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Hydrological and geochemical processes controlling salinity of the groundwater dependent ecosystems in the Corangamite CMA

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CONTENTS

List of Tables

List of Figures

Executive Summary

This report details methodology, results and conclusions for the Corangamite Catchment Management Authority (CCMA) project WLE/42-009 – Understanding the processes causing salinity of the groundwater dependent ecosystems in the CCMA. This work is driven by the need to better understand the hydrological processes affecting the lake ecosystems, specifically related to salinity and their dependence on groundwater.

The CCMA region occupies part of the Victorian Volcanic Plains and contains several hundred lakes and wetlands, including several that are Ramsar listed. The region is a gently undulating volcanic plain and bounded to the south by the Otway Ranges and the north by the central Victoria uplands. There are several types of wetlands and lakes within the region: many of the smaller wetlands are shallow depressions in the landscape and many were dry or became dry during the course of the study. There are a few large shallow brackish to hypersaline permanent lakes (e.g., Lake Colac and Lake Corangamite) and in the western part of the area there are a number of crater lakes ranging in depth from 8 to 18m.

This study involved initially an inventory of lakes from the databases followed by a reconnaissance survey and regional sampling in July 2006 of about 46 lakes (only 26 had enough water for sampling). The sampling was repeated twice more in October 2006 and April 2007 during which time there was very little rainfall within the region. Detailed monitoring of the hydrology and chemistry of three lakes (West Basin, Lake Colac and Lake Weering) was conducted fortnightly throughout 2007. Water level loggers were installed in about 20 monitoring boreholes as well as several piezometers installed within three above-mentioned lakes as part of this study.

The chemistry of the lakes ranges over more than two orders of magnitude, from ~1500 mg/L at Lake Purrumbete to Lake Corangamite and Lake Weering at ~2000 000 to 300 000 mg/L respectively. The chemical composition of the lakes tends to be sodium chloride dominated, especially the more saline lakes, with significant fraction of bicarbonate in the lower salinity end of the spectrum. The lakes and wetlands resemble the chemistry of seawater except for relatively higher calcium and bicarbonate concentrations in some fresh lakes. The isotopic composition of the lakes are all enriched in the heavy isotopes of water (^{2}H and ^{18}O) relative to the local rainfall and groundwater and all lie on a common 'evaporation line'. The ultimate salinity of the lakes is driven by evaporation which in turn is controlled by water residence time within each of the respective lakes. The Br/Cl ratio is similar to that of the marine Br/Cl mass ratio of 290 indicating that the salt is predominating derived from concentration of marine aerosols deposited in rainfall rather than dissolution of salt deposits within the regolith.

A classification scheme based on the chemical and isotopic composition of the lakes was developed as a way of rapid evaluation of the main source of solutes and lake residence time. The lakes are classified according to a continuum of main hydrological 'types' of lakes are thought to occur throughout the region: two 'types' with relatively short water residence time and groundwater or surface water dominated respectively, and one 'type' with long water residence time and groundwater dominated. The rationale is that lakes with relatively high HCO_3^- relative to Cl^- have a higher component of surface water relative to regional groundwater due to shallow subsurface weathering of the volcanic rock minerals while regional groundwater has very low HCO_3^- relative to Cl^- due to carbonate mineral precipitation. While none of the lakes or wetlands is completely sourced from one or the other end-member, they appear to be dominated by groundwater component and only a few lakes appear to be surface water dominated in terms of salt input. Almost every lake surveyed had some component of its water balance contributed by groundwater, and more than 75% of lakes surveyed this appears to be the dominant component of solutes. While direct rainfall contributes a significant component of the water input, a greater component is removed by direct evaporation and rainfall provides only a minor amount of salt directly. The isotopic composition of the inflows (rainfall, surface runoff or groundwater) are indistinguishable from each other therefore cannot be used as an indicator of groundwater dependence. However, the enriched isotopic values indicate increasing water residence time within the lakes.

Because of the long water and salt residence time in the lakes and wetlands the salinity has enough inertia to be buffered by short term variations in the water balance or local effects such as groundwater pumping. The viability of the wetlands is driven by persistent drought causing regional water tables to decline over the past several years. The recovery of lake levels in response to the 2007 spring rainfall was short lived and salinity rapidly returned to early 2007 by middle of 2007/2008 summer.

1. INTRODUCTION

1.1. Background

The Corangamite Catchment Management Authority (CCMA) jurisdiction occupies an area of 13 340 km^2 in south-western Victoria and consists of four major river basins, namely Moorabool River, Barwon River, Lake Corangamite and Otway Coast (CCMA, 2004b). Within this area are many wetlands "which have been identified as highly valuable elements of the region's natural ecosystems" (CCMA, 2005). Most of these (72%) are found within the Victorian Volcanic Plain bio-region which occupies 46% of the Corangamite CMA area (Figure 1).

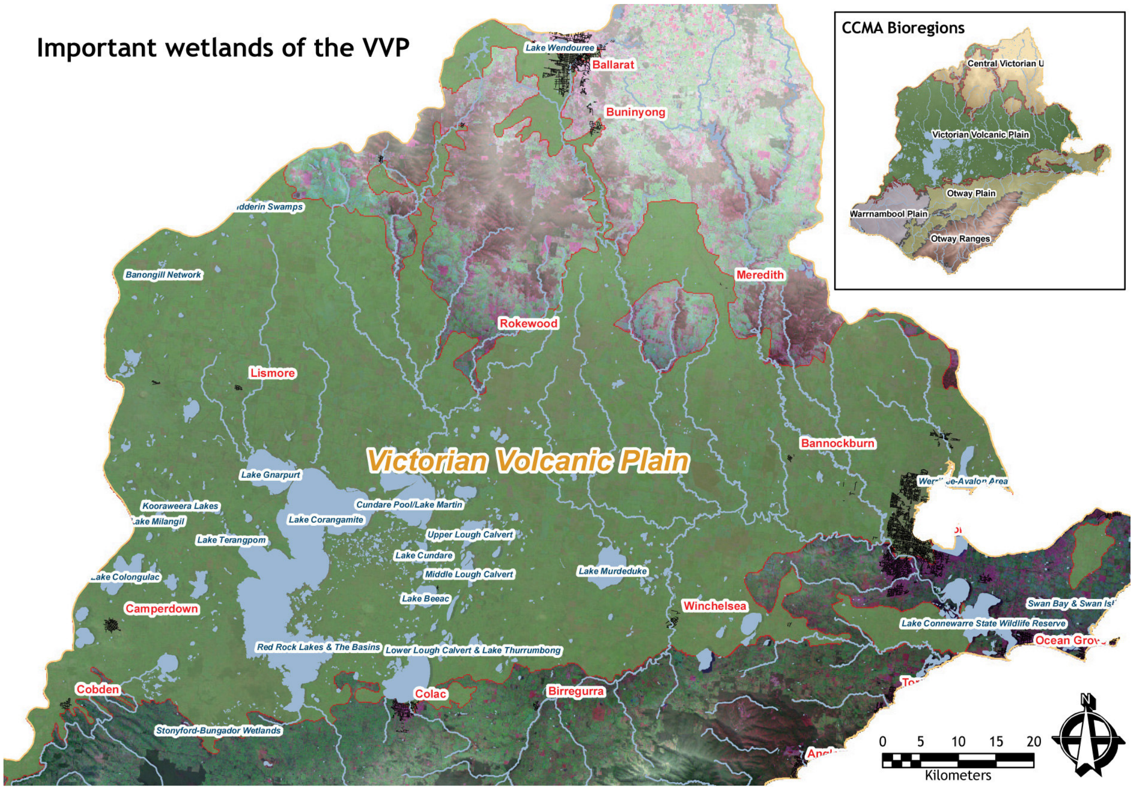

Figure 1. Wetland and major waterways of the Victorian Volcanic Plain

The Victorian Volcanic Plain (VVP) is recognised as an ecologically significant region of Australia. The landscape has been radically altered within the last 150 years. Most of the region is private freehold dominated by agriculture and there are small blocks of public land. The native vegetation of the Victorian Volcanic Plain bioregion is one of the most depleted in the State. Only 4.5% still has a cover of native vegetation, and less than 1.2% is in formal reserves (Taylor *et al.*, 2003). The bioregion is characterised by a volcanic plain vegetated mainly by native grasses and woodlands with many natural wetlands; more than 40% of these have been altered significantly but some internationally and nationally important wetlands remain. Lake Corangamite is the largest permanent saline lake in continental Australia.

The Corangamite CMA area contains numerous wetlands ranging from fresh to hypersaline of national and international significance, of which the majority are found in the VVP segment of the catchment.

Many of these are partially or wholly dependent on groundwater for their ecological integrity – which is now being threatened through changes in salinity levels. Observed increases and decreases in salinity concentrations, as well as the complete drying out of some wetlands, is thought to have resulted from human activity. Changes to flow regimes through surface water diversions or discharges, increased surface runoff from expanding urban areas and extensive groundwater extraction have all impacted on the salinity levels of the lakes and wetlands. Furthermore, changes in the groundwater balance due to altered land-use such as removal of perennial grasslands and replacement with annual grasses, irrigation development and forestry plantations natural vegetation from catchments and its replacement by pasture and other agricultural crops are also major factors affecting wetland health.

1.2. Salinity and the Corangamite CMA wetlands

This project is funded under the auspices of the National Action Plan (NAP) for Salinity and Water Quality which is promoting the development of action plans in those regions in Australia most affected by salinity and water quality problems. Region 18, consisting of the Glenelg-Hopkins and Corangamite CMAs, is one of the 21 NAP target areas and the purpose of this project is provide the scientific basis for the development and management of catchment plans for the Corangamite CMA aimed at addressing salinity and water quality issues. This project is specifically aimed at identifying and creating a knowledge base for those groundwater dependent ecosystems and significant wetlands that are affected by changes in salinity and water quality.

Groundwater-dependent ecosystems require the input of groundwater to maintain their current composition and functioning (Murray *et al.*, 2003). Removal of groundwater from these ecosystems, or a change in the timing, quantity, quality or distribution of groundwater may influence ecosystems by, for example, changing the availability of water for transpiration by vegetation and the recruitment of seedlings into the adult population. This generally results in changes in associated fauna assemblages.

Maddocks, 1967) describes research into the chemical composition of the lakes of the western district of Victoria, and points to evidence of the lakes being linked to the groundwater table. He describes the topography of the area in which both open drainage (where rivers flow from the plain to the sea) and closed drainage patterns are present and observes that the predominance of lakes in the closed basins "suggests an overall high water table, and so the influence of ground water on the composition of lake water … particularly in lowland areas and very deep lakes". Maddocks supports the hypothesis of cyclic salt origins for the lakes but suggests that the phenomenon of saline lakes being found in close proximity to brackish and freshwater lakes is best explained by differences in the salinity of their principal water source – groundwater: Maddocks lists evaporation as another mechanism by which increases in salinity occur. He concludes that the lakes fall into two categories: ground water lakes and surface runoff lakes – with various intermediates.

Lake Corangamite and lakes along the Lough Calvert are examples of saline ground water inflow coupled with solar evaporation while Lake Colac, Lake Modewarre, and Lake Bolac are low salinity lakes due to their large surface catchment areas (Maddocks, 1967). Lake Purrumbete, Lake Elingamite, and Lake Bullenmerri are possible examples of lakes connected to fresh ground water aquifers.

While the base source of the water may be responsible for the type of lake (freshwater, brackish, saline, etc) there is evidence to suggest that fluctuations in lake salinity levels, associated with seasonal events, have also been natural occurrences. McNiven, 1998) has reported research into drinking water sources for the aboriginal peoples which historically inhabited the Corangamite region. He points to evidence showing salinity variability due to seasonal factors. He comments that "seasonality studies suggest that salinity levels in some lakes may decrease by a third with winter rains" while anecdotal evidence points to times of drought when "it was possible to walk across Lakes Colac and Corangamite". Williams, 1995) observes that "salt lakes are more sensitive to climatic and other factors affecting hydrological budgets than are freshwater lakes" and draws on evidence associated with the saline Lake Corangamite to show "the concept of a 'mean' or 'normal' level or salinity for the lake has no scientific basis". Some of these processes are applicable to the Corangamite CMA. The activities that have brought on these processes fall broadly into two categories: agricultural and drainage. These are discussed in more detail below.

McNiven, 1998) reports that pre-European vegetation on the Victorian Volcanic Plain consisted mainly of open grassland with scattered shrubs and trees, while forests and woodlands were found mostly in the northern sections of the Corangamite basin around the upper reaches of the Woady Yaloak River. On the Otway Ranges along the southern boundary of the Volcanic Plain are tall wet forests and on the sands flanking these ranges grow shorter drier forests, heaths and woodlands (Land Conservation Council, 1976).

Agricultural activities have dominated the Corangamite region since the mid 1800s. The basaltic plains provided good pasture land for sheep and cattle grazing and strong wool and dairying industries developed. The short lived timber industry that sprang up in the Otway Ranges in the early days of white settlement led to the clearing of large tracts of country which were then taken up for dairying. This has continued to be a major primary industry in the higher-rainfall areas of the Corangamite area (Land Conservation Council, 1976). In the Corangamite Basin today "agricultural production accounts for over 80% of … land use including dairying, stock grazing, broad acre cropping in the north, and row cropping, notably potato growing, in the south" (NRE, 2002). As a result of these agricultural pursuits much of the indigenous vegetation has been lost (Figure 2).

Removal of native vegetation and supplementation with exotic species can affect both surface and groundwater systems. Impacts may include rising groundwater tables and/or changes to the quantity and quality of surface runoff.

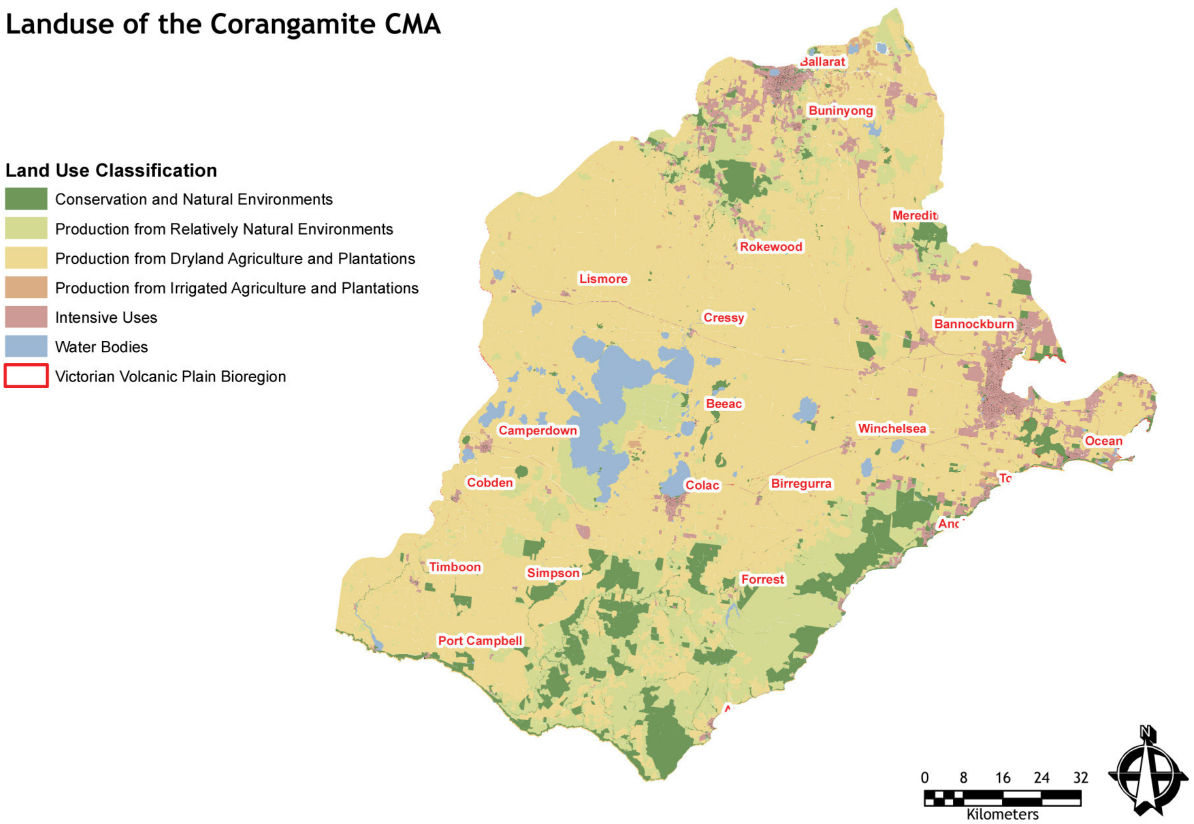

Figure 2. Aggregated land use for the CCMA, showing predominant dryland agriculture within the VVP Bioregion.

Two major drainage schemes operate in the Western District Lakes area of the Corangamite CMA. These schemes – the Woady Yaloak diversion scheme and the Lough Calvert drainage scheme – were constructed during the 1950s to protect rural properties from flooding.

The Woady Yaloak River is the largest tributary of the terminal lakes Corangamite and Gnarpurt. Prior to the construction of the diversion channels and after periods of heavy rainfall, the water level in the land-locked lakes would rise; lakes Corangamite, Gnarpurt and Martin would become virtually one lake and extensive areas of the surrounding agricultural lands would be inundated (CCMA, 2004a). The Woady Yaloak diversion scheme channels water from the Woady Yaloak River (Cundare Pool) east, to Warrambine Creek, a tributary of the Barwon River (Figure 3). The *Review of Regional Drainage Schemes Summary Document* (CCMA, 2004a) states that “since its creation, about 50% of the Woady Yaloak River flow has been diverted to the Barwon River instead of Lake Corangamite”. During that time the water level in the lake has tended downwards.

A similar situation applied for Lake Colac and the lower, middle and upper loughs into which it overflows. Due to the land-locked nature of the Lough Calvert system, large tracts of farming land inundated during wet periods would remain submerged for even years (CCMA, 2004a). The Lough Calvert system is drained via a channel from the lower lough to Birregurra Creek – another tributary of the Barwon River – and a second channel diverts water from Lake Colac to this main channel.

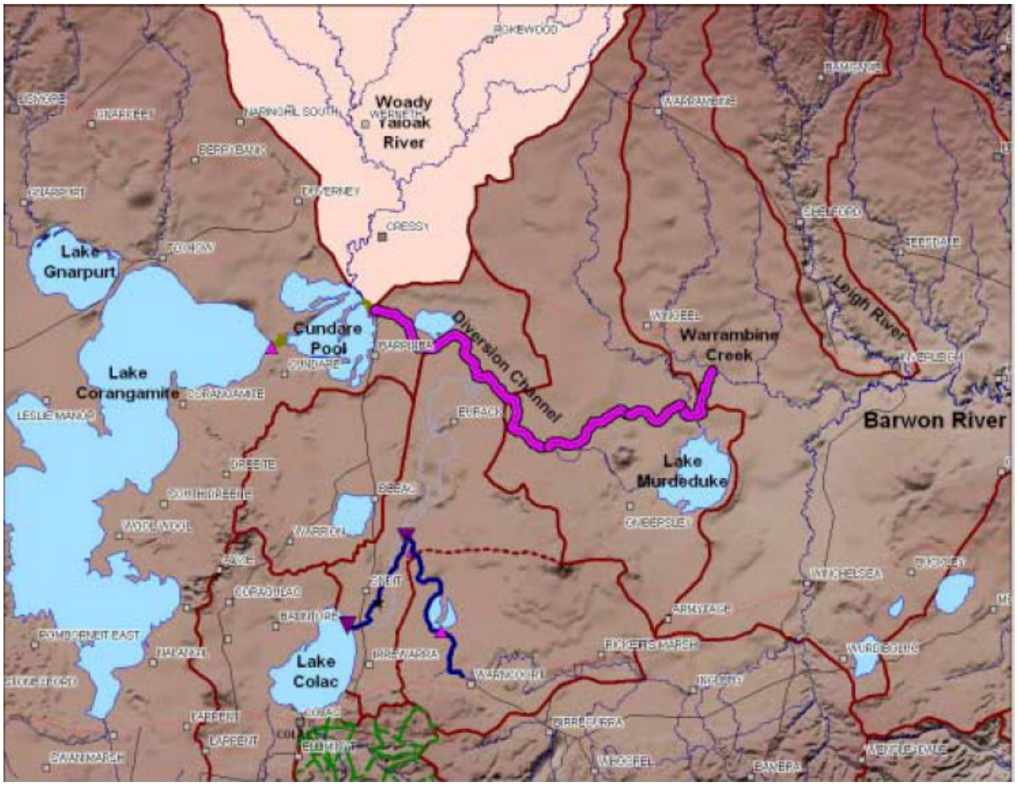

Figure 3. Woady Yaloak Diversion Scheme (Source: CCMA Review of Regional Drainage Schemes – Summary, 2004).

1.3. Objectives and approach

The objectives of this study are to provide a scientific basis for the management and maintenance of wetlands health including:

- Develop an understanding of the hydrological processes affecting the CCMA wetlands, particularly methods to quantify groundwater and surface water inputs
- Develop an understanding of the processes causing salinization of the wetlands.

The approach used for this study is as follows:

- Overview of previous work on wetlands in the CCMA
- Assessment of the current state of wetlands including sampling of lakes for geochemistry and isotopic composition and classification of wetlands
- Monitoring water levels of wetlands and groundwater in relation to changes in rainfall
- Hydrological modelling
- Detailed monitoring and assessment of geochemistry for three sites.

2. BACKGROUND ON THE WETLANDS OF THE CCMA

2.1. Literature review

Williams and Buckney, 1976) investigated the ionic proportions in Lakes Beeac, Cundare, Eurack, Weering and Pink Lake over a 4 year period (1969-1973). "Remarkable constancy" was found in the ionic proportions in each of the five lakes though variations, particularly in the most abundant ions, was found between the lakes. The authors suggested that such differences between localities so close "argues for strong geochemical control processes maintaining ionic constancy".

Changes to salinity levels in Lake Corangamite reported by Williams, 1995) showed that prior to inflow diversions there has been large fluctuations in the lake salinity levels due mainly to seasonal factors. Since the inception of the Woady Yaloak drainage scheme, salinity levels have shown a steady increase.

Coram, 1996) focused on the groundwater-surface water interactions around the shallow lakes Beeac, Bookar, Colongulac, Gnarpurt and Murdeduke, and builds on the research of Thompson, 1971 and Gill, 1989. Coram used potentiometric surface analysis and lake hydrology and hydrogeology to assess groundwater dependence and groundwater-surface water interactions. Water and salt balances were undertaken to determine the dominant controls on lake hydrology and salinity.

Analysis of the potentiometric surface indicated that regional groundwater flows move from the "west, north and south into the central Lake Corangamite/Lough Calvert area which acts as a regional discharge area" and "continue from this area to the east, towards the Barwon River". "The shallow lakes appear to intercept the water table, suggesting that some interaction may occur between the lakes and the groundwater system". Lakes were described as "throughflow" (lakes Murdeduke, Bookar, Colongulac and Gnarpurt) or "discharge" (Lake Beeac and the other lakes of the Lough Calvert). Data suggested that shallow lakes with permeable hydrostratigraphic units down gradient behaved as "thoughflow" lakes, while those with relatively impermeable hydrostratigraphic units down gradient behave as "discharge" lakes.

Coram argues that variations in the lakes is due to "variations in the local hydrostratigraphy down gradient of the lakes, differences in the relative proportion of groundwater discharged from the lakes compared with other inflowing waters, and differences in the TDS content and relative proportions of major ions in the lakes".

The chemical characteristics of lake waters were found to be dominated by Na^+ and Cl^-. Water budgets pointed to precipitation and evaporation as being the dominant control on lake hydrology - "being at least as order of magnitude greater than the contribution of average surface inflows (which vary seasonally) and average groundwater inflows and outflows (which are relatively constant)". Salt budget analysis indicated that "groundwater and surface water are likely to contribute substantial masses of salt to the lakes" with the concentration of these salts dependent on the extent to which discharge of evaporatively concentrated lake waters occurs".

Coram found that TDS content (and hence density) has a bearing on the groundwater discharge characteristics of lakes. "Throughflow" lakes were found to have lower TDS content waters and salt mass discharge was of the same order of magnitude as salt mass inflow. Those lakes discharging small salt masses were found to have higher TDS content waters.

2.2. Assessment of wetland condition

In July 2006 the first reconnaissance field trip was undertaken to sample and assess the lakes in the CCMA region. Table 1 gives a listing of the 46 lakes visited and a brief comment on the condition of these lakes. This exercise was repeated in October 2006 (Table 2). Specific sampling localities are shown in Figure 4.

Sampling involved collecting a grab sample (most often using a bucket) and aliquots collected in plastic and glass bottles for chemical and isotopic analysis. Extraction of dissolved radon into scintillant was done on site (July 2006 only). Electrical conductivity (EC), pH, dissolved oxygen (DO) and temperature were measured in the field. Water and radon samples were freighted back to the CSIRO laboratory in Adelaide for analyses.

In July 2006, approximately half of the lakes were found to be dry or the water depth so small as to make it all but impossible to take a sample of water without disturbing and sampling lake sediments in the process. In a number of instances deep mud obstructed access, although for these cases it was thought that even if the water's edge had been reached it would have been too shallow to sample.

Of particular interest was the sample collected from the Kooraweera Lakes at Westbank Road. Both the lake sampled, and others in the chain, appeared essentially dry however at this location a streamlet was discharging into one of the lakes and had formed a sizeable pond at its northern tip. Local knowledge suggests that the water emanates from Larra Spring which runs down from Mt Elephant to the north-west and feeds into the Kooraweera chain of lakes (pers. comm. D. Smithyman). This would indicate that the water sampled is groundwater and that these lakes typically have some groundwater dependence.

Table 1. Name and visual condition of lakes visited in July 2006

Lake Name/Reference	Condition
Deep Lake	Completely dry. No sample.
Lake Logan	Assumed dry. No sample.
Lake Tooliorook	Sample taken.
Kooraweera Lakes (3)	Water running into lake on Westbank Rd. Spring? Otherwise dry. Sample taken.
Lake Milangil	Virtually dry. Water too shallow to sample.
Lake Round	Dry. No sample.
Lake Kariah	Dry. No sample.
Lake Colongulac	Camperdown WWTP. Did not access due to signage from the South West Water Authority. Water visible.
Lake Bullen Merri	Sample taken.
Lake Gnotuk	Suds around rim. Sample taken.
Lake Purrumbete	Sample taken.
Lake Koreetnung	Dry (farmer's advice). No sample.
Lake Weeranganuk	Dry. No sample.
Lake Corangamite	Dry in northern part. Very shallow in others and difficult to access due to mud. Only a small sample obtained.
Lake Terangpom	Shallow. Sample taken.
Lake Coradgill	Dry. Lakes Bulkil Narra, Punpundal & Tatutong assumed likewise.
Lake Gnarpurt	Dry. No sample.
Lake Struan	Sample taken.
Lake Rosine	Sample taken.
Cundare Pool/Lake Martin	Water running into inlet. Otherwise dry. Sample taken of inlet water.
Weering Lake	Sample taken.
Upper Lough Calvert	Shallow. Sample taken.
Middle Lough Calvert	Dry. No sample.
Lower Lough Calvert	Dry. No sample.
Lake Cundare	Sample taken.
Thomas Lake	Dry. No sample.
Lake Beeac	Water at surface. No sample.
Lake Ondit	Dry. No sample.
Lake Purdiguluc	Completely dry. Lakes Coragulac & Gnalinegurk assumed likewise.
The Basins (2)	Water in both lakes. Sample taken from West Basin.
Lake Colac	Sample taken.
Lake Thurrumbong	Dry. No sample.
Lake Burn	Very shallow. Could not access due to mud. No sample.
Murdeduke Lake	Sample taken.
Gherang Lake	Dry. No sample.
Modewarre Lake	Sample taken.
Breamlea Wetlands	Mostly dry. Sample taken from small pool.
Reedy Lake	Mostly dry. Sample taken from small pool.
Connewarre Lake	Much algae in water. Sample taken.
Connewarre Swamp	Sample taken.
Barwon Estuary/Mouth	Sample taken.
Murtnagurt Swamp	Mostly dry. No sample.
Victoria Lake	Sample taken.

Table 2. Listing of lakes visited in October 2006

No.	Lake Name/Reference	Comment
1	Lake Tooliorook	
2	Kooraweera Lakes	
3	Lake Bullen Merri	
4	Lake Gnotuk	At golf links.
5	Lake Purrumbete	
6	Lake Corangamite	
25	Gnarkeet Chain of Ponds	Tributary to Lake Corangamite (northern end).
7	Lake Terangpom	Dry. No sample.
8	Lake Struan	
9	Lake Rosine	No sample due to mud.
10	Cundare Pool/Lake Martin	
11	Weering Lake	
12	Upper Lough Calvert	Almost dry. No sample.
13	Lake Cundare	Dry. No sample.
14	Lake Colac	
27	Barongaruk Creek	Tributary to Lake Colac. Uncertain if stagnant or flowing.
15	The Basins (West)	
16	Murdeduke Lake	
17	Modewarre Lake	
18	Breamlea Wetlands	Dry. No sample.
28	Breamlea Inlet	
19	Barwon Estuary/Mouth	Western side, at jetty. No sample taken.
20	Barwon Estuary/Mouth	Eastern side, at caravan park. Sample taken.
21	Victoria Lake	
22	Connewarre Lake	
29	Connewarre lake Inlet	
23	Reedy Lake	Considerably more water since last visit.
24	Barwon River	Inlet to Reedy Lake.
26	Lake Colongulac	

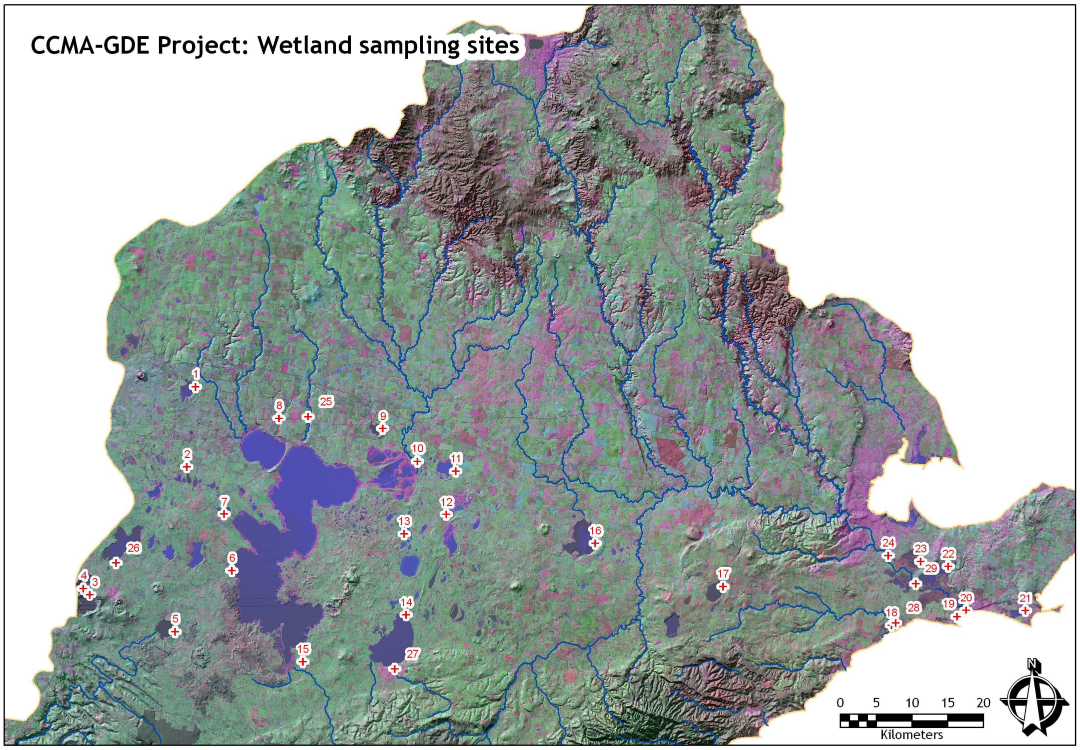

Figure 4. Location map of lake and wetland sampling sites in the CCMA area.

3. REGIONAL SURVEY OF LAKES

3.1. Geochemistry of lakes

Field measurements and analytical results for the July and October 2006 samples are given in Table 4 and Table 5 (Appendix A). Electrical conductivity (EC) ranges over more than two orders of magnitude from ~1 dS/m for Lake Purumbete and Kooraweera Lakes to 224 dS/m for Lake Weering. The higher EC values are likely to underestimate the salinity due to the non-linearity of EC to TDS relationship at high salinity. pH values tend to be in the alkaline range from 7.84 to 9.24 and these are reflected in high measured total alkalinity. Most of the surface water had dissolved oxygen concentration <100% of that of atmospheric equilibrium indicating active biogeochemical oxidation occurring due to high organic matter concentrations.

The dissolved solutes of the CCMA are dominated by Na^+ and Cl^- except for the most dilute lakes (Kooraweera Lakes and Lake Purrumbete) which have a slightly higher proportion of HCO_3^- as anions (Figure 5). Most notably, Ca^{2+} and HCO_3^- remain low throughout the entire salinity range indicating control of these dissolved ions through precipitation of carbonate minerals. The low salinity VVP groundwater and lake waters (TDS <2,500 mg/L) have higher proportion of HCO_3^- and alkaline earth ions (Mg^{2+} and Ca^{2+}) relative to other ions than the more saline surface and ground waters (>2,500 mg/L). These waters probably have a majority of their solutes derived from mineral weathering and a lesser fraction from marine aerosols. The amount of SO_4^{2-} relative to HCO_3^- tends to increase with increasing TDS. The Cl^-/Br^- values observed in all lakes are slightly higher than that of seawater (290) which indicates the dominance of the marine origin of Cl^- and by inference Na^+.

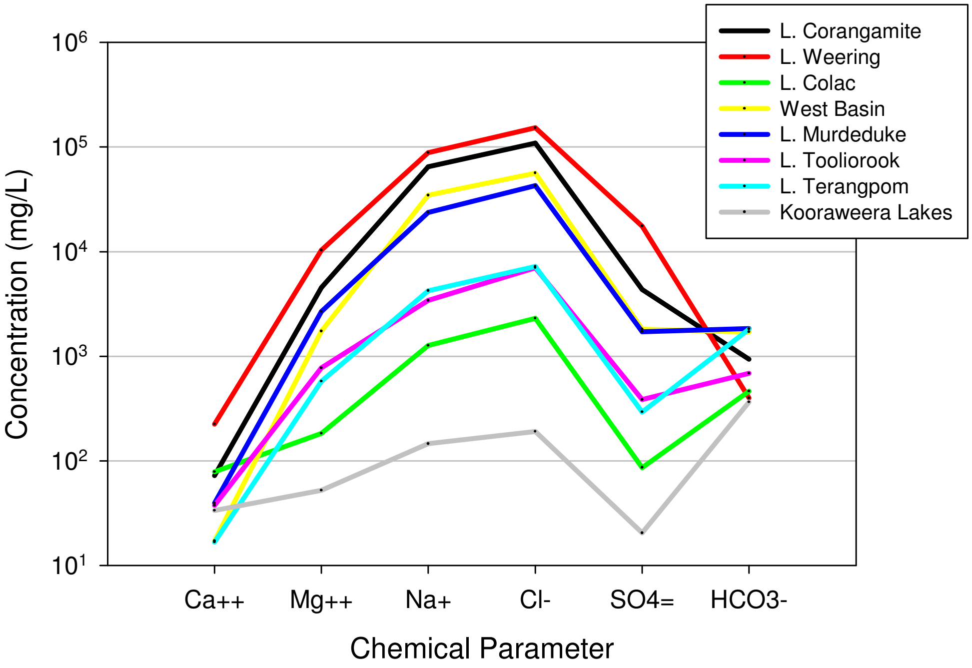

Figure 5. Schoeller plot showing the chemical composition for eight lakes in the Corangamite CMA region, July 2006.

The composition of the more saline lake waters (>2,500 mg/L) are similar to that of seawater and the more saline groundwaters of the VVP. In general, the dominance of Na^+ and Cl^- over the other ions increases linearly as a function of TDS (Figure 6). In all cases, the ultimate salinity level is determined by the extent of evaporation in the respective lakes rather than amount or source of salt input. The relative amount of dissolved sulphate exceeds that of HCO_3^- once the TDS reaches about 2,500 mg/L The relative proportion of all cations remain approximately constant from TDS 1,000 mg/L and greater.

The ratio of HCO_3^-/Cl^- ranges over nearly three orders of magnitude with an overall decrease with increasing TDS (Figure 7). The freshest lakes (<2,500 mg/L) tend to have higher HCO_3^-/Cl^- which is indicative of surface and inter-flow runoff components which tends to have higher component of HCO_3^- due to mineral-solution reactions that produce HCO_3^- as a by-product. Lakes with salinities >2,500 mg/L show HCO_3^-/Cl^- <0.08 reflecting a higher saline groundwater component to the water balance. Therefore one may be able to separate the lakes into two groups – low salinity (<2,500 mg/L) and high HCO_3^-/Cl^- (>0.08) that are surface water and inter-flow dominated, and higher salinity (>2,500 mg/L) and low HCO_3^-/Cl^- (<0.01) that are groundwater dominated. The intermediate samples shown in Figure 7 may represent mixing between the two end-members.

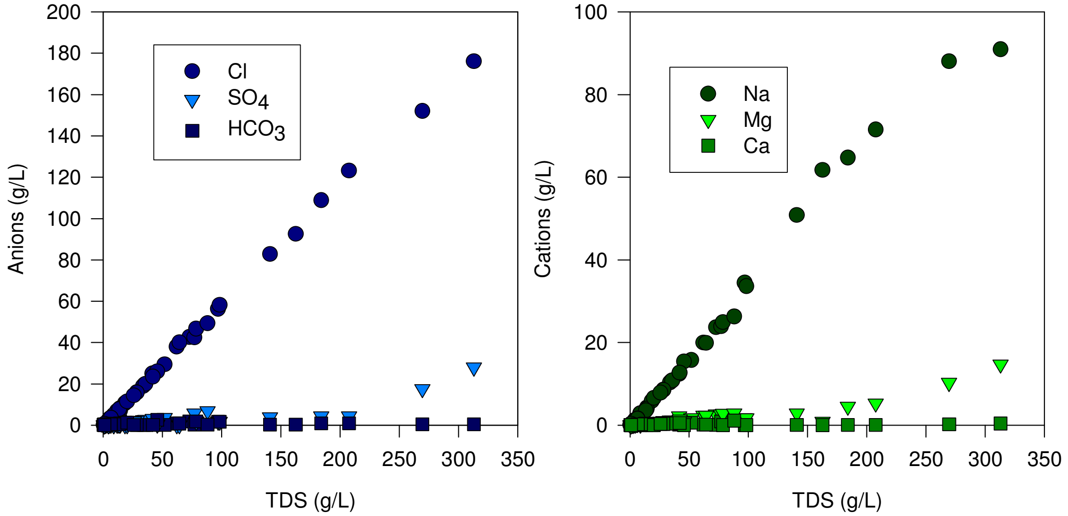

Figure 6. CCMA lake water anions and cations as a function of TDS for samples collected in July and October 2006.

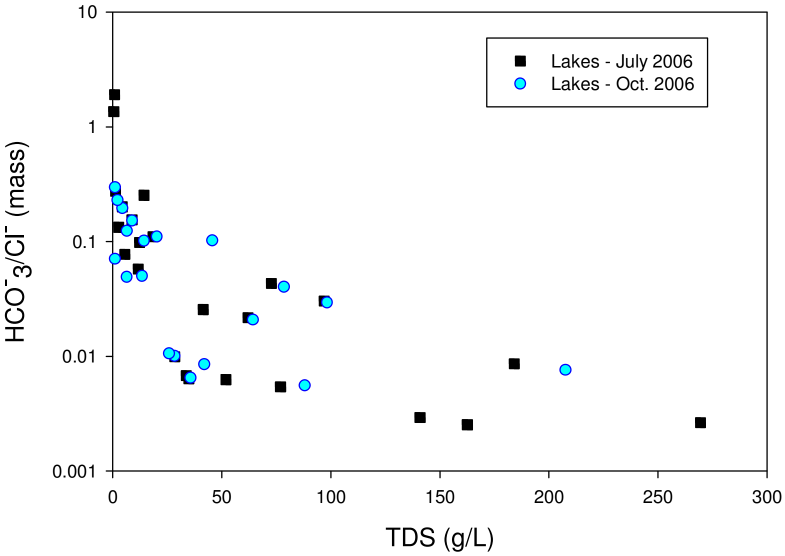

Figure 7. HCO3-/Cl- as a function of TDS for CCMA lake and wetland samples.

The total salinity and relative proportion of the major ions within the lakes varies subtly across the CCMA region according as shown in the Schoeller plots in Figures 8-10. The highest salinities tend to be observed in the Warrion/central lakes region (Figure 8) all of which are Na^+-Cl^- dominated throughout the entire salinity range and appear to reach a limit to HCO_3^- concentrations through carbonate mineral precipitation relatively moderate salinity. Lake Weering has high proportion of SO_4^{2-} relative to other lakes possibly due to dissolution of gypsum deposited previously within the lake sediments.

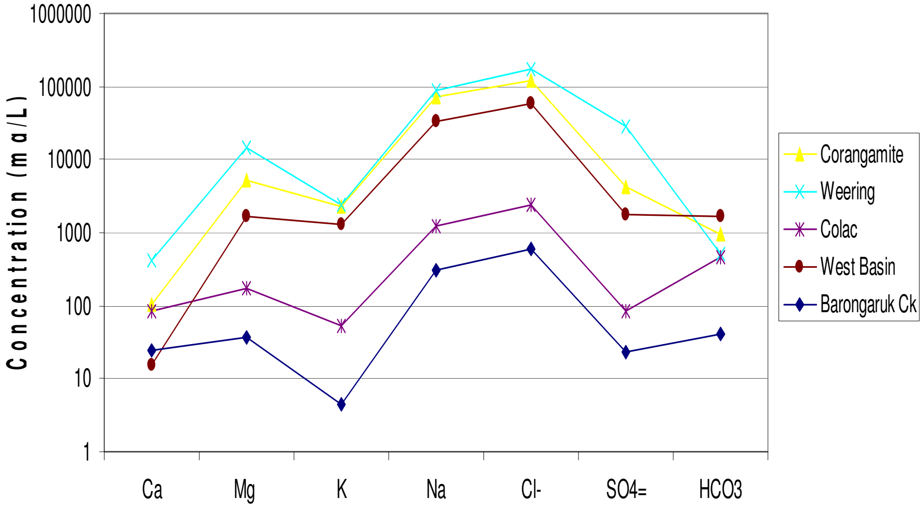

Figure 8. Schoeller plot of Warrion/ central region lakes.

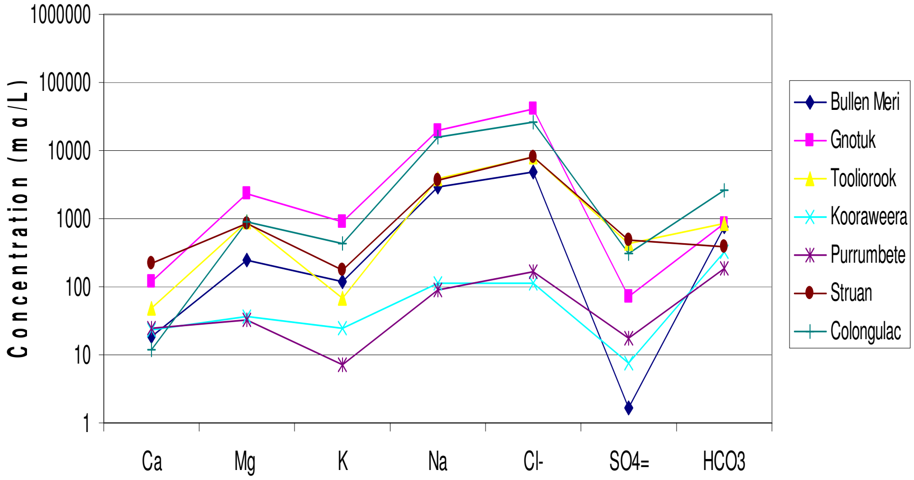

Figure 9. Schoeller plot of Lakes west of Corangamite.

The chemical composition of lakes west of Lake Corangamite (Figure 9) cover a wide salinity range and generally have the least variation in chemical composition and have the highest relative proportion of Ca^{2+}-Mg^{2+}-HCO_3^- of lakes in the CCMA region (although they are still Na^+-Cl^- dominated). These lakes also tend to have the lowest relative proportion of SO_4^{2-} compared with other CCMA lakes and all but Lake Struan have HCO_3^- concentrations greater than SO_4^{2-} and at the lowest salinity, exceed Chloride concentrations.

The eastern lake systems, predominantly located on the Bellarine Peninsula have the least range in total salinity (excluding the tributaries and surface water drainage) (Figure 9). The lakes in this region tend to display chemical composition reflecting evaporative concentration of the surface drainage to the lakes except for Lake Modewarre which is enriched in SO_4^{2-} and depleted in Mg^{2+} compared to other lakes in this part of the CCMA.

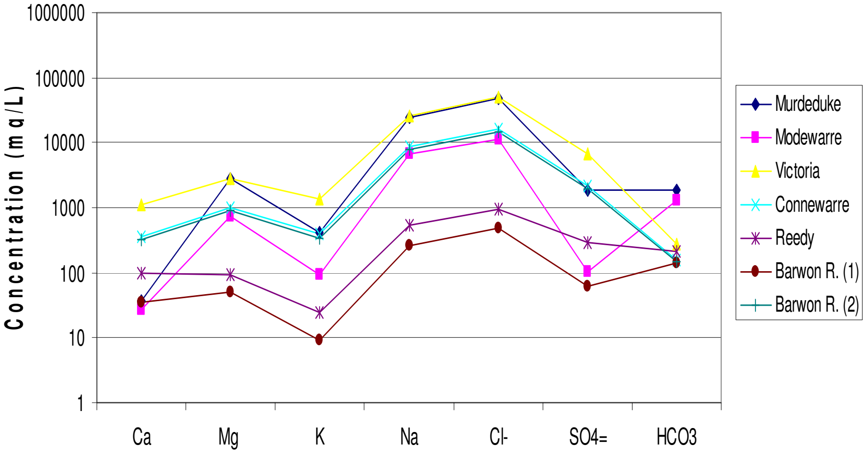

Figure 10. Schoeller diagram of eastern region lakes.

3.2. Stable isotopes

The stable isotopes of water ($^2H/^1H$ and $^{18}O/^{16}O$) are considered to be one of the most useful tracers in establishing a lake water balance, particularly with respect to the subsurface components (Rozanski *et al.*, 2000) Evaporation processes lead to measurable increases in the ratio of $^2H/^1H$ and $^{18}O/^{16}O$ with the isotopic concentrations evolving linearly in δ^2H - $\delta^{18}O$ space. The degree of isotopic enrichment is dependent on the amount of water lost by evaporation, atmospheric relative humidity over the lake and the relative proportion of water lost by evaporation relative to outflow.

Results for stable isotopes deuterium (δ^2H) and oxygen-18 ($\delta^{18}O$), for the CCMA lakes sampled in July 2006, are presented in δ^2H - $\delta^{18}O$ space and compared with monthly isotopic data for Melbourne rain (Figure 11). The data show that the lakes plot on a linear trend that has a lower slope (5.9) than the local meteoric water line defined by the monthly Melbourne rainfall data (slope ~7.9) and are more enriched in the heavy isotopes of water compared with rainfall. In general the further to the right on the trend the greater the evaporation influence on lake waters. The highest enrichments of ^2H and ^{18}O were recorded in the crater lakes (Gnotuk, West basin, Bullen Merri and Purrumbete) while the large shallow saline lakes such as lake Corangamite and Lake Weering in particular show only moderate evaporative enrichment effects. The trend of the data for the lakes intersect the Melbourne rainfall data trend at a value very close to that for the long term annual mean. Despite the variations in lake setting and the geographical spread of the lakes, they plot very tightly on the linear trend with an r^2 of 0.965.

A similar trend was observed for samples collected in October 2006 (Figure 12) Note that the data from the lakes extrapolate back to the groundwater data (Cox et al., 2008) which show very similar composition to that of the Melbourne rainfall. This clearly shows the importance of rainfall recharge to the groundwater system with very little influence of evaporation of rainwater prior to recharge. This indicates that recharge to the groundwater via lakes or ponded surface water is not significant because the groundwater displays virtually no displacement from the local meteoric water line.

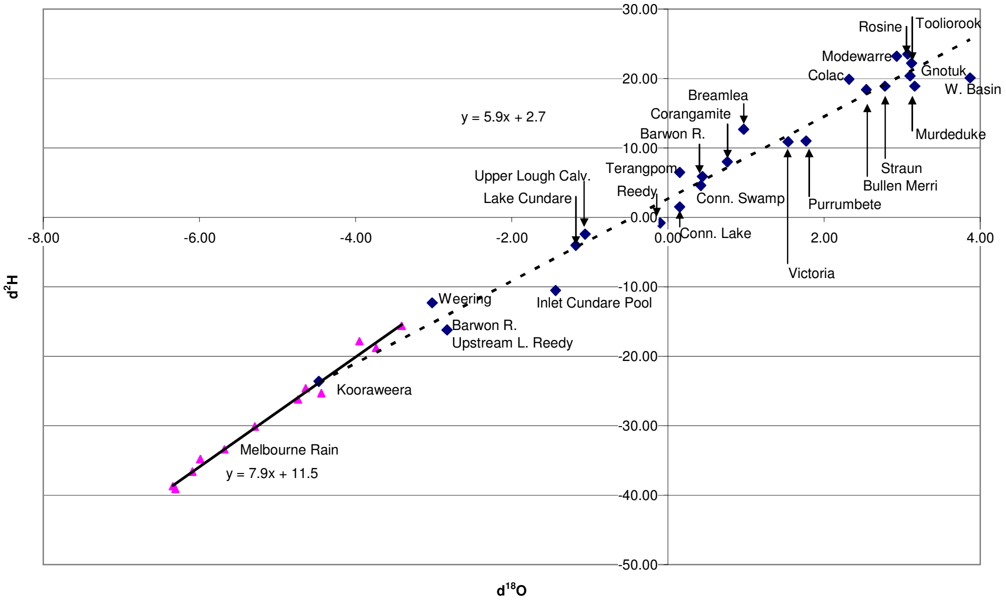

Figure 11. Stable isotope data for CCMA lakes collected in July 2006, together with average monthly values for Melbourne rain (triangles).

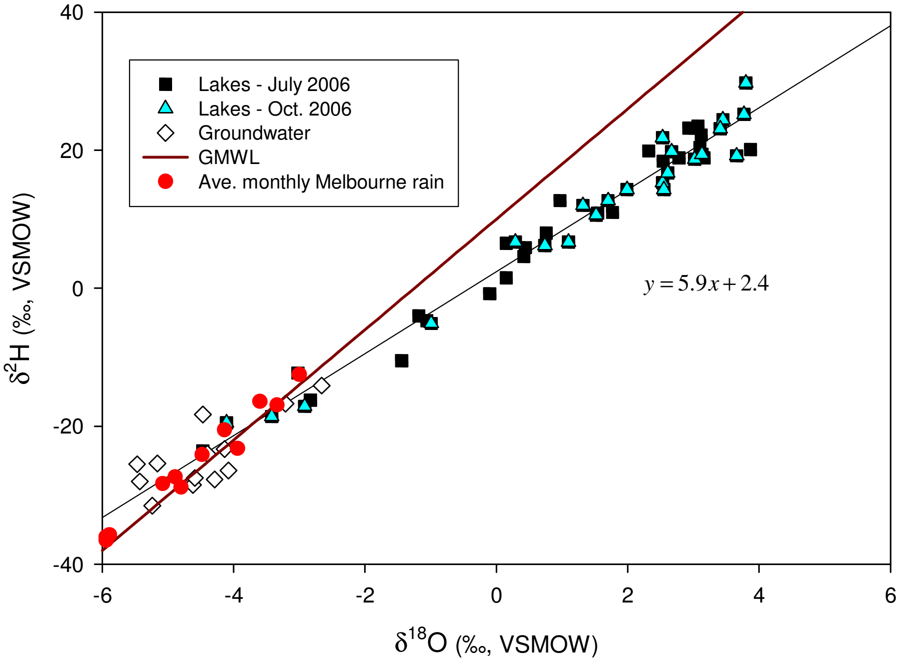

Figure 12. Lake stable isotopes shown in space together with average monthly values for Melbourne rain and values for local groundwater

3.3. Monitoring of lake and groundwater levels

3.3.1. Selection of three study lakes

To assess the connectivity between the lakes and the groundwater three “study lakes” were selected for detailed hydrological and geochemical monitoring. The study lakes were selected on the basis of the following criteria:

- Each of the three lakes represented an end-member of the three types classified (groundwater dominated/through-flow; surface water dominated/through-flow; groundwater dominated/long residence time).
- The lakes fall within the Victorian Volcanic Plain (VVP) region and the main area of interest for the Groundwater Flow Systems project. This is the region where the majority of the groundwater sampling has been undertaken.
- The lakes lie within, or in close proximity to, the Warrion Water Supply Protection Area – the main groundwater pumping region of the VVP.
- It was believed the lakes would maintain a water body for the duration of the project.

On the basis of the above criteria the following three lakes were selected for further monitoring:

- Lake Weering (TDS ~313,000 mg/L)
- West Basin (TDS ~98,300 mg/L)
- Lake Colac (TDS ~4,500 mg/L)

These lakes also showed a range in salinity and chemical composition. Lake Weering is the most saline lake of the Corangamite Basin lakes, dominated by Na^+ and Cl^- but also exceptionally high concentrations of Mg^{2+} and SO_4^{2-} ions. West Basin is relatively high in HCO_3^- and represents the crater lake type morphology. Lake Weering is typical of the ephemeral playa lakes while Lake Colac as a permanent “fresh” lake.

3.3.2. Establishment of field sites

Location of the three study lakes, together with the location of the data loggers to measure groundwater and surface water levels in shown in Figure 13.

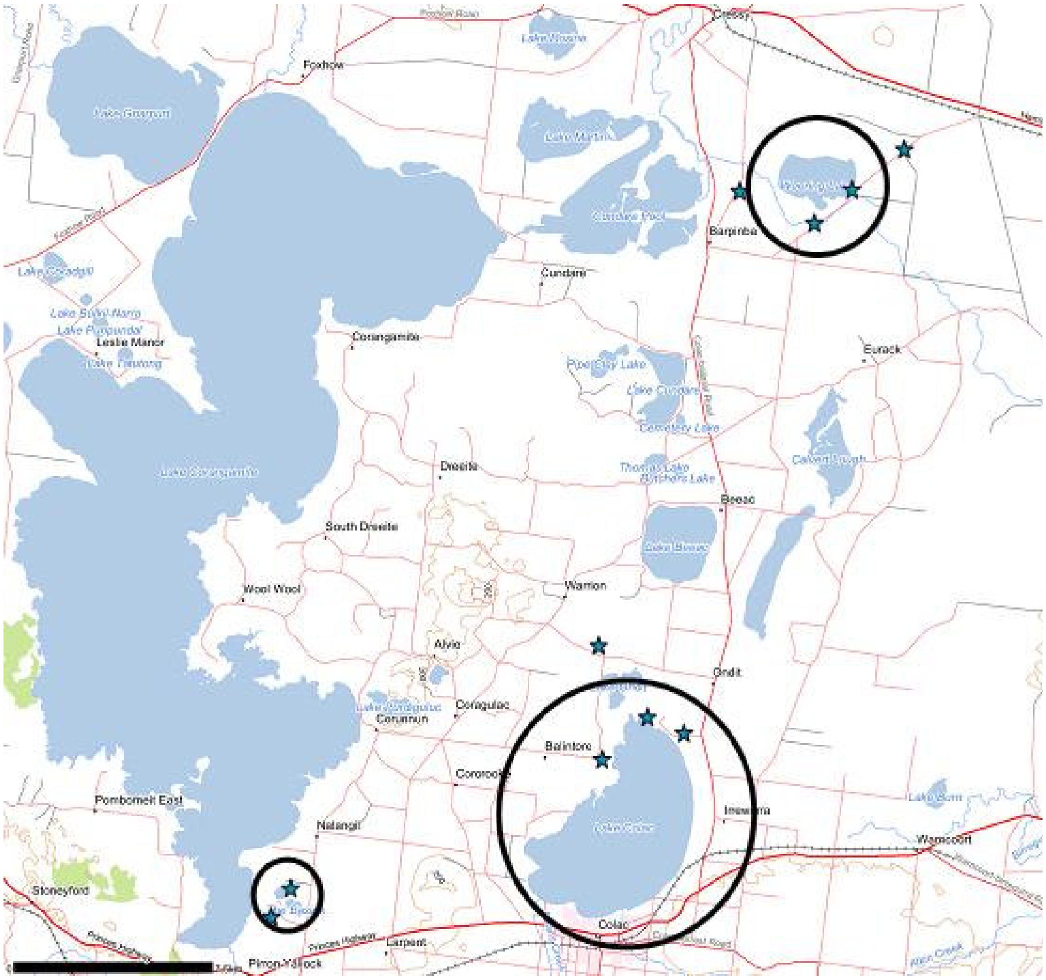

Figure 13. Map showing location of data loggers (lakes and bores)

Piezometers were installed in the three study lakes in February/March 2006. In April 2006 loggers were installed in the observation bores. Observation bore details are as follows:

Observation Bores proximate to West Basin	Observation Bores proximate to Lake Colac	Observation Bores proximate to Weering Lake
146931	142703	57506
	142712	26657
	26687	36061

Location of observation bores in the vicinity of the three study lakes is given in Figure 14 (Weering Lake), Figure 15 (Lake Colac) and Figure 16 (West Basin).

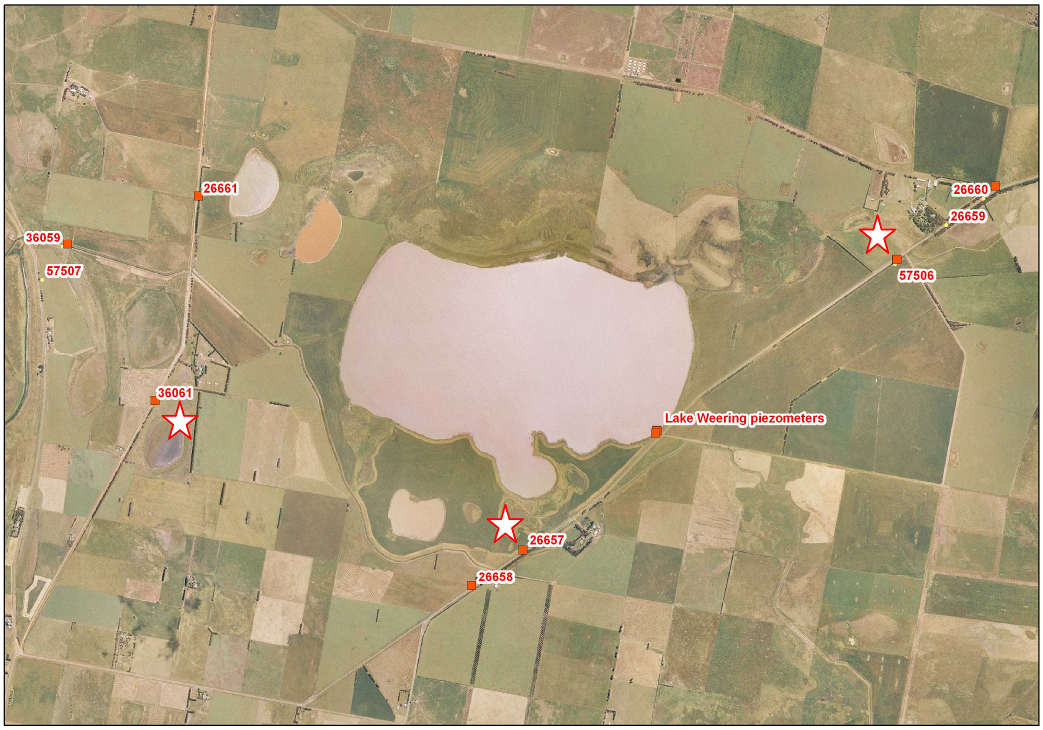

Figure 14. Location of observation bores in the vicinity of Weering Lake (marked with a star)

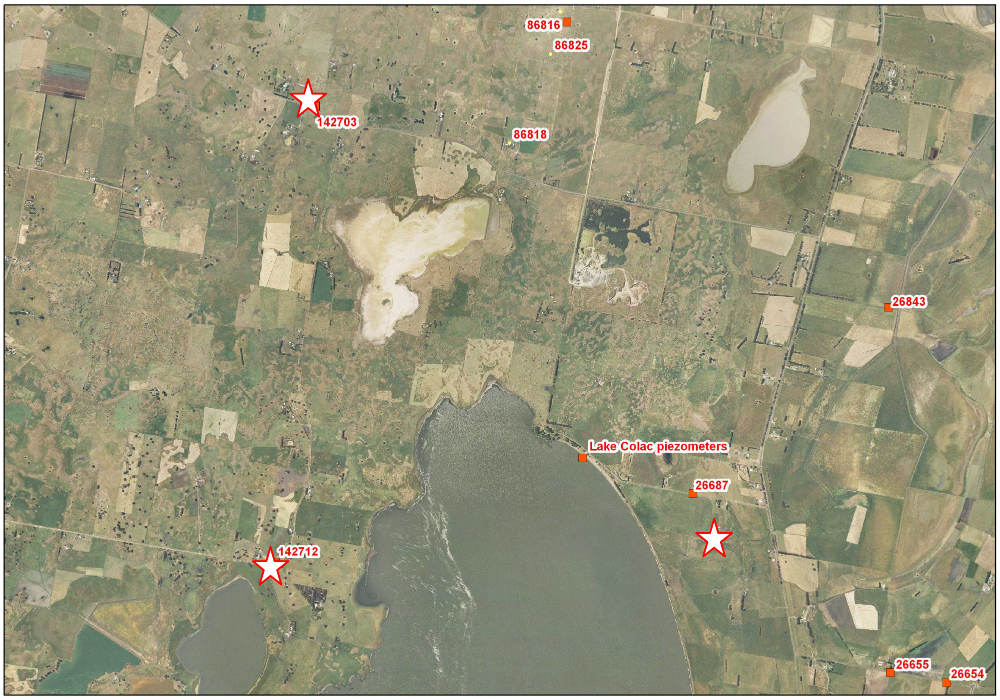

Figure 15. Location of observation bores in the vicinity of Lake Colac (marked with a star).

Figure 16. Location of observation bores in the vicinity of West Basin (marked with a star).

A real time kinematic (RTK) GPS survey was conducted across the study area in late February, 2007. The aim of the survey was to gather accurate (+/-5cm) height information for three water bodies (Lake Weering, Lake Colac and West Basin,) and key groundwater monitoring bores screened at a depth (below surface) of less than 25 m. The technical aspects relating to the conduct of the RTK-GPS survey are detailed in Williams (2004).

A total of fifty four survey points at thirty bore sites (Figure 17) were collected along with points for the piezometers and study lakes. Of these, seven points were not surveyed accurately due to a lack of good RTK verification. Another six bore sites were not surveyed due either to difficulties in location or the sites being within private property.

Due to the difficulty in locating survey marks in the field of a sufficiently high enough order, the raw GPS data was post-processed using the Victorian GPSnet base station at Colac (http://www.gpsnet.com.au/). The horizontal (x, y - meters) and vertical (z - mAHD) values obtained from RTK-GPS survey are compared to values obtained from the Victorian Water Resource Data Warehouse (http://www.vicwaterdata.net/vicwaterdata/) and the computed difference (Δ) shown.

Mean Δ values for the horizontal and vertical components of each survey point are:

X_Δ: 20.96 m

Y_Δ: 19.98 m

Z_Δ: 0.35 mAHD.

The discrepancy between the mean difference in height between RTK-GPS and VicDW may warrant a further survey. Furthermore, there may be additional bores that will need to be surveyed that do not have elevations in Victorian Data Warehouse.

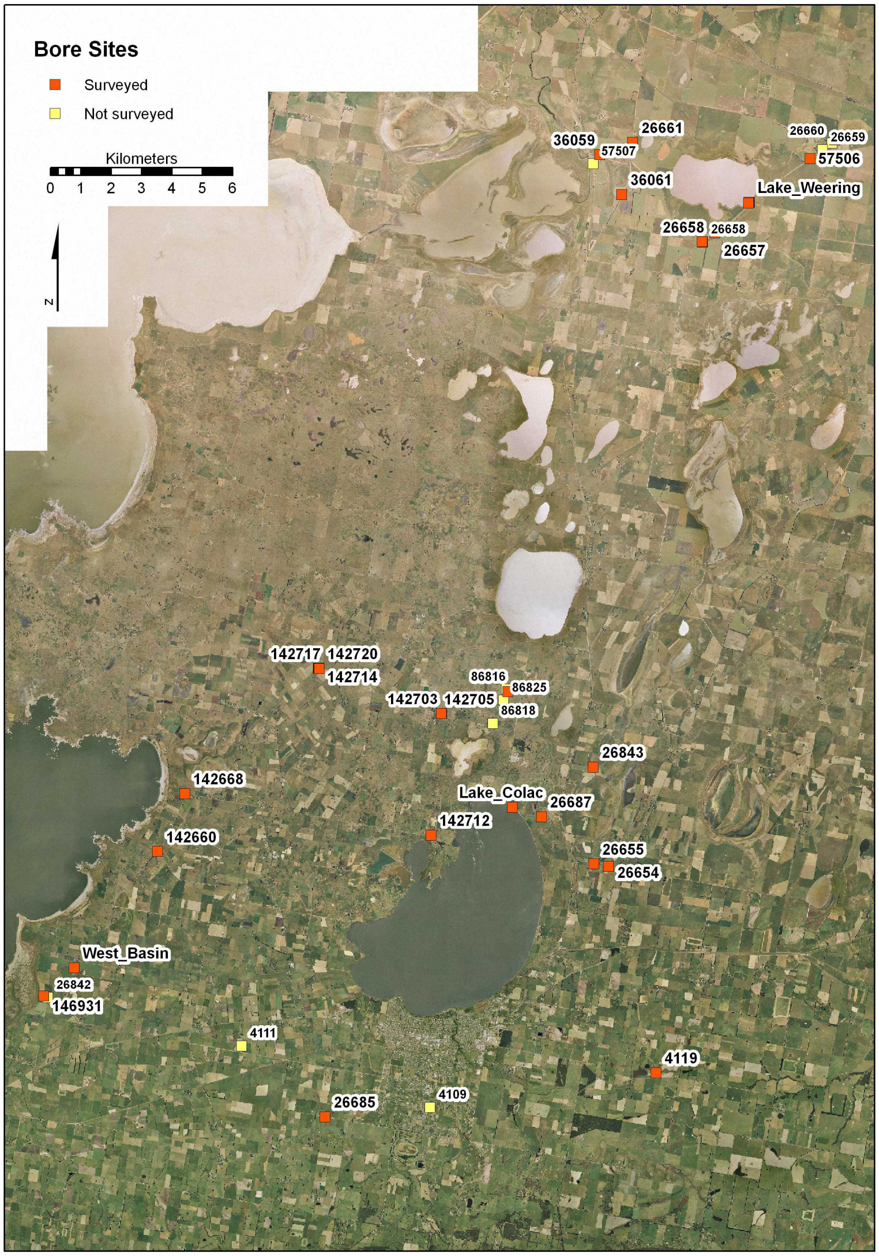

Figure 17. Bore survey sites for the study area.

The reduced levels for each lake and the surrounding bores have been graphed in Figure 18 (Weering Lake), Figure 19 (Lake Colac) and Figure 20 (West Basin). For Weering Lake the groundwater levels are all higher than the lake indicating a hydrostatic gradient toward the lake. Hence the lake appears to be a groundwater discharge point at the present time. This situation is the same for West Basin. In the case of Lake Colac the lake level lies between the western and eastern bore heights indicating a groundwater through-flow case.

The water level plots for the three lakes also show a close relationship – and hence connectivity – between the surface water bodies and the groundwater table. For Weering Lake the lake levels follow the bore levels however where a “step” has occurred in the groundwater plot this is not so evident in the lake plot. This is similar for Lake Colac and the two bores adjacent the lake. In the case of the third bore, it would appear that this bore is responding more significantly to rainfall events than the other two. It may be too, that this bore is also influenced by groundwater pumping. Groundwater levels in the vicinity of West Basin also exhibited a similar trend to that of the lake for the first four months of data collection, however groundwater levels appear to respond more significantly, or more rapidly, to rainfall events than the lakes. It is possible also that evaporation would impact on the lake level and not so significantly on groundwater levels.

In Figure 30 the historic monthly water levels record for bore 146931, south of West Basin, has been plotted in conjunction with the monthly rainfall values for the same period. It is evident from this plot that groundwater levels respond extremely quickly to significant rainfall events.

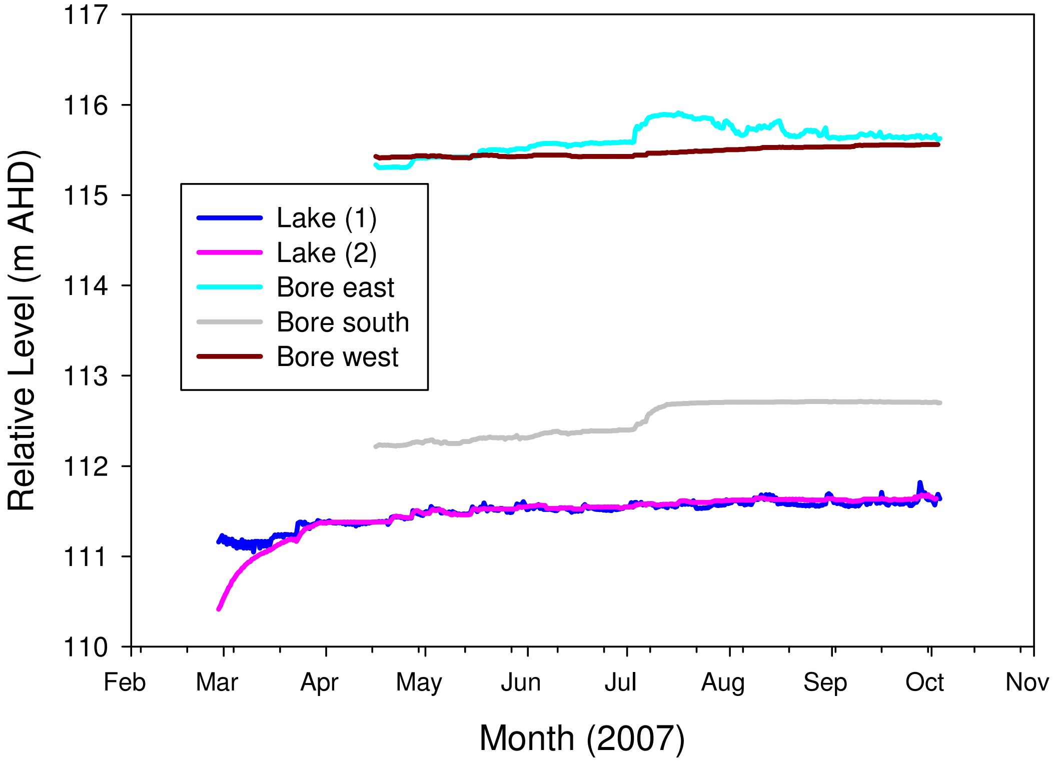

Figure 18. Reduced groundwater levels in Weering Lake and surrounding bores.

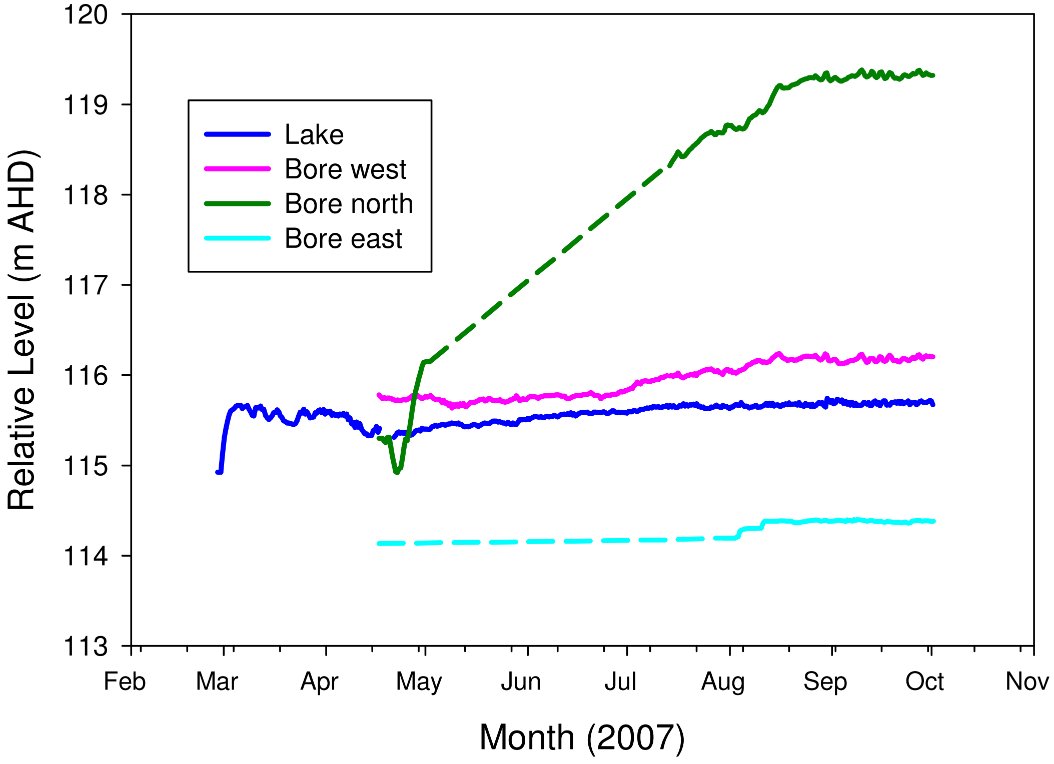

Figure 19. Reduced groundwater levels in Lake Colac and surrounding bores.

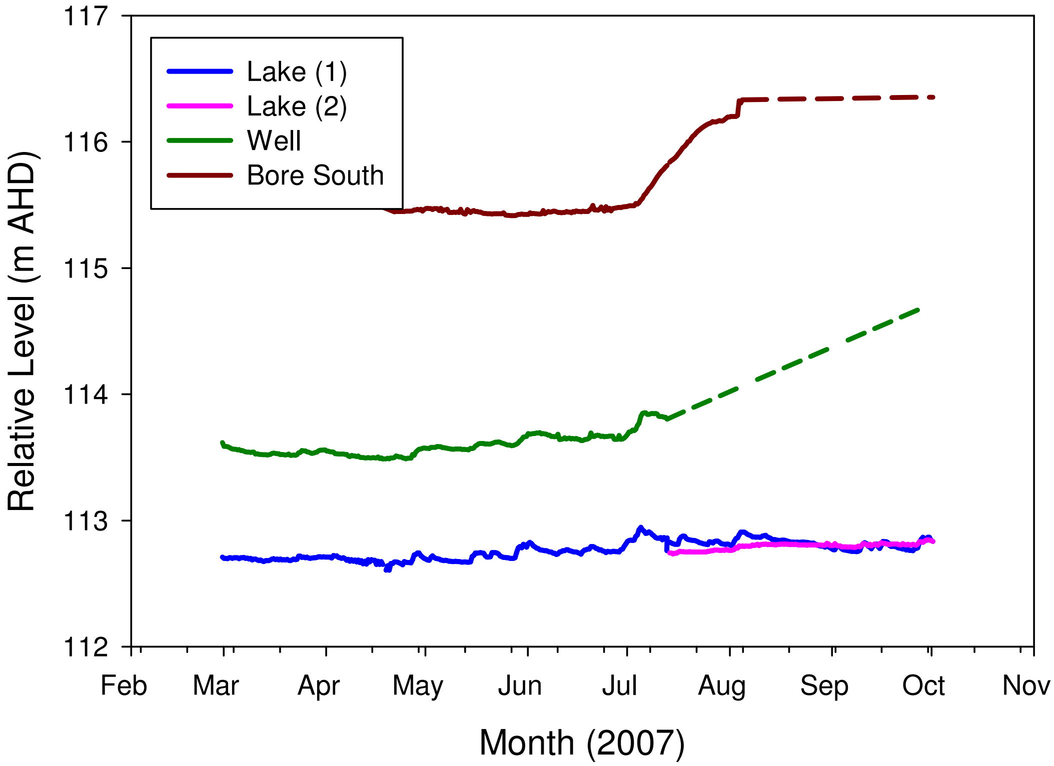

Figure 20. Reduced groundwater levels in West Basin and surrounding bores.

3.4. Chemistry monitoring results

The chemistry results for three lakes monitored throughout 2007 are given in Tables X-Y in Appendix A. and results for chloride and oxygen-18 concentrations shown in Figures 21-23. The data for the three sites show a general increase in chloride concentration during February to May, 2007 while oxygen-18 concentrations remained roughly constant. Following the winter rains there was a decrease in chloride and oxygen-18 concentrations of the lakes although the percentage change was much smaller for West Basin than for either of the other two lakes. None of the lakes reached the pre-winter oxygen-18 values by the following summer.

Chloride concentrations in Lake Weering recovered to pre winter values by the mid spring and remained there to the end of the year despite the δ^{18}O lagging behind (Figure 21). The Cl^- values appear to be very sensitive to individual rain events which indicate little mixing of water below the subsurface and indicative of surface water with little interaction with the subsurface reservoir at least on the time scale of monitoring. The values of both chloride and oxygen-18 appear to be approaching steady state by the end of the monitoring period in early November 2007.

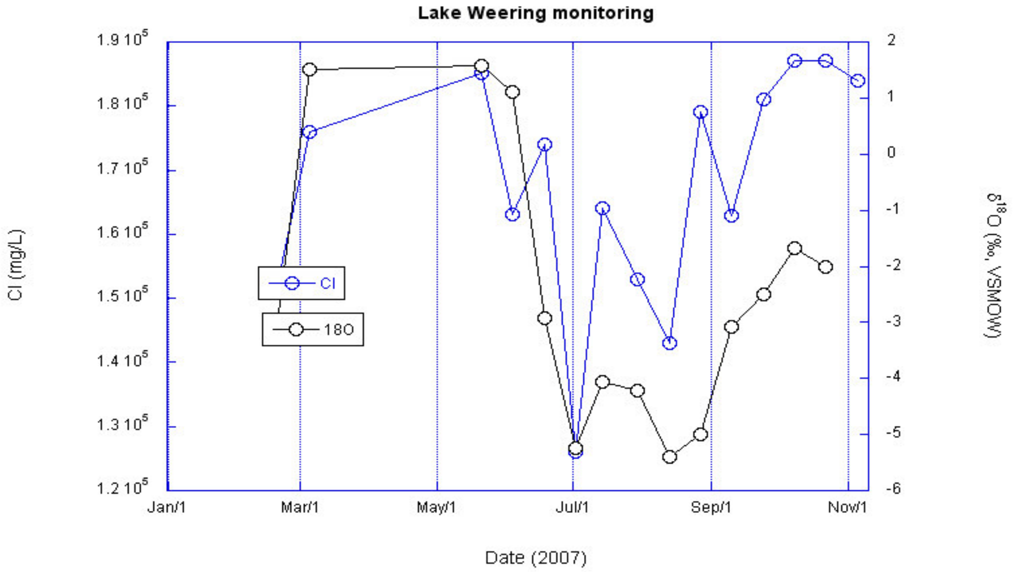

Figure 21. Chloride and δ^{18}O concentrations of Lake Weering, 2007.

Lake Colac data show a steady increase in Cl^- concentrations January to April while the stable isotopes of water (reflected in oxygen-18 data) appear to be at steady-state (Figure 22). Following the winter rains the chloride and oxygen-18 values continue to slowly decline except for late spring when oxygen-18 slowly increases but chloride remains steady at values almost half that of the preceding summer. The decline in oxygen-18 is about equal to that where contribution of water in late 2007 is half from lake water (+6per mille) and half from winter rainfall (-6 per mille). The increasing trend on oxygen-18 is probably due to evaporation which has a much more noticeable effect on stable isotopic composition than chloride.

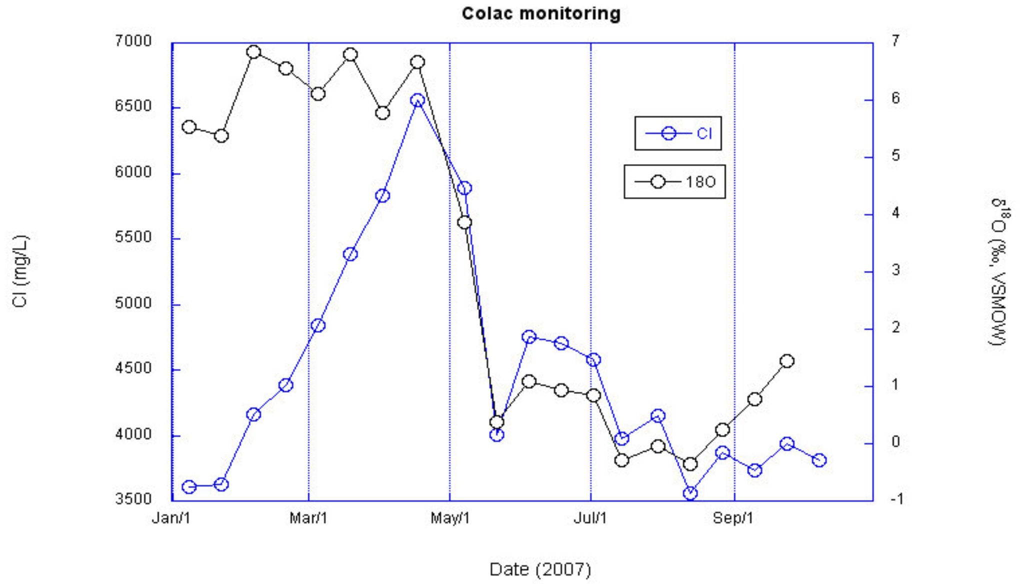

Figure 22. Chloride and δ^{18}O concentrations of Lake Colac, 2007.

West Basin shows only a 15% decline in chloride concentration through the winter and 2 per mille decline in oxygen-18 (cf. ~6 per mille for Lakes Weering and Colac) (Figure 23). During the summer of 2006/07 the lake appears to have reached isotopic steady-state and slowly incleasing in chloride concentration. The rapid decrease in winter of 2007 may be partly explained by incomplete mixing below the top few decimetres of the lake surface, and the recovery in August more liekyl due to mixing with the main body of lake water, The large volume to surface area ratio for the lake meakes this lake system less sensitiuve to short term fluctaions in rainfall and the large inventory of dissolved salts is likely the result of a long period of accvumulation in this lake.

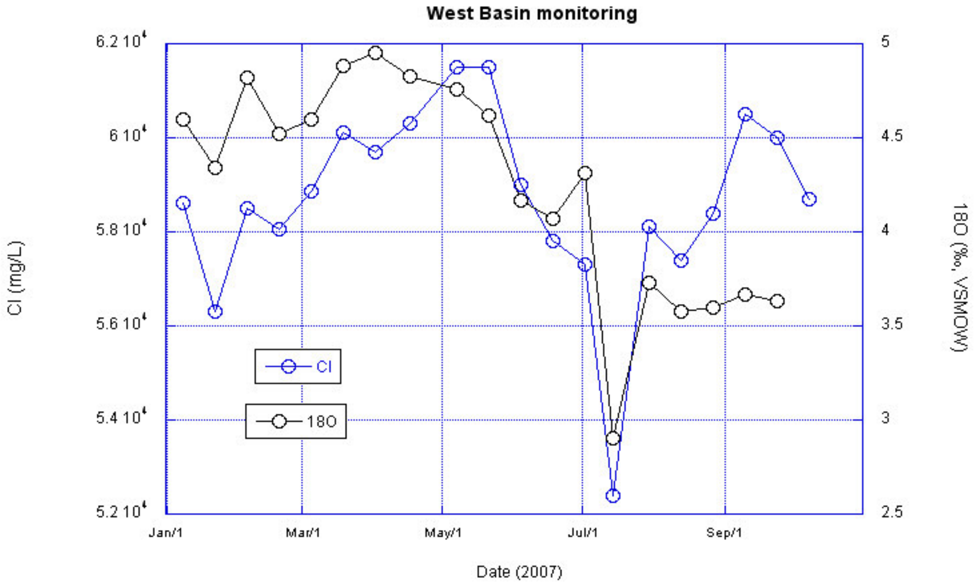

Figure 23. Chloride and $\delta^{18}O$ concentrations of West Basin, 2007.

3.5. Classification of lake hydrological balance

Determining the hydrological water balance of the CCMA lakes relative importance of surface water input and groundwater input

The lake water balance can be simply represented by a balance between the relatively light isotopic composition of inflow, and the tendency of evaporation to remove the lighter isotope preferentially to the heavier isotope thereby enriching the remaining water in the heavier isotope. In a semi-quantitative way the lakes increase in residence time (Residence time = total volume/total inputs) the further they lie to the right of line beginning at the Kooraweera point and ending at West Basin.

One can assume that the isotopic composition of groundwater is slightly more negative than surface water (refer Figure 12) but for the purposes of this discussion it may be assumed to be indistinguishable. Therefore, the evaporation trend observed for the lakes would be identical for the two types of inflow. However, if groundwater inflow were substantial and large, one could do an experiment where during a dry period without surface water inflows, say in summer, a time series of selected lakes would assist with determining if groundwater is a significant contributor by monitoring the isotope composition of lake water with respect to the theoretical path of evaporation.

Deuterium excess ($\delta_{xs} = \delta^2H - 8*\delta^{18}O$) is a number that reflects the deviation of a given sample from the meteoric water line. Lower values indicate increasing influence of evaporation. Most of the groundwater samples have a deuterium excess of between 7 and 12, which is slightly less than the local meteoric water values of 13. The lake waters have a δ_{xs} between 5 and -5, and if there was a large flow-through of groundwater, then the δ_{xs} would be higher (that is approaching the groundwater δ_{xs} values). However plotting the δ_{xs} values data as a function of HCO_3^-/Cl^- (Figure 24) can at least qualitatively distinguish between the relative importance of surface water, groundwater and evaporation dominated lakes. Type 1: High δ_{xs}, low HCO_3^-/Cl^- → groundwater dominated, through-flow; Type 2: Low δ_{xs}, low HCO_3^-/Cl^- → groundwater dominated, long residence time; Type 3: High δ_{xs}, high HCO_3^-/Cl^- → surface water dominated, through-flow. Conceptual diagrams of lake types are shown in Figure 25.

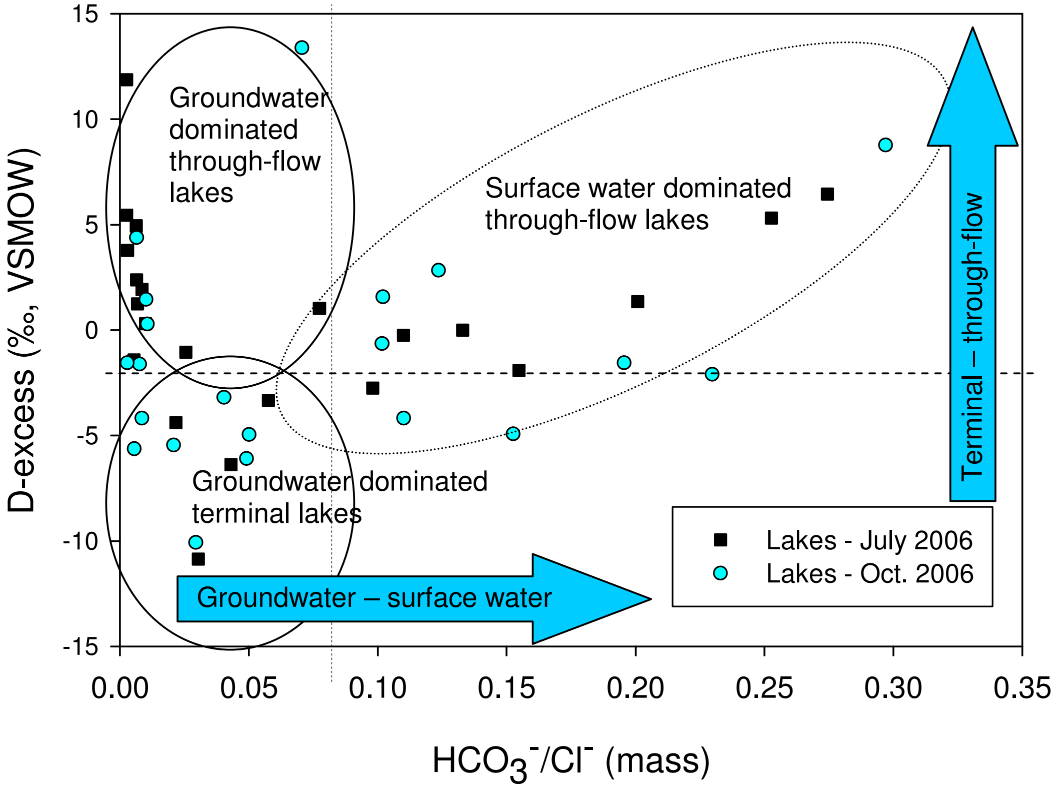

Figure 24. Deuterium "excess" versus HCO3-/Cl-.

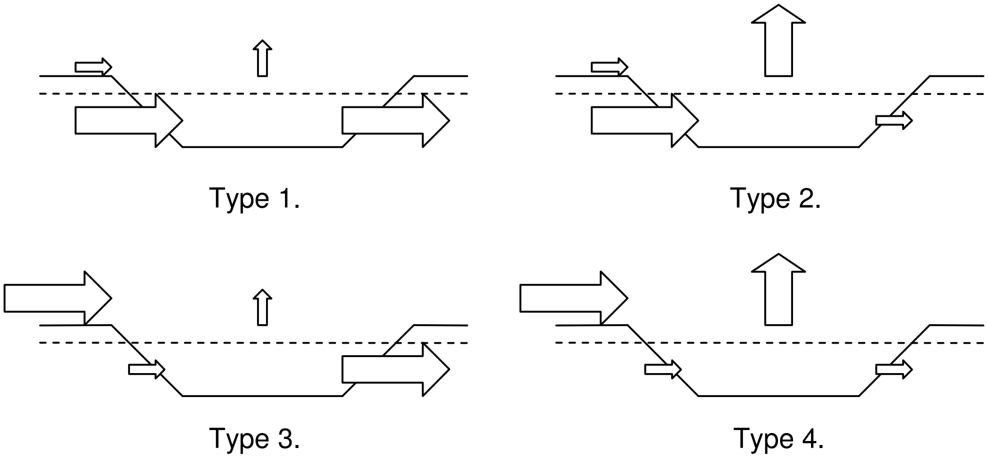

Figure 25. Conceptual representation of lake typesording to surface and subsurface inflows and relatively fraction of water lost by evaporation relative to subsurface outflow.

In Table 3 the lakes have been grouped into their various types on the basis of Figure 24. Most lakes do not fall clearly within one type lie along a continuum between two or more groups. Furthermore variation in hydrologic condition (e.g. rising or falling groundwater tables, or changes in surface runoff) may result in a change to the lake's status.

Table 3. Wetland delineation on the basis of deuterium "excess" and the HCO_3^-/Cl^- ratio as determined at July 2006

Wetland Type	**Type Description**	**Wetland Names**
Type 1	High δ_{xs}, low HCO_3^-/Cl^- : groundwater dominated, through-flow	Lake Corangamite; Cundare Pool/Lake Martin; Lake Weering; Upper Lough Calvert; Lake Cundare; Breamlea Wetlands; Connewarre Swamp; Connewarre Lake.
Type 2	Low δ_{xs}, low HCO_3^-/Cl^- : groundwater dominated, long residence time	Lake Tooliorook; Lake Gnotuk; Lake Struan; Lake Rosine; West Basin; Lake Murdeduke; Lake Victoria.
Type 3	High δ_{xs}, high HCO_3^-/Cl^- : surface water dominated, through-flow	Kooraweera Lakes; Lake Bullen Merri; Lake Purrumbete; Lake Terangpom; Lake Colac; Lake Modewarre; Reedy Lake;.

3.6. Rainfall variability and wetland response

Climate has been seen to be a significant driver with respect to lake and groundwater levels.

Modelling has shown that climate factors and lake levels can account for a significant drop in groundwater levels in the Warrion region.

Investigations into the hydrologic processes relating to the Corangamite lakes, including their groundwater and surface water inputs, has principally focused on:

- the relevance of climate factors (rainfall and evaporation) to lake levels; and
- the connectivity of the lakes to the groundwater table.

Investigation into the relevance of climate factors to lake levels have involved an assessment of climate trends using climate data obtained from SILO.

Assessment of the connectivity of the lakes with groundwater has required the collection and analysis of hydrostatic data from bores and lakes.

Systems modelling has also been undertaken which has endeavoured to describe the behaviour of the groundwater table in the Warrion region in relationship to climate trends.

Surface runoff and infiltration to the groundwater table is driven by rainfall, vegetation and geomorphic attributes. Rainfall varies across the Corangamite CMA region with higher rates in the more mountainous areas and lower rates on the plain. Colac has an annual average rainfall of around 735 mm while the average for Lismore is about 620 mm. Annual potential evaporation exceeds annual rainfall.

Historic rainfall and evaporation data for Colac, obtain as a SILO patched point dataset, has been plotted in Figure 26. The thicker line shows the 5 year moving average, which since 1998 has been below average and surpassed previous lows first in 2001 and then again in 2006. Figure 27 shows the percent deviation from the annual mean since 1889. It is evident from this plot that rainfall has been below average since 1997, excepting for 2001. These results suggest the region is experiencing one of the driest periods on record.

The cumulative rainfall deficit for Colac has been plotted in Figure 28. This graph shows the cyclic nature of dry and wet periods. For the 50 years between 1895 and 1945 the rainfall deficit was generally negative, that is, rainfall was generally below average. This situation was reversed between in the following 50 years. The region now appears to have commenced another period of negative rainfall deficit. Of concern is the steepness with which the deficit curve is falling, due the number of consecutive years of low rainfall.

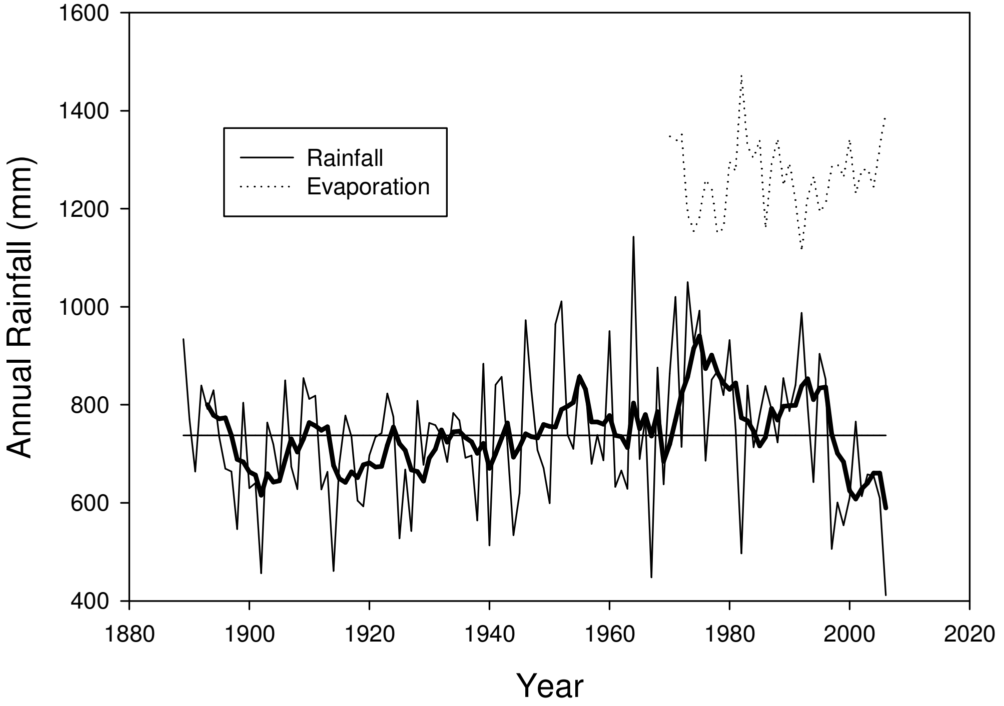

Figure 26. Rainfall and evaporation for Colac (1889 - 2006). The thicker line tracks the 5 year moving average.

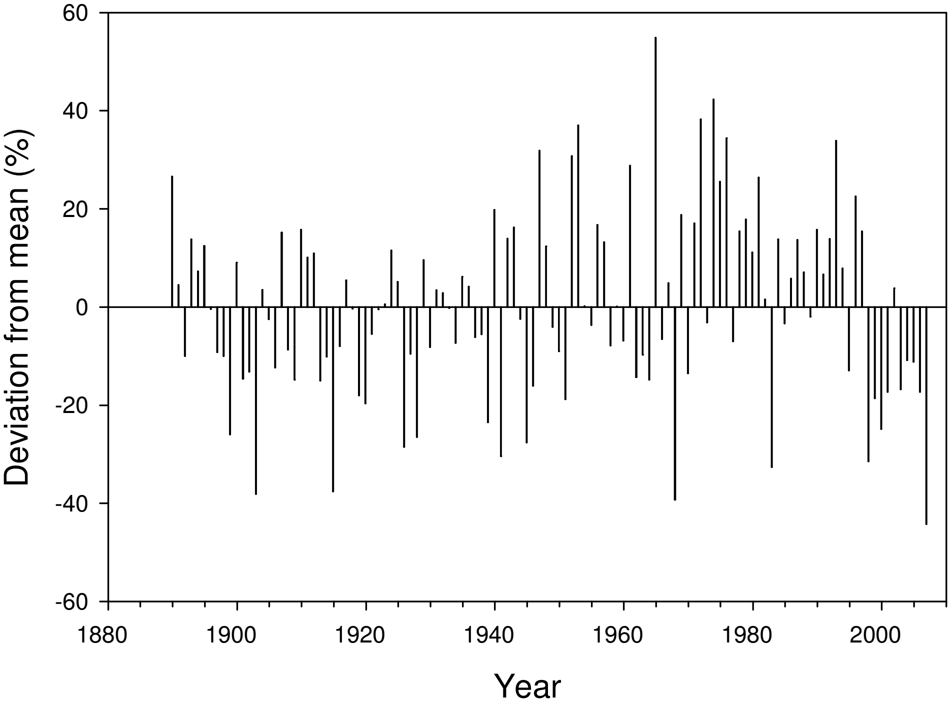

Figure 27. Percent deviation from mean rainfall for Colac (1889-2006).

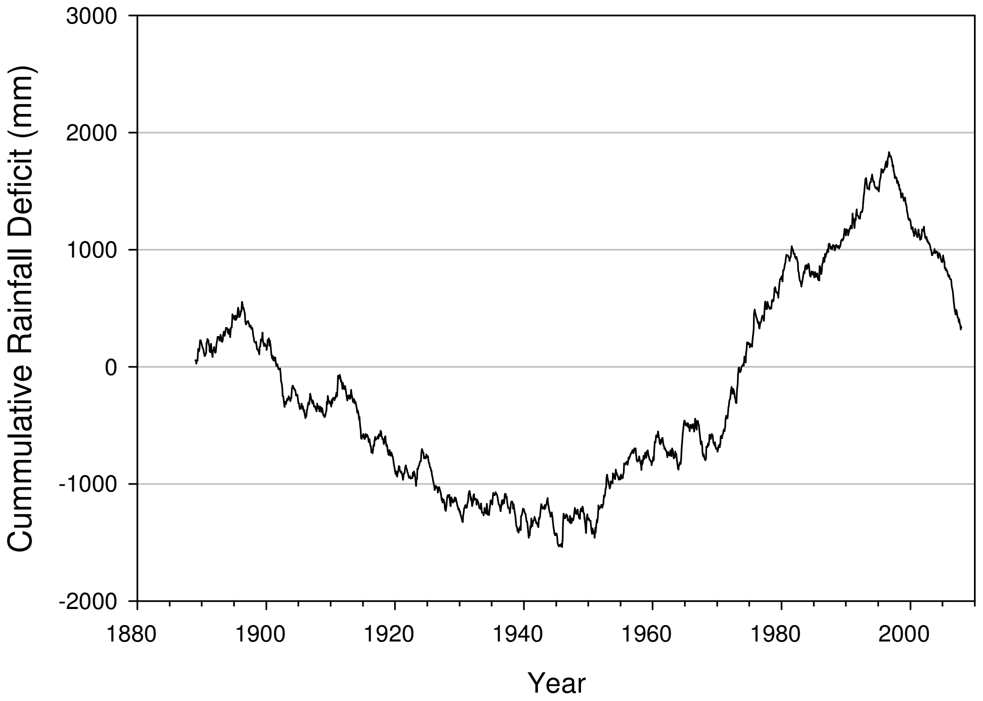

Figure 28. Cumulative rainfall deficit for Colac 1889 – 2007.

It is to be expected that climate trends would impact on the levels of surface water bodies and groundwater, although, in the case of the lakes, evaporation and off takes would alter the effects.

Historic lake level data available for Lakes Corangamite and Colac is shown in Figure 29 together with annual rainfall for Colac. Lake level data for Lake Colac commences in 1942 while that for Lake Corangamite commences in 1959 – the same year as the Woady Yallock diversion channel was commissioned. While seasonal fluctuations are evident for both lakes, it is evident that trends in Lake Colac closely follow rainfall trends confirming a relationship between the two. Levels in Lake Corangamite however, have systematically fallen. While initially its level was above that of Lake Colac it has fallen to be 2.5 m below in 2006. Since the diversion channel began operating Lake Corangamite has become a highly regulated water body with much of the flow from its northern tributary, the Woady Yallock, being diverted west to the Barwon River. It could be assumed from the levels recorded between 1960-70 that under natural conditions Lake Corangamite would fluctuate similar to, but slightly higher than, Lake Colac, in response to climatic conditions. It can be hypothesised that the significant drop in Lake Corangamite may have impacted on levels in adjacent lakes, e.g. the Red Rocks Complex.

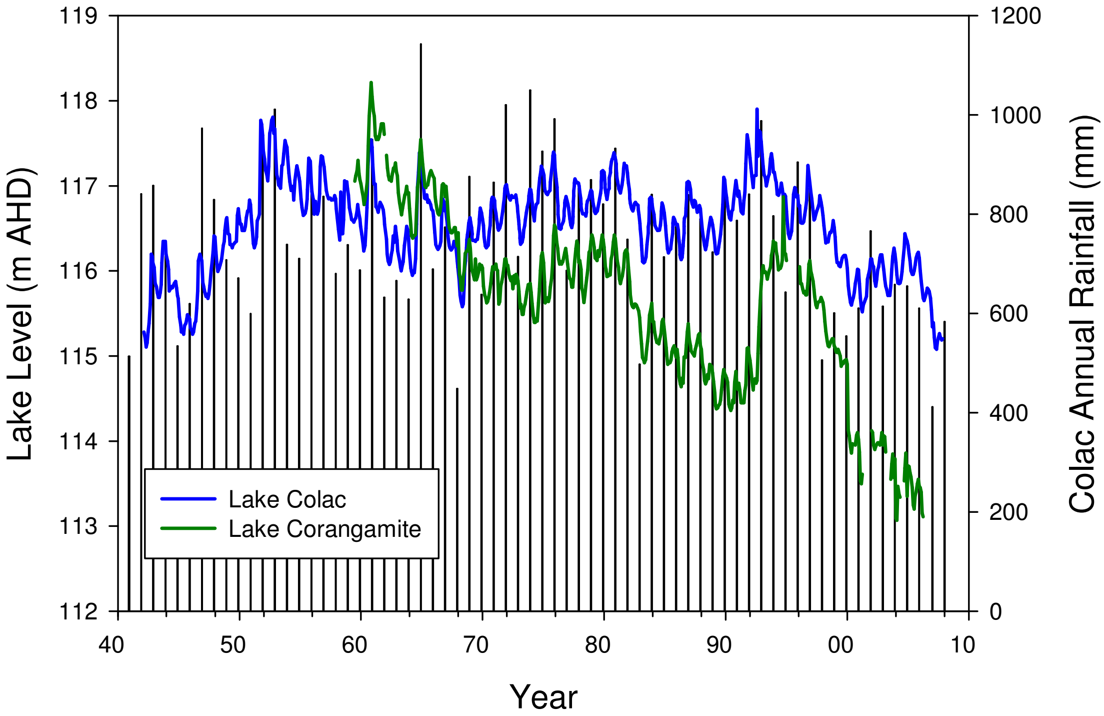

Figure 29. Trends in lake levels and annual rainfall (1942-2006).

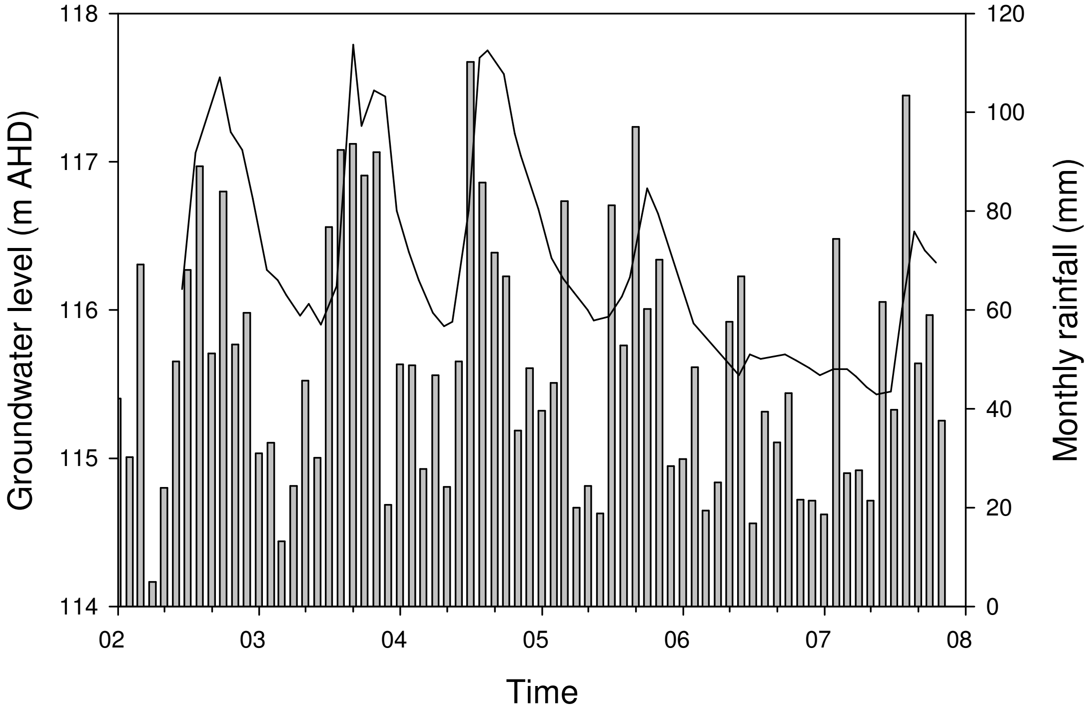

Figure 30. Plot of groundwater levels for Bore 146931 (West Basin) and monthly rain for Colac.

3.7. Groundwater in the Warrion irrigation Area

3.7.1. Compilation of groundwater data

The relationship between climate factors and groundwater and between groundwater and surface water levels provides a starting point for the modelling of groundwater-surface water interactions in the Warrion region.

To firstly gain an understanding of the hydrostatic surface, groundwater flow data was obtained from the Victorian Data Warehouse for those observation bores lying along the four transects (A, B, C & D) depicted in Figure 31.

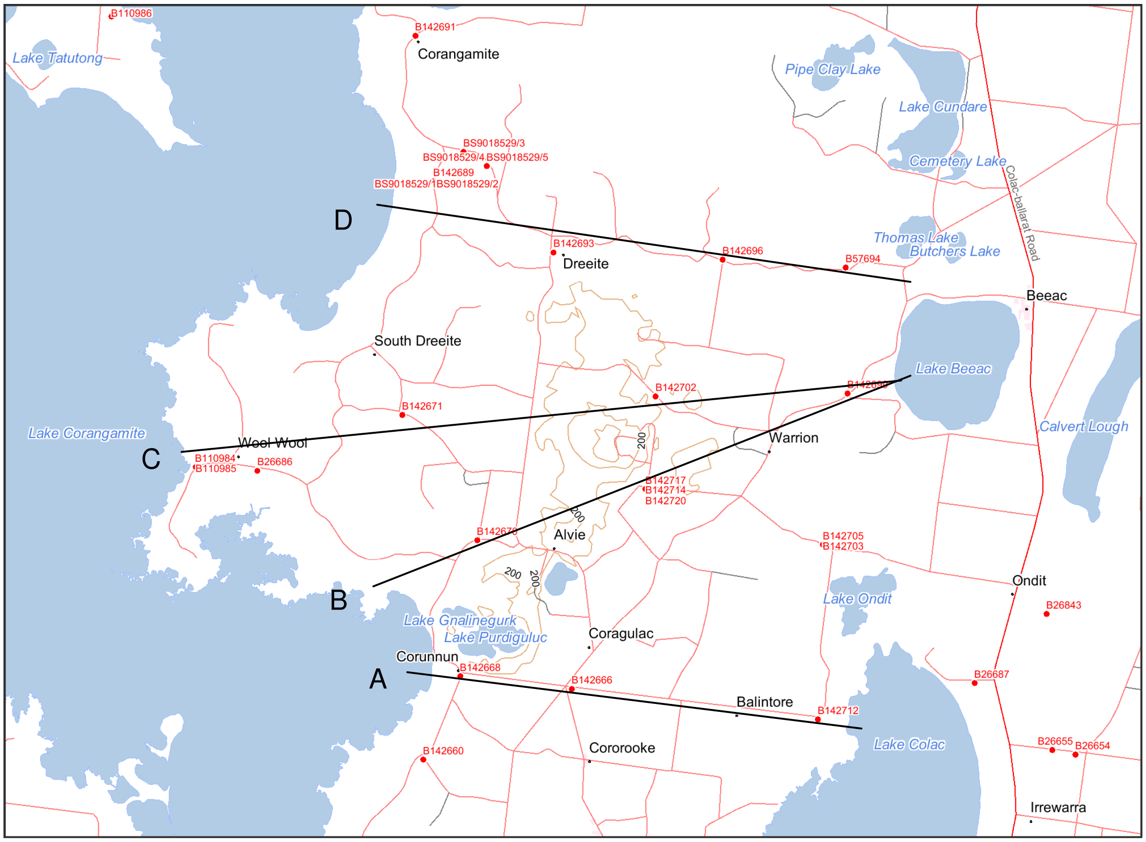

Figure 31. Location of observation bores in the Warrion and delineation of transects.

The time series data for the bores along each transect are shown in Figure 32 (A), Figure 33 (B), Figure 34 (C) and Figure 35 (D). Of particular interest in that groundwater levels are higher to the north and west of Mt Warrion – the highest point in the landscape. This suggests that the roughly north-south Warrion Range may not be the groundwater divide. It is possible that intensive groundwater extraction in the vicinity of Alvie has led to changes in the hydrostatic surface.

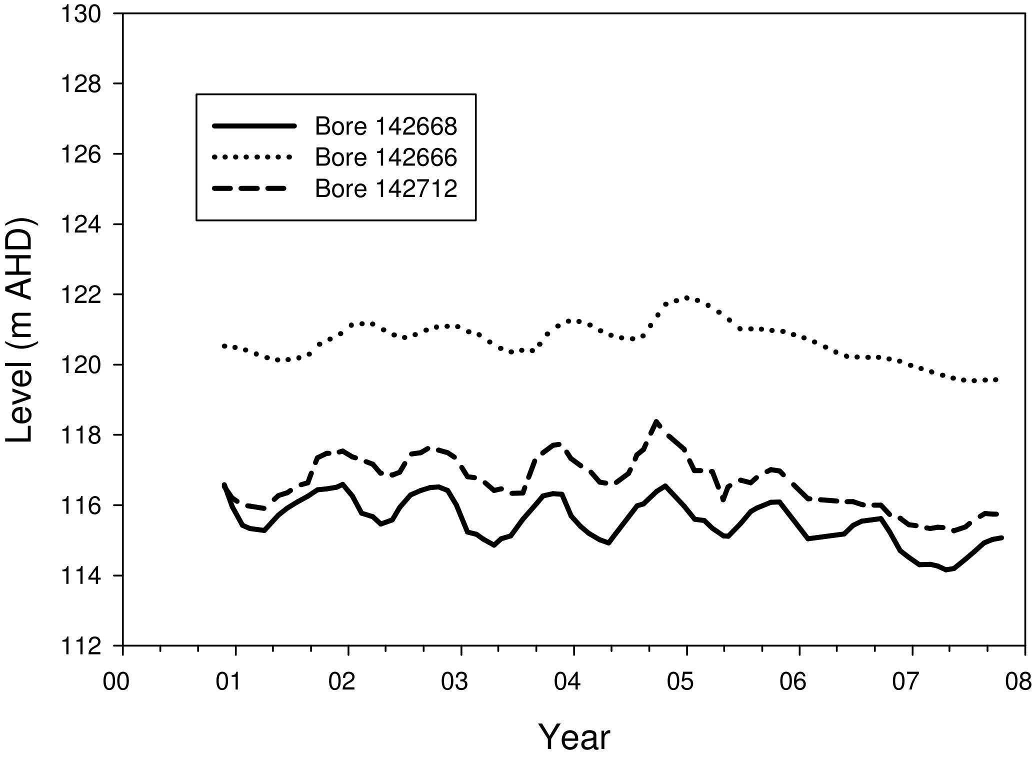

Figure 32. Water level trends for Transect A.

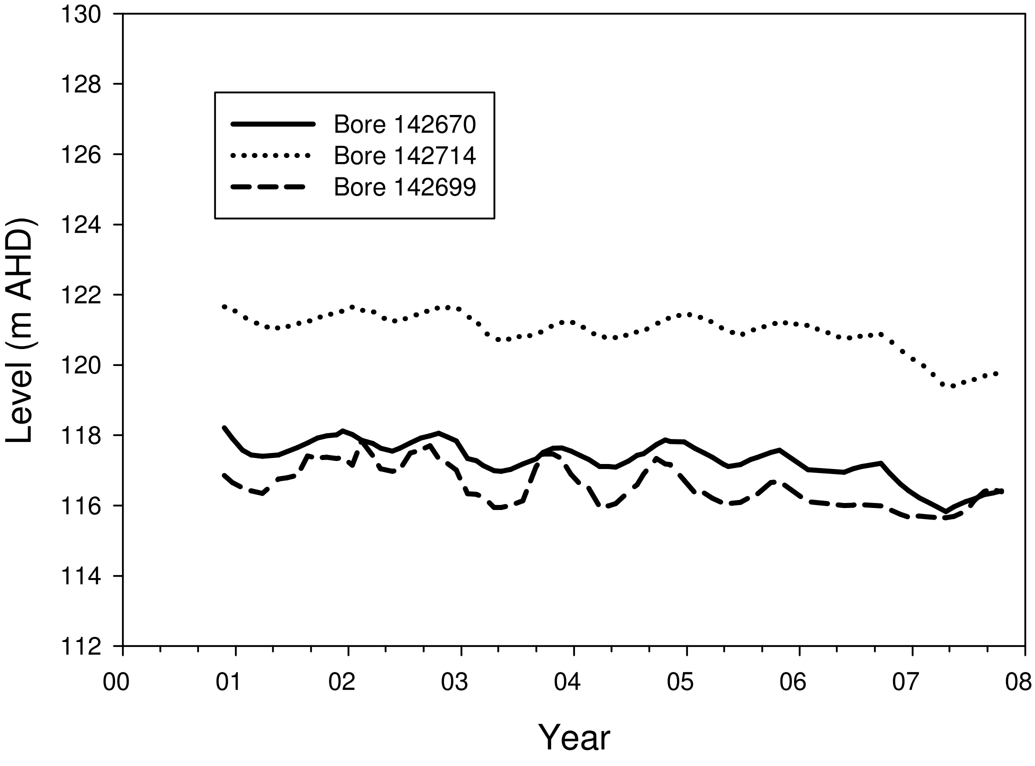

Figure 33. Water level trends for Transect B.

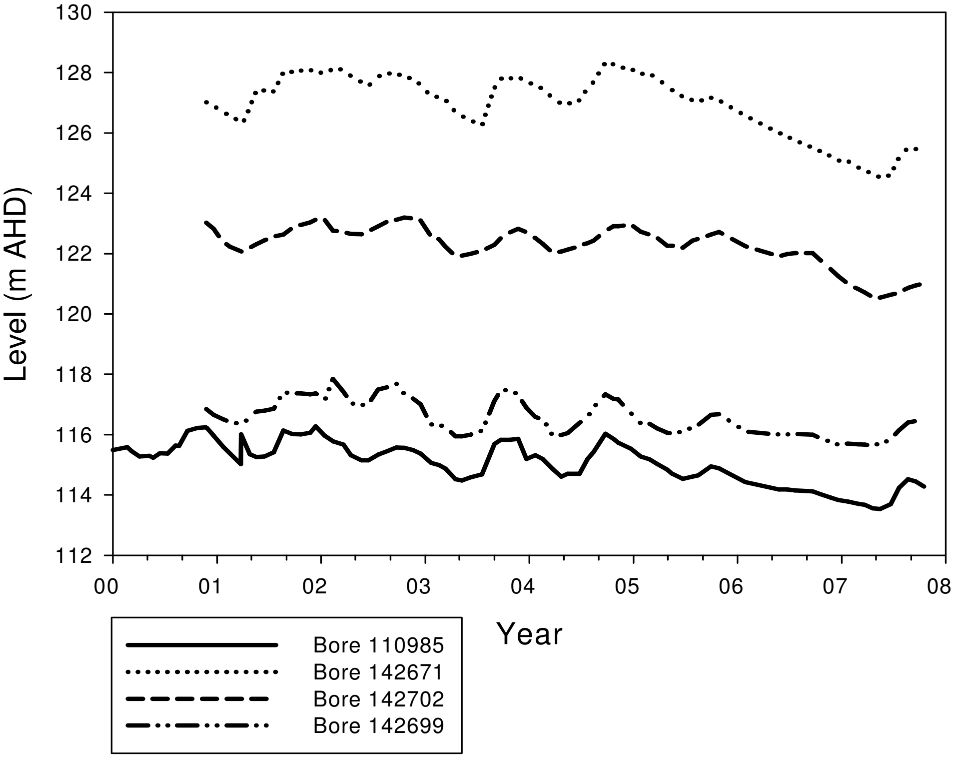

Figure 34. Water level trends for Transect C.

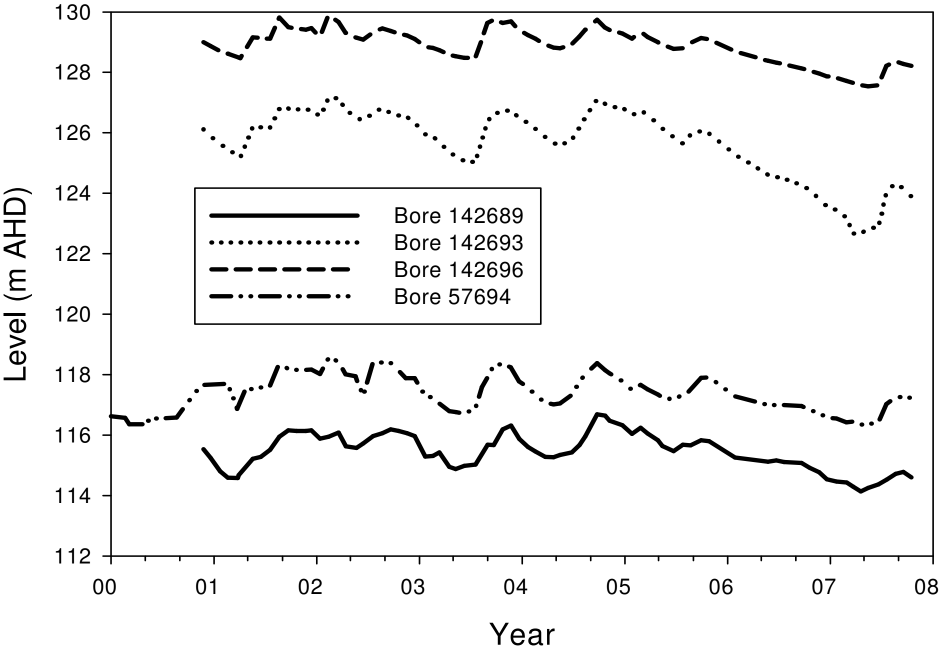

Figure 35. Water level trends for Transect D.

3.7.2. Modelling of the Warrion system

Bore 142714 (Figure 31) lies close to Mt Warrion at a point which appears to be along the groundwater divide with the directions of flow being west-south-west to Lake Corangamite and east to the Colac-Beeac-Cundare valley. A simple model was developed to simulate the groundwater store at bore 142714 using the Vensim modelling tool. "Vensim is a visual modelling tool that allows you to conceptualize, document, simulate, analyse, and optimize models of dynamic systems". "Vensim provides a simple and flexible way of building simulation models from causal loop or stock and flow diagrams" (Ventana Systems, 2005).

The model assesses the impact of climate trends and assumed in the first instance that irrigation extraction was negligible. Infiltration was determined by the following equation:

Infiltration = monthly rainfall-(evaporation loss*evap loss rate)

with a minimum value (understood to be the maximum evaporation from the soil store in a month) and a maximum value (understood to be the maximum infiltration before runoff).

Flow to the lakes was based on Darcy's equation:

GW flow = Hydraulic Cond., K * (Groundwater store level – Lake level)/distance

An "aquifer factor" was used as a correction factor to account for porosity and the differences between the catchment and storage areas.

The model diagram showing parameters and links are given in Figure 36.

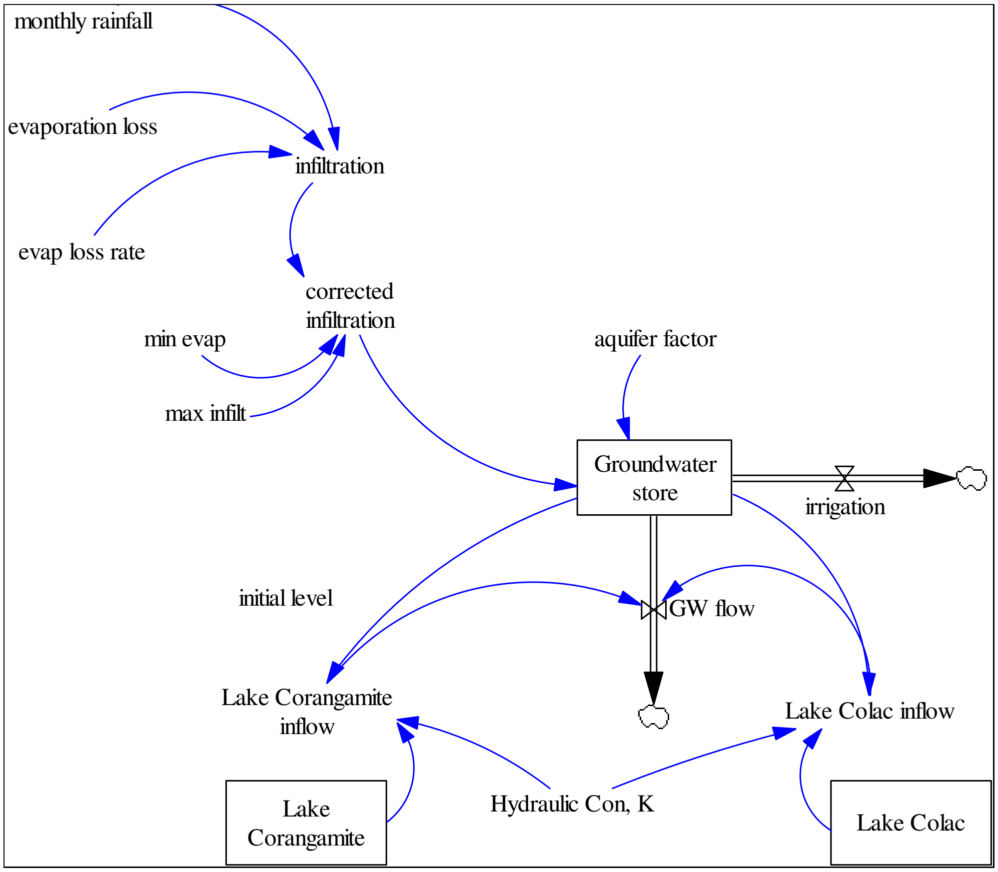

Figure 36. Conceptual diagram of the Vensim model of groundwater store.

Historic data from the Victorian Data Warehouse provided 83 monthly values (2001-2007). The model was calibrated on half of the record (40 values) and validated on the remaining. The best calibration (R^2 = 0.954) was obtained for the 40 end values with no shift required between the rainfall data and the water level data. An R^2 of 0.9254 was obtained for the full historic record.

The calibration results were as follows:

Parameter	**Calibrated value**
Hydraulic Con, K	102.952 m/month (~4.0x10^{-5} ms^{-1})
Aquifer factor	8.705
Evap loss rate	0.1457
Max evap	-82.6811 mm/month
Max infilt	37.6549 mm/month

The calibrated values of the model constants are considered realistic. The hydraulic conductivity value is valid for basaltic rock – as is found in the Warrion region. The evaporation factor is very low, which accords with a quick recharge environment.

Results have been plotted in Figure 37. A very good fit has been obtained between the measured and modelled levels.

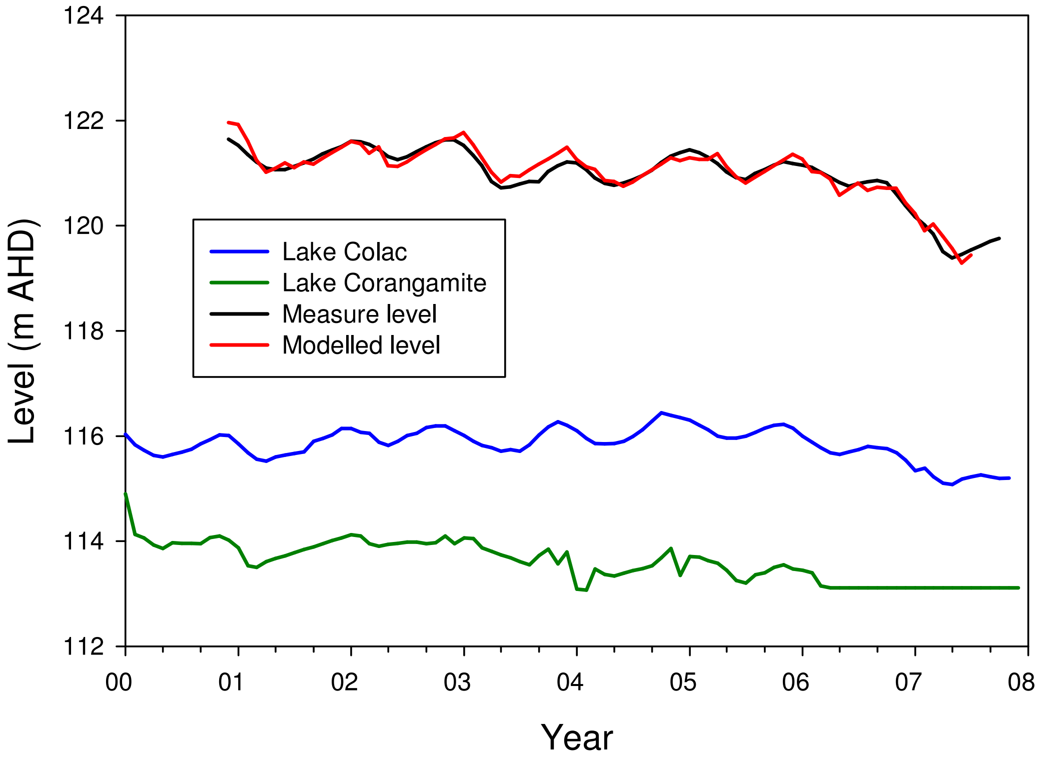

Figure 37. Graph of the measured and modelled groundwater level at Bore 142714. Lake levels for Lake Corangamite and Lake Colac are also plotted.

The calibrated model has been used to estimate historic groundwater levels based on climate factors alone. The model was run for the full record of lake level data and results have been plotted in Figure 38. According to these results groundwater levels reach a peak in the mid 1990s, at the time when a sudden jump occurred in Lake Corangamite. Since that time the groundwater level fell some 4 m.

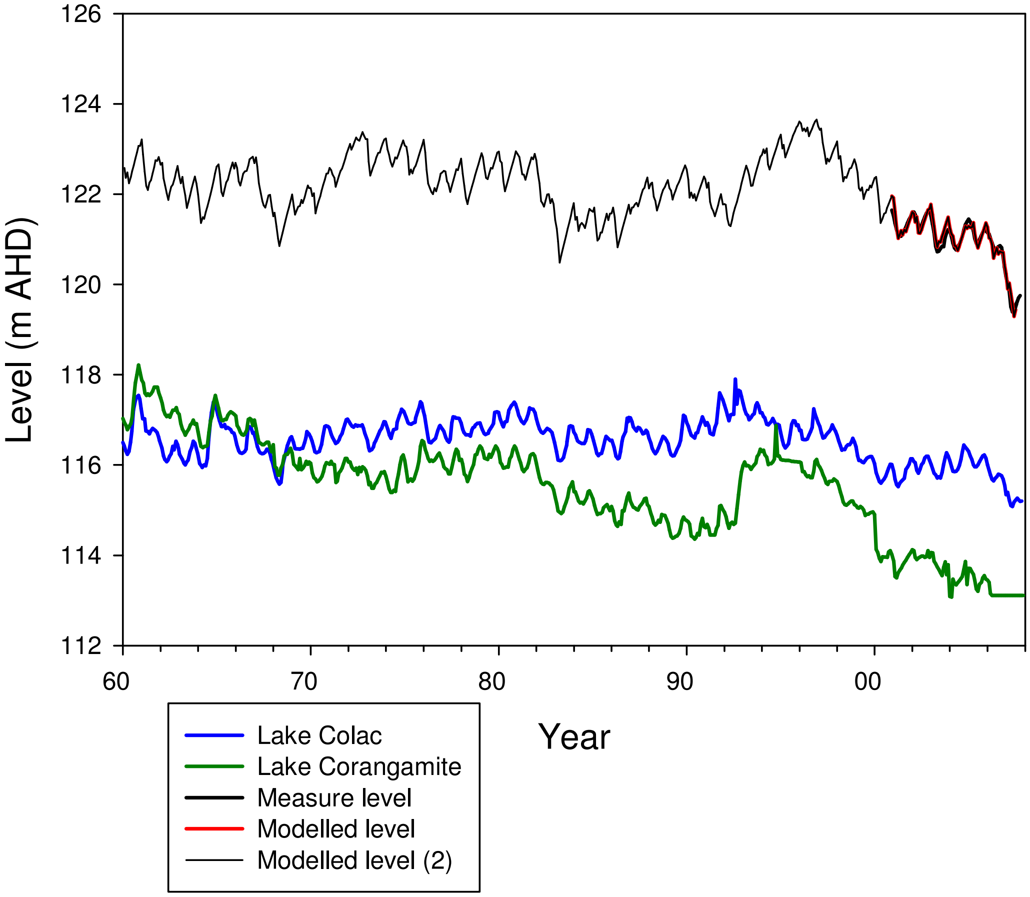

Figure 38. Graph showing the modelled historic behaviour of groundwater store at Bore 142714 (Modelled level (2)) based on climate and lake level trends.

4. CONCLUSIONS

This work combines geochemical and water level monitoring of wetlands and lakes during a relatively dry period between 2006-2007 within the CCMA to better understand the hydrological processes affecting the lake ecosystems, specifically related to salinity and their dependence on groundwater.

A field survey of ~46 lakes found that about 20 were dry or had only very shallow veneer of surface water at the surface. Of the 26 wetlands sampled in July, twenty were resampled in October 2006 and April 2007 during which time there was very little rainfall within the region. Detailed monitoring of the hydrology and chemistry of three lakes (West Basin, Lake Colac and Lake Weering) was conducted fortnightly throughout 2007. Water level loggers were installed in about 20 monitoring boreholes as well as several piezometers installed within three above-mentioned lakes as part of this study.

The chemistry of the lakes ranges over more than two orders of magnitude, from ~1500 mg/L at Lake Purrumbete to Lake Corangamite and Lake Weering at ~2000 000 to 300 000 mg/L respectively. The chemical composition of the lakes tends to be sodium chloride dominated, especially the more saline lakes, with significant fraction of bicarbonate in the lower salinity end of the spectrum. The lakes and wetlands resemble the chemistry of seawater except for relatively higher calcium and bicarbonate concentrations in some fresh lakes. The isotopic composition of the lakes are all enriched in the heavy isotopes of water (^{2}H and ^{18}O) relative to the local rainfall and groundwater and all lie on a common 'evaporation line'. The ultimate salinity of the lakes is driven by evaporation which in turn is controlled by water residence time within each of the respective lakes. The Br/Cl ratio is similar to that of the marine Br/Cl mass ratio of 290 indicating that the salt is predominating derived from concentration of marine aerosols deposited in rainfall rather than dissolution of salt deposits within the regolith.

The lakes are classified according to a continuum of main hydrological 'types' of lakes are thought to occur throughout the region: two 'types' with relatively short water residence time and groundwater or surface water dominated respectively, and one 'type' with long water residence time and groundwater dominated. While none of the lakes or wetlands is completely sourced from one or the other end-member, they appear to be dominated by groundwater component and only a few lakes appear to be surface water dominated in terms of salt input. Almost every lake surveyed had some component of its water balance contributed by groundwater, and more than 75% of lakes surveyed this appears to be the dominant component of solutes. While direct rainfall contributes a significant component of the water input, a greater component is removed by direct evaporation and rainfall provides only a minor amount of salt directly. The isotopic composition of the inflows (rainfall, surface runoff or groundwater) are indistinguishable from each other therefore cannot be used as an indicator of groundwater dependence. However, the enriched isotopic values indicate increasing water residence time within the lakes.

Because of the long water and salt residence time in the lakes and wetlands the salinity has enough inertia to be buffered by short term variations in the water balance or local effects such as groundwater pumping. The viability of the wetlands is driven by persistent drought causing regional water tables to decline over the past several years. The recovery of lake levels in response to the 2007 spring rainfall was short lived and salinity rapidly returned to early 2007 by middle of 2007/2008 summer.

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Appendix A: Analytical results

Note 1: TDS is calculated as the sum of the Cl, SO4, HCO3, Na, K, Ca and Mg ions.

Table 4. Analytical results for CCMA Lakes July 2006

Lake Number	Lake Name	Field E.C.	Field pH	Field DO	Field Temp	pH	TotAlk	Cl^-	Br^-	$SO_4^=$	HCO_3^-	Ca^{2+}	K^+	Mg^{2+}	Na^+	Sr	TDS	222 Rn	$\delta\ ^{18}O$	δ^2H
		dS/m		%sat.	celcius		meq/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	Bq/L	‰ rel SMOW	‰ rel SMOW
1	Lake Tooliorook	21.3	8.94	57.0	7.5	8.7	11.2	6990	19	385	686	37	46	772	3407	2	12323	0.07	3.12	22.2
2	Kooraweera Lakes	1.3	8.82	112.0	6.9	8	6	191	0	20	364	34	32	52	146	0	839	0.08	-4.47	-23.6
3	Lake Bullen Merri	15.6	8.98	78.0	11.9	9	12	4830	11	8	748	18	102	250	2886	<1.0	8843	0.00	2.54	18.4
4	Lake Gnotuk	93.6	8.23	104.0	13.8	8	14	38000	94	105	824	118	716	2339	19990	8	62090	0.03	3.1	20.4
5	Lake Purrumbete	0.87	8.8	104.0	12.1	8	3	136	0	17	184	23	6	31	88	0	485	0.11	1.77	11
6	Lake Corangamite					7.7	15.3	108800	470	4330	935	72	770	4520	64700	10	184128	0.11	0.76	8
7	Lake Terangporm	23	9.11	114.0	13.8	9.1	29.7	7180	18	294	1814	17	184	576	4225	<2.5	14290	0.05	0.15	6.5
8	Lake Struan	20.8	9.04	157.0	11.1	8.5	6.5	6870	19	423	395	211	32	729	3073	6	11734	0.08	2.78	18.9
9	Lake Rosine	65.4	9.24	124.0	11.4	8.9	10.5	24990	68	1110	639	136	109	2179	12386	10	41549	0.35	3.07	23.5
10	Cundare Pool/Lake Martin Inlet	10.4	8.55	85.0	6.5	8	4	3106	8	299	240	160	20	340	1408	<2.5	5572	0.00	-1.44	-10.5
11	Lake Weering	224	7.91	65.0	8.1	8	7	152000	438	17528	400	224	1065	10283	88056	13	269556	0.12	-3.02	-12.3
12	Upper Lough Calvert	175	8.1	86.1	10.8	8	4	82800	202	3912	242	73	185	2848	50824	22	140883	0.04	-1.06	-4.7
13	Lake Cundare	187.3	8.24	83.0	14.2	8	4	92500	209	6900	235	27	386	859	61751	10	162657	0.04	-1.18	-4
14	Lake Colac	7.8	8.89	106.0	12.2	9	8	2302	5	86	462	78	34	183	1265	2	4410	0.08	2.32	19.9
15	West Basin	132.3	8.98	115.0	13.9	9	28	56249	147	1815	1705	17	937	1732	34449	<5.0	96904	0.03	3.87	20.1
16	Lake Murdeduke	104.8	8.73	90.0	9.6	9	30	42599	121	1711	1835	39	216	2671	23669	6	72740	0.12	3.16	18.9
17	Lake Modewarre	30.9	9.65	82	10	9.43	19.14	10620	18.84	120.09	1168	21	48	640	5847	3	18463	0.07	2.93	23.2
18	Breamlea Wetlands	76.8	8.91	78	11.4	8.61	3.021	29400	80.33	3590	184	632	560	1720	15767	11	51854	0	0.97	12.7
19	Barwon River	55	8.33	69	12.8	7.98	2.052	19600	53.71	2560	125	399	412	1216	10633	7	34946	0	0.44	5.9
20	Barwon River Mouth (C'van Pk)	53	8.25	68	13.3	7.93	2.104	18900	51.2	2490	128	388	398	1176	10276	7	33756	0.09	0.42	4.6
21	Lake Victoria	107	7.84	57	13	7.6	3.768	42500	119.64	5790	230	926	925	2668	23938	18	76978	0.13	1.54	10.9
22	Connewarre Lake	45.5	8.33	68.8	14.3	8.1	2.58	15900	41.72	2070	157	330	331	1001	8607	6	28396	0.38	0.15	1.5
23	Reedy Lake	4.8	7.88	63.7	14.2	7.39	2.401	1102	2.5	598	146	152	30	129	642	1	2799	0.08	-0.1	-0.8
24	Inlet to Reedy Lake (Barwon R.)	2.5	8.38	71	11.5	7.91	2.704	601	1.12	80.17	165	41	11	64	319	1	1281		-2.83	-16.2

Table 5. Analytical results for CCMA Lakes October 2006

Lake Number	Lake Name	Field E.C.	Field pH	Field DO	Field Temp	Tot Alk	F^-	Cl^-	Br^-	NO_3^-	$SO_4^=$	HCO_3^-	Ca	K	Mg	Na	S	Si	TDS	d O18	dD
		dS/m		%	celcius	meq/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	‰ rel SMOW	‰ rel SMOW
1	Lake Tooliorook	23.9	9.07	47.3	13.8	13.55	<1	8130	24	3	438	827	48	67	884	3950	169	<0.5	14344	3.8	29.75
2	Kooraweera Lakes	0.85	8.71	104	13.2	5.295	0.2	111	0	12	8	323	23	25	36	112	4	11.38	637	-2.92	-17.1
3	Lake Bullen Merri	15.61	9.13	82	13.7	12.33	<1	4930	12	1	2	752	19	117	249	2850	1	<0.5	8918	2.53	15.3
4	Lake Gnotuk	94.5	8.69	69	15.7	13.67	<5	40100	113	8	73	834	121	904	2320	19920	27	<5	64272	3.02	18.7
5	Lake Purrumbete	0.82	9.12	88	15.8	3.07	0.17	162	0	0	18	187	24	7	32	90.5	7	1.31	521	1.7	12.7
6	Lake Corangamite					15.36	<2	123200	391	4	4330	937	105	2230	5310	71500	1430	<5	207612	1.99	14.3
7	Lake Terangporm																				
8	Lake Struan	22.8	8.96	96.3	15.6	6.418	<1	7820	25	1	481	391	216	175	827	3560	179	<0.5	13470	3.77	25.2
9	Lake Rosine																				
10	Cundare Pool/Lake Martin Inlet	17.1	9.3	155	17.5	2.907	<1	3610	10	<1	414	177	132	47	396	1660	150	<0.5	6436	2.55	14.3
11	Lake Weering	214	7.97	29	10.2	8.246	<10	176000	722	23	28000	503	415	2400	14700	90900	9540	<5	312918	1.52	10.6
12	Upper Lough Calvert																				
13	Lake Cundare																				
14	Lake Colac	7.89	8.89	73	15.9	7.597	0.54	2370	6	1	82	463	84	53	177	1260	37	0.988	4490	2.67	19.8
15	West Basin	131	8.95	60.1	16.3	28.1	<10	58200	163	13	1780	1714	15	1280	1710	33600	617	<2	98299	3.66	19.2
16	Lake Murdeduke	107.4	8.77	64	16.4	30.92	<5	46700	145	6	1820	1886	36	422	2800	24900	641	<2	78564	3.45	24.4
17	Lake Modewarre	33	9.9	105	16.9	20.75	<2	11500	24	<2	105	1266	27	92	720	6570	45	<2	20279	3.41	23.1
18	Breamlea Wetlands																				
19	Barwon River																				
20	Barwon River Mouth (Caravan Pk)	54.6	8.23	67	18	2.128	<2	20000	64	3	2670	130	424	481	1220	10800	955	<2	35725	0.29	6.7
21	Lake Victoria	115.4	7.87	58	18.3	4.498	<10	49300	140	16	6850	274	1120	1330	2870	26300	2410	3.702	88044	3.13	19.4
22	Connewarre Lake	44.5	8.47	84.3	18.4	2.611	<2	15800	48	2	2140	159	348	394	984	8500	762	<0.5	28325	1.32	12
23	Reedy Lake	3.83	8.43	83.8	18.1	3.567	<0.3	947	2	<0.3	286	218	99	25	93	530	103	<0.5	2198	1.1	6.7
24	Inlet to Reedy Lake (Barwon R.)	1.95	8.26	70.5	16.5	2.342	<0.3	481	1	0	62	143	36	9	50	259	23	<0.5	1039	-3.42	-18.6
25	Gnarkeet Chain of Ponds River	11.57	7.93	44.3	13.1	7.313	<1	3610	10	<1	313	446	195	18	418	1530	112	4.172	6530	-0.99	-5.1

Lake Number	Lake Name	Field E.C.	Field pH	Field DO	Field Temp	Tot Alk	F^-	Cl^-	Br^-	NO_3^-	$SO_4^=$	HCO_3^-	Ca	K	Mg	Na	S	Si	TDS	d O18	dD
26	Lake Colongulac	67.7	9.03	74	14.4	43.5	<5	26000	78	6	304	2654	12	428	896	15400	120	<2	45693	2.53	21.8
27	Barongaruk Creek	2.06	8.69	68.6	13.6	0.6825	<0.3	590	1	1	24	42	25	4	38	304	9	3.509	1026	-4.11	-19.5
28	Breamlea Inlet	62.7	8.65	67	15.1	3.287	<5	23500	70	6	3150	201	512	537	1420	12700	1100	<2	42019	2.61	16.7
29	Connewarre Lake Inlet	41.3	8.41	76	16.7	2.496	<2	14400	44	4	1950	152	319	334	900	7840	694	<0.5	25895	0.74	6.2

Table 6. Analytical results for CCMA Lakes October 2007

Lake Number	Lake Name	Field E.C.	Field pH	Field DO	Field Temp	pH	EC	Alk (pH 4.5)	Alk (pH 8.3)	F^-	Cl^-	Br^-	NO_3^-	$SO_4^=$	HCO_3^-	Ca	K	Mg	Na	S	Si	Reac Si	Sr	TDS		222 Rn	223 Rn - Error	d O18	dD
		dS/m		%	celcius		dS/m	meq/L	meq/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L		Bq/L	Bq/L	‰ rel SMOW	‰ rel SMOW
1	Lake Tooliorook	OVR	8.24		14	8.67	23.51	16.55	2.046		10900	34	6	680	1010	67	73	1295	5030	247	<4	0.234		19054					
2	Kooraweera Lakes	1.256	7.8		13	7.85	0.921	4.982			139	0	14	13	304	28	21	41	106	5	14.143	11.216		652					
3	Lake Bullen Merri	15.03	8.38		14	8.76	13.33	12.32	1.249		4950	14	5	6	752	19	100	259	2840	1	<1	0.044		8926					
4	Lake Gnotuk	OVR	7.89		17	8.42	55.84	13.83	0.9208		40500	117	15	95	844	120	744	2430	21300	30	<4	0.066		66033					
5	Lake Purrumbete	1.645	7.96		14	7.85	0.814	3.0313			151	0	1	19	185	24	6	32	87	7	1.551	1.264		504					
6	Lake Corangamite																												
7	Lake Terangporm																												
8	Lake Struan	14.39	7.33		17	7.86	13	5.098			4850	15	3	565	311	193	29	560	2090	198	1.26	1.121		8597					
9	Lake Rosine																												
10	Cundare Pool/Lake Martin Inlet	6.15	7.82		10	7.88	4.976	3.537			1760	5	1	260	216	100	10	204	866	90	0.287	0.275		3416					
11	Lake Weering	214	7.97	29	10	7.2	148.8	3.067			184000	264	112	11030	187	453	659	5430	115000	3763	<20	0.174		316759					
12	Upper Lough Calvert																												
13	Lake Cundare	OVR	7.68		14	8.13	114.8	5.74			60400	177	38	4820	350	34	331	666	40200	1708	<10	0.289		106801					
14	Lake Colac	12.42	7.91		19	8.44	10.99	7.464	0.2915		3810	11	4	138	455	74	48	297	2010	50	<1	0.617		6832					
15	West Basin	OVR	8.07		16	8.71	93	26.79	5.415		58700	171	37	1850	1634	20	960	1740	34500	643	<10	0.514		99404					
16	Lake Murdeduke	OVR	7.63		15	8.16	97	20.57			71900	231	38	2990	1255	55	367	4310	39100	1062	<10	0.249		119976					
17	Lake Modewarre																												
18	Breamlea Wetlands																												
19	Barwon River																												
20	Barwon River Mouth (Caravan Pk)																												
21	Lake Victoria																												
22	Connewarre Lake																												
23	Reedy Lake																												
24	Inlet to Reedy Lake (Barwon R.)																												
25	Gnarkeet Chain of Ponds River																												
26	Lake Colongulac	OVR	8.45		16	8.95	36.67	14.93	2.755		17000	52	14	321	911	18	248	490	10100	115	<4	0.797		29088					
27	Barongaruk Creek	2.297	6.62		13	6.7	2.225	0.6143			640	1	1	32	37	30	5	47	323	12	4.372	3.476		1114					
28	Breamlea Inlet																												
29	Connewarre Lake Inlet																												
30	Milangil	OVR	7.91		16	8.39	35.69	5.275	0.2669		17400	57	10	1370	322	114	96	1180	9480	489	<4	0.018		29962					
31	East Basin	OVR	8.26		17	8.84	58.99	38.73	8.277		38800	106	30	464	2363	27	785	1590	21200	157	<10	0.299		65228					
32	Corangamite East	OVR	7.22		22	7.87	128.8	8.541			109000	363	59	4110	521	65	733	4370	64100	1416	<10	0.308		182898					
33	Beeac	OVR	7.65		13	8.11	92	5.145			46500	143	40	3190	314	34	370	664	28500	1116	<10	0.907		79571					
34	Pirron Yallock	0.935	7.35		13	6.82	0.728	0.8275			149	0	3	29	50	19	13	17	72	11	3.173	2.464		350					
35	Deans Ck	2.386	6.93		11	6.91	2.347	1.135			703	2	1	26	69	38	9	54	326	9	3.663	2.915		1225					

Table 7. Monitoring results for Weering Lake

Date		19/02/2007	5/03/2007	21/05/2007	4/06/2007	18/06/2007	2/07/2007	14/07/2007	30/07/2007	13/08/2007	27/08/2007	10/09/2007	24/09/2007	8/10/2007	22/10/2007	5/11/2007
Field Values																
E.C.	dS/m	224.0	214	Over scale	Over scale	Over scale	Over scale	Over scale	Over Scale		Over scale	Over scale	Over scale	Over scale	Over scale	
pH		7.91	7.97	6.4	7	7.09	7.18	6.96	7.02		6.92	6.84	6.85	6.8	6.76	
DO	%	65	29													
Temp	celcius	8.1	10.2	21	22.6	13.6	10.2	8.2	10.5		12.1	10.8	16.6	15.6	13.6	
Analytical Values																
pH		7.7	7.5	6.8	6.9	7.7	7.7	7.44	7.6	7.7	7.55	7.49	7.38	7.17	7.1	7.2
EC	dS/m			116	131	203	174	182	194.3	186.4	198.7	20/07/1900	162.2	142.6	142.1	148.8
Alk (pH 4.5)	meq/L	6.6	8.2	35.8	18.1	3.8	2.644	2.883	3.2	2.3	2.593	2/01/1900	2.935	3.135	3.0	3.1
F$^-$	mg/L		<10	<25	<25	<10	<10	<10			<25	<25	<10			
Cl$^-$	mg/L	152000	176000	185100	163100	174000	126000	164000	153000	143000	179000	163000	181000	187000	187000	184000
Br$^-$	mg/L	438	722	2730	1370	408	249.61	286.53	202	163	553.28	462.45	207.78			264
NO$_3^-$	mg/L		23	28	<25	<10	<10	11.29	44	80	<25	169.72	<10			112
SO$_4^=$	mg/L	17528	28000	48100	65400	16800	11000	13000	9470	7730	10040	9440	9558.37	11800	12200	11030
HCO$_3^-$	mg/L	400	503	2186	1102	231	161	176	195	140	158	154	179	191	186	187
Ca	mg/L	224	415	90	152	198	211.08	281.29	275	265	375	349	370	423.3095	419	453
K	mg/L	1065	2400	5280	3250	761	623.53	747.6	759	664	380	401	615	603.305	637	659
Mg	mg/L	10283	14700	54700	34900	8532	6170	6820	5340	3960	4450	4080	4850	5250	5420	5430
Na	mg/L	88056	90900	39100	68100	96528	79200	107300	95000	85000	116500	102400	112000	121700	121000	115000
S	mg/L	6100	9540	17000	22100	5418	3940	4460	3623	2752	3220	3000	3440	3780	3880	3763
Sr	mg/L	13		16	10									19.195	18.889	
TDS	mg/L	269556	312918	334555	336004	297050	223366	292325	264039	240759	310903	279824	308572	326968	326862	316759
δ O18	‰ rel SMOW	-3.02	1.52	1.57	1.10	-2.93	-5.24	-4.06	-4.22	-5.40	-5.00	-3.08	-2.50	-1.67	-2.01	
δD	‰ rel SMOW	-12.30	10.60	6.30	1.40	-11.80	-29.10	-16.80	-10.50	-19.30	-19.30	-13.90	-9.30	-1.80	-0.80	

Table 8. Monitoring results for Weering spring

Date		8/01/07	22/01/07	5/02/2007	19/02/07	5/03/07	19/03/07	2/04/07	17/04/07	7/05/07	21/05/07	4/06/07	18/06/07	2/07/07	14/07/07	30/07/07	13/08/07	27/08/07	10/09/07	24/09/07	8/10/07
Field Values																					
E.C.	dS/m	7.0	6.7	5.9	6.6	5.7	7.9	6.8	5.7	6.6	6.6	6.5	6.46	8.0		7.0	Off scale	6.18	6.11	6.27	
pH		8.51	8.18		7.9	8.17	8.39	8.34	8.41	8.31	7.42	7.57	7.49	7.78		7.56	7.22	7.55	6.4	7.26	
DO	%																				
Temp	celcius	22.4	18		21.6	18.6	19.9	18.3	20	15.9	14.2	13.6	12.3	12.9		13.3	13.1	15.2	15.4	15.5	
Analytical Values																					
pH		8.2	8.1	8.2	6.2	8.1	8.0	8.1	8.3	8.3	8.1	8.07	8.08	8.1	8.2	8.19	7.96	8.02	7.9	8.0	
EC	dS/m	5.8	5.9	6.6	6.1	6.0	7.1	6.2	6.1	6.0	5.9	5.524	5.721	5.4	5.5	6.097	42.6	5.19	4.739	4.8	
Alk (pH 4.5)	meq/L	7.0	7.2	7.2	2.1	7.3	7.5	7.5	7.4	7.9	7.4	7.366	7.306	6.9	6.9	7.042	7.392	7.03	7.016	7.1	
F^-	mg/L	<0.5	<0.5	<0.5	<0.5	<0.5	<0.3	<0.3	<0.3	<0.5	<0.5	<0.5	<0.5			0.31	0.44	<0.5			
Cl^-	mg/L	1864	1865	2132	1869	1853	2270	1850	1890	1960	1920	1910	1860	1780	1820	2000	16590	1790	1770	1790	
Br^-	mg/L	4.9	4.9	5.7	6.3	5.6	7.1	5.9	6.0	6.0	6.1	5.47	5.37	5.1	5.2	5.53	46.18	5.08			
NO_3^-	mg/L	<0.5	1.8	<0.5	344	<0.5	<0.3	0.4	<0.3	0.6	<0.5	1.12	1.7	0.9	0.7	<0.3	3.24	<0.5			
$SO_4^=$	mg/L	112	118	118	193	183	266	126	129	134	132	125.59	126.52	115	116	136.8	1300	127.15	124.55	113	
HCO_3^-	mg/L	426	441	442	126	443	460	456	452	480	452	449	446	424	422	430	451	429	428	432	
Ca	mg/L	26	27	27	26	26	29	28	28	28	27	26.13	26.22	24	25	27.9	62	25.316	24.4	24	
K	mg/L	31	31	35	37	39	37	35	35	35	34	34.41	33.99	33	34	31.2	77	49.654	31.7	31	
Mg	mg/L	307	317	321	297	296	376	322	325	326	318	312.25	309.81	280	293	323	755	292.577	297	291	
Na	mg/L	814	810	965	728	849	954	754	771	797	771	782.74	778.81	751	753	936	9950	790.563	766	776	
S	mg/L	43	46	46	51	50	92	44	45	46	45	43.36	43.89	41	41	49.1	429	47.295	42.9	43	
Si	mg/L	4.6	4.8	4.5	8.2	7.8	6.8	7.9	7.6	7.6	8.1	7.9	7.4			6.603	6.3	6.5	7.2	6.9	
Reactive Si	mg/L																				
Sr	mg/L				4.2	3.1													3	3	
TDS	mg/L	3579	3609	4040	3276	3690	4391	3571	3630	3758	3655	3640	3581	3409	3464	3884	29185	3504	3442	3458	
δ O18	‰ rel SMOW	-2.57	-2.76	-2.68	-2.87	-2.86	-2.75	-2.85	-2.79	-2.80	-2.77	-2.76	-2.90	-2.77	-2.74	-2.67	-2.83	-2.83	-2.69	-2.86	
δD	‰ rel SMOW	-25.30	-25.00	-17.00	-16.90	-16.70	-15.20	-14.70	-18.10	-17.40	-16.90	-13.50	-14.00	-13.20	-13.90	-13.90	-16.10	-15.80	-16.90	-16.40	

Table 9. Monitoring results for Lake Colac

Date		8/01/07	22/01/07	5/02/2007	19/02/07	5/03/07	19/03/07	2/04/07	17/04/07	7/05/07	21/05/07	4/06/07	18/06/07	2/07/07	14/07/07	30/07/07	13/08/07	27/08/07	10/09/07	24/09/07	8/10/07
Field Values																					
E.C.	dS/m	12.2	12.1	11.5	14.8	13.8	17.3	18.8	20.2	17.6	13.3	14.8	15.76	14.0		14.8	11.18	12.91	12.57	12.77	
pH		8.79	8.75		8.8	9.1	9.17	9.63	9.47	8.31	8.8	8.34	8.32	8.24		8.21	8.08	7.59	8	8.22	
DO	%																				
Temp	celcius	14.6	17.4		22	18.7	18.3	17.3	17	16.1	14.5	9.1	8	10.1		10.9	9.2	14.6	14.8	15.6	
Analytical Values																					
pH		8.5	8.7	8.8	8.7	8.8	8.8	9.2	9.3	8.8	9.2	8.69	8.63	8.5	8.6	8.62	8.58	8.59	8.41	8.6	8.4
EC	dS/m	11.5	11.4	12.8	13	15	16	17	19	16	11	12.8	13.05	13	10	12.67	10.88	10.99	10.89	11.1	11.0
Alk (pH 4.5)	meq/L	9.3	8.8	9.9	10.2	10.6	11.1	11.9	12.5	10.7	7.9	9.676	9.442	9.1	8.0	8.833	7.41	8.13	7.889	7.9	7.5
Alk (pH 8.3)	meq/L	0.3	0.6	0.9	0.8	1.1	1.2	2.8	3.1	1.2	1.4	0.8032	0.6403	0.4	0.3	0.51	0.3239	0.5176	0.2835	0.6	0.3
F^-	mg/L	0.7	0.8	0.8	<0.5	<0.5	<1	<1	1.0	<1	<1	<1	<1			<1	<1	<1			
Cl^-	mg/L	3603	3623	4162	4385	4846	5390	5830	6560	5890	4010	4750	4710	4580	3980	4150	3560	3870	3730	3940	3810
Br^-	mg/L	9.0	8.8	10	12	13	15	17	19	17	11	12.53	11.81	11	9	10.5	8.89	10.27			10.8
NO_3^-	mg/L	1.0	1.0	<0.5	1.3	<0.5	2.5	1	<1	<1	2	1.65	8.38	2.1	10.8	2.24	<1	<1			3.9
$SO_4^=$	mg/L	117	114	129	155	154	187	190	197	175	91	133.52	137.77	130	120	134	123.99	135.45	141.88	141	138
HCO_3^-	mg/L	567	538	605	620	646	679	726	763	651	484	590	576	555	489	539	452	496	481	482	455
Ca	mg/L	83	74	81	78	76	77	79	83	84	56	72.27	74.08	71	69	73.8	65	68.408	73.472	75	74
K	mg/L	45	44	50	61	65	66	69	73	66	49	52.69	56.69	53	51	44.2	39.2	54.824	48.877	50	48
Mg	mg/L	277	276	314	326	357	416	458	504	431	281	379.81	380.03	335	289	332	280	283.83	307.443	306	297
Na	mg/L	1993	1980	2252	2390	2710	2861	3161	3475	3096	2099	2539.67	2560	2380	2040	2310	1970	2069.772	2160	2160	2010
S	mg/L	46	45	50	57	57	64	66	68	60	32	48.73	52.79	50	45	49	45.2	49.654	50.148	52	50
Si	mg/L	<0.5	<0.5	<0.5	<1	<1	<1	<1	<1	<1	<1	<0.5	<0.5			<1	<1	<1	<0.5	<0.5	<1
Reactive Si	mg/L																				0.6
Sr	mg/L				3.4	2.6													2.1	2.1	
TDS	mg/L	6685	6647	7594	8014	8854	9677	10513	11655	10392	7070	8518	8495	8104	7038	7583	6490	6978	6943	7155	6832
δ O18	‰ rel SMOW	5.54	5.37	6.84	6.56	6.11	6.80	5.79	6.66	3.86	0.37	1.10	0.93	0.85	-0.28	-0.04	-0.35	0.25	0.77	1.44	
δD	‰ rel SMOW	28.90	33.30	40.60	42.60	41.80	40.70	36.70	39.80	27.90	9.50	15.60	13.50	14.40	6.60	8.00	7.50	8.90	12.20	15.40	

Table 10. Monitoring results for West Basin

Date		8/01/07	22/01/07	5/02/2007	19/02/07	5/03/07	19/03/07	2/04/07	17/04/07	7/05/07	21/05/07	4/06/07	18/06/07	2/07/07	14/07/07	30/07/07	13/08/07	27/08/07	10/09/07	24/09/07	8/10/07
Field Values																					
E.C.	dS/m	Off scale	Off scale	Off scale	Off scale	Off scale	Off scale	Off scale	Off scale	Off scale	Off scale	Off scale	Off scale	Off scale	Off scale	Off scale	Off scale	Off scale	Off scale	Off scale	Off scale
pH		8.83	8.8		8.5	8.79	8.88	8.95	8.81	8.17	8.19	8.21	8.1	8.18		8.15	8.16	8.17	8.14	8.05	
DO	%																				
Temp	celcius	19.3	20.1		24.4	21.8	22.1	20.9	18.2	16.2	14.9	12.7	11.7	11.7		11.8	12.4	13.8	13.7	15	
Analytical Values																					
pH		8.7	8.8	8.7	8.7	8.7	8.7	8.7	8.7	8.8	8.8	8.69	8.73	8.7	8.8	8.73	8.68	8.71	8.69	8.67	8.7
EC	dS/m	123	119	123	121	121	126	126	126	122	122	106.7	105.1	111	100	107.7	107.6	94.4	92.1	87.5	93.0
Alk (pH 4.5)	meq/L	28.8	27.9	28.8	29.4	28.4	28.5	28.6	28.6	28.0	27.8	27.51	27.03	27.4	23.9	27.01	26.94	26.79	27.01	26.86	26.8
Alk (pH 8.3)	meq/L	5.3	5.3	5.4	5.1	4.6	4.7	4.8	4.8	5.0	5.0	4.979	4.747	4.9	4.2	4.84	4.33	5.317	5.334	5.499	5.4
F$^-$	mg/L	<5	<5	<5	<10	<10	<10	<10	<10	<5	<5	<10	<10			<10	<10	<5			
Cl$^-$	mg/L	58600	56300	58500	58060	58870	60100	59700	60300	61500	61500	59000	57800	57300	52400	58100	57400	58400	60500	60000	58700
Br$^-$	mg/L	162	152	165	167	172	192	191	195	219	193	170.67	171.64	157	135	164.73	162.38	166.82			171
NO$_3^-$	mg/L	8	32	9	<10	11	11	<10	<10	9	<5	<10	<10	5	13	16.25	5.39	<5			37
SO$_4^=$	mg/L	1760	1640	1780	1750	1770	2020	2030	2050	2000	2020	1800	1800	1620	1510	1880	1850	1836.47	1860	1830	1850
HCO$_3^-$	mg/L	1759	1700	1757	1793	1732	1739	1746	1742	1705	1695	1678	1649	1672	1460	1648	1643	1634	1648	1638	1634
Ca	mg/L	12	10	14	17	17	19	19	20	20	19	20.94	20.35	18	16	19.5	18.9	14.614	19.129	18.4775	20
K	mg/L	845	820	861	973	984	975	977	983	985	985	1010	1020	1030	931	906.9	876	916.279	1020	1010	960
Mg	mg/L	1845	1777	1833	1700	1670	1810	1818	1821	1817	1811	1900	1890	1760	1510	1810	1730	1757.03	1780	1760	1740
Na	mg/L	35210	34160	35210	35300	35300	35088	35245	35399	35972	35923	36500	36200	36000	31000	36600	35300	33003	36800	36400	34500
S	mg/L	610	590	620	620	630	678	683	684	679	681	680.91	686.71	644	555	669	644.6	669.484	662.085	656.345	643
Si	mg/L	<2	<2	<2	<5	<5	<1	<10	<10	<10	<10	<5	<5			<10	18.328	<5	<5	<5	<10
Reactive Si	mg/L																				0.5
Sr	mg/L				11	<5													<5	<5	
TDS	mg/L	100032	96408	99956	99593	100343	101751	101534	102315	103999	103953	101909	100379	99400	88827	100964	98818	97562	103627	102657	99404
δ O18	‰ rel SMOW	4.59	4.34	4.82	4.52	4.60	4.88	4.95	4.83	4.76	4.62	4.17	4.07	4.31	2.90	3.73	3.58	3.60	3.67	3.63	
δD	‰ rel SMOW	14.10	13.40	17.20	24.50	25.30	24.70	28.10	24.40	25.60	25.10	23.00	22.00	24.80	18.20	20.60	19.20	18.90	19.70	21.40	

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