# 2016 - 2017 Technical Works Program

Barwon Water

## Yeodene Swamp Study

IS191000-GW-RP-001 | FINAL DRAFT

9 November 2017



## 2016 - 2017 Technical Works Program

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## Contents

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*The sole purpose of this report is to present the findings of a desktop and field investigation carried out by Jacobs for Barwon Water ('the Client') in connection with the Yeodene Swamp ("the site"). This report was produced in accordance with and is limited to the scope of services set out in the contract between Jacobs and the Client.*

*The scope of work was limited to two sampling events conducted in autumn and winter. This report is based on assumptions that the site conditions as revealed through these sampling events are indicative of conditions throughout the site. The findings are the result of standard assessment techniques used in accordance with normal practices and standards, and (to the best of Jacobs' knowledge) they represent a reasonable interpretation of the current conditions on the site.*

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# Executive Summary

## KEY FINDINGS

- This study has characterised the chemical and physical processes occurring in and around Yeodene (Big) Swamp to improve the understanding of the swamp's behaviour and how that affects the volume and quality of water being released downstream.

- Building on previous technical studies, the following is known:
  - The monitoring program has shown that groundwater levels in the regional aquifer have declined. This has caused an adverse impact in lower reaches of Boundary Creek, through the mechanism of reduced flow in Boundary Creek.
  - The regional aquifer is present at the surface (outcrops) in the middle reach of Boundary Creek which is also known as Reach 2. Historically Reach 2 was a gaining reach (i.e. groundwater flows into the creek), however it is now a losing reach, where the creek loses flow to groundwater, through seepage.
  - The use of the borefield over the past 30 years has been responsible for most (two thirds) of the reduction in groundwater flow to Boundary Creek. The dry climate experienced during the same period accounts for the remaining part of the reduction (about one third). As the borefield was anticipated to impact stream flows in this part of the catchment, a supplementary flow of 2 ML/day has been released by Barwon Water into the upper reaches of Boundary Creek since 2002 to offset the reduction in groundwater flow to the creek.
- A review of existing information undertaken for this study highlighted:
  - The licence holder of the on-stream storage on Boundary Creek, known as McDonalds Dam, is required to pass all inflows to the dam between 1st November and 30th June. However, flow downstream of the Dam is often less than flow upstream of the Dam during this time period. Barwon Water discharges the supplementary flow in accordance with the conditions of the groundwater licence. Since monitoring commenced in 2014, flows immediately downstream of McDonalds Dam during the warmer months (November to April) were significantly less than flow upstream of the dam, confirming that not all the inflow to the Dam is being released particularly during critical low flow periods.
  - Since 1999, significant declines in pH of water have occurred in Reach 3 of Boundary Creek and are related to the drying of acid sulfate soils in Yeodene Swamp. Drying acid sulfate soils allows acid water to discharge to Boundary Creek.

- The field program conducted during this study determined:
  - Surface water flow in Boundary Creek often increases between McDonalds Dam and Damplands and this is likely to be the result of surface runoff from the catchment and potentially inflow to the creek from the local alluvial aquifer that is very close to the creek.
  - Surface water flow losses between the Damplands and Yeodene Swamp are as a result of groundwater recharge to the alluvial aquifer and evapotranspiration (water use by vegetation near the stream). The losses through this part of the catchment will fluctuate throughout the year depending on the seasonal climate. The surface water losses ranged between 2.9 and 9.9 ML/day in May and August respectively, and are representative of the Damplands and Swamp wetting up after a period of no flow.
  - The most significant changes in water quality in Boundary Creek occur through Yeodene Swamp and are consistent with the effects of acid sulfate soils. These effects include reduced pH, increased salinity, and increased concentrations of sulfate and dissolved metals.
  - Winter high flow conditions of greater than 15 ML/day in 2017 did not dilute acidic inputs or the concentration of dissolved metals significantly.
- Analysis of the data and field program concluded that:
  - The decline in pH (acidic water) appears to be correlated to reduced flow and in particular, periods when Boundary Creek has recorded cease to flow (no flow) at the Yeodene stream gauge.

  - It can be asserted that the processes contributing to flow reductions in Boundary Creek during 1990-1992 and since 1999 are the key factors driving pH change at those times. Those factors are known to be primarily groundwater extraction and contribution from a drier climate.
  - Cease to flow events have caused:
    - The swamp to dry and switch from a reducing to an oxidising environment,
    - Potential Acid Sulphate Soils turning into Actual Acid Sulphate Soils, and
    - Release of acidic water with high concentrations of dissolved metals downstream of the swamp.
  - The drying of the swamp and subsequent acidic water being released has been further exacerbated due to the 2 ML/day supplementary flow not reaching the swamp because the flows have not been passed at McDonalds Dam over the summer months.

- A review of possible management options to remediate the swamp indicated that:
  - Of the six options considered, inundating the swamp is recommended as the most technically feasible option. Improvements in water quality (increasing pH levels) are expected to be achieved within six months. Key features of this management option are:
    - Increasing the supplementary flow initially from 2 ML/day to 3 ML/day as recorded downstream of McDonalds Dam. It is possible that additional supplementary flows could be required during extreme dry weather events to prevent cease to flow periods at the Yeodene stream gauge (downstream of the swamp). It is also possible that this volume could be reduced to 2 ML/day once the swamp is permanently inundated. This is expected to take up to three years. Ongoing monitoring will help to assess the requirement for the supplementary flow.
    - Infilling fire trenches and agricultural drains at the eastern end the swamp to minimise water flow out of the swamp, therefore helping to keep areas saturated.

- Ongoing adaptive management would likely include:
  - Ongoing surface water and groundwater monitoring, and
  - Regular site visits during summer months to complete spot flow gauging and surface water quality monitoring.

## BACKGROUND

The Yeodene (Big) Swamp is a peat swamp that contains acid sulfate soils that have dried out, resulting in the release of acidic water to the lower reach of Boundary Creek and ultimately, the Barwon River.

The current state of the swamp reflects the culmination of numerous events throughout the catchment's history. This includes:

- The initial deposition of acid sulfate soils in the swamp,
- The construction of nearby agricultural drains and farming in the area over 100 years ago,
- Step changes in climate (including the Millennium Drought),
- The construction of an on-stream dam upstream of the swamp,
- Groundwater extraction by Barwon Water and the release of supplementary flows to Boundary Creek, and
- Peat fires in the swamp and the excavation of trenches by CFA to control these fires.

Before the study that is documented in this report there has been limited assessment of the swamp to understand the relative contributions of each of these factors and the hydraulic controls of the swamp.

In addition to Yeodene swamp itself, there have been limited scientific studies that have focussed on characterising the lower reaches of Boundary Creek. While monitoring downstream of Yeodene Swamp

(Yeodene gauge at Colac-Forrest Rd) has been conducted since 1979, subsequent changes in the flow and quality of the water as it moves past this gauge and into the Barwon River have not been undertaken.

## OBJECTIVES

The objectives of the Yeodene Swamp study were to:

- Improve the conceptual understanding of the processes that affect the volume and quality of water between McDonalds Dam and the Barwon River
- Recommend future management options for Yeodene Swamp to improve the condition and water quality downstream of the swamp (i.e. Reach 3 of Boundary Creek).

## APPROACH

This study involved three stages of work:

1. Review available data on groundwater levels, surface water flows and water quality changes over time.
2. An in-field program involving:
    a. Soil sampling and installation of six shallow bores (< 3m) in Yeodene Swamp to improve understanding of soils and groundwater level fluctuations.
    b. Surface water flow and water quality monitoring upstream and downstream of Yeodene Swamp to understand changes and potential causes.
3. To determine the feasibility of possible remediation options to neutralise the acid sulfate soils in Yeodene Swamp.

## SUMMARY OF FINDINGS

**Improved conceptual understanding**

The review of existing data, together with the new information collected during the field program, has significantly improved the conceptual understanding of the lower reaches (Reach 2 and 3) of Boundary Creek.

A conceptual diagram focussed on Reach 2 is shown below in Figure 0-1-1. For the purpose of describing the conceptual understanding, Boundary Creek is divided into three reaches that are hydraulically and hydrogeologically distinct:

- **Reach 1** (upstream of McDonalds Dam): the creek flows over basement and receives minor groundwater inflows. This section is considered to be gaining water from surrounding aquifers.
- **Reach 2** (downstream of McDonalds Dam to Yeodene Swamp): the creek flows over the regional aquifer (Lower Tertiary Aquifer). This reach used to receive groundwater inflow, however groundwater extraction and a drier climate have lowered the groundwater level in the aquifer and the creek now mostly loses water in Reach 2 via seepage. Yeodene Swamp is located at the downstream end of the Reach 2 and is situated on the boundary of the regional aquifer and the regional aquitard. This section is considered to be losing water to the surrounding alluvial aquifer.
- **Reach 3:** The creek flows over aquitard and receives minor groundwater inflow. This section is considered to be gaining water (albeit to a very minor degree).

The key features of the conceptual model are summarised in Table 0-1-1.

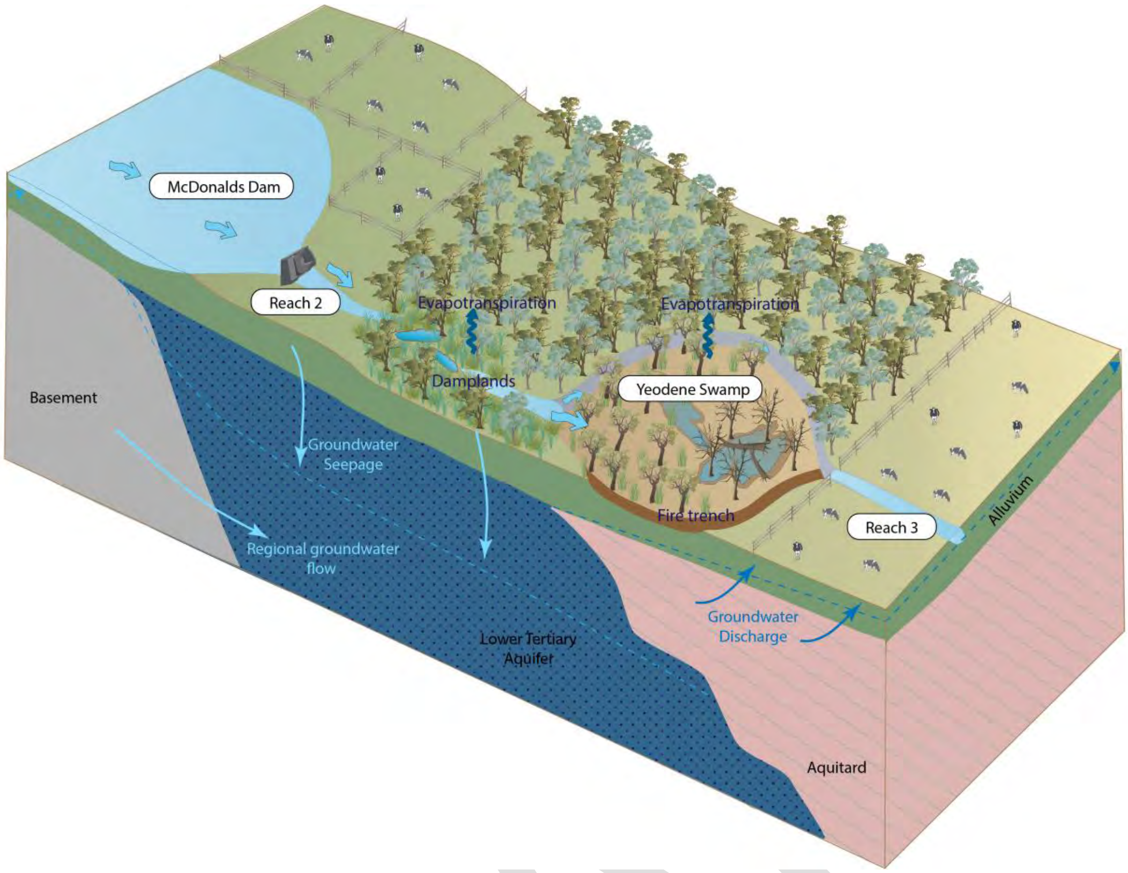



Figure 0-1-1 Conceptual diagram of Reach 2 in Boundary Creek

Table 0-1-1 Key features of the conceptual model of the lower reaches of Boundary Creek

| Feature | Key findings |
|---|---|
| **Catchment history** | The major changes to the Boundary Creek catchment include:<br>• Land clearing and channelisation of sections of Boundary Creek through the 1900s for agriculture and farming,<br>• Installation of an on-stream dam (McDonalds Dam) of 160 ML capacity in 1979,<br>• Major groundwater extraction by Barwon Water between 1985-1990, 1997-2001 and 2005-2010.<br>• Peat fires at Yeodene Swamp in 1997, 1998 and 2006.<br>• Excavation of fire trenches in 2010 by the CFA for fire control. |
| **Hydrogeology** | • Saturated alluvial sediments are likely to be present upstream of Yeodene Swamp as a localised perched aquifer (that is, separated to a large extent from the regional aquifer).<br>• Depth to watertable in the regional aquifer is 10-15 m below ground level upstream of Yeodene Swamp.<br>• Saturated peat sediments in Yeodene Swamp are hydraulically separated from the underlying regional aquifer (LTA) by the aquitard.<br>• The eastern end of swamp comprises saturated alluvial deposits overlying aquitard.<br>• The aquitard thins to the west and is absent upstream of the swamp, however the exact location where aquitard is absent is not known. |
| **Groundwater quality** | • Groundwater in the centre of the swamp is most affected by acid sulfate soils and less so downstream of the swamp (A3 and TB1a).<br>• Groundwater upstream of the swamp and in Reach 3 (downstream of the Yeodene stream gauge) is relatively unaffected by acid sulfate soils. |

| Feature | Key findings |
|---|---|
| **Surface water flow** | • Review of existing data showed that since monitoring commenced in 2014, flow downstream of McDonalds Dam during the warmer months (November to April) was less than flow upstream of the Dam.<br>• Surface water flows increase between McDonalds Dam and the top of the Damplands, which is likely to be result of surface runoff from the catchment and potential inflow from the local (perched) alluvial aquifer.<br>• Two spot flow measurement showed that surface water flow declines through the Damplands and Yeodene Swamp which is interpreted to be a result of groundwater recharge and evapotranspiration. The losses will vary seasonally, and were 2.9 ML/day in May 2017 and 9.9 ML/day in August 2017 which represents the swamp re-wetting after a period of no flow.<br>• Surface water flows are variable gaining and losing in Reach 3. |
| **Surface water quality** | • Review of existing data showed that since 1999, significant declines in pH have occurred in Reach 3 of Boundary Creek and are related to the drying of acid sulfate soils in Yeodene Swamp.<br>• The most significant changes in water quality occur through Yeodene Swamp. These changes are consistent with the effects of acid sulfate soils including reduced pH, increased salinity, and increased concentrations of sulfate and dissolved metals.<br>• Winter high flow conditions of greater than 15 ML/day recorded during the field investigation program did not dilute acidic inputs or the concentration of dissolved metals significantly. |
| **Groundwater – surface water interaction** | • Immediately downstream of McDonalds Dam to the Damplands the spot flow measurements indicate the creek could be gaining water. Inflows to the creek are likely to be result of surface runoff from the wider catchment and potential inflow from the local (perched) alluvial aquifer. This is new information and improves the conceptualisation of the Reach 2.<br>• The Damplands and Yeodene Swamp were observed to be losing water to groundwater, which is consistent with the existing conceptualisation.<br>• Reach 3 of Boundary Creek is variable gaining/losing to groundwater, consistent with the existing conceptualisation. |
| **Water balance** | • The greatest losses of surface water occur through the Damplands and Yeodene Swamp. This is estimated to range between 2.9 ML/day in May and 9.9 ML/day in August 2017. These volumes of water are representative of the swamp re-wetting after a period of no flow. It is estimated that the majority of the loss is recharge to groundwater with evapotranspiration making up less than 1 ML/day during these months.<br>• Evaporation losses will be higher during the summer months and could be up to 2.5 ML/day. |
| **Vegetation** | • This part of Yeodene Swamp was not a permanent swamp historically (i.e. greater than 50 years ago) as the tree ferns and trees would not have established unless there was periodic drying. This could be the result of the construction of agricultural drains in the area.<br>• The trees and tree ferns are likely to have died as a result of root death caused by permanent inundation.<br>• Inundated area is un-vegetated as a result of the acidic water which is toxic to most plant species. |

**Remediation options for Yeodene Swamp**

Potential management strategies to improve the quality and volume of water flowing in Reach 3 of Boundary Creek were considered. Six options were reviewed:

1. Do nothing
2. Direct treatment of soils with neutralising agents in Yeodene Swamp
3. In-drain water treatment with limestone in Reach 3 of Boundary Creek (downstream of swamp)
4. Diluting acidic discharge in Reach 3 of Boundary Creek.
5. Revising flow release location to Reach 3 of Boundary Creek and isolating the swamp from the creek.
6. Inundating Yeodene Swamp

A summary of the feasibility of each option is provided below in Table 0-1-2.

Table 0-1-2 Summary of the key findings of the potential management options

| Option | Feasibility for Yeodene Swamp | Rationale |
|---|---|---|
| **Do nothing** | Not feasible | • Yeodene Swamp will continue to release acidic water in Reach 3. This is considered unacceptable |
| **Treatment of soils** | Not feasible | • Significant works would be required to access the entire swamp to distribute neutralising agents, which will be very disruptive to existing flora and fauna.<br>• Significant costs associated with first application and subsequent applications are likely to be required. |
| **Installation of a lime drain in Reach 3** | Not feasible | • A limestone drain has the potential to improve water quality during low flow periods, however there would be limited benefit during high flow events.<br>• Significant capital costs would be required which would result in major modifications to Reach 3 and ongoing maintenance would also be necessary. Furthermore, water quality in Yeodene Swamp would not improve.<br>• This option is more fixing the symptom rather than the problem. |
| **Diluting acidic discharge** | Not feasible | • Volumes of water required for dilution cannot be sourced in this region and would increase flooding and adversely impact Reach 3:<br>o 250 ML/day during low flows<br>o 1,200 ML/day during high flows |
| **Revising flow release location** | Not feasible | • Require the hydraulic isolation of Yeodene Swamp from Boundary Creek.<br>• Improve water quality in Reach 3 under summer low flow conditions, however likely to cause adverse impacts on water quality under high flow conditions when the swamp floods as pent up acid would be flushed out in high flows.<br>• This would increase drying in the swamp, which would exacerbate the acid sulphate soils in the swamp. |
| **Inundating Yeodene Swamp** | Feasible | • Key indicator for low pH events is “cease to flow” conditions at the Yeodene Swamp. This objective of inundating the swamp is to prevent cease to flow events at Yeodene.<br>• Technically feasible and cost effective option to inundate swamp by increasing supplementary flows and infilling fire trenches and agricultural drain at eastern end. Approach to complete this would involve:<br>o Infill the fire trenches and block the agriculture drain, ideally before April 2018 (pending approvals) to allow the swamp to retain more water over the winter months.<br>o Minimum flow required initially is 3 ML/day as measured below McDonald’s Dam.<br>• Low flow requirement of 3 ML/day is a best estimate based on a detailed assessment of the historical data. It is possible that more water could be required for short time periods during very dry conditions. Equally it’s also possible that this volume could be reduced to 2 ML/day within 2-3 years as the swamp remains saturated.<br>• Ongoing adaptive management is required that involves regular monitoring and site visits are recommended to ensure the minimum flow requirement is meeting the objective. |

## CONCLUSIONS

This Yeodene Swamp study has improved the conceptual understanding of water related processes in the lower reaches of Boundary Creek. The improved understanding was used to assess potential remediation options to improve the condition of the Yeodene Swamp and subsequent water quality issues in Reach 3 of Boundary Creek.

Inundating Yeodene Swamp to reduce the availability of oxygen to create reducing conditions, would ultimately reinstate the acid generation profile of the Swamp to pre 1999 conditions and is considered to be both technical feasible and is likely to be cost effective. A review of the historical data and an estimate of the losses through the Damplands and the swamp, indicate that approximately 3 ML/day is likely to be required (as measured downstream of McDonalds Dam) to ensure the swamp remains saturated and flow is maintained at the Yeodene stream gauge.

In addition to the increased supplementary flow, the fire trenches and agricultural drain at the eastern end the swamp would also need to be infilled to minimise water losses from the swamp by drainage.

## RECOMMENDATIONS

It is recommended that in order to improve the volume and quality of water draining the Yeodene Swamp, and to rehabilitate the swamp itself, permanent inundation should be undertaken as a remediation strategy.

Monitoring data suggests that an initial increase of flow of approximately 3 ML/day measured downstream of McDonalds Dam is likely to be sufficient to achieve this outcome.

Recommendations to implement this remediation strategy are:

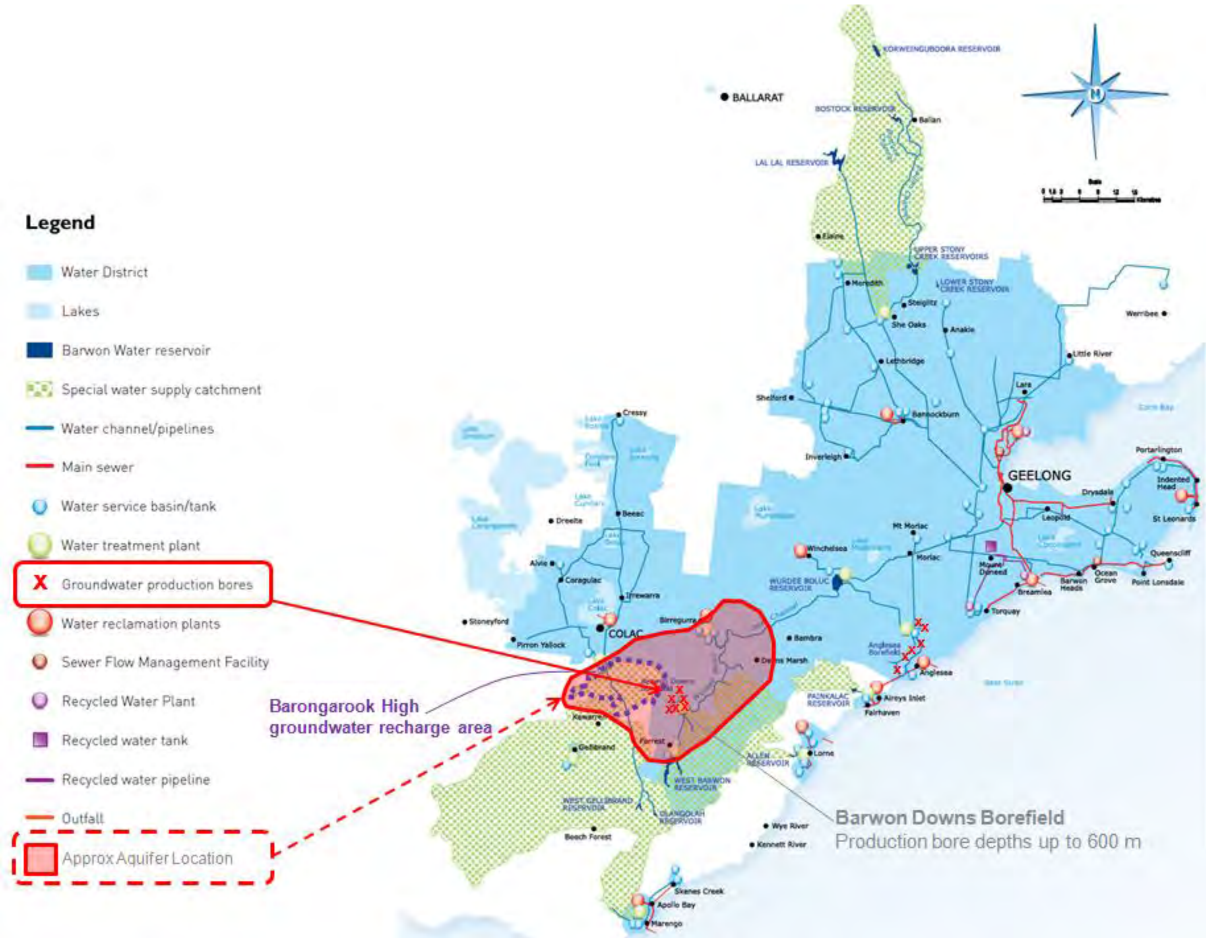
- Confirm design and method to infill fire trenches and agricultural drain.
- Undertake capital works to infill trenches and agricultural drain, ideally before April 2018 to have inundation start during the coming winter (pending approvals).
- Automate flow control from McDonalds Dam to ensure minimum 3 ML/day is released between November and June before the end of 2017.
- Continue groundwater and surface water monitoring.
- Install data loggers in bores YS01, YS02 and YS05.
- Decommission bores YS03, YS04, YS06.
- Monthly site visits between November and May until water quality in Reach 3 has improved to complete spot flow gauging and surface water quality monitoring.

# 1. Introduction

## 1.1 Barwon Downs region

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

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



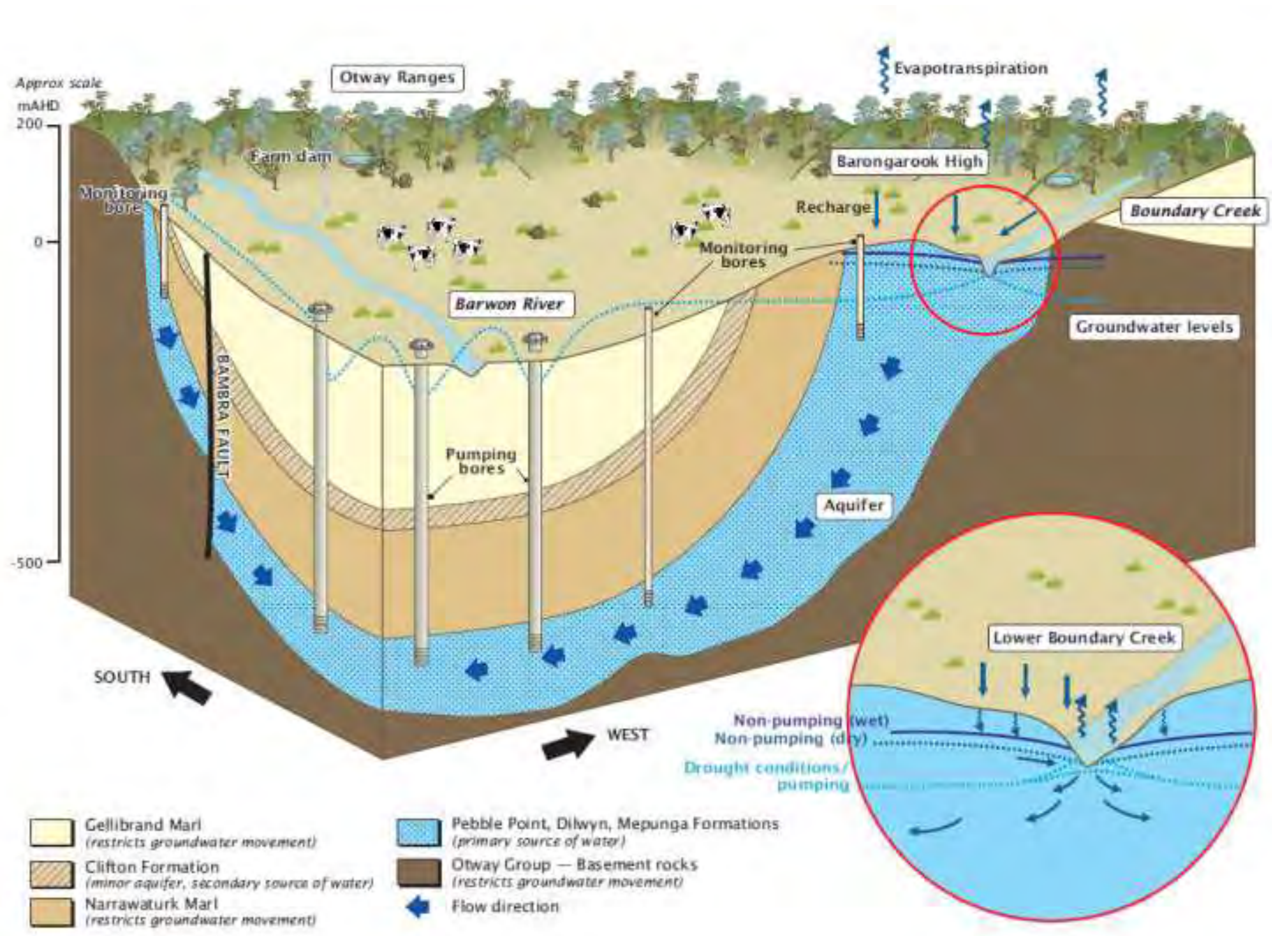

The regional groundwater system extends beneath two surface water catchments, the Barwon River catchment and the Otways Coast catchment.

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

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

The borefield taps into an underground source of water, known as the Lower Tertiary Aquifer, with depths of up to 600 metres at the borefield. The aquifer covers an area of approximately 500 km$^2$ below the surface and is connected to the surface in both the Barwon River catchment (Barongarook High) and the Otways Coast catchment near Gellibrand. Barongarook High is the main recharge area of the aquifer because of its unconfined nature.

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




## 1.2 History of the Barwon Downs borefield

### 1.2.1 Borefield history

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

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

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

### 1.2.2 Groundwater extraction

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

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

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

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

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

### 1.2.3 Licence history

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

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

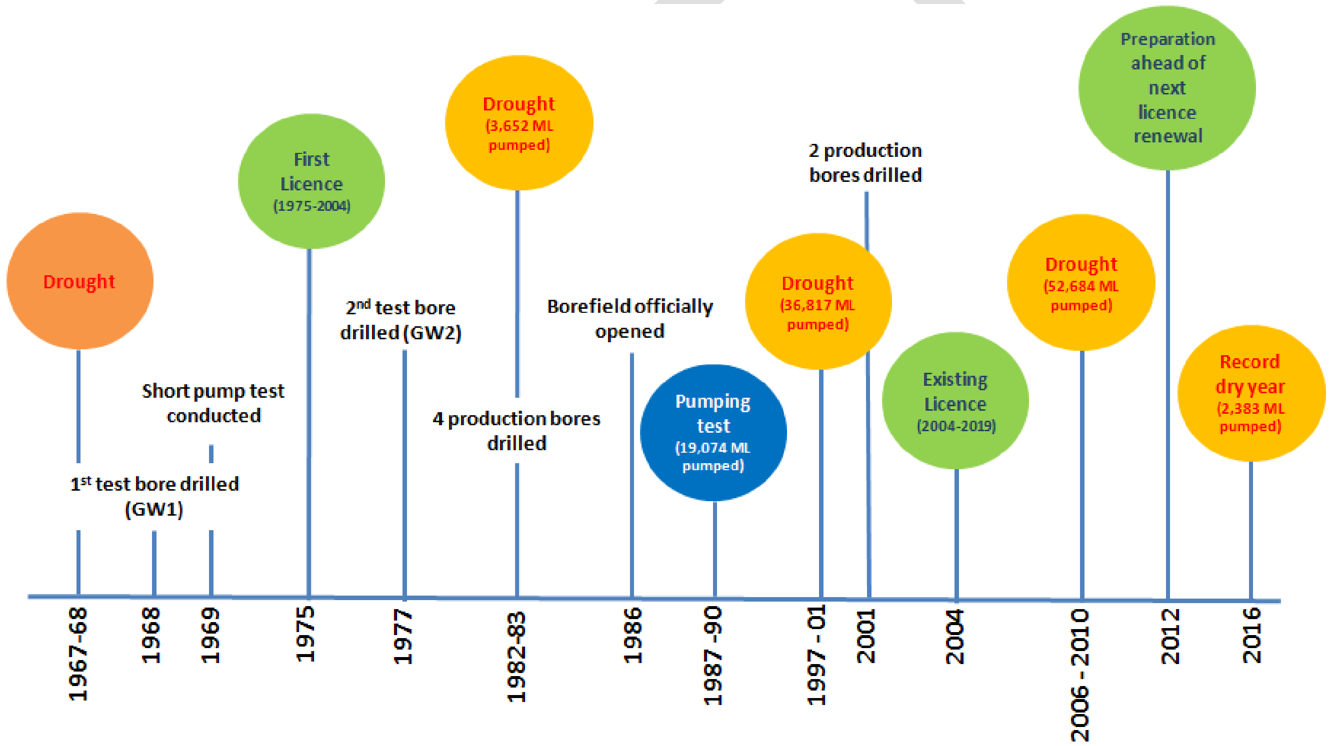
The licence was subsequently renewed for two periods of five years up to 2000. From 2000, the licence was temporarily extended three times for a total of four years to allow the licence renewal to take place through to 31 August 2004.

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

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

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

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




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

## 1.3 Current groundwater licence

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

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

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

## 1.4 Strategic drivers for the Barwon Downs technical works monitoring program

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

Driving the need for this monitoring program is the reliance on the borefield to provide water security for Barwon Water customers.

### 1.4.1 Water security

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

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

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

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

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

### 1.4.2 Community issues

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

Areas of community interest recently have included the:

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

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

### 1.4.3 Informing the licence renewal

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

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

## 1.5 Overview of the technical works monitoring program

### 1.5.1 Monitoring program development

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

Stage 1: Review of the existing monitoring program

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

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

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

Stage 2: Technical works monitoring program scope refinement

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

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

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

Stage 3: Construction of additional monitoring assets

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

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

Stage 4: Ongoing monitoring

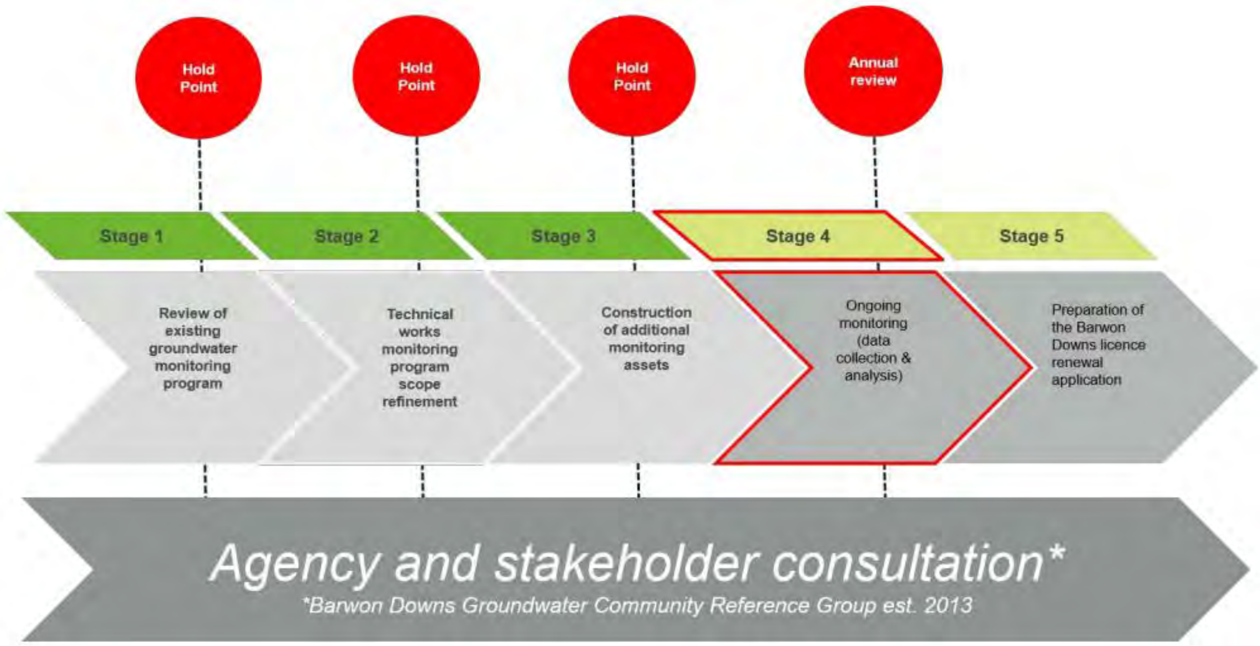
The technical works monitoring program is now in a phase of data collection and preliminary analysis. The intention of this stage is to update the conceptual understanding of the hydrogeology in the Barwon Downs region. This will be based on data collected from additional and existing monitoring assets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

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

Stage 5: Preparation for licence renewal submission

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

Figure 1-4 Development of the technical works monitoring program




### 1.5.2 The inter-relationships of the technical works monitoring program

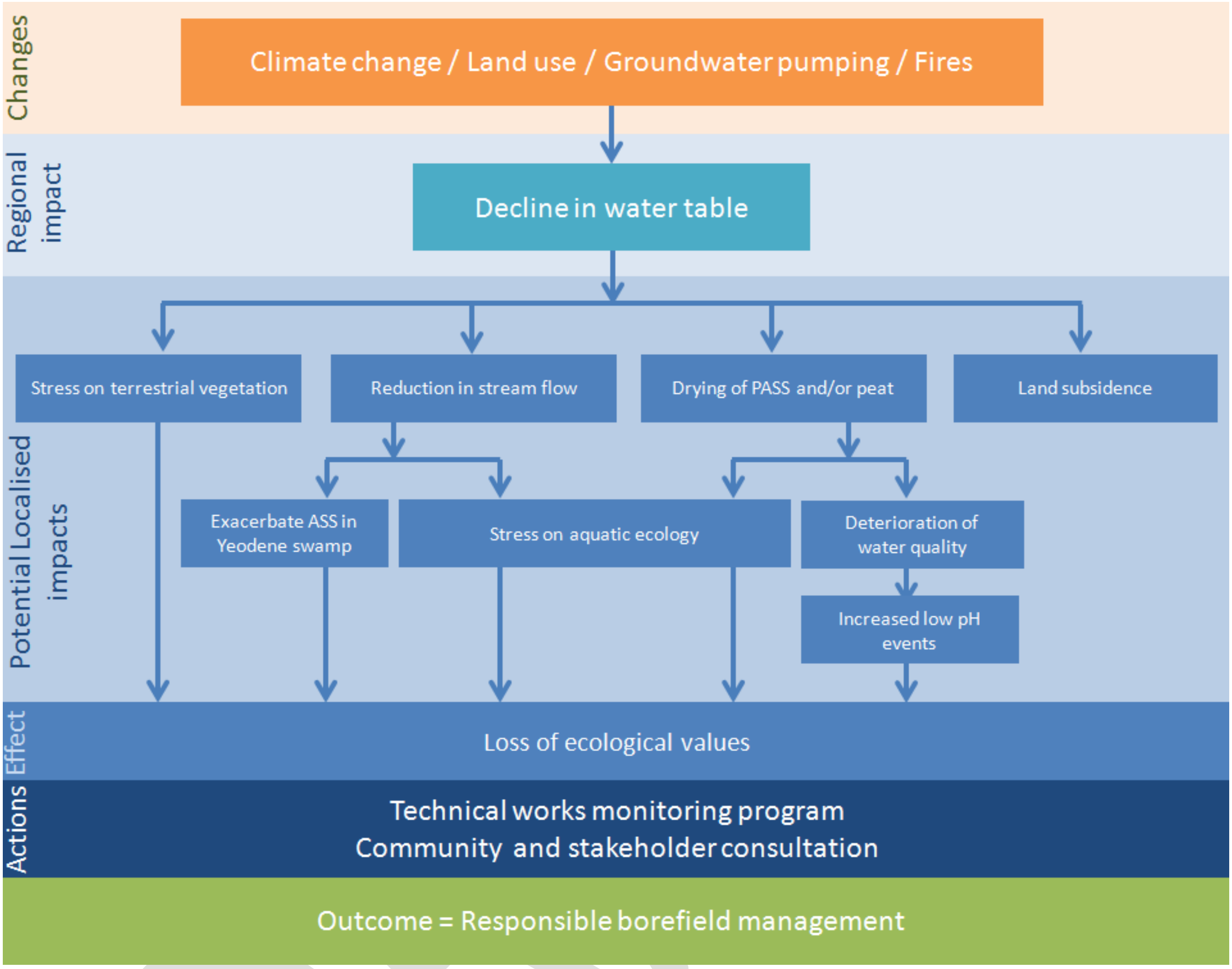
The technical works monitoring program is a complex, multi-disciplinary project due to the overlapping nature of the various components of the program as shown in Figure 1-5.

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

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

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

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




## 1.6 This report

This report documents the findings of the Yeodene Swamp. The purpose of this study is to characterise the chemical and physical processes affecting the volume and quality of water which will be used to inform potential strategies to help manage current water quality issues in the lower reaches of Boundary Creek.

### 1.6.1 Scope of work

Understanding the processes that affect the volume and quality of water as it moves through the Boundary Creek Catchment requires an understanding of both the processes that have led to the current state of the catchment, and of how the catchment operates currently.

The first section of this study provides a summarised history of the Boundary Creek catchment. This includes a timeline of major events that have occurred in the Boundary Creek catchment historically, and the potential impact that these may have had on water flow and quality. Additionally, existing monitoring data and information provided by past studies will be reviewed within the context of this report.

The second section of the study details a field program aimed at characterising the current state of the Boundary Creek system. The field program includes the installation of piezometers, lithological analysis, soils analysis, surface water flow gauging, and both surface and groundwater quality monitoring. The results of the field program are then used to estimate the movement of water through Yeodene Swamp and Boundary Creek, and the major processes affecting water quality as it moves through the system.

The final section of this study builds on the understanding developed during the first two sections, to assess potential strategies for the management of Yeodene Swamp and Boundary Creek. This includes a review of the potential positive and negative impacts of different strategies, and the estimated costs associated with each strategy.

# 2. Boundary Creek Catchment

## 2.1 Chapter overview

The purpose of this chapter is to describe the changes over time in the Boundary Creek catchment and how these have influenced the volume and quality of water moving through Boundary Creek.

This chapter also describes the conceptual understanding of the local hydrology and hydrogeology of the lower reaches of the creek, including Yeodene (Big) Swamp.

The key findings are summarised in Table 2-1.

Table 2-1 Key findings of the conceptual understanding of the lower reaches of Boundary Creek

| Feature | Key findings |
|---|---|
| Catchment history | The major changes to the Boundary Creek catchment include:<br>• Land clearing and channelisation of sections of Boundary Creek through the 1900s for agriculture and farming,<br>• Installation of an on-stream dam (McDonalds Dam) of 160 ML capacity in 1979,<br>• Major groundwater extraction by Barwon Water between 1985-1990, 1997-2001 and 2005-2010.<br>• Peat fires at Yeodene Swamp in 1997, 1998 and 2006.<br>Excavation of fire trenches in 2006 by the CFA for fire control. |
| Groundwater surface water interactions | For the purpose of describing the conceptual understanding, Boundary Creek is divided into three reaches that are hydrogeologically distinct:<br>• Reach 1 flows over basement and receives minor groundwater inflows.<br>• Reach 2 flows over the regional aquifer. This reach used to receive groundwater inflows, however groundwater extraction and changes in climate have lowered the groundwater level in the aquifer, and the creek now loses water in Reach 2 via seepage. Yeodene Swamp is located at the downstream end of Reach 2 on the boundary between the aquifer and aquitard.<br>• Reach 3 flows over aquitard and receives minor groundwater inflows. |
| Surface water flows | • Since 2014, flow downstream of McDonalds Dam during the warmer months (November to April) was less than flow upstream of the Dam.<br>• Since 1999, significant declines in pH have occurred in Reach 3 of Boundary Creek and are related to the drying of acid sulfate soils in Yeodene Swamp. |

## 2.2 Catchment history

<u>Agriculture and farming</u>

The Boundary Creek catchment has undergone significant modification over the last century. In 1886 the Gerangamete drain was completed, followed by a series of adjacent drains inn 1888 (Jennings, 2008). These drains claimed low lying land for agricultural production, and resulted in the removal of large sections of lowland forest and grassy woodland, as evidenced by Ecological Vegetation Class mapping (Figure 2-1). The drainage of these areas is likely to have lowered the groundwater level near the drains and increased runoff, while reduced forest coverage may have increased groundwater recharge in these areas.

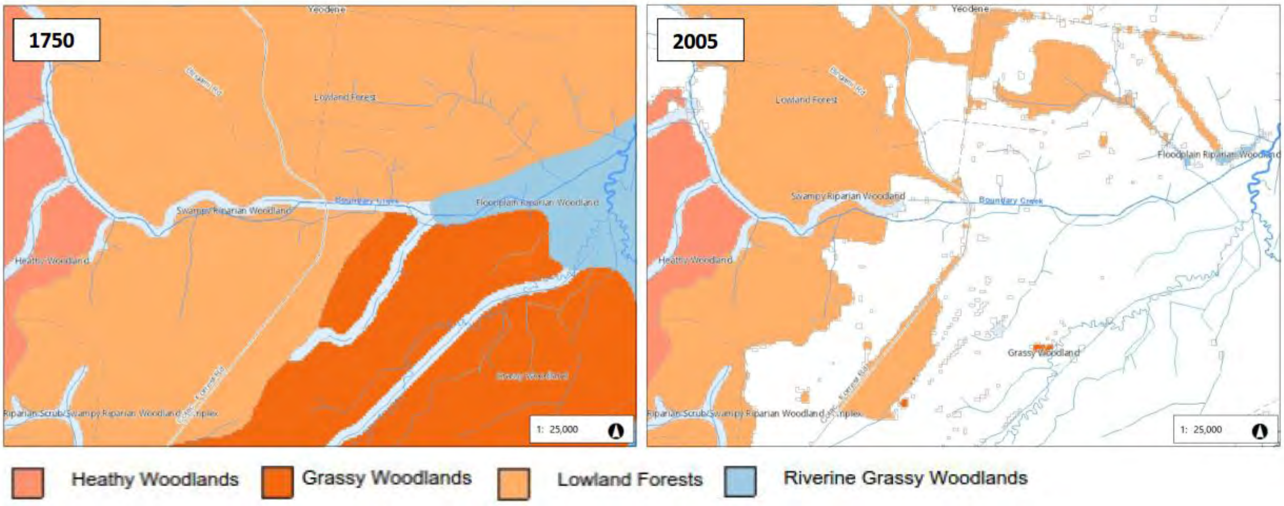



Figure 2-1 Ecological Vegetation Class mapping of Boundary Creek catchment in 1750 and 2005

McDonalds Dam

In 1979, a dam (referred to as McDonalds Dam) was constructed in the central reach of the creek. The dam has a storage capacity of 160 ML, is between 8 and 9 hectares in surface area and is a source of evaporation and flow retardation in the catchment.

Groundwater extraction

In August 1982, the first period of groundwater extraction from the Barwon Downs borefield commenced. This continued until June 1983, resulting in the extraction of approximately 3,650 ML of water (Figure 2-2). This represented an initial test phase, and was followed by further extraction tests between 1985 and 1990, resulting in the extraction of over 22,000 ML. Subsequent periods of borefield operation have occurred from 1997-2001, 2005-2010 and in 2016, resulting in the extraction of a further 80,000 ML over these periods.

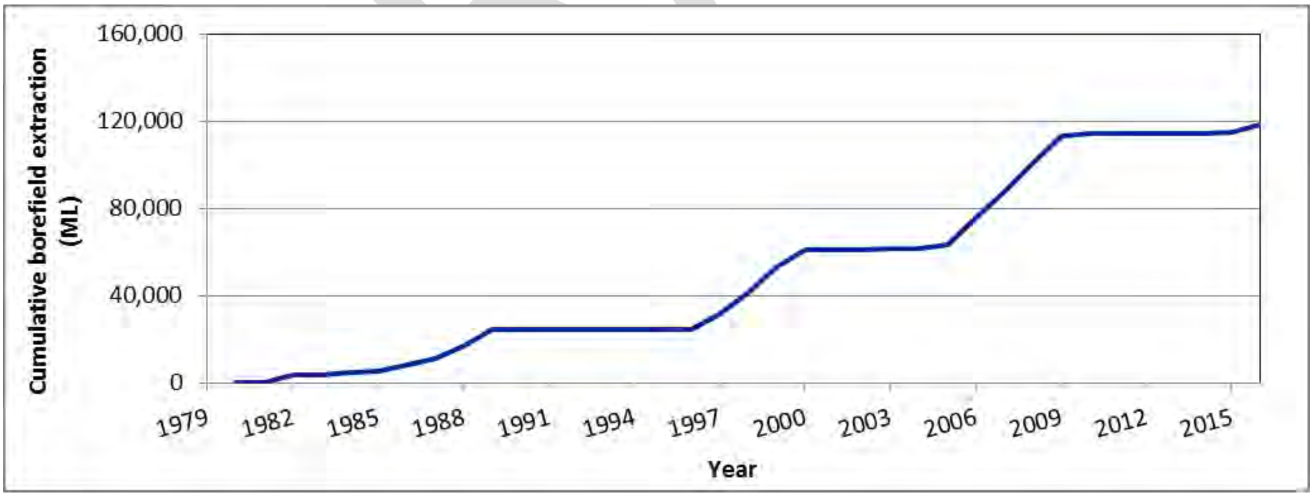



Figure 2-2 Cumulative volume of borefield extraction

Climate variability

In addition to borefield operation, there have been significant shifts in the long term climatic conditions across Victoria and the Boundary Creek catchment. Table 2-3 shows the rainfall plotted as cumulative departure from the mean. This figure shows rising trends when the rainfall is above average and declining trends when the rainfall is below average. The rainfall during this time includes an extended period of reduced rainfall in between 1900 and 1955, and has been followed by a period of increased rainfall between 1955 and 1997. More recently, climatic variability has included a period of drought between 1982 to 1983, a period of above average rainfall between 1983 and 1995, the millennium drought between 1995 and 2010, and below average rainfall between 2014 and today.

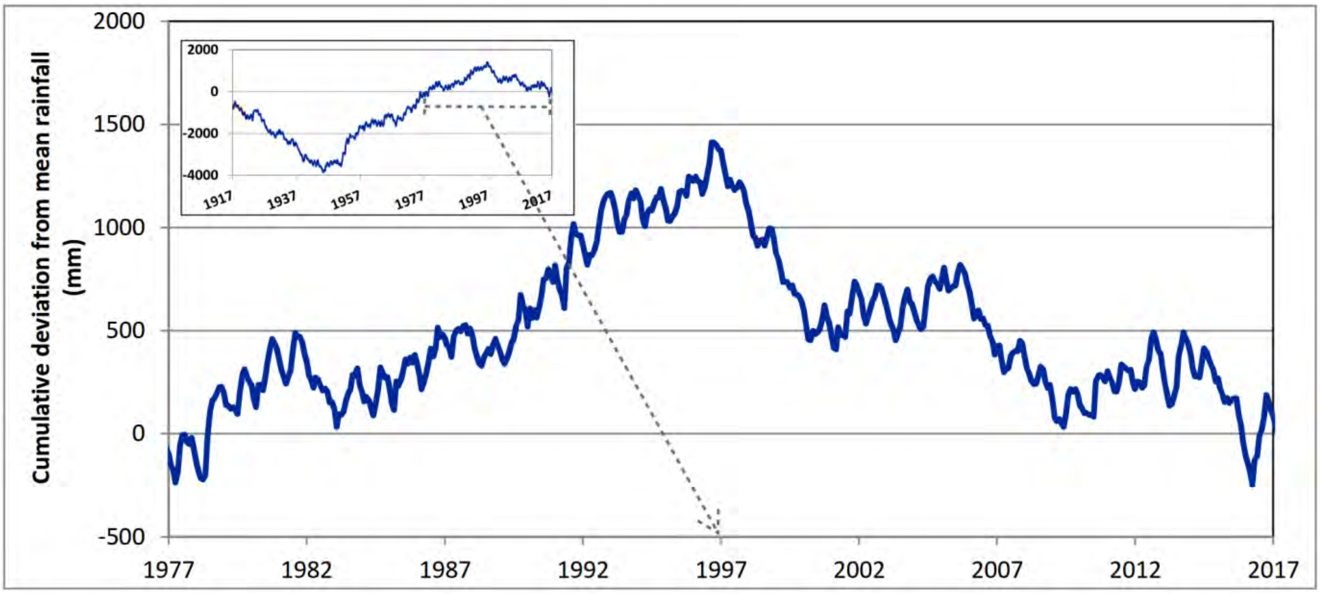



Figure 2-3 Cumulative deviation from mean annual rainfall at Forest State gauge (BOM gauge 090040)

<u>Fires in Yeodene Swamp</u>

At the start of the millennium drought, in the summer of 1997, a bushfire through the state forest in Yeodene resulted in the ignition of peat in the Yeodene Swamp (Glover, 2014). Infra-red scans by the CFA in 1998 suggested that the fire had been put out, however anecdotal records of smoke in the swamp, and subsequent re-ignition of the fire in 2010 suggest that peat may have been smouldering in the subsurface of the swamp between 1998 and 2010 (Himmelreich, 2010).

In response to the 2010 re-ignition, a fire trench up to 3 m deep and 1 km long was excavated by the local CFA along the southern and eastern boundaries of the swamp (see Figure 2-4) to contain the peat fire in early 2010 (Glover, 2004). The construction of these fire trenches is likely to have intersected some runoff to the swamp from the southern uphill slopes. Further, the trenches are likely to have intersected the water table, resulting in the drainage of groundwater and the lowering of the water table.

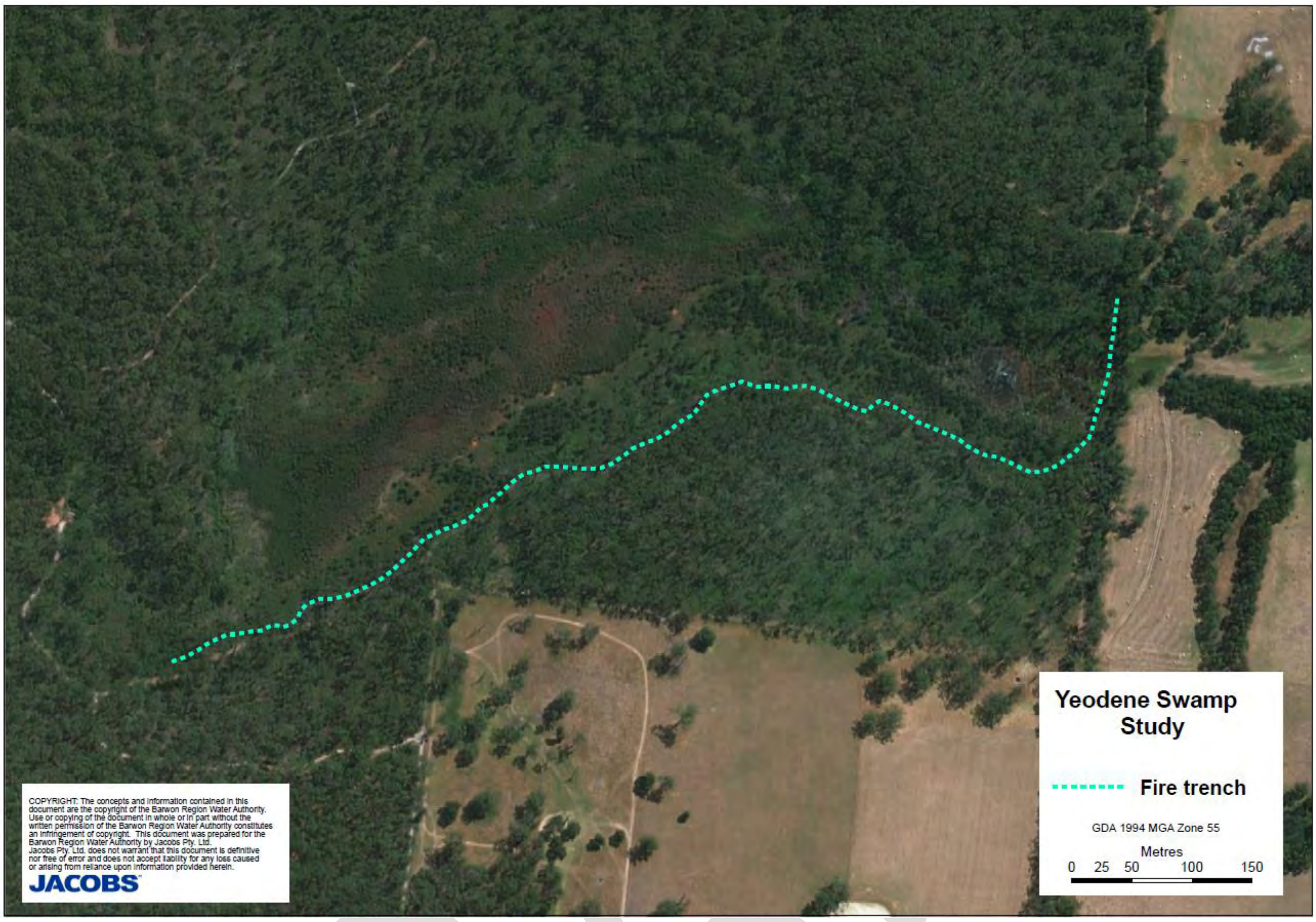



Figure 2-4 Approximate location of the fire trench excavated by the CFA in 2010

## 2.3 Hydrogeology

Boundary Creek flows through three distinct hydrogeological settings. These have been classified as Reaches 1, 2 and 3 (Jacobs, 2017a) and are illustrated in Figure 2-5 below.

- The upper reach (Reach 1) flows predominantly over outcropping bedrock which is characterised by impermeable Palaeozoic sandstone, siltstone and mudstone.
- The central reach of the creek (Reach 2) flows over the outcropping regional aquifer (the Lower Tertiary Aquifer or LTA), which is characterised by permeable sands of the Mepunga, Dilwyn and Pebble point formations. The Yeodene Swamp is located at the downstream end of Reach 2 on boundary between the regional aquifer and the aquitard.
- The lower reach of Boundary Creek (Reach 3) flows over an aquitard (the Mid-Tertiary Aquitard or MTD) and is characterised by silty clays of the Gellibrand Marl.
- Shallow Quaternary alluvium occurs locally along the flow path and overlies most of these regional formations. This includes swamp deposits and acid sulfate soils that occur throughout the Yeodene Swamp.

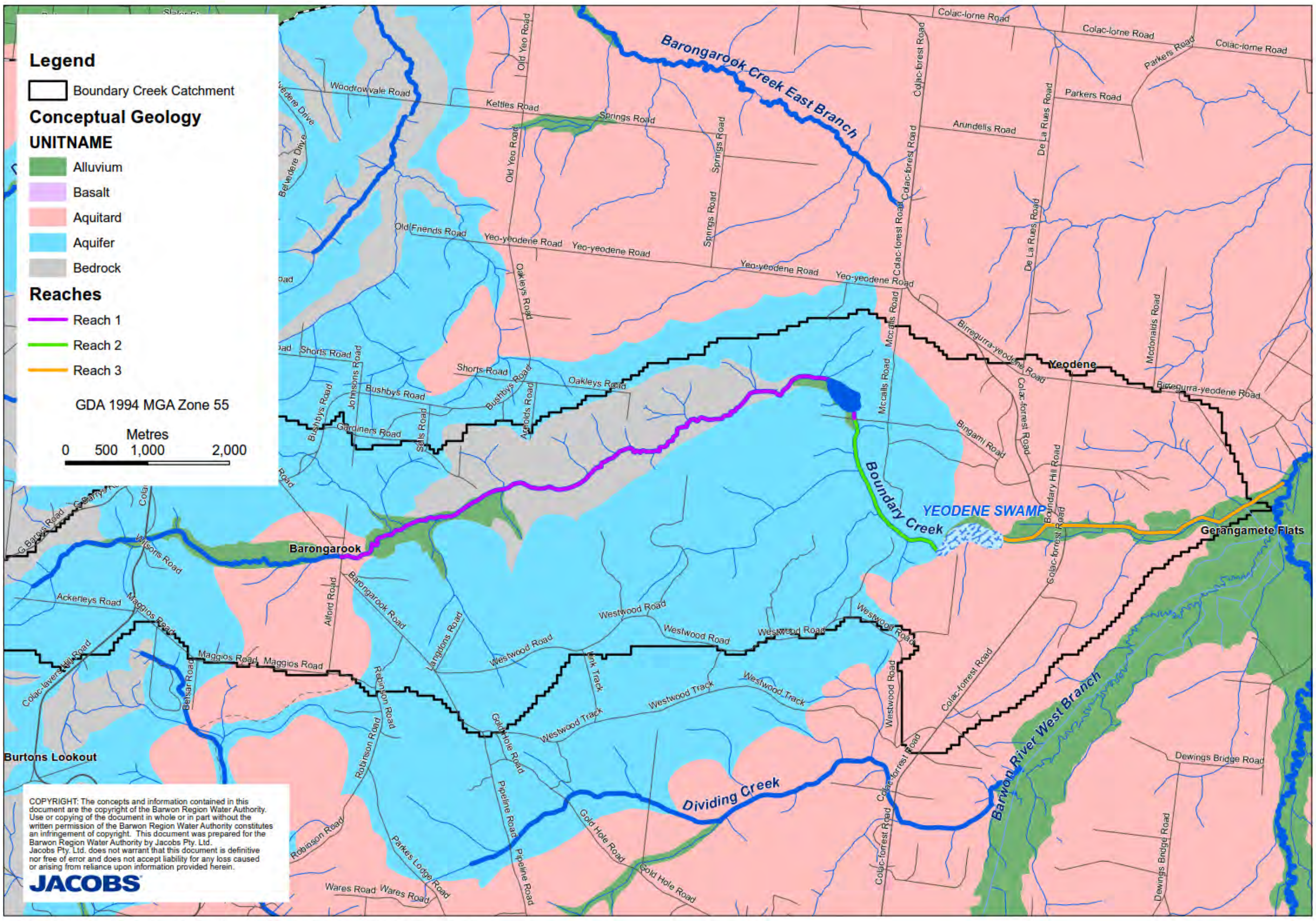



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Figure 2-5 Simplified geology of the Boundary Creek Catchment

### 2.3.1 Groundwater levels and groundwater surface water interaction

Groundwater levels adjacent to the river in this part of the catchment are monitored by several groundwater bores as listed in Table 2-2 and shown in Figure 2-6.

Table 2-2 Summary of existing bores monitoring groundwater levels adjacent to the river

| Bore | Depth (m) | Screened interval (m) | Unit monitored | Water level record | Water quality available |
|---|---|---|---|---|---|
| 109108 | 12 | 6 - 10 | Regional aquifer (LTA) | 1983-2010 | Yes |
| 109110 | 99 | 67 - 77 | Regional aquifer (LTA) | 1981-2017 | Yes |
| 109111 | 42 | 22 - 40 | Regional aquifer (LTA) | 1980-2015 | Yes |
| 109112 | 59 | 24 - 59 | Regional aquifer (LTA) | 1984-2017 | Yes |
| 109113 | 271 | 198 - 231 | Regional aquifer (LTA) | 1984-2017 | Yes |
| 109130 | 18 | 8 - 16 | Regional aquifer (LTA) | 1986-2017 | Yes |
| 109143 | 24 | 12 - 18 | Regional aquifer (LTA) | 1987-1989 | No |
| TB1a | 13 | 9 - 12 | Alluvial aquifer | 2014-2017 | Field only |

| Bore | Depth (m) | Screened interval (m) | Unit monitored | Water level record | Water quality available |
|---|---|---|---|---|---|
| TB1b | 19 | 17 - 19 | Aquitard (MTD) | 2015-2017 | Field only |
| TB1c | 37 | 33 - 37 | Regional aquifer (LTA) | 2015-2017 | Field only |
| TB2b | 7 | 4 - 7 | Alluvial aquifer | 2014-2015 | Field only |
| TB2c | 3 | 2 - 3 | Alluvial aquifer | N/A | Field only |
| A3 | 14 | 10 to 13 | Aquitard (MTD) | 2014-2017 | Yes |
| PASS1 | 10 | 4 to 9 | Aquitard (MTD) | 2015-2017 | Yes |

Groundwater levels in the Boundary catchment vary in each of the four hydrogeological units outlined above.

Recently installed monitoring bores in the basement (bedrock) indicate that Boundary Creek receives groundwater discharge from the basement in Reach 1. However, due to the low permeability of the basement, inflows volumes to Boundary Creek in Reach 1 are small. Seasonal groundwater fluctuations in the basement aquifer are around 1 to 2 m (Jacobs, 2016a).

In the Lower Tertiary Aquifer, historical monitoring indicates a significant decline in regional groundwater levels in this part of the Boundary Creek catchment. This is predominantly attributed to borefield operation and changes in climate over this time. This decline has resulted in groundwater levels falling below the streambed elevation in Reach 2 (Figure 2-7), and a transition from a system that receives groundwater, to one that loses water via seepage.

Monitoring bores in the aquitard indicate groundwater level fluctuations of around 1 to 2 m between 2014 and 2017 (Jacobs, 2016a). Fluctuations are consistent with seasonal trends in rainfall. This indicates that the upper layers of the aquitard are more influenced by rainfall recharge than the operation of the borefield. Where Boundary Creek intersects the aquitard in Reach 3, groundwater levels are above the streambed, indicating that Boundary Creek receives groundwater through this reach. However, groundwater discharge volumes are limited by the low permeability of the aquitard, resulting in periods of no flow in Reach 3.

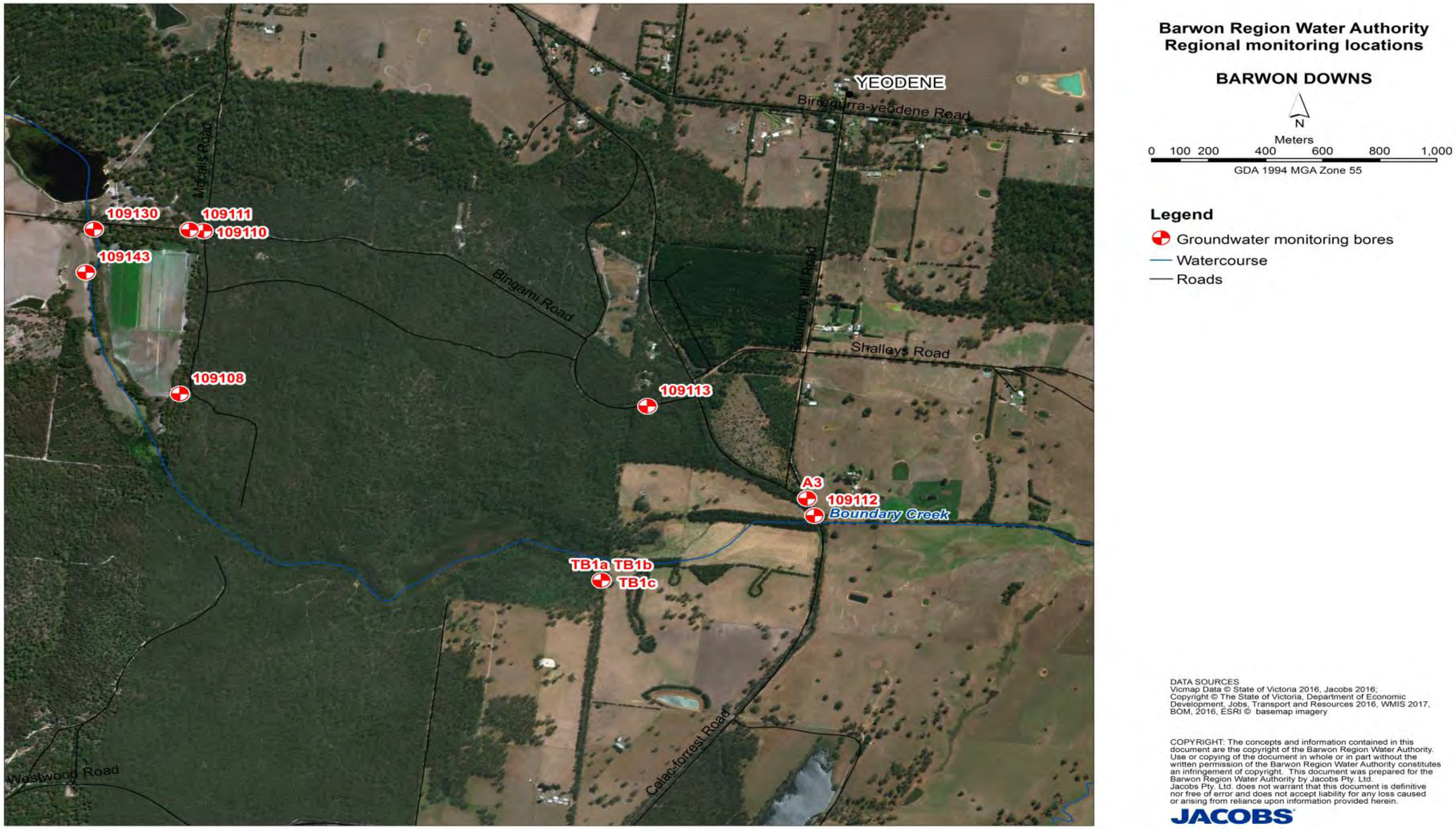


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Figure 2-6 Location of regional groundwater monitoring bores

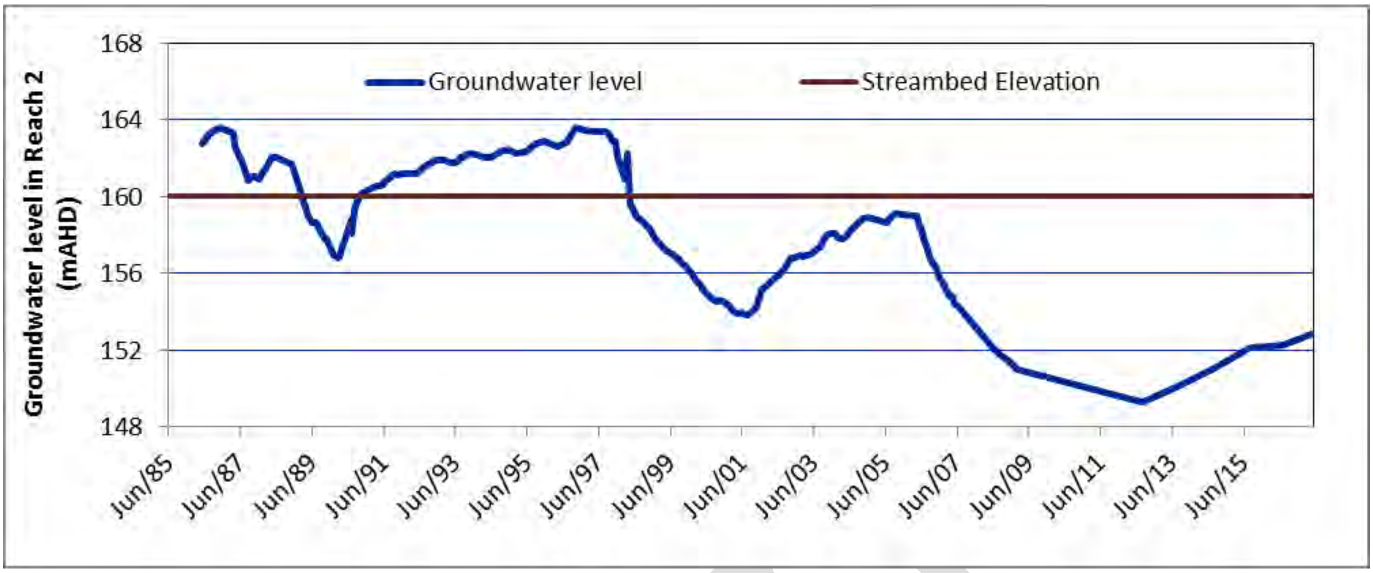


Figure 2-7 Historical monitoring of regional aquifer in Reach 2 (bore 109130)

### 2.3.2 Groundwater quality

Historical groundwater quality information is not typically available for the basement and aquitard units in the Boundary Creek catchment. However, monitoring bores installed by Jacobs in 2014 indicate that groundwater in the basement in Reach 1 has an EC between 4,000 and 6,000 µS/cm and is slightly acidic, with a pH of between 5.5 and 7.0 (Jacobs, 2016b). It is not uncommon for groundwater to be slightly acidic, so this is not interpreted to be linked to the acid events in the swamp.

Water quality data is available for bores installed in the regional aquifer in Reach 2 following their construction and development. The data has been summarised in Table 2-3 below and show that groundwater in the regional aquifer around Boundary Creek is typically fresh (TDS < 500 mg/L) and slightly acidic, with pH generally ranging between 5.5 and 7.0. The dissolved major ions are dominated by Cl and Na, consistent with rainfall recharge.

Groundwater monitoring in the aquitard in Reach 3 by Jacobs (2016b) indicates that groundwater ranges in EC between 1,300 and 2,500 µS/cm and ranges between slightly acidic and slightly basic (pH between 5.45 and 7.56).

Table 2-3 Summary groundwater quality data for the aquifer in the Boundary Creek Catchment

| Bore | Date sampled | EC (µS/cm) | pH (units) | TDS | Na | K | Ca | Mg | Cl | $HCO_3$ | $SO_4$ | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 109108 | 13/09/1983 | 220 | 7.5 | 118.4 | 28 | 0.4 | 2.8 | 6.4 | 46 | 34.2 | 9.0 | 24.0 |
| 109110 | 24/11/1980 | 910 | 5.9 | 470.0 | 148 | 2.0 | 2.0 | 12.0 | 255 | 23.0 | 15.0 | n/a |
| | 25/11/1980 | 880 | 5.7 | 458.0 | 143 | 2.0 | 8.0 | 11.0 | 248 | 21.0 | 16.0 | n/a |
| | 25/11/1980 | 880 | 5.8 | 460.0 | 143 | 2.0 | 8.0 | 12.0 | 248 | 23.0 | 15.0 | n/a |
| | 28/01/1987 | 860 | 6.4 | 427.0 | 140 | 2.1 | 7.1 | 9.3 | 260 | 8.5 | 0.3 | 9.6 |
| 109111 | 28/01/1987 | 370 | 5.5 | 176.9 | 55 | 0.9 | 3.1 | 5.9 | 99 | 9.8 | 6.6 | 0.0 |
| | 24/02/1987 | 910 | 4.3 | 416.8 | 140 | 0.8 | 8.1 | 16.0 | 260 | 1.2 | 14.0 | 0.0 |
| | 29/01/1987 | 770 | 9.2 | 403.5 | 94 | 5.5 | 19.0 | 17.0 | 210 | n/a | 0.3 | 0.2 |
| 109112 | 23/02/1987 | 890 | 5.8 | 402.7 | 100 | 5.6 | 42.0 | 20.0 | 210 | 24.4 | 76.0 | 0.0 |
| 109113 | 29/01/1987 | 610 | 7.3 | 322.3 | 98 | 2.8 | 4.2 | 7.6 | 170 | 39.0 | 0.3 | 7.0 |

## 2.4 Surface water

### 2.4.1 Surface water flows

Flow has been monitored continuously in Boundary Creek at Yeodene since 1979. Additional gauges were installed both upstream and downstream of McDonalds dam in 1989, but fell into disrepair by 1994. These were repaired in 2014 and since then, automated monitoring of flow has occurred at all three gauges. The flow gauges in the catchment and a summary of the flows are listed in Table 2-4.

Table 2-4 Flow gauges in the Boundary Creek catchment

| Gauge Number | Gauge Name | Period of record | Average annual flow (ML/year) | Average daily flow (ML/day) | Average low flow December - March (ML/day) |
|---|---|---|---|---|---|
| **233273** | Barongarook | July 2014 - current | 2,210 | 6.1 | 2.6 |
| **233231** | Upstream McDonald Dam | Dec 1989 – Feb 1994 | 4,039 | 11.1 | 1.7 |
| | | June 2014 to current | 2,276 | 6.2 | 2.3 |
| **233230** | McDonald Dam | Dec 1989 – Feb 1994 | Level only | | |
| | | June 2014 to current | | | |
| **233229** | Downstream McDonald Dam | Dec 1989 – Feb 1994 | 4,451 | 12.2 | 1.9 |
| | | June 2014 to current | 3,145 | 8.6 | 7.3 |
| **233228** | Yeodene | Mar 1985 - current | 2,874 | 7.9 | 1.1 |

Historical flows in Boundary Creek at the Yeodene stream gauge have been illustrated in Figure 2-8 below. The figure illustrates a clear step change in flow in the lower reach of Boundary Creek. The creek rarely stopped flowing at any time of year prior to 1999. However since then, the creek has generally ceased to flow during summer months.

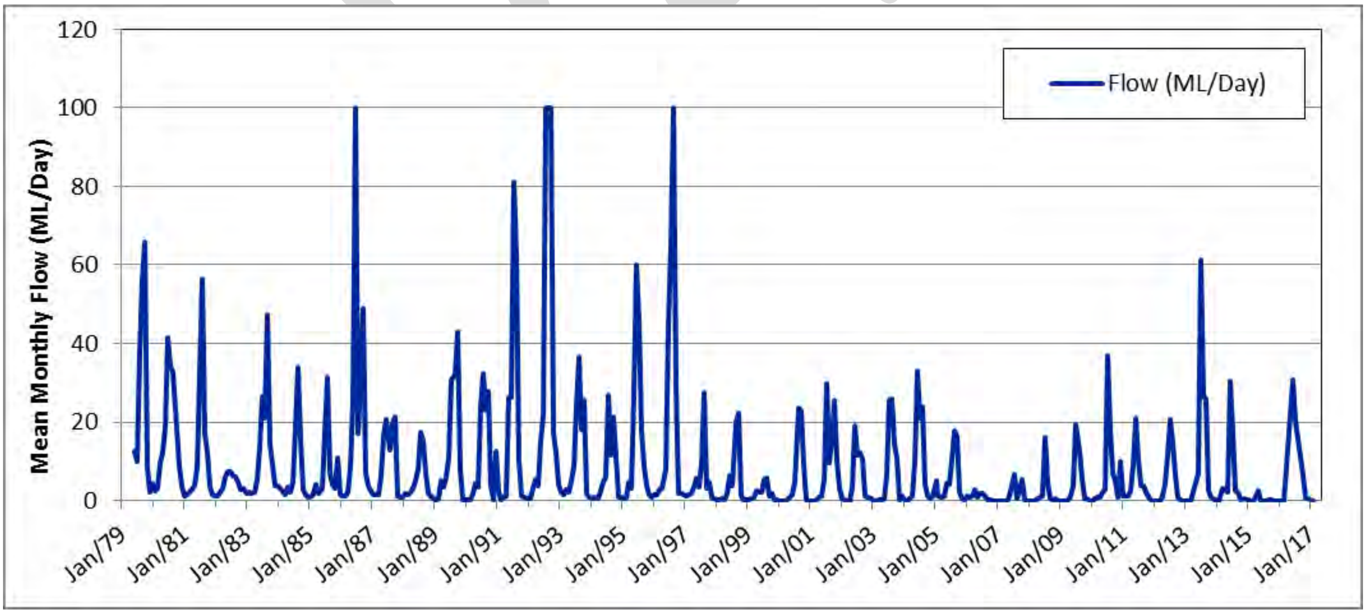


Figure 2-8 Average monthly flow in Boundary Creek at Yeodene

Reduced streamflow in Boundary Creek can be attributed to the reduction of groundwater discharge into the creek through Reach 2. In response to this Barwon Water releases a supplementary flow of 2 ML/day into the upstream reach of Boundary Creek (when triggered by licence conditions) since 2002 (Jacobs 2017b, Jacobs 2016a, SKM 2011, and SKM 2001).

The supplementary flow is released upstream of McDonalds Dam and the licence holder of the Dam is required to pass all inflows between 1st November and 30th June. However, flow downstream of the Dam is often less than flow upstream of the Dam during this time period.

The table below shows the difference in flows into and out of McDonalds Dam. Table 2-5 supports Figure 2-9 to Figure 2-11 below, which shows periods of time where there is a significant difference in the flow upstream and downstream of the Dam as recorded by the stream gauges. This has reduced the total volume of water delivered to the lower reaches of Boundary Creek.

Table 2-5 Difference in flows into and out of McDonalds Dam

| Period | | Barwon Water Flow Release (ML) | Flow McDonalds Dam upstream (ML) | Flow McDonalds Dam downstream (ML) | Difference: U/S vs D/S (ML) | Average daily difference (ML/Day) |
|---|---|---|---|---|---|---|
| 1 Nov 2014 | 10 Dec 2014 | 85 | 121 | 77 | 44 | 1.1 |
| 16 Jan 2015 | 16 Feb 2015 | 67 | 73 | 34 | 39 | 1.2 |
| 1 Nov 2015 | 1 Apr 2016 | 329 | 315 | 159 | 156 | 1.0 |
| 14 Jan 2017 | 10 Apr 2017 | 175 | 188 | 66 | 122 | 1.4 |

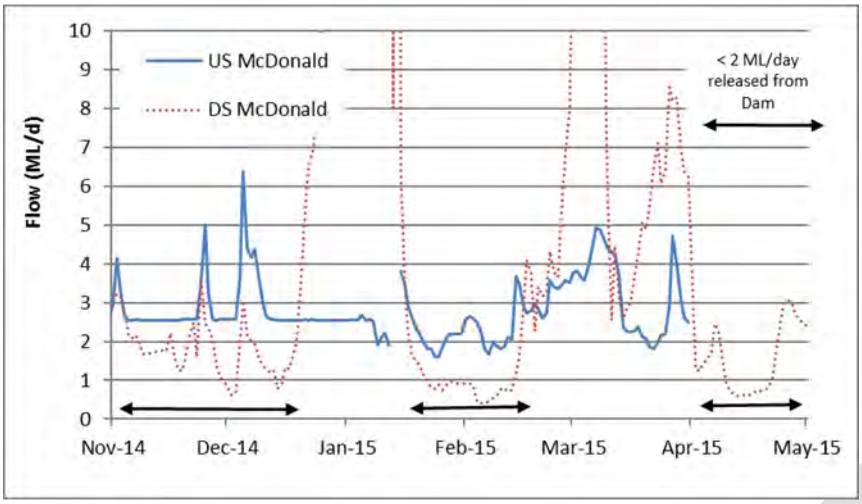


Figure 2-9 Surface water flows upstream and downstream of McDonalds Dam (2014/15)

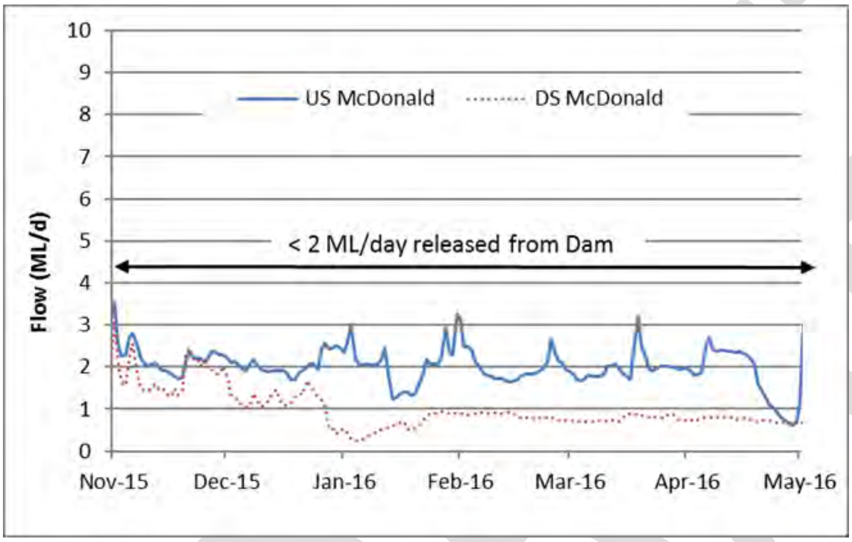


Figure 2-10 Surface water flows upstream and downstream of McDonalds Dam (2015/16)

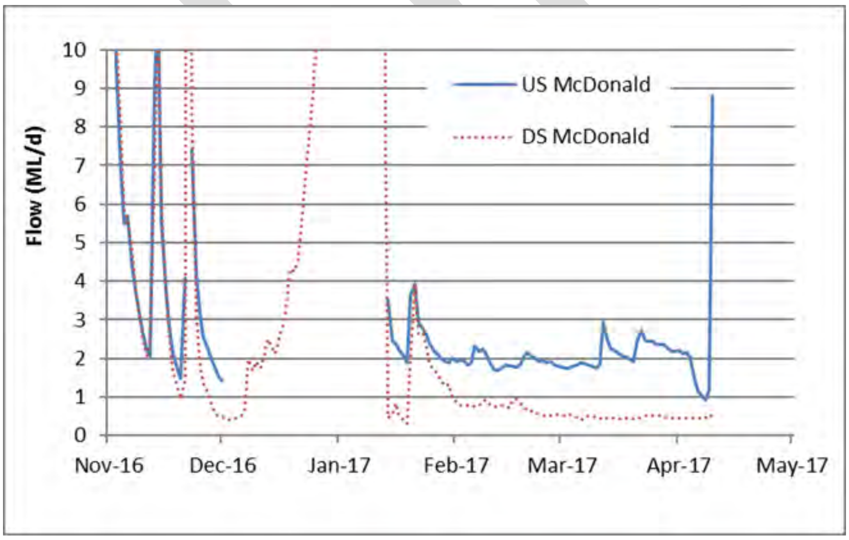


Figure 2-11 Surface water flows upstream and downstream of McDonalds Dam (206/17)

#### 2.4.2 Surface water quality

Electrical conductivity (EC) and pH have been monitored at monthly intervals at the Yeodene stream gauge since 1985. The pH of water in Boundary Creek in the 5 years prior to 1990 was an average of pH 6.5.

Between 1990 and 1992, monthly pH readings fell to a median pH of 5.1, and readings below 4 were recorded in the summer and autumn periods when flows in the creek were reduced. Between 1992 and 1999, the median pH increased to 5.9, with only two readings below 4.0.

Since 1999, the median pH at the Yeodene stream gauge has fallen to 3.8 and has rarely been above 5. The median pH of water at McDonalds Dam between 2014 and 2017 is ~7.0, indicating that the decline in pH occurs between McDonalds Dam and the Yeodene stream gauge.

The decline in pH in Boundary Creek appears to be related to a reduction in flow and in particular, periods when Boundary Creek has ceased to flow at the Yeodene stream gauge. This is illustrated in Figure 2-12 below which shows trends in surface water pH and the number of days each year when Boundary Creek ceases to flow as recorded at the Yeodene stream gauge.

This shows that after 38 days of no flow in Boundary Creek in 1990, there was a significant decline in pH for approximately 2 years. Additionally, cease to flow events have occurred annually since 1999 after a step change of reduced flow in the creek. Over this time, pH has fallen and has not recovered.

This suggests that there is a correlation between cease to flow events and a progressive lowering in pH levels.

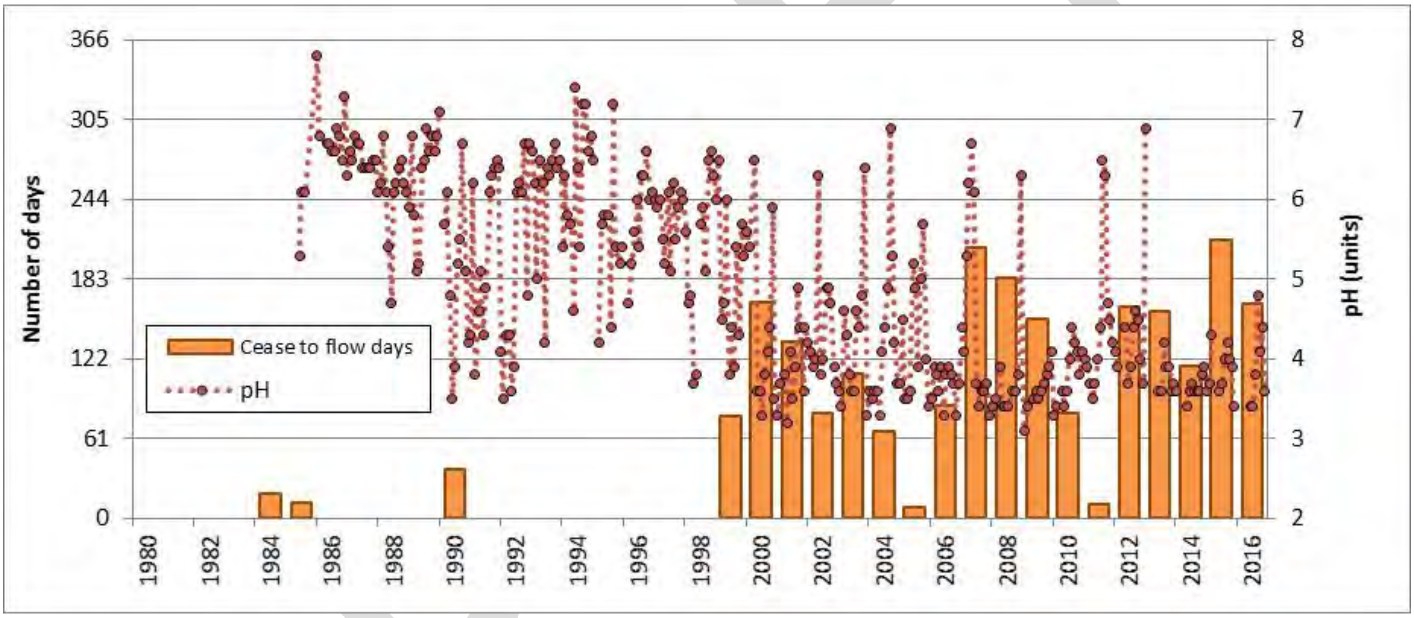


Figure 2-12 Number of cease to flow days in Boundary Creek at Yeodene vs monthly pH at Yeodene

## 2.5 Causes of changes in water quality

The above data indicates that when Boundary Creek ceases to flow at Yeodene, drying and oxidation of acid sulfate soils in the Yeodene Swamp occurs, resulting in the release of acid and pH values of less than 4 at Yeodene. **It can therefore be asserted that the processes contributing to flow reductions in Boundary Creek in 1990 and since 1999 are the key factors driving pH change at those times**.

Given this, as the installation of agricultural drains occurred in the early 1900’s, these are unlikely to be a key contributor to shifts in pH since the 1980’s. Similarly, while the installation of McDonalds Dam may have reduced flow into the middle and lower reaches of Boundary Creek, its presence through the late 1980’s (when pH values were typically above 5) suggest that during relatively wet conditions, sufficient water was being held in Yeodene Swamp to limit acidification of acid sulfate soils.

While both the peat fire in 1997-2010 and the excavation of fire trenches in Yeodene Swamp in 2010 are likely to have altered the current drainage regime in the swamp, they are unlikely to be the direct cause of drying, as low pH events (pH <4) have occurred since 1990.

Although all these factors will have contributed to the changing landscape in the Boundary Creek catchment, the two variables that appear to have had the greatest influence on flows in Boundary Creek (and the resulting water moving through Yeodene Swamp) are climate and borefield operation.

The period between 1990 and 1992 represents when groundwater extraction had lowered groundwater levels in the regional aquifer. Over this time, Boundary Creek ceased to flow during summer periods, resulting in the acidification in Yeodene Swamp and Boundary Creek.

This suggests that borefield operation was the major factor controlling acidification in Yeodene Swamp by lowering the groundwater levels leading to a loss of groundwater base flow into the creek. This is further supported by numerical modelling results which indicate that approximately two thirds of flow reduction in Boundary Creek was borefield driven (Jacobs 2017b). The groundwater model was used to determine the historical impact of borefield operations on flow in Boundary Creek, as illustrated in Figure 2-13. This shows that there was groundwater flow into the creek until the mid-1980s (indicated by positive values) and since then the flow has reversed and surface water flows to the groundwater (indicated by negative values). With no pumping, the groundwater would have continued to discharge to the river, as demonstrated by the orange line.

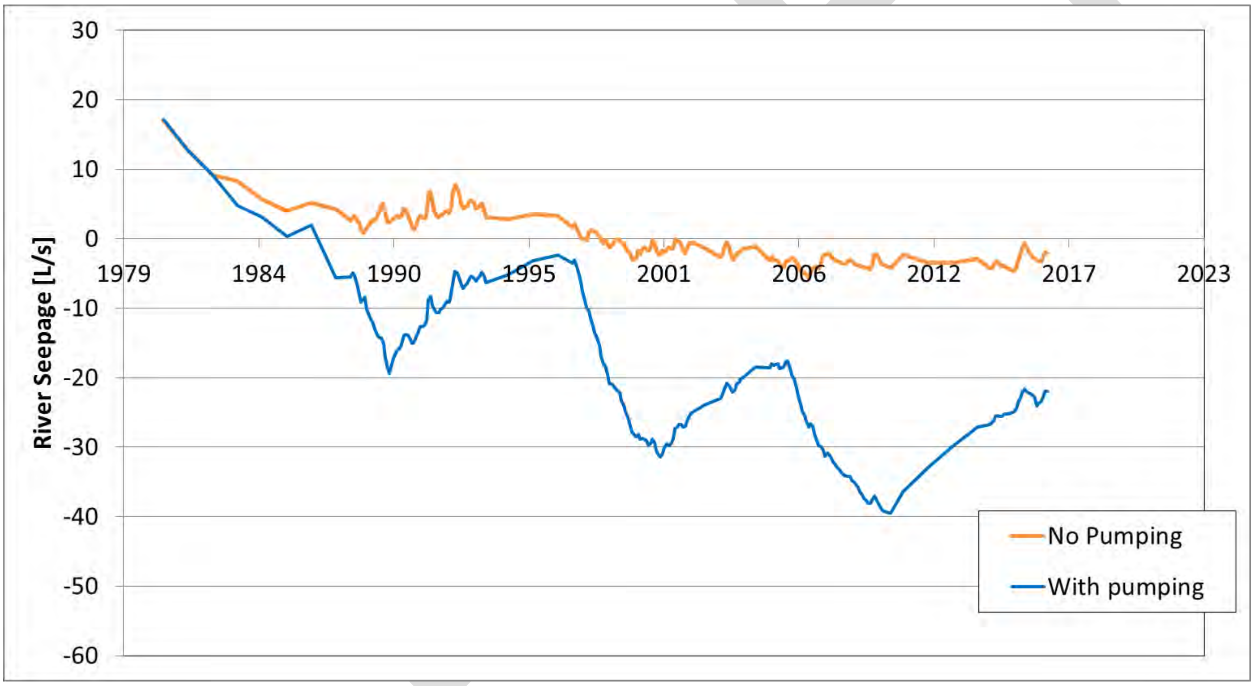


Figure 2-13 Numerical model results – changes in seepage to Boundary Creek from borefield operation

# 3. Field program

## 3.1 Chapter overview

This chapter provides an overview of the field works undertaken as part of this study. It summarises the methods used during monitoring and sampling so that the results can be assessed with rigor and within the context of the program.

The program was designed to better characterise the physical and chemical processes occurring within the Boundary Creek catchment and to inform potential remediation strategies focussed on managing water quality in Boundary Creek. The field program included the installation of piezometers (shallow bores <3 m deep), lithological analysis, chemical soils analysis, surface water flow gauging, and both surface and groundwater quality monitoring.

Groundwater and surface water monitoring was conducted twice during 2017 to understand how the water quality changes through the wetter months after a period of cease to flow. The location of the monitoring locations is shown in Figure 3-1. The first monitoring period occurred on the 4th and 5th of May. This represented the first period of flow in Boundary Creek following the 2016-2017 summer. The second monitoring period occurred between the 22nd and 23rd of August and represented high flows following winter rainfalls.

More detail on the field program is provided in the sections below and key findings from the field program are discussed in Chapter 4.

## 3.2 Piezometer installation

Six piezometers were installed in Yeodene Swamp and two bores were installed along the lower reach of Boundary Creek in order to assess groundwater-surface water interaction in those areas. The construction details of these bores, their method of construction and lithological analysis has been detailed in Appendix A.

## 3.3 Groundwater monitoring

Groundwater monitoring was conducted at previously established monitoring bores in the Boundary Creek catchment, as well as those constructed as part of these investigations. A complete list of the groundwater monitoring locations and the data collected at each site is provided in Table 3-1 below and illustrated in Figure 3-1.

At each of the monitoring locations listed in Table 3-1, the groundwater level was recorded using an electronic water level tape and groundwater samples were collected for analysis. Bores and piezometers were purged prior to sample collected using a hand bailer and field water quality parameters were recorded using an YSI pro plus water quality meter. Samples were collected in bottles containing requisite preservatives according to Eurofins sampling guidelines. Samples were field filtered (where necessary) and stored on ice in the field before being refrigerated on return from field.

Groundwater level loggers in A3, PASS1 and TB1 were downloaded during investigations (see Figure 2-6 for locations).

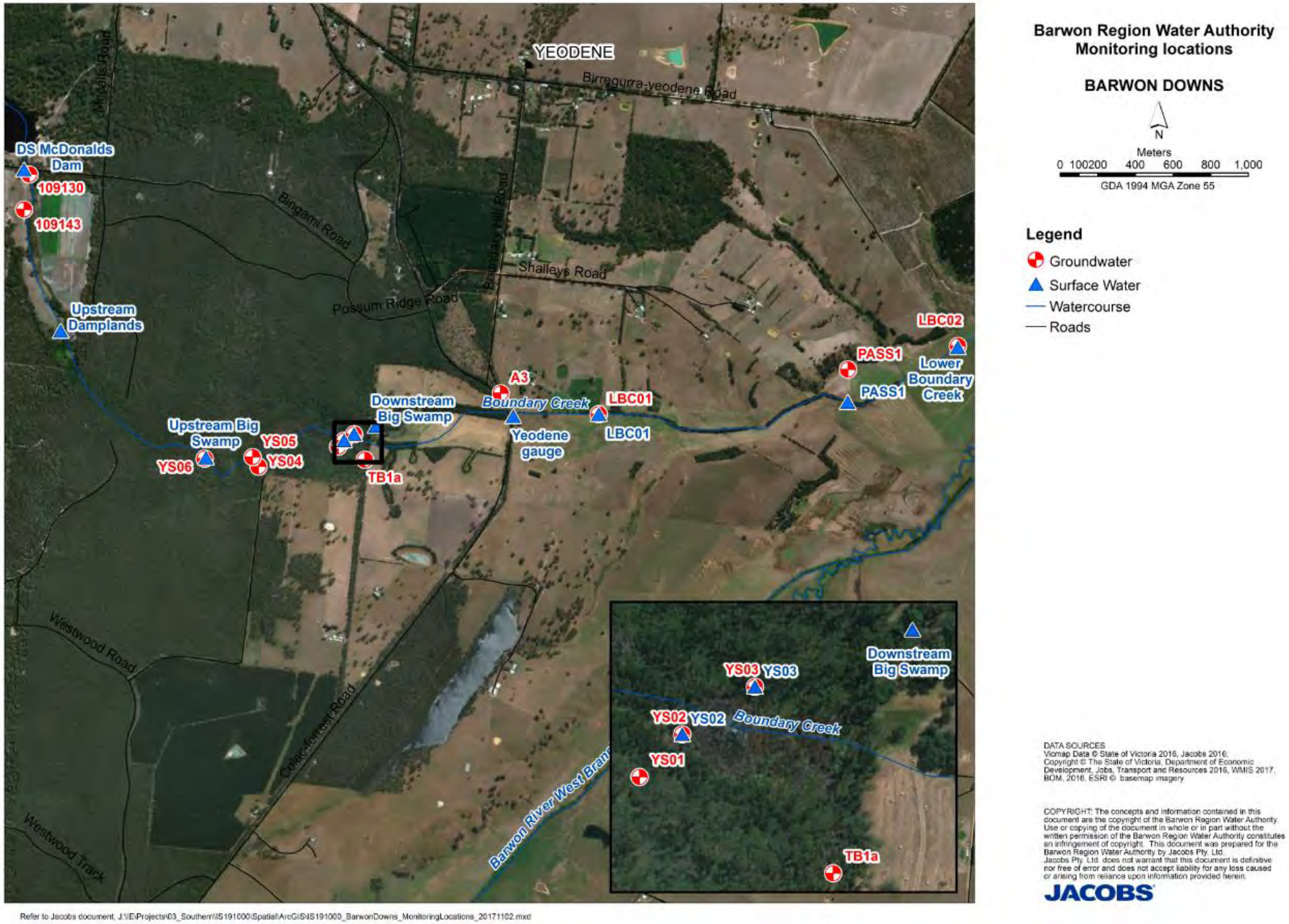


Figure 3-1 Location of groundwater and surface water monitoring locations

Table 3-1 Groundwater monitoring locations for Yeodene Swamp study

| ID | Zone | Easting | Northing | Manual water level monitoring | Water quality monitoring | Water level monitoring with logger |
|---|---|---|---|---|---|---|
| A3 | 55 | 212792 | 5742428 | x | x | x |
| LBC01 | 55 | 213312 | 5742317 | x | x | |
| LBC02 | 55 | 215218 | 5742679 | x | x | |
| PASS1 | 55 | 214635 | 5742553 | x | x | x |
| TB1a, b, c | 55 | 212070 | 5742075 | x | x | x |
| YS01 | 55 | 211929 | 5742145 | x | x | |
| YS02 | 55 | 211960 | 5742176 | x | x | |
| YS03 | 55 | 212013 | 5742211 | x | x | |
| YS04 | 55 | 211506 | 5742039 | x | x | |
| YS05 | 55 | 211475 | 5742090 | x | x | |
| YS06 | 55 | 211220 | 5742081 | x | x | |

## 3.4 Surface water monitoring

Surface water monitoring was conducted at 9 locations. These have been listed in Table 3-2 below. The monitoring included a combination of water level measurement to assess groundwater and surface water interaction, spot flow measurement to assess change in flow along the creek under different conditions and sampling for water quality analysis.

Spot flow gauging was conducted downstream of McDonalds Dam, upstream of the Damplands, upstream and downstream of Yeodene Swamp, at the existing Yeodene stream gauge and at the lower end of Boundary Creek before its discharge point at the Barwon River. Flow velocity was recorded at 0.3 m intervals using a propeller driven flow meter to allow calculation of volume moving through the cross section in accordance with Olsen and Morris (2007).

Surface water levels along Boundary Creek were recorded relative to surveyed monitoring bores (see Table 3-1) and streambed cross sections. Spot flow gauging results were calibrated using permanent flow gauging information collected at downstream of McDonalds Dam and the Yeodene streamflow gauges.

Field surface water quality parameters were recorded using an YSI pro plus water quality meter and samples were collected in polyethylene containers in the field. Subsequently, samples were field filtered (where necessary) and transferred to bottles containing requisite preservatives according to Eurofins sampling guidelines. These were stored on ice in the field before being refrigerated on return from field.

Table 3-2 Surface water monitoring locations for Yeodene Swamp study

| ID | Zone | Easting | Northing | Water level | Water quality | Spot gauge | Constant gauge |
|---|---|---|---|---|---|---|---|
| Downstream McDonalds Dam | 55 | 210261 | 5743613 | x | x | x | x |
| Upstream Damplands | 55 | 210455 | 5742757 | x | | | |
| Upstream Yeodene Swamp | 55 | 211227 | 5742086 | x | x | x | |
| YS02 | 55 | 211960 | 5742176 | x | x | | |
| Downstream Yeodene Swamp | 55 | 212127 | 5742252 | x | x | x | |
| Yeodene gauge | 55 | 212858 | 5742305 | x | x | x | x |
| LBC01 | 55 | 213312 | 5742317 | x | x | | |
| PASS1 | 55 | 214633 | 5742380 | x | x | | |

| ID | Zone | Easting | Northing | Water level | Water quality | Spot gauge | Constant gauge |
|---|---|---|---|---|---|---|---|
| **Lower Boundary Creek** | 55 | 215218 | 5742671 | x | x | x | |

## 3.5 Soil analysis

During bore and piezometer installation, soil samples were collected at ~1 m intervals. Subsequent to lithological characterisation (as detailed in Appendix A), soil samples were placed in plastic re-sealable bags and stored on ice in the field. These were frozen on the night of collection and sent to Eurofins Laboratories for acid sulfate soil analysis (via screen tests and chromium reducible sulfur suite). The results of the analysis have been summarised in Appendix B and detailed in full in Appendix C.

## 3.6 Hydraulic testing

Hydraulic testing was conducted between the 26th and 27th of April, 2017. Hydraulic testing was conducted via the introduction and removal of a weighted PVC slug to displace approximately 1 m of water. Changes in water level during the tests were recorded at 1 second intervals using a solinst water level logger and cross checked at regular intervals using an electronic water level tape. The hydraulic conductivity (k) value given by the tests were determined using the Bouwer-Rice (1976) analytical method in the aquifer testing software program Aqtesolv. The results of hydraulic testing have been detailed in Appendix D.

## 3.7 Vegetation survey

A survey of the abundance and type of vegetation in Yeodene Swamp was conducted on 6 June 2017 along a transect extended from YS01 to YS03 (Figure 2-6). The transect was ~110m in length and included eight 5 x 5 m quadrats at 15 m intervals on alternating sides of the transect line in a method adapted from previous vegetation surveys throughout the Otway Forest in groundwater dependant ecosystems.  All flora species within the plot were identified and cover estimated to the nearest 5%.

# 4. Results of field program

## 4.1 Chapter overview

This chapter summarises the results of the field program and the significance of the results within the context of this project. The chapter presents the results of geological logging, acid sulfate soils analysis, flow in Boundary Creek, surface water quality and groundwater quality analysis, a water balance for Boundary Creek and a vegetation survey of Yeodene Swamp.

The key results presented in each section are summarised in Table 4-1.

Table 4-1 Summary of results and findings of field program

| Feature | Key findings |
|---|---|
| **Hydrogeology** | • Saturated alluvial sediments are likely to be present upstream of Yeodene Swamp as a localised perched aquifer.<br>• Depth to watertable in the regional aquifer is 10-15 m below ground level upstream of Yeodene Swamp.<br>• Saturated peat sediments in Yeodene Swamp are hydraulically separated from the underlying regional aquifer (LTA) by the aquitard.<br>• The eastern end of swamp comprises saturated alluvial deposits overlying aquitard.<br>• The aquitard thins to the west and is absent upstream of the swamp, however the exact location where aquitard is absent is not known. Shallow bores indicate that the western end of the swamp the alluvial deposits overlie the regional aquifer. |
| **Acid sulfate soils** | • The highest concentration of net and potential acidity were found in the central and lower lying areas of Yeodene Swamp. |
| **Surface water flow** | • Surface water flows increase between McDonalds Dam and the top of the Damplands, which is likely to be result of surface runoff from the catchment and potential inflow from the local alluvial aquifer.<br>• Two spot flow measurement showed that surface water flow declines through the Damplands and Yeodene Swamp as a result of groundwater recharge and evapotranspiration. The losses will vary seasonally, and were 2.9 ML/day in May 2017 and 9.9 ML/day in August 2017 which represent the swamp re-wetting after a period of cease to flow.<br>• Surface water flows are variable gaining and losing in Reach 3. |
| **Surface water quality** | • The most significant changes in water quality occur through Yeodene Swamp.<br>• Changes in water quality through the swamp are consistent with the effects of acid sulfate soils including reduced pH, increased salinity, and increased concentrations of sulfate and dissolved metals.<br>• Winter high flow conditions of greater than 15 ML/day did not dilute acidic inputs or the concentration of dissolved metals significantly. |
| **Groundwater quality** | • Groundwater quality affected by acid sulfate soils typically has low pH values a relatively high proportion of sulfate and dissolved metals. Accordingly:<br>o Groundwater in the centre of the swamp was the most affected by acid sulfate soils.<br>o Groundwater downstream of the swamp (A3 and TB1a) was somewhat affected by acid sulfate soils.<br>o Groundwater upstream of the swamp and in Reach 3 (downstream of Yeodene gauge) is relatively unaffected by acid sulfate soils. |
| **Groundwater – surface water interaction** | • Immediately downstream of McDonalds Dam to the Damplands the spot flow measurements indicate the creek could be gaining. Inflows to the creek are likely to be result of surface runoff from the catchment and potential inflow from the local alluvial aquifer. This is new information and improves the conceptualisation of the Reach 2.<br>• The Damplands and Yeodene Swamp are losing to groundwater, which is consistent with the existing conceptualisation.<br>• Reach 3 of Boundary Creek is variable gaining/losing, and consistent with the existing conceptualisation. |

| Feature | Key findings |
|---|---|
| **Water balance** | • The greatest losses of surface water occur through the Damplands and Yeodene Swamp – ranging between 2.9 ML/day in May and 9.9 ML/day in August 2017. These volumes of water are representative of the swamp re-wetting after a period of no flow. It is estimated that the majority of the loss is recharge to groundwater with evapotranspiration making up less than 1 ML/day during these months.<br>• Evaporation losses will be higher during the summer months and could be up to 2.5 ML/day. |
| **Vegetation** | • This part of Yeodene Swamp was not a permanent swamp historically (i.e. greater than 50 years ago) as the tree ferns and trees would not have established unless there was periodic drying. This could be the result of the construction of agricultural drains in the area.<br>• The trees and tree ferns are likely to have died as a result of root death cause by permanent inundation.<br>• Inundated area is un-vegetated as a result of the acidic water which is toxic to most plant species. |

## 4.2 Geology

The location of monitoring bores is shown in Figure 4-1.

Lithological logs from YS01, YS02 and YS03 indicate the presence of silty and sandy clays to a depth of ~4 m. This is consistent with regional mapping and previous drilling at TB1 which indicated the alluvial deposits overlie aquitard deposits towards the eastern end of the swamp (Jacobs, 2016b). A schematic cross section extending between YS01 to YS03 has been illustrated in Figure 4-2.

Lithological logs indicate coarse sands at YS04. While regional mapping suggests the occurrence of outcropping aquitard material in this area (Figure 4-1), it is possible that drilling has penetrated through thin alluvial deposits and into the regional aquifer. Lithological logs at YS05 are consistent with alluvial deposits, while sandy and silty clay deposits at YS06 could be consistent with either shallow alluvial deposits.

Based on these results, it remains unclear as to the exact boundary between outcropping aquifer deposits in the west, and aquitard deposits in the east.

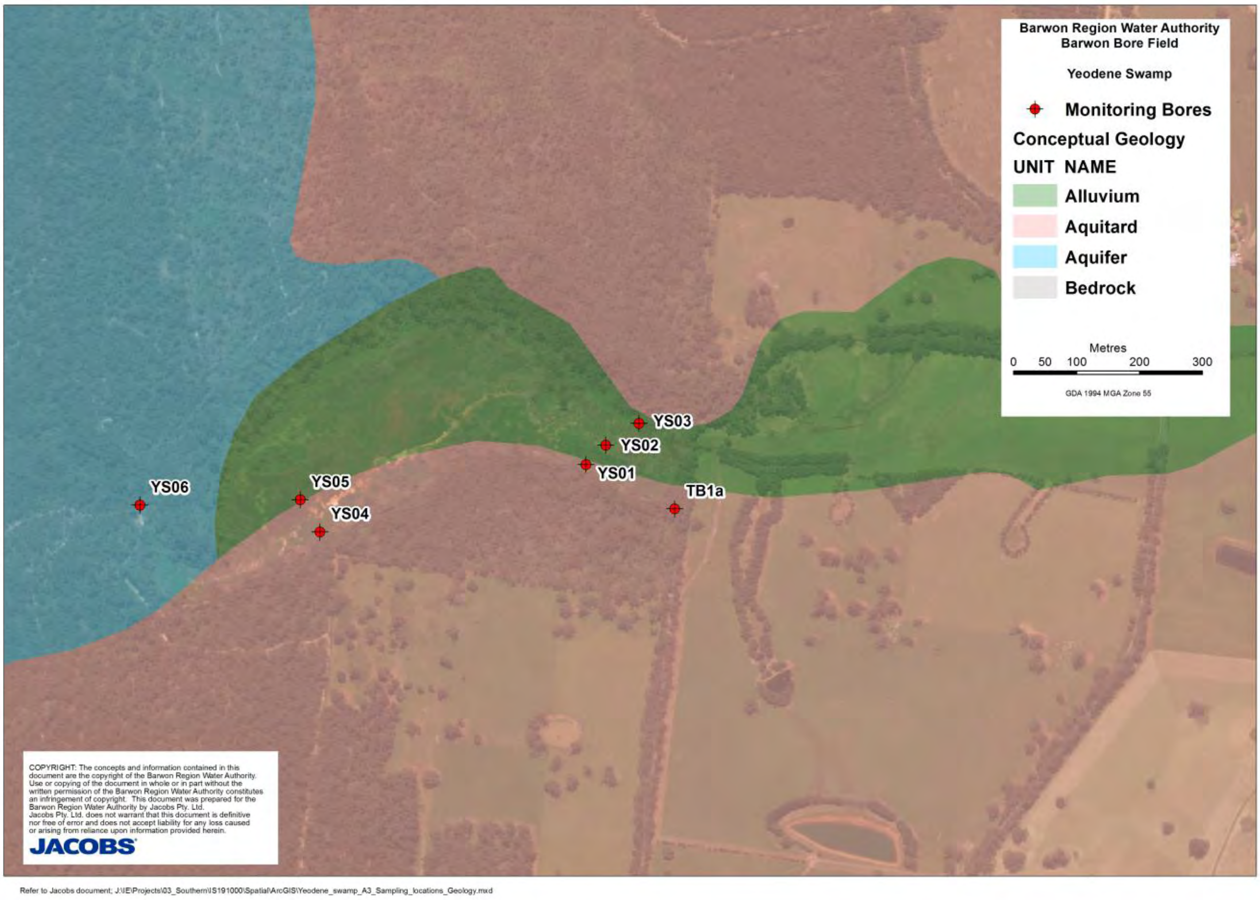


Figure 4-1 Surface geology and monitoring locations (points of lithological analysis)

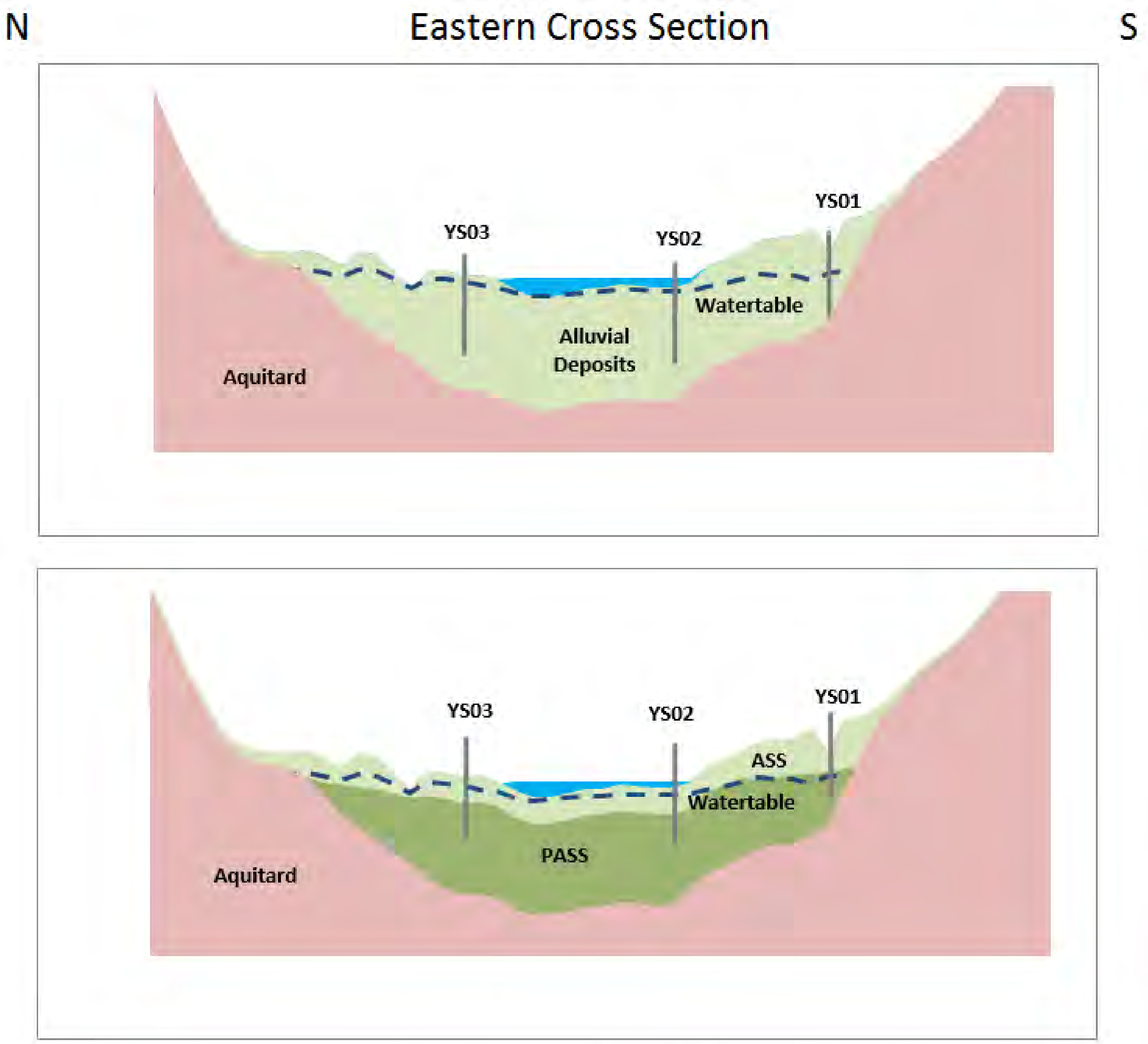


Figure 4-2 Schematic cross sections of eastern end of Yeodene Swamp

## 4.3 Soils

Soil samples were collected at one metre intervals in the six shallow bores installed across Yeodene Swamp. The soils were analysed to determine the extent of actual and potential aid sulfate soils. This information is required to determine how much acid is in the swamp to understand the viability of different remediation options.

The results of acid sulfate soils analysis are provided in Appendix D and complete laboratory reports in Appendix E. This includes screen tests and chromium reducible sulfur analysis. A summary of these results can be found below.

### 4.3.1 Screen tests

The results of the acid sulfate soil screen tests provide four preliminary indicators of acid sulfate soils:

- The soil pH ($pH_F$) which provides an indication of the current pH of the soils.
- The pH after addition of peroxide ($pH_{FOX}$), which provides an indication of the potential soil pH after oxidation.
- The change between the two pH values (ΔpH) and
- The reaction rate (RR) observed, which provides an indication of the rate at which oxidation occurs (a rate of 1 is unreactive indicating a slow rate of oxidation, while a rate of 4 is highly reactive and indicates rapid oxidation).

A total of 30 screen tests were collected at approximately 1 m intervals in each bores to understand the variability in soil pH spatially and with depth in the swamp. Analysis was conducted at Eurofins with results summarised in Table 7-1 of Appendix B. These have been compared against the guidelines provided in publication 655.1 (EPA, 2009) as illustrated in Table 4-2 below.

Table 4-2 Guideline criteria for acid sulfate soil screen tests

| $pH_F$ | $pH_{FOX}$ | ΔpH | Reaction Rate | Action required |
|---|---|---|---|---|
| ≥ 5.0 | ≤ 5.0 | ≤ 2 | 1–2 | If no other field indicators or acid sulfate soil risk indicators are present, no further action is required |
| $>4.0$ and $<5.0$ | $>3.0$ and $<5.0$ | $>2$ | ≥ 2 | PASS may be present, further assessment is required |
| ≤ 4.0 | ≤ 3.0 | $>2$ | ≥ 2 | AASS or PASS are likely to be present, further assessment is required |

The results of the screen tests can be summarised as follows:

- Soil pH ($pH_F$) results ranged between 2.8 and 6.3.
    - 6 of 30 samples had a $pH_F$ below 4, indicating the presence of actual acid sulfate soils in these samples.
    - these occurred in the upper 1 m of the profile at YS01, YS02, YS03 and YS05 and correlate with parts of the swamp that are lower in elevation.
- Soil pH after addition of peroxide ($pH_{FOX}$) ranged from 1.5 to 4.0.
    - 17 of 30 samples had a $pH_{FOX}$ below 3.0, indicating the presence of acid sulfate soils in Bores YS02 and YS05 and intervals in other bores (except LBC02)
    - 13 of 30 samples had a $pH_{FOX}$ between 3 and 5, indicating the possible occurrence of acid sulfate soils. These results were found in intervals in all bores except YS02 and YS05 where $pH_{FOX}$ values were lower.

- Soil ΔpH was >2 in 10 of 30 samples, indicating the presence of potential acidity. This was more common below 1 m depth soil profiles where reducing conditions persist and occurred at LBC01, LBC02, YS02, YS03 and YS06.

- Reaction rates were ≥2 in 29 of the 30 samples, suggesting the potential for rapid pyrite oxidation and acidification during drying and exposure to oxygen.

### 4.3.2 Acid sulphate soil testing

Chromium suite analysis was conducted on 30 samples. The chromium suite identifies different stores of acidity in the soil samples in order to estimate their acid generating potential, this includes:

- titratable actual acidity (which estimates the **actual acidity**)
- HCl and KCl extractable sulfur (which combined estimate the **retained acidity**)
- chromium reducible sulfur (which estimates the **potential acidity**)
- the **acid neutralising capacity** (which estimates the capacity of the soils to neutralise any acidity present)

Together, these results are used to estimate the **net acidity** present in the soils by subtracting the neutralising capacity from the combined actual, residual and potential acidities. This provides an estimation of the total (potential and actual) acid that could to be released from the swamp.

The results of the chromium suite have been summarised in Table 7-2 of Appendix B. The results have been compared against the texture based criteria for classification of acid sulfate soils, as illustrated in Table 4-3 below.

Table 4-3 texture based criteria for classification of acid sulfate soils (EPA, 2009)

| Soil or sediment texture[f] | Approximate clay content (%) | Net acidity criteria (1-1000 tonnes) | | Net acidity criteria (>1000 tonnes) | |
|---|---|---|---|---|---|
| | | (%S) (oven-dry basis) | mol $H^+$ /tonne (oven-dry basis) | (%S) (oven-dry basis) | mol $H^+$ /tonne (oven-dry basis) |
| Sands to loamy sands | <5 | 0.03 | 18 | 0.03 | 18 |
| Sandy loams to light clays | 5-40 | 0.06 | 36 | 0.03 | 18 |
| Medium to heavy clays and silty clays | >40 | 0.1 | 62 | 0.03 | 18 |

The concentration of **actual acidity** ranged from 3.7 to 910 moles of acid (H+/tonne). The highest concentrations were recorded in samples from YS02 and YS05 located through the centre of the swamp. These areas are most susceptible to inundation, pyrite formation and any resulting acidification. Additionally, acidic leachate is more likely to pool and concentrate in these lower areas of the swamp.

Concentrations of actual acidity were >18 moles of acid (H+/tonne) in all but 4 samples, indicating the widespread occurrence of actual acid sulfate soils. Actual acid sulfate soils were absent below 1 m depth at YS04 and YS06. These locations are higher in elevation than other areas of Yeodene Swamp and as such, are less susceptible to inundation, pyrite formation and any resulting acidification. In addition, there is evidence to suggest that aquitard deposits at YS04 and YS06 are limited. This could also increase drainage of these areas, reducing their susceptibility of inundation.

**Retained acidity** generally contributed little to the net acidity of samples. Concentrations were below detection (10 moles of acid (H+/tonne)) in 25 of the 30 samples. Concentrations only exceeded 18 moles of acid (H+/tonne) in two samples, including one sample from YS03 and one from YS05.

Concentrations of **potential acidity** ranged from below detection (3 moles of acid (H+/tonne)) to 9,000 moles of acid (H+/tonne), and were greater than 18 moles of acid (H+/tonne) in 12 of 30 samples. This indicates the presence of **significant additional stores of acidity which may be released in the event of ongoing drying and oxidation in the swamp**. Concentrations were highest below 1 m depth at YS02, YS03 and YS05. It is likely that these areas are often below the water table where pyrite oxidation is limited, resulting in greater stores of potential acidity.

As the mass of material affected in Yeodene Swamp is greater than 1000 tonnes, the results have been compared against the guideline level of 18 moles of acid ($H^+$) per tonne (EPA, 2009). As the pH of all samples under addition of KCl solution was acidic (<6.5), samples were determined to be void of **acid neutralising capacity**.

The resulting **net acidities** based on the above analysis confirms the widespread distribution of acid sulfate soils throughout Yeodene Swamp. Concentrations of net acidity ranged from <10 to 9,600 mole of acid ($H^+$/tonne) and were greater than the criteria level of 18 mole of acid ($H^+$/tonne) in 26 of 30 samples.

The net acidity was used to estimate how much acid was in the swamp.  Assuming that acidity in the upper 1 m of the soil profile could be mobilised, there is estimated to be 134 million moles of acid in the swamp. The creek flows for approximately 6 months of the year and the annual flux leaving the Yeodene Swamp is estimated to be around 55,000 moles of acid per year (assuming a flow of 2 ML/day for 6 months a year).  Based on this, it is estimated that conditions similar to those observed currently could persist for several hundred years.

## 4.4 Surface water flow

Flow measurements in Boundary Creek were recorded in May and August 2017. Flows were initially measured via spot flow gauging at multiple locations between McDonalds Dam and Yeodene stream flow gauges. These results were then calibrated to the constant gauging data recorded at both McDonalds Dam and Yeodene stream gauges.

Rainfall in the week leading up to flow gauging on May 4th was minimal and flow records from both the McDonalds Dam and Yeodene stream gauges indicate that flow in Boundary Creek was at a relatively steady state (Figure 4-3).  Given this, no allowance has been made for any lag in flow peaks moving through the creek.

Significant rainfall was recorded in the week preceding flow gauging on August 22nd, however gauging records indicate that the flood peak had passed through the system on the day of gauging. As such, allowance for flood peak lag was unnecessary during August flow gauging.

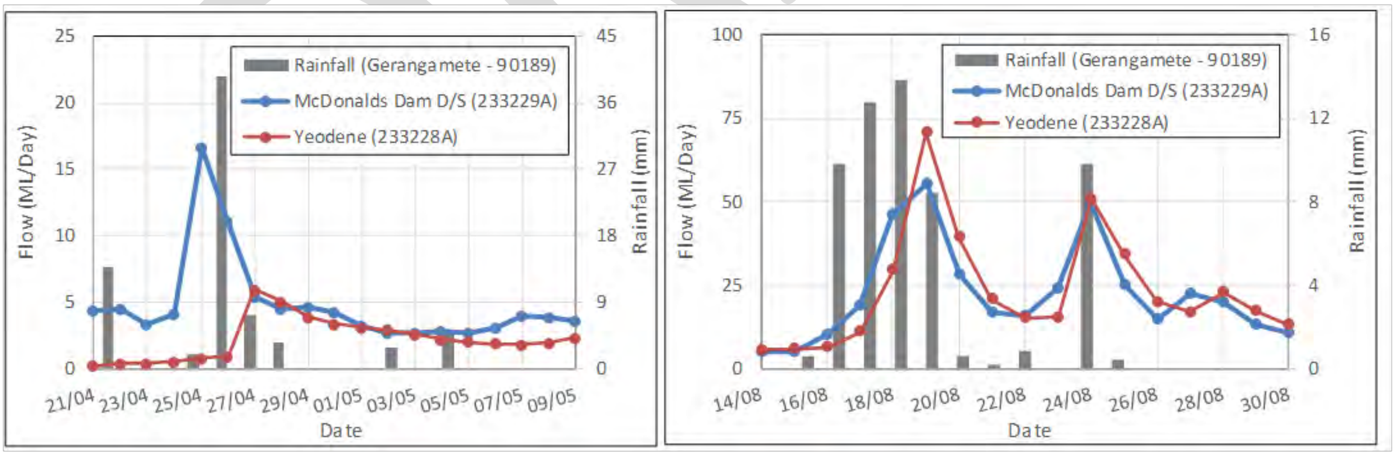


Figure 4-3 Streamflow in Boundary Creek at McDonalds Dam D/S flow gauge (233229A) and Yeodene (233228A) in response to rainfall recorded at Barwon Downs (Gerangamete gauge - 90189)

Typical of spot gauging, the spot gauging results overestimated the flow compared to the metered flow gauging data by an average of 19% in May and an average of 16% in August. As such, spot flow measurements have been reduced by 19% in May and 16% in August in order to calibrate the results to constant flow data. The results of the spot flow gauging and the calibrated flow measurements have been listed in Table 4-4 below.

The results highlighted that surface water flow increased between McDonalds Dam and the top of the Damplands in both sampling events. This is likely to be result of surface runoff from the catchment and potential inflow from the local alluvial aquifer. Streamflow declined through the Damplands and Yeodene Swamp in both sampling events with losses of 2.9 ML/day recorded in May and 9.9 ML/day in August. These losses are attributed to a combination of evapotranspiration (ET) and recharge to the shallow groundwater. Given the time of year, recharge to the shallow groundwater is considered to be domination process, with ET making up less than 1 ML/day.

Between the swamp and the Yeodene gauge, flow decreased marginally in May and increased marginally in August. Surface water flow was lost to the shallow aquifer in May as this was after a period of cease to flow where groundwater levels would have declined. The shallow aquifer would have been recharged between May and August which meant groundwater levels rose sufficiently by August, allowing groundwater to discharge to the creek.

Downstream of the Yeodene gauge, surface water flows increased in May and August as a result of runoff in this part of the catchment and groundwater discharge.

Table 4-4 Summary of stream flow along Boundary Creek

| Condition | Location | Spot gauging | Constant gauging | Calibrated flow | Losses/Gains |
|---|---|---|---|---|---|
| | | ML/Day | ML/Day | ML/Day | |
| First flow 4/05/2017 | Downstream of McDonald's Dam | 3.9 | 3.0 | 3.2 | |
| | Upstream Damplands | 6.6 | | 5.3 | Gain 2.1 ML/day |
| | Upstream of Big Swamp | 4.7 | | 3.8 | Loss 1.5 ML/day |
| | Downstream of Big Swamp | 3.0 | | 2.4 | Loss 1.4 ML/day |
| | Yeodene Gauge | 2.6 | 2.2 | 2.1 | Loss 0.3 ML/day |
| | Lower Boundary Creek | 4.6 | | 3.7 | Gain 1.6 ML/day |
| Winter high flow 22/08/2017 | Downstream of McDonald's Dam | 19.5 | 15.6 | 16.3 | |
| | Upstream Damplands | 28.0 | | 23.4 | Gain 7.1 ML/day |
| | Upstream of Big Swamp | 23.0 | | 19.2 | Loss 4.2 ML/day |
| | Downstream of Big Swamp | 16.1 | | 13.5 | Loss 5.7 ML/day |
| | Yeodene Gauge | 17.2 | 15.0 | 14.4 | Gain 0.9 ML/day |
| | Lower Boundary Creek | 20.2 | | 16.9 | Gain 2.5 ML/day |

## 4.5 Water quality

### 4.5.1 Surface water

Water quality samples were collected at the same time as the spot gauging. The results of field and laboratory analysis of surface water from Boundary Creek has been summarised in Appendix B and detailed in full in Appendix C. The key findings of these analysis are summarised below.

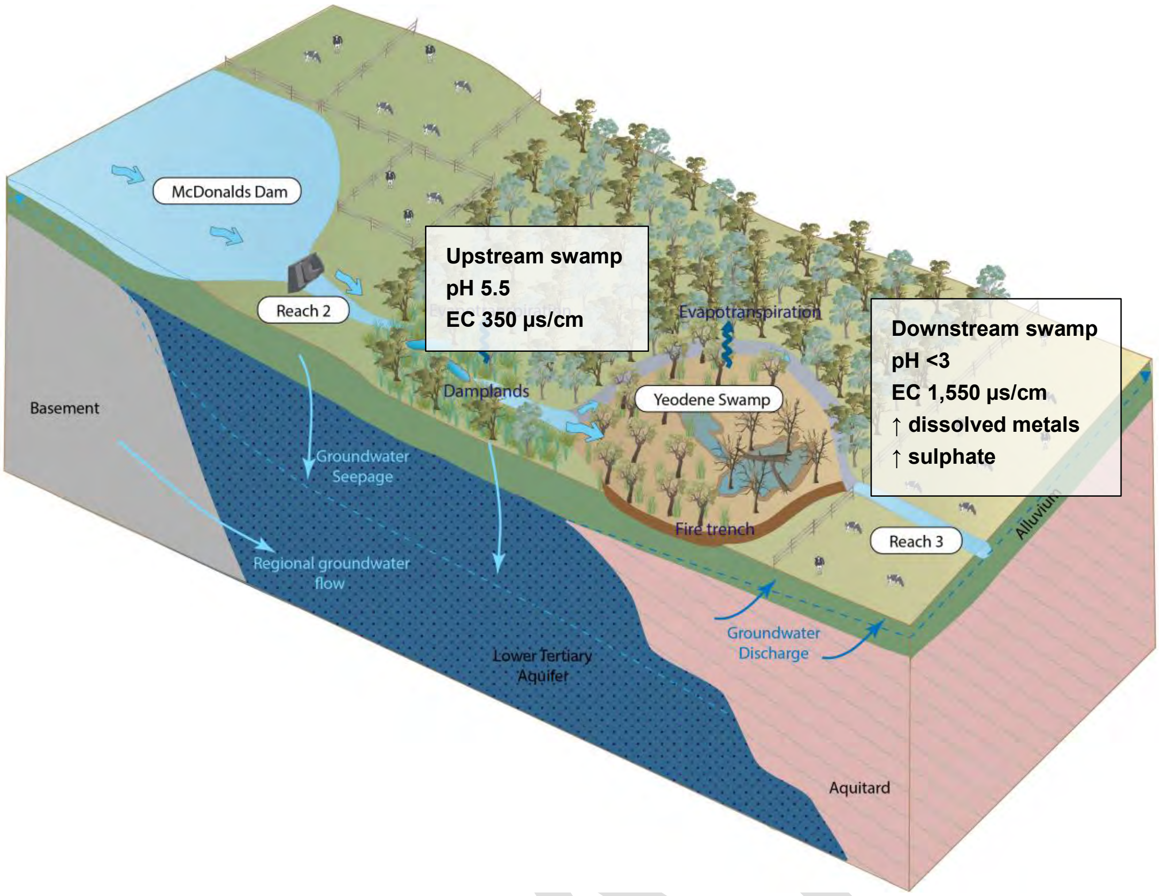


Figure 4-4 Conceptual model showing changes in water quality

In May 2017, water upstream of the Damplands was slightly acidic ranging in pH between 5.5 and 5.76, and fresh ranging in EC between 337 and 392 µS/cm (see Figure 4-5). Water pH fell significantly through Yeodene Swamp, resulting in a pH of 2.95 downstream of the swamp. This is symptomatic of acidic inputs from acid sulfate soils and is further evidenced by an increase in sulfate concentrations from ~6 mg/L to 700 mg/L (see Figure 4-5). Surface water downstream of the swamp also increased in EC (to 1,553 µS/cm) along with the concentrations of various dissolved metals such as Aluminium (which increased from <0.05 mg/L to 75 mg/L), indicating the acidic mobilisation of metals.

Between Yeodene Swamp and Yeodene Gauge, pH increased slightly (to 3.21) while EC and the concentration various dissolved metal species fell (see Figure 4-5). The increase in pH may be related to minor inputs of surface water runoff, as well as any buffering from streambed sediment or oxidation. Runoff may have also contributed to the dilution of various metal species and the reduction in EC, however this may also be related to the sorption of dissolved metal species on streambed sediments or their precipitation at slightly higher pH levels. Between the Yeodene stream flow gauge, and the Lower Boundary Creek site, the pH improved with concentrations of sulfate and various metals and pH falling while EC increased. This is likely to be related to inputs of water that is saltier and higher in pH than Boundary Creek, such as groundwater or tributary inflows.

In August 2017, surface water in the upper reaches of Boundary Creek was circum-neutral, ranging in pH between 7.54 and 7.28, and fresh, with an EC of ~450 µS/cm. Water pH again declined through Yeodene Swamp, resulting in a pH of 3.60 downstream of the swamp (see Figure 4-5). Similar trends in EC, sulfate and dissolved metals were also observed, with EC increasing to 645 µS/cm, sulfate increasing from 16 to 68 mg/L and dissolved metals such as Aluminium increasing from 0.23 mg/L to 8.0 mg/L. These results were again consistent with the input of acidic leachate from acid sulfate soils.

Less variation was observed in the chemistry of water downstream of Yeodene Swamp in August compared to May. Changes in pH were minor, increasing from 3.60 downstream of Yeodene Swamp site to 3.74 at the Lower Boundary Creek site (see Figure 4-5). Concentrations of sulfate increased through this section, from 68 mg/L to 110 mg/L, along with aluminium from 0.23 to 8.0 mg/L and EC from 645 to 901 µS/cm. Reduced surface water variability through this reach during August may be related to the higher volume of water that was moving through the creek at this time, and a reduced capacity for things like groundwater inflow, streambed and atmospheric interactions which affect water chemistry.

It is also noted that the concentration of many dissolved metals, including Aluminium, Cadmium, Nickel and Zinc were below or near the analytical detection limit upstream of Yeodene Swamp. These increased by several orders of magnitude downstream of the swamp, and were above the ANZECC guideline for the protection of 80% of freshwater species (ANZECC, 2000). Similar trends were observed in August for Aluminium, Nickel and Zinc.

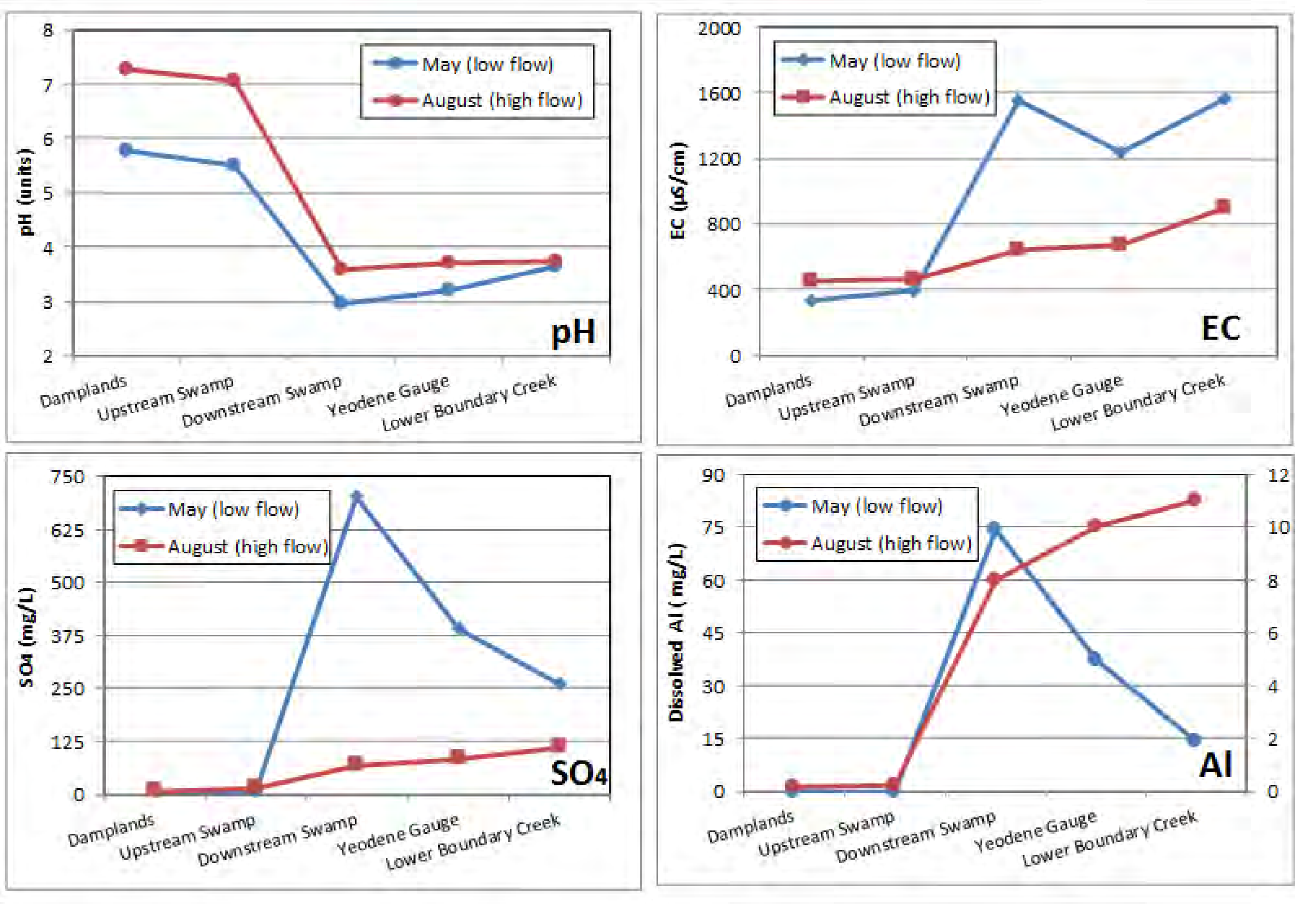


Figure 4-5 Change in pH, EC, sulfate and Al concentrations in Boundary Creek during May and August

### 4.5.2 Groundwater

Groundwater pH in the shallow alluvial aquifer was the lowest in YS01, YS03 and YS05, ranging between 1.58 and 2.72 in May and between 2.59 and 3.80 in August, 2017. Groundwater downstream of Yeodene Swamp (in bores A3 and TB1a) was also acidic, ranging in pH between 4.03 and 4.19 in May and 4.56 and 5.0 in August. Groundwater in the remaining bores (YS02, YS06, LBC01, LBC02 and PASS1) was circum-neutral to mildly acidic, ranging between 5.33 and 6.28 in May and between 5.71 and 6.64 in August.

The results suggest that the shallow alluvial aquifer is affected by acid sulphate soils. Groundwater at YS01, YS03 and YS05 are the most affected by acid sulfate soils, followed by A3 and TB1a. Further, groundwater upstream of the swamp and downstream of Yeodene streamflow gauge does not appear to be affected by the local occurrence of acid sulfate soils, and is consistent with regional groundwater pH throughout the catchment.

This is also demonstrated by the concentration of sulfate and chloride in groundwater supports this assertion, with a higher proportion of sulfate relative to chloride in groundwater with lower pH values (Figure 4-6). This is expected in groundwater affected by acid sulfate soils, as sulfate is released during the oxidation of acid sulfate soils, but not chloride.

Similar trends are also observed between metal concentrations and pH, with elevated concentrations of dissolved metals observed in groundwater affected by acid sulfate soils. This correlation is related to the acidic leaching of metals from soils and is well documented in scientific literature. The trends have been illustrated in Figure 4-7 below which shows a logarithmic correlation between aluminium and zinc concentrations and pH. These have been presented relative to the concentration of chloride in order to account for any increase in metal or sulfate associated with increased salinity.

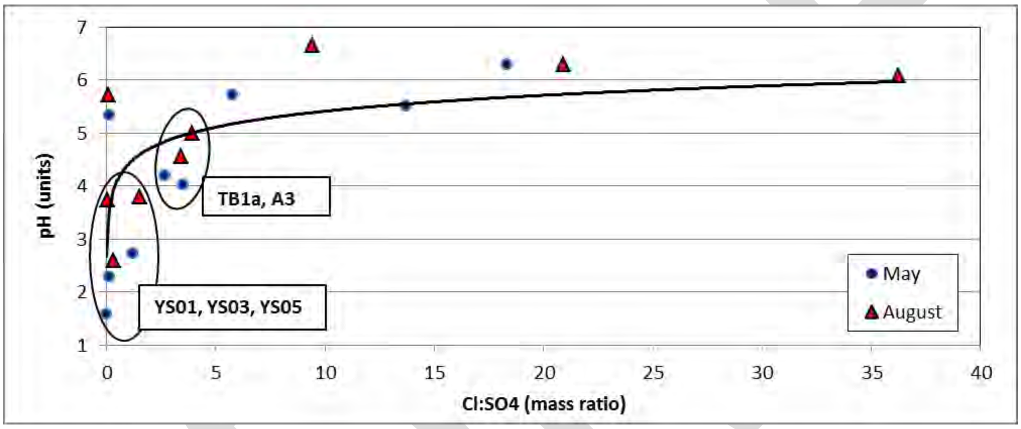


Figure 4-6 Covariance between groundwater pH and ratio of Cl:$SO_4$

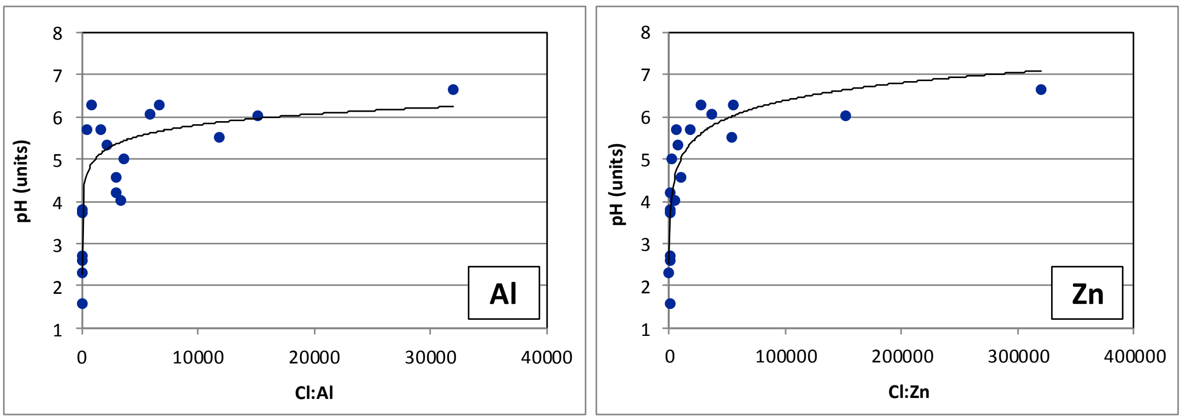


Figure 4-7 Covariance between groundwater pH and ratio of Cl:Al and Cl:Zn

## 4.6 Groundwater and surface water interaction

Groundwater and surface water levels were measured at 8 locations along Boundary Creek and Yeodene Swamp. These were collected during May, after the creek had resumed flowing from summer flow cessation, and during August, after 3 months of continuous flow in the creek. The levels have been listed in Table 4-5 and the gaining or losing status of each site has been listed.

Downstream of the dam, surface water flow increase and this could be the result of runoff in the catchment or discharge from a local alluvial aquifer. There are no shallow existing bores in this part of the catchment to confirm the presence of a local alluvial aquifer. Existing bores are around 10 m deep and groundwater levels in these bores are below the stream bed elevation confirming that creek is losing to the regional aquifer system. However it is possible that there is a local alluvial aquifer system perched that provides some flow to creek. Equally it is also possible that there are small drainage lines that direct runoff to the creek, or potentially there could be some leakage from the dam.

The results indicate that the Damplands and Yeodene Swamp were losing during May 2017, however the hydraulic gradient between groundwater and surface water was much lower through the swamp than in Damplands. The lower reaches of Boundary Creek were gaining in May, with groundwater levels higher than surface water levels between the Yeodene gauge (at bore A3) and the lower Boundary Creek site (at bore LBC02).

The Damplands was again losing during August, as were the upper parts of Yeodene Swamp at YS06 and YS05. However, through some lower parts of Yeodene Swamp, groundwater recharge over winter had increased the groundwater levels such that they were equal to surface water levels. This indicates that at this point in time, groundwater and surface water levels were hydraulically neutral, resulting in a zero net water exchange at this location (YS02). The lower reaches of Boundary Creek between the Yeodene Gauge and the Lower Boundary Creek site were again gaining.

Table 4-5 Summary of gaining and losing conditions along Boundary Creek

| Condition | Location | Surface Water mAHD | Groundwater mAHD | Status |
|---|---|---|---|---|
| First flow | **109130** | 159.40 | 152.64 | Losing |
| | **109143** | 156.70 | 151.05 | Losing |
| | **YS06** | 149.38 | 149.17 | Losing |
| | **YS05** | 148.16 | 148.02 | Losing |
| | **YS02** | 141.51 | 141.37 | Losing |
| | **A3** | 132.90 | 138.28 | Gaining |
| | **LBC01** | 130.38 | 130.56 | Gaining |
| | **LBC02** | 118.68 | 118.72 | Gaining |
| Winter high flow | **109130** | 159.83 | 153.14 | Losing |
| | **109143** | 157.06 | 151.57 | Losing |
| | **YS06** | 149.68 | 149.57 | Losing |
| | **YS05** | 148.40 | 147.95 | Losing |
| | **YS02** | 141.55 | 141.55 | Neutral |
| | **A3** | 133.57 | 139.21 | Gaining |
| | **LBC01** | 129.40 | 130.92 | Gaining |
| | **LBC02** | 119.00 | 119.23 | Gaining |

## 4.7 Vegetation

The area assessed at the eastern extent of Yeodene Swamp (as detailed in Section 3.7) showed signs of change in the relatively recent past. The transect began and ended in terrestrial environments that showed no sign of regular inundation, however the majority of the area was a seemingly permanent swamp of between 10 cm and 1 m depth. The permanence of the swamp is assumed due to the lack of any emergent vegetation on the fringes that commonly develops if a swamp is ephemeral such as annual grasses, sedges or small seedlings of surrounding shrubs and trees. The area was clearly not a permanent swamp in the recent past due to the presence of remnant tree fern stumps and fallen eucalypt trees within the permanent swamp. The size of the trees would suggest that they were more than 50 years old.

Whilst both tree ferns and the eucalypts, most likely Swamp Gum based on surrounding vegetation at the fringes of the swamp, rely on damp conditions and can tolerate periodic inundation, these species cannot survive constant inundation, particularly in slow moving water with little dissolved oxygen. The conditions of constant inundation would likely have resulted in root death. It is therefore most likely that both the trees and the tree ferns died due to an increase in the duration of inundation at the location due to changes in the local hydrology. Whilst this may have been exacerbated by the acidic conditions and increases in toxic metallic ions (e.g. zinc, cadmium and aluminium) as described in section 4.5.1, the primary cause of the change in vegetation noted is the change in hydrology resulting in increased inundation. The timing of the change cannot be pinpointed based on the observations made at the site but is estimated to have been within the last 10-30 years based on the decay in the logs observed and the fact the tree ferns are still standing.

The current vegetation present at the fringes of the swamp is typical of the vegetation along Boundary Creek and within Yeodene Swamp upstream of the assessed area. A cover of Scented Paperbark and Prickly Tea-tree shrubs over sedges and rushes (Po’ongort and Tall Rush) was recorded in areas not subject to constant inundation on the edges of the inundated swamp with Swamp Gums present where the topography was slightly higher.

Further up the banks at the ends of the transect, obligate terrestrial species such as Hazel Pomaderris, Forest Wire-grass and Hemp Bush were dominant due to being slightly elevated again, although all measurements within the transect were within only ~1.5 m elevation. Within the water of the swamp only Nodding Club-rush was noted and then only at the fringes. Largely, the only vegetation noted other than Nodding Club-rush within the water was large amounts of filamentous green algae attached to the fallen logs submerged in the swamp. It would be expected that other obligate aquatic species known to occur upstream such as Southern Water-ribbons, Twig-Sedges and even Tall Rush would be present within the inundated sections of the swamp and are conspicuous in their absence. This is most likely due to the relatively high acidity as a pH<4 is considered to be generally toxic to the majority of plant species. Coupled with the potential presence of potentially toxic concentrations of metallic ions, it is likely that the inundated portion of the swamp will remain largely un-vegetated without a change in water quality.

In summary, the vegetation at this location indicates:

- This part of Yeodene Swamp was not a permanent swamp historically (i.e. greater than 50 years ago) as the tree ferns and trees would not have established unless there was periodic drying. This could be the result of the construction of agricultural drains in the area.
- The trees and tree ferns are likely to have died as a result of root death cause by permanent inundation.
- Inundated area is un-vegetated as a result of the acidic water which is toxic to most plant species.

Figure 4-8 : 180 degree photo from centre of transect in Yeodene Swamp.

## 4.8 Conclusions and flow recommendations

The review of historical data, together with the new information collected during the field program, highlights the importance of maintaining flow all year round at the Yeodene gauge to prevent drying at Yeodene Swamp, thereby improving the existing water quality issues downstream of the swamp.

The first cease to flow event where there is both surface water flow and quality data available was in 1990. The creek was dry for one month which allowed the swamp to dry and for acid sulphate soils to oxidise. The groundwater quality at Yeodene gauge had a pH < 5 for approximately 3 months. Low pH events were also recorded in the following two summers (1991 and 1992) as a result of low summer flows. The low pH events extended for a period of 4-5 months and the pH levels improved during the winter months.

It is difficult to determine the actual flow required to improve and maintain the water quality downstream of the swamp as for significant periods of time during the warmer months, less than 2 ML/day has been recorded downstream of McDonalds Dam. Consequently it is certain that more than 1.5 ML/day is required.

It could be that 2 ML/day is sufficient, but there is no scientific evidence to support this. However, flow records at Yeodene gauge start declining when the flow drops below 3 ML/day downstream of McDonalds Dam. The streamflow gauging also estimated that approximately 3 ML/day was being lost through the Damplands and the Yeodene Swamp.

Therefore it is recommended that the environmental flow requirement of Reach 2 is increased initially from 2ML/day to 3 ML/day as recorded downstream of McDonalds Dam. It is possible that additional supplementary flows could be required during extreme dry weather events during the short term to prevent cease to flow events at the Yeodene stream gauge (downstream of the swamp). It is also likely that this volume would be reduced to 2 ML/day once the swamp is permanently inundated. This is expected to take up to three years.

Ongoing groundwater and surface water monitoring in the context of adaptive management is recommended to confirm that the flow recommendation is meeting the desired outcome.

# 5. Management strategies

## 5.1 Chapter overview

This section considers a range of management strategies with the aim to improve the quality and volume of water flowing in Reach 3 of Boundary Creek. Each of these strategies is discussed in terms of its specific objective, how it may be implemented conceptually, the potential outcomes of the strategy and the estimated costs (if feasible). The strategies that have been considered in this report include:

1. Do nothing
2. Direct treatment of soils with neutralising agents
3. In drain water treatment with limestone
4. Diluting acidic discharge
5. Revising flow release location
6. Inundating Yeodene Swamp

The outcomes of the below assessment have been summarised in Table 5-1 below. More detail on each option is provided in the following sections.

Table 5-1 Summary of management options

| Option | Feasibility for Yeodene Swamp | Rationale |
|---|---|---|
| **Do nothing** | Not feasible | • Yeodene Swamp will continue to release acidic water in Reach 3. This is considered unacceptable |
| **Treatment of soils** | Not feasible | • Significant works would be required to access the entire swamp to distribute neutralising agents, which will be very disruptive to existing flora and fauna.<br>• Significant costs associated with first application and subsequent applications are likely to be required. |
| **Installation of a lime drain in Reach 3** | Not feasible | • A limestone drain has the potential to improve water quality during low flow periods, however there would be limited benefit during high flow events.<br>• Significant capital costs would be required which would result in major modifications to Reach 3 and ongoing maintenance would also be necessary. Furthermore, water quality in Yeodene Swamp would not improve.<br>• This option is more fixing the symptom rather than the problem. |
| **Diluting acidic discharge** | Not feasible | • Volumes of water required for dilution cannot be sourced in this region and would increase flooding and adversely impact Reach 3:<br>o 250 ML/day during low flows<br>o 1,200 ML/day during high flows |
| **Revising flow release location** | Not feasible | • Require the hydraulic isolation of Yeodene Swamp from Boundary Creek.<br>• Improve water quality in Reach 3 under summer low flow conditions, however likely to cause adverse impacts on water quality under high flow conditions when the swamp floods as pent up acid would be flushed out in high flows.<br>• This would increase drying in the swamp, which would exacerbate the acid sulphate soils in the swamp. |
| **Inundating Yeodene Swamp** | Feasible | • Key indicator for low pH events is "cease to flow" conditions at the Yeodene Swamp. This objective of inundating the swamp is to prevent cease to flow events at Yeodene.<br>• Technically feasible and cost effective option to inundate swamp by increasing supplementary flows and infilling fire trenches and agricultural drain at eastern end. Approach to complete this would involve: |

| Option | Feasibility for Yeodene Swamp | Rationale |
|---|---|---|
| | | o Infill the fire trenches and block the agriculture drain, ideally before April 2018 (pending approvals) to allow the swamp to retain more water over the winter months.<br>o Minimum flow required initially is 3 ML/day as measured below McDonald's Dam.<br>• Low flow requirement of 3 ML/day is a best estimate based on a detailed assessment of the historical data. It is possible that more water could be required for short time periods during very dry conditions. Equally it's also possible that this volume could be reduced to 2 ML/day within 2-3 years as the swamp remains saturated.<br>• Ongoing adaptive management is required that involves regular monitoring and site visits are recommended to ensure the minimum flow requirement is meeting the objective. |

## 5.2 Do nothing

### 5.2.1 Objective

This option considers the likely environmental outcomes if active management strategies for Boundary Creek and Yeodene Swamp are not implemented. As such, consideration of this option provides a baseline against which subsequent options can be assessed.

### 5.2.2 Concept

In the event that no remedial or management actions are undertaken in Yeodene Swamp or the Boundary Creek catchment, then it is expected that the creek system would operate in a similar way to those observed currently. Periods of flow cessation would be expected to continue in Boundary Creek, along with periods of drying in Yeodene Swamp, acid generation, and the input of acidic and metalliferous leachate into the lower reaches of Boundary Creek.

### 5.2.3 Potential outcomes

The absence of remediation would result in continued acid generation in Yeodene Swamp, and the input of acidic and metalliferous leachate into the lower reaches of Boundary Creek. It would be expected that the lower reach of Boundary Creek would cease to flow during summer/autumn periods. Winter and spring flows would be acidic (pH <4) and contain toxic concentrations of dissolved metals (including Al, Cd, Ni and Zn) as currently observed.

Under current conditions (assuming a concentration of acid of around 1,800 moles of acidity ($H^+/L$) and a flow of 2 ML/day for 6 months of the year), the annual flux of acid leaving Yeodene Swamp has been estimated to be around 55,000 moles of acid per year ($H^+/year$). The mass of acid currently stored in the swamp (according to net acidities measured during this study and the assumption only acidity in the upper 1 m of the soil profile will be mobilised) is estimated to be 134 million moles of acid ($H^+$).

**Based on this, it is estimated that conditions similar to those observed currently could persist for several hundred years.**

Given the "do nothing" will not achieve the desired objective of improving the volume and quality of water in Reach 3, it is not considered to be a feasible option and therefore cost estimates have not been provided.

## 5.3 Direct treatment of soils with neutralising agents

### 5.3.1 Objective

This option aims to neutralise the acidity present in soils in Yeodene Swamp, and to enhance the quality of water in the lower reaches of Boundary Creek.

### 5.3.2 Concept

The addition of chemical agents to neutralise acidity is a well-established management practice in the treatment of acid sulfate soils. The agents are compounds with a high acid neutralising capacity such as calcium carbonate (often in the form of agricultural lime), calcium oxide, calcium hydroxide and others. These are either added to water flowing through the affected system, or are directly incorporated into sediments.

A variety of application methods are also available pending the nature of the site and access limitations. These include the direct application of lime (CaOH) powder, the application of agricultural lime ($CaCO_3$) slurries via pressure hose, or dusting large areas with agricultural lime from an aircraft (see Figure 5-1).

Figure 5-1 Application of XX slurry to Lower Murray Lakes (left) and aerial application of lime to Currency Creek (right) (EPHC & NRMMC, 2011).

One of the main disadvantages of using neutralising agents is the difficulty of ensuring its effective application. For example, the agent may be eroded and mobilised from a system before it has had sufficient time to neutralise the acid present. Additionally, the agent may not fully dissolve in the aquatic system, further reducing its efficacy. The neutralising capacity of the agent can also be further reduced if it becomes coated with iron oxides or gypsum.

In addition to the above factors, if the agent is to be incorporated into the soil profile (to improve its effectiveness), sediment disruption can impact species and habitats. Finally, neutralisation of a water column will cause the precipitation of any heavy metals dissolved during acidification, leading to sediment surfaces being coated with a sludge that is enriched by heavy metals. This can be subsequently released if acidic conditions return, resulting in highly metalliferous “slugs” of water.

Examples of direct application over acid sulfate soils in the Lower Murray River region has been shown to have immediate effects on soil and water quality, increasing pH by around 2 units (Mosley et al., 2014). However, multiple applications may need to be undertaken over time if the efficacy of the agent is reduced.

### 5.3.3 Potential outcomes

It is likely that given sufficient treatment, the acidity present in Yeodene Swamp could be neutralised. This would have the effect of increasing soil and water pH, and reducing the export of acidic and metalliferous leachate to the lower reaches of Boundary Creek.

However, the effective application of agents throughout the swamp presents significant logistical difficulties. For example, the mobilisation of equipment to deliver slurries through the swamp would require the clearing of access tracks. Further, in order to deliver such slurries into the soil profile, existing vegetation or trees occupying that soil would either need to be cleared or would at least, become highly disturbed. In addition, the treatment material and precipitated metals will be incorporated into the food chain by bottom-feeding and filter-feeding organisms.

### 5.3.4 Option summary

The direct treatment of soils in Yeodene Swamp with neutralising agents is likely to be highly disruptive to the existing flora and fauna, and logistically difficult to execute. Given the issues associated with applying the lime treatment and the ongoing monitoring requirements, this option is not considered to be a feasible management option.

## 5.4 In drain treatment with limestone

### 5.4.1 Objective

The objective of installing a lime drain is to neutralise the acidic water discharging from Yeodene Swamp, and thereby improving water quality in the lower reach of Boundary Creek.

### 5.4.2 Concept

A range of drain designs exist for the treatment of acidic discharge from water bodies. These include systems aimed at directly treating acidic discharge with neutralising agents, and others aimed at removing acidity from a water column via the precipitation of compounds under reducing conditions. This section considers an open limestone drain, as is illustrated in Figure 5-2 below.

The advantage of this kind of system is that it can be modified or managed (i.e. agents can be added to the drain in varying quantities) to suite a desired outcome. Further, and unlike direct in swamp treatment (section 0), if sludge's enriched in heavy metals form during neutralisation, these can be dredged and removed from the drains.

However there are several disadvantages of this option related to the initial capital works, ongoing maintenance and that it only benefits Reach 3, not Yeodene Swamp. The main disadvantages are:

- Initial design and construction costs to ensure the water quality objectives are achieved.
- Modification of Reach 3 would be required.
- Ongoing maintenance costs - materials added to the drain can become buried, coated with by-products of chemical reactions, eroded or transported from the channel over time, and will be consumed during neutralisation. Regular dredging could be required to remove this material and/or further limestone could be required to ensure their ongoing efficacy.
- Limestone drains would only affect the quality of water flowing out of Yeodene Swamp and not the swamp itself.

Such systems have been employed in a range of settings with varying levels of success. For example, after the addition of lime sand to an acidic drainage channel in Becon, WA, the effectiveness of the drain became negligible after only 3 weeks (Degnes, 2009). In contrast, a 230 m long lime drain on Lasilva Stream in Spain was shown to increase water pH from <3.0 to up to 4.5 for over a year, with no apparent reduction in efficiency (Santofimia and Lopez-Pamo, 2016).

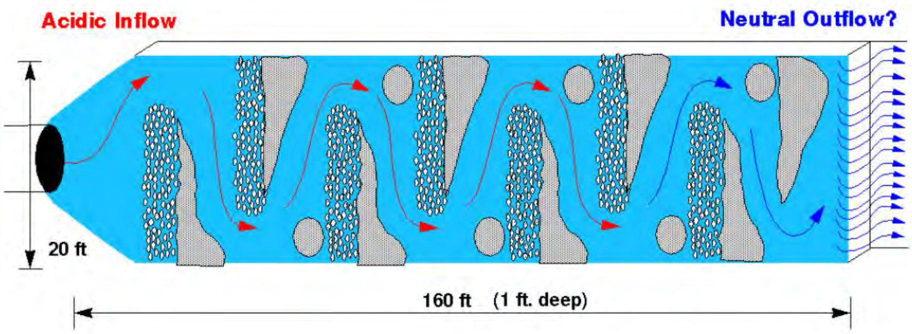


Figure 5-2 Example of open limestone drain - images from Taylor et al., 2005 (left) and Cravotta 2010 (right)

#### 5.4.3 Potential outcomes

The installation of a limestone drain is likely to result in somewhat improved water quality in the lower reaches in Boundary Creek. A review of case studies suggest that limestone drains are likely to increase water pH by anywhere between 0.2 and 2.0 units, and that concentrations of dissolved metals in the outflow water will be reduced (Ziemkiewicz et al., 2003).

However, the effect of the limestone drain on water quality will depend on the design of the drain, the velocity and residence time of water in the drain, the volume of water moving through the drain, and the initial quality of water entering the drain. Under high flow conditions such as those observed in August 2017 (~15 ML/day), reduced residence times and high flow volumes are likely to render a limestone drain ineffective.

However, under low flow conditions such as those observed in May 2017 (~2.5 ML/day), a well-designed drain may be effective. Work by Santomartino and Webb (2007) has estimated the decline in efficiency of such drains over time in response to metal coating, based on the amount of limestone used, the mass of metals fluxing through the system and their retention rate. While this work was specifically related to dissolved $Fe^{2+}$ under reduced conditions, it is likely to provide a first order estimate as to the timing of drain failure.

Based on conditions observed during May (total dissolved Al and Fe = 102 mg/L) and assuming Al and Fe behave similarly, with 20% retention in the drain, the estimated lifespan of a drain containing 5,000 tonnes of limestone is ~7 years.

#### 5.4.4 Option summary

A limestone drain along Reach 3 has the potential to improve the water quality during low flow periods, however there would be limited benefit during high flow events. There are also several disadvantages related to the initial capital costs, ongoing maintenance and significant modifications required to Reach 3. Further, this option will not improve the water quality in Yeodene Swamp. Therefore, this is not a feasible option to improve the water quality in the lower reaches of Boundary Creek.

### 5.5 Dilution of acidic discharge

#### 5.5.1 Objective

Increasing surface water flows in Boundary Creek aims to directly buffer or dilute the acidity moving through the system, in order to improve the quality of water moving through Boundary Creek.

#### 5.5.2 Concept

The effect of increasing the release volume has been assessed using the hydro-chemical modelling package PHREEQC. The package has been used to simulate the quality of water likely to result from different mixtures of release water and leachate from the swamp. The outputs are highly conservative with respect to the estimated release volumes required to increase pH and reduce metal concentrations. This is because the model considers the effects of mixing, and does not account for in catchment processes including flow loss in Reach 2 (which would reduce any dilution or buffering) or any increased mobilisation of acid and metals through Yeodene Swamp as a result of greater flow rates.

The chemistry of the release water has been assumed to be the same or similar as water sampled downstream of McDonalds Dam during low flow conditions in May 2017. This assumption is reasonable as the upper reaches of Boundary Creek where the water is released predominantly flows over outcropping bedrock. As such, groundwater inflows to the release water are minor and unlikely to result in appreciable changes in flow and water quality.

The chemistry of swamp leachate has been characterised by that measured flowing out of the swamp under both low flow (~2.5 ML/day) and high flow (~15 ML/day) conditions. The chemical nature of these waters is detailed in Appendix C.

### 5.5.3 Potential outcomes

The effect of flow release on water quality has been illustrated in Figure 5-3 and Figure 5-4. These figures show the expected change in pH and aluminium concentrations associated with the mixing of release water with swamp leachate.

The figures illustrate that to achieve a pH of >4.5, release water would need to reflect ~99% of the water exiting the swamp under low flow conditions (~250 ML/day) and ~80% under high flow conditions (1,200 ML/day). This is because release water has a very limited buffering capacity and as such, only begins to effect pH at exceptionally high input volumes. Given this, changes in metal concentrations such as Al are only likely to be affected by dilution and not precipitation that would occur under higher pH conditions.

The release of such volumes of water would also significantly change the current environmental setting of Boundary Creek and Yeodene Swamp and negatively impact the existing flora and fauna. Further, such flow releases would also almost certainly result in flooding in the catchment.

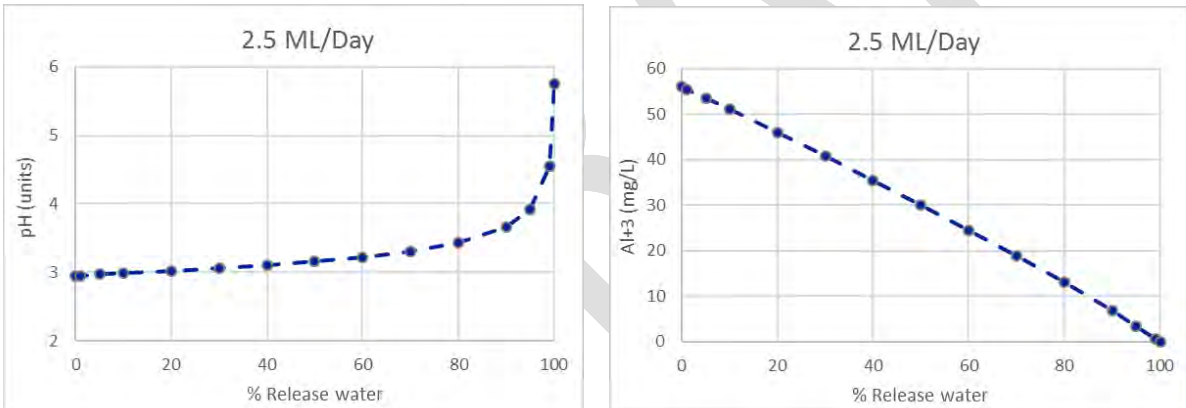


Figure 5-3 Change in pH and $Al^{+3}$ concentration under addition of release water to swamp water at 2.5ML/day

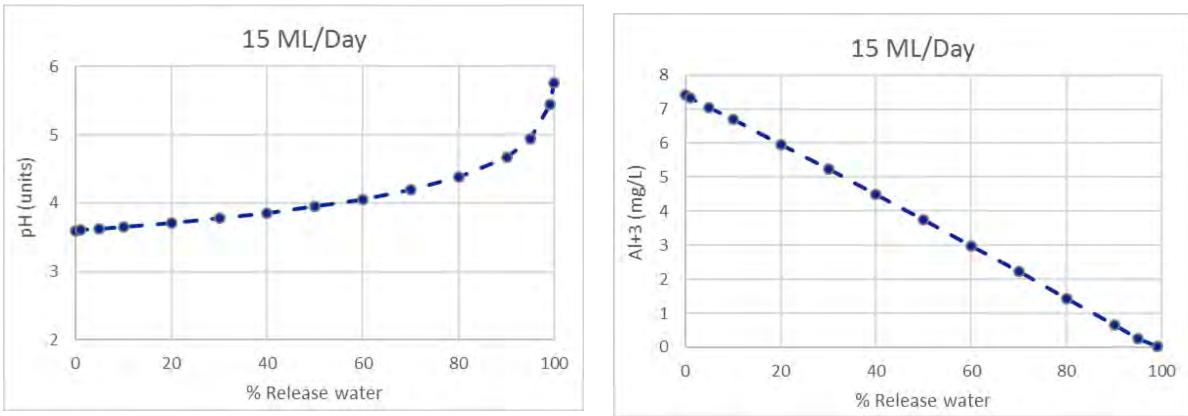


Figure 5-4 Change in pH and $Al^{+3}$ concentration under addition of release water to swamp water at 15ML/day

### 5.5.4 Option summary

The above results indicate that the release volumes necessary to have a manifest influence on water quality in Boundary Creek are impractical, would increase flooding and negatively impact the existing flora and fauna. As such, this management option is not feasible in the Boundary Creek catchment and therefore not costed.

## 5.6 Revising flow release location / swamp isolation

### 5.6.1 Objective

The objective of this option is to improve the volume and quality of water flowing through the lower reach (Reach 3) of Boundary Creek by delivering supplementary flows directly into Reach 3. Given the findings from the previous management option discussed in Section 5.5, the volume of water required for dilution is impractical to improve the water quality in Reach 3. Therefore this option also requires Yeodene Swamp to be isolated from Boundary Creek to prevent acidic water discharging into Reach 3.

### 5.6.2 Concept

Currently, Boundary Creek flows predominantly through incised channels. However, observations during this field program indicate that the flow path is less defined at Yeodene Swamp, where multiple minor flow paths braid out. This allows for the interaction between the inflowing water and acid sulfate soils in the swamp, resulting in the outflow of acidic and metalliferous water. This option considers channelizing the existing northern drainage line around Yeodene Swamp in order to limit the interaction between the flowing water and the acid sulfate soils. Simultaneously, the option considers the potential water quality effects of flow release downstream of the swamp.

### 5.6.3 Potential outcomes

This option has several potential outcomes:

- The Damplands upstream of the swamp are likely to be adversely impacted by reduced surface water flows.
- Isolating Yeodene Swamp from Boundary Creek will likely cause the swamp to dry out further and therefore increasing acidification and evapo-concentration from increased drying. It will also be difficult to completely isolate the swamp during high flow events, and is likely to result in the periodic discharge of acidic into Reach 3.
- During low flow conditions, the water quality in Reach 3 is likely to improve due to the absence of acid discharge from the swamp and a permanent flow of good quality water.

- Given the difficulty in isolating the swamp during high flow conditions, it is likely that the water quality would be influenced by acidic flushes of water released into Reach 3.

However, as asserted in section 5.5, increasing the release of water to Boundary Creek is unlikely to have any significant effect on the quality of water draining from the swamp via either dilution or buffering. This is because release water has very little buffering capacity. As such, the volume of water required to effectively buffer acidity, or dilute the concentration of metals in water draining the swamp, far exceed any practical release volume.

Given this, it is likely that under high flow conditions, flooding through the swamp will result in overbanking and the discharge of acidic and metalliferous water into Boundary Creek. Further, the quality of this water is likely to be worse than currently recorded in the swamp, as a result of increasing acidification and evapo-concentration from increased drying.

In addition, the segregation of Yeodene Swamp from Boundary Creek would reduce the inflow of water onto the swamp. This would reduce the water available for the existing vegetation and fauna in the swamp.

#### 5.6.4 Option summary

The segregation of Yeodene Swamp from Boundary Creek and introduction of flow release into Reach 3 is only likely to improve water quality in Reach 3 under summer low flow conditions, and may deteriorate water quality under high flow conditions. Further, it would increase drying in the swamp, which would have a deleterious effect on the existing flora and fauna. Accordingly, this option is not feasible for managing Boundary Creek and has therefore not been costed.

### 5.7 Inundating Yeodene Swamp

#### 5.7.1 Objective

The objective of inundating Yeodene Swamp is to induce reducing conditions that would neutralise in situ acidity in Yeodene Swamp and reduce the acidity and concentration of dissolved metals in water draining from Yeodene Swamp.

#### 5.7.2 Concept

Inundating the Swamp and inducing reducing conditions would largely reinstate the environmental setting that formed acid sulfate soils in the swamp initially. The process that produces acid sulfate soils under reducing conditions also produces alkalinity, which can neutralise acidity in the system.

This management strategy has been shown to be effective in a number of freshwater acid sulfate soil wetlands in Australia and Victoria. This includes Partridge Creek and Darawakh Wetland (Johnson et al., 2008), the Lower Murray Lakes (Baker, 2014), Lake Mealup (Jenkinson and Appleyard 2014) and in Bottle Bend Lagoon.

Reducing conditions are formed in carbon rich environments that are kept permanently inundated and oxygen poor, such as those that have historically existed within Yeodene Swamp. Given this, this option considers the flow and drainage requirements necessary to induce such conditions in Yeodene Swamp.

Two aspects are required to keep the swamp inundated and create reducing conditions:

1. Minimum low flow requirement released from McDonalds Dam, and
2. Infilling the fire trench and agricultural drain at the eastern end of Yeodene Swamp.

**Minimum low flow requirement**

Historical pH and flow monitoring at Yeodene suggests that reducing conditions persisted through significant portions of Yeodene Swamp prior to 1990 and between 1990 and 1999, as evidenced by pH values typically >5 during these periods (Figure 2-12). Flow in Boundary Creek at Yeodene was typically perennial during these periods, indicating that flow cessation and swamp drying was the major driver of acid release.

This is further supported by low pH values in 1992, the only period of flow cessation in Boundary Creek between 1990 and 1999 (Figure 2-12). Given that groundwater levels in the catchment had largely recovered in 1992 and that Reach 2 was gaining (Figure 2-7), it can be asserted that acid release during this time was controlled by reduced surface water flows and not groundwater processes. It is therefore concluded that a drainage regime similar to pre-1999 conditions could induce reducing conditions in areas of Yeodene Swamp, and increase the pH of water draining form the swamp to >4.5.

Limited gauging data is available for both the downstream McDonalds Dam and Yeodene stream flow gauging stations over the same time series. However, data collected during the summers of 2014-15, 2015-16 and 2016-17 suggest that an outflow of at least 3 ML/day at downstream of McDonalds Dam gauge is necessary to yield flows at the Yeodene gauge under summer low flow conditions (Figure 5-5).

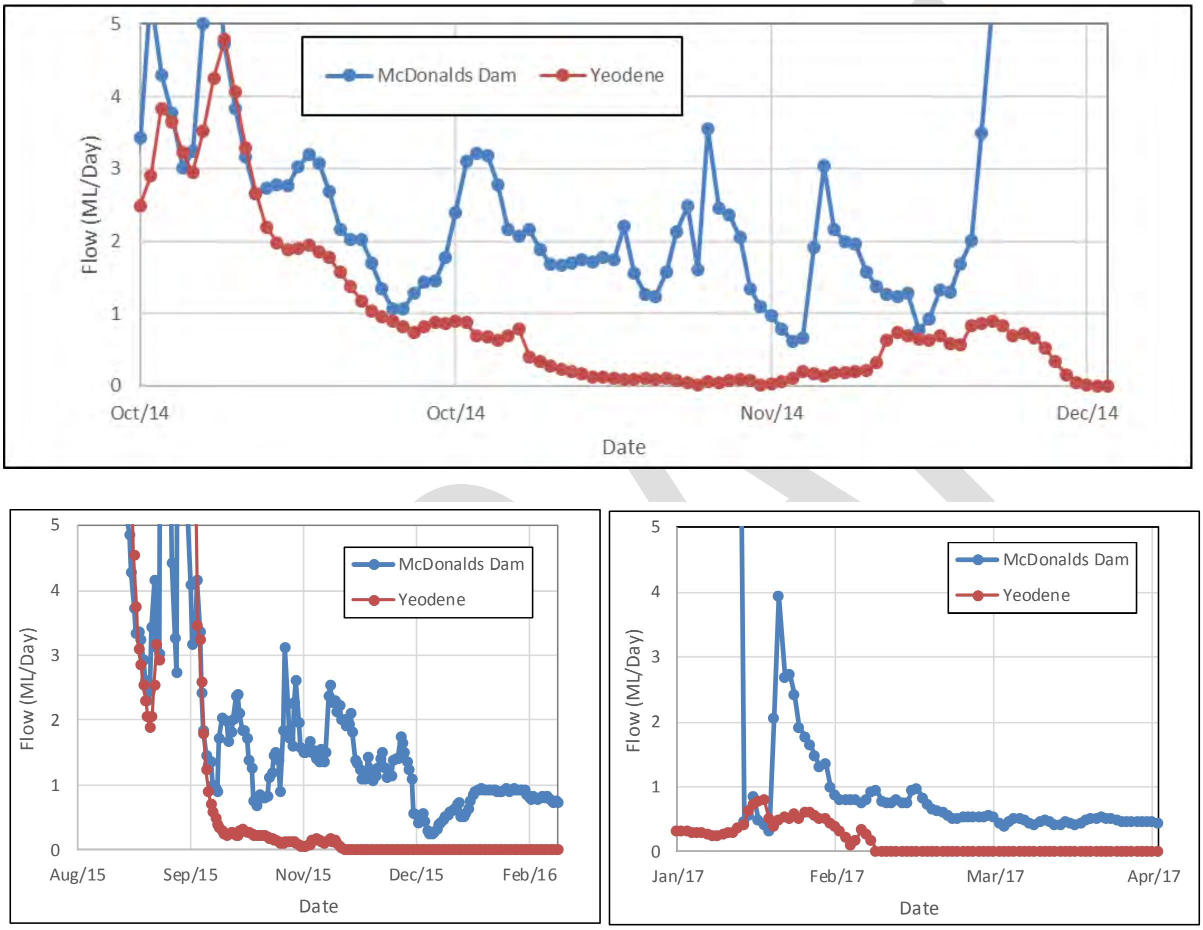


Figure 5-5 Flow measurements at D/S McDonalds Dam and Yeodene gauges

**Infill fire trench and agricultural drain**

The construction of fire trenches in Yeodene Swamp has altered the swamps drainage regime. Currently, significant volumes of water are drained from the swamp via these trenches and their connection with existing drainage lines. The introduction of hydraulic barriers at inflection points in this drainage network, to levels consistent with pre-trench elevations, would increase the surface water elevation required to drive outflows from the swamp.

This could (along with increased inflows) increase the depth and extent of inundation in the swamp, promote reducing conditions, and neutralise the acidity present within Yeodene Swamp. A schematic design for such a barrier has been illustrated in Figure 5-6 where the fire trench crosses the major drainage line from Yeodene Swamp.

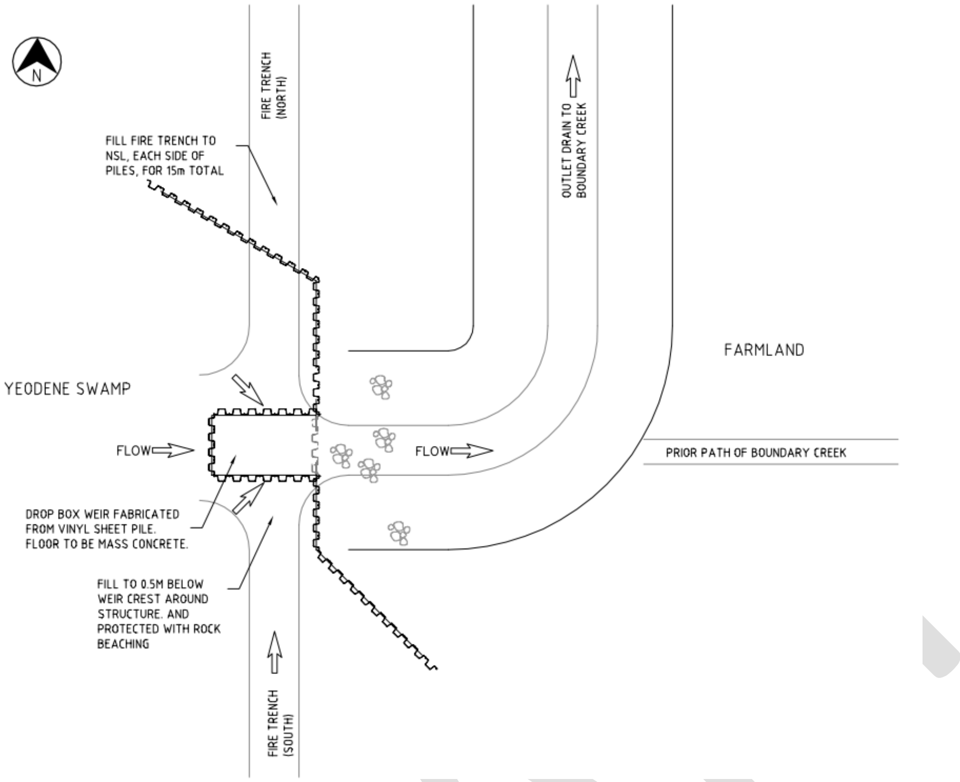


Figure 5-6 Schematic drainage paths from Yeodene Swamp

### 5.7.3 Potential outcomes

The return of large portions of Yeodene Swamp to reducing conditions, similar to those between 1992 and 1999 is likely to increase the pH of the water draining from the swamp. Historical monitoring suggests that if such conditions are sustained, the median pH of water draining from the swamp may increase to ~6, with summer low flow pH closer to 4 (if parts of Yeodene Swamp dry out).

Such conditions would also result in the precipitation of dissolved metals species that currently exist in Yeodene Swamp. This would reduce the outflow of heavy metals to the lower reaches of Boundary Creek and the Barwon River. However, the precipitation of metals could lead to sediment surface being coated with a sludge that is enriched by heavy metals. If acidic conditions subsequently return, these could be mobilised as a highly metalliferous “slug” downstream.

Vegetation is likely to change if the area of permanent inundation increases. The vegetation will shift to species that can tolerate inundation. As the water quality improves aquatic vegetation will also return to the area.

### 5.7.4 Cost estimate

A cost estimate to install an automated flow release from McDonalds Dam to ensure that supplementary flows are being passed is based on the requirements below:

- Upgrade the existing stream gauges immediately upstream and downstream of the dam to allow for telemetry.
- Installation of a manual control valve.
- Installation of a flow meter with solar and battery backup.

- Construction and site works.

Accordingly the cost estimated for the installation of an automated flow release would be upwards of $130,000.

A cost estimate of the hydraulic barrier described in 5.7.2 is based on the arrangement described below:

- It consists of a drop box type structure fabricated primarily from vinyl sheet pile. The piles extend across the fire trench (north side) which would be blocked to natural surface level. This leaves the original outlet drain as the only swamp outlet.
- The floor of the drop box would be mass concrete placed over gravel which would act to prop the piles in the box.
- Earth fill would be placed in the fire trench (north) and for part height on the upstream side of the box.
- Rock beaching placed over geotextile would be provided on the outlet channel until the downstream side of the bend to prevent erosion toward the prior creek line.
- Sheet piles would be placed by an excavator with a vibrating attachment. It is assumed the peat would need to be removed and the piles vibrated into place in the underlying sands. Piles would terminate at the underlying rock.
- Seepage resistance would be achieved by a combination of the pile length and fill material.

Accordingly the cost estimated for the construction of a once-off hydraulic barrier would be upwards of $500,000. See Appendix E for detailed cost estimates.

#### 5.7.5 Option summary

It is likely that returning Yeodene Swamp to similar conditions as those prior to 1999 would significantly increase the pH and decrease the concentration of dissolved metals both in the swamp, and draining from the swamp into Boundary Creek.

A review of flows downstream of McDonalds Dam and Yeodene suggests that a discharge of 3 ML/day at McDonalds Dam may be sufficient to perennially inundate enough of Yeodene Swamp to have such an outcome. This effect could be further enhanced by blocking drainage lines formed during the excavation of fire trenches.

This option is a feasible and cost effective option which will improve both the Yeodene Swamp and Reach 3. It aims to re-instate conditions similar to those that existed through the 1990’s and that currently exist for large periods of the year. As such, if the area of permanent inundation increases significantly, the vegetation in this area is likely to change to species that can tolerate permanent inundation.

The timeframes to implement this option are also an important consideration. The first step is to infill the fire trenches and block the agriculture drain. Preferably this should be completed before April 2018 pending approvals. This would allow the swamp to retain more water over the winter months. Once the trenches and agricultural drain have been infilled, the minimum flow requirement of 3 ML/day is required to be released from McDonald’s Dam.

It is important to highlight that the low flow requirement of 3 ML/day is a best estimate based on a detailed assessment of the historical data. An ongoing adaptive management approach that involves regular monitoring and site visits is recommended to ensure the low flow requirement is meeting the objective (i.e. always flow at Yeodene Gauge).

Improvements in water quality are likely to take up to 6 months. Previous studies suggest that a return to such conditions could significantly improve water quality in Yeodene Swamp over a period of several months.

The total cost is estimated to be upwards of $500,000 associated with the capital works and ongoing maintenance would be minimal.

# 6. Conclusions and recommendations

## 6.1 Conclusions

This report documents the findings of a study focussed on Yeodene Swamp. The purpose of this study was to characterise the chemical and physical processes affecting the volume and quality of water which will be used to inform potential strategies to help manage acidic water in the lower reaches of Boundary Creek.

The Boundary Creek catchment has experienced significant change including land clearing, construction of a dam, groundwater extraction, climate changes, and peat fires at Yeodene Swamp and the subsequent excavation of trenches to control the fire. These changes have contributed to the drying of acid sulfate soils in Yeodene Swamp which has resulted in poor water quality (low pH, metalliferous water) as a result of borefield operation combined with reduced rainfall in the catchment.

This study involved a field program to better characterise the physical and chemical processes occurring within the Boundary Creek catchment and to inform potential strategies focussed on managing water quality in Boundary Creek. The field program includes the installation of piezometers (shallow bores <3 m deep), lithological analysis, chemical soils analysis, surface water flow gauging, and both surface and groundwater quality monitoring.

The field program described in this report characterised a range of physical and chemical processes occurring within the Boundary Creek catchment. The major findings of the program included:

- Aquitard deposits occur towards the east of the swamp, and aquifer deposits towards the west of the swamp.
- The most severe acid sulfate soils (highest acidity) occurred in the central and lower lying areas of the swamp.
- Surface flows increase between McDonalds Dam and the Damplands.
- Boundary Creek losses surface water via groundwater seepage through the Damplands and Yeodene Swamp. Reductions in streamflow was 2.9 ML/day between the Damplands and Yeodene Swamp in May 2017.
- Changes in water quality through the swamp were consistent with the influence of acid sulfate soils, and the export of acid and dissolved metals were effectively estimated.
- Groundwater monitoring characterised the areas most affected by acid sulfate soils as those immediately down hydraulic gradient of the acidic soils.

As a result of the improved conceptual understanding, and chemical characterisation of both Boundary Creek and Yeodene Swamp, the effectiveness of different management options was assessed. Six options were considered:

1. Do nothing,
2. Direct treatment of soils with neutralising agents,
3. Treatment of outflows through a limestone drain,
4. Dilution with more surface water flows,
5. Relocating the flow release and isolating the swamp, and
6. Inundating Yeodene Swamp.

Options 1 to 5 were not considered to be feasible management options.

The permanent inundation of acid sulfate soil wetlands has been shown to be an effective management strategy in a number of case studies in Australia. This option is a feasible and cost effective option which will improve both the Yeodene Swamp and Reach 3.

It aims to re-instate conditions similar to those that existed through the 1990's and that currently exist for large periods of the year. Flow and water quality monitoring in Boundary Creek indicates that permanent inundation of the swamp has effectively neutralised acidic outflows historically, after periods of acidification.

## 6.2 Recommendations

It is recommended that in order to improve the volume and quality of water draining Yeodene Swamp, and to rehabilitate the swamp itself, permanent inundation be undertaken as a remediation strategy. Monitoring data suggests that a flow of initially 3 ML/day immediately downstream of McDonalds Dam could be sufficient to achieve this outcome.

It is important to highlight that the low flow requirement of 3 ML/day is a best estimate based on a detailed assessment of the historical data. An ongoing adaptive management approach that involves regular monitoring and site visits is recommended to ensure the low flow requirement is meeting the objective (i.e. constant flow at the Yeodene stream flow gauge).

Given this, it is recommended that Barwon Water adaptively manage flow release volumes and monitor the surface water level in Yeodene Swamp in order to keep it inundated. **It is noted that even brief periods (<1 week) of drying and flow cessation in Boundary Creek are likely to result in significant acidification historically, and as such, should be avoided.**

Ongoing monitoring at bores YS03, YS04 and YS06 is unlikely to be necessary and could be decommissioned. Bores YS01, YS02 and YS05 provide the most hydraulic and chemical information in Yeodene Swamp and as such, it is recommended that these continue to be monitored.

Recommendations to implement this remediation strategy are:

- Confirm design to infill fire trenches and agricultural drain.
- Undertake capital works to infill trenches and agricultural drain as soon as practicable.
- Automate flow release from McDonalds Dam to ensure minimum 3 ML/day is released between November and June as soon as practicable.
- Continue groundwater and surface water monitoring.
- Install data loggers in bores YS01, YS02 and YS05.
- Decommission bores YS03, YS04, YS06.
- Regular site visits (e.g. monthly) between November and May to complete spot flow gauging and surface water quality monitoring.

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# Appendix A. Installation of additional monitoring assets

To be provided.

# Appendix B. Summary Field and Laboratory Results

Table 7-1 Summary of acid sulfate soil screen tests

| Site | Depth (m) | $pH_F$ units | $pH_{FOX}$ units | ΔpH units | Reaction Rate (1-4) |
|---|---|---|---|---|---|
| LBC01 | 0.5 | 4.7 | 3.4 | 1.3 | 4 |
| LBC01 | 1.5 | 4.6 | 2.4 | 2.2 | 4 |
| LBC01 | 3.0 | 6 | 2.8 | 3.2 | 4 |
| LBC02 | 0.5 | 5.1 | 4 | 1.1 | 4 |
| LBC02 | 1.0 | 4.5 | 3 | 1.5 | 4 |
| LBC02 | 3.0 | 6.3 | 3.6 | 2.7 | 4 |
| YS01 | 0.5 | 4.6 | 2.9 | 1.7 | 4 |
| YS01 | 1.0 | 3.9 | 3.1 | 0.8 | 4 |
| YS01 | 1.5 | 3.9 | 2.6 | 1.3 | 2 |
| YS01 | 3.0 | 4.1 | 3.1 | 1 | 2 |
| YS02 | 1.0 | 3.4 | 1.6 | 1.8 | 3 |
| YS02 | 2.0 | 4.5 | 1.5 | 3 | 4 |
| YS02 | 3.0 | 5.9 | 1.8 | 4.1 | 4 |
| YS03 | 0.5 | 4.8 | 3.6 | 1.2 | 4 |
| YS03 | 1.0 | 3.9 | 2.7 | 1.2 | 4 |
| YS03 | 2.0 | 5.9 | 1.9 | 4 | 4 |
| YS03 | 3.0 | 5.9 | 2.2 | 3.7 | 4 |
| YS04 | 0.5 | 4.3 | 2.6 | 1.7 | 3 |
| YS04 | 1.0 | 4.3 | 3.4 | 0.9 | 1 |
| YS04 | 2.0 | 4.3 | 3.6 | 0.7 | 1 |
| YS04 | 3.0 | 4.2 | 3.4 | 0.8 | 1 |
| YS05 | 0.5 | 3.6 | 1.6 | 2 | 4 |
| YS05 | 1.0 | 2.8 | 1.6 | 1.2 | 4 |
| YS05 | 2.0 | 4.1 | 2.3 | 1.8 | 4 |
| YS05 | 3.0 | 4.2 | 2.3 | 1.9 | 4 |
| YS06 | 0.5 | 5.6 | 2.1 | 3.5 | 3 |
| YS06 | 1.0 | 5.8 | 3.2 | 2.6 | 4 |
| YS06 | 1.5 | 5 | 2 | 3 | 3 |
| YS06 | 2.5 | 5.3 | 3.5 | 1.8 | 1 |
| YS06 | 3.0 | 5.2 | 3.8 | 1.4 | 2 |

Table 7-2 Summary of chromium reducible sulfur tests

| Site | Depth | Actual acidity | Potential acidity | Retained acidity | Net Acidity |
|---|---|---|---|---|---|
| | (m) | Mole H+/t | Mole H+/t | Mole H+/t | Mole H+/t |
| LBC01 | 0.5 | 250 | 8 | < 10 | 270 |
| LBC01 | 1.5 | 260 | 14 | < 10 | 280 |
| LBC01 | 3.0 | 120 | 190 | 12 | 320 |
| LBC02 | 0.5 | 150 | 4 | 13 | 170 |
| LBC02 | 1.0 | 200 | 6 | < 10 | 210 |
| LBC02 | 3.0 | 28 | 5 | n/a | 33 |
| YS01 | 0.5 | 270 | 5 | < 10 | 280 |
| YS01 | 1.0 | 39 | < 3 | n/a | 39 |
| YS01 | 1.5 | 89 | < 3 | < 10 | 89 |
| YS01 | 3.0 | 28 | < 3 | n/a | 28 |
| YS02 | 1.0 | 910 | 550 | < 10 | 1500 |
| YS02 | 2.0 | 470 | 2900 | < 10 | 3400 |
| YS02 | 3.0 | 81 | 1200 | n/a | 1200 |
| YS03 | 0.5 | 110 | 3 | 16 | 130 |
| YS03 | 1.0 | 240 | 23 | 43 | 310 |
| YS03 | 2.0 | 72 | 230 | n/a | 300 |
| YS03 | 3.0 | 78 | 150 | n/a | 230 |
| YS04 | 0.5 | 49 | 4 | < 10 | 54 |
| YS04 | 1.0 | 59 | < 3 | < 10 | 68 |
| YS04 | 2.0 | 13 | < 3 | n/a | 13 |
| YS04 | 3.0 | 7.3 | < 3 | n/a | < 10 |
| YS05 | 0.5 | 570 | 31 | 37 | 640 |
| YS05 | 1.0 | 580 | 9000 | < 10 | 9600 |
| YS05 | 2.0 | 110 | 120 | < 10 | 230 |
| YS05 | 3.0 | 48 | 44 | < 10 | 93 |
| YS06 | 0.5 | 21 | 4 | n/a | 25 |
| YS06 | 1.0 | 81 | 10 | < 10 | 91 |
| YS06 | 1.5 | 44 | 22 | < 10 | 65 |
| YS06 | 2.5 | 3.7 | < 3 | n/a | < 10 |
| YS06 | 3.0 | 5.5 | < 3 | n/a | < 10 |

# Appendix C. Laboratory Reports

To be provided.

# Appendix D. Hydraulic testing

The results of hydraulic testing have been summarised in Table 7-3 below. The results indicate that the hydraulic conductivity of the sediments in Yeodene Swamp and Reach 3 of Boundary typically ranged between 0.02 and 0.2 m/day. This falls within the range of hydraulic conductivities given for silty material similar, to that encountered during these investigations (Domenico and Schwartz, 1990). The exception to this range was YS05 which recorded a hydraulic conductivity of 1.5 m/day. This is at the upper bound of what is expected for unconsolidated silty material (Domenico and Schwartz, 1990) and may reflect a higher sand content at this site.

The results suggest that the hydraulic conductivity of sediments in Yeodene Swamp and Reach 3 of Boundary Creek are in relative terms, moderate to low. However, areas of higher hydraulic conductivity may exist where sands become more abundant. Such areas could facilitate greater groundwater and surface water exchange.

Table 7-3 Summary of hydraulic test analysis

| Bore Identification | Test type | Test hydraulic conductivity m/day | Representative hydraulic conductivity m/day |
|---|---|---|---|
| **YS01** | Falling | 0.30 | 0.20 |
| **YS01** | Rising | 0.11 | |
| **YS02** | Falling | 0.021 | 0.036 |
| **YS02** | Rising | 0.052 | |
| **YS03** | Falling | 0.052 | 0.048 |
| **YS03** | Rising | 0.044 | |
| **YS05** | Falling | 1.3 | 1.5 |
| **YS05** | Rising | 2.0 | |
| **YS05** | Falling | 0.7 | |
| **YS05** | Rising | 1.8 | |
| **YS06** | Falling | 0.28 | 0.19 |
| **YS06** | Rising | 0.11 | |
| **LBC01** | Falling | 0.041 | 0.038 |
| **LBC01** | Rising | 0.036 | |
| **LBC02** | Falling | 0.022 | 0.017 |
| **LBC02** | Rising | 0.013 | |

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# Appendix E. Cost Estimate for Inundating Yeodene Swamp

| Item | Description of work | Qty | Unit | Rate | Amount ($) | Subtotal ($) |
|---|---|---|---|---|---|---|
| 1 | **Design and Planning** | | | | | |
| | Survey | 1 | Item | $ 13,000 | $ 13,000 | |
| | Geotechnical | 1 | Item | $ 10,000 | $ 10,000 | |
| | Environmental Management | 1 | Item | $ 7,000 | $ 7,000 | |
| | Detailed Design | 1 | Item | $ 25,000 | $ 30,000 | |
| | Tendering | 1 | Item | $ 10,000 | $ 10,000 | |
| | Environmental Offset (net gain) for vegetation removal | 1 | Item | $ 30,000 | $ 30,000 | |
| | | | | | | $ 100,000 |
| 2 | **Project Management** | | | | | |
| | Manage Design and Planning | 1 | Item | $ 10,000 | $ 10,000 | |
| | Tendering | 1 | Item | $ 12,000 | $ 12,000 | |
| | Construction Management | 1 | Item | $ 12,000 | $ 12,000 | |
| | | | | | | $ 34,000 |
| 3 | **Construction Preliminaries** | | | | | |
| | Contract work insurance | 1 | Item | $ 450 | $ 450 | |
| | Public Liability Insurance | 1 | Item | $ 600 | $ 600 | |
| | Facilities (toilet, lunchroom, storage) | 4 | week | $ 125 | $ 500 | |
| | Facilities - delivery | 1 | Item | $ 500 | $ 500 | |
| | Construction Set out | 1 | Item | $ 5,000 | $ 5,000 | |
| | | | | | | $ 7,050 |
| 4 | **Move in / Move Out** | | | | | |
| | Prime Mover and Float | 8 | hrs | $ 200 | $ 1,600 | |
| | Excavator - 30 T with operator | 4 | hrs | $ 180 | $ 720 | |
| | Compactor | 4 | hrs | $ 90 | $ 360 | |
| | Staff | 18 | hrs | $ 90 | $ 1,620 | |
| | | | | | | $ 4,300 |
| 5 | **Create Access - including tree clearing and gravel access - mix of private and public land** | | | | | |
| | Excavator - 30 T with operator | 32 | hrs | $ 180 | $ 5,760 | |
| | Grader | 24 | hrs | $ 175 | $ 4,200 | |
| | Material - class 3 gravel - 100mm thick, 3m wide | 351 | tonne | $ 32 | $ 11,232 | |
| | Fencing - Reinstate and install gate | 1 | Item | $ 3,000 | $ 3,000 | |
| | Staff - crew of 2 + vehicle | 1 | days | $ 2,000 | $ 2,000 | |
| | | | | | | $ 26,192 |
| 6 | **Clear Vegetation - and move off site short distance** | | | | | |
| | Excavator - 30 T with operator | 16 | hrs | $ 180 | $ 2,880 | |
| | Truck | 16 | hrs | $ 90 | $ 1,440 | |
| | Staff - crew of 2 + vehicle | 2 | days | $ 2,000 | $ 4,000 | |
| | | | | | | $ 8,320 |
| 7 | **Site Retention - Create coffer dam and pump out** | | | | | |
| | Excavator - 30 T with operator | 8 | hrs | $ 180 | $ 1,440 | |
| | Pump Hire 100mm diesel | 16 | days | $ 200 | $ 3,200 | |
| | Pump Fuel | 1 | Item | $ 2,000 | $ 2,000 | |
| | Staff - crew of 2 + vehicle | 2 | days | $ 2,000 | $ 4,000 | |
| | | | | | | $ 10,640 |
| 8 | **Sheet Pile Weir Construction - including excavation, sheet pile, concrete** | | | | | |
| | **Assuming 3 weeks for weir construction** | | | | | |
| 8.1 | LABOUR | | | | | |
| | Labourer - Class 1 x 2 | 260 | hrs | $ 84 | $ 21,840 | |
| | Foreman | 260 | hrs | $ 100 | $ 26,000 | |
| | | | | | | $ 47,840 |
| 8.2 | PLANT | | | | | |
| | Excavator - 30 T with operator | 120 | hrs | $ 180 | $ 21,600 | |
| | Compactor- up to 5 t or vibrating plate | 24 | hrs | $ 90 | $ 2,160 | |
| | Vibrating head-for sheet pile placement | 60 | hrs | $ 80 | $ 4,800 | |
| | Jig for sheet pile | 1 | Item | $ 5,000 | $ 5,000 | |
| | Crew vehicle | 15 | days | $ 250 | $ 3,750 | |
| | | | | | | $ 37,310 |
| 8.3 | MATERIALS | | | | | |
| | Sheet pile - Vinyl CL 9000 or heavier | 219 | sqm | $ 140 | $ 30,660 | |
| | Imported fill | 516 | Tonne | $ 25 | $ 12,900 | |
| | Rock Beaching | 161 | Tonne | $ 25 | $ 4,025 | |
| | Transport Crushed rock and rock beaching | 677 | Tonne | $ 9 | $ 6,093 | |
| | Geotextile Bidum A44 | 538 | sqm | $ 5 | $ 2,690 | |
| | Mass Concrete in apron | 6 | cum | $ 300 | $ 1,800 | |
| | Filter rock under apron (included in other rock) | | | | | |

| Item | Description of work | Qty | Unit | Rate | Amount ($) | Subtotal ($) |
|---|---|---|---|---|---|---|
| | Misc. materials | 1 | Item | $ 5,000 | $ 5,000 | $ 63,168 |
| | **Exclusions**<br>Any additional levee works to separate the swamp from private land | | | | | |
| | | | | | **DIRECT COST (DC)** | $ 338,820 |
| | | | Contingencies | 0.5 | | $ 169,410 |
| | | | | | **Total Construction Cost** | $ 508,230 |