Barwon Downs Hydrogeological Studies 2015/16

Barwon Water

Recharge Rate Assessment

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16 September 2016

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Executive Summary

Background

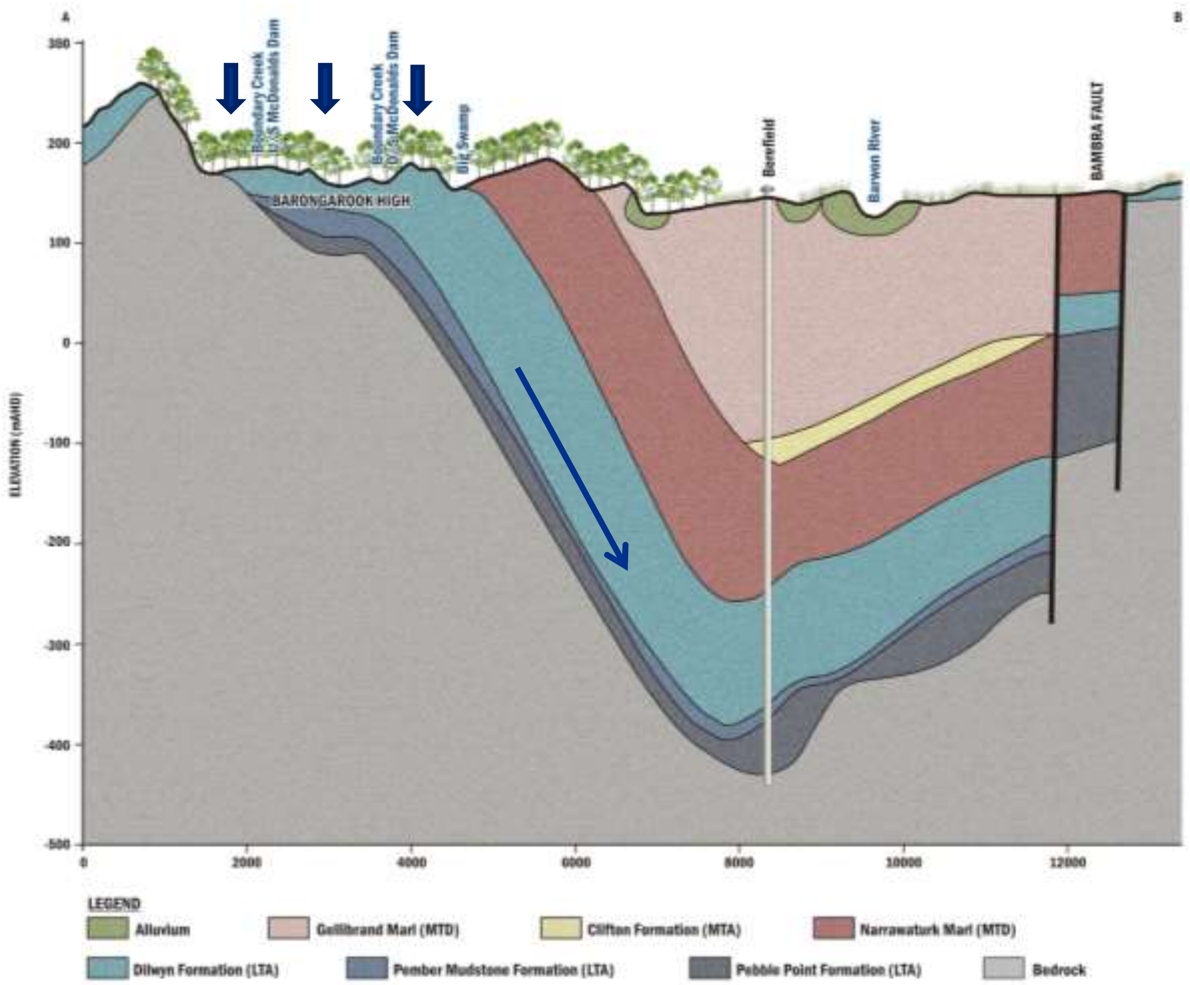
Barwon Water uses the Barwon Downs Borefield to augment Geelong's potable supplies during dry times. The groundwater extraction licence for Barwon Downs is due for renewal in 2019and to be prepared for this, Jacobs has undertaken a range studies under the Technical Works Monitoring Program. The focus of this study is to improve the understanding of recharge to groundwater across the study area.

An accurate understanding of recharge to an aquifer is imperative to understand how much water can be responsibly extracted and to predict impacts to groundwater levels, streamflow and groundwater dependent ecosystems. The existing numerical model for the Barwon Downs region assumes a recharge rate of 20% of rainfall and whilst this is considered to be high, to date there have been no independent recharge estimates to validate this.

Objective of this study

The overall objective of this study is to provide estimated rates of recharge to the Lower Tertiary Aquifer in the Barwon Downs region using independent techniques to estimate actual recharge rates to improve the accuracy and confidence in the numerical model. As shown in Figure 1 recharge to the Lower Tertiary Aquifer is conceptualised to occur via direct rainfall across the Barongarook High, where the aquifer outcrops.

Figure 1 : Recharge to the Lower Tertiary Aquifer



Approach

There are many ways to estimate groundwater recharge including calculating a water balance for a system, developing a numerical model to characterise groundwater responses or unsaturated zone modelling to characterise water movement through the soil. There are also field based methods such as monitoring seepage rate or using chemical tracers such as chloride and isotopes like tritium.

There is considerable variability in the spatial and temporal distribution of recharge and it is considered best practice (Cartwright et al., 2007) to apply multiple methods to help to refine the conceptual model of recharge processes and reduce the uncertainty of recharge estimates. This study uses two methods to estimate recharge using chemical tracers – the tritium method and the chloride mass balance method. These methods were selected as they use field data to characterise actual recharge to the aquifer, integrate unsaturated zone processes and are applicable over the time scales of interest.

The **tritium method** uses the natural levels of tritium found in water to calculate the age of groundwater. The groundwater age is then combined with information on the soils and groundwater to provide estimates of recharge. This study uses three different approaches to calculate groundwater recharge using tritium - independent estimates at each site, differential estimates between bores and the interface method to identify the spike present in natural tritium levels in the 1960s.

The **chloride mass balance method** was also used to estimate recharge. This method uses the concentration of chloride in groundwater. Groundwater chloride concentration is higher than rainfall concentration due to evaporation. Groundwater recharge can be estimated by dividing the annual deposition of chloride by groundwater chloride concentrations.

The data requirements for both methods were mostly available from previous studies undertaken during the Technical Works Monitoring Program and other studies such as Witebski (1995), Crosbie et al., (2012) and SKM (2012). Groundwater tritium levels were not available from previous studies, so this project involved a groundwater sampling program to collect information on tritium in groundwater.

Key findings

The results suggest that that best representation of current/modern recharge to the LTA on the Barongarook High are derived from the application of the independent and interface methods. This suggests that modern recharge rates are most likely to be around 9 to 11% of the average annual rainfall in the area of aquifer outcrop.

Recharge over the longer term (i.e. thousands of years) is likely to about half of the modern day estimates based on the last 50 to 70 years. The modern day recharge rates are considered to be more relevant to this study as they represent the current climate conditions. The reason for this difference is not determined by this study.

Recommendations

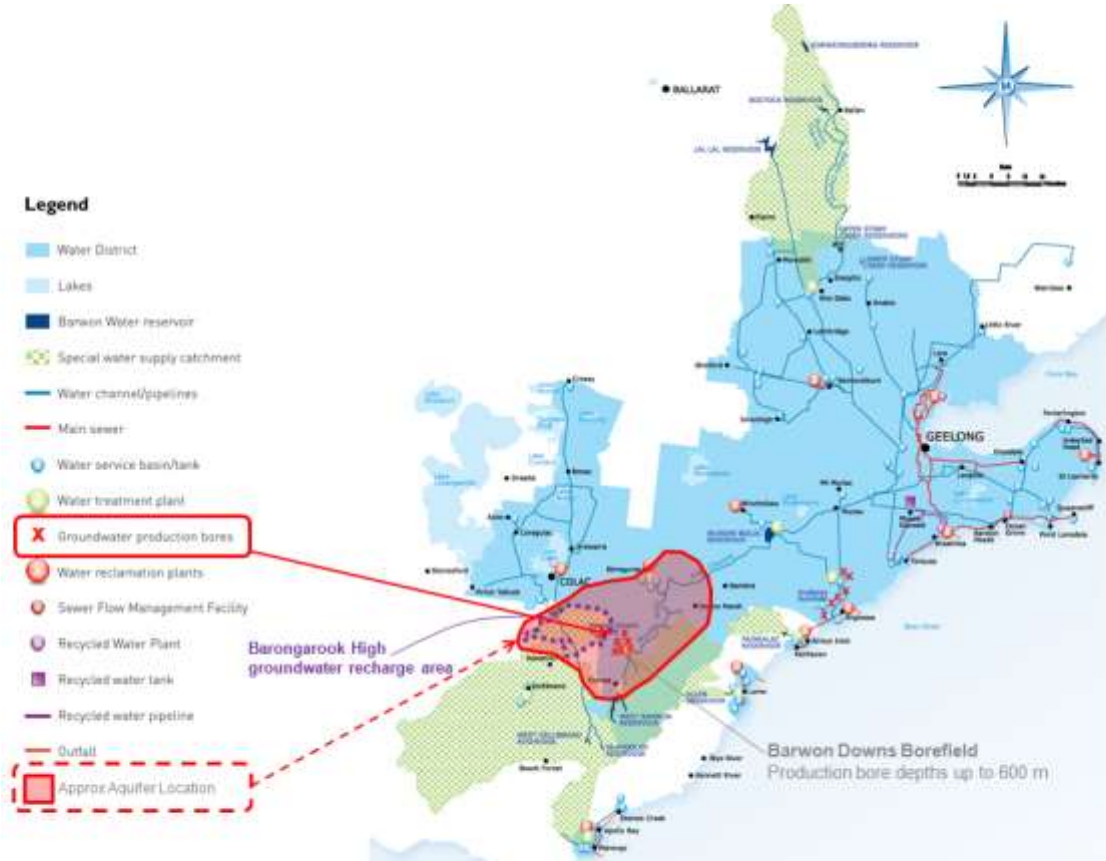
These results suggest that recharge to the Barongarook High is approximately 10% of average rainfall and unlikely to exceed 14% of average rainfall. We recommend that the updated numerical model use these recharge rates as a starting point for calibration.

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 catchment 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 groundwater recharge area



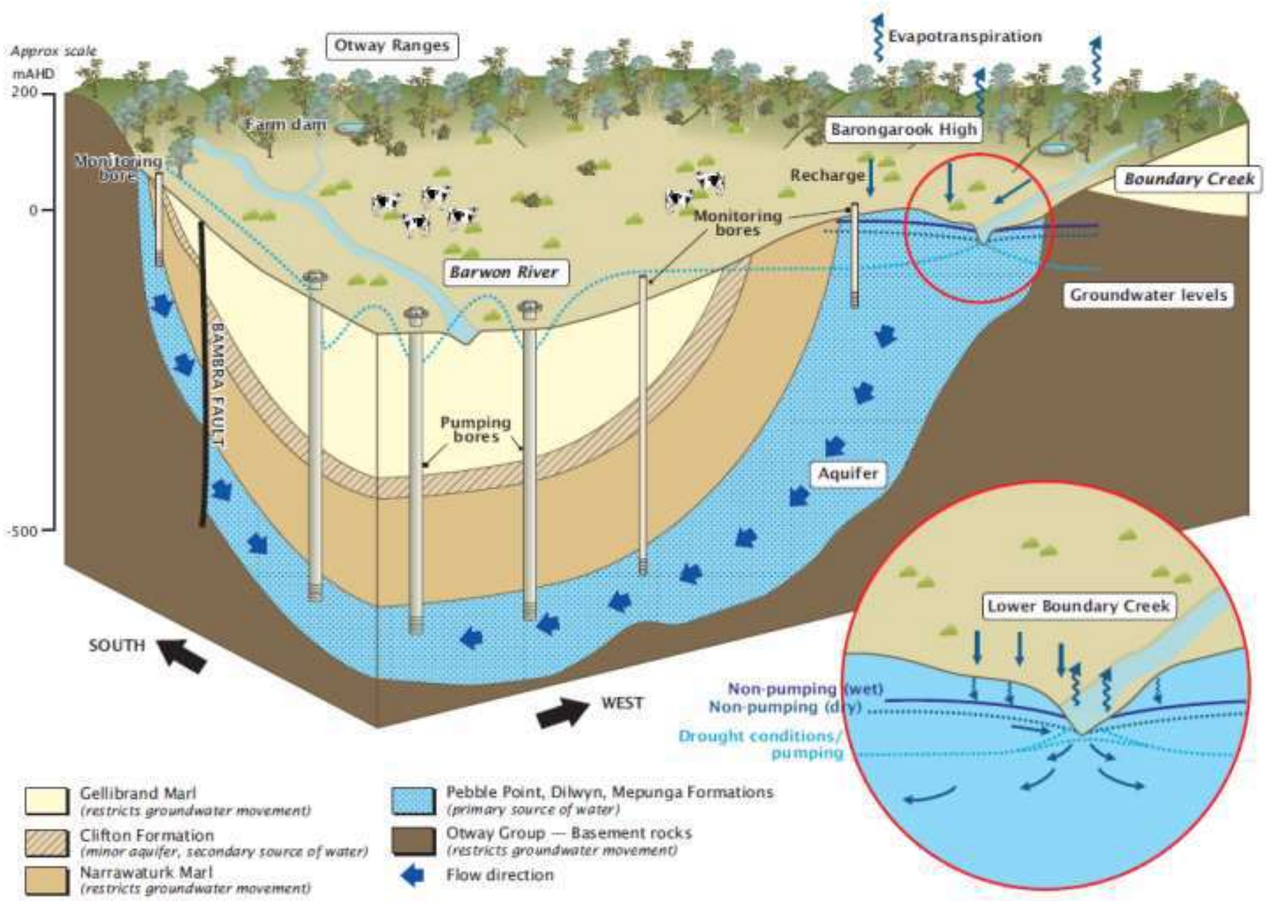
The regional groundwater system extends beneath two surface water catchments, the Barwon River catchment and the Otways Coast catchment.

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 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 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 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 record 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).

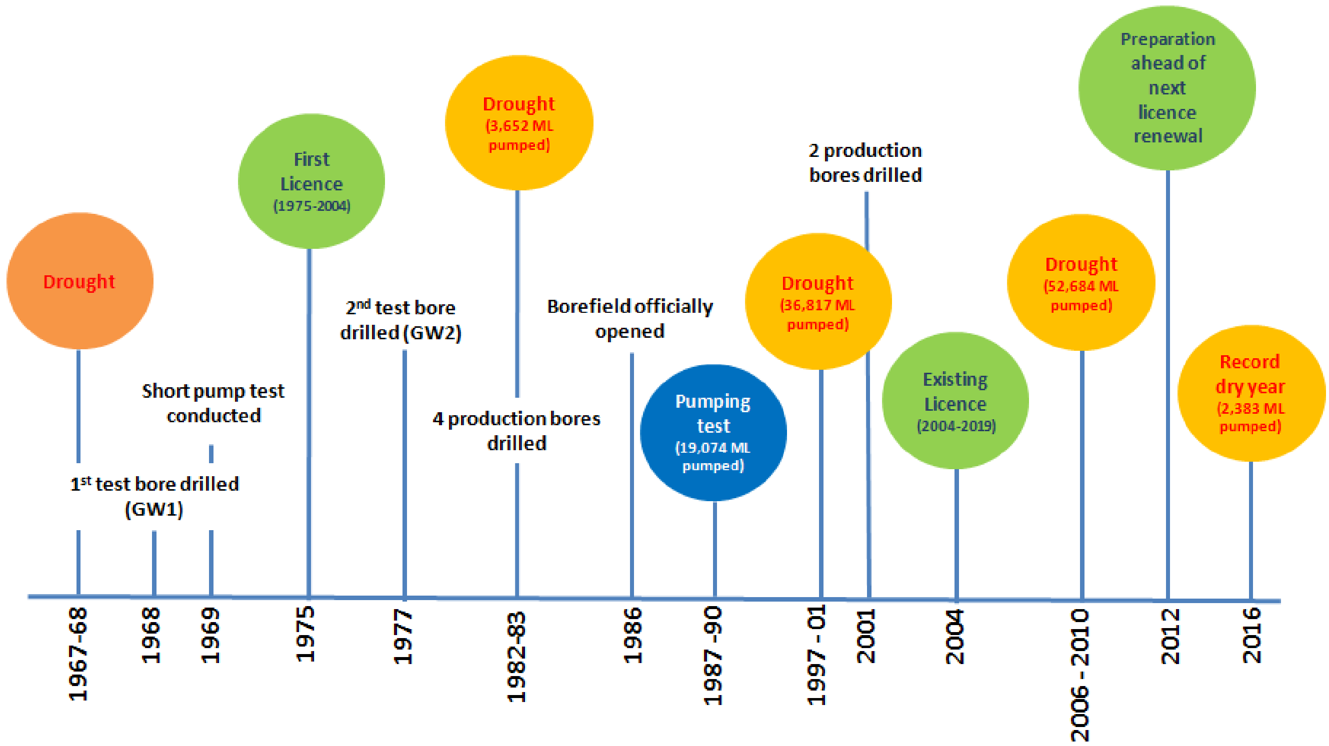
The licence was subsequently renewed for two periods of five years up to 2000. From 2000, the licence was temporarily extended three times for a total of four years to allow the licence renewal to take place through to 31 August 2004.

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
- 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 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. Barwon Water has and will continue to operate the borefield in accordance with current licence conditions.

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 our 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, Geelong residents 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;
- Determine the cause and relative contribution of groundwater variability (for example, groundwater extraction, drought and land use changes) 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 ensure a successful licence renewal 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,
- refurbishment of three existing bores,
- Four new potential acid sulphate soils monitoring bores,
- 32 data loggers and two barometric loggers installed in new and existing bores,
- two new stream flow gauges installed, and
- two existing stream flow gauges replaced.

Stage 4: Ongoing monitoring

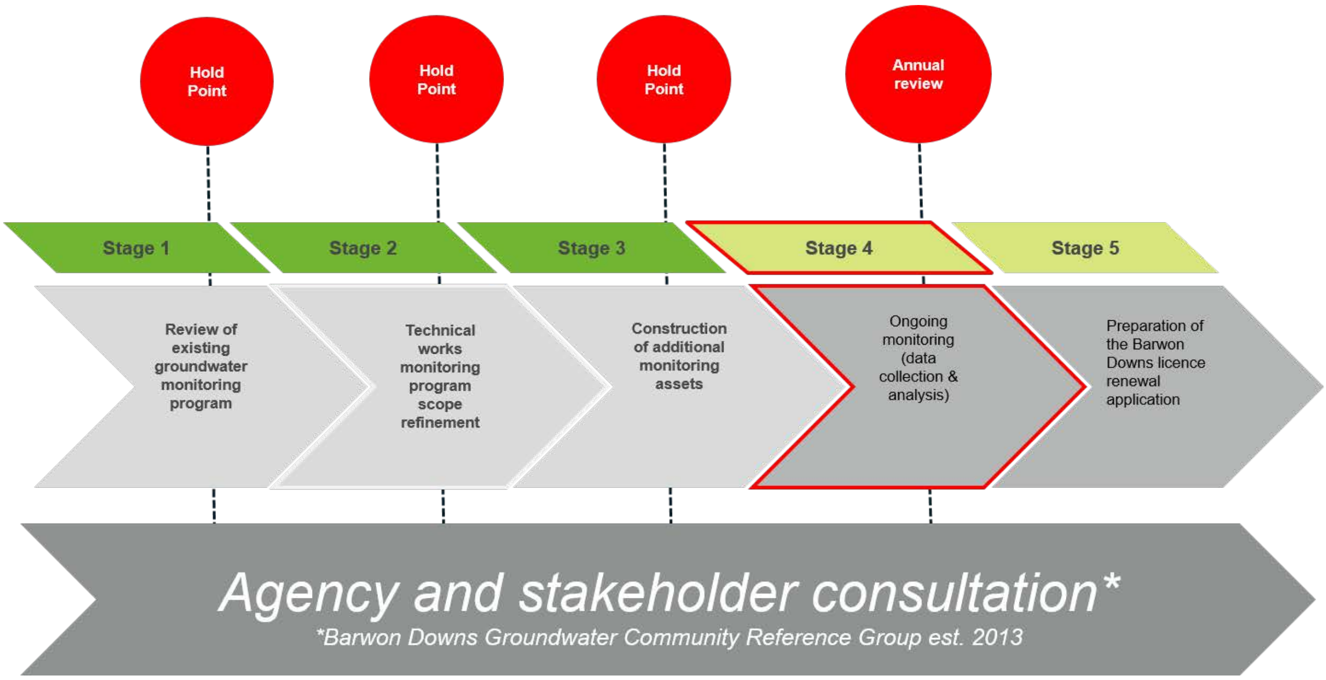
The technical works monitoring program is now in a phase of data collection and preliminary analysis. The intention of this stage is to update the conceptual understanding of the hydrogeology in the Barwon Downs region. This will be based on data collected from additional and existing monitoring assets 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

During 2018, Barwon Water will need to formally submit a licence renewal application to be 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

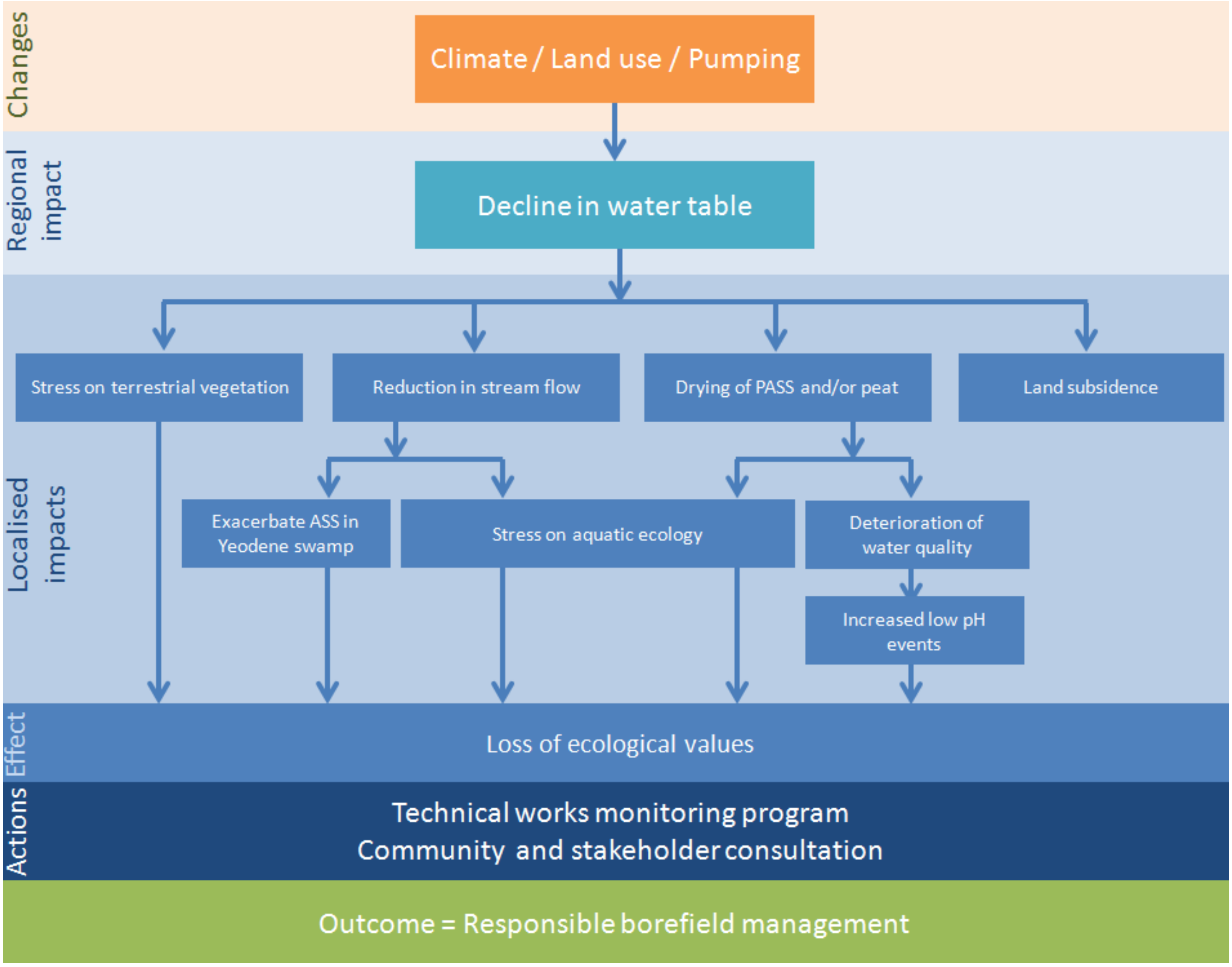
The technical works monitoring program is a complex, multi-disciplinary project due to the overlapping nature of the various components of the program as shown in Figure 1-5.

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 activate potential acid sulphate soils and cause water quality impacts.

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

1.6.1 Background and study area

The Barwon Downs borefield draws on water from the Lower Tertiary Aquifer (LTA) in Barwon Downs Graben. The LTA is principally recharged by rainfall infiltration to at the Barongarook High, a large elevated area where the LTA outcrops (Figure 1-6). Accurate estimation of groundwater recharge to the aquifer is imperative to understand and predict the changes to groundwater levels under different stresses. Changes to groundwater levels have the potential to influence many other receptors such as streamflow and groundwater dependent ecosystems (aquatic and terrestrial). Therefore accurate estimates of recharge will improve understanding of potential impacts as well as the calibration and certainty of the numerical model.

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. For example, Blake (1974) computed recharge at 5,340 ML/year by selecting a recharge rate of 5% of rainfall (using an annual rainfall of 890 mm/yr) but it is unclear what the percentage was based on. Conversely, Lakey and Leonard (1984) used flow net and baseflow analysis to estimate a recharge rate of 14% of rainfall to 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 critical recharge in the aquifer outcrop area.

Initial numerical modelling of the Barwon Downs Graben by Jacobs (2001) was calibrated using recharge rates 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. Subsequent modelling by Jacobs (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 overall objective of this study is to review the estimated recharge rates using independent field based methods to calculate recharge.

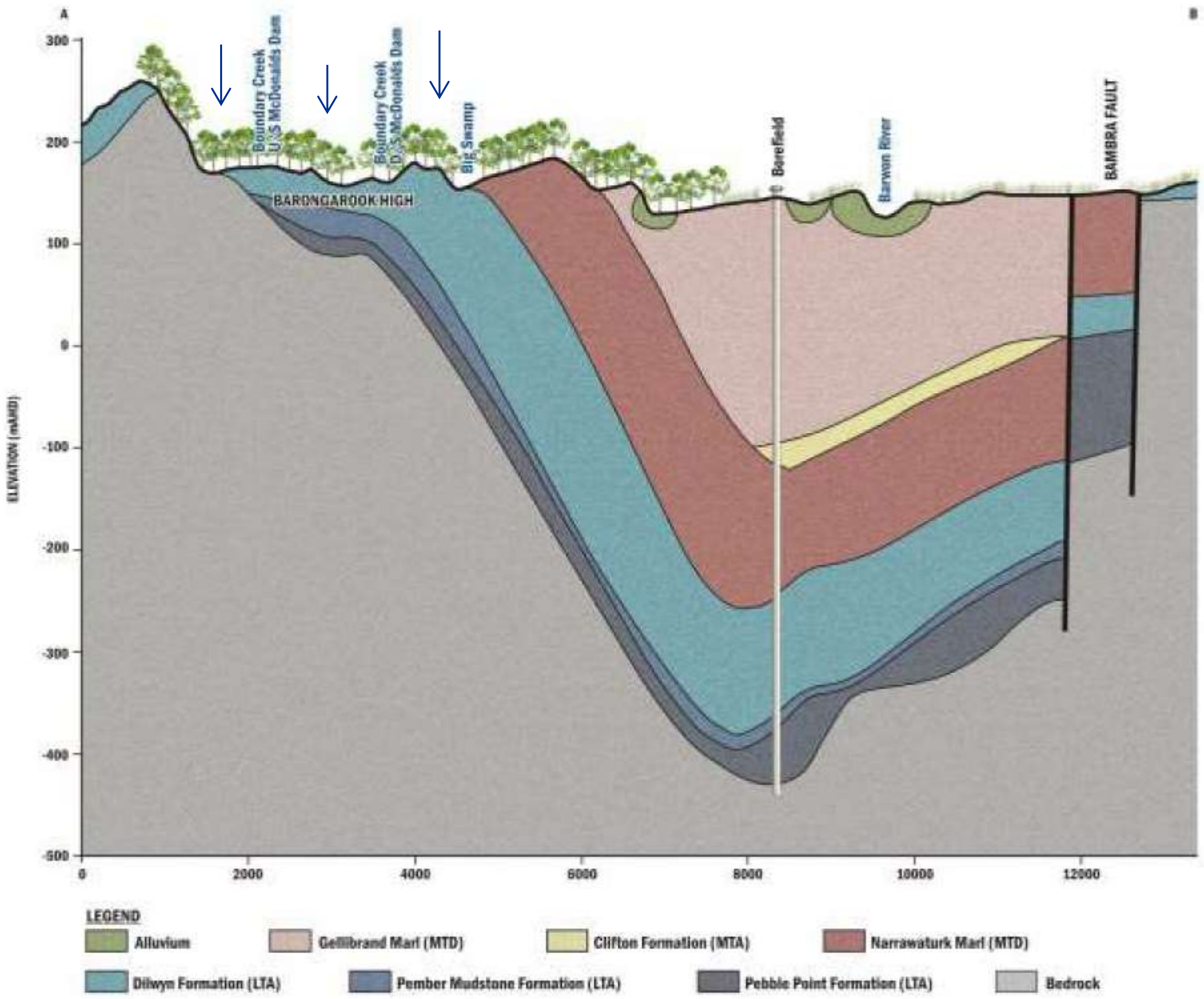


Figure 1-6 Cross section of Barwon Downs graben, illustrating Barongarook High recharge and borefield

1.6.2 Objective and scope

The objective of this study is to review the estimated recharge rates using independent field based methods to calculate recharge. This will provide input to the revised numerical model.

The study does this by combining currently available data with a field program in order to provide robust recharge estimates using a number of different approaches. By doing this, the groundwater model can be more accurately calibrated (to recharge and groundwater responses over recent decades) in order to better predict future groundwater responses under different conditions.

2. Method

2.1 Introduction to estimating recharge

Recharge is the process by which water moves downward from the ground surface, through the root zone and unsaturated zone, and finally into the saturated zone where it forms part of aquifer storage (Figure 2-1).

There are dozens of different methods or techniques available for estimating groundwater recharge. These can involve desktop based methods such as developing a water balance or modelling groundwater movement through the unsaturated zone and groundwater responses to recharge. Conversely, recharge estimates can be made by application of field based methods such as measuring vertical groundwater gradients, using seepage meters, or tracing groundwater recharge using chemical tracers such as tritium and chloride. As the spatial and temporal variability of recharge can be very high, it is important that appropriate recharge methods are selected in order to best address study objectives. These methods can often be used to complement each other, by verifying desktop based estimates using field results.

The selection of techniques for this study was based on the objective of characterising groundwater recharge to the LTA over recent decades. As such, recharge estimates for this study were calculated using the historical tracer tritium to date groundwater, and the chloride mass balance method.

These techniques were chosen for the following reasons:

(1) They characterise actual recharge to the aquifer and integrate unsaturated zone processes, reducing spatial and temporal uncertainty, and

(2) Are applicable over the time scales of interest.

Further, as demonstrated by recharge studies in Victoria (e.g. Cartwright et al., 2007), the application of multiple methods also helps to refine the conceptual model of recharge processes and reduce the uncertainty of recharge estimates. The principle behind the application of these methods is described briefly below in section 2.2 and discussed in more detail in Appendix A, Appendix B and Appendix C.

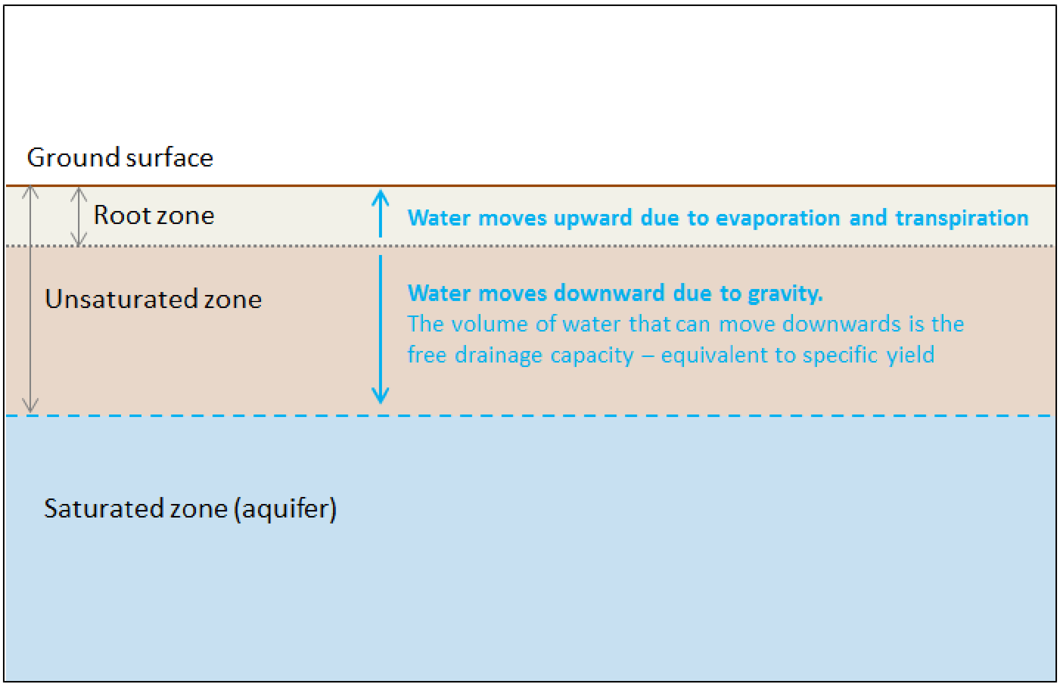


Figure 2-1 Schematic showing simplified movement of water in the unsaturated zone

2.2 Description of methods and requirements

The **tritium method** can be applied in a variety of different ways in order to estimate recharge. Principally, the method works by first estimating the age of groundwater by measuring the activity of tritium in a groundwater sample. This is possible because the activity of tritium in rainfall is well known and declines (decays) at a constant rate. Additionally, it is possible to date recharge since the 1960's by tracing a spike in tritium levels that occurred at that time. Once the age of a groundwater sample is calculated, the depth at which the sample was taken can then be used to calculate recharge rates by dividing the volume of water that has accumulated above the depth of the sample by its age. In Victoria, this method is applicable over timescales of 1 to 70 years, as tritium decays to levels below detection over this time scale. This study has used the tritium method in three different ways to estimate recharge:

- Independent method – estimates recharge on a site by site basis and requires the volume of water in the unsaturation zone above the groundwater sample depth.
- Interface method – estimates recharge to the aquifer as a whole by trying to trace the tritium spike. The volume of water in the unsaturated zone must also be accounted for using the method to accurately estimate recharge.
- Differential method – estimates recharge using two bores located close together (i.e. nested site). The strength of the differential method is that assumptions around the flow rates or volumes of water in the unsaturated zone are not required. The major assumption however is that the aquifer material and recharge processes in nearby bores are sufficiently similar that recharge rates are comparable.

The **chloride mass balance method** for estimating recharge is based on the principle that known amounts of chloride from precipitation are deposited annually to land surface. As water percolates downward, some evaporates directly or is taken up and transpired by plants. When this occurs, the concentration of chloride in the water increases because water is removed, leaving the chloride behind. This yields higher chloride concentrations in groundwater. Thus, groundwater recharge can be estimated by dividing the annual deposition of chloride by groundwater chloride concentrations. This method estimates recharge for the time and conditions when recharge occurred. As such, the recharge rates generated by this method represent that of the mean groundwater age of the sample and as such, is applicable on time scales ranging from 1 year to thousands of years (Figure 2-2 Flow chart).

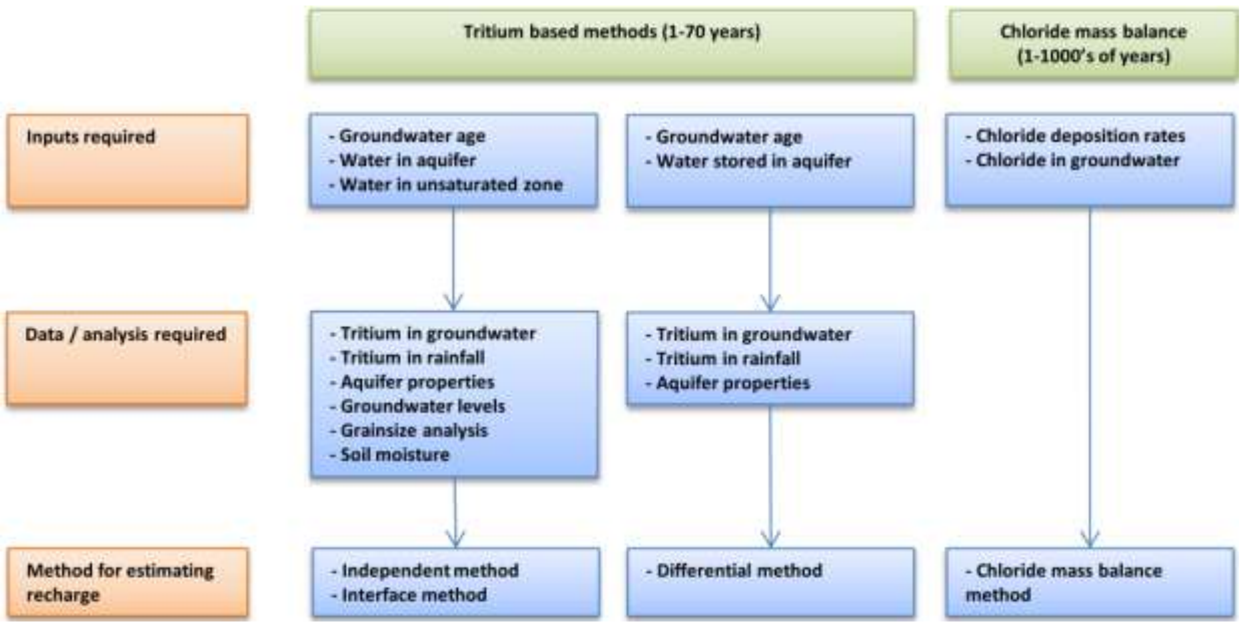


Figure 2-2 Flow chart showing methods and data requirements

2.3 Existing data

The vast majority of the data required to conduct these estimates has been compiled from previous studies or during works conducted by Jacobs in recent years, such as the Field Investigations Report (Jacobs, 2016a) and Terrestrial Vegetation Study (Jacobs, 2016b). However, groundwater sampling and analysis for tritium was required for application of the tritium based methods. A summary of the existing data and its sources has been listed in section 2.3 and sampling/analysis of tritium is described below in section 2.4.

Table 2-1 below lists available data required for estimation of recharge rates and relevant sources. The majority of data required for estimation of water stored in the unsaturated zone is available in Jacobs (2015). The rate of chloride deposition for the chloride mass balance method was available in Crosbie et al. (2012) and Jacobs (2012), while a variety of sources have compiled groundwater chloride concentrations in the LTA.

Table 2-1 Summary of existing data for calculation of recharge rates via chloride mass balance and tritium methods

Data	Source	Reference
Tritium method		
Grain size analysis	Soils cores taken via push tube sampling during terrestrial vegetation investigations	Jacobs (2016b)
Soil moisture content		
Aquifer properties (specific yield)	Measured effective porosity of Eastern View Formation	Love et al. (1993)
	Review of pump test results	Witebski (1995)
Tritium in rainfall	Recorded for Global Network for Isotopes in Precipitation database	Tadros et al. (2014)
Chloride mass balance method		
Groundwater chloride concentrations	Measured chloride in groundwater from LTA at Barongarook High	Jacobs (2016a)
	Measured chloride in groundwater from LTA in Gellibrand Catchment	Atkinson et al. (2014)
	Measured chloride in groundwater from LTA throughout Barwon Downs Graben	Petrides and Cartwright (2006)
	Measured chloride in groundwater from LTA throughout Barwon Downs Graben	Witebski (1995)
Chloride deposition	Regional scale mapping of chloride deposition rates	Crosbie et al. (2012)
	Local scale chloride concentrations in rainfall	SKM (2012)

2.4 Groundwater sampling and analysis

As indicated above, sampling and analysis for tritium in groundwater presented the only data gap required for estimation of recharge for application of the method. Bores were selected in an attempt to use as many samples as possible during the application of the tritium method. Sampling occurred at both established bores and those installed as part of the 2014/15 monitoring program upgrade (Jacobs, 2016). The location of the bores sampled across the Barongarook High where the LTA outcrops is illustrated in Figure 2-3 and include TB1a, TB2b, TB4b, TB6, TB7, TB14, 47996, 48001, 109130, 109136, 109140. Further details regarding sampling program development is described in Appendix D.

Bores were sampled between the 9th and 11th of December, 2015, using a high flow 12V electrical pump that was lowered to the screened section of the bore during sampling. For high yielding bores, greater than 3 bore volumes were removed prior to sample collection. For low yielding bores, the bore was purged until dry, then allowed to recover and sampled using a hand bailer. Water level data and field water quality parameters were taken during sample collection and are included in Appendix E.

Tritium was analysed with ultra-low detection limits at the Australian Nuclear Science and Technology Organisation (ANSTO) laboratories. Samples were distilled before electrolytic concentration and analysis by liquid scintillation. Further detail regarding the analytical procedure is detailed in Appendix F.

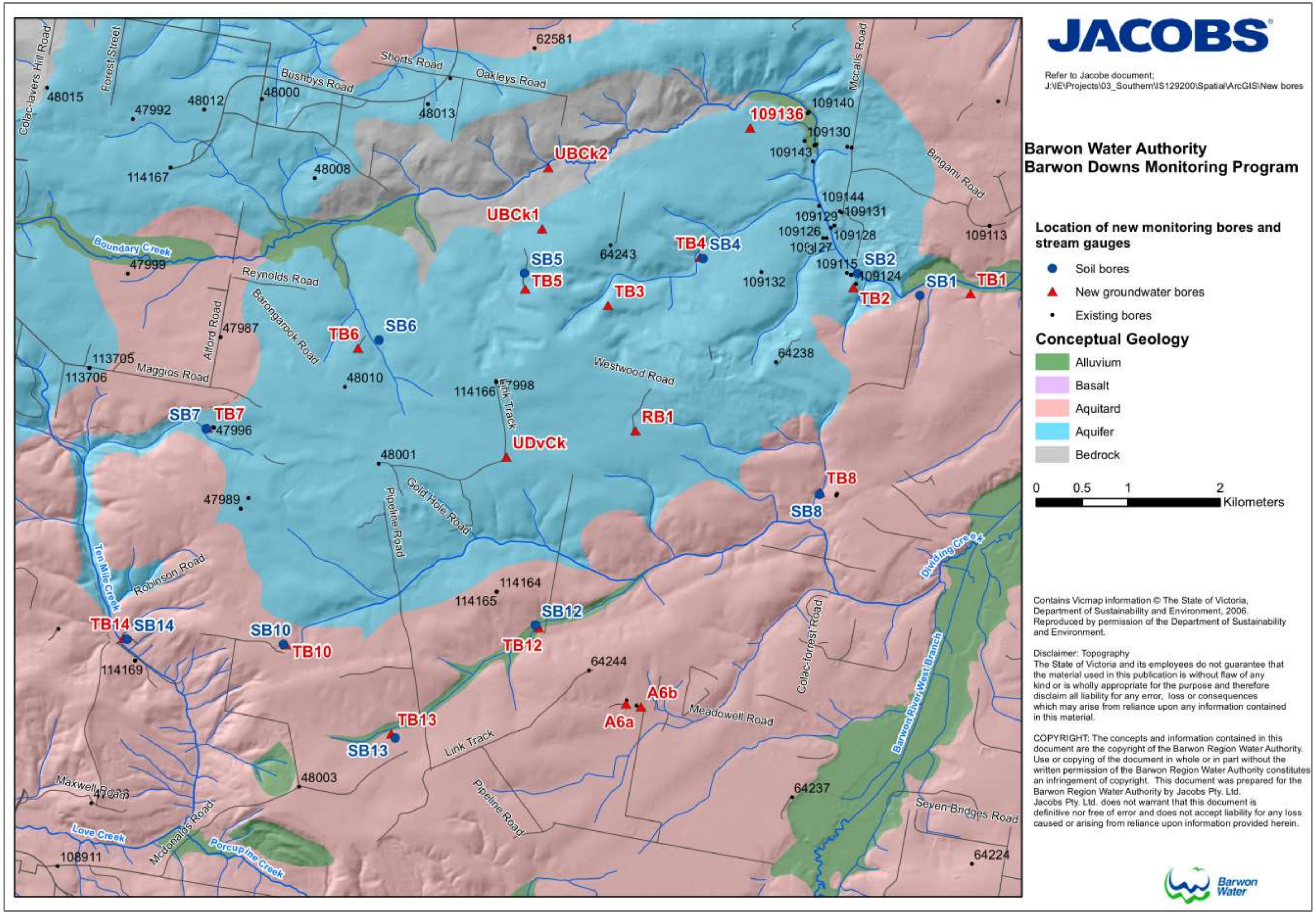


Figure 2-3 : Study location and outcropping geology. Barongarook High is the large outcropping area of LTA

3. Results

3.1 Tritium activities and age estimates

The activity of tritium in each sample has been summarised in Table 3-1 below. The age of the each sample has subsequently been estimated based on known tritium inputs from rainfall and the decay rate of tritium. The key assumption in this calculation is that groundwater movement in the aquifer is dominantly vertical and that little mixing has occurred. This is a reasonable assumption in this setting as the sampling program targeted relatively shallow bores within outcropping LTA receiving recharge. The age estimates have been provided in Table 3-1 and further details regarding age calculations are provided in Appendix A.

Table 3-1 Summary tritium activities and ages

Bore ID	Date sampled	Tritium Activity (TU)	Uncertainty in tritium activity (TU)	Age (years)	Screen centre (mbgl)	Comment on setting
TB1a	9/12/2015	0.01[1]	0.02	>70	10.2	Shallow bore, groundwater discharge site
TB2b	10/12/2015	2.14	0.1	2	5.2	Shallow bore, preferential recharge site
TB4b	11/12/2015	1.97	0.09	2.5	5.7	Shallow bore, preferential recharge site
TB6	10/12/2015	0.51	0.04	26	19.4	Groundwater recharge site
TB7	10/12/2015	0.74	0.04	20	6.7	Groundwater recharge site
TB14	10/12/2015	0.01[1]	0.02	>70	10.0	Shallow bore, groundwater discharge site
47996	10/12/2015	0.01[1]	0.02	>70	30.0	Deep bore, slow recharge rate
48001	10/12/2015	0.32	0.03	55	37.8	Groundwater recharge site
109130	11/12/2015	0.83	0.05	18	11.8	Groundwater recharge site
109136	11/12/2015	0.01[1]	0.02	>70	32.5	Deep bore, slow recharge rate
109140	11/12/2015	0.93	0.05	16	8.5	Groundwater recharge site

[1] Tritium activities are below detection

Tritium activities in groundwater at TB1a and TB14 are below the detection level of 0.05 tritium units (TU). Accordingly, groundwater sampled from these bores is estimated to be greater than 70 years in age. Given that these bores are shallow (screen depth of TB1a and TB14 is between 8 and 12 m), it is unlikely that these sites are dominated by recharge. Recharge rates of around 15 mm/year or less (<2% of rainfall) would be necessary to allow complete decay of tritium during vertical infiltration. Further, in reviewing the hydrogeological setting of these bores, both are located near drainage lines in topographic lows. This suggests that these bores are near groundwater discharge points and are not suitable for calculation of recharge rates.

Bores 47996 and 109136 also have tritium levels below detection limits, again indicating groundwater greater than 70 years in age. Both of these bores are screened at relatively deep intervals (28-44 m bgl), suggesting that the vertical infiltration of precipitation takes longer than 70 years to migrate over that distance.

Groundwater from bores TB6, TB7, 48001, 109130 and 109140 contain tritium activities ranging from 0.32 to 0.93 TU, inferring ages between 16 and 55 years. Given the screen depths ranging from 5.2 to 33.0 m, these results are within the range that would be expected for sites dominated by groundwater recharge.

Groundwater from TB2b and TB4b had relatively high tritium activities, ranging from 1.97 to 2.14 TU, indicating recharge within the last three years. These bores were installed along drainage lines that appear to be losing surface water to groundwater. Water flow in these areas is ephemeral and is only observed after high rainfall periods. Furthermore, the upper stratigraphy at these locations is dominated by alluvial material with a relatively high hydraulic conductivity. Given this, it is likely that these results reflect preferential groundwater recharge zones, where recharge rates are higher than the majority of the LTA.

3.2 Recharge rate estimates using groundwater age

Groundwater age can be used in a variety of ways to provide an estimate of groundwater recharge rates. This section provides such estimates according to three methods (the independent, differential and interface methods). Each of these methods has different strengths and weaknesses according to the relative assumptions inherent in each method. By applying a number of different methods, a range of likely recharge rates can be estimated. Further details and calculations describing the production of these results are presented in Appendix A to Appendix C.

3.2.1 Independent estimates

The recharge rates calculated at each site using the independent method are detailed in Table 3-2 below. This details the relative proportions of water in the saturated zone and unsaturated zone and the resulting range of potential recharge rates.

The results indicate that recharge rates generally range from 26 to 95 mm/year and are broadly consistent across the data set. The exception to this is bores TB2b and TB4b which are located in preferential recharge zones and yield recharge rates ranging from 132 to 195 mm/year. As discussed in section 3.1, as these sites are located along drainage lines these sites are likely to represent zones where recharge rates are higher than the majority of the LTA. A visual analysis of the Barongarook High undertaken using ArcGIS mapping suggests that such drainage lines may represent up to 5% of the total outcrop area. This needs to be accounted for during accurate estimation of recharge rates to the LTA as a whole.

In contrast to these bores, TB7 reflects the lowest recharge rates in the study, ranging from 26 to 40 mm/year. This may be attributed to greater vegetation density at the site which commonly reduces recharge rates. Bores 47996 and 109136 (with no detectable tritium) are likely to have received rainfall recharge over 70 years ago. While estimates below are based on an age of 70 years, resulting in rates ranging from 57-93 mm/year, these rates are likely to be upper estimates as the groundwater may be older than this at these sites.

Excluding the significantly higher recharge rates form TB2b and TB4b from the data set, the independent method presents an overall average recharge rate of 61±20 mm/year, or 8.1% of the annual rainfall. This increases to 67 mm/year or 8.9% of rainfall once preferential recharge pathways that represent around 5% of the outcrop area are accounted for.

Table 3-2 Recharge rate estimates at each site for independent estimates

ID	Age estimate (years)	Volume in aquifer		Volume unsaturated zone (mm)	Recharge rate	
		mm (Sy = 0.15)	mm (Sy = 0.25)		mm/year (Sy = 0.15)	mm/year (Sy = 0.25)
TB1a	>70	1,178	1,963	0	n/a	n/a
TB2b	2.0	37	61	289	163	175
TB4b	2.5	237	395	94	132	195
TB6	25.9	221	369	1,341	60	66
TB7	20.0	444	740	67	26	40
TB14	>70	1,151	1,918	0	n/a	n/a
47996	>70	1,854	3,090	2,020	70	93
48001	55.0	3,963	6,605	52	57	95
109130	17.8	376	626	674	59	73
109136	>70	2,529	4,215	1,453	57	81
109140	16.0	184	306	410	37	45

Sy = specific yield which is thought to range between 0.15 and 0.25 in the Dilwyn Formation

3.2.2 Differential age estimates

As outlined in section 2.2, recharge rates can be estimated if the groundwater age is known for two nearby bores screened at different depths. For the bores sampled during this study, three sites were close enough to be defined as suitable locations:

- Area 1 between bores TB7 and 47996;
- Area 2 between bores 109130 and 109136; and
- Area 3 between bores 109140 and 109136.

The recharge rates estimated using this method are listed in Table 3-3 below. It should be noted that as the deeper bores in these areas were void of detectable tritium, which means groundwater is at least 70 years old, and could be older. Given this, the recharge rates presented are likely to represent upper limits, as the difference in ages used will also reflect the minimum possible.

The results Table 3-3 indicate recharge rates ranging from 66 to 156 mm a year with an average recharge rate of 104±33 mm/year, or 14% of rainfall. While these estimates are higher than those calculated independently, this is because these results are more likely to represent a maximum potential recharge rate while independent estimates are more likely to represent a best estimate.

Table 3-3 Recharge rate estimates using nested (nearby) bores for the differential method

Area	Age difference (years)	Volume difference		Recharge rates	
		mm (Sy = 0.15)	mm (Sy = 0.25)	mm /year (Sy = 0.15)	mm/year (Sy = 0.25)
1	50.0	4,665	7,775	93	156
2	52.2	3,451	5,751	66	110
3	54.0	4,084	6,806	76	126

3.2.3 Interface estimates

Recharge estimates using the interface method are presented in Table 3-4. While the exact depth of the tritium spike was not identified, the data set suggests it occurs at around 24 to 29 m below ground surface (Appendix B).

The results suggest that groundwater recharge to the LTA as a whole may range from 58 to 114 mm/year. This equates to an average of 84±24 mm/year or 11% of the annual rainfall to the area. This is consistent with estimates given by the independent estimates.

Table 3-4 Recharge rate estimates using the interface method

Depth of peak (m bgl)	Volume mm (Sy = 0.15)	Volume mm (Sy = 0.25)	Recharge rate	
			(mm/year) (Sy = 0.15)	(mm/year) (Sy = 0.25)
24	2,730	4,130	58	88
29	3,480	5,380	74	114

Sy = specific yield which is thought to range between 0.15 and 0.25 in the Dilwyn Formation

3.3 Recharge rates using chloride mass balance

Groundwater recharge rates were estimated via chloride mass-balance based on the method outlined in Section 2.2 and detailed in Appendix C. The results are presented in Table 3-5 below and suggest recharge rates between 25 and 65 mm/yr.

Groundwater chloride results were collated from four separate studies and used to estimate recharge rates. Of these results, the groundwater recharge rates estimated using the groundwater chloride concentrations presented in Witebsky (1995) are likely to provide the best recharge estimate. This is because the study incorporates the greatest number of bores for estimation of groundwater chloride concentrations throughout the LTA. This is important because local processes can impact groundwater chloride concentrations greatly, resulting in high variability in groundwater chloride concentrations throughout a groundwater catchment.

Based on this, the results in Table 3-5 suggest that the best groundwater recharge estimated by chloride mass balance is 41 mm/year, reflecting 5.4% of annual recharge to the Barongarook High. These estimates are lower than those estimated using tritium because they represent recharge rates averaged over a longer period than tritium results. The presence of tritium in the groundwater can date the age of groundwater within the last 50 to 70 years, whereas the chloride concentration provides an estimate of the recharge rate under the conditions and timing under which recharge occurred. The majority of bores for which chloride data exists are deep bores located closer to the borefield and are likely to contain water that is thousands of years in age (Atkinson et al., 2014). As such, it is likely that these lower rates reflect historic recharge prior to vegetation clearing, when vegetation may have consumed a higher proportion of rainfall.

Table 3-5 Recharge rates estimated from chloride mass balance

Data set	Groundwater Chloride (mg/L)	Groundwater Recharge (mm/yr)	Groundwater Recharge (% rainfall)
Witebsky (1995)	80	41	5.4
Petrides and Cartwright (2006)	130	25	3.3
Atkinson (2014)	50	65	8.7
Jacobs (2014-2016)	170	19	2.5

3.4 Summary of results

Based on the above results and analysis:

- Estimates at each bore using the independent method indicates recharge of around 61±20 mm/year or 8.1% of the annual rainfall. This increases to 67 mm/year or 8.9% of rainfall if preferential recharge pathways representing around 5% of the outcrop area are accounted for.
- Estimates using the differential method indicates recharge rates ranging from 66 to 156 mm a year with an average recharge rate of 104±33 mm/year, or 14% of rainfall. This is considered to be an upper estimate.
- Estimates using the interface method suggest groundwater recharge rates to the LTA ranging from 58 to 114 mm/year. This equates to an average of 84±24 mm/year or 11% of the annual rainfall to the area.
- Estimates using the chloride mass balance approach suggest recharge rates of 41 mm/yr or 5.4 % of the annual rainfall to the area. However, this is more likely to represent historic conditions prior to any land clearing.

These results suggest that that best representation of current/modern recharge to the LTA of the Barongarook High are derived from the application of the independent and interface methods. This suggests that modern recharge rates are most likely to reflect around 9 to 11% of the average annual recharge at the high.

These estimates have significantly improved our understanding of recharge to the Barongarook High. Previous modelling of the system was calibrated with a recharge rate of greater than 20% of rainfall in some places. These results suggest that areal average recharge to the LTA is more likely to be closer to 10% and unlikely to exceed 14%.

4. Conclusions and Recommendations

4.1 Conclusions

This report provides a series of recharge rate estimates for the major aquifer supplying the Barwon Downs Borefield (the Lower Tertiary Aquifer) where it outcrops at the Barongarook High area.

Groundwater recharge rates to the LTA were estimated using both age based methods and chloride mass balance methods. While the results indicate local variability in recharge rates, the best estimates given by each method have generally good agreement. The estimates are summarised in Table 4-1.

Table 4-1 Groundwater recharge rates to the LTA estimated from various methods

Method	Average annual recharge rate (mm/year)	Recharge rate as a percentage of rainfall
Age dating: independent method	67 ± 20	8.9%
Age dating: differential method (1)	104 ± 33	14%
Age dating: interface method	84 ± 24	11%
Chloride mass balance method	41	5.5%

(1) Result from differential method is considered an upper estimate as groundwater from deeper bores was assumed to be 70 years old, but may in fact be older

The average groundwater recharge rate to the LTA at the Barongarook High given by the independent and interface age estimates ranged between 67 and 84 mm/year, these are considered the best estimate of recharge and reflect between 8.9 and 11% of the long term mean annual rainfall for the area.

The average recharge rate determined by comparison of nearby bores was 104 ± 33 mm/year or 14% of rainfall. This is considered likely to represent an upper recharge estimate

The recharge estimated using the chloride mass balance method was 41 mm/yr or 5.5% or rainfall. This is likely to represent historical recharge prior to any land use change in the area.

The results presented in this study suggest the rainfall recharge to the LTA at the Barongarook High is most likely to represent between 8.9 and 11% of rainfall to the area. While rates may be higher in areas of preferential recharge, it is unlikely that recharge to the Barongarook High as a whole will exceed 14% of rainfall.

4.2 Recommendations

The study has highlighted that the annual average recharge rates to the Lower Tertiary Aquifer across the Barongarook High are likely to be around 10% of rainfall, and unlikely to exceed 14% of rainfall. We recommend that these values be used as a starting point for recharge rates in the updated groundwater model.

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Appendix A. Detailed methodology for age estimates

A.1 Background

Groundwater age was estimated by measuring the levels of the isotope tritium in the groundwater. Tritium (^3H) is a radioactive isotope of hydrogen that naturally forms part of water molecules in the atmosphere during their interaction with cosmic rays. Once water vapour in the upper atmosphere forms precipitation and falls to the ground, it is removed from sources of significant atmospheric tritium inputs. When this occurs, the activity of tritium in water droplets begins to decrease as the tritium decays with a half-life of 12.32 years (Lucas and Unterweger, 2000).

As the activity of tritium in rainfall is well known over the past 60 years and its radioactivity declines at a constant rate, it is possible to calculate the time at which groundwater entered an aquifer by measuring its tritium activity. Tritium has a relatively short half-life, so activities tend to fall below detection over decades, limiting its use to the last century (USGS, 2000).

Additional tritium was released into the atmosphere between 1952 and 1963 as a result of nuclear weapons testing, causing what is known as the “bomb pulse” (Figure A.1). The level, or activity of tritium in modern rainfall is relatively well known and robust records of tritium activities in Australian rainfall have been collated (e.g. Tardos et al., 2014).

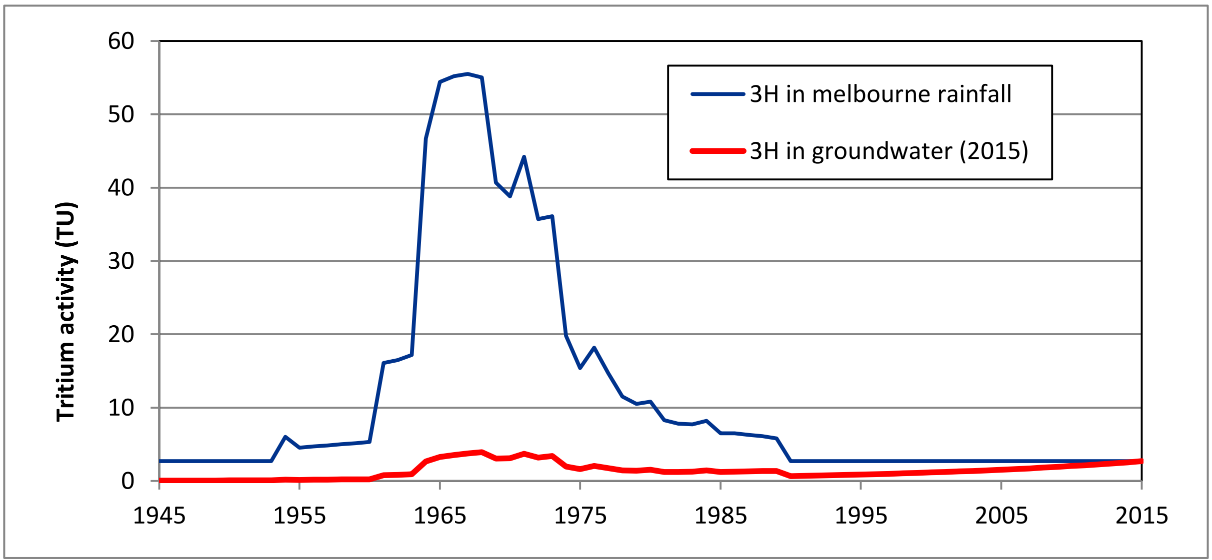

Figure A.1 : Activity in Melbourne rainfall and example (expected) groundwater in year 2015 (see appendix B) (International Atomic Energy Association, 2015; Tadros et al., 2014)

Elevated tritium levels from nuclear weapons testing have resulted in an ambiguity of ages before and after the bomb pulse. As such, an understanding of the hydrogeological system in question (i.e. flow directions, likely recharge rates) must be coupled with potential ages to estimate recharge that has occurred within the last ~50 years. This ambiguity can be reduced by combining tritium recharge estimates with other (often less quantitative) methods.

A.2 Application in this study

Groundwater age estimates require estimation of the input of tritium from rainfall. An activity of 2.7 TU has been used for modern (post 1989) and pre-bomb pulse rainfall based on the tritium activity of rainfall measured at Monash University (Atkinson et al., 2014) and that expected in Southern Victoria (Tadros et al., 2014). The mean weighted average of tritium activities in Melbourne precipitation was extracted from the International Atomic Energy Agency (IAEA) Melbourne record for the interim years.

When considering the age (or tritium activity) of groundwater sampled from a well, there is potential for a sample to consist of many parcels of water with different ages and recharge histories. This is because a well can be screened across several meters which intercept various groundwater flow paths (Jurgens et al., 2012). Moreover, dispersion and mixing in heterogeneous aquifers can lead to broad distributions of ages, even in wells with short screen intervals (Weissmann and others, 2002).

Such groundwater flow systems can be described by terms including piston flow, exponential mixing, exponential-piston flow, partial exponential flow and dispersion. Piston flow describes groundwater that enters a system and moves to a discharge point with little mixing or dispersion (Figure A.2a). In contrast, exponential mixing describes water that mixes exponentially with increasing depth below the water table (Figure A.2b). As the sampling program for this study was designed to target relatively shallow bores within an outcropping area of the LTA receiving recharge (Figure A.2c), piston flow is likely to provide the best description of the groundwater flow regime in this setting.

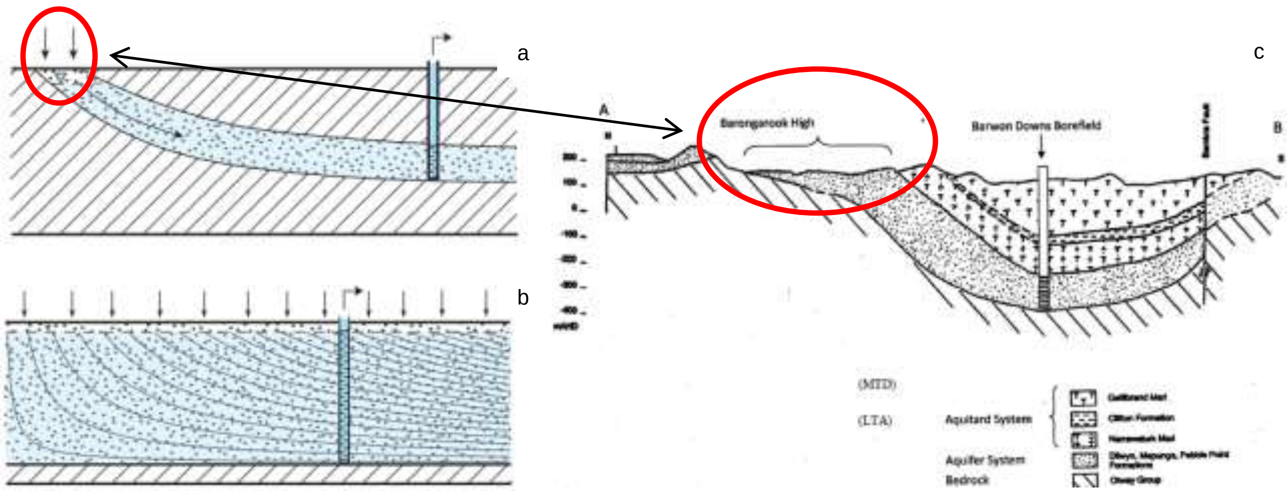

Figure A.2 : Schematic representation of piston flow (a) exponential mixing (b) and cross section of field area (c). Flow schematics after Jurgens et al., 2012.

In order to check the validity of this assumption on the data set, the expected activity of tritium in groundwater recharge in 2015 resulting from only decay (i.e. no mixing) was plotted against the measured tritium activity and depth of collection on a secondary y axis (this assumes vertical downward movement of recharge - Figure A.3). The secondary y axis was then iterated to yield the lowest average tritium deviation from the expected trend. Samples collected from TB1a and TB14 have not been plotted in this figure as they are near drainage lines and sites of upward hydraulic gradient, suggesting groundwater discharge zones and not zones of groundwater recharge. The remainder of the groundwater samples provide a relatively good fit with the anticipated trend, yielding an average difference of only 0.2 TU. This suggests that piston flow is a reasonable description of groundwater flow in this area.

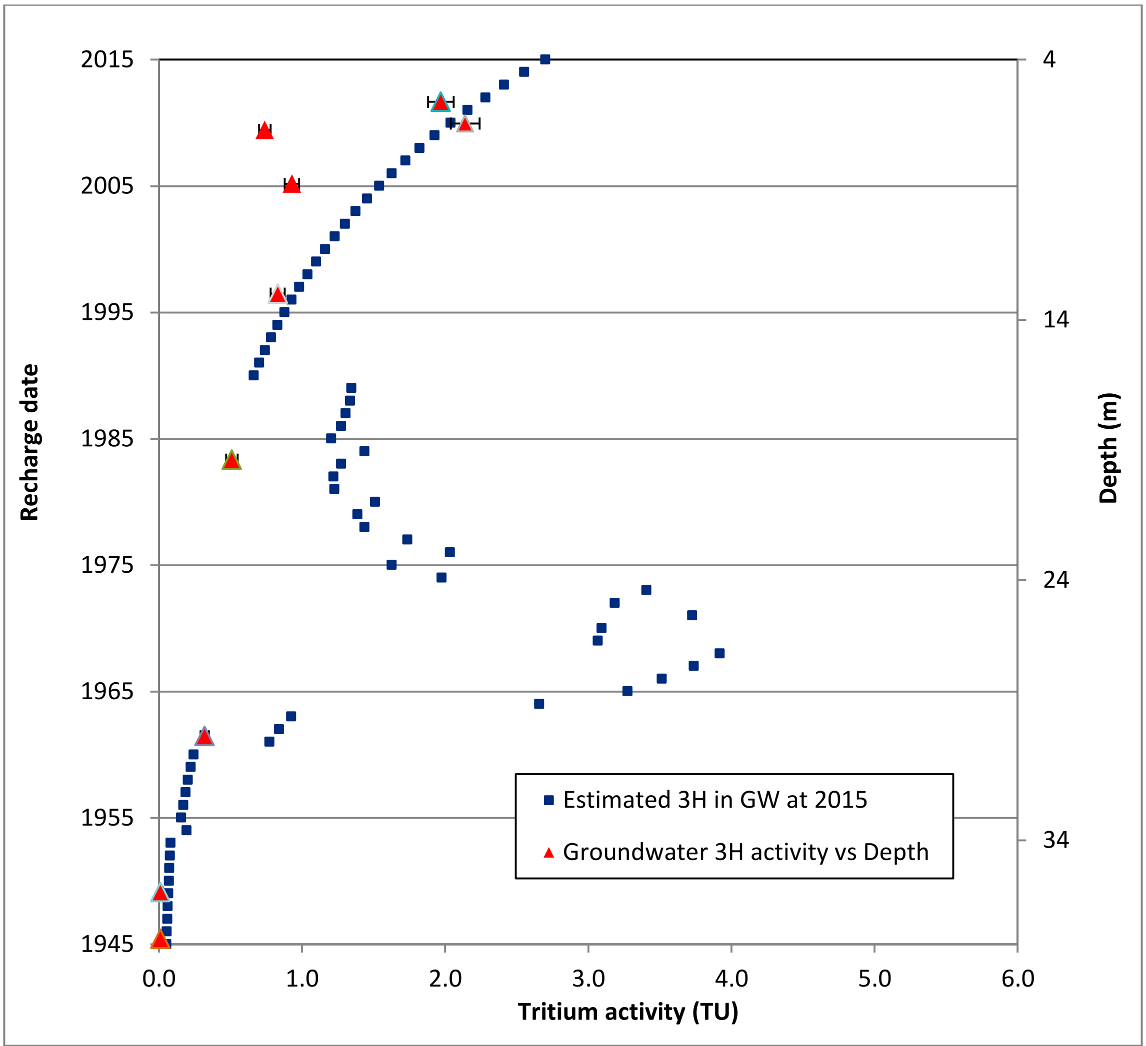

Figure A.3 : Expected tritium activity of groundwater over time assuming only decay and recorded tritium groundwater tritium activity with depth.

Under this assumption, groundwater ages can be estimated by using the piston flow setting within the TracerLPM interactive excel workbook (Jurgens et al., 2012). This uses a mathematical model of transport based on piston flow as described by equation (1):

$$C_{out}(t) = C_{in}(t - \tau_s)e^{(-\lambda - \tau_s)} \quad \textbf{(1)}$$

where C_{out} is the groundwater tritium activity, C_{in} is the concentration of tritium in rainfall at a given time, t is the sample date, λ is the decay constant for tritium and t_s is the mean age of the water sample.

Appendix B. Detailed methodology for calculating groundwater recharge using age

Once the age of groundwater samples have been estimated, recharge rates can be estimated via a number of ways, including:

- Independently: Estimating recharge at each sample location by dividing the volume of water that has accumulated in the aquifer at each site by the age of each sample.
- Interface method: Estimating recharge to the whole aquifer by locating the depth of the tritium spike (or bomb pulse) and dividing the volume of water that has accumulated in the aquifer by the age of the spike.
- Differential method: Estimating recharge by calculating the volume of water in an aquifer section using two nearby bores.

Each of these variations in method have been described in further detail below.

B.1.1 Independent estimate of groundwater age

The recharge rate at each sample location (as a volume per unit time) will be equal to the volume of water residing in the stratigraphic column above the sample depth, divided by the time it took to accumulate (the sample age). When the water table is close to the surface, the volume of water can simply be calculated by multiplying the saturated aquifer thickness above the sample by the effective porosity of the aquifer. This is described mathematically by equation (2) below (McMahon et al., 2011),

$$R = (n \times Z) / t \qquad (2)$$

where R is the recharge rate, n is the effective porosity, Z is the saturated aquifer thickness above the sample point and t is the sample age. For the purpose of this assessment the effective porosity is considered to be equivalent to specific yield. From here on the report will refer to the specific yield. Therefore to calculate the recharge rate at a sample depth, the saturated thickness of the aquifer above the sample depth is multiplied by the specific yield and this number is divided by the sample age as determined by the tritium activity level.

The specific yield using in this study was based on grain size analysis of the soil cores (Jacobs, 2015) and literature derived values presented by Witebski et al. (1995) and Love et al. (1993). The soil cores indicate material that consists of sandy clays to sands with effective porosities of 0.13 to 0.24. Literature values indicate that specific yields (Sy) ranging from 0.10 to 0.20 are appropriate for the Dilwyn formation. Given the above, estimates for this study were based on a range of 0.15 to 0.25.

Independent estimates focus on dating groundwater within a metre or two of a shallow water table. By doing so, it is very unlikely that tritium activities will be influenced by the “bomb pulse” (which should have penetrated deeper groundwater) and therefore, exhibit a unique, recent age.

As mentioned above, if the water table is sufficiently close to the ground surface, then the water stored above the water table (in the unsaturated zone) will be negligible. However, the thickness of the unsaturated zone is not negligible for a number of the bores sampled during this study. As such, the volume of water stored in the unsaturated zone should also be accounted for. This process has been documented in Appendix I.

B.1.2 Differential estimates of groundwater age

The differential dating method involves dating the water from two different depths at the same or nearby locations. By estimating the volume of water that resides between the two depths and the time it took to accumulate, it is possible to estimate the average recharge rate over that period.

For this method, the recharge rate is simply the volume of water in the saturated zone of the aquifer defined by the difference in sample depths divided by the difference in age as described by equation (3) below:

$$R = [(D_1-D_2) \times n] / (t_1-t_2) \qquad (3)$$

Where D_1 and D_2 represent the depths of the two bores and t_1 and t_2 represent the age of groundwater sampled form the two different bores. The strength of this method is that assumptions around the flow rates or volumes of water in the unsaturated zone are not required. The major assumption is that the aquifer material and recharge processes in nearby bores are sufficiently similar that recharge rates will be comparable.

B.1.3 Identification of the bomb pulse “interface”

The “interface method” aims to integrate the entire tritium data set to build an understanding of recharge to the aquifer as a whole. This is done by plotting groundwater tritium activities against depth to try and identify the depth at which the bomb peak occurred. As it is known that the peak occurred in the late 1960s, a recharge rate for the entire aquifer can be estimated based on some assumptions around the typical conditions of the aquifer.

Tritium activities in groundwater samples have been plotted against sample depth in Figure B.1 below along with an idealised trend of tritium activities in groundwater with age (depth) based on inputs from rainfall and decay. While the data do not identify the bomb pulse itself, it suggests that bomb pulse recharge may occur between 24-29 m bgl.

Based on the data collected in the field, the average water level is 9.2 m bgl. For simplification, a depth to water table of 10 m bgl has been used for this calculation. As with the independent method, the volume of water in the saturated zone is based on a range in Sy of 0.15 to 0.25, and the volume of water in the unsaturated zone calculated following Appendix I.

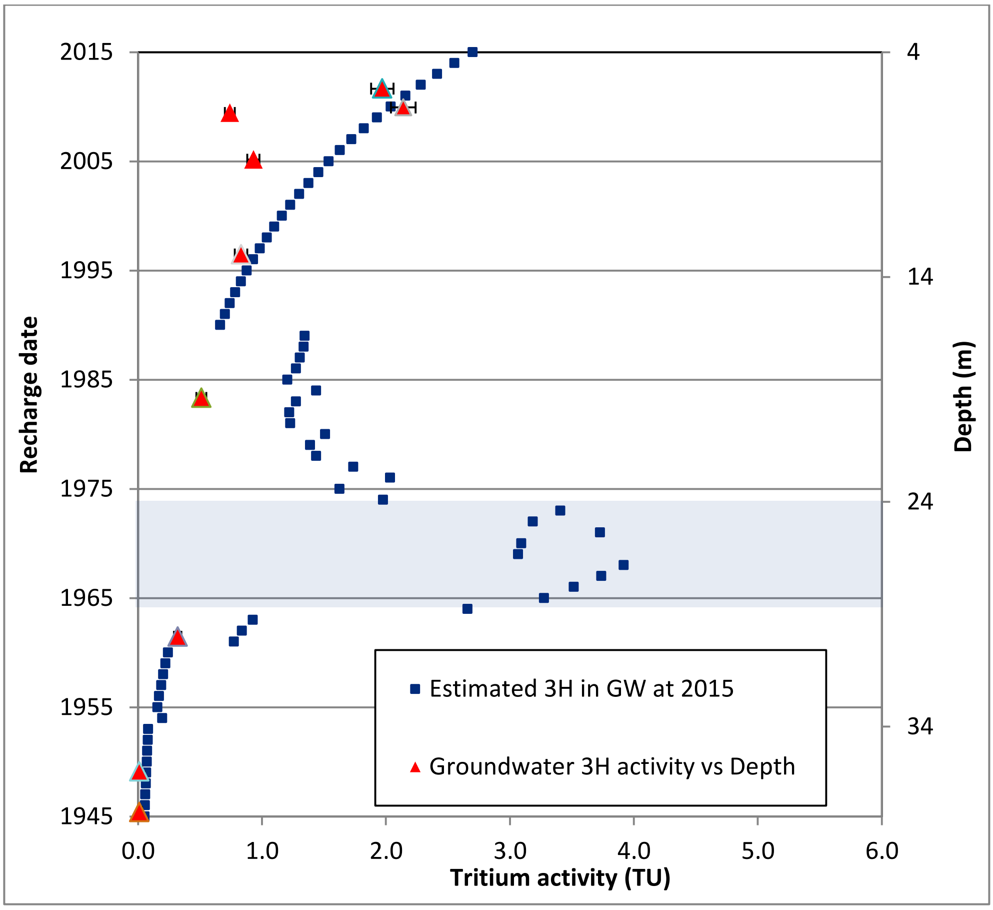

Figure B.1 : Expected tritium activity of groundwater over time assuming only decay and recorded tritium groundwater tritium activity with depth – location of tritium spike highlighted.

Appendix C. Detailed methodology of chloride mass balance methodology

The chloride mass-balance method was used as another means of estimating recharge in the study area that did not rely on groundwater age estimates. It is recommended practice to use multiple methods for assessing groundwater recharge, as each method operates on a particular temporal and spatial scale and imbedded within each method are assumptions which are usually not fully met (Scanlon et al. 2002 and Healy, 2010). As such, checking one method against another can be a means of identifying any significant errors or poor assumptions.

C.1 Method and assumptions

The chloride mass balance method for estimating recharge is based on the principle that known amounts of chloride in precipitation and dry atmospheric deposition are transported to the watertable by the downward flow of water. As water percolates downward, some evaporates directly or is taken up and transpired by plants. When this occurs, the concentration of chloride in soil water increases because water is removed from the soil, leaving the chloride behind. This tends to yield increasing chloride concentrations with depth as evaporation and transpiration continue to affect the downward percolating water. At greater depths however, where evapotranspiration does not occur, the chloride concentration should be uniform if climate, soil, and other conditions near the surface have been steady for a sufficiently long time.

The chloride mass-balance method uses the assumption that precipitation is the only source of chloride in groundwater and in surface-water runoff. Other common sources of chloride in the groundwater are unlikely to impact on the chloride concentrations in the recharge area in the vicinity of the Barongarook High, which is located in a rural area. Human sources such as septic systems and animal sources such as cow manure are likely to contribute minimal amounts of chloride as there is only a small amount of open pasture and very limited number of houses. Natural sources such as evaporite rock dissolution are not present in the study area (Jacobs, 2016; Atkinson et al., 2014).

A mass balance of chloride in precipitation, surface runoff, and groundwater is expressed in the following equation (Maurer et al, 1996; Prych, 1998):

$$P \times C_p = (GWR \times C_g) + (SWR \times C_p) \quad \textbf{(4)}$$

where

- P is annual rainfall, in mm;
- Cp is concentration of chloride in precipitation, in mg per litre;
- GWR is annual groundwater recharge, in mm;
- Cg is concentration of chloride in groundwater; and
- SWR is annual surface-water runoff, in mm.

Rearranging the terms in equation 2 and solving for groundwater recharge gives:

$$GWR = [(P \times C_p) - (SWR \times C_p)] / C_g \quad \textbf{(5)}$$

Implicit in this equation is the assumption of piston flow which assumes that (after USGS, 2002):

1) The direction of water flow and chloride transport is vertical and downward.
2) Areal distributions of the rate of percolation of water and of chloride on the local scale (a few tenths of a metre) are uniform (i.e. no preferred pathways).
3) All chloride is dissolved in soil water, and the distribution of the dissolved chloride in the soil water is relatively uniform within a pore (i.e. no solid chloride phase, sorption by soil or anion exclusion).
4) Advection is the dominant mode of chloride transport, and dispersion is relatively unimportant.
5) Minerals in the soil are not a source of chloride – the only sources are precipitation and dry atmospheric deposition.
6) Measured chloride concentrations are at depths great enough that seasonal variations in concentration are small.
7) Chloride concentrations in surface-water runoff are the same as those in precipitation.

The method is still valid if chloride is taken up by growing vegetation as long as it is also released by decaying vegetation at the same rate. For the assessment undertaken here, it is also implicit that recharge to the LTA is dominated by recharge at the Barongarook High, where it outcrops.

C.2 Inputs

The inputs to the mass balance equation were obtained from:

- *Chloride deposition rates*: a rate of 5.0 mg/L was adopted as obtained from rainfall sampling by SKM (2012) in the nearby Gellibrand catchment. This is a reasonable estimate as an intermediate between the rate for Melbourne rainfall (5.4 mg/L) estimated by CSIRO (Crosbie et al., 2012) and that interpolated for this area (4.4 mg/L) as part of Australia wide chloride deposition mapping by the CSIRO (Davies and Crosbie, 2014).
- *Rainfall:* 750 mm/yr. The nearest long term rainfall gauge is the Barwon Downs gauge (BOM station 90004) which has a record of over 100 years. Another nearby gauge in the opposite direction from the site is the Gerangamete rainfall gauge (BOM station 90189) but this has only a short record. The BOM rainfall distribution mapping indicates a 10% difference in the rainfall between these gauges (i.e. the long term average rainfall at the Gerangamete gauge is 10% less than the long term average rainfall at the Barwon Downs gauge) and therefore the long term rainfall at the Barongarook High is assumed to be somewhere between the rainfall recorded at these gauges. The average long term rainfall at the site has been assumed to be 5% less than the long term average rainfall at the Barwon Downs rainfall gauge (which has the longest record of the two gauges) to reflect the rainfall gradient across the site..
- *Surface runoff:* 100 mm/yr. Surface runoff is directly related to stream flow as the majority of stream flow is generated by surface runoff. Therefore, surface runoff can be calculated from stream flow data. The average annual runoff for the Barongarook High was estimated from the Boundary Creek Yeodene gauging station (WMIS station 233228) by subtracting summer low flow or baseflow (0.5 ML/day) from its average streamflow (10.5 ML/day). The surface runoff was then estimated by dividing this average annual runoff (10 ML/day) by the area of outcropping LTA at the Barongarook High (~36 km^2). Note, these estimates were made for the period between 1985 and 1999, prior to any impacts from the fire at Big Swamp.
- *Chloride in groundwater:* chloride concentrations were taken as the average concentrations from bores across three different times and bore data sets. There have been several studies undertaken in the area which have collected this information:
  - Median concentrations measured in 160 bores screened throughout the LTA in the Barwon Downs Graben as reported by Witebsky (1995) in a hydrogeological conceptualisation study of the area.
  - Median concentrations measured in 31 bores screened throughout the LTA in the Barwon Downs Graben as reported by Petrides and Cartwright (2006) in a geochemical characterisation study of the area.

- Median concentrations measured in 5 bores screened in the LTA near discharge zones as reported by Atkinson et al. (2014) in a groundwater surface water interaction study of the area.
- Median concentrations measured in 11 monitoring bores screened in the LTA at the Barongarook High throughout 2014/2015 hydrogeological investigations (Appendix 0). These were interpolated from in field EC measurements using empirically derived conversion factors for the LTA (Appendix I).

Appendix D. Sampling plan

Bores for sampling and analysis of tritium in groundwater were selected to optimised results to allow as many samples as possible for the application of the three tritium methods described in Appendix A. This involved a trade-off between the interface method which targets a variety of screen depths, the independent method which targets the water table and the differential method which targets nested sites. Table D.1 below summarises each of the bores selected and the selected dating methodology.

Table D.1 : Bores selected for tritium analysis

Bore ID	Screen top (m bgl)	Screen bottom (m bgl)	Indicative Water level (m bgl)	Indicative water column (m)	Tritium dating method		
					Interface	Independent	Differential
TB1a	8.65	11.7	0.31	9.84	✓		
TB2b	3.69	6.69	2.15	3.04	✓	✓	
TB4b	4.17	7.17	2.67	3.00	✓	✓	
TB6	17.9	20.9	17.2	2.12	✓	✓	
TB7	5.20	8.20	2.20	4.50	✓	✓	✓
TB14	8.50	11.5	0.44	9.56	✓		
47996	32.0	43.6	2.30	35.5	✓		✓
48001	27.0	33.0	25.1	4.87	✓	✓	
109130	8.00	14.3	11.0	0.21	✓	✓	✓
109136	28.0	37.0	18.3	14.2	✓		✓
109140	7.0	10.0	6.36	2.14	✓	✓	✓

Appendix E. Field results

E.1 Existing data

Since 2011, Jacobs has conducted a number of studies for Barwon Water which contain potentially useful data for the estimation of groundwater recharge rates to the LTA at the Barongarook High. This principally includes groundwater level and quality data, soil moisture profiles, grain-size analyses and stratigraphic logs. The collection and quality of these data have been documented in detail in Jacobs 2016 and Jacobs 2015.

The locations of groundwater monitoring and soil bores from which these data were collected are illustrated in Figure 2-3**. The soil moisture potential collected in soil cores is detailed in Table E.1. Table E.1 : Soil moisture potential in soil bores**

These data were collected between February and April 2015. Groundwater level data are currently being collected from data loggers installed in the new groundwater bores illustrated in Figure 2-3 and general water quality data were collected in these bores during bore installation (Jacobs 2016a). Bore construction details, water quality data and water level data have been summarised in Table E.2.

Table E.1 : Soil moisture potential in soil bores

Depth (m)	Moisture Potential (MPa)												
	SB1	SB2	SB4	SB5	SB6	SB7	SB8	SB9	SB10	SB11	SB12	SB13	SB14
0.4	-0.81	-0.62	-0.22	-0.24	-0.19	-0.01	-0.90	-0.79	-0.05	-0.22	-0.11	-0.08	-0.27
0.8	-0.62	-0.09	-0.33	-0.13	-0.02	-0.06	-0.23	-0.71	-0.18	-0.07	0.00	-0.18	-0.16
1.2	-1.06	-0.03	-0.79	0.00	-0.07	-0.02	-0.37	-0.48	-0.14	-0.01	-0.01	-0.08	-0.23
1.6	-1.03	0.00	-0.65	-0.07	-0.09	-0.04	-0.74	-0.66	-0.11	-0.01	-0.02	-0.21	-0.23
2	-0.79	0.00	-0.62	-0.21	-0.04	-0.12	-0.42	-0.63	-0.02	-0.05	0.00	-0.67	-0.34
2.4	-0.83	0.00	-0.23	-0.43	-0.07		-0.50	-0.76	-0.06	-0.04		-0.47	-0.37
2.8	-1.04	0.00	-0.02	-0.34	-0.02	-0.19	-0.47	-0.64	-0.31	-0.15		-0.43	-0.30
3.2			0.00	-0.40	-0.03		-0.50	-0.76	-0.03	-0.01		-0.16	-0.25
3.6			-0.24		-0.02		-0.76	-0.42	-0.02	-0.02		-0.12	-0.14
4			-0.01				-0.56	-0.25	-0.09	-0.06		-0.26	-0.08
5			-0.04				-0.37		-0.01	0.00		-0.02	-0.07
6			-0.02				-0.19						0.00

Table E.2 : Bore construction, indicative water level and water quality data of bores on or near the Barongarook High

Bore ID	Construction details			Indicative water level/quality	
	Bore depth (m bgl)	Screen top (m bgl)	Screen bottom (m bgl)	Water level (m bgl)	Electrical conductivity (µS/cm)
TB1a	12.91	8.65	11.65	0.31	878[1]
TB1b	19	19	17.5	1.275	15,800[1]
TB1c	36.5	36	33	1.525	579[1]
TB2a	17.1	13.7	16.7	Dry	N/A
TB2b	7.19	3.69	6.69	2.15	259[1]
TB2c	2.8	2.8	1.5	Dry	N/A
TB3	39.52	31.5	37.5	33.03	7,704[1]
TB4a	14.89	11.2	14.2	Dry	N/A
TB4b	7.67	4.17	7.17	2.67	274[1]
TB4c	31.01	27.45	30.45	28.95	848[1]
TB5	32.58	29	32	20.75	1,361[1]
TB6	22.01	17.85	20.85	17.23	1,306[1]
TB7	9.41	5.2	8.2	2.2	198[1]
TB14	11.59	8.5	11.5	0.44	405[1]
UBCk1	21.47	16.5	19.5	12.56	4,140[2]
UDvCk	60.98	55.8	58.8	28.07	545[2]
47989	12.8	2.5	12.48	11.28	N/A
47996	94	32	43.6	2.3	430[2]
47998	62	23	29	28.8	N/A
48001	43	27	33	25.13	232[2]
48010	33	30	33	21.55	1,202[3]
64238	98.7	70	87.4	86.41	2,202[3]
64243	91.9	30	36	7.69	N/A
109130	14.31	8	14.31	10.95	2,518[2]
109132	123	106.2	109.3	65.14	6,302[2]
109136	40	28	37	18.325	6,220[2]
109140	10.16	7	10	6.36	801[2]
109143	22.25	11.5	17.5	8.62	729[2]
114166	60.5	51.5	57.5	46.42	N/A

[1]Average based on multiple field readings
[2]Based on single field reading
[3]Based on online data

E.2 Field sampling results

Groundwater quality parameters were recorded at regular intervals during bore sampling/purging using a calibrated YSI ProPlus water quality meter. The parameters at the point of sampling have been detailed in Table E.3. Water quality was not measured regularly during the sampling of TB4b, 109136 and 109140 due to relatively slow recovery in those bores. Groundwater pH was circumneutral to slightly acidic, ranging from 5.24 to 6.74. Groundwater electrical conductivity (EC) ranged from 232 to 1,320 µS/cm and temperature ranged from 8.0 to 11.3 °C. Dissolved oxygen (DO) in groundwater ranged from 0.2 to 6.4 mg/L while the oxidation reduction potential (ORP) ranged from -114 to 83.0 mV.

Table E.3 : Summary water quality data during sampling for tritium analysis

Bore ID	Water level (m bgl)	Temperature (°C)	Electrical conductivity (µS/cm)	pH units	Oxidation reduction potential (mV)	Dissolved oxygen (mg/L)
TB1a	1.77	10.4	990	5.95	9.0	0.9
TB2b	5.72	9	298	5.59	83.0	6.4
TB4b	3.56	n/a	n/a	n/a	n/a	n/a
TB6	17.35	11.2	1,320	6.11	-25.0	4.0
TB7	3.13	9.8	224	5.24	16.0	4.7
TB14	1.76	11.3	433	6.40	9.8	1.1
47996	2.32	10.4	430	5.24	-114.0	0.2
48001	25.04	11.3	232	6.74	-113.0	0.5
109130	1.76	11.3	433	6.40	9.8	1.1
109136	18.52	n/a	n/a	n/a	n/a	n/a
109140	6.91	n/a	n/a	n/a	n/a	n/a

Appendix F. Tritium certificate of analysis

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Institute for Environmental Research Analytical Report

Client:	**Jacobs SKM** **ANZ Infrastructure & Environment** **452 Flinders Street** **Melbourne, Victoria, 3000** **Nicolaas Unland**
Contact:	**Nicolaas.unland@jacobs.com**
Tel:	**03 8668 3086**

Report Number:	**2015/0429**
Batch Description:	**Tritium in groundwater**
Samples Received:	**11**
Registration Date:	**22-Dec-2015**
Report Date:	**11-Apr-2016**
Logged By:	**Kellie-Anne Farrawell**
ANSTO Cost Code:	**0205v-1**
Funds Type:	**Project - Commercial**
Supervising Analyst:	**Robert Chisari**

Signature:___________________________________ Date 11-Apr-2016

Robert Chisari

Ultra Low Level Tritium Analysis

Ultra low level tritium in water analysis is conducted at ANSTO within specialised laboratories that are isolated from the outside world to ensure ultra-low limits of detection are achieved.

The analytical process [1] begins with sub-boiling distillation of the sample to remove salts and organics.

Electrolytic concentration of tritium follows, whereby a set of samples along with a recovery standard and blank are processed as a batch. Each of the samples and standards has a current of < 100 $mA.cm^{-2}$ passed through it, which preferentially drives off the lighter isotopes of hydrogen as H_2. A 68 fold concentration is achieved via electrolysis, over a period of 2 weeks, which enables tritium in natural waters to be quantified.

The concentrate is distilled to produce a solution suitable for liquid scintillation counting.

The samples, recovery standard & blank are weighed out, along with counting standards and instrument background checks, into 20 mL polyethylene vials. Ultima Gold™ uLLT scintillation cocktail is added to each of these solutions and well mixed.

Water used to make standards/blanks/background checks is of artesian origin and free of tritium. Standards are prepared utilising NIST certified tritium labelled water:

Supplier:	**Amersham plc, Buckinghamshire**
Product code:	**TRY64**
Batch:	**133**

Measurement of all samples, standards and reagents is via mass, using calibrated analytical balances to a minimum of 4 significant figures.

Liquid scintillation spectrometry is conducted using Perkin Elmer Quantulus™ instruments. Each of the samples and standards is counted for 2000# minutes over a period of 4+ weeks in 20 minute cycles to reduce bias created by fluctuations in cosmic radiation. A narrow counting window between 2 – 20 keV is selected to ensure sample & standard data has the lowest possible contribution from background radiation, thus further reducing the lower limit of detection.

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Data reduction is undertaken utilising Excel, all counting data is assessed to ensure it fits a Poisson distribution with a confidence interval of 95% [2],[3]. A full uncertainty budget is calculated for this analysis [2]. Along with a lower limit of detection (LLD) of ~0.005 Bq/kg (~0.05 TU) corresponding to the fractional measurement standard uncertainty (σ(C)/C) equal to 0.5, achieved utilising the conditions described above, [4].

References

[1] VP-2869 Tritium Analysis; ISO9001 Quality Management System Procedure (ANSTO)

[2] L'Annunziata (ed); Handbook of Radioactivity Analysis, 2nd edition; Academic Press 2003; ISBN" 0-12-436603-1

[3] NIST/SEMATECH e-Handbook of Statistical Methods, http://www.itl.nist.gov/div898/handbook/eda/section3/eda3674.htm, 16-Feb-2010.

[4] Morgenstern, U and Taylor, C.B.; Ultra Low-Level Tritium Measurement using Electrolytic Enrichment and LSC; Isotopes in Environmental and Health Studies, Vol. 45, No.2 June 2009

Sample Identification

LIMS ID	Client Identification	Sample Description
2015/0429-1	TB1	Groundwater
2015/0429-2	TB2b	Groundwater
2015/0429-3	TB6	Groundwater
2015/0429-4	48001	Groundwater
2015/0429-5	47996	Groundwater
2015/0429-6	TB7	Groundwater
2015/0429-7	TB14	Groundwater
2015/0429-8	TB4b	Groundwater
2015/0429-9	109130	Groundwater
2015/0429-10	109136	Groundwater
2015/0429-11	109140	Groundwater

Institute for Environmental Research
Analytical Report

Report Number: 2015/0429

Tritium Concentration at Sampling Date

Client Identification	Sample No.	Date Sample Collected	Tritium Activity Bq/kg	Uncertainty[1] Bq/kg	LLD[2] Bq/kg	Tritium Ratio TU	Uncertainty[1] TU	LLD[2] TU
TB1	1	9-Dec-2015	0.001^	0.003	0.006	0.01^	0.02	0.05
TB2b	2	10-Dec-2015	0.255	0.012	0.006	2.14	0.10	0.05
TB6	3	10-Dec-2015	0.061	0.004	0.006	0.51	0.04	0.05
48001	4	10-Dec-2015	0.038	0.004	0.006	0.32	0.03	0.05
47996	5	10-Dec-2015	0.001^	0.003	0.006	0.01^	0.02	0.05
TB7	6	10-Dec-2015	0.088	0.005	0.006	0.74	0.04	0.05
TB14	7	10-Dec-2015	0.001^	0.003	0.006	0.01^	0.02	0.05
TB4b	8	11-Dec-2015	0.234	0.011	0.006	1.97	0.09	0.05
109130	9	11-Dec-2015	0.099	0.006	0.006	0.83	0.05	0.05
109136	10	11-Dec-2015	0.001^	0.003	0.006	0.01^	0.02	0.05
109140	11	11-Dec-2015	0.110	0.006	0.006	0.93	0.05	0.05

Notes:

1. Values reported are combined standard uncertainty, calculated to 1 sigma. A Coverage factor, *k*, of 2 may be used to calculate Expanded Uncertainty to 95% confidence.
2. The lower limit of detection (LLD) corresponds to the fractional measurement standard uncertainty (σ(C)/C) of 0.5 [4].

^ This result is below the LLD and therefore has an unacceptable level of uncertainty

Signature:________________________________ Date: 11-Apr-2016
Robert Chisari

Appendix G. Soil cores

JACOBS	FIELD BOREHOLE / WELL LOG	BOREHOLE / WELL NUMBER: SB1

PROJECT NUMBER: **IS039500**
PROJECT NAME: **Barwon Downs Vegetation Investigations**
LOCATION: **Barwon Downs**
DRILLING CO: **Drillmax**
DRILLING METHOD: **Hollow Auger**
BOREHOLE DIAMETER: **125 mm**
DATE STARTED: **26/02/2015** DATE COMPLETED: **26/02/2015**

WELL PERMIT NUMBER: **N/A**
TOTAL DEPTH (m bgl): **3**
REFERENCE POINT: **Ground Surface**
STATIC WATER LEVEL
Date: Depth (mbRP): **3**
PROJECTION: **GDA 1994, Zone 54**
EASTING: **735316** NORTHING: **5743753**

DRILLING INFO. | MATERIAL PROPERTIES | FIELD RECORDS / CONSTRUCTION INFO.

METHOD	BIT LOG	PENETRATION RATE (m/min)	DEPTH (m)	GRAPHICAL LOG	LITHOLOGY	INTERPRETIVE LOG	WATER CUTS	Soil moisture (MPa)	Soil EC (uS/cm)	COMMENTS	WELL CONSTRUCTION	SOIL TEXTURE ANALYSIS % SAND, % SILT, % CLAY
Hollow Augers	125mm Hollow Auger		0.0		Sandy silt: Light brown, soft, loose, poor cohesion.							
					Sandy silt: Light grey/yellow/brown, fine grained, dry minor gravels; up to 20mm, rounded to subrounded, silicic.			-0.81		Roots 1mm diameter to 0.7m		
					Sandy Clay: Orange/yellow with brown, fine grained, minor mica, minor clay.			-0.62				
			1.0						232			42% Sand, 8% Silt, 50% Clay
								-1.06				
					Clayey Sand: Light grey with minor diffuse orange/brown mottling, fine grained becoming courser with depth, firm, friable, low cohesion, minor mica, minor clay.			-1.03				
			2.0					-0.79	334			73% Sand, 6% Silt, 21% Clay
								-0.83				
										damp from 2.5m		
								-1.04				
			3.0		EOH @ 3 metres					Refusal at 3m		
			4.0									
			5.0									
			6.0									

LOGGED: N. Unland DATE: 26/02/2015
CHECKED: L. Randell DATE: 20/03/2015

JACOBS

FIELD BOREHOLE / WELL LOG

BOREHOLE / WELL NUMBER

SB2

PROJECT NUMBER: **IS039500**
PROJECT NAME: **Barwon Downs Vegetation Investigations**
LOCATION: **Barwon Downs**
DRILLING CO: **Drillmax**
DRILLING METHOD: **Hollow Auger**
BOREHOLE DIAMETER: **125 mm**
DATE STARTED: **02/03/2015** DATE COMPLETED: **02/03/2015**

WELL PERMIT NUMBER: **N/A**
TOTAL DEPTH (m bgl): **3.2**
REFERENCE POINT: **Ground Surface**
STATIC WATER LEVEL
Date: **02/03/2015** Depth (mbRP): **1.7**
PROJECTION: **GDA 1994, Zone 54**
EASTING: **734639** NORTHING: **5743993**

DRILLING INFO. | MATERIAL PROPERTIES | FIELD RECORDS / CONSTRUCTION INFO.

METHOD	BIT LOG	PENETRATION RATE (m/min)	DEPTH (m)	GRAPHICAL LOG	LITHOLOGY	INTERPRETIVE LOG	WATER CUTS	Soil moisture (MPa)	Soil EC (uS/cm)	COMMENTS	WELL CONSTRUCTION	SOIL TEXTURE ANALYSIS % SAND, % SILT, % CLAY
Hollow Augers	125mm Hollow Auger		0.0		Silty sand: Dark brown, fine grained, loose, dry, organic matter.							
					Sand: Light grey to yellow/brown, medium to fine grained, well sorted, dry.			-0.62	37	Roots up to 3mm in diameter to 0.8m		86% Sand, 10% Silt, 4% Clay
			1.0		Silty Sand: Light grey, fine grained, soft to firm.			-0.09		damp from 0.8m		
								-0.03				
					Sand: Light brown to yellow/brown, fine grained, loose.		WC	0		Wet after 1.6m		
			2.0					0				
								0	12			95% Sand, 2% Silt, 3% Clay
								0				
			3.0		Sand: Light brown to yellow/brown, iron cemented, fine grained.							
					EOH @ 3.2 metres					Refusal at 3.3m		
			4.0									
			5.0									
			6.0									

LOGGED: N. Unland DATE: 02/03/2015
CHECKED: L. Randell DATE: 20/03/2015

FIELD BOREHOLE / WELL LOG

JACOBS

BOREHOLE / WELL NUMBER: SB4

PROJECT NUMBER: **IS039500**
PROJECT NAME: **Barwon Downs Vegetation Investigations**
LOCATION: **Barwon Downs**
DRILLING CO: **Drillmax**
DRILLING METHOD: **Hollow Auger**
BOREHOLE DIAMETER: **125 mm**
DATE STARTED: **26/02/2015** DATE COMPLETED: **26/02/2015**

WELL PERMIT NUMBER: **N/A**
TOTAL DEPTH (m bgl): **6.5**
REFERENCE POINT: **Ground Surface**
STATIC WATER LEVEL
Date: **26/02/2015** Depth (mbRP):
PROJECTION: **GDA 1994, Zone 54**
EASTING: **732955** NORTHING: **57444156**

DRILLING INFO. | MATERIAL PROPERTIES | FIELD RECORDS / CONSTRUCTION INFO.

Method: Hollow Augers (0.0–6.5 m)
Bit log: 125mm Hollow Auger (0.0–6.5 m)

DEPTH (m)	LITHOLOGY	Soil moisture (MPa)	Soil EC (uS/cm)	COMMENTS	SOIL TEXTURE ANALYSIS % SAND, % SILT, % CLAY
0.0	Sandy silt: Light brown to light grey, fine grained, dry, poor cohesion.				
	Silty sand: Grey/yellow, fine grained, dry.	-0.22			
	Clayey Sand: Yellow/brown to orange, firm to hard.	-0.33			
1.0			44		66% Sand, 13% Silt, 21% Clay
		-0.79			
		-0.65			
2.0	Sandy Silt: Yellow/brown, fine grained, minor quartz clasts.	-0.62		Minor roots ~1mm in diameter above 2m	
		-0.23			
	Sand: Orange/brown, soft, well sorted, damp.	-0.02		Damp from 2.8m	
3.0	Sandy silty clay: Orange with light grey mollting, soft to firm, low plasticity.	0			
	Sandy silty clay: Orange with light grey mollting, soft to firm, low plasticity, interlayered with clay bands.	-0.24			
4.0	Sand: Light grey/brown, fine grained, minor silt, soft, poor cohesion.	-0.01	42		89% Sand, 4% Silt, 7% Clay
	Sand: Light grey/brown with minor orange diffued mottling, fine grained, minor silt, soft with poor cohesion.				
5.0		-0.04			
6.0		-0.02			
6.5	EOH @ 6.5 metres				
7.0					

LOGGED: N. Unland DATE: 26/02/2015
CHECKED: L. Randell DATE: 20/03/2015

FIELD BOREHOLE / WELL LOG

JACOBS

BOREHOLE / WELL NUMBER: SB5

PROJECT NUMBER: **IS039500**
PROJECT NAME: **Barwon Downs Vegetation Investigations**
LOCATION: **Barwon Downs**
DRILLING CO: **Drillmax**
DRILLING METHOD: **Hollow Auger**
BOREHOLE DIAMETER: **125 mm**
DATE STARTED: **02/03/2015** DATE COMPLETED: **02/03/2015**

WELL PERMIT NUMBER: **N/A**
TOTAL DEPTH (m bgl): **3.3**
REFERENCE POINT: **Ground Surface**
STATIC WATER LEVEL
Date: **02/03/2015** Depth (mbRP):
PROJECTION: **GDA 1994, Zone 54**
EASTING: **731011** NORTHING: **5743996**

DRILLING INFO. | MATERIAL PROPERTIES | FIELD RECORDS / CONSTRUCTION INFO.

METHOD: Hollow Augers (0.0–3.3 m)
BIT LOG: 125mm Hollow Auger (0.0–3.3 m)

DEPTH (m)	LITHOLOGY	Soil moisture (MPa)	Soil EC (uS/cm)	COMMENTS	SOIL TEXTURE ANALYSIS % SAND, % SILT, % CLAY
0.0	Sandy silt: Brown, fine grained, organic matter, soft, dry.				
	Silty sand: Light grey, fine grained, soft, low cohesion.		8		76% Sand, 20% Silt, 4% Clay
	Clayey Sand: Orange with red mottling, firm to hard, fine grained.	-0.24		Minor roots up to 3 mm in diameter to 0.8m depth	
		-0.13	20		52% Sand, 12% Silt, 36% Clay
1.0		0		Damp	
	Sandy Clay: Orange with red mottling, firm to hard with depth, fine grained, minor clay, minor iron rich clasts, 20 to 30 mm in size, sub angular.	-0.07			
2.0		-0.21			
		-0.43			
		-0.34			
3.0	Sandy Clay: Orange with red, firm to hard with depth, fine grained, damp, minor clay, minor iron rich grains, ~15 mm in size, sub angular.	-0.4			
3.3	EOH @ 3.3 metres			Refusal at 3.3m due to hard sandy material (possibly lithic sandstone)	
4.0					
5.0					
6.0					

LOGGED: N. Unland DATE: 02/03/2015
CHECKED: L. Randell DATE: 20/03/2015

FIELD BOREHOLE / WELL LOG

JACOBS

BOREHOLE / WELL NUMBER: SB6

PROJECT NUMBER:	**IS039500**	WELL PERMIT NUMBER:	**N/A**
PROJECT NAME:	**Barwon Downs Vegetation Investigations**	TOTAL DEPTH (m bgl):	**4**
LOCATION:	**Barwon Downs**	REFERENCE POINT:	**Ground Surface**
DRILLING CO:	**Drillmax**	STATIC WATER LEVEL	
DRILLING METHOD:	**Hollow Auger**	Date: **23/02/2015**	Depth (mbRP):
BOREHOLE DIAMETER:	**125 mm**	PROJECTION:	**GDA 1994, Zone 54**
DATE STARTED: **23/02/2015**	DATE COMPLETED: **23/02/2015**	EASTING: **729425**	NORTHING: **5743269**

DRILLING INFO. | MATERIAL PROPERTIES | FIELD RECORDS / CONSTRUCTION INFO.

METHOD: Hollow Augers (0.0–4.0 m)
BIT LOG: 125mm Hollow Auger (0.0–4.0 m)

Depth (m)	Lithology
0.0–0.3	Sandy silt: Brown, medium to course grained, poor cohesion, minor organic matter.
0.3–0.6	Sand: Light grey, medium to course grained, sub rounded, soft, poor cohesion.
0.6–2.8	Sand: Orange to brown/orange, medium to course grained, sub rounded, soft, poor cohesion.
2.8–4.0	Sand: Red/orange with medium brown diffuse mottling, course grained, subrounded.
4.0	EOH @ 4 metres

Depth (m, approx.)	Soil moisture (MPa)	Soil EC (uS/cm)	Comments	Soil Texture Analysis (% Sand, % Silt, % Clay)
0.25			Minor roots 0 to 0.5m	
0.45	-0.19			
0.85	-0.02			
1.05		6		81% Sand, 13% Silt, 6% Clay
1.25	-0.07			
1.55			Damp from 1.5m	
1.65	-0.09			
2.05	-0.04			
2.45	-0.07			
2.85	-0.02			
3.25	-0.03			
3.65	-0.02			
4.0		4	Refusal at 4m	97% Sand, 1% Silt, 2% Clay

LOGGED: N. Unland DATE: 23/02/2015

CHECKED: L. Randell DATE: 20/03/2015

JACOBS

FIELD BOREHOLE / WELL LOG

BOREHOLE / WELL NUMBER

SB7

PROJECT NUMBER: **IS039500**
PROJECT NAME: **Barwon Downs Vegetation Investigations**
LOCATION: **Barwon Downs**
DRILLING CO: **Drillmax**
DRILLING METHOD: **Hollow Auger**
BOREHOLE DIAMETER: **125 mm**
DATE STARTED: **24/02/2015** DATE COMPLETED: **24/02/2015**

WELL PERMIT NUMBER: **N/A**
TOTAL DEPTH (m bgl): **3**
REFERENCE POINT: **Ground Surface**
STATIC WATER LEVEL
Date: **24/02/2015** Depth (mbRP):
PROJECTION: **GDA 1994, Zone 54**
EASTING: **727544** NORTHING: **5742302**

DRILLING INFO. | MATERIAL PROPERTIES | FIELD RECORDS / CONSTRUCTION INFO.

METHOD	BIT LOG	PENETRATION RATE (m/min)	DEPTH (m)	GRAPHICAL LOG	LITHOLOGY	INTERPRETIVE LOG	WATER CUTS	Soil moisture (MPa)	Soil EC (uS/cm)	COMMENTS	WELL CONSTRUCTION	SOIL TEXTURE ANALYSIS % SAND, % SILT, % CLAY
Hollow Augers	125mm Hollow Auger		0.0		Sand: Orange/brown/grey, medium to course sands, sub rounded, minor silts and clays.							
					Silty Sand: Dark brown/black, medium sub rounded grains.			-0.01		Abundant plant roots 0 to 0.5 m		
					Sand: Light grey, meduim to fine sub rounded grains, well sorted, minor silt.			-0.06		Sample Wet		
			1.0		Clayey Sand: Dark brown, medium subrounded grains, silicaoucous.			-0.02	2			89% Sand, 10% Silt, 1% Clay
					Clayey Sand: Light grey with diffuse orange, medium to course grains, rounded.			-0.04				
			2.0					-0.12	14			59% Sand, 15% Silt, 26% Clay
					Sandy Clay: Light grey with orange mottling, stiff, high plasticity.			-0.14				
								-0.19				
			3.0		EOH @ 3 metres				28			33% Sand, 15% Silt, 52% Clay
			4.0									
			5.0									
			6.0									

LOGGED: N. Unland DATE: 24/02/2015
CHECKED: L. Randell DATE: 20/03/2015

FIELD BOREHOLE / WELL LOG

BOREHOLE / WELL NUMBER: SB8

PROJECT NUMBER:	**IS039500**	WELL PERMIT NUMBER:	**N/A**
PROJECT NAME:	**Barwon Downs Vegetation Investigations**	TOTAL DEPTH (m bgl):	**6.5**
LOCATION:	**Barwon Downs**	REFERENCE POINT:	**Ground Surface**
DRILLING CO:	**Drillmax**	STATIC WATER LEVEL	
DRILLING METHOD:	**Hollow Auger**	Date: **25/02/2015**	Depth (mbRP):
BOREHOLE DIAMETER:	**125 mm**	PROJECTION:	**GDA 1994, Zone 54**
DATE STARTED: **25/02/2015**	DATE COMPLETED: **25/02/2015**	EASTING: **734226**	NORTHING: **5741587**

DRILLING INFO. — MATERIAL PROPERTIES — FIELD RECORDS / CONSTRUCTION INFO.

Columns: METHOD | BIT LOG | PENETRATION RATE (m/min) | DEPTH (m) | GRAPHICAL LOG | LITHOLOGY | INTERPRETIVE LOG | WATER CUTS | Soil moisture (MPa) | Soil EC (uS/cm) | COMMENTS | WELL CONSTRUCTION | SOIL TEXTURE ANALYSIS % SAND, % SILT, % CLAY

METHOD: Hollow Augers (0.0–6.5 m)

BIT LOG: 125mm Hollow Auger (0.0–6.5 m)

DEPTH (m): 0.0, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0

LITHOLOGY

- Silty sand: Light brown to yellow, medium grained, roots and organic matter, minor clay.
- Sandy Silt: Yellow/brown, minor fine grained sand.
- Silty Sand: Yellow/brown to grey, fine grained.
- Clayey Sand: Yellow /brown with diffuse grey mottling, minor clay, sand; medium to large grains, rounded, poorly sorted.
- Clayey Sand: Light grey, fine grained, firm.
- Gravel: Yellow /brown to light grey, well rounded, pooly sorted alluvial, quatrz, clay matrix; grey, firm cohesive, medium plasticity.
- Silty clay: Light grey with yellow mottling, firm to hard, low to medium plasticity.
- Silty Sandy Clay: Grey with red orange mottling, firm to hard, low to medium plasticity.
- Silty Clay: Soft to firm, low to medium plasticity.

EOH @ 6.5 metres

FIELD RECORDS

Soil moisture (MPa)	Soil EC (uS/cm)	COMMENTS	SOIL TEXTURE ANALYSIS
-0.9		Roots ~1mm diameter.	
-0.23			
	22		73% Sand, 17% Silt, 10% Clay
-0.37			
-0.74			
-0.42	64	Minor roots >1mm in diameter 1.5 to 2.5m	65% Sand, 14% Silt, 20% Clay
-0.5		Hard ground	
-0.47			
	143		69% Sand, 12% Silt, 18% Clay
-0.5			
-0.76			
-0.56			
		Damp, minor roots, 10 to 15 mm 3.5 to 5.7m	
-0.37	217		38% Sand, 27% Silt, 35% Clay
-0.19		minor roots <1mm 5.7 to 6.5m	

LOGGED: N. Unland DATE: 25/02/2015

CHECKED: L. Randell DATE: 20/03/2015

FIELD BOREHOLE / WELL LOG

JACOBS

BOREHOLE / WELL NUMBER: SB9

PROJECT NUMBER: **IS039500**
PROJECT NAME: **Barwon Downs Vegetation Investigations**
LOCATION: **Barwon Downs**
DRILLING CO: **Drillmax**
DRILLING METHOD: **Hollow Auger**
BOREHOLE DIAMETER: **125 mm**
DATE STARTED: **27/02/2015** DATE COMPLETED: **27/02/2015**

WELL PERMIT NUMBER: **N/A**
TOTAL DEPTH (m bgl): **4**
REFERENCE POINT: **Ground Surface**
STATIC WATER LEVEL
Date: **27/02/2015** Depth (mbRP):
PROJECTION: **GDA 1994, Zone 54**
EASTING: **731968** NORTHING: **5735446**

DRILLING INFO. | MATERIAL PROPERTIES | FIELD RECORDS / CONSTRUCTION INFO.

METHOD: Hollow Augers (0.0–4.0 m)
BIT LOG: 125mm Hollow Auger (0.0–4.0 m)

DEPTH (m)	LITHOLOGY
0.0 – 0.2	Sandy silt: Light brown, fine grained, soft, poor cohesion.
0.2 – 0.7	Clayey silt: Light brown/grey, firm to hard, cohesive, low to medium plasticity.
0.7 – 1.5	Clayey silt: Light grey with diffuse yellow brown mottles, dry friable, firm to hard.
1.5 – 2.2	Silty Sand: Light grey with minor diffuse orange mottling, fine grained, soft, low cohesion, dry.
2.2 – 3.7	Silty clay: Dark grey with diffuse yellow mottling, firm to soft, low plasticity, low cohesion, minor fine grained sands increasing with depth.
3.7 – 4.0	Sandy clay: Dark grey, soft, low plasticity, minor fine sands.
4.0	EOH @ 4 metres

Approx. depth (m)	WATER CUTS	Soil moisture (MPa)	Soil EC (uS/cm)	COMMENTS	SOIL TEXTURE ANALYSIS (% SAND, % SILT, % CLAY)
0.25				Minor roots 0 to 0.2m	
0.45		-0.79			
0.55				Damp	
0.85		-0.71			
1.05			37	Abundant roots to 1mm diameter 0.8 to 1.2m	17% Sand, 46% Silt, 38% Clay
1.25		-0.48			
1.65		-0.66			
2.05		-0.63	669	Minor fine roots with one 8 mm root at 2.1m.	20% Sand, 44% Silt, 36% Clay
2.45		-0.76			
2.85		-0.64			
3.05	WC			Sample wet from 3m	
3.25		-0.76		Minor roots >1mm in diameter 2.2 to 3.7m	
3.65		-0.42			
4.05		-0.25	208		58% Sand, 30% Silt, 12% Clay

LOGGED: N. Unland DATE: 27/02/2015
CHECKED: L. Randell DATE: 20/03/2015

JACOBS

FIELD BOREHOLE / WELL LOG

BOREHOLE / WELL NUMBER

SB10

PROJECT NUMBER: **IS039500**
PROJECT NAME: **Barwon Downs Vegetation Investigations**
LOCATION: **Barwon Downs**
DRILLING CO: **Drillmax**
DRILLING METHOD: **Hollow Auger**
BOREHOLE DIAMETER: **125 mm**
DATE STARTED: **24/02/2015** DATE COMPLETED: **24/02/2015**

WELL PERMIT NUMBER: **N/A**
TOTAL DEPTH (m bgl): **5**
REFERENCE POINT: **Ground Surface**
STATIC WATER LEVEL
Date: **24/02/2015** Depth (mbRP):
PROJECTION: **GDA 1994, Zone 54**
EASTING: **728385** NORTHING: **5739951**

DRILLING INFO. | MATERIAL PROPERTIES | FIELD RECORDS / CONSTRUCTION INFO.

Columns: METHOD | BIT LOG | PENETRATION RATE (m/min) | DEPTH (m) | GRAPHICAL LOG | LITHOLOGY | INTERPRETIVE LOG | WATER CUTS | Soil moisture (MPa) | Soil EC (uS/cm) | COMMENTS | WELL CONSTRUCTION | SOIL TEXTURE ANALYSIS % SAND, % SILT, % CLAY

METHOD: Hollow Augers (0.0–5.0 m)
BIT LOG: 125mm Hollow Auger (0.0–5.0 m)

Depth (m)	Lithology
0.0–0.3	Silt: Dark brown with yellow brown mottling, minor sands, fine grained, dry, poor cohesion.
0.3–0.5	Clayey silt: Yellow/brown to brown grey, minor fine sands, poor cohesion, soft.
0.5–1.5	Clay: Light grey with orange mottling, heavy, high plasticity, firm to hard.
1.5–1.8	Clay: Light grey, heavy, hard, minor silts and fine sands.
1.8–2.0	Sand: Orange/brown, fine to medium grained.
2.0–2.5	Clayey Silt: Light grey, minor sands, fine grained, poor cohesion.
2.5–3.0	Clayey Silt: Orange, minor fine sands, poor cohesion.
3.0–3.3	Silty Clay: Light grey with diffuse orange mottling, medium plasticity, minor sands; light grey, fine grained.
3.3–4.0	Silty clay: Light grey, moderate plasticity,minor sands increasing with depth.
4.0–5.0	Clay: Brown to orange, firm to soft, high plasticity, traces of mica.
5.0	EOH @ 5 metres

Depth (m) (approx.)	Water Cuts	Soil moisture (MPa)	Soil EC (uS/cm)	Comments	Soil Texture Analysis
0.45		-0.05		Slightly damp minor roots <1mm diameter	
0.85		-0.18			
1.05			19		12% Sand, 26% Silt, 62% Clay
1.25		-0.14			
1.65		-0.11		Slightly damp minor roots <6mm diameter	
2.05		-0.02	16		52% Sand, 23% Silt, 25% Clay
2.45		-0.06			
2.85		-0.31			
3.05			16		19% Sand, 34% Silt, 47% Clay
3.25		-0.03			
3.65		-0.02			
4.05		-0.09			
4.55	WC			Sample wet following 4.5m	
5.05		-0.01			

LOGGED: N. Unland DATE: 24/02/2015
CHECKED: L. Randell DATE: 20/03/2015

FIELD BOREHOLE / WELL LOG

JACOBS

BOREHOLE / WELL NUMBER: SB11

PROJECT NUMBER: **IS039500**
PROJECT NAME: **Barwon Downs Vegetation Investigations**
LOCATION: **Barwon Downs**
DRILLING CO: **Drillmax**
DRILLING METHOD: **Hollow Auger**
BOREHOLE DIAMETER: **125 mm**
DATE STARTED: **02/03/2015** DATE COMPLETED: **02/03/2015**

WELL PERMIT NUMBER: **N/A**
TOTAL DEPTH (m bgl): **5**
REFERENCE POINT: **Ground Surface**
STATIC WATER LEVEL
Date: **02/03/2015** Depth (mbRP):
PROJECTION: **GDA 1994, Zone 54**
EASTING: **730561** NORTHING: **5736699**

DRILLING INFO. | MATERIAL PROPERTIES | FIELD RECORDS / CONSTRUCTION INFO.

METHOD	BIT LOG	PENETRATION RATE (m/min)	DEPTH (m)	GRAPHICAL LOG	LITHOLOGY
Hollow Augers (0.0–5.0)	125mm Hollow Auger (0.0–5.0)		0.0–0.4		Sandy silt: Yellow/brown to grey/brown, firm, minor sands.
			0.4–1.5		Silty clay: Orange/brown/white with light grey mottling, moderate plasticity, friable.
			1.5–2.5		Silty Clay: Light grey with diffuse yellow brown mottling, heavy, high plasticity, highly coheasive, firm to hard, minor mica.
			2.5–3.0		Clay: Light grey with diffuse red mottling, heavy, high plasticity, highly coheasive, firm, minor mica.
			3.0–5.0		Silty Clay: Light grey with diffuse red mottling, heavy, high plasticity, highly coheasive, soft to firm, getting harder with depth, minor mica.
			5.0		EOH @ 5 metres

Depth (m)	INTERPRETIVE LOG	WATER CUTS	Soil moisture (MPa)	Soil EC (uS/cm)	COMMENTS	WELL CONSTRUCTION	SOIL TEXTURE ANALYSIS % SAND, % SILT, % CLAY
0.4			-0.22		Abundant roots 1 to 2mm in diameter		
0.8			-0.07	38			8% Sand, 34% Silt, 58% Clay
1.0					Damp from 0.5m onwards		
1.2			-0.01				
1.6			-0.01				
2.0			-0.05	24			6% Sand, 59% Silt, 35% Clay
2.4			-0.04				
2.8			-0.15				
3.2			-0.01				
3.6			-0.02				
4.0			-0.06				
4.2				26			2% Sand, 51% Silt, 47% Clay
5.0			0				

LOGGED: N. Unland DATE: 02/03/2015
CHECKED: L. Randell DATE: 20/03/2015

FIELD BOREHOLE / WELL LOG

JACOBS

BOREHOLE / WELL NUMBER

SB12

PROJECT NUMBER: **IS039500**
PROJECT NAME: **Barwon Downs Vegetation Investigations**
LOCATION: **Barwon Downs**
DRILLING CO: **Drillmax**
DRILLING METHOD: **Hollow Auger**
BOREHOLE DIAMETER: **125 mm**
DATE STARTED: **27/02/2015** DATE COMPLETED: **27/02/2015**

WELL PERMIT NUMBER: **N/A**
TOTAL DEPTH (m bgl): **4**
REFERENCE POINT: **Ground Surface**
STATIC WATER LEVEL
Date: **27/02/2015** Depth (mbRP):
PROJECTION: **GDA 1994, Zone 54**
EASTING: **731130** NORTHING: **5740159**

DRILLING INFO.				MATERIAL PROPERTIES			FIELD RECORDS / CONSTRUCTION INFO.					
METHOD	BIT LOG	PENETRATION RATE (m/min)	DEPTH (m)	GRAPHICAL LOG	LITHOLOGY	INTERPRETIVE LOG	WATER CUTS	Soil moisture (MPa)	Soil EC (uS/cm)	COMMENTS	WELL CONSTRUCTION	SOIL TEXTURE ANALYSIS % SAND, % SILT, % CLAY
Hollow Augers (0.0–4.0)	125mm Hollow Auger (0.0–4.0)		0.0		Sandy silt: Brown, minor gravels; well rounded quartz, to 15mm, organic matter, moderate cohesion.					Abundant roots 0 to 0.5m		
					Silty sand: Orange brown, medium to fine grained, soft, poor cohesion, minor clay, damp to very damp, minor course sands; silicic, rounded grains.			-0.11	9			77% Sand, 9% Silt, 14% Clay
					Silty Sand: Grey, soft, cohesive, low plasticity.			0		Very damp to wet from 0.6m		
			1.0		Clay: Grey, moderate to high plasticity, soft to firm, coheasive.			-0.01	12	Abundant roots, red staining surrounding roots possibly iron hydroxide related to potential acid sulphate soil.		55% Sand, 33% Silt, 12% Clay
								-0.02				
			2.0		Sandy clay: Light grey with horizontal orange mottled layers ~1mm thick, moderate to high plasticity, minor fine sands.			0		Minor roots 1mm one 3mm root at ~2.5m		
			3.0		Silty Clay: Light grey, with orange horizontal mottling, firm, minor mica.							
			4.0		EOH @ 4 metres				11			13% Sand, 37% Silt, 50% Clay
			5.0									
			6.0									

LOGGED: N. Unland DATE: 27/02/2015
CHECKED: L. Randell DATE: 20/03/2015

JACOBS

FIELD BOREHOLE / WELL LOG

BOREHOLE / WELL NUMBER: SB13

PROJECT NUMBER:	**IS039500**	WELL PERMIT NUMBER:	**N/A**
PROJECT NAME:	**Barwon Downs Vegetation Investigations**	TOTAL DEPTH (m bgl):	**5.5**
LOCATION:	**Barwon Downs**	REFERENCE POINT:	**Ground Surface**
DRILLING CO:	**Drillmax**	STATIC WATER LEVEL	
DRILLING METHOD:	**Hollow Auger**	Date: **25/02/2015**	Depth (mbRP):
BOREHOLE DIAMETER:	**125 mm**	PROJECTION:	**GDA 1994, Zone 54**
DATE STARTED: **25/02/2015**	DATE COMPLETED: **25/02/2015**	EASTING: **729600**	NORTHING: **5738929**

DRILLING INFO.: METHOD: Hollow Augers (0.0–4.0 m); BIT LOG: 125mm Hollow Auger (0.0–4.0 m)

DEPTH (m)	LITHOLOGY	WATER CUTS	Soil moisture (MPa)	Soil EC (uS/cm)	COMMENTS	SOIL TEXTURE ANALYSIS % SAND, % SILT, % CLAY
0.0–0.3	Silt: Brown, dry, poor cohesion.					
0.3–0.6	Silt: Light brown/yellow, firm friable, dry.		-0.08		Roots up to 8mm in diameter.	
0.6–1.5	Silty Clay: Yellow/brown with light grey mottling, firm friable, poor to moderate cohesion.		-0.18		Roots ~1mm diameter	
				72	Slightly damp	21% Sand, 40% Silt, 39% Clay
			-0.08			
1.5–2.0	Clay: Light grey with yellow/brown diffuse mottling, firm, moderate plasticity.		-0.21			
2.0–3.0	Clayey silt: Light grey with yellow/brown diffuse mottling, friable, firm, minor sands; fine grained.		-0.67			
			-0.47			
			-0.43			
3.0–4.0	Silty clay: Yellow/brown, firm, low plasticity.		-0.16			
			-0.12			
4.0–5.5	Silty clay: Yellow/brown with light grey mottling, firm, low plasticity.		-0.26	114	Minor roots (5 to 10mm) at 4m	1% Sand, 51% Silt, 48% Clay
		WC			Sample wet below 4.8m	
			-0.02			
5.5	EOH @ 5.5 metres					

LOGGED: N. Unland DATE: 25/02/2015

CHECKED: L. Randell DATE: 20/03/2015

FIELD BOREHOLE / WELL LOG

JACOBS

BOREHOLE / WELL NUMBER: SB14

PROJECT NUMBER: **IS039500**
PROJECT NAME: **Barwon Downs Vegetation Investigations**
LOCATION: **Barwon Downs**
DRILLING CO: **Drillmax**
DRILLING METHOD: **Hollow Auger**
BOREHOLE DIAMETER: **125 mm**
DATE STARTED: **28/02/2015** DATE COMPLETED: **28/02/2015**

WELL PERMIT NUMBER: **N/A**
TOTAL DEPTH (m bgl): **6**
REFERENCE POINT: **Ground Surface**
STATIC WATER LEVEL
Date: **28/02/2015** Depth (mbRP):
PROJECTION: **GDA 1994, Zone 54**
EASTING: **726683** NORTHING: **5740005**

DRILLING INFO.: METHOD: Hollow Augers (0.0–6.0 m); BIT LOG: 125mm Hollow Auger (0.0–6.0 m)

Depth (m)	Lithology	Water Cuts	Soil moisture (MPa)	Soil EC (uS/cm)	Comments	Soil Texture Analysis (% Sand, % Silt, % Clay)
0.0–0.3	Silt: Black, fine grained, loose, organic matter.					
0.3–0.7	Silty Sand: Light grey, fine grained, loose, organic matter.		-0.08	9	Abundant roots 0 to 0.7m	68% Sand, 29% Silt, 3% Clay
0.7–1.5	Clay: Orange with grey mottling, low plasticity.		-0.18 -0.08			
1.5–2.0	Silty Sand: Dark brown, low plasticity.		-0.21	114		35% Sand, 30% Silt, 35% Clay
2.0–4.5	Silty Sand: Grey with orange mottling, low plasticity.		-0.67 -0.47 -0.43 -0.16 -0.12 -0.26		Sample damp from 3.8m	
4.5–5.7	Silty Sand: Light grey, fine grained.	WC	-0.02		Sample saturated from 4.5m	
5.7–6.0	Silty Sandy: Black, fine grained.					63% Sand, 25% Silt, 12% Clay
6.0	EOH @ 6 metres					

LOGGED: L.Randell DATE: 28/02/2015
CHECKED: L. Randell DATE: 20/03/2015

Appendix H. Calculating soil moisture content

Soil moisture potential was converted to soil moisture content in a two-step process. Firstly, the known relationship between moisture potential and moisture content for different soil types was used to calculate the moisture content using soil descriptions and grain size analysis from Figure H.1.

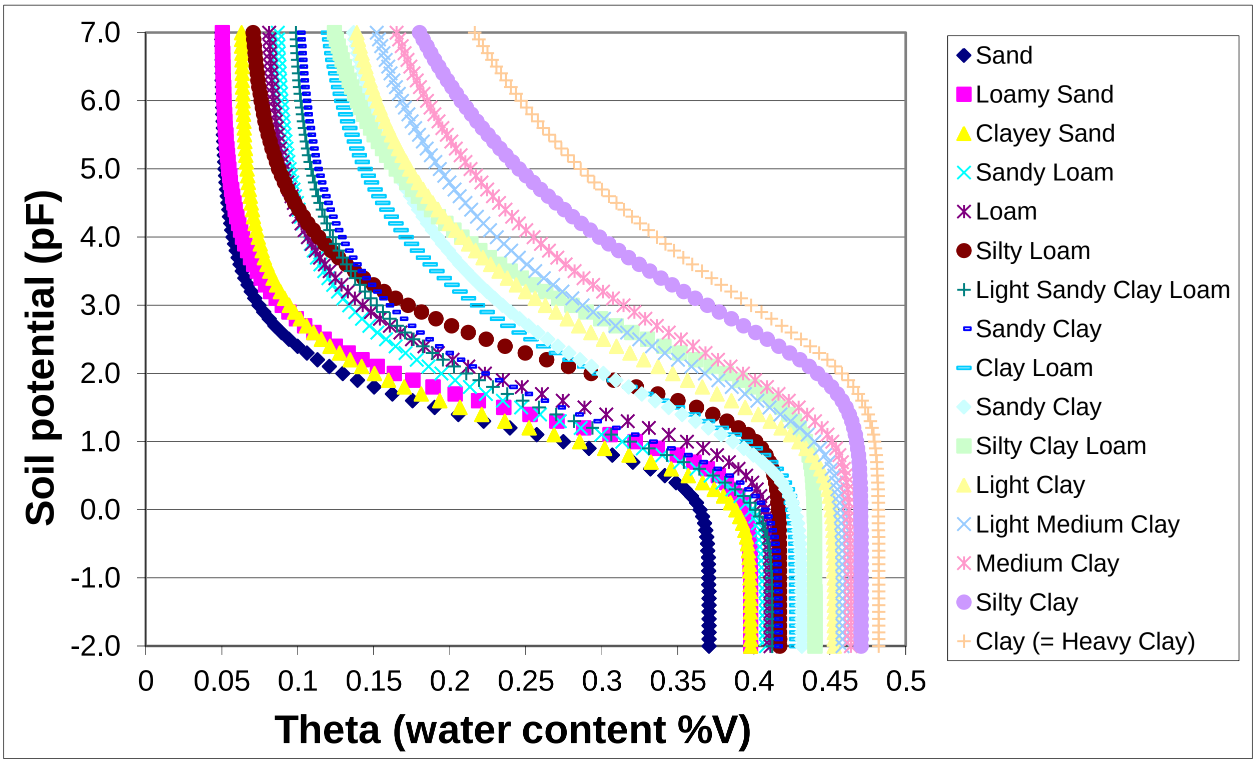


Figure H.1 : Relationship between moisture potential and moisture content for different soils types (Van-Genuchten, 1980)

These results were then compared to the moisture content provided by laboratory analysis for a number of samples that were collected as illustrated in Figure H.2. The relationship suggests that the calculated soil moisture content is an accurate representation of the data set.

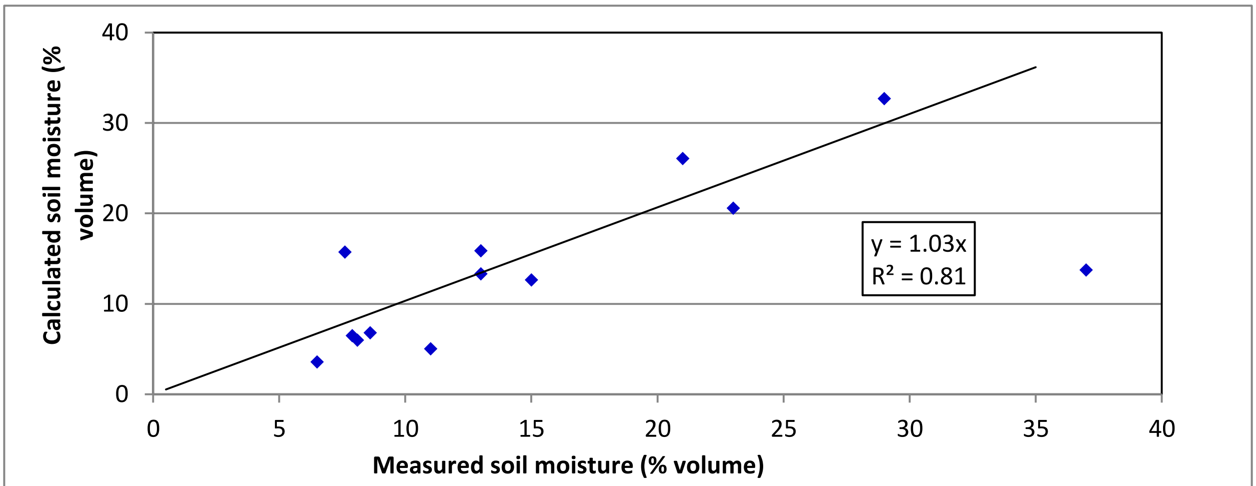
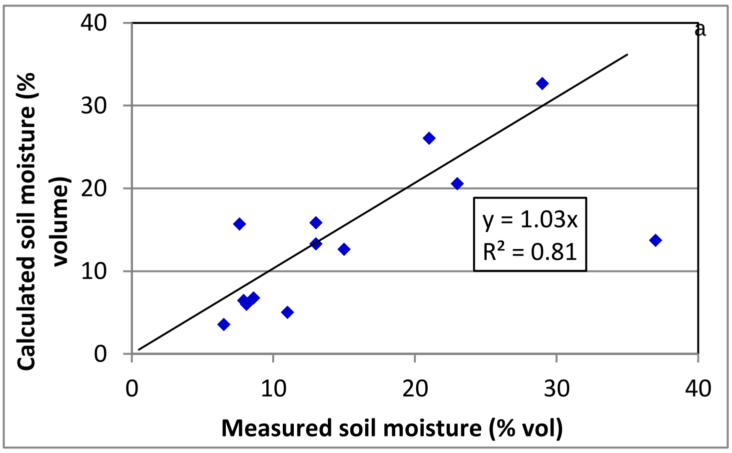


Figure H.2 : Covariance between calculated and actual soil moisture content

Appendix I. Calculating water in the unsaturated zone

The soil moisture content (the volume of water in a given volume of soil) was calculated for a number of soil profiles using measured soil water potential, sample descriptions and grain size analysis. These measurements were taken at 0.4 m intervals in soil cores taken throughout the field area as part of the tree water use study (Jacobs, 2015). Soil moisture content is estimated by using known relationships between moisture potential and water content for different soil types (Appendix G) and cross checked with samples analysed in the laboratory for soil moisture content (Figure I.1a). The soil moisture content estimates based on these calculations are presented in Figure I.1b.

The below figure illustrates that that majority of soil cores exhibit a soil moisture content of around 10 to 20% by volume. For simplification, an average soil moisture content of 17% by volume in the unsaturated zone has been applied in the volumetric analysis. For the soil types encountered, the average residual water content (the amount of water that remains when the soil is drained) is 8%. The residual water content has been subtracted from the average moisture content to give an average free drainage capacity of 9% by volume. The free drainage capacity is the volume of water that can be drained from the soil under gravity, which is equivalent to specific yield in an aquifer. While the free drainage capacity will be variable throughout each soil profile, this simplification is considered to be reasonable as recharge estimates are not particularly sensitive to this parameter. For example, a 50% reduction in the free drainage capacity results in approximately 20% reduction in the average recharge rate estimate.



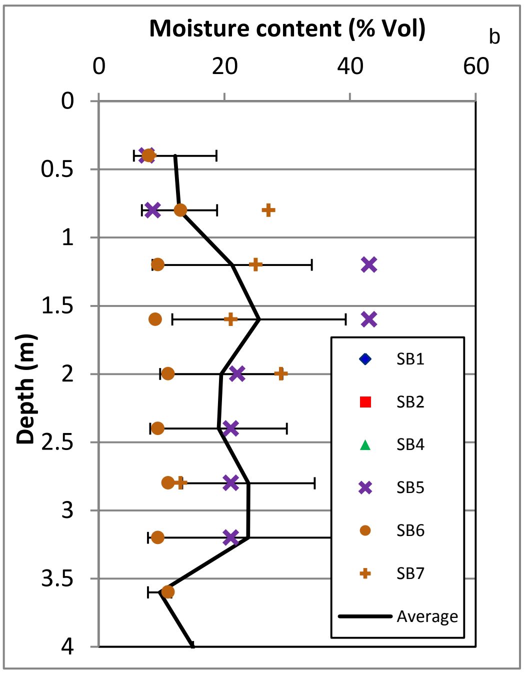


Figure I.1 : Calculated vs measured soil moisture content (a)1 and resulting soil moisture content with depth in soil at the Barongarook High (b)

[1]Outlier omitted from linear regression in Fig. 3a

[2]Horizontal error bars reflect 1SD from average in Fig. 3b

The soil moisture potential results measured in the soil cores suggest that water is typically being taken up by vegetation within 3 m of the surface. Below depths of 3 to 4 m, vegetation is essentially not able to use water as soil suction (Mpa) values approach zero. For the calculations in this study, it has been assumed that water above 3 m depth will be taken up by vegetation, while water below 3 m depth will be incorporated into the groundwater system and thus, incorporated into volumetric calculations. The volume of water in the unsaturated zone will therefore be calculated as the thickness between 3 m below ground level (bgl) (the base of the root zone) and the depth.

Appendix J. Estimating TDS and Cl concentrations

While Jacobs field investigation and terrestrial vegetation studies (Jacobs, 2015; Jacobs, 2016) provide new and localised groundwater data at the Barongarook High, chloride concentrations in groundwater were not analysed for bores screened in the LTA as part of these studies. However, these can be interpolated from EC data using known relationships between EC, TDS and Cl in groundwater from the area.

As part of work conducted by Petrides and Cartwright (2006) in the Barwon Downs Graben, comprehensive geochemical analysis was undertaken on 31 bores screened in the LTA. The results indicate a relationship of around 0.6 TDS units (mg/L) for every 1 EC unit (µS/cm). This relationship is illustrated in Figure J.1.

Similarly, a relationship of 0.5 to 1 was found when comparing Cl and TDS concentrations Figure J.2. By using these known relationships, it was possible to calculate the concentration of Cl in groundwater in the LTA based on EC data and a conversion factor of 0.3 Cl units (mg/L) to 1 EC unit (µS/cm).

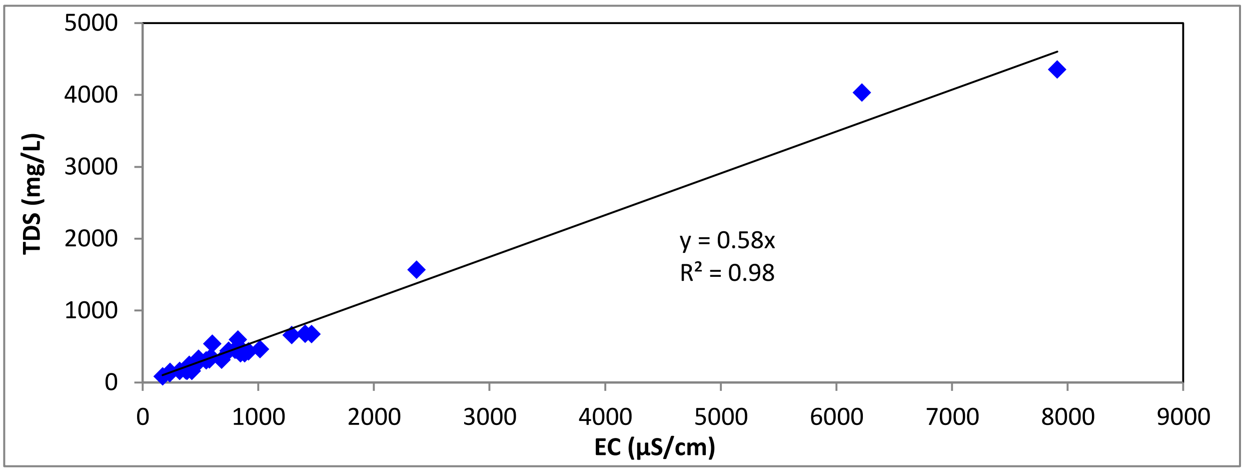


Figure J.1 : Relationship between TDS and EC from Petrides and Cartwright (2006)

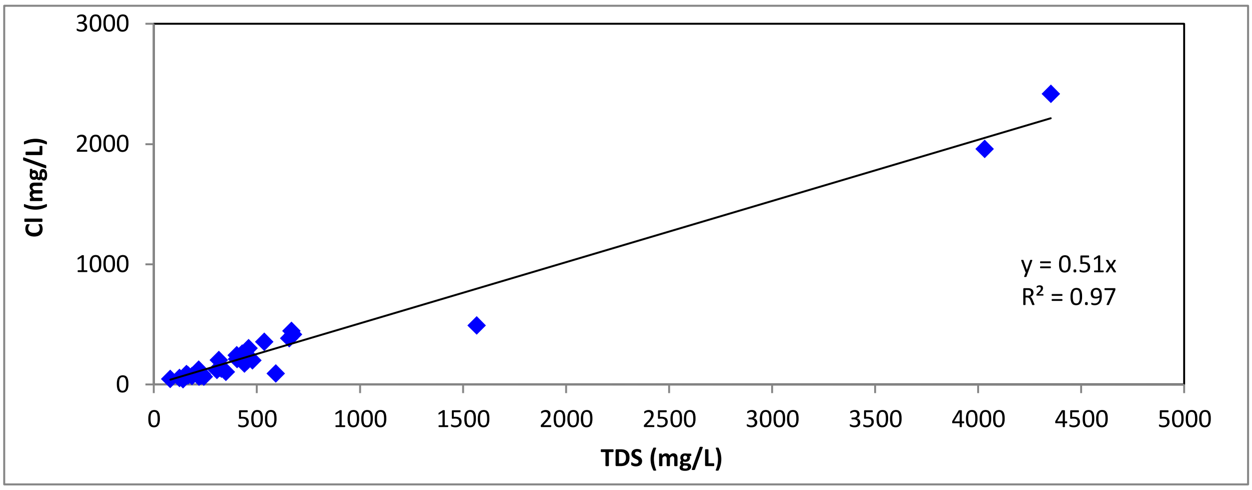


Figure J.2 : Relationship between CL and TDS from Petrides and Cartwright (2006)