. The *"storage out"* component reflects the flux of water taken into storage as a result of various processes that replenish the aquifer. The relatively high evapotranspiration flux indicates that evapotranspiration from regions of shallow groundwater is a significant contribution to the model water budget.

Figure 7-8 : Calibration model water budget



8. Fit-for-purpose assessment

In assessing whether or not the model is fit-for-purpose it is necessary to consider the Confidence Level Classification as described in Section 3.3. The target Confidence Level Classification was defined as being Class 3 on the basis of the available data and the value of the environmental and engineering assets at risk. In order for the model to be fit-for-purpose, it must meet the target class (Class 3) and this assessment is aided by a set of qualitative and quantitative criteria and indicators included in the Guidelines.

8.1 Purpose (Model uses)

This model has been designed and built to assess potential impacts of future groundwater extraction from the borefield. These impacts are likely to include:

- **Declining groundwater levels**. The model will be required to determine whether the extraction of groundwater from the borefield can be sustained over a period of decades into the future.
- **Baseflow impacts**. The model will predict changes in groundwater discharge to rivers and creeks and also changes in river seepage to groundwater that may occur in the future as a result of borefield operations.
- **Impacts on groundwater dependent ecosystems (GDEs).** Impacts on GDEs can be assessed through the estimation of drawdown that is likely to occur at key locations adjacent to or within important GDEs. The model will also be used to predict the change in groundwater discharge fluxes through evapotranspiration under the assumption that evapotranspiration represents the extraction of groundwater by groundwater dependent vegetation.
- **Acid sulfate soils.** Predicted drawdown in shallow soils that are susceptible to acid sulfate generation will be determined by the model.

The impacts will be predicted across the entire model domain and will require the model to assess drawdown and flux impacts in the aquifers and in the overlying aquitards. The model is therefore required to estimate impacts that manifest in the shallow aquitard that outcrops over much of the model domain. The impacts will also be predicted in the aquifer layers where they are confined and in the unconfined area where they outcrop.

8.2 Confidence Level Classification

The Australian Groundwater Modelling Guidelines (Barnett et al., 2012) introduces a Confidence Level Classification that provides a qualitative indication of the relative confidence with which model predictions can be made. The intention of the Classification is to facilitate a dialogue in non-technical language that helps to convey the modellers understanding of the reliability of model predictions. The Classification recognises the fact that high levels of confidence (involving significant investment in time and effort) are not required for all modelling projects. There is a similar recognition that in some cases the available hydrogeological data may not be sufficient to be able to develop a high confidence level model and that additional data collection and further calibration may be required before the desired Confidence Level Classification can be attained.

The Classification is important in that the determination of whether a model is “fit-for-purpose” depends, among other things, on the Confidence Level Classification identified as being appropriate for a given model and whether or not a reviewer considers that this Classification has been achieved.

The Guidelines, and the Confidence Level Classification in particular, are considered to provide a benchmark of industry best practice by the groundwater modelling community and environmental regulators. To this end, a model can be described as meeting industry best practice if;

A target Confidence Level Classification is defined that is consistent with the project objectives and is consistent with the risks to both environmental assets and to the development in question.

The model is developed in a manner that is consistent with qualitative and quantitative criteria that define the target Confidence Level Classification.

Where a model is unable to meet the target Confidence Level Classification, a plan to collect additional data and subsequent upgrading of the model (including re-calibration) is recommended.

The model described in this report is located in an area of relative high environmental values and the borefield development is the subject of intense community interest. It is clear that a **high Confidence Level Classification** (Class 3) target is warranted in this case. Furthermore the available data for this project is consistent with and should support the development of a Class 3 model. In particular, the relatively long history of groundwater extraction with associated monitoring of groundwater responses in an extensive network of monitoring bores has provided an excellent calibration data set that meets the Guideline criteria for a Class 3 model.

The classification criteria for a Class 3 model are listed in Table 2-1 of the Guidelines and the key aspects of this table are reproduced here as Table 8-1.

From Table 8-1 it can be seen that the model has all of the relevant features of a Class 3 model. It is noted that the model criteria related to model validation are not relevant since a validation process has not been undertaken. Model validation involves calibrating the model to an incomplete data set where some of the relevant data is withheld. The calibrated model is then compared to the withheld data to determine whether the calibration is still valid when tested against the additional observations. Although validation is commonly used throughout the industry, it is becoming accepted that using all of the available data for calibration is a more appropriate approach (Barnett *et al.,* 2012). This recognition is largely due to the fact that once a model is shown to be deficient through a validation procedure, it is invariably refined to improve calibration to the validation data set and hence the validation data eventually becomes part of the calibration.

Table 8-1 indicates full compliance with all relevant indicators included in the Guidelines. Accordingly it is concluded that the model has met the Class 3 Confidence Level Classification as targeted at the start of modelling and is therefore fit-for-purpose.

Table 8-1: Class 3 Confidence Level Classification (after Barnett *et al.*, 2012)

Data	Calibration	Prediction	Key Indicator
Spatial and temporal distribution of groundwater head observations adequately define groundwater behaviour, especially in areas of interest and where outcomes are to be reported.	Adequate validation* is demonstrated.	Length of predictive model is not excessive compared to length of calibration period.	Key calibration statistics are acceptable and meet agreed targets.
Spatial distribution of bore logs and associated stratigraphic interpretations clearly define aquifer geometry.	Scaled RMS error (refer Chapter 5) or other calibration statistic is acceptable.	Temporal discretisation used in the predictive model is consistent with the transient calibration.	Model predictive time frame is less than 3 times the duration of transient calibration.
Reliable metered groundwater extraction and injection data are available.	Long term trends are adequately replicated where these are important.	Level and type of stresses included in the predictive model are within the range of those used in the transient calibration.	Stresses are not more than 2 times greater than those included in calibration.
Rainfall and evaporation data are available.	Seasonal fluctuations are adequately replicated where these are important.	Model validation* suggests calibration is appropriate for locations and/or times outside the calibration model.	Temporal discretisation in predictive model is the same as that used in calibration.
Aquifer testing data define key parameters	Transient calibration is current i.e. uses recent data.	Steady state predictions used when the model is calibrated in steady state only.	Mass balance closure error is less than 0.5% of total.
Stream flow and stage measurements are available with reliable baseflow estimates at a number of points	Model is calibrated to heads and fluxes.		Model parameters consistent with conceptualisation.
Reliable land use and soil mapping data available	Observations of the key modelling outcome data set are used in calibration		Appropriate computational methods used with appropriate spatial discretisation to model the problem.
Reliable irrigation application data (where relevant) are available			The model has been reviewed and deemed fit for purpose by an experienced independent hydrogeologist with modelling experience.
Good quality and adequate spatial coverage of digital elevation model to define ground surface elevation			

Green shading indicates full compliance, yellow shading indicates partial compliance and no shading indicates that the issue is not applicable to the Barwon Downs model.

Note: * No validation exercise has been undertaken. Calibration has used all of the available data.

8.3 Fit-for-purpose conclusion

The model meets industry standard expectations with reference to the quality and quantity of data used to conceptualise the hydrogeology of the area, the calibration methods and proposed predictive scenarios. Accordingly it is concluded that modelling results can be used with a level of confidence that is consistent with the modelling objectives and with the value of the economic and environmental assets under consideration. It is therefore considered fit-for-purpose for assessing potential impacts of future operations of the Barwon Downs borefield.

Even though the model is considered fit-for-purpose, it is recognised that there will be uncertainties associated with all predictive model scenarios. In accordance with the Australian Groundwater Modelling Guidelines (Barnet *et al.,* 2012) it is recommended that an appropriate uncertainty analysis accompany future predictive analysis. The uncertainty analysis should be aimed at illustrating the likely range of predictive model outcomes that are consistent with the hydrogeological conceptualisation and with information contained within the calibration data sets. The intention of an uncertainty analysis is to provide decision makers and regulators with an appropriate understanding of underlying uncertainties so that the risk of making decisions based on erroneous model outcomes can be effectively communicated.

9. Historical impact assessment

9.1 Chapter summary

The purpose of this chapter is to describe the historical impacts of the borefield. The calibrated model was used to assess the historical impacts of the operation of the Barwon Downs borefield. The was done by using the model to predict the groundwater level responses without pumping over the period 1980 to 2016 and assessing the differences between pumping and no pumping scenarios.

An overview of the predicted historical impacts of the bore field is provided in Table 9-1.

Table 9-1 Overview of the historical impact of the Barwon Downs borefield

Impact assuming no pumping	Impacts with pumping	Assessment of historical impact
Regional groundwater levels		
• Regional groundwater levels have declined up to 4 m throughout the region in response to climate conditions over the model timeframe.	• Operation of the Barwon Downs bore field caused an additional 10 m decline in regional groundwater drawdown over the model timeframe.	• Regional groundwater levels fluctuate naturally in response to climate variability and pumping. • Pumping from Barwon Downs has had more of an impact on groundwater levels compared to changes in climate driven recharge. • Deeper groundwater levels are more influenced by pumping compared the shallow aquifers near the surface
Groundwater contribution to flow in Boundary Creek		
• Climate conditions caused approximately 10 L/sec (approximately 1 ML/day) reduction in groundwater discharge to the creek. • This is a 100% reduction in baseflow in the creek and means the creek would have become marginally losing over the model timeframe.	• Operation of the bore field over time has caused an additional 20 L/sec (less than 2 ML/day) reduction in groundwater discharge to Boundary Creek in 2016. • This reduction in flow caused the creek to switch from a gaining creek and to a losing creek.	• Boundary Creek was gaining and is now losing. • Climate conditions over the model timeframe could have caused a reduction in streamflow for short periods of time. • Operation of the bore field is most likely the primary cause of reduction in streamflow in Boundary Creek.
Groundwater contribution to flow in Gellibrand River		
• Climate conditions caused a reduction in groundwater discharge of approximately 7 L/sec (0.6 ML/day) which is about 10% reduction in streamflow contribution in the model area.	• Operation of the bore field caused an additional 4 L/sec (0.3 ML/day) reduction in groundwater discharge which is equivalent to 6% reduction in streamflow.	• Groundwater naturally discharges to the Gellibrand River along much of the length of the River • The model intersects only part of the Gellibrand River. • Climate conditions have caused more of reduction in baseflow to the River compared to pumping from the bore field in this section of the River that the model intersects.
Vegetation and groundwater dependent ecosystems		
• Vegetation and groundwater dependent ecosystems are reliant on groundwater in shallow aquifers near the surface. • Shallow aquifers across large areas of the study area have not been influenced by operation of the bore field. • Operation of the bore field has had caused declining groundwater levels in shallow aquifers in some parts of catchment, particularly where the Lower Tertiary Aquifer outcrops. • Overall operation of the bore field has cause an 8% decline in ET between 1980 and 2016.		

9.2 Method

The calibration process has resulted in the simulation of groundwater extraction from the Barwon Downs Borefield and the associated groundwater responses that have occurred since 1980. As a result the model includes predictions (in this case the term *"prediction"* refers to a model estimation of historic groundwater responses) of the impacts that have occurred as a result of historic borefield operations. The model provides a useful tool as it can distinguish those impacts that have occurred as a result of borefield operation as opposed to those changes that have occurred over the same time due to variability in climate.

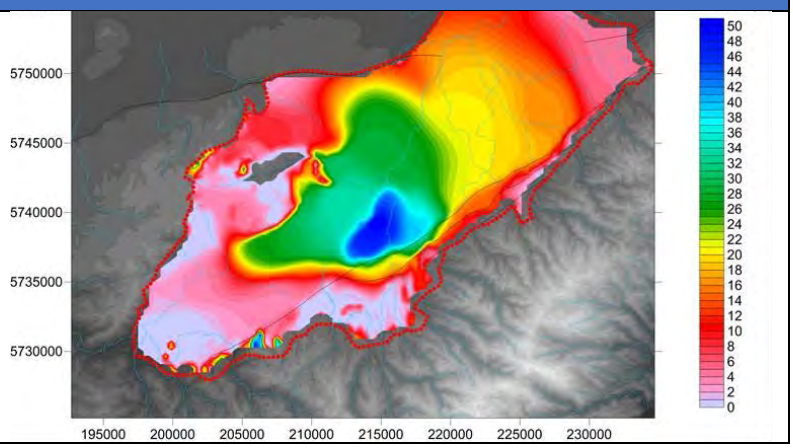
The historic impacts of borefield operations can be isolated from other climate driven impacts by running a second model over the same time frame that includes no groundwater extraction from the borefield, the so called "null case" model. The borefield impact predictions are then obtained by subtracting the heads and flux results from the calibrated model (with borefield pumping) from those of the null case model. The approach is advocated in the Australian Groundwater Modelling Guidelines (Barnett *et al.,* 2012) as a means of not only obtaining the results of interest, but also of reducing uncertainty associated with model bias.

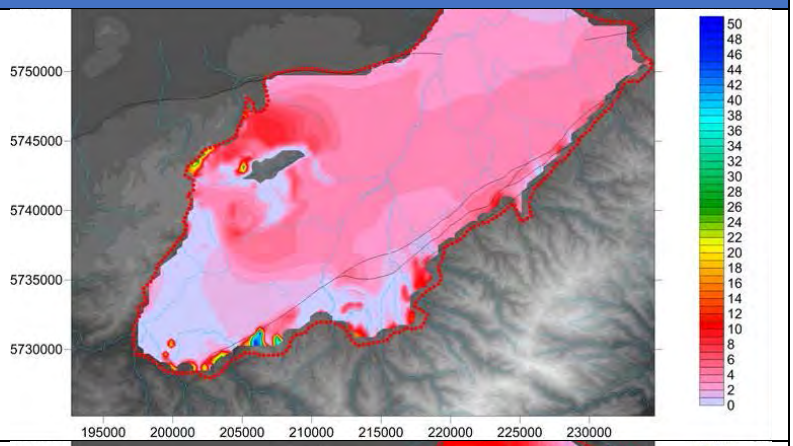
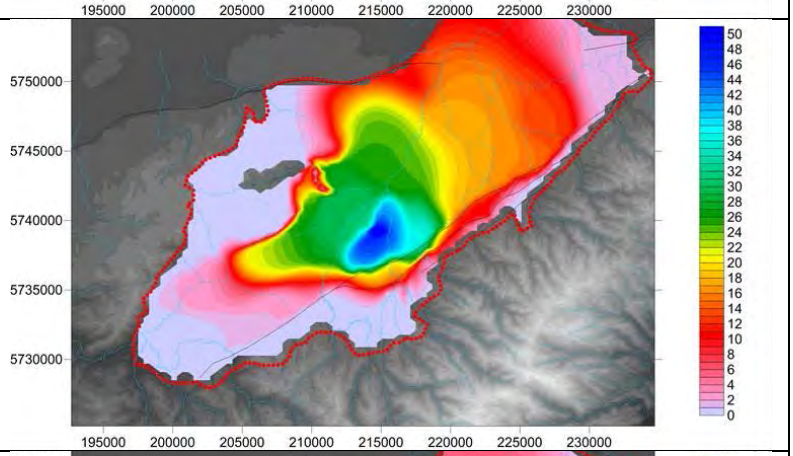
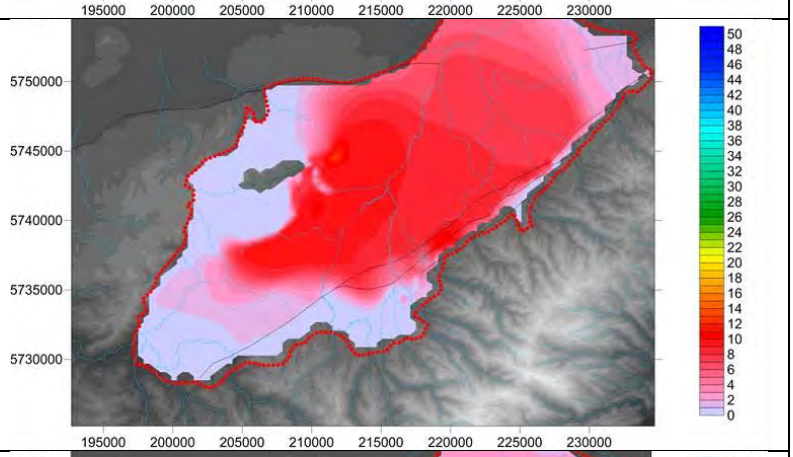
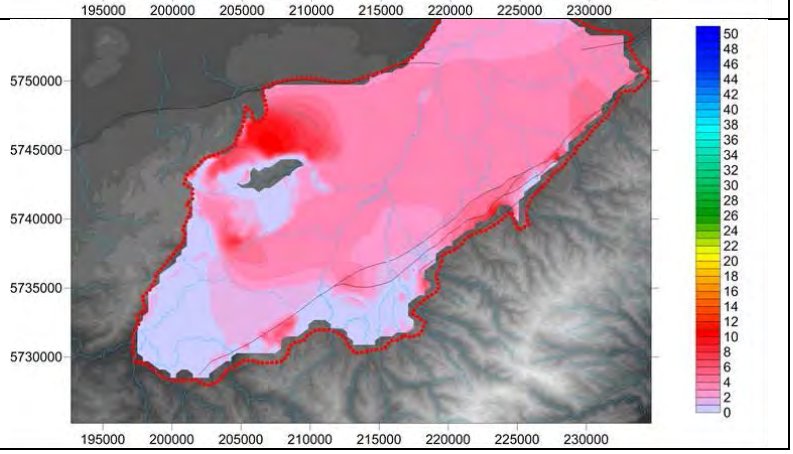
9.3 Results

9.3.1 Drawdown in the Lower Tertiary Aquifer

In this section drawdown is defined as the difference between the modelled heads in 1987 and those predicted at any time after 1987. 1987 was chosen as the base for the drawdown calculation because there were good records of measured groundwater heads at this time and there were no residual effects seen from early borefield pumping trials. Earlier dates were not suitable due to a lack of observed data to validate the model predicted heads.

A summary of the drawdown at different times under different scenarios is provided below.

Scenario	Predicted drawdown (LTA)	Diagram
Pumping (2010)	Drawdown is centred on the borefield where more than 40 m of drawdown is predicted.	

Scenario	Predicted drawdown (LTA)	Diagram
No pumping (2010)	It illustrates that the relatively dry climate between 1987 and 2010 has contributed up to about 10 m of drawdown in peripheral areas of the aquifer and more broadly about 5 m throughout much of the central parts of the aquifer.	
Pumping (2010) No climate influence	The drawdown is centred on the borefield, but the area with more than 40 m drawdown is predicted to less expansive. This highlights that climate has contributed to the observed drawdown in the deep aquifer at the borefield.	
Pumping (2016)	The result illustrates the level of predicted drawdown after a period of recovery in which there has been no borefield extraction.	
No pumping (2016)	The result shows some drawdown effects due to climate effects only.	

Drawdown is the change in groundwater head caused by historic operation of the Barwon Downs Borefield combined with changes that occurred as a result of climatic conditions. The effects of borefield operation can be separated from climatic effects by subtracting the predicted heads at any time in the calibrated model from those in the null case model (with no borefield pumping).

The model predicts drawdown varies with time and is influenced by the periods of groundwater extraction from the borefield. The temporal pattern of drawdown can be seen in time series plots of predicted heads in observation wells located across the model domain as illustrated in Appendix E. It can be seen that the drawdown peaked in 1989, 2000 and 2010 at times that coincide with the extraction of water from the borefield.

The model predicts that the greatest level of drawdown occurred in 2010 after a period of sustained borefield pumping. The predicted drawdown in the calibration model as a result of groundwater extraction and climate influence in the LTA in 2010 is illustrated in Figure 7-1. It shows that drawdown is centred on the borefield where more than 40 m of drawdown is predicted.

Figure 7-2 shows the predicted drawdown in the LTA that would have occurred in 2010 if there had been no borefield pumping. This map has been plotted with the same drawdown scale as that used for Figure 7-1 to aid comparison. It illustrates that the relatively dry climate between 1987 and 2010 has contributed up to about 10 m of drawdown in peripheral areas of the aquifer and more broadly about 5 m throughout much of the central parts of the aquifer.

Figure 7-3 shows the predicted drawdown in the LTA that can be attributable to borefield operations alone. This figure illustrates the impact due to pumping without any climate influence. The drawdown is centred on the borefield, but the area with more than 40 m drawdown is predicted to less expansive. This highlights that climate has contributed to the observed drawdown in the deep aquifer at the borefield.

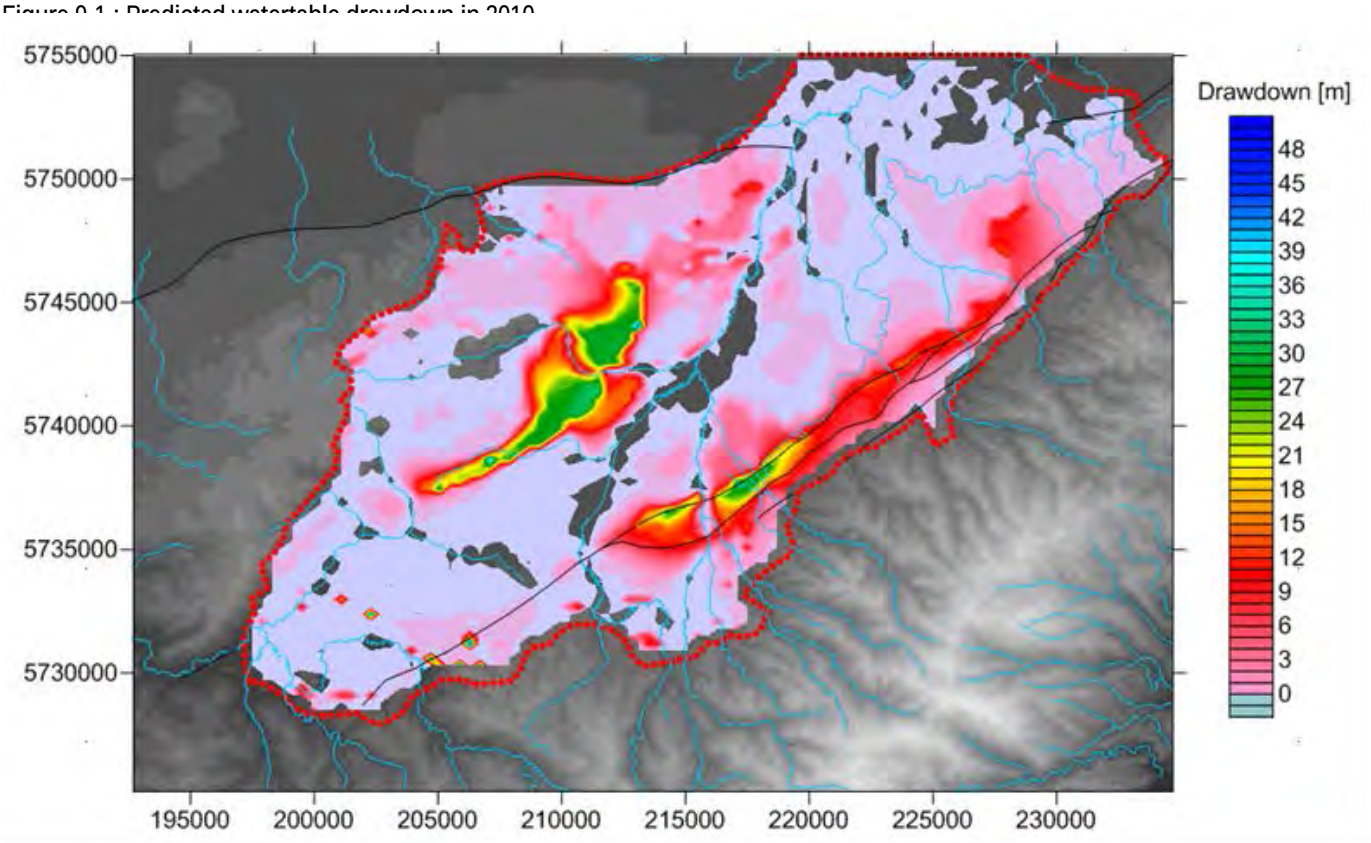
Figure 7-4 and Figure 7-5 show the predicted drawdown in 2016 in the LTA from borefield pumping only and from climate influences respectively. Figure 7-4 illustrates that the drawdown caused by pumping has decayed significantly from that predicted in 2010 (refer to Figure 7-3). By 2016 the levels of pumping induced drawdown are less than about 12 m. The result illustrates significant levels of groundwater recovery that occurs during periods when there is no pumping from the borefield.

9.3.2 Impacts on groundwater dependent ecosystems

The model provides an estimate of drawdown in near surface aquifers and aquitards that has occurred over the period of borefield operation. This drawdown has the potential to reduce the availability of water for groundwater dependent ecosystems (GDE's) that rely on groundwater discharge to the surface or to the presence of groundwater at to near the ground surface. The shallow water table drawdown is illustrated in Figure 7-10 as composite of predicted drawdown in all model layers that host the watertable.

When the evapotranspiration rates predicted in the calibration model (i.e. with pumping) are compared with a similar model without borefield extraction, the impacts of groundwater extraction on evapotranspiration rates can be illustrated. In this manner it has been found that the predicted drawdown caused by borefield pumping has led to a reduction in the estimated average evapotranspiration rate of 617 ML/year across the entire model. This change in evapotranspiration represents an average of 8% reduction in water used by vegetation and in water naturally discharging to the ground surface. However, separate analysis of groundwater impacts on tree health suggests vegetation condition has not been materially impacted by this change (SKM, 2016).

Figure 9.1 : Predicted watertable drawdown in 2010

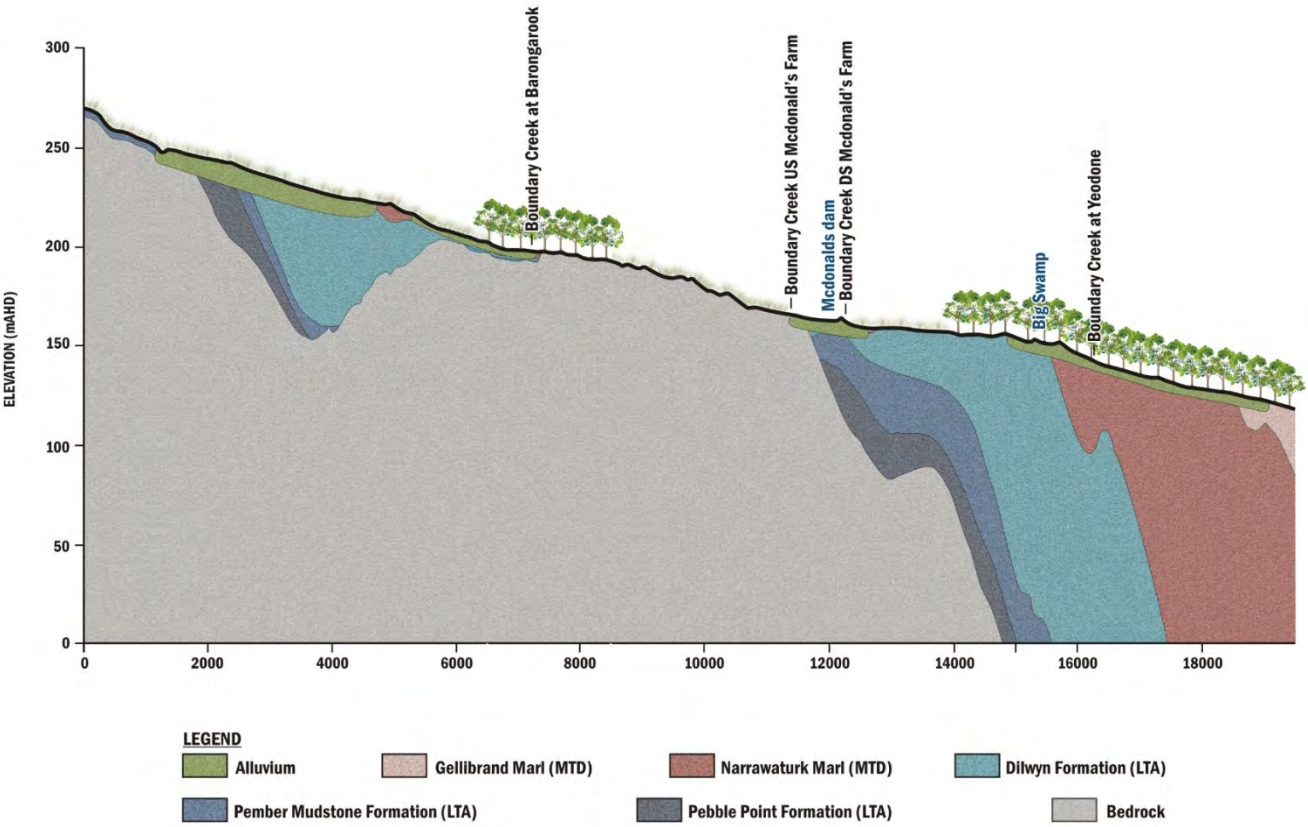


9.3.3 Impacts on Boundary Creek

Historically, the changes in baseflow in Boundary Creek have been a major source of community concern. Accordingly, efforts have been made to improve the model calibration and representation of groundwater behaviour in the region of Boundary Creek.

Modelled impact on gaining and losing reaches

Conceptually, it is understood that where Boundary Creek crosses the LTA outcrop in Reach 2, there is a potential for significant levels of interaction between the creek and the aquifer. Other rivers are either isolated from the main aquifers by varying thicknesses of poorly permeable aquitards (marls) or are located outside the region of influence of the borefield and hence are less prone to impacts from groundwater extraction.



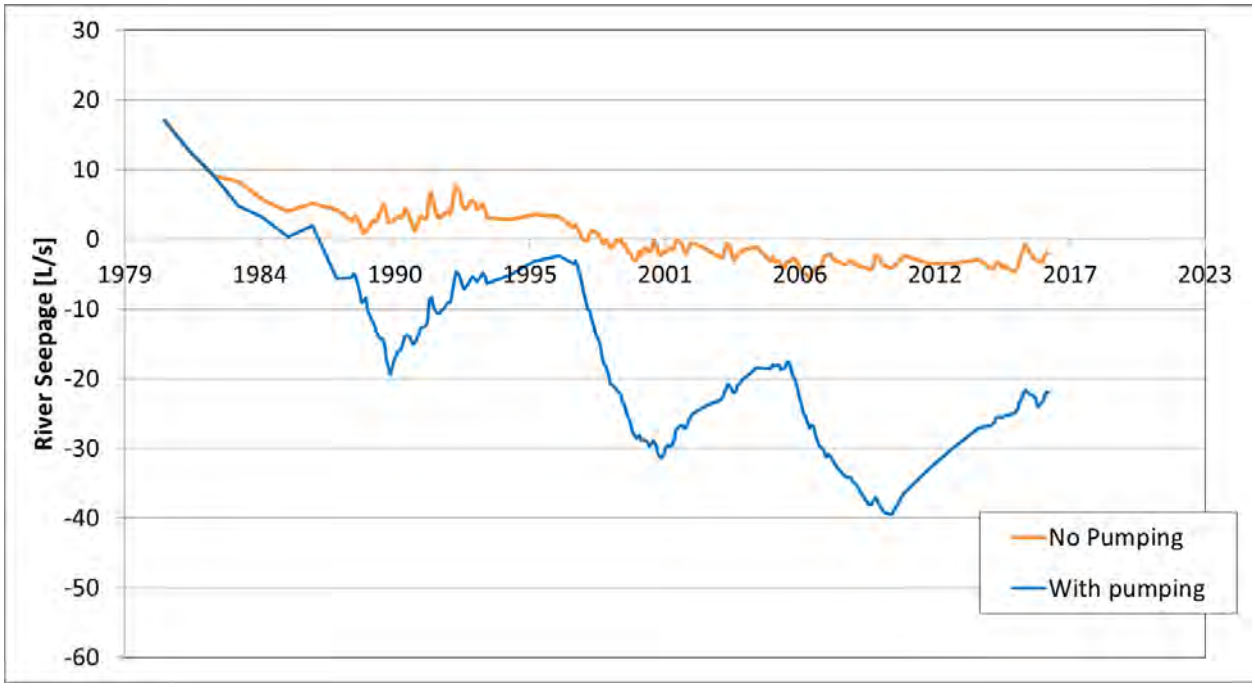
At Boundary Creek the drawdown in the LTA has caused the creek to change from being a gaining creek (groundwater provides baseflow) to being a losing creek (water flows from the creek to the groundwater). The groundwater model is able to simulate these processes; the predicted interactions for Boundary Creek in Reach 2 over the calibration period are shown in Figure 7-6.

The no pumping result shown in Figure 7-6 suggests that dry climatic conditions from the late 1980's would have caused a reduction in the baseflow to Boundary Creek to the point where it would have been in an approximately neutral condition in which water loss from the creek marginally exceeds the baseflow contribution.

The changes in groundwater flow to Boundary Creek caused by borefield operation are also shown in Figure 7-6 as periods of increasing seepage out of the river channel (shown as negative seepage in Figure 7-6). The figure indicates that borefield operations have led to a complete loss of baseflow and an increase in seepage from the river bed and into groundwater within Reach 2.

It should be noted that losses from Boundary Creek are hypothetical in that for significant parts of the year, the flow in the creek may be insufficient to support the predicted losses, i.e. they are a maximum loss assuming water availability.

Figure 9-2 : Predicted surface water groundwater interaction for Boundary Creek (Reach 2)



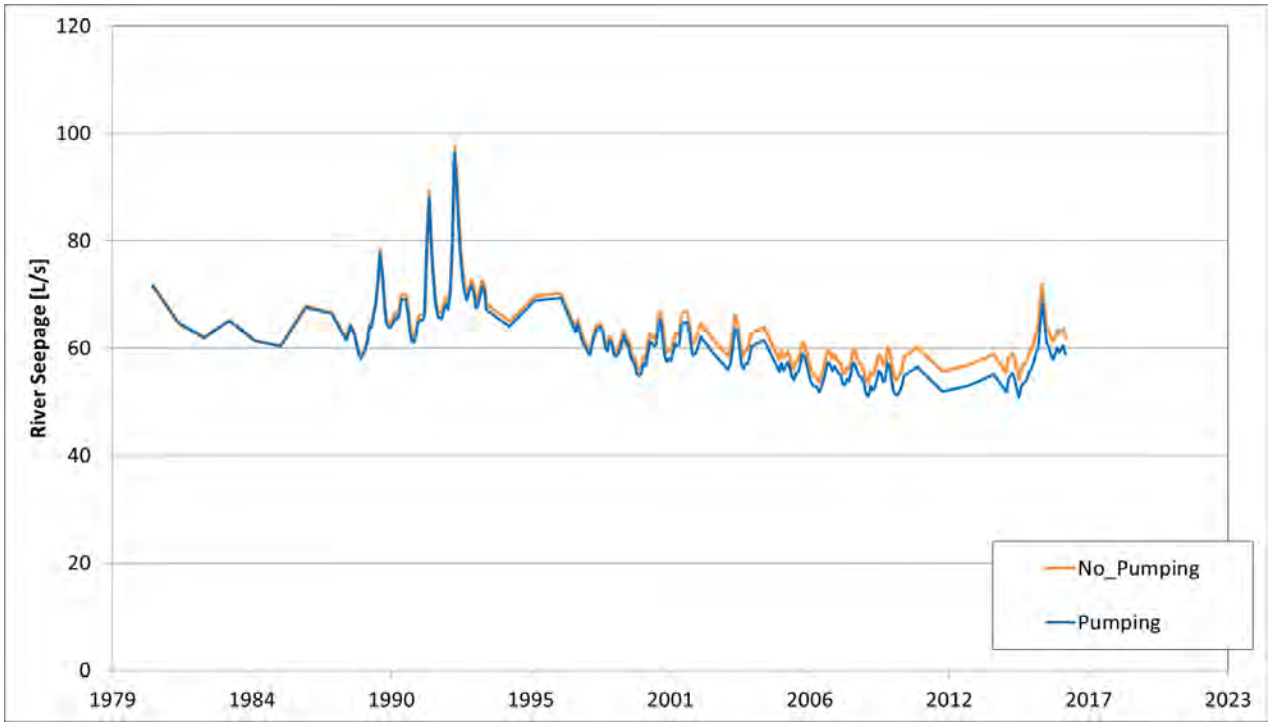
9.3.4 Impact on the Gellibrand River

Predicted groundwater surface water interactions for the Gellibrand River and the Barwon River are shown in Figure 7-7 and Figure 7-8 respectively. The figures show very little predicted changes in baseflow due to borefield operation.

This outcome reflects the fact that relatively small levels of drawdown are predicted in the Gellibrand catchment suggesting that it is at the margins of influence of borefield pumping. In 2016, pumping from the borefield is predicted to have caused a slight reduction in baseflow to the river from 63 L/sec to 59 L/sec, which is approximately a 6% reduction in baseflow contribution within the model domain.

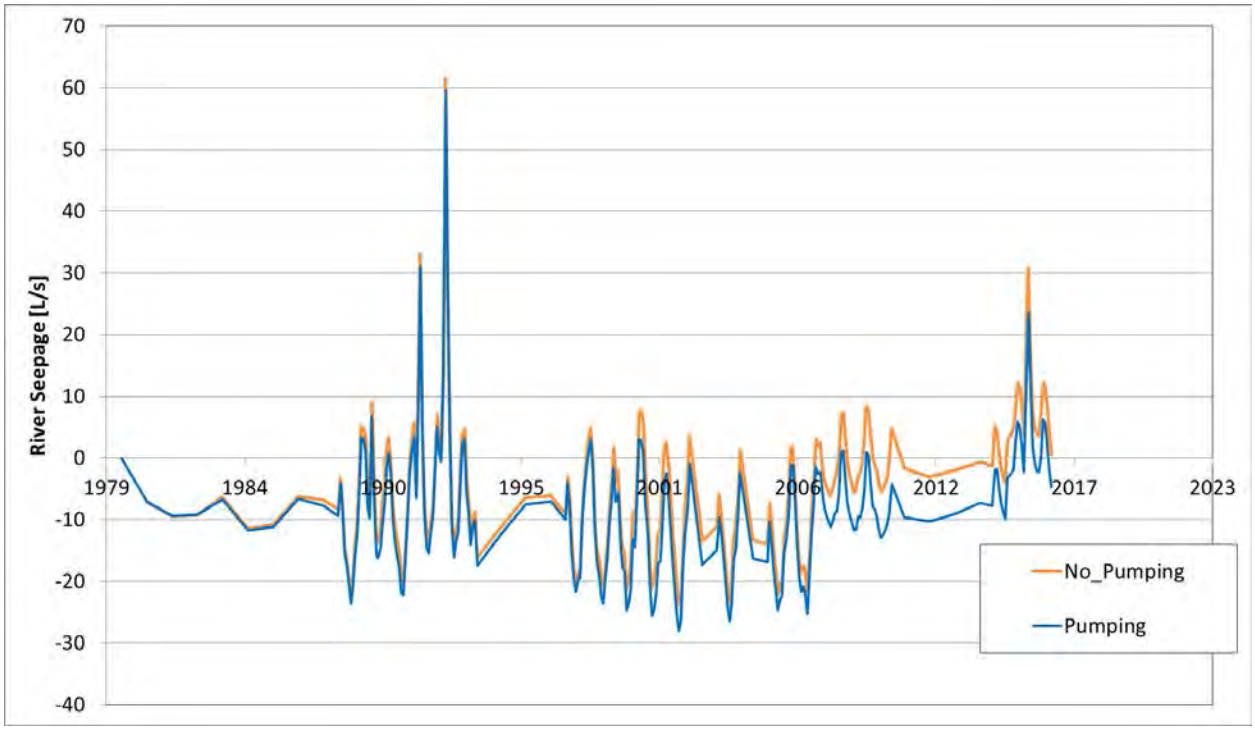
It should be noted that baseflow contribution from the region upstream of the model domain is not modelled and is not influenced by borefield pumping.

Figure 9-3 : Predicted surface water groundwater interaction for the Gellibrand River



Similarly the Barwon River mostly flows across the poorly permeable MTD that effectively isolates it from the deeper aquifer where most of the drawdown impacts are predicted to occur. Figure 7-8 indicates that the Barwon River is predominantly losing and this is largely due to the fact that the river crosses a small region of outcropping aquifer to the south of Bambra Fault where groundwater levels are quite low and the river is predicted to have significant losses. Further downstream the river is predicted to be gaining from groundwater discharge at rates that are relatively low as influenced by the poorly permeable MTD through which it is flowing.

Figure 9-4 : Predicted surface water groundwater interaction in the Barwon River



9.3.5 Changes to the water balance

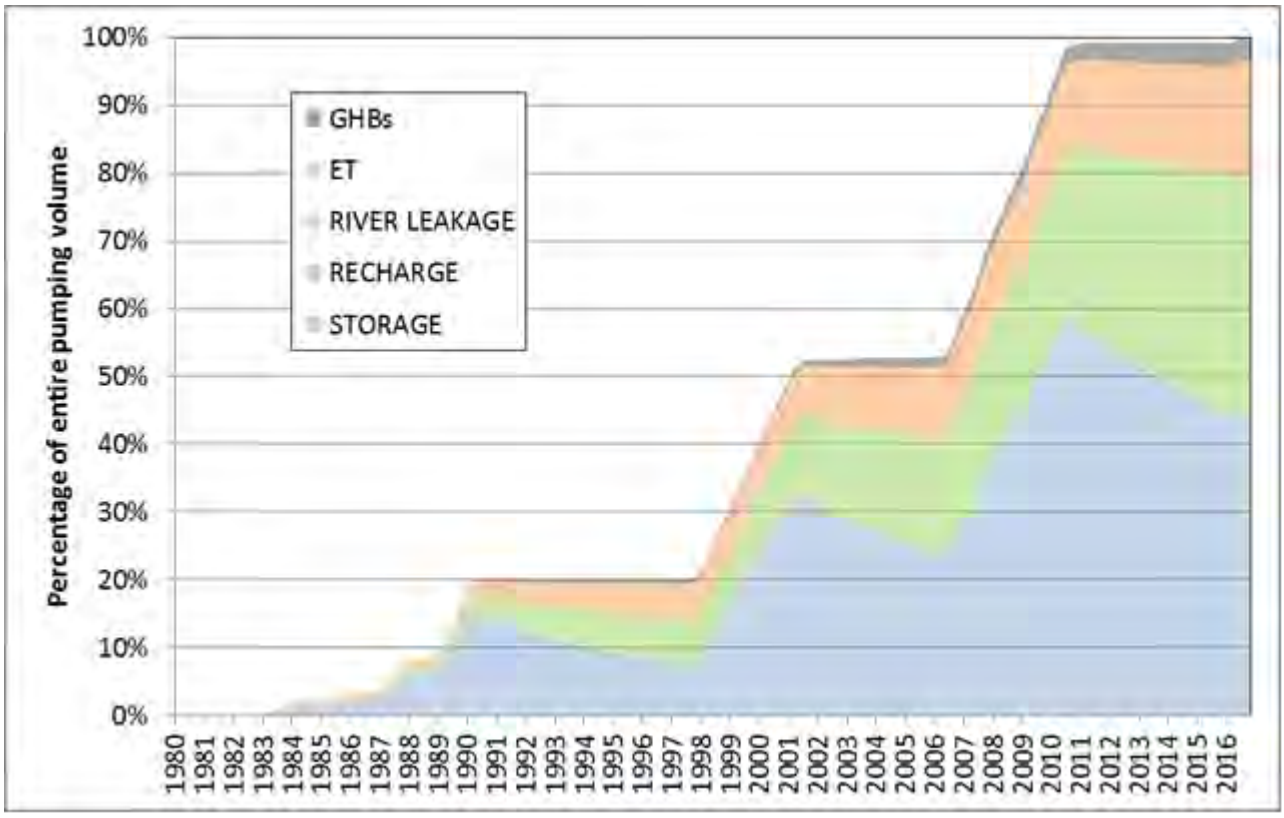
The conceptual water balance presented in Jacobs (2016a) is shown in Figure 2-5. This shows that the primary recharge mechanism (inflow) for the LTA is recharge from rainfall. Groundwater discharges from the aquifer via vertical flow to the overlying MTD, baseflow to rivers and smaller amounts to ET and lateral groundwater flow. The MTD is recharged from rainfall and from the underlying LTA and discharge mechanisms are primarily ET and baseflow to rivers with a very small amount of lateral groundwater flow.

Predicted changes to the model water budget arising from all extraction of groundwater from the borefield between 1980 and 2016 are shown in Figure 7-9. This figure shows the relative changes to various model components as a means of compensating for the removal of groundwater from the aquifer, where:

- The storage changes shown in this figure reflect the drawdown caused by pumping.
- The GHB changes indicate changes in water entering the model from regions surrounding the model domain.
- Evapotranspiration changes are caused by drawdown propagating to shallow levels and causing the water table to drop below the rooting depth of surface vegetation.

The changes in river leakage shown in Figure 7-9 represent the combination of reduced groundwater discharge to the river bed and increased seepage of river water into groundwater. Although recharge changes are plotted in this figure the values are 0% at all times. The result illustrates the fact that recharge does not change as a result of groundwater extraction and hence it does not compensate for the removal of groundwater from the model.

Figure 9-5 : Predicted changes in the model water budget caused by groundwater extraction



10. Conclusions and Recommendations

10.1 Conclusions

The groundwater model has been updated to allow:

1. The inclusion of recently acquired groundwater pumping and groundwater level observation data,

2. The representation of an updated hydrogeological conceptualisation that has drawn on a substantial amount of recently acquired groundwater data,

3. The use of recent advances in groundwater modelling software (Modflow USG) that allows a more efficient modelling grid and hence provides for a more efficient use of available computer processing capabilities,

4. A more faithful representation of the hydrogeological setting (including the aquifer and aquitard units that make up the stratigraphic sequence within the Graben), the rivers and creeks that interact with groundwater and the ground surface elevation as defined by the Digital Elevation Model.

The model has been calibrated to illustrate how well it is able to reproduce historically observed groundwater behaviour and to refine the parameter values and boundary conditions that influence groundwater behaviour. The calibration has been extended to include comparison between model predicted heads and fluxes into and out of Boundary Creek with baseflow estimates obtained from river gauging stations. This is a significant advance on previous models that were calibrated on groundwater heads alone. Calibration focussed on the region of Boundary Creek and the results indicate that the model is well tuned to the groundwater system in this part of the model domain.

The calibrated model has been used to quantify the groundwater impacts that have resulted from historic operations of the borefield. The assessment has considered the following impacts that have occurred since the introduction of large scale groundwater extraction in 1987:

1. Drawdown in groundwater levels including that which has occurred in the deep aquifer and in the shallow near surface groundwater system (the watertable),

2. Changes in groundwater contributions to rivers and creeks,

3. Changes to the water availability for Groundwater Dependent Ecosystems.

The modelling has been undertaken in a manner that has allowed the distinction between impacts that have arisen as a result of borefield operations and those arising from natural climate variability.

Important findings include the following:

1. Drawdown extends across most of the aquifer where it is confined in the centre of the graben. However drawdown is rapidly suppressed as it propagates westward into the region where the aquifer outcrops.

2. The water table drawdown appears to be influenced by the thickness of the aquitards that overly the aquifer. Relatively high levels of watertable drawdown are predicted to occur where the aquitards are thin around the margins of the graben and where the aquifer rises towards the ground surface to the east of the area of aquifer outcrop.

3. Groundwater extraction from the borefield is predicted to result in significant changes to the baseflow in Boundary Creek and insignificant changes in the baseflow in all other rivers.

4. Groundwater extraction and associated watertable drawdown is predicted to have led to a decrease in evapotranspiration of about 8% when compared to undisturbed conditions.

The model has attained a Class 3 Confidence Level Classification which is consistent with the modelling objectives and with the high value of the environmental and economic assets at risk. It is considered to be fit-for-purpose for on-going use to assess future groundwater behaviour and impacts that may occur from borefield operations.

10.2 Recommendations

The model should be used to assess a number of predictive scenarios to help illustrate the potential changes in groundwater behaviour that may occur as a result of future borefield operation.

Future assessment of predictive scenarios should be accompanied by an appropriate uncertainty analysis that provides a range of predicted impacts that illustrates the likely range of possible model outcomes.

11. References

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