GROUNDWATER-SURFACE WATER INTERACTION OF THE RED ROCK COMPLEX, VICTORIA, AUSTRALIA

Lake Coragulac 2003

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ABSTRACT

This work examines the groundwater-surface water interactions of the Red Rock Complex, in the Volcanic Plains of Western Victoria. Until recent years, the series of lakes within the Red Rock Complex had significant social and environmental value and supported a rich ecology. Between 1998-2000, the lake levels declined and have not since returned. The cause of this drying has been of considerable contention within the community, as it occurred during an extended period of substantial groundwater development and a nationally recognized drought episode.

Precipitation data during the recent dry period shows no significant deviation from historical 20th century trends and there is no confirmed evidence of the lakes having previously dried up, suggesting that the lowering of the water table is primarily due to the increasing groundwater extraction since 1970. Furthermore, recent drilling through the bed of one lake (L. Purdiguluc) confirmed a scoriaceous basaltic lithology, which is extended over much of the local surface geology. This comprises the upper unit of the Newer Volcanics unconfined aquifer, which is tapped by numerous irrigation bores. Previous observations of the salinity of the water in the lakes, 1970-1991, showed a higher salinity (10 000-35 000 mg/l TDS) than the surrounding groundwater indicating that the lakes were principally of the discharge type. The water table is now about 2.5 m below the bed of the lakes, indicating that there has been a net fall in the water table by approximately 5 m.

Preliminary hydrological budgets for the 1960s, prior to the current phase of groundwater development, illustrate the previous contribution of the groundwater to the lakes. The consequent groundwater extraction has reversed this contribution, and thereby converting the Red Rock lakes to an area of recharge and causing some inflow from the large saline Lake Corangamite to the west.

ACKNOWLEDGEMENTS

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CHAPTER 1: INTRODUCTION

1.1 General

Irrigated agriculture is the greatest consumer of Australia's freshwater resources from lakes, rivers and aquifers (National land and Water Resources Audit (NLWRA) 2002). Within the last two decades this consumption has dramatically increased from 14 600 GL in 1983-84 to 23 300 GL in 1996-97 (NLWRA 2001). Of this a growing proportion is being derived from groundwater, which have resulted in environmental impacts. In a number of regions of Victoria, wetlands, lakes and their associated ecosystems have become degraded along with this rapidly increasing trend of groundwater extraction (State of Environment (SOE) 2002).

A decline in a lake level can represent changes in groundwater behavior and is often first observed by the community, although a time lag may occur between the groundwater behavior and observed lake response. Where these lake waters have declined in quality and quantity, there is a growing conflict over economic versus environmental/aesthetic value of groundwater-surface water systems. Management plans are playing an important role in tackling these issues.

This condition is further complicated in the study area (Figure 1.3) in the Western District of Victoria, as there are conflicting views about whether over extraction of groundwater, or reduced natural recharge, has been the primary cause of the decreasing levels of the groundwater-surface water system. Until this cause is correctly identified and quantified, the production and implementation of management plans lacks the rigor needed for insuring sustainability of the groundwater resource.

An introduction to the concepts of groundwater-surface water interaction, recharge and sustainability is presented in the following sub-sections. The remainder of this chapter introduces the study which includes location, problem, objectives and previous investigations.

1.1.1 Groundwater-surface water interaction

Groundwater –surface water interaction of lakes occurs where there is no impermeable layer beneath the lake to inhibit flow. This interaction can determine where lakes occur, influence their hydrology, hydrochemistry, and ecology. In the Volcanic Plains of Western Victoria there are numerous lakes, varying in size and water connection.

Groundwater interactions with lakes are influenced by the height of the water table relative to the lake; ratio of horizontal to vertical aquifer hydraulic conductivity; the width and the depth of the lake relative to the aquifer thickness; the net recharge to the lake; the presence of high hydraulic conductivity units down gradient of the lake; the existence of variable water density systems; and whether there is a surface stream entering or leaving the lake (Winter 1978).

Born et al. (1979) characterised groundwater - lake relationships as 'discharge', 'recharge' or 'through-flow', based on the possible configurations of groundwater flow systems around lakes (Figure 1.1). These categorizations allow for more strategic planning and management of lakes, however significant changes to the groundwater system will cause these relationships to alter (Born et al. 1979).

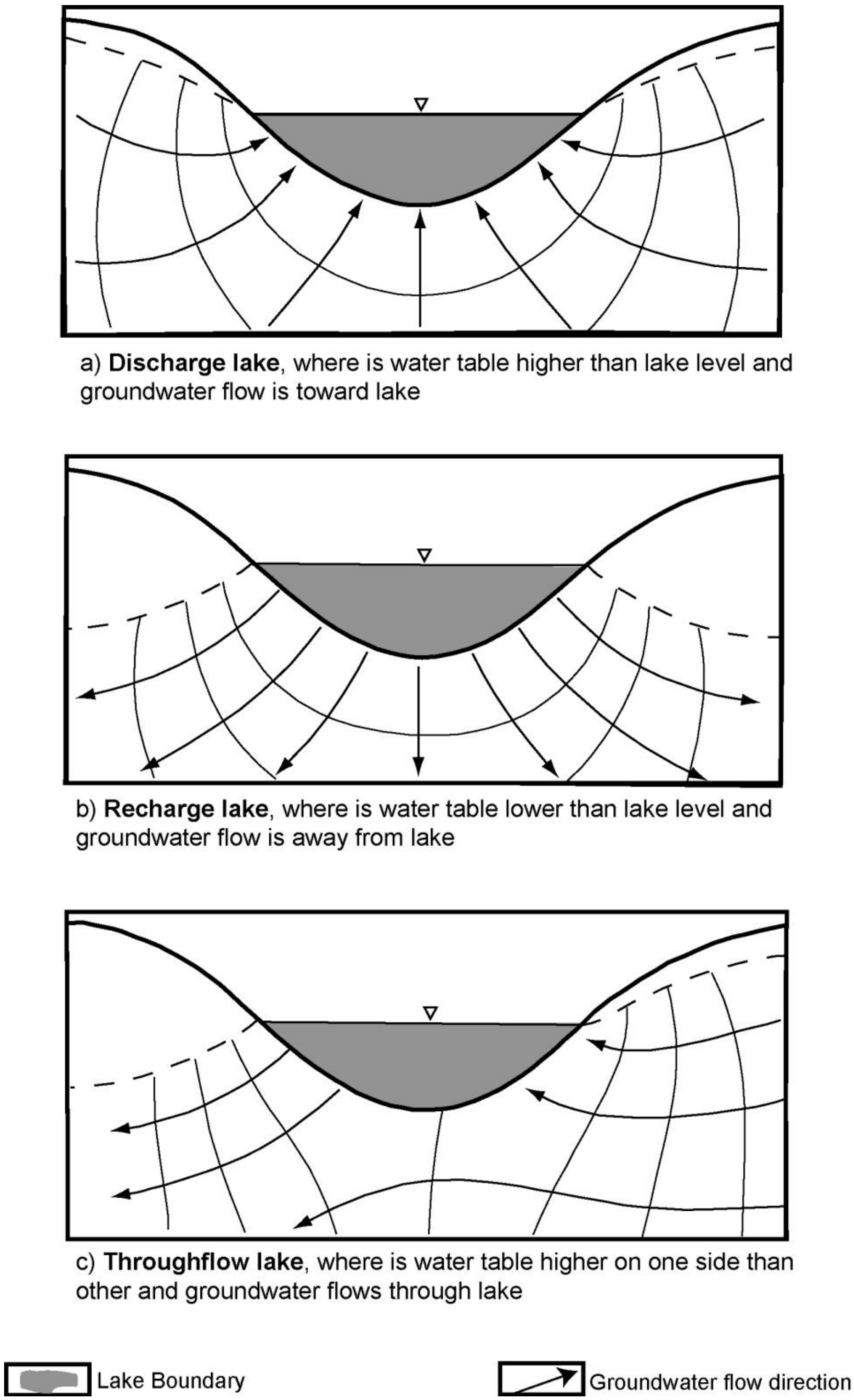

Figure 1.1: The configurations of groundwater flow systems around lakes; a) recharge, b) discharge, c) throughflow, after Born et al. (1979).

1.1.2 Recharge

Recharge may be derived from both natural and artificial sources. Precipitation naturally recharges the underlying aquifer by diffuse mechanisms or from streams, whereas irrigation return or dams are artificial sources. The quantity of precipitation that infiltrates through to the aquifer is dependant upon the surface/subsurface geology and its seasonal occurrence.

As with the case of the study area, the amount of water that recharges an unconfined aquifer is determined by 3 factors: (1) the amount of precipitation that is not lost by evapotranspiration (2) the vertical hydraulic conductivity (3) transmissivity and hydraulic gradient of the aquifer.

The natural recharge to an undeveloped aquifer may be estimated by a water-budget analysis of the recharge area, where the 'input' and 'output' components are identified (Fetter, 1988):

Recharge = Inputs – Outputs (Equation 1.1)

Where;

Inputs = precipitation + surface water inflow + groundwater inflow

and Outputs = evapotranspiration + surface water outflow + groundwater outflow

Where there is development of an aquifer, the extraction volumes must be accounted for in the 'Outputs'.

1.1.3 Sustainability and its threats in the study region

The concept of sustainability includes the preservation of both the quantity and quality of the groundwater for future generations, whilst ensuring that it is used for development and the environment. Indications of an unsustainable system include a decline in the interacting surface water levels, and declines in groundwater quality.
In the study area, over extraction and active saline intrusion are two major threats to groundwater sustainability (Nolan ITU 2001; Southern Rural Water (SRW) 2001b).

Over extraction from the aquifer

The term 'over extraction' refers to the rate of extraction relative to recharge. When extraction is greater than the potential recharge, over development of the aquifer occurs. In high producing agricultural regions with reliance on groundwater, the threat of over extraction is high if the groundwater system is not understood and managed appropriately.

The assignment of a Permissible Annual Volume (PAV) or 'safe yield' is a primary and widely used management limit for potentially over-developed groundwater systems. The purpose of the PAV is to obtain a balance between the groundwater extracted and the recharge for a given area, by restriction and allocation of extraction amounts. Ideally the PAV should be calculated by considering the following components of the hydrologic budget (Hiscock et al. 2002);

- Annual precipitation
- Evapotranspiration
- Aquifer recharge
- Runoff
- Surface water outflows and inflows
- Use (extraction)

In the study area, many of these parameters are difficult to quantify, and a simple 'recharge estimation method' based on the precipitation was used to estimate the PAV (Warrion Groundwater Supply Protection Area Consultative Committee (WGSPACC) 2002). However this type of estimate does not consider groundwater dependent ecosystems or the impact of groundwater extraction on baseflows associated with surface waters. (SOE, 2001).

Saline Intrusion

Under natural conditions a salt water wedge will develop in an aquifer adjacent to a saline lake due to a density difference between the saline and fresh groundwater (Figure 1.2 (a)). Pumping of groundwater from an irrigation bore creates a localized cone of depression, where the reversed hydraulic gradient allows groundwater flow towards the point of extraction. Active saline intrusion occurs when this cone of depression develops in close proximity to the saline lake or sea and induces the flow of saline water (Figure 1.2 (b)). If the pumping is prolonged the saline-freshwater interface will move towards the point of extraction and contaminate the aquifer.

The occurrence of active saline intrusion is characterized by an abnormally high salinity at the close of the irrigation season compared to the commencement.

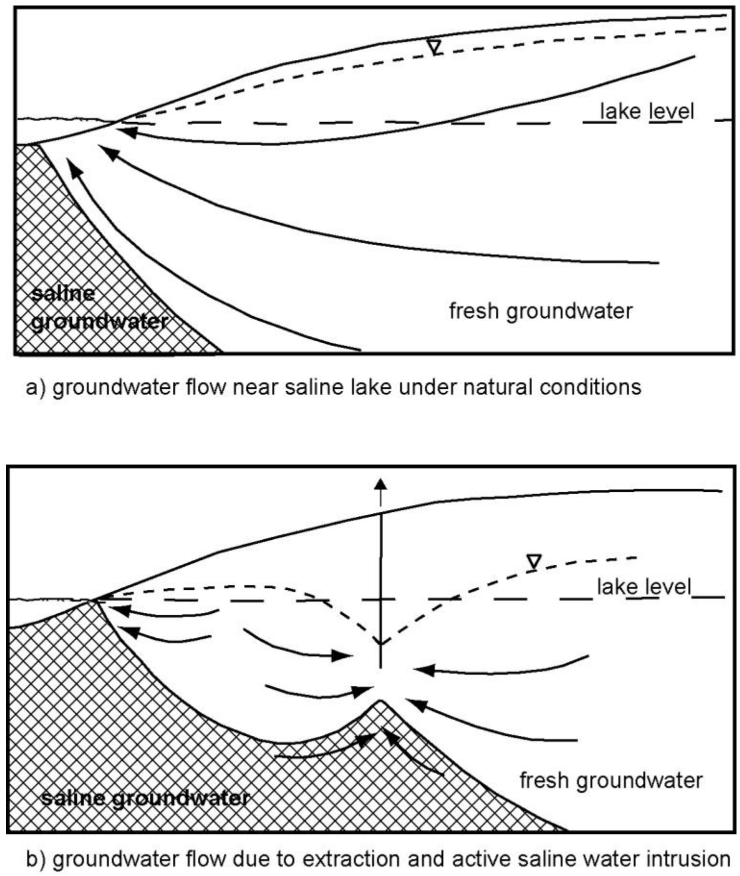

Figure 1.2: Active saline intrusion.
(a) natural conditions of groundwater flow near lakes including development of salt wedge (b) Active saline intrusion due to groundwater extraction nearby a saline lake, modified from SRW (2001b).

1.2 Location of study area

The Red Rock Complex is located 10 km north of Colac within the Volcanic Plains of Western Victoria. It lies west of Lake Corangamite and northeast of Lake Colac, within the Warrion Parish and nearby to the townships of Alvie, Cororooke and Coragulac. Four main lakes and a number of minor lakes occupy a series of depressions in the Red Rock Complex, including Lake Werowarp, Lake Gnalinegurk, Lake Purdiguluc and Lake Coragulac (Figure 1.3).

While this study focuses on the groundwater-surface water of the Red Rock Complex, a boarder study block has been selected, which includes the high producing agricultural areas surrounding the Red Rock Complex, Mt Alvie and Warrion Hill, a section of the south-eastern shore of Lake Corangamite and eleven State Observation Bores (SOBs). This study block has an approximate total surface area of 80 000 000 m^2 and is delineated by the following Australian Map Grid co-ordinates (Zone 54):

Northwest corner: 717159, 5768136
Northeast corner: 724550. 5768400
Southwest corner: 716794, 5757797
Southeast corner: 723700, 5758300

Geological coverage of the Corangamite region is provided by the Colac 1: 50 000 Map and Geological report (Tickell et al. 1991) and the Colac 1:250 000 map sheet (Edwards et al. 1996).

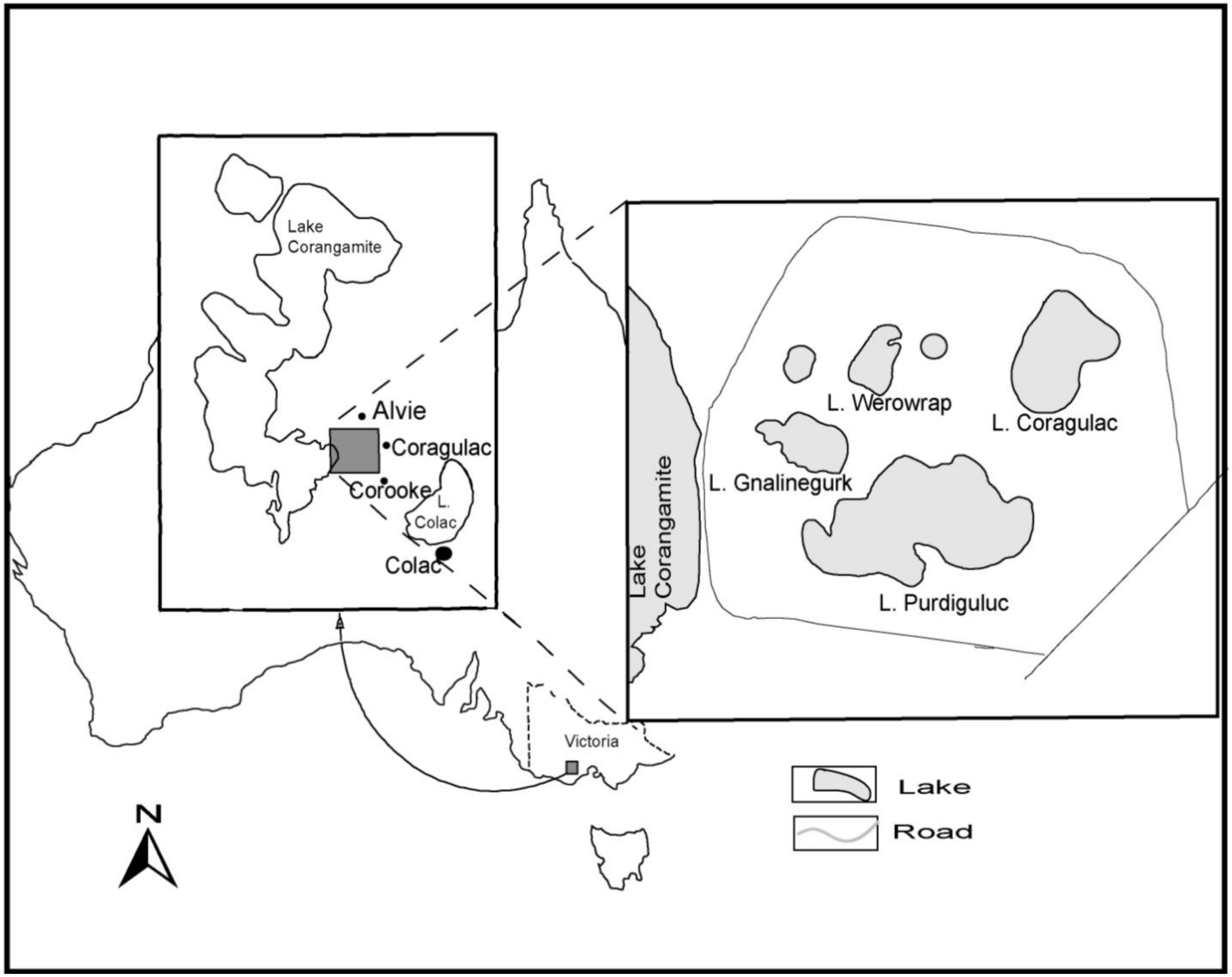

Figure 1.3: Locality map of the Red Rock Complex in Western Victoria, modified from Bayly (1969).

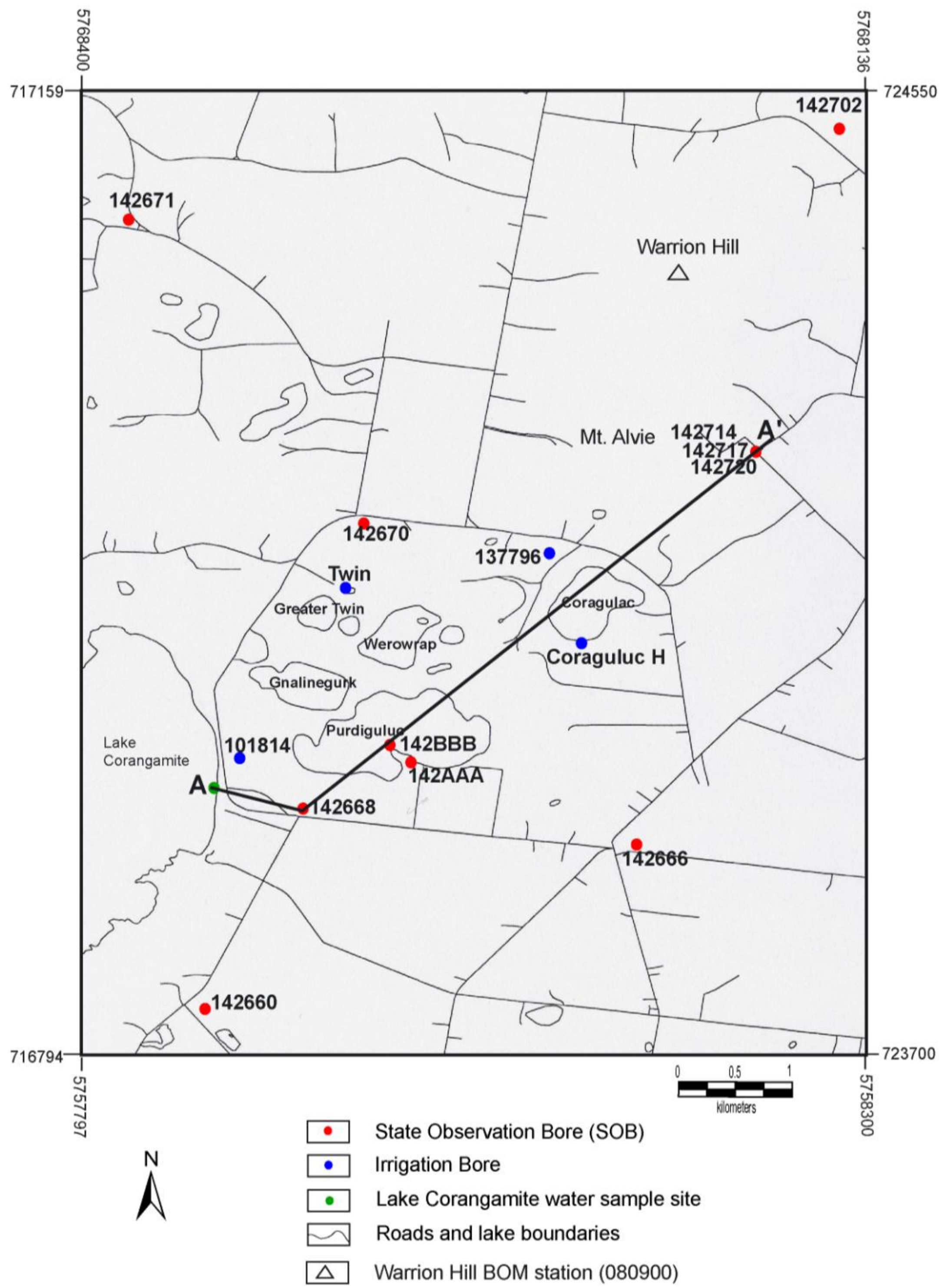

Figure 1.4: Delineation of study block indicating the locations of the SOBs and irrigation bores monitored and sampled. A-A', the hydrogeological transect.

1.3 The mystery of the decreasing lake levels

In contrast to other lakes in the Western District, all the Red Rock lakes have recently dried out for the first ever-reported period. Local anecdotal evidence suggests that the earliest significant reduction in lake levels were observed during 1998 (Figure1.6) and the aerial photo (Figure 2.4) indicates that they were dry by 2000. It is locally considered that the lakes dried out in the following approximate order: Lesser Twin, Greater Twin, Coragulac, Purdiguluc, Werowarp, Gnalinegurk and the Red Rock Tarn (pers. comm. Mahoney).

The preliminary alternative hypotheses for the cause of the drying of the Red Rock lakes are:

A. Decreased recharge to the shallow aquifer of the Newer Volcanics that is atypical to historical meteorological trends;

B. Increasing groundwater extraction, which has caused the local water table to fall below the lake beds.

The following figures show snapshots of the changing appearance of the Red Rock Complex over the past 100 years, facing south-southwest.

Figure 1.5: Early 1900's, indication of appearance of the Red Rock Complex, prior to removal of natural She-Oak vegetation.

Figure 1.6: 1998, the first signs of decreasing levels of Lake Werowrap.

Figure1.7: 2003, the present dry Lake Werowrap. This is drying is also apparent in the other lakes.

1.4 Objectives of the study

The study of the groundwater - surface water interaction of the Red Rock Complex was conducted from February to October 2003. It was designed to investigate the influence of hydrogeology, hydrology and hydrochemistry on the groundwater system and lakes. The endpoint of this study is the evaluation of the factors responsible for the decreasing lake levels and thereby assisting in the development of appropriate future management plans.

The objectives of this study are to determine:

- The physical and chemical relationship between groundwater and surface water in the Red Rock Complex;
- The cause of the recent drying of the lakes, by analysing meteorological data, and the pattern of groundwater usage and behavior nearby.

This study is being supported by the Department of Sustainability and Environment (DSE), which is directing the management of the groundwater of the Warrion Groundwater Supply Protection Area (WGSPA) (Appendix A) in conjunction with Southern Rural Water (SRW).

1.5 Previous geological, hydrological and environmental investigations

Due to the recent volcanic history of the Western District and reliance on groundwater for irrigation, the region has received attention from geologists, hydrogeologists, limnologists and environmentalists over the past century.

Skeats & James (1937) were the first to attempt an explanation for the formation of the 'stony rise' topography, which both underlies the pyroclastic deposits and outcrops in the study area. Ollier & Joyce (1964) discussed the volcanic physiography of the Western District plains, and noted the contrast between the plains and the Red Rock Complex.

Thompson (1971) carried out the first comprehensive study of the hydrogeology and hydrochemistry of the region, including the depositional sequence of the Red Rock Complex. This study hypothesized that groundwater was important in the transfer of dissolved salts throughout the region and that it also assisted in maintaining the salt balances in the Red Rock lakes, as halite precipitation had never been documented. Thompson (1971) was also the first to put a value on the recharge through the 'Later' Newer Volcanics in the Red Rock /Warrion Hill area. This 30% estimation was later used to quantify the Permissible Annual Volume (PAV) and consequently the allocation amounts in the Warrion Groundwater Supply Protection Area (WGSPA). Leach (1977) expanded on Thompson's (1971) geological findings and discussed the possibility of deposition of lake sediments and lunettes from the former extent of Lake Corangamite above and below the Red Rock Volcanic sequence.

Coram (1996) constructed a regional flow net, and water budgets for the larger regional lakes and showed that groundwater was the major contributor in the hydrological budgets of Lake Murdeuke. The regional groundwater flow direction in the study area was described as being from the northeast with a hydraulic gradient of 1.6×10^{-3}.

Blackham (1999) used computer modelling to simulate transient and steady state flow of the groundwater in the Corangamite region, and produced contour maps, colour flood plots of hydraulic head and groundwater flow vectors. The proposed groundwater divide through the Red Rock Complex and Warrion Hill is additional to the regional flow net of Coram (1996).

Jones et al. (2001) investigated the long-term change in lake levels of three volcanic crater lakes in Western region. Based on a water balance model simulating the historical decline, it was concluded that these lakes fell in response to long-term climate change, as precipitation/ evaporation is the major influence on the lake levels.

Bayly (1969) investigated the occurrence of biological species in the Red Rock surface waters and noted the high pH of the waters compared with other lakes in Western District. The study lakes were classified as being (sodium) chlorocarbonate saline waters.

The Warrion Parish first received environmental government attention in 1999, after 'sustainability concerns' were raised by farmers and residents. The threat of saline intrusion, especially along the corridor between Lake Corangamite and the Red Rock Complex, and the possible over development of groundwater resources prompted the production of the Nolan ITU (2001) Groundwater Technical Report and the Southern Rural Water (2001a) Groundwater Salinity Risks Report. Subsequent reports produced were SRW Groundwater Technical Report Warrion GMA (2001b); SRW (2002) 1st Annual Report for Warrion Groundwater management Plan; WGSPACC (2002) WGSPA Explanatory Notes; and SRW (2003) 2nd Annual Report for Warrion Groundwater management Plan. These all acknowledge the deficiency of the available information to resolve the sustainability concerns.

CHAPTER 2: PHYSICAL DESCRIPTION OF THE STUDY AREA

The Red Rock Complex groundwater flow system is part of the larger Otway Basin system. Since European settlement in c.1872 the study area has been a successful farming district, which locals attribute to the rich volcanic soils and high quality groundwater (Mahoney pers. comm.). The physical characteristics of the study area, including, geology, land-use, hydrology and climate, influence the extent of the groundwater-surface water interactions and set the scene for appraising the cause of the declining lake levels.

2.1 Geology

The study region lies within the northern margin of the Otway Sedimentary Basin, an east-west trough that developed as a result of the separation of the Australian and Antarctica plates during the Lower Cretaceous. The Otway Sedimentary Basin contains a thick succession of Mesozoic and Cainozoic sedimentary and volcanic rocks that reflect a succession of marine transgression and regressions related to subsidence and eustatic changes of sea level (Douglas & Ferguson 1988).

The following depositional sequence relates only to the study region and is adapted from the 1:250 000 Colac Geological Map & accompanying cross section and Warrion 5 borehole data (Appendix B) (Tickell et al. 1991). As this study focuses on the groundwater occurrences of the unconfined Quaternary Newer Volcanics aquifer, the geological history prior to the sedimentation of the

Gellibrand Marl, during the Tertiary, is only briefly described.

2.1.1 Pre-Quaternary Geology

Otway Group (Klp)

During the initial rifting phase of the Early Cretaceous, a thick sequence of fluviatile sediments accumulated on the Paleozoic bedrock. These Klp sediments largely consist of volcanogenic sandstone with minor amounts of silt, mudstone, shale and coal. The Otway Group of sediments outcrop in the Otway Ranges to the south east.

Demons Bluff Formation (Ted)

The Demons Bluff Formation is a late Eocene-mid Miocene marine deposition of carbonaceous and calcareous silt. It is locally sandy and clayey and contains abundant shelly fragments and foraminifera and is up to 70 m thick, according to Warrion 5 bore hole (Appendix B). This marine formation was deposited in a quiet offshore or lagoonal environment with limited circulation (Tickell et al.1991).

Gellibrand Marl (Tmi)

The Gellibrand Marl is a Late Eocene- Mid Miocene marine deposition, consisting of grey calcareous silt. It is up to 300 m thick and is commonly clayey, but may be sandy and shelly in parts. This unit was deposited during deep water during a marine transgression and may be up to 300 m thick (Thompson 1971). The Gellibrand Marl belongs to the Heytsbury Group, which is elsewhere represented by the Port Campbell Limestone and Moorabool Viaduct Formation. Tectonic events ended this marine transgression which was followed by a period of volcanic activity.

2.1.2 Quaternary Volcanology and Surface Geology

The surface geology and present-day lakes of the Red Rock Complex have been greatly influenced by the two phases of Quaternary volcanic activity (Figure 2.1). The Newer Volcanics lie directly on the Gellibrand Marl (Figure 2.2) and forms the Newer Volcanics aquifer. The schematic geological cross section along A-A' displays the relationships between the hydrostratigrahic units (Figure 2.2), and was constructed using drillers' logs of irrigation bores & SOBs (Appendix D) and the regional geological cross section (Tickell et al. 1991).

'Earlier' Newer Volcanics (Qvn, Qve)

The 'Earlier' Volcanics are of Lower Pliocene age with flows up to 30 m thick. "The lavas are partially weathered and consist of sheet-like bodies of olivine basalt" (Thompson 1971). The basalt is very vesicular and may contain a high proportion of calcite, which was derived from the underlying Gellibrand Marl. Unlike the 'Later' volcanic phase, these lavas erupted from fissures and vents without a significant build up of cones (Thompson 1971).

'Later' Newer Volcanics (Qvh, Qvs)

The 'Later' Newer Volcanics dominate the surface geology in the study block (Figure 2.1). Away from the Red Rock Complex, Mt Alvie and Warrion Hill area, the 'Later' Newer Volcanics are characterized by 'stony rise' basalt flows (Qvh). However, the surface geology of the study block is dominated by pyroclastic deposits (Qvs), which overlie the stony rise basalt (Qvh).

More specifically, there are 3 divisions of the surface geology of the Red Rock Complex, based on the 1:50 000 geological map (Tickell et al. 1991). These divisions are outlined in the following box, however for the remainder of this thesis they will collectively be referred to as pyroclastic deposits (Qvs).

Qvs1: scoria, lava spatter and minor agglutinated basalt

Qvs2: pyroclastic surge and fall deposits: ash and lapilli (tuff); including bombs, current-bedded ash, minor agglutinated basalt and breccia

Qvs3: pyroclastic fall deposits (minor surge deposits): ash and lapilli (tuff); including bombs and minor agglutinated basalt

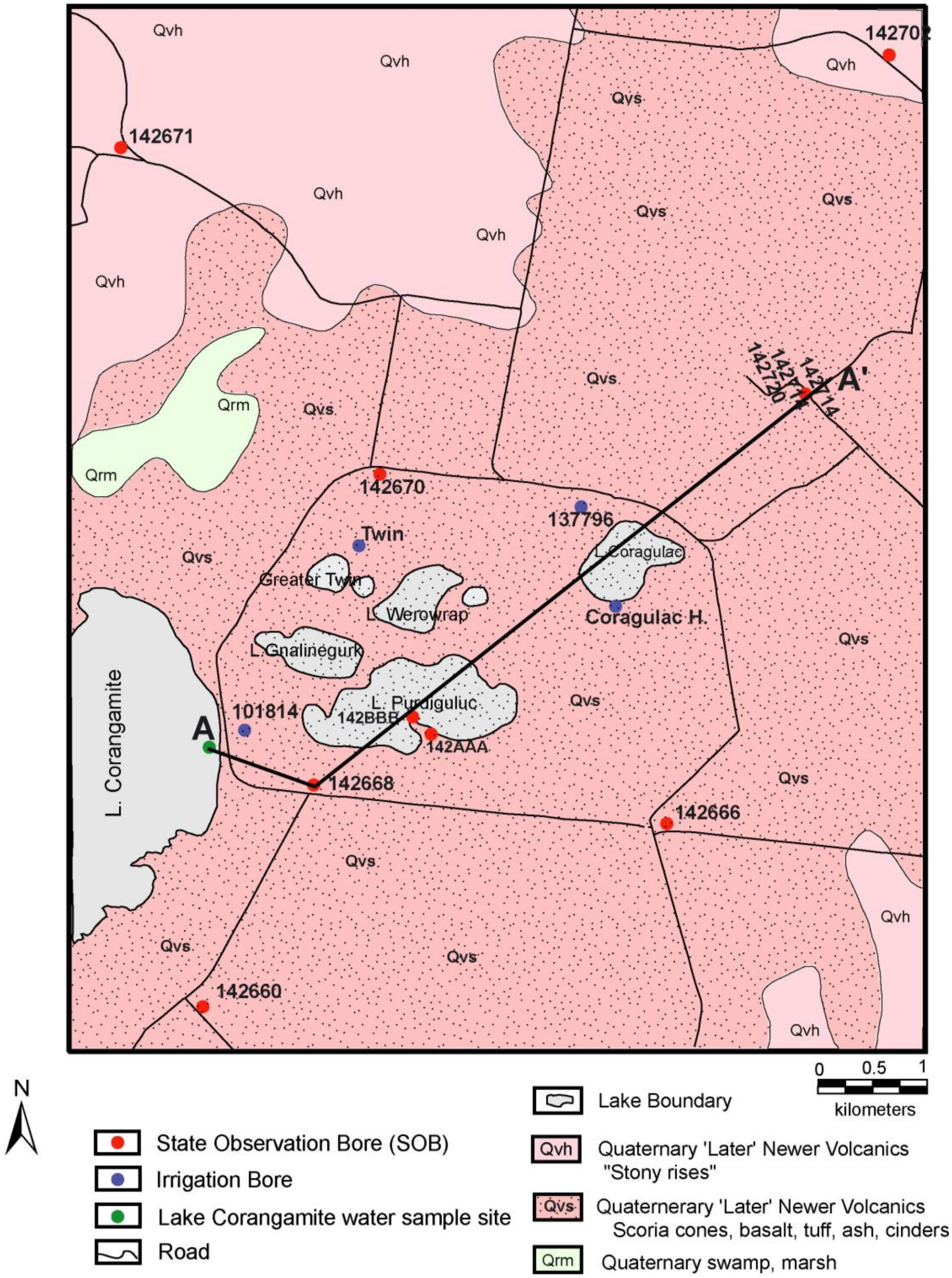

Figure 2.1: The surface geology of the study block, illustrating the pyroclastic dominance, modified from Edwards et al. (1996).

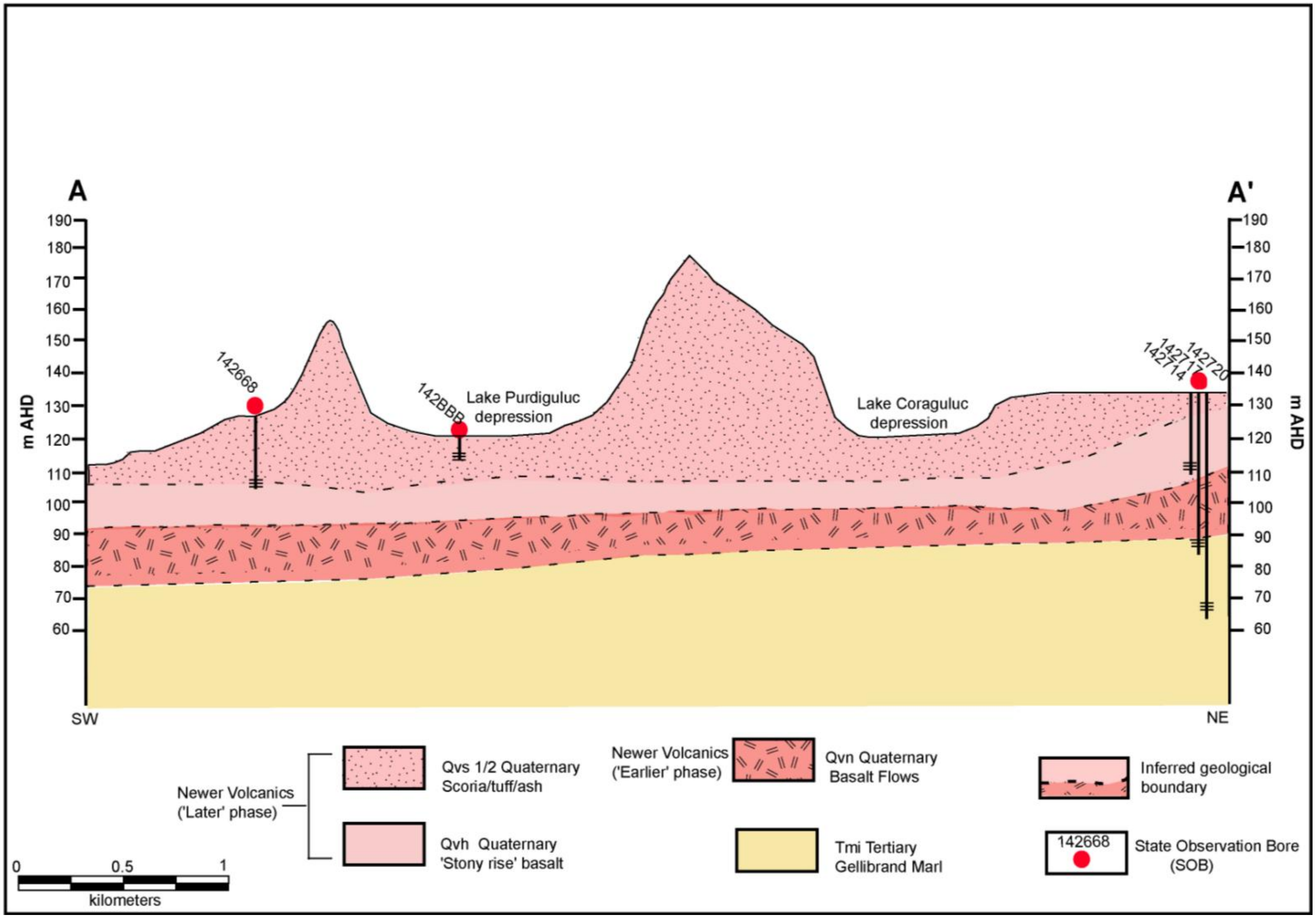

Figure 2.2: Schematic geological cross section from SW to NE along A-A', modified from Tickell et al. (1991) and Edwards et al. (1996)

Relative timing of the formation of the Red Rock Complex

The Red Rock Complex is part of the Newer Volcanic Plains of Western Victoria. Collectively the scoria cones and multiple eruption points form the Red Rock Complex and was given its name due to the characteristic red scoria deposits.

Radiocarbon dating on the soil carbonate indicates that the minimum age of the Red Rock complex is 7810+/-115 years B.P. (Tickell et al. 1991). Leach (1977) outlined four distinct stages involved in the formation of the Red Rock Complex

1. Eruption of the stony rise lavas (Qvh) immediately north of Red Rock Complex.

The 'stony rise' hummocky topography, with ridges and depressions, results from a solid outer crust forming on the lava flows and collapsing when the liquid lava in the interior drains away through a breach in the crust (Tickell et al. 1991).
The overlapping flows, marked by fresh and decomposed layers, suggest that there were periods of exposure and weathering and that the volcanicity was prolonged (Tickell et al. 1991). The basalt has 3 cm vesicles.

2. Withdrawal from the magma chamber causing the collapse of overlying strata.

3. Renewal of activity, with magma forced up the main fracture.

The interaction of the magma with groundwater-laden Tertiary sediments gave rise to the formation of the maar craters, and caused an explosive eruption due to the production of steam. Lake Coragulac, Purdiguluc, Gnalinegurk and Werowrap now lie within these craters. "The cuspate form of the maar lakes, and their peninsulas being composed of the underlying lava, indicates that each lake contains several eruption points with walls separating these mostly having being destroyed by the later eruptions" (Leach 1977).

The material ejected was mostly ash (finer than 2 mm), lapilli (2-64 mm) and beds of breccia (coarser than 64 mm). Volcanic bombs (up to 1m) are also found throughout the deposits. Ash was deposited by 2 mechanisms: (1) airfall, where ash rains down and forms planar bedded units (2) surge, where a cloud of ash and steam moves radially outwards from the maar due to the collapse of the eruption column and produces cross-bedding (Tickell et al. 1991). The Qvs2 unit contains both surge and airfall deposits, while Qv3 contains exclusively airfall deposits including scoria. The scoria was formed when the groundwater supply was locally depleted and the gas-charged lava fountained out (Tickell et al. 1991). This airfall unit (Qvs3) is mostly seen in the northern part of the Red Rock Complex, near Lake Coragulac. The Red Rock complex was constructed by cyclic events of phreatomagmatic and magmatic eruptions, depending on the groundwater availability (Tickell et al. 1991).

4. <u>The formation of the scoria cones</u>.

The Red Rock scoria cones represent at least 28 points of eruption and were formed due to magma being forced up small fractures between the main collapse boundary and the original eruption centre (Leach 1977). These cones, seen around Lake Werowrap are up to 70m high and comprise scoria, lava spatter and minor agglutinated basalt forming the Qvs1 unit. The scoria is 1-5 cm in size but decreases with increasing distance from the crater rims (Tickell et al. 1991). Most of the scoria is black but may be a reddish-brown due to oxidation caused by chemical conditions at the time of eruption (Tickell et al. 1991).

2.2 The lakes of the Western District

There is an extensive lake system within the Western District, many of which are listed on international treaties for the protection of wetlands and migratory birds' habitat, under the Ramsar convention, to which Australia has international obligations (Williams 1992).

2.2.1 Lakes within the Red Rock Complex

These study lakes lie within depressions in the Red Rock Complex from the maar type eruptions and production of the scoria cones. They are of irregular shape due to the interference from adjacent maars or cones and because of coalesence (Timms 1992), and have varying salinities and chemical compositions which reflect their shallow depths and large surface areas (Walker 1972).

2.2.2 Lake Corangamite

Lake Corangamite is the largest permanent lake in continental Australia and the largest permanent saline lake in Australia (Williams 1992). Lake Corangamite was formed by the damming effects of lava flows blocking the pre-existing drainage system (Cas et al. 1993). Lake Corangamite's southeastern shore lies <100m to the west of the Red Rock Complex, is considered in this study due to the threat of active saline intrusion (Figure 1.2). The surface water level of Lake Corangamite has fluctuated over the recorded history.

The 'Woady Yaloak Diversion Scheme' was introduced in 1959, as high rainfall during 1951 to 1956 caused a substantial rise in the level of Lake Corangamite and other lakes nearby, and inundated thousands of hectares of surrounding land (Land Conservation Council (LCC) 1972). Under this scheme, 50% of the water that would naturally flow from the Woady Yaloak Creek into the lake is diverted and discharged into the Barwon River (Williams 1992). Prior to the diversion scheme, Lake Corangamite had a maximum height of 118.21 mAHD in October 1960. Presently Lake Corangamite has a surface level of 114 mAHD and increasingly high salinity levels have been recorded since the implementation of the diversion scheme (Williams 1992).

2.3 Regional Hydrology

The Western District region of lakes forms a basin of internal drainage, where the regional groundwater flow paths from the west, north and south terminate at the Lake Corangamite regional discharge area (Coram 1996). In the study area, the principal direction of regional groundwater flow is westward, towards Lake Corangamite.

2.4 Local Hydrogeology

Groundwater-surface water interactions in the Red Rock Complex are limited to the Newer Volcanics aquifer as the Gellibrand Marl aquitard restricts vertical flow. Discharge from the Newer Volcanic aquifer occurs locally in low-lying depressions, wetlands and lakes.

The Newer Volcanics aquifer, consisting of the ‘Earlier’ and ‘Later’ Newer Volcanic units, has a total thickness of 30 m (Warrion 5 borehole data, Appendix B) and an average saturated thickness of 20 m, according to 2003 water level monitoring. The aquifer is heterogeneous, as it is composed of pyroclastics (Qvs), ‘stony rises’ (Qvh) and at least 2 basaltic flows (Qvn). In addition, the hydraulic characteristics of the Newer Volcanic aquifer vary with the presence or absence of cooling joints, gas exsolution vesicles, and interflow soil or sand/gravel layers (Tickell et al. 1991).

Basaltic flows from the ‘Earlier’ Newer Volcanics are more weathered and less fractured. They are regarded as poor aquifer potential due to the infilling of fractures and joints by clays and the limited connection between the vesicles (Gill 1989). Hydraulic parameters have recorded ranges of: transmissivity - 10 to 700 m^2/day and hydraulic conductivity - $4x10^{-6}$ to $3x10^{-4}$ m/sec (Gill 1989).

In contrast, the ‘Later’ Newer Volcanics are considered a better aquifer potential, and have a recorded hydraulic conductivity (K) range of $1x\ 10^{-3}$ to 1×10^{-5} m/sec (Coram 1996). Three of the bores measured by Coram (1996) and are located in the study block, and have an average K of 1×10^{-5} m/sec.

In the 'Later' Newer Volcanics both the pyroclastics and 'stony rises' favour rapid recharge. The pyroclastic deposits are highly permeable and the 'stony rises' lack clay soil development associated with weathering and contain depressions, sink holes and cavens (Tickell et al. 1991). Thompson (1971) estimated that 30 % of precipitation recarges the Newer Volcanics aquifer. However this was based on an estimated average transmissivity (T) of 3 x 10^{-4} g/d/ft (4.5 x 10^{-6} m^2/day), a hydraulic gradient (I) of 0.0028 sourced from only two surveyed bores, with a resultant throughflow of 1.5 x 10^7 m^3/year. This throughflow correlates to ~30 % of the annual precipitation in the Red Rock Complex/Warrion Hill area (Thompson 1971). These values appear be over-estimated and will be discussed in Chapter 6.

Due to the rapid recharge, the higher quality groundwater occurs in the 'Later' Newer Volcanics, with an average Total Dissolved Solids (TDS) of 800 mg/L. The bore yield from the Newer Volcanics aquifer is locally variable due to preferential flow, however the highly vesicular zones and pyroclastic deposits have a potential bore yield of up to 60 l/sec (Edwards et al. 1996). The higher quality groundwater and higher yielding bores are closest to the scoria cones and used for irrigation. The lower quality and/or lower yielding bores further away from the eruption centers, are used for stock watering.

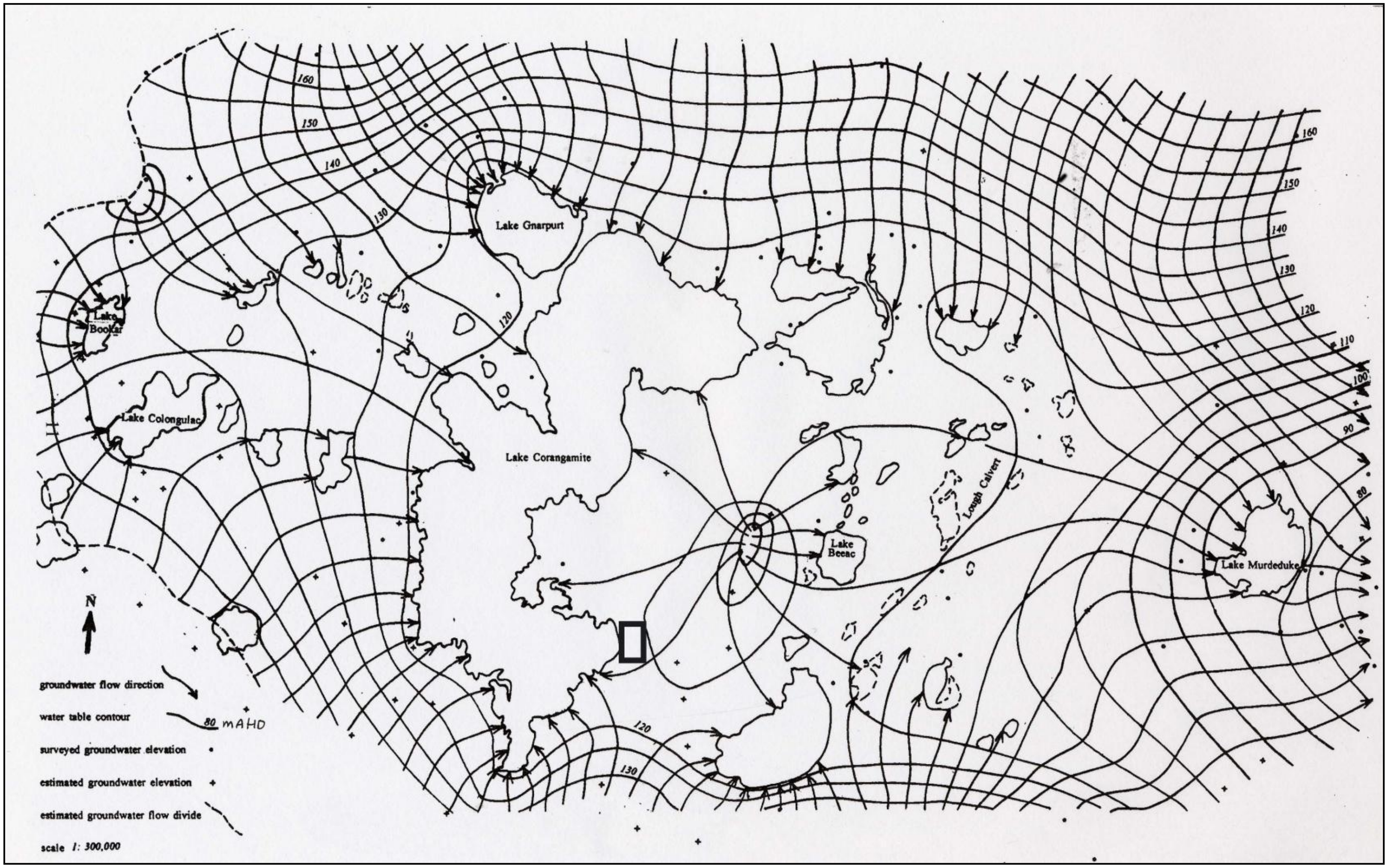

Figure 2.3: The regional groundwater flow paths in the Corangamite region, after Coram (1996).

The location of the study block is indicated by the bold rectangle.

2.5 Bore Network of Study Area

Within the study area, several observation bores were constructed in 2000 to be included as part of the State Observation Bore (SOB) network, and were initiated due to the concern of groundwater sustainability in the WGSPA (Appendix A). These bores were constructed by Sinclair Knights and Merz Pty Ltd (SKM), for the DSE and SRW, and their water levels are monitored monthly. Within the study block there are nine bores belonging to the SOB network, including a nest of three towards the north (Figure 1.4). As recently as August 2003, two additional SOBs (142 BBB & 142 AAA) were drilled beneath and adjacent to Lake Purdiguluc, and their construction is discussed in Chapter 4. Characteristics of all SOBs within the study block are given in Appendix E. SOBs in this network are identifiable by a ‘142’ identification number. Four irrigation bores (IB) within the study block were considered by this study.

2.6 Topography and Land Use

The Red Rock Complex physiographically contrasts the undulating form of the Western Plains. The Red Rock Complex summit is 210 mAHD, which is 90m above the Western District plains. The basalt, scoria and tuff/ash products from the volcanic eruptions at the Red Rock Complex, Mt Alvie and Warrion Hill produced the centrally steep topography in the study block.

Due to the steep slopes of the Red Rock Complex, land is only used for grazing and minor crops. Outside its boundary the gently sloping rich volcanic tuff/ash soils are ideal for cultivation. The primary products include potatoes, onions, and fodder crops for the prolific dairy industry. The frequency of ' central pivot' and 'large boom' irrigation systems in the landscape indicates the large scale of the agricultural practices. Figure 2.4 shows a 2000 aerial view of the Red Rock Complex, and surrounding area, including the dry Red Rock lakes (Figure 1.4). The intensive irrigation practices are clearly depicted by the contrasting darkened circles, which indicate areas irrigated using central pivots. This effect is only apparent in the Red Rock Complex/Warrion Hill area.

The local irrigation season is from late November to June, with the larger farms irrigating for up to 8 months in dry periods (Mathews pers. comm.). Many farms irrigate at night due to the high potential evaporation rate during the day light hours. The significance of these irrigation practices within the study area is discussed in Chapter 5.

The use of groundwater in the study area is not a recent phenomenon, evidenced by Skeats & James (1937) observation of the hundreds of windmills in the stony rises. At that time the water was used mainly for stock, domestic purposes and minor cultivation; however technology and demand has changed. Pumps on irrigation bores mean that higher yields are obtained, and subsequently the Newer Volcanics aquifer is given less time to recover. This creates regional cones of depressions centered on clusters of irrigation bores, and the likelihood of saline intrusion from Lake Corangamite is increased.

Figure 2.4: 2000 aerial view of the Red Rock Complex and surrounding agricultural area.
The dry lake beds and intensity of groundwater use in the Red Rock Complex/Warrion Hill area indicated by darken circles due to central pivot irrigation systems.

2.7 The inherent value of the Red Rock Complex

The Red Rock Complex is classified as a nature reserve. Visitors are attracted to the region by the volcanic features and advantageous lookout points. Prior to the drying of the Red Rock lakes, they supported a rich ecology and community-based recreational activities. The boat shed and jetty beside Lake Coragulac is an indication of the frequency of its previous use.

Environment Australia (1995) reports that there have been up to 510 Black Swans (*Cygnus atratus*) and 660 Eurasian Coots (*Fulica atra*) at Lake Coragulac. There is also an occasional active Silver Gull nesting colony at Lake Werowarp.

The Corangamite Water Skink (*Eulamprus tympanum marieae*) inhabits pockets in the study region. This skink is listed as 'endangered' under the Environment Protection and Biodiversity Conservation Act, 1999 and is 'critically endangered' according to Department of Natural Resources and Environment (1995). Lake Coragulac and Gnalinegurk are 2 of only 29 sites in the region where the Corangamite Water Skink has been found (Robertson & Peterson 2002).

The Red Rock lakes have a unique ecology compared to other Western District lakes (Timms 1983). There is now added concern that due to the length of time that the lakes have been dry, some/many species will be become extinct because the eggs of most species of planktonic crustaceans and csysts can only survive 7-11 years of dryness (Timms pers. comm.). This may cause ecosystems to become stressed and biodiversity to be lost.

2.8 Climate

The Western District of Victoria experiences a temperate sub-humid climate, with warm dry summers and cool wet winters (WGSPACC 2002). Temperature averages (1982-2002) from the Weearoinah temperature station (90083), indicate that July is the coldest month, with an average daily temperature of 11.44^{o}C, and February the hottest with a daily average of 25.78^{o}C (Bureau of Meteorology (BO M) 2003).

Highest precipitation occurs between April and October, with an average annual rainfall of 560.64 mm/yr (1887-2002) at the Warrion rainfall station (080900) (Appendix F). The greatest evaporation occurs between December and March, with an average annual potential evaporation of 1328.4 mm/yr (1969-2002) recorded at the Wurdiboluc Reservoir meteorological station (87126), 40 km east of Colac (BOM 2003). In general, potential evaporation exceeds precipitation for most of the year, except for the months June to August (Figure 2.6). The implications of this climate on aquifer recharge are discussed in Chapter 4.

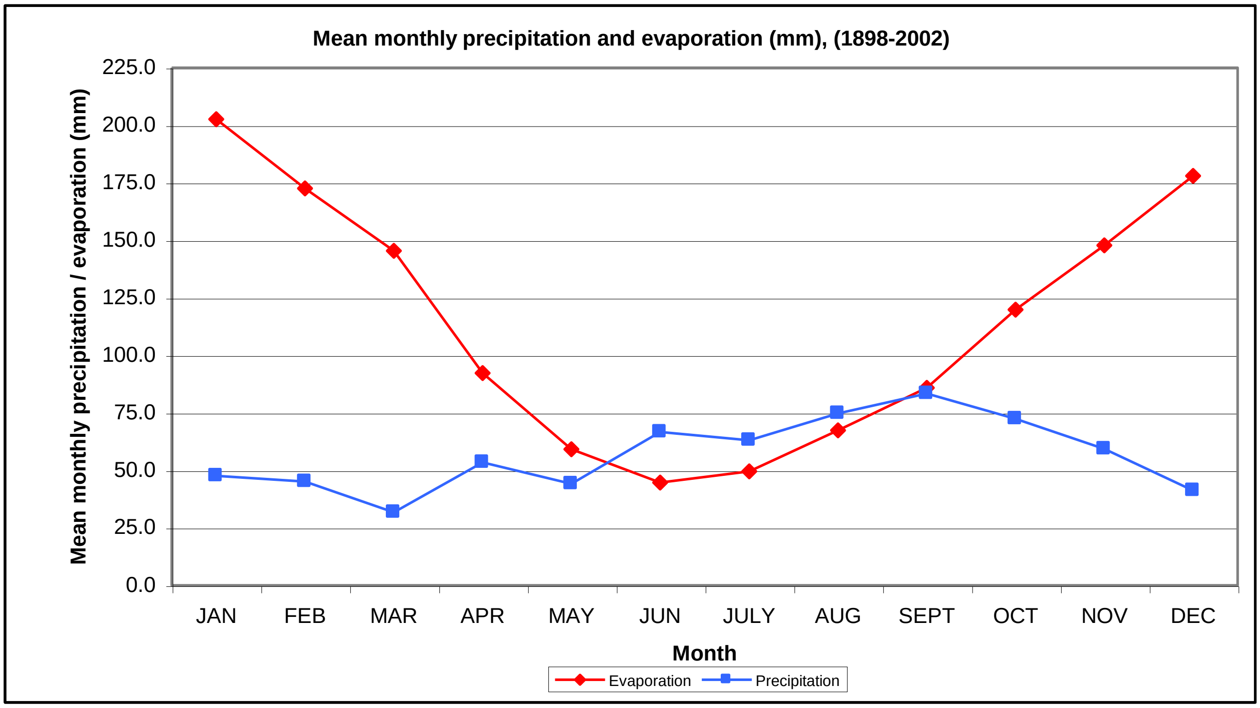

Figure 2.5: Mean monthly Pan Evaporation (red) and precipitation (blue).
For the period 1990 to 2002 from the BOM sites 87126 and 080900 respectively.

CHAPTER 3: METHODOLOGY AND RESULTS

Assessing the physical and chemical relationship between the groundwater and surface water and the cause of the decreased surface water levels required a multi-pronged approach in the methodology. This included; analysing past and present climate trends, interviewing residents and farmers in the neighborhood of the lakes for their recollections of lake and irrigation bore behavior; examining growth of change of the number of irrigation bores and potential extraction volumes; drilling of SOBs; examination of hydrographs; measurement of SOB water levels; sampling of groundwater from SOBs and irrigation bores for chemical analysis.

3.1 Construction of additional State Observation Bores

The DSE contracted the construction of six additional SOBs to SKM. The approximate location of these bores within and nearby the lakes' beds was decided upon during a field trip (February 2003), and later confirmed by a hydrogeologist in consultation with representatives from the DSE. There was some delay between this confirmation and the field program due to wet weather restricting the accessibility. Consequently at the time of writing, only two of the six proposed SOBs had been completed. The nature of previous groundwater-surface water interactions at the other lake sites is inferred based on those from the Lake Purdiguluc site. Refer to Appendix C for the SOB construction details. Also, surveying of critical bore locations had not been completed, so only schematic representation of their locations is possible in this thesis.

These six new SOBs were considered vital in understanding the groundwater surface interactions occurring within the lakes' separately and as a whole. The objectives were the following:

- Obtain a lithological profile of the lake substrate
- Assess groundwater levels beneath the lake beds and approximate flow directions
- Take water samples to determine the hydrochemistry
- Establish permanent sites for future groundwater quality and quantity monitoring

3.2 Monitoring, Sampling and Analysis

Groundwater samples were collected from SOBs and IBs with screened intervals in the Quaternary Newer Volcanics aquifer, except 142720 which is screened in the Tertiary units. Water samples from nine SOBs, four IBs, and the surface water of Lake Corangamite (Figure 1.4) were collected during the first field round on 02.06.03-03.06.03. Water samples from the two new SOBs constructed in early August, were taken two weeks after construction to allow groundwater stabilisation. A second complete round of water samples from the same bores were collected on 06.10.03, to assess any changes in salinity over the winter period and since the end of the irrigation season. Samples were collected from the SOBs using a stainless steel bailer and after purging three litres of water, and from the IBs following several minutes of pumping.

Prior to sampling, depth to water readings in the SOBs were recorded using an electronic 'depth to water' meter and a ‘fox whistle’ for the October readings. For continuity these were recorded at the start of each month, between June and October 2003. The monthly water level readings from the SOBs are reported in Section 3.3, Table 1.

Field Parameters

Water samples were tested for pH, Redox potential (Eh), Electrical Conductivity (EC), dissolved oxygen (DO), and alkalinity (HCO_3). These parameters were only measured once per bore (except EC), because it was considered they would not significantly change during the study period. These parameters were measured within 24 hours to minimise alteration by degassing and oxygenation. The results of the field parameters are reported in Section 3.3. Table 2.

pH and Eh were measured using an Orion model 250 A meter, which includes an automatic temperature compensation (ACT) probe. The pH Ross Sure-Flow electrode was auto-calibrated relative to the pH 7 and pH 10 buffers, as existing data showed that this was the expected range for the pH. Eh was measured with an ORP platinum Ag/AgCl electrode and was standardized using the Orion ORP standard (Fe^{2+}/Fe^{3+}) with a redox potential of 220 mV at 20°C. Electrical conductivity (EC) was measured using the Orion Model 128 meter.

HCO_3 and DO were measured using a Hach digital titration kit. Samples for cation analysis were filtered using 0.45 um nitrate filter paper and then acidified with 2.00ml of HNO_3 (16N). The anion samples remained unfiltered and un-acidified.

Laboratory analysis

Major cations, Ca^{2+}, Mg^{2+}, Na^+ and K^+ were analysised by Inductively Coupled Plasma-mass Spectrometer (ICPOES) by Australian Laboratory Services Environmental (ALS), Clayton. Major anions, Cl^-, F^-, Br^-, $NO3^-$, $SO4^-$ were analysised by Monash University by Metrohm Ion Exchange Chromatography (IC). The stable isotopes of ^{18}O and ^{2}H were analysised at the Stable Isotope Laboratory, Monash University and reported relative to V-SMOW.

Major ion analyses of the new SOBs samples were conducted solely by ALS, and Fe^{2+} was also reported, however time restrictions prohibited isotope analysis. Results of the major ions and stables isotopes are reported in Section 3.3, Table 3.

3.3 Results of monitoring and chemical analysis

The following sections introduce the results of the SOB monitoring and water sampling program to allow for interpretation and analysis in Chapter 4.

3.3.1 SOB groundwater monitoring

The monthly (June-October, 2003) monitoring of the SOB water levels is presented in Table 4. The groundwater elevation measurements recorded during the study period were collated with the previous recordings by SKM to give a more expansive data set highlighted by the larger data points in the hydrographs (Figure 3.1).

The SOB hydrographs show no obvious decline in groundwater levels for the period 2000-2003, and the fluctuations represent seasonal changes to recharge and groundwater use. This suggests that the 2000-2003 groundwater system is steady state, however would be referred to as quasi-steady state as was previously transient. SOB 142660 and 142671 located with the stony rises, appear to be most sensitive to seasonal changes in recharge events. 142720 is the least sensitive, as its screened interval is within the underlying Gellibrand Marl unit (Appendix E).

The relative higher levels in 142660, 142671 and 142702 and the lower levels in 142668 and 142670 suggest that the local groundwater flows toward the Red Rock Complex from the northwest, northeast and southwest. A plan view of the water table (mAHD) in November 2002 (SRW 2002) is presented in Figure 3.2. The November, 2002 water levels represent the most recent groundwater flow system which was recharged by winter precipitation, without any significant groundwater extractions during the irrigation season.

The hydrogeological cross section A-A’, October 2003 (Figure 3.3), shows the water table approximately 3 m beneath the lakes. The water table is inferred to be higher underneath the pyroclastic mounds due to local runoff. The nested bores (142720,142717,142714) indicate an upward vertical hydraulic gradient.

Table 1: June-Oct SOB water level records (mAHD).

Bore ID	Total Bore Depth (m)	Date	Surface elevation (m AHD)	Measured Depth to water (m)	Reduced Groundwater elevation (mAHD)
142668	24	02.06.03	127.6	13.32	114.28
		07.07.03	127.6	12.91	114.69
		05.08.03	127.6	12.67	114.93
		02.09.03	127.6	12.34	115.26
		06.10.03	127.6	12.15	115.45
142670	19	02.06.03	125.3	9.125	116.175
		07.76.03	125.3	9.05	116.25
		05.08.03	125.3	8.91	116.39
		02.09.03	125.3	8.78	116.52
		06.10.03	125.3	8.56	116.74
142666	31	02.06.03	134.95	15.4	119.55
		07.07.03	134.95	15.31	119.64
		05.08.03	134.95	15.42	119.53
		02.09.03	134.95	15.3	119.65
		06.10.03	134.95	14.94	120.01
142702	31	03.06.03	143.83	22.65	121.18
		07.07.03	143.83	23.55	120.28
		05.08.03	143.83	22.47	121.36
		02.09.03	143.83	22.29	121.54
		06.10.03	143.83	22.05	121.78
142720	72	03.06.03	136.98	16.21	120.77
		07.07.03	136.98	16.28	120.7
		05.08.03	136.98	16.19	120.79
		02.09.03	136.98	16.16	120.82
		06.10.03	136.98	16.145	120.835
142717	52	03.06.03	137.22	16.63	120.59
		07.07.03	137.22	16.595	120.625
		05.08.03	137.22	16.55	120.67
		02.09.03	137.22	16.44	120.78
		06.10.03	137.22	16.35	120.87
142714	25	03.06.03	137.25	16.85	120.4
		07.07.03	137.25	16.8	120.45
		05.08.03	137.25	16.77	120.48
		02.09.03	137.25	16.69	120.56
		06.10.03	137.25	16.6	120.65
142671	19	03.06.03	134.46	8.75	125.71
		07.07.03	134.46	8.85	125.61
		05.08.03	134.46	8.13	126.33
		02.09.03	134.46	7.63	126.83
		06.10.03	134.46	7.36	127.1
142660	24	03.06.03	135.82	12.56	123.26
		07.07.03	135.82	12.56	123.26
		05.08.03	135.82	11.65	124.17
		02.09.03	135.82	9.64	126.18
		06.10.03	135.82	8.42	127.4
142AAA[1]	12	02.09.03	…	3.92	…
		06.10.03	…	3.76	…
142BBB[1]	7	02.09.03	…	2.08	…
		06.10.03	…	2.05	…

[1] These SOBs were constructed in August 2003, hence only two water level recordings

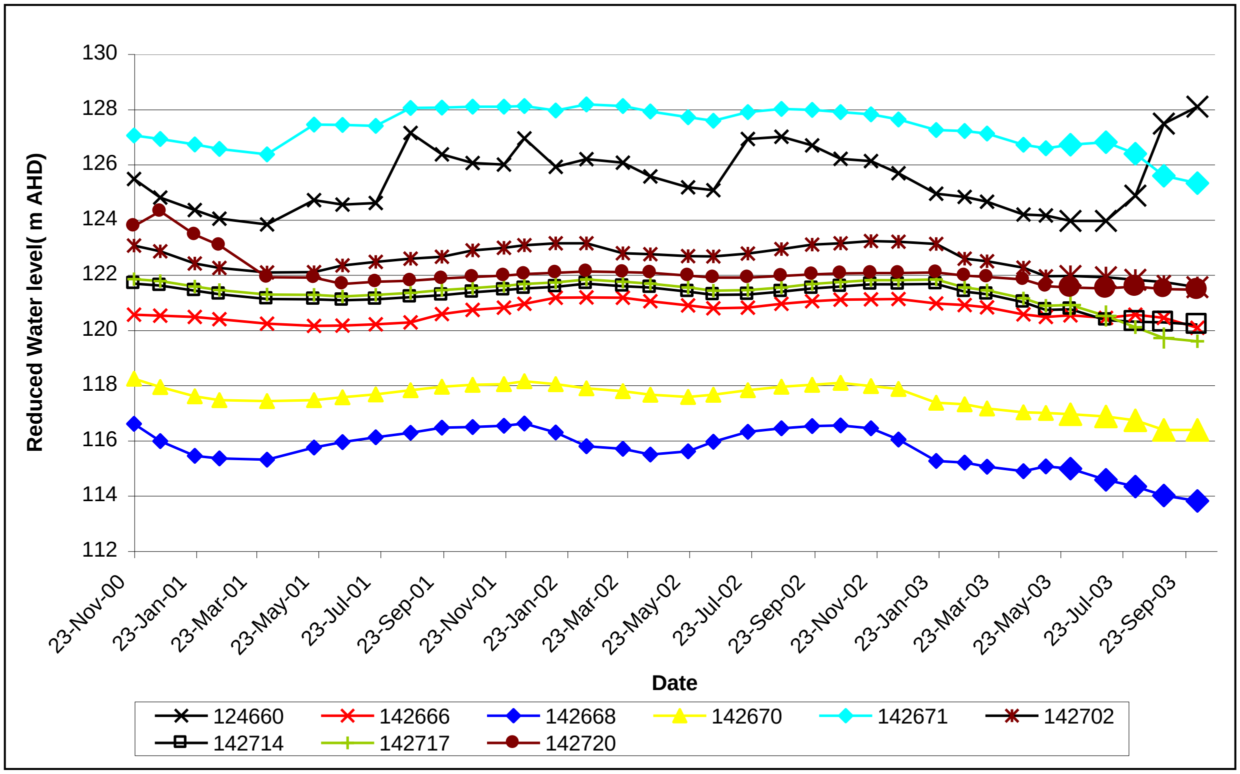

Figure 3.1: SOB hydrographs, 2000-2003, modified from SKM (2003)

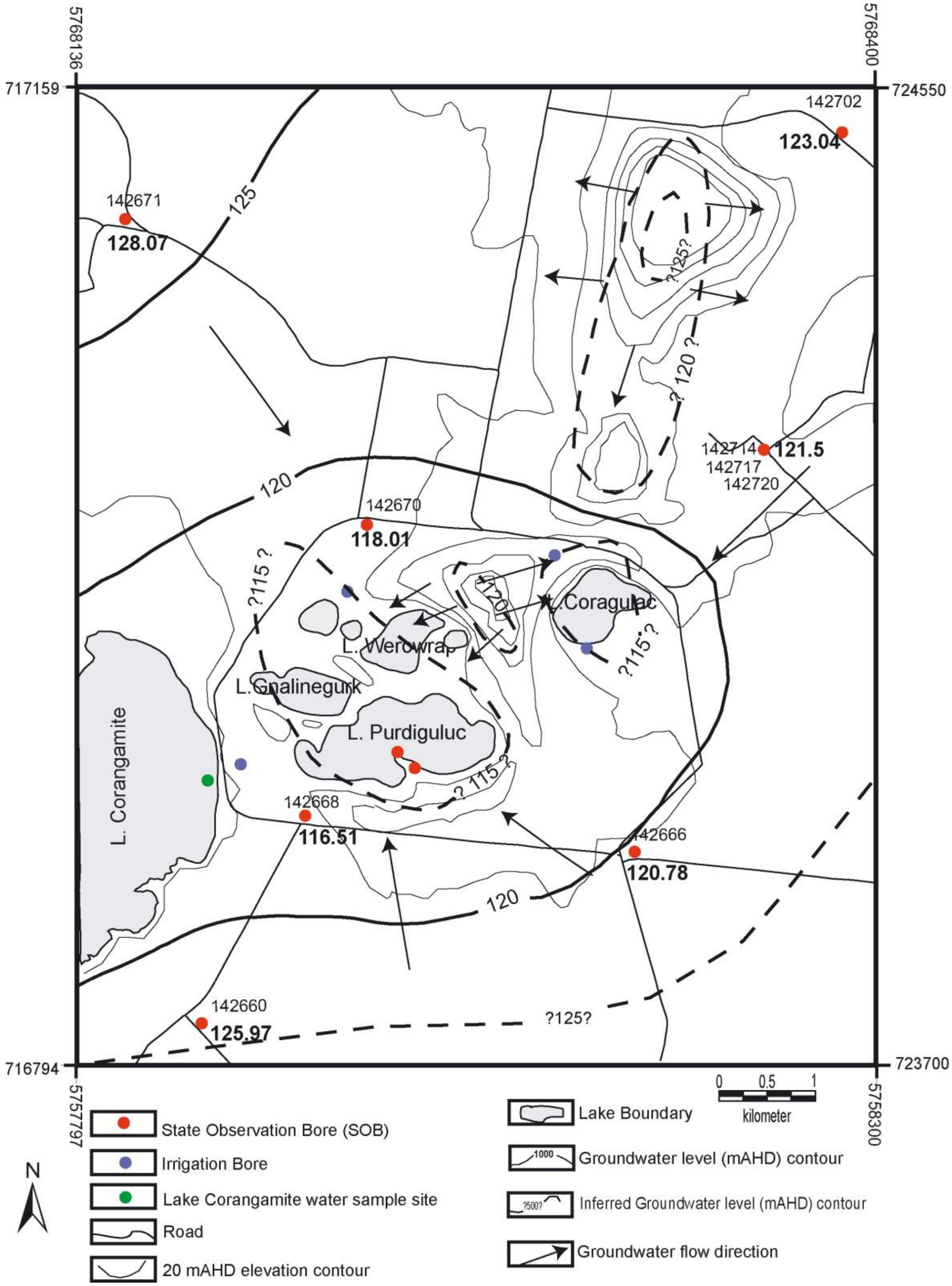

Figure 3.2: Local groundwater flow paths within the study block at the start of the 2002/2003 irrigation season.

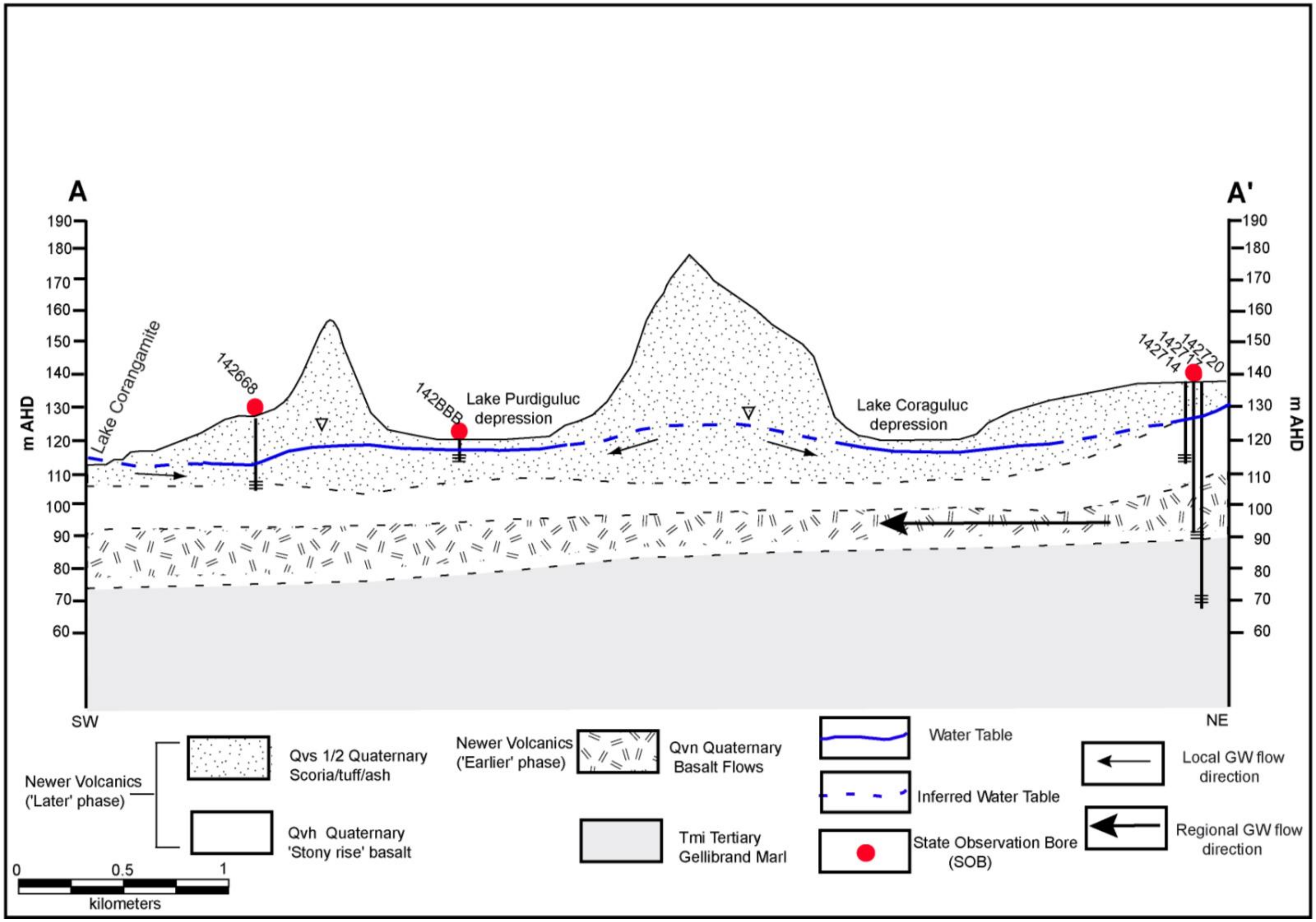

Figure 3.3: October (2003) hydrogeological cross-section along A-A', from SW to NE.

3.3.2 Field and Laboratory Chemistry

Field parameters

The field parameters are presented in Table 3. There is a general increasing trend of TDS (mg/L), EC and pH from the along the local flow path. The EC measurements taken in June 2003 are generally lower than October, 2003. pH varies from 7.01 (142 671) to 8.92 (142666).

The EC contour map (Figure 3.5) for the June measurements (note: 142BBB and 142 AAA values were recorded in September 2003) shows that the EC trend is reflective of the local groundwater flow paths presented in Figure 3.3. Groundwater with the highest EC was collected in the Red Rock lake depressions, and IB 11084. The other IBs show intermediate EC between those in the recharge and discharge areas.

There are no apparent trends in DO along the flow path suggesting that samples were oxygenated prior to the DO titration. HCO_3- appears to increase relative to pH. The redox potential is greater than > 144mV, indicating that the groundwater have come from environments that had once had contact with the atmosphere. However this may also be due to oxygenation during sampling.

Table 2: Raw results of field parameters

Bore ID	Date	EC µS/cm	pH (SLP 97.8)	DO (mg/L)	Eh (mv)	HCO_3 (mg/L)
142668	02.06.03	1830	8.28	4.5	218.8	475.80
101814	02.06.03	5700	7.86	3.2	250.5	527.04
142670	02.06.03	1120	8.49	3.6	235	344.04
142666	02.06.03	1340	8.92	3.2	247.3	380.64
142702	03.06.03	530	7.75	7.5	260.4	146.40
142720	03.06.03	2380	7.43	3.3	249.8	141.52
142717	03.06.03	1110	8.23	3.4	258	268.40
142714	03.06.03	1160	7.88	6.6	254.7	312.32
137796	03.06.03	1860	7.93	5.1	171.8	539.24
142671	03.06.03	550	7.01	5.3	248.4	148.84
Twin	03.06.03	1720	7.35	5.45	161.5	514.84
Coragulac H.	03.06.03	2000	7.97	7.6	149.5	441.64
142660	03.06.03	930	7.65	6.4	145.2	424.56
Lake Coragamite	03.06.03	153200	8.65	1.2	164.1	1512.80
142AAA	02.09.03	1200	7.79	3.4	310.7	451.4
142BBB	02.09.03	7400	7.99	3.1	295	666.12

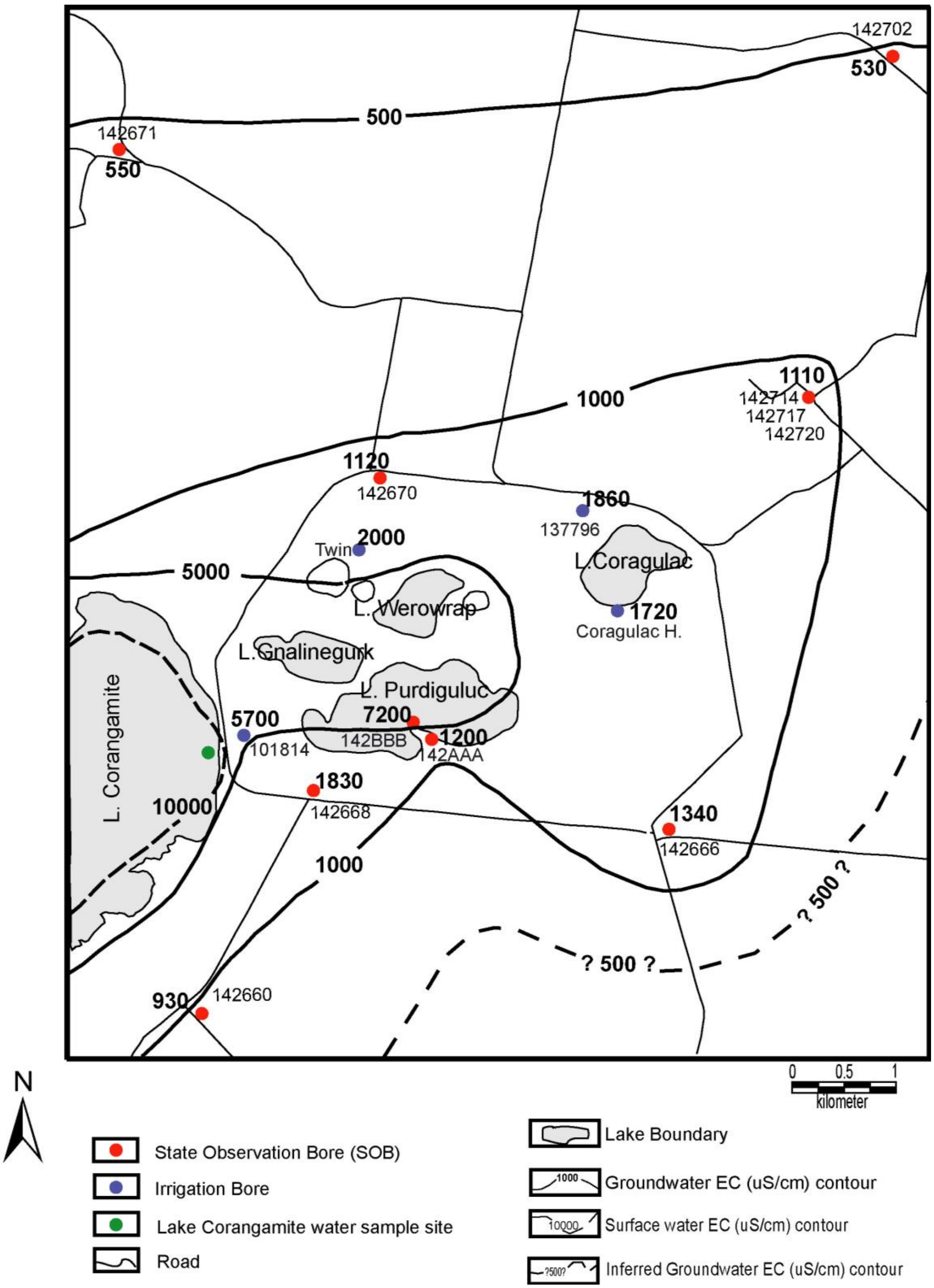

Figure 3.4: Study block EC contour map (June 2003).
Identification of recharge and discharge zones is by relative low (530) and high (7200) EC.

Major ions and stable isotopes

Major ions and stable isotopes considered in the laboratory analysis are presented in Table 3. Na^+ and Cl^- dominate the ionic composition the groundwater of the Newer Volcanics aquifer and Lake Corangamite (LC) surface water (Figure 3.4). However 3 differing groups can be identified: **Group 1**: (LC, 101814 and 142 702); **Group 2**: (142BBB and 142AAA); **Group 3**:(remaining groundwater samples). Discrimination between these groups is based on relative molar concentrations (Figure 3.5).

Group 1: Includes the older more evolved and evaporated waters that are, indicated in Lake Corangamite, IB 101814 and SOB 142702. They have greatly increased Na and Cl compared to Ca, Mg, SO4 and HCO3: Na »Ca$\cong$Mg, Cl >SO4 $\cong$HCO3

Group 2: Includes the groundwater beneath (142 BBB) and adjacent (142AAA) to Lake Purdiguluc depression. This group is distinguished by the increased concentration of Mg with respect to Ca: Na >Mg>Ca, Cl »SO4>HCO3.

Group 3: Includes the remaining groundwater samples, and are considered to reflect the general Newer Volcanics aquifer groundwater composition. Concentration changes in individual samples would represent migration along the flow path: Na>Ca>Mg, Cl>HCO3>SO4.

Table 3: major ions and stable isotopes

Bore ID	Ca^{2+} mg/L	Mg^{2+} mg/L	Na^{+} mg/L	K^{+} mg/L	Fe^{2+} mg/L	F^{-} mg/L	Cl^{-} mg/L	Br^{-} mg/L	$NO3^{-}$ mg/L	$SO4^{2-}$ mg/L	TDS mg/L	$\delta\ ^{18}O$	$\delta\ ^{2}H$
142668	15.00	0.50	335.00	20.00	N/A	0.20	475.75	0.95	1.80	69.90	1434.42	-4.37	-21.20
101814	72.00	32.00	948.00	76.00	N/A	0.10	2864.20	5.40	1.10	138.40	4693.52	-3.86	-21.09
142670	8.00	0.50	232.00	12.00	N/A	0.10	234.88	0.52	17.68	20.14	896.7	-5.02	-27.36
142666	0.50	0.50	335.00	20.00	N/A	0.20	331.10	0.58	1.72	18.22	1112.86	-5.00	-23.86
142702	10.00	0.50	89.00	0.50	N/A	0.09	95.76	0.26	16.20	11.16	382.07	-5.43	-26.58
142720	33.00	2.00	515.00	2.00	N/A	0.45	902.15	2.00	7.90	271.30	1896.84	-1.49	-8.90
142717	19.00	0.50	253.00	3.00	N/A	0.08	300.92	0.60	2.34	47.52	914.88	-5.19	-28.41
142714	34.00	0.50	172.00	2.00	N/A	0.10	269.52	0.58	27.78	27.40	865.72	-5.18	-25.48
137796	45.00	6.00	295.00	16.00	N/A	0.15	473.95	0.85	45.45	46.20	1499.56	-4.62	-24.24
142671	10.00	0.50	95.00	0.50	N/A	0.12	96.18	0.27	16.21	11.37	393.63	-5.24	-26.16
Coragulac H	51.00	16.00	245.00	12.00	N/A	0.10	392.05	0.85	46.40	48.25	1343.57	-4.53	-25.22
Twin	35.00	0.50	279.00	14.00	N/A	0.15	565.45	1.00	56.85	46.90	1440.49	-4.48	-24.78
142660	6.00	10.00	188.00	4.00	N/A	0.16	186.54	0.48	24.86	24.34	722.54	-4.56	-21.89
Lake Corangamite	36.00	2600	33500	908.0	N/A	0.00	12628.0	248.0	450.00	3626.00	155801.60	2.83	15.12
142AAA	25	46	210	22	0.05	0.2	228	0.69	359.02	85	974.94	N/A	N/A
142BBB	91	305	1220	95	0.05	0.2	1630	3.45	578.69	1340	5263.39	N/A	N/A

N/A = Not Analysed for

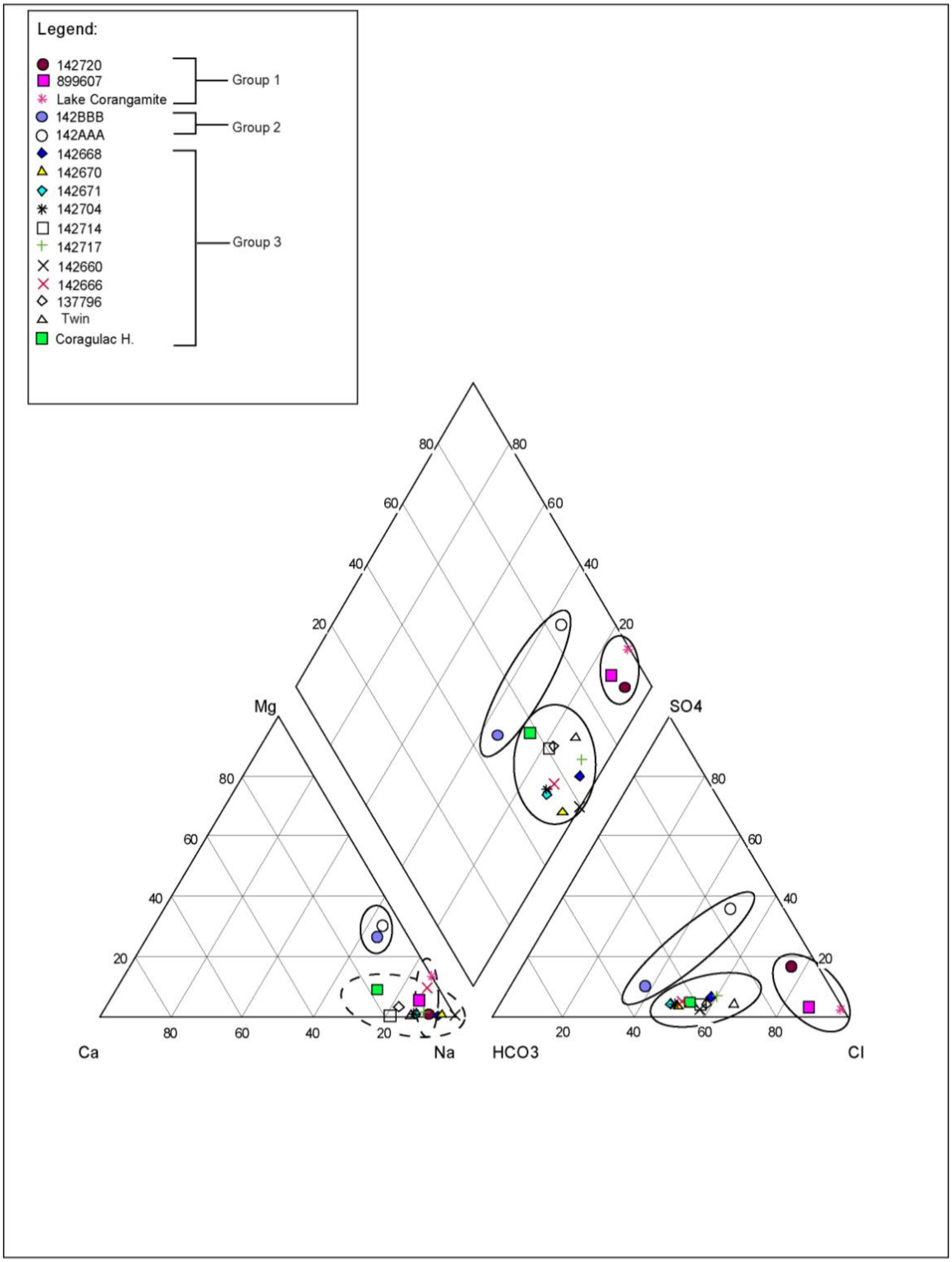

Figure 3.5: The relative concentrations (mmol) of the dominant ions.
The relative groups are circled.

CHAPTER 4: METEOROLOGICAL DATA

The 1998-2000 drying of the Red Rock lakes was the first ever recorded. This drying may be partly attributed to decreased aquifer recharge if coinciding with an atypical period of decreased precipitation.

The magnitude of aquifer recharge by precipitation is dependant upon, its totality, frequency of intensity and occurrence during potential evaporation maxima or minima. The study area has an extensive meteorological data record, which allows interpretation and comparison of current and historical climatic trends. Appendix H for full record of data used.

4.1 Annual Precipitation Totals

Since 1898, daily precipitation has been recorded at the Warrion Hill Bureau of Meteorology (BOM) station north of Red Rock Complex (Figure 1.4). The recorded total annual precipitation oscillates about the 1898-2002 annual average, of 589.27 mm/yr (Figure 4.1).

The nationally recognized periods of drought 1965-69, 1982-85 and 1996-2001 are indicated in Figure 4.1 by the corresponding periods below average annual precipitation. In terms of totality below the 104 year average, the recent drought period (1996-2001) does not appear as severe as either 1965-69 or 1982-85.

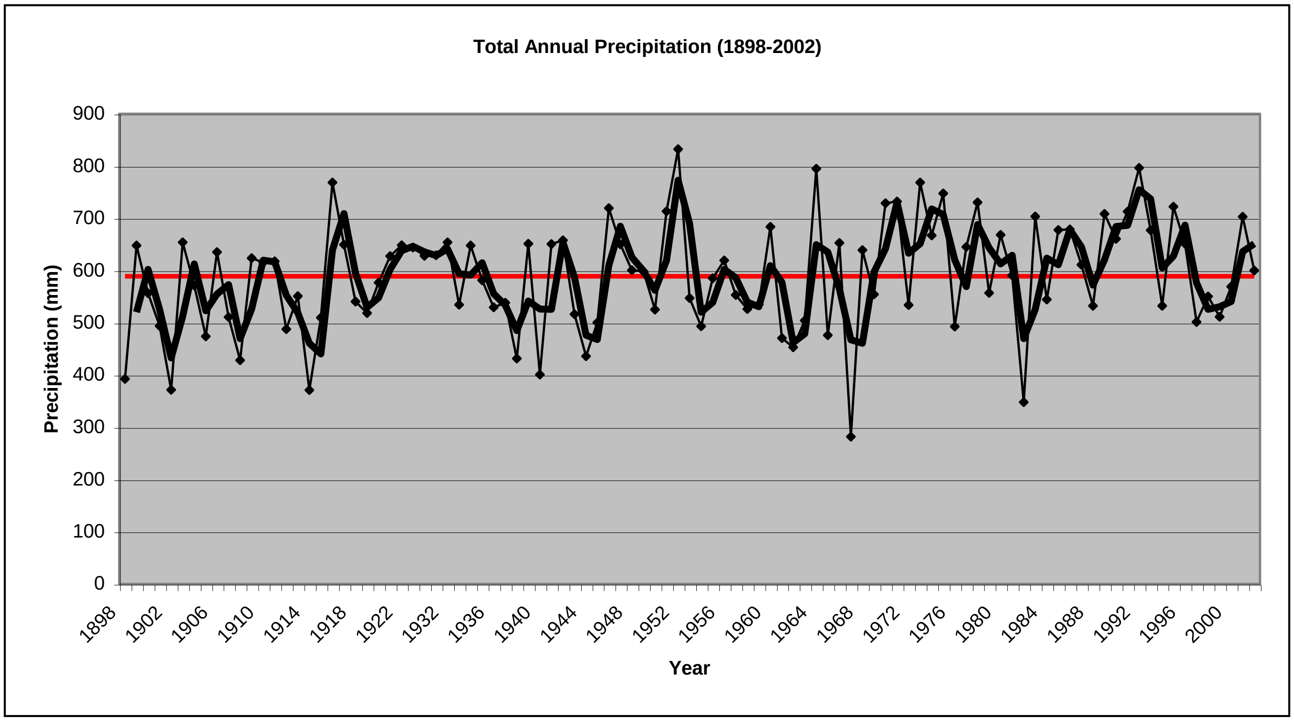

Figure 4.1: The 1898- 2002 annual precipitation recorded at Warrion Hill.
The average annual precipitation (red) is 589.27 mm/yr.

4.2 Recharge during Potential Evaporation Maxima and Minima

Evaporation occurs when "water molecules passing the vapour state exceeds those in a liquid state" (Fetter 1994). The Wurdiboluc Reservoir evaporation station is 45 km east of the study area, and can be assumed that measured potential evaporation is identical to that in the study area. Daily standard US Class 'A' pan evaporation measured at the Wurdiboluc Reservoir station can be used as a surrogate for evapotranspiration (BOM 2003). This gives an indication of the timing of potential evaporation maxima and minima in the study area.

The Class 'A' pan evaporation measurements should be multiplied by a co-efficient < 1, as the water in a Class A land pan is heated more readily by solar radiation than the surface water of a lake (Fetter 1994). A co-efficient of 0.8 is suitable for the Western District, given its distance from the sea and climate (Blackham 2001; Coram 1996).

As introduced in Section 2.9, potential evaporation exceeds precipitation for most the year, excepting for the winter months. It is inferred that this winter period is more conducive to recharge (George 1984), thus it is necessary to examine any changes in the trend of winter precipitation (Figure 4.2). For the purpose of this study, the term 'winter precipitation' relates to the total precipitation during the months June –September.

Although Figure 4.2 shows that during the 1998-2000 Red Rock lakes drying period, there was below average winter precipitation, two previous similar periods are apparent. 1944 -1950 and 1957 -1963 were both periods of below average winter rainfall, and actually received less average winter annual rainfall than the 1998-2000 period. Furthermore, the years leading up to the 1998-2000 period received more winter precipitation, than the 1944-50 and 1957-63 periods.

In terms of winter precipitation, the 1998-2000 period does not appear atypical to historical trends.

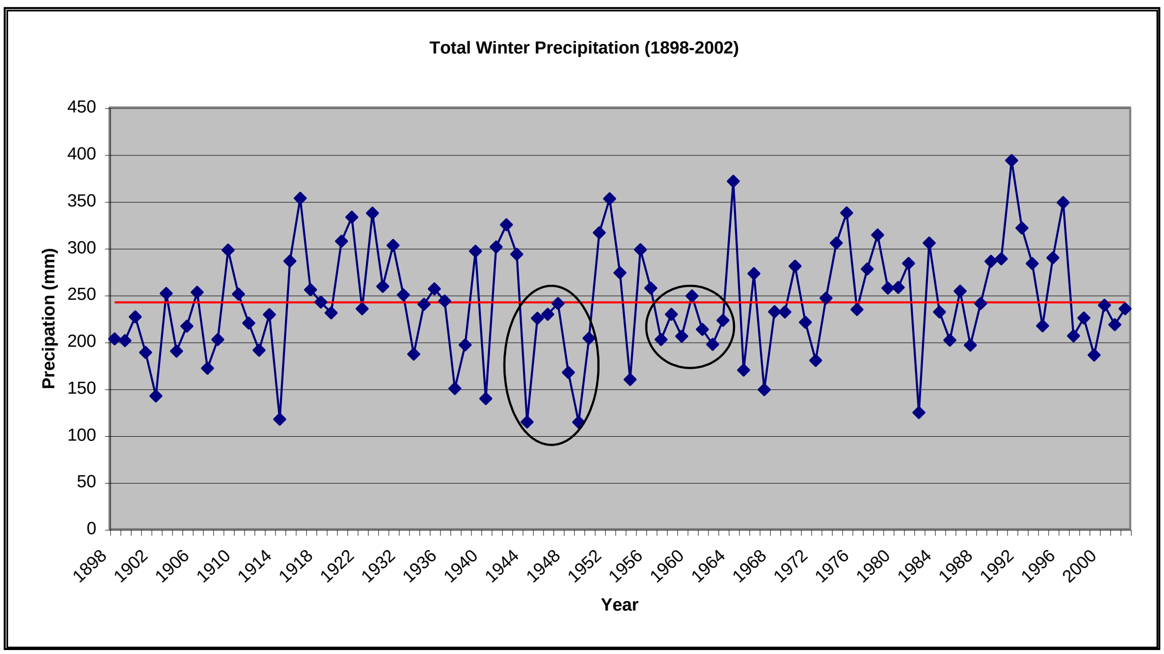

Figure 4.2: Annual winter precipitation 1898-2002.
The circles highlight the two previous periods of below average winter precipitation of 1944-1950 and 1957-1963.

4.3 Frequency of precipitation intensity

Ten millimeters of precipitation within a day is considered to be a sufficient intensity, for filtration through the unsaturated zone and into the Newer Volcanics saturated. This 10mm/day threshold was decided upon after deliberation with meteorologists, DSE (Walker pers. comm.) and local residents'.

Based on this synopsis, the higher the number of >10 mm intensity days, the greater the recharge. Figure 4.3 shows that the annual number of > 10 mm intensity days has varied since 1898 (note that the daily record is missing during 1925-34). The highest recorded annual frequency is 33 days (1954), and the lowest is 3 days (1969). The 1998-2000 period is below the 1898-2002 annual average of 15.2.

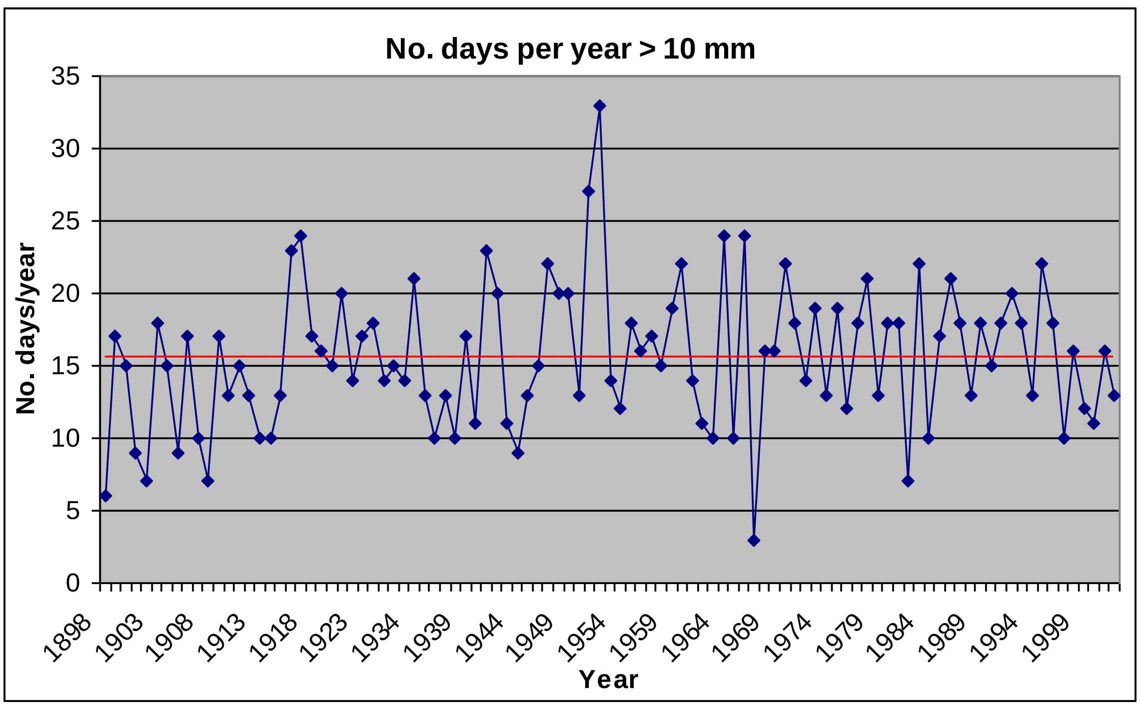

Figure 4.3: 1898-2002, annual number of days > 10mm precipitation recorded.

4.4 Discussion of Meteorological Data

Although the annual precipitation during 1998-2000 was not significantly below average, the annual winter precipitation marked a divergence from historical trends. If only the 1998-2000 period was observed, a corresponding decrease in recharge could be inferred as the primary cause of the declining lake levels. However as 1944 -1950 and 1957 –1963 show the similar deviation in winter precipitation, and the lakes did not go dry, an alternative change in the hydrological budget could be inferred (Equation 1.1).

Consideration of other climatic components that would impact aquifer recharge, including wind direction/intensity and number of daily sunlight hours, was out of the scope of this study. However, based on precipitation trends, the 1998-2000 period was not unusual. Total annual precipitation frequency > 10 mm/day is the only aspect that could be interpreted as nonconforming, however quantification of its statistical significance to recharge is also out of the scope of this study.

CHAPTER 5: PHYSICAL AND CHEMICAL HYDROGEOLOGY, INCLUDING GROUNDWATER DEVELOPMENT

Integration of the physical and chemical hydrogeology is necessary for understanding the groundwater flow system including groundwater-surface water interaction. An important aspect of the physical hydrogeology is consideration of the impact of groundwater development in the study region. Unsustainable pumping of irrigation bores can lead to alteration of steady state systems, and a regionally depleted water table with localized areas of distorted hydraulic gradients and chemistry.

5.1 Groundwater Development

Groundwater in the study region is primarily used for irrigation, and its demand has greatly increased during the previous 30 years, in line with the national trend. Figure 5.1 depicts the increase in irrigation bore construction and amount of groundwater extracted from the Newer Volcanics aquifer since 1967. This graph is based on current allocation values (SRW 2003), and assumes that annual groundwater requirements and hence extraction would have been consistent since the time of construction.

According to Figure 5.1, the greatest period of irrigation bore construction occurred between 1970 and 1987, with 33 new bores. Within these 17 years the potential extraction more than doubled, from 3063 ML/year to 7577 ML/year. Since 2000, no new licenses have been issued due to sustainability concerns (WGSAPCC 2002). Currently there are 66 irrigation bores in the study block, with licenses to extract up to 7773 ML/year of groundwater (SRW 2003).

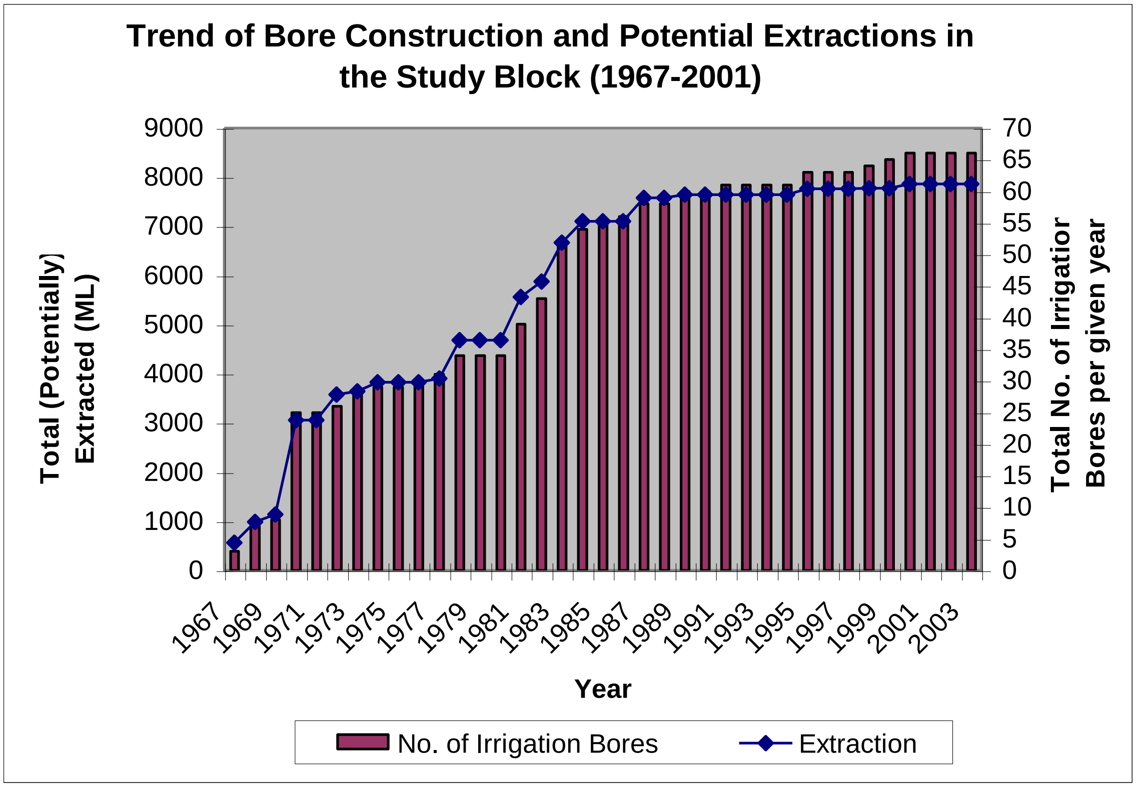

Figure 5.1: Trend of bore construction and groundwater extraction in the study block, after SRW (2003).

Based on Thompson's (1971) estimate of 30% recharge and using a rainfall recharge method, the PAV for the entire WGSPA was calculated at 14 100 ML/yr (WGSPACC 2002). SRW (2003) describes that the total licensable extractions in WGSPA during 2002-2003 was 13769.2 ML from the Newer Volcanics aquifer, which is below the estimated PAV. Within the study block for this same period, the total licensable extractions were 7773 ML. Although the study block area represents only approximately 20% of the total WGSPA (395-40 km^2), its licensable extractions are 56 % of the total for the WGSPA.

Metering of all 125 irrigation bores within WGSPA commenced in 2002 with 66 of them located within the study block (SRW 2003). Metering during 2002-2003 describes that ~62% of the actual extractions occurred within the study block. This indicates that there is a much greater intensity of extraction occurring within Red Rock Complex/Warrion Hill area than the other regions of the WGSPA. This data suggests that allocations in the study area that are based on the entire WGSPA PAV estimate may not be sustainable.

5.2 Physical Hydrogeology

Physical groundwater - surface water interactions

As introduced in Chapter 1, lakes may be classified as recharge, discharge or through-flow, depending on the relative hydraulic gradient and direction of flow between the groundwater and surface water (Born et al. 1979). However these classifications are only relevant if groundwater - surface water interaction is physically capable.

In order for groundwater - surface water interaction to occur, there must no significant low permeability zone beneath the lakebeds that would perch the lakes and prohibit flow. The lithological log from the SOB (142 BBB) drilled through Lake Purdiguluc depression. (Appendix C) shows that there is at least 7 m of highly permeable scoriated basalt beneath the lake, which would allow groundwater-surface water interaction. Similarly the SOB (142 AAA) drilled through the sediments adjacent to Lake Purdiguluc, indicates the potential for groundwater flow to the lake bed. Groundwater - surface water interaction of the other major lakes in the Red Rock Complex is implied based on their similar geology and synchronised water level decline.

A conceptual model of the groundwater surface water interaction along A-A’ (Figure 1.4) has been developed as part of this study. As the physical interactions will be altered as recharge and extraction parameters change, a time series of stages (Figure 5.2) from pre development steady state to transient, are given. This has led to what is interpreted as the current quasi steady state from the 2000-2003 hydrographs (Figure 3.3). It is assumed that a steady state system existed during the 1960’s prior to extensive groundwater development, and as this development increased (Figure 5.1) there was a transient change by the late 1990s.

The steady state system (1960-1990) depicted in Figure 4.2(a) has a regional groundwater flow direction from the northeast, toward Lake Corangamite. The water table would have been high enough to intersect the depressions in the Red Rock Complex (blue), forming the Purdiguluc and Coragulac lakes. There is sufficient local flow/run off from the pyroclastic mounds and groundwater to flow into the lakes. The freshwater/saline water interface (FW/SW) would be at its natural equilibrium state, closer to Lake Corangamite than the Red Rock Complex.

The transient system would have developed by the 1990s, characterised by a reducing water table (red) and decreased regional groundwater throughflow. The water table would no longer have been significantly higher underneath the pyroclastic mounds, and there would have been less local groundwater flow into the lakes. This lower water table beneath the lakes indicates that surface water would have flowed back into the groundwater system. In addition groundwater extraction near Lake Corangamite would have shifted the freshwater/saline water interface (FW/SW) towards the point of extraction (Figure 1.2). It is consequently interpreted that there would have been some flow from Lake Corangamite towards the Red Rock Complex in localized areas.

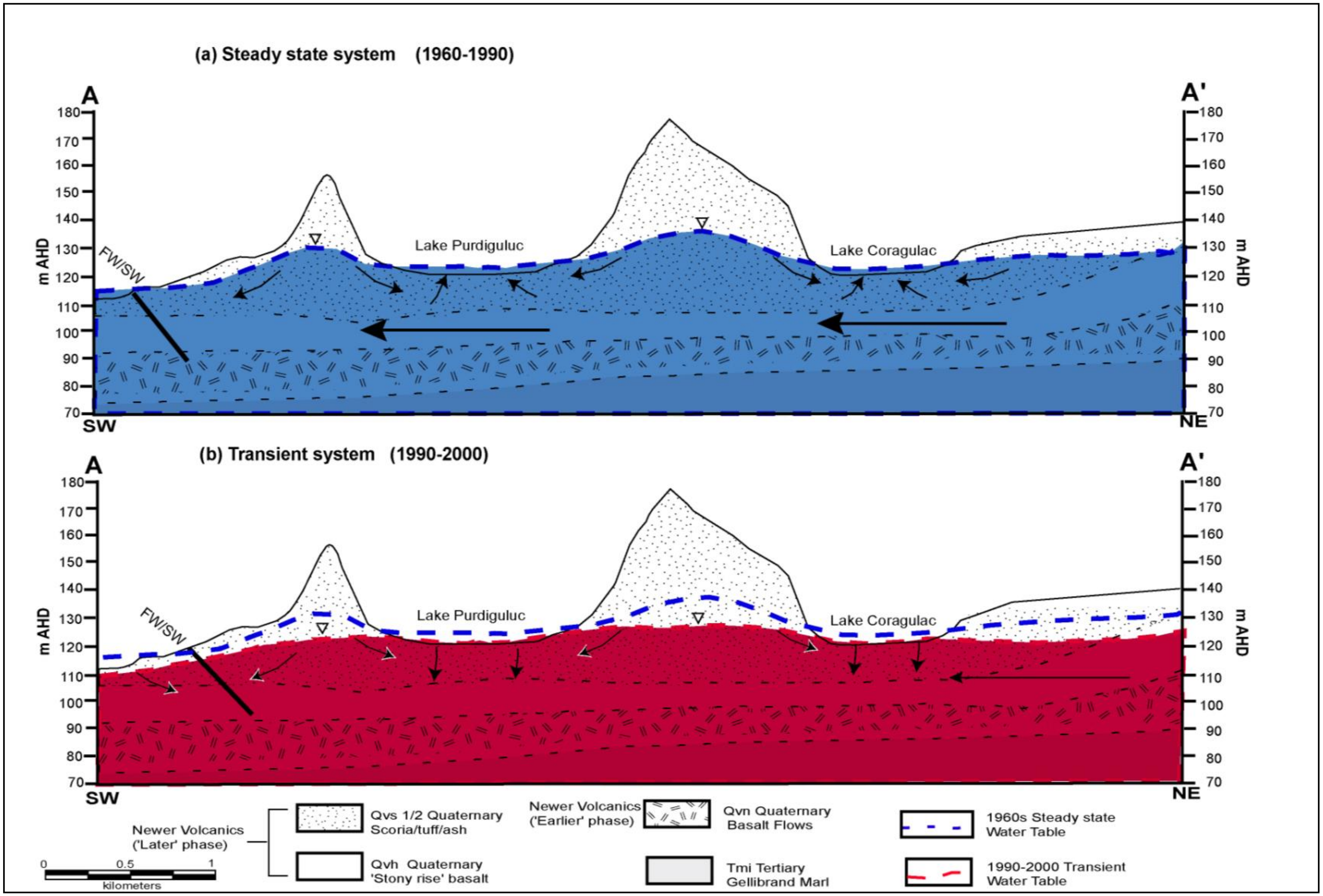

Figure 5.2: Conceptual model of groundwater-surface water interaction along A-A' (a) 1960s, (b) 1990s

5.3 Chemical Hydrogeology

Stable isotopes (^2H / ^{18}O) and molar ratios (including Na/Cl, Cl/Br) can indicate processes since recharge that have affected the chemical composition of the groundwater (Davis et al. 1998; Drever 1997; Kehew 2001; Langmuir 1997). Evidence of evaporation is of particular interest, as the relative salinity of surface water and nearby groundwater can indicate a physical interaction. Consideration of the processes that alter the chemical composition of the groundwater along the flow path will be briefly considered. A 0.7 conversion factor has been used to compare EC (uS/cm) to TDS (mg/L). The graphs presented in the following section do not include Lake Corangamite data points, as it was found these extremities misrepresented the trends (Appendix G).

5.3.1 Origin and evaporation of groundwater and surface water

Cyclic salts would be the main source of Na^+ Cl^- in the groundwater, as the rapid infiltration implies that there would be limited opportunity for water rock interaction. Previous data has been considered in the absence of surface water during the study period.

Walker (1972) discussed the chemical differences between surface water in the Red Rock Complex lakes and nearby groundwater and noted that the Na^+/ Cl^- molar ratio of the surface water and nearby grşoundwater were similar. It was suggested by Walker (1972) that they originated from the same source.

Table 4: Previous Lake Werowrap and groundwater chemistry after Walker (1972).

	Na^+ (mg/L)	K^+ (mg/L)	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)	Cl^- (mg/L)	HCO_3^- (mg/L)	$CO2^{2-}$ (mg/L)	TDS (mg/L)	pH
Lake Werowrap	13076	868	81	4	13864	8385	2142	38 420	9.8
Groundwater[1]	439	54.7	8.0	6.1	492	470	21	1 491	9.0

[1] The groundwater samples were taken from a windmill bore hole on the eastern shore.

Analysis of the rainfall composition (Table 4) in the Warrion Hill area by Coram (1996) indicates that the molar Na^+/Cl^- ratio is also1:1. This suggests that the principle source of both Lake Werowrap surface water and groundwater may be precipitation, however Lake Werowrap has higher Na^+ and Cl^- concentrations due to evaporation. It should however be noted that the Coram (1996) ratio may not be indicative of 1972 precipitation.

Table 5: The major ion composition of rainwater at Warrion Hill, after Coram (1996).

	Cl^-	Na^+	HCO_3^-	Ca^{2+}	Mg^{2+}	K^+
Molar Concentration Rainwater	0.090	0.100	0.050	0.015	0.015	0.004

Evaporation and condensation fractionate ^{18}O and ^{2}H isotopes of groundwater. When compared to a meteoric water line can distinguish the source of the groundwater (Drever 1997). Most of the water samples lie to the left of the global meteoric water line (GMWL), except Group 1, which lie to the right of the GMWL. Group 2 and 3 could be considered as having a meteoric source and they plot almost parallel to the local meteoric water line (LMWL), where as the proportional increase of ^{2}H relative to ^{18}O of Group 1 waters is indicative of evaporation. SOB 142720 is screened in the Gellibrand Marl, and its evaporation signature may be indicative of connate pore waters (Thompson 1971). Lake Corangamite displays the greatest displacement, which is consistent with intensive evaporation associated with salt lakes (Appendix G).

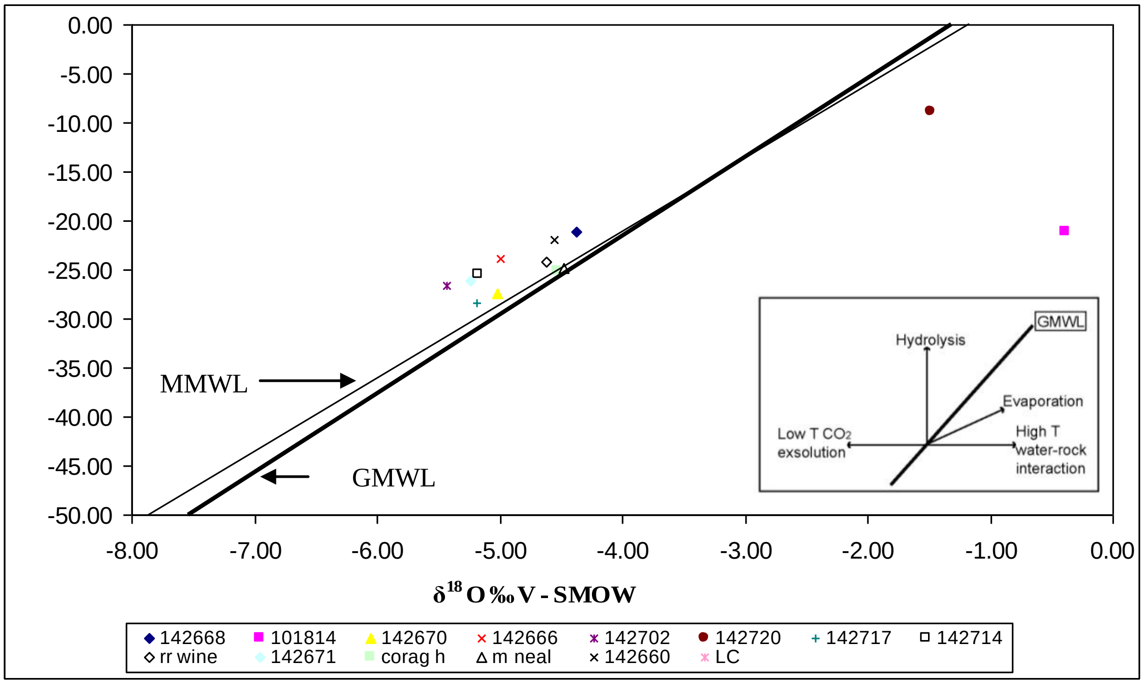

Figure 5.3: Stable isotope ratios, relative to the Melbourne meteoric water line (MMWL) (Cheng 1998) and the global meteoric water line (GMWL) (Craig 1961).

5.3.2 Water-rock interaction

In general, Na/Cl groundwater ratios greater than the global mean precipitation ratio of 0.86 indicate an increase of Na^+ due to water rock interaction (Drever1997;Clark& Fritz 1997). Na/Cl molar ratios greater than the local rainfall ratio of 1.1 (Coram 1996) will instead be considered a better indication of increased Na^+, in the study region (Figure 5.4). Water samples have a range of Na/Cl ratios between 0.5 and 1.6. The water samples which have a Na/Cl ratio > 1.1 were collected from recharge areas where a small increase in Na will have a significant effect on the Na/Cl molar ratio.

Irving and Green (1976) specified the typical percentage mineral composition of the Later Newer Volcanics in the study area as: 29% albite ($NaAlSi_3O_8$), 19% Olivine (Mg_2SiO_4), 17% anorthite ($CaAl_2\ Si_2O_8$), 17% diopside (Ca $(Mg,Fe)Si_2O_6$), 9% orthoclase ($KAlSi_3O_8$), 4% ilmenite ($FeTiO_3$), 3% magnetite (Fe_3O_4), 1% apatite ($Ca(F,Cl)(PO_4)_3$) and 1% nephheline ($NaAlSiO_4$).

The relative molar increase of Na in the recharge zones of the Newer Volcanics could be due to the weathering of albite, given by the following reaction (Kirste & de Cariat 2003):

$2NaAlSi_3O_8 + 2H^+ + 9H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2Na^+ \; 4H_4SiO_4$ (*Equation 5.1*)
albite *kaolinite*

In addition to increased Na^+, albite weathering, is also indicated by the increasing pH relative to HCO_3^- (Figure 5.6) due to the consumption of H+ ions and relative to Na^+ (Figure 5.5) SiO_4^+ would also be expected to increase, however it was not considered in the laboratory analysis.

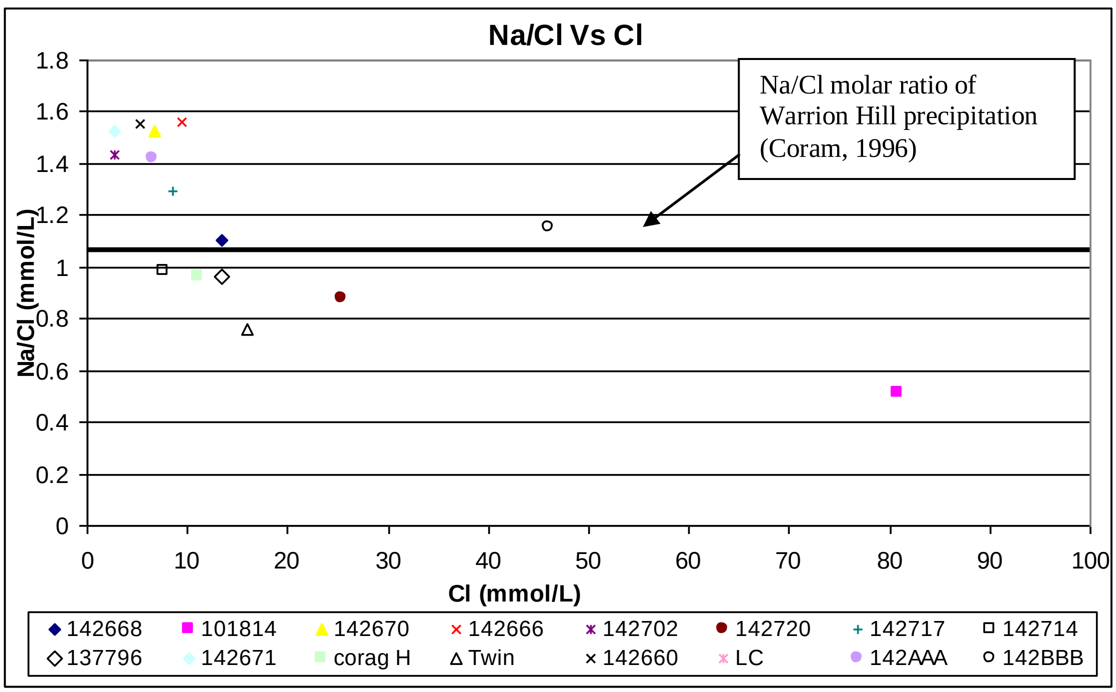

Figure 5.4: Molar Na/Cl vs Cl^-

Evaporation of Group 1 waters is also indicated in Figure 5.4 by the increased Cl^- compared to Na/Cl ratios.

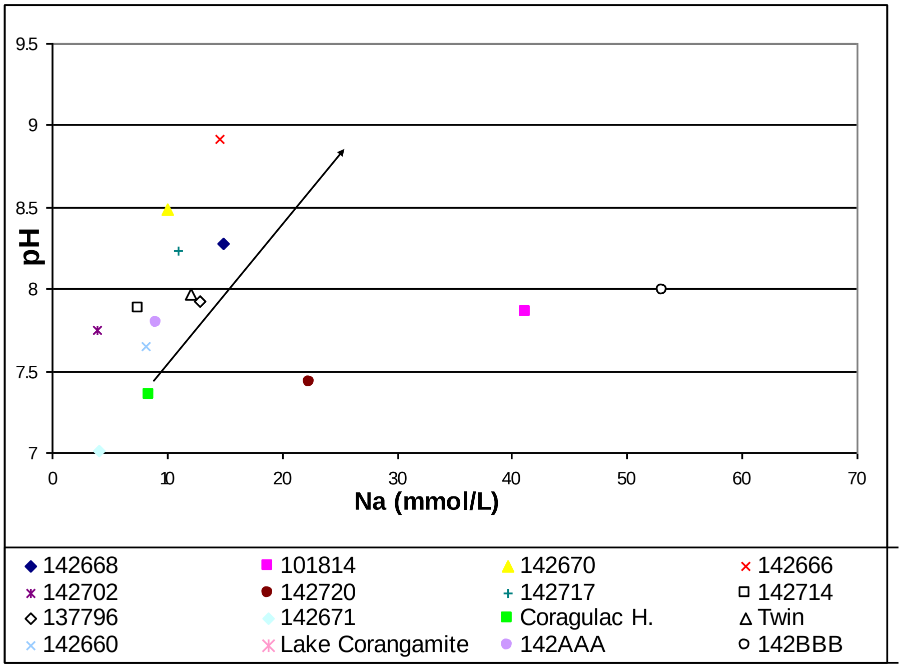

Figure 5.5: pH vs Na^+ (mmol)

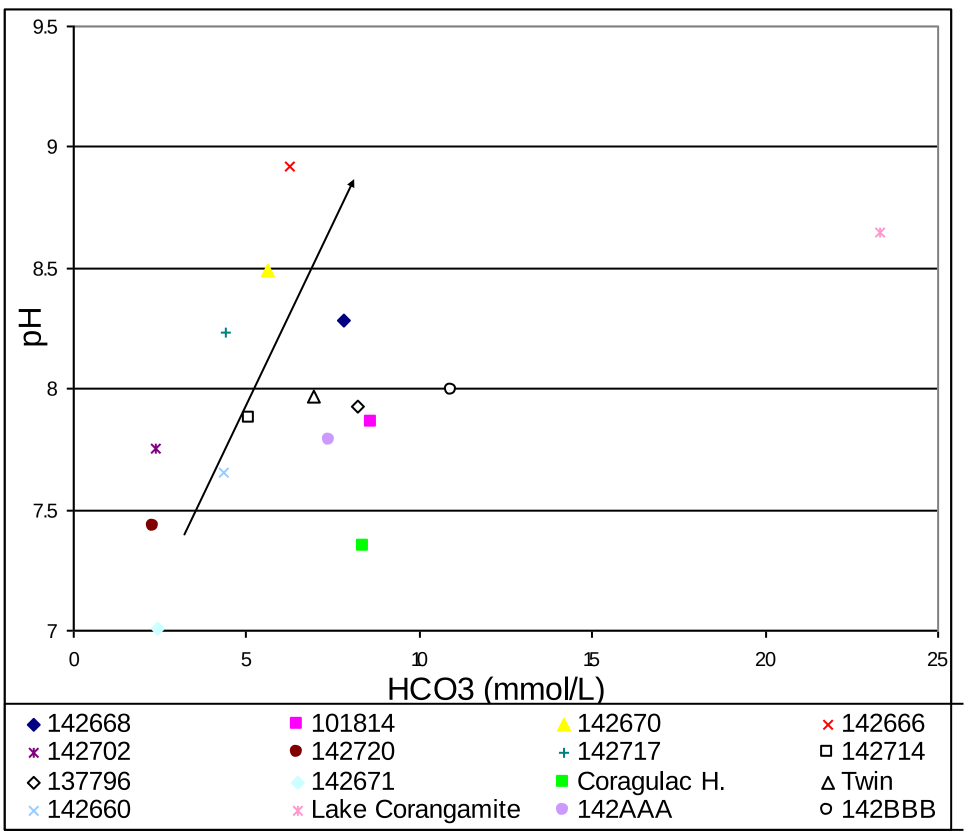

Figure 5.6: pH vs HCO-3 (mmol/L)

Group 2 is identified as having a relative increase of Mg^{2+} to Ca^{2+}, compared to Groups' 1 and 3 (Figure 3.6). The Mg^{2+} increase appears localized in the discharge areas and may be reflective of the mineral composition of the eruption points in the Red Rock Complex. Water rock interaction with the Mg rich-olivine forsterite, could cause the increase of Mg^{2+}, according to the following reaction (Faust & Aly 1981):

$Mg_2SiO_4 + 4H_2CO_3$ -> $2Mg^{2+} + 4HCO^{3-} + H_4SiO_4$ (*Equation 5.2)*

forsterite

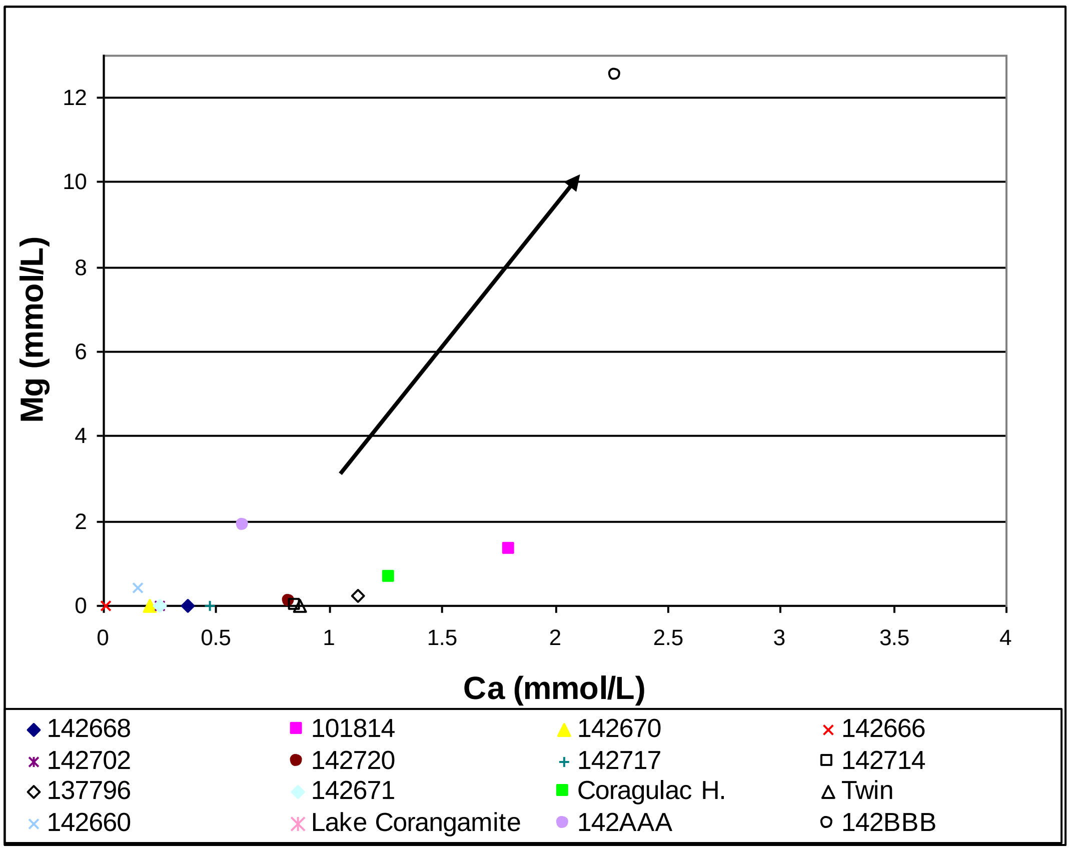

Figure 5.7: Molar Mg^{2+} vs Ca^{2+}

5.3.3 Halite Dissolution

The dissolution of halite (NaCl) contributes equal concentrations of Na^+ and Cl^-, without an increase in Br. Typical coastal rainwater has a Cl/Br ratio of 650 (Herzceg et al. 2001). The occurrence of halite dissolution is characterized by a significantly greater Cl^- concentration compared to Br^-, and a Cl/Br molar ratio of 1000-10 000 (Davis 1998). All the water samples have molar Cl/Br ratios > 700 (Figure 5.8), and the most are greater than 1000.

Irving and Green (1976) indicate that Cl^- bearing minerals only make up 1 % of the typical mineral assemblage of the Newer Volcanics, and Figure 5.3 indicates that this observed increase in Cl^- could not be due to high temperature water rock interaction. It is suggested Figure 5.8 indicates the occurrence of halite dissolution. Halite precipitation is not observed in the study area, thus a wind blown origin from Lake Corangamite is probable due to its extensive history as a saline lake, and obvious halite precipitation on surrounding soil. Halite may have also been sourced from the cyclic salts in soil profile, and fertilizer input.

Figure 5.8 further highlights evaporative processes in Group 1 sample waters by the increasing Cl^- concentrations with a relatively constant Cl/Br ratio of 1000-1200.

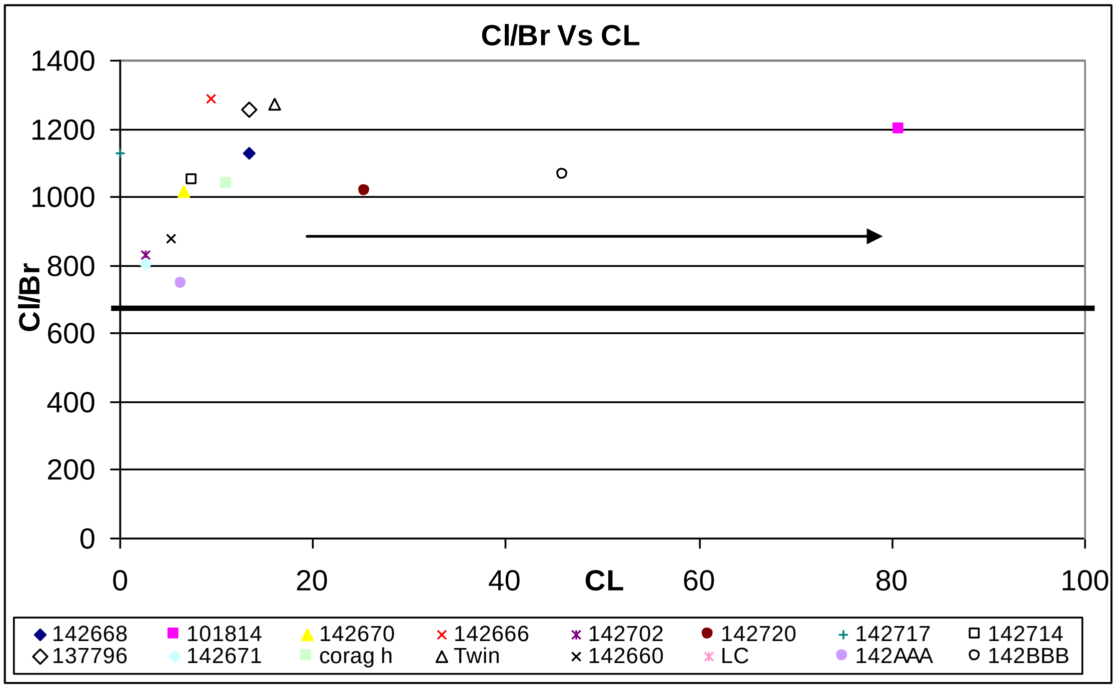

Figure 5.8: Molar ratios of Cl/Br vs Cl
Arrow indicates increasing evaporation

5.3.4 Active saline intrusion

The EC contour map (Figure 3.4) shows the EC trend at the close of the 2003 irrigation season (June), and highlights IB101814 as having higher EC (5400 uS/cm) than the general groundwater EC (1000-2000 uS/cm). This IB is located down the flow path, near Lake Corangamite, and may be expected to have a relative incr şease in EC, however as the nearby SOB (142668) does not show this increase in EC, an alternative process is implied.

IB 101814 is screened within the Newer Volcanics unit, so the increased EC can be considered indicative of active saline intrusion due to the development of a cone of depression nearby Lake Corangamite (Figure 1.2). Furthermore IB 101814 has the similar evaporation signature to Lake Corangamite (Figure 5.3; 5.4; 5.7), which could occur by induced flow of Lake Corangamite highly saline and evaporated waters. Groundwater extraction in this area would induce flow from both Lake Corangamite and the Newer Volcanics aquifer, and its evaporative signature would be representative of mixing of both waters. The isotopic ratios from the nearby the SOB (142668) is comparable to those of the Group 3, which further indicates IB 101814 has a actively induced flow from Lake Corangamite, or it is occurring nearby.

5.3.5 Comparison of groundwater and surface water salinity

The lack of surface water in the Red Rock Lakes during the study period restricts the detail for which the salinity from recent groundwater-surface water interactions can be interpreted. In this absence, previous data is considered.

A Rural Water Commission (1991) investigation of the relative electrical conductivity (EC) of the surface water and groundwater within the Red Rock Complex, suggests that the groundwater was fresh compared to the saline lake waters. This comparison was also noted by Baly (1969), Walker (1972) and Thompson (1971). EC readings during 1991 from Lake Purdiguluc and Lake Coragulac were
12 000- 13 000μS/cm, whereas the groundwater from nearby sumps was
1200- 1330 μS/cm. This suggests that evaporation concentrated the salts of the surface waters. SOB 142BBB is considered to represent evaporated surface which flowed in the groundwater system, which is support by Na/Cl and Cl/Br ratio plots (Figure 5.4; Figure 5.7). If the stable isotopes had been analysised for, one may expect to see a similar evaporative signature to Group 1 waters. The surface waters were not saturated, which implies there was a component of groundwater in flow.

EC measurements recorded during this study period indicate spatial and temporal changes. The EC contour map (Figure 3.5) highlights the higher EC along the flow path towards the discharge zones. The EC of SOB 142 BBB, was 7400 uS/cm in September 2003, which was much higher than surrounding bores, (~ 2000 uS/cm including 142 AAA). As it is considered that the surface water in the Red Rock Complex was saline, the current saline groundwater beneath Lake Purdiguluc indicates interaction between the groundwater and surface waters.

During October 2003, the EC of SOB 142BBB was 11 000 uS/cm, which is more representative of previous surface water salinity. This increase was observed after significant precipitation, and may be due to the winter precipitation 'pushing' the higher salinity waters down into the groundwater system or due to the remobilization of salts in the unsaturated zone.

5.4 Integration of physical and chemical hydrogeology

The possibility of groundwater-surface water interaction is apparent by the 7 m of highly permeable scoriated basalt beneath Lake Purdiguluc. Studies of relative EC of the groundwater and surface water suggest that Lake Purdiguluc and Coragulac were highly saline due to evaporative concentration of salts. The current EC of 11 000 μS/cm of the groundwater beneath Lake Purdiguluc suggests that Lake Purdiguluc surface water has flowed into the groundwater system and furthermore implies that during steady state conditions (1960-1990) groundwater-surface water interaction was occurring in the Red Rock Complex (Figure 4.2). Furthermore the current lack of halite precipitation, suggests that the lakes received groundwater inflows, as originally suggested by Thompson (1971).

During steady state conditions, Lake Purdiguluc could have been classified as discharge (Figure 1.1a), however due to a lowering of the water table and a reversal of the hydraulic gradient, it is now an area where there would be some diffuse recharge through the dry lake bed. The lowering of the water table could be due to the unsustainable groundwater extraction, as indicated by the increasing trend and the inaccurate PAV estimate. A detailed discussion of the possible causes of the drying of the Red Rock lakes is presented in the following chapter.

CHAPTER 6: DISCUSSION ON THE DECLINING LAKE LEVELS

The occurrence of lakes in the Red Rock Complex is determined by the topographic depressions and interception of the water table. In recent years there have been significant changes in the levels of the lakes; during 1998-2000 the lakes levels continually declined and for the last 3 years the Red Rock lakes have been dry. Walker (1972) noted that Lake Werowrap fluctuated seasonally by a few centimeters, but never before have all the lakes been reportedly dry for an extended period.

This discussion on the cause of the declining lakes levels is limited because for this critical time there was no monitoring of the lakes and it was only in 2000, after the lakes had dried completely, that the SOB monitoring network was established nearby. Since 2000, the SOBs have only shown monthly groundwater fluctuations related to seasonal recharge and groundwater extraction, which are representative of a steady state system (Figure 5.2). Consequently, there has been the need on this aspect to use a qualitative research approach and to seek out historical information from a number of sources including interviewing past and present residents of the Red Rock Complex area.

Insight into the lake hydrology with respect to groundwater is particularly indicated at Lake Purdiguluc, where drilling has been confirmed a bed of highly permeable scoriated basalt. Also, historical observations of high salinity surface waters compared with the surrounding groundwater suggests that the groundwater inflow would have been concentrated by evaporation. The current observation of high salinity water immediately beneath the Lake Purdiguluc depression indicates that the surface water flowed into the groundwater system (Figure 1.1).

6.1 Potential causes of the decreasing lake levels

Consideration of the, historical and recent, meteorological and groundwater extraction trends suggest that the lakes within the Red Rock Complex potentially dried due to:

A Decreased inputs of precipitation;

B A lowering of the water table due to groundwater extraction or;

C A combination of both.

These scenarios are discussed below, as the cause of the drying of the lakes is essential for the management of the lakes and the future direction of groundwater development in the study area.

6.1.1 Hypothesis A: The drying of the lakes due to decreased inputs, coinciding with a period of decreased precipitation.

This hypothesis implies that under a prolonged drier period, inputs to the lake via direct precipitation, local discharge related to local groundwater flow systems and any surface runoff would have declined.

The evidence to support this hypothesis is that during 1998-2000 there was below average annual total (Figure 4.1) and winter precipitation (Figure 4.2) recorded at the Warrion Hill rainfall station. There is a prominent local flow system coinciding with the topographic highs of highly permeable scoriaceous basalt surrounding the lakes. Thus it could be assumed that input would be instantaneous and the response to change in precipitation would occur sympathetically.

The 2000-2003 SOB hydrographs substantiate this synopsis by depicting fluctuations which reflect changes in seasonal recharge (Figure 3.1). Also, based on the anecdotally estimated 10 mm daily frequency of intensity, the 1998-2000 period could be considered atypical to historical trends (Figure 4.4) However, there are no monitored moisture or groundwater levels directly under these scoria rims upon which to determine the response to rainfall events, so the effect of frequency of intensity on recharge in the study area can only be speculated.

Evidence of terraces or benches surrounding the major lakes indicates during the upper Quaternary there had been fluctuations in lake levels before European settlement, presumably in response to climatic changes.

If merely a 5 year period of decreased winter precipitation was sufficient for the lakes to go dry, then as the lakes have never gone dry before, it would be expected the current dry period is uncharacteristic in historical trends. Furthermore the lakes elsewhere in the Newer Volcanics of western Victoria should behave sympathetically to the Red Rock lakes. Neither is the case.

The total annual precipitation during the drying period of 1998-2000 was not significantly below average, as fluctuations have been recorded since 1898 (Figure 5.1). In addition the periods, 1945-1951 and 1963-67, are identified as also having below average winter rainfall (Figure 5.2), however there is no reported evidence that the lakes went dry during either of these periods. This suggests that inputs by precipitation are not considerable in the lakes' hydrological budgets. Groundwater development was minimal during these previous periods (Figure 4.1).

6.1.2 Hypothesis B: Unsustainable groundwater extraction from the Newer Volcanics aquifer lowered the water table to beneath the lakes depressions

Groundwater usage has dramatically increased since 1968, and is concentrated in two clusters upgradient of the Red Rock Complex, on either side of Warrion Hill (Figure 2.4). The greater intensity of groundwater development in the Red Rock Complex/Warrion Hill area, is indicated by the percentage of total allocations and actual use compared to other areas in the WGSPA. This is reflective of the fertile volcanic soils and high quality/yielding bores.

However the PAV on which these allocations are based and compared to, was calculated using a 30% recharge estimate by Thompson (1971). Preliminary hydrologic budget figures now indicate that this percentage is too high, and the decline in the water table infers that the current usage per annum is unsustainable.

Farmers now report a general decline in the water level and the yield of their irrigation bores over recent years, and some have even noted a complete drying in shallower bores. The license holder of IB 101814 indicated that the yield from his irrigation bore over the last 20 years has declined from 40 000 gallons/day to 4 000 gallons/day.

Timms (1983) observed that the average depth of the Red Rock lakes was 1.4 - 2 m. According to the SOB data within the Lake Purdiguluc, the water table is now 3.5 m below the bottom of the lakebed (August 2003), which suggests that the local water table has declined by at least 5.5 m since 1983. Away from the lakes where the groundwater level was higher than the lake level the irrigation bore records nonetheless show that at the time of construction, the water levels were at least 10 m below the ground surface (Appendix D). As evaporation from the water table occurs when it is within 2 m of the surface, this could not have caused the lowering water table.

It is highly likely then that unsustainable groundwater extraction, in part at least, is responsible for the lowering of the water table, as is the only major component of the hydrological budget that has significantly changed in the last 30 years (refer to the preliminary hydrological budgets following this discussion). Furthermore in the WGSPA, the levels of all the Red Rock lakes have decreased in unison and any changes seen in nearby lakes and wetlands have been minor and have since recovered. Nearby residents of The Basins, 5 km south west of the study block, indicate that the lakes levels have not dramatically declined over the last 6 years, in fact The Basin levels were noted as being higher now than 12 years ago. However, irrigation practices are not as intense in that area.

6.1.3 Hypothesis C: A combination of both decreased precipitation and increased groundwater extraction.

For the Red Rock lake levels to respond immediately to the 1997-2001 decline in winter precipitation and intensity, the groundwater surface water system must already have been under stress, as during similar past climatic episodes the lakes did not go dry. The water table would have already been lowered due to unsustainable groundwater extraction, however the 1997 /1998 decreased winter precipitation years with an assumed increased groundwater extraction would have triggered the current response. The already lowered water table would have been unable to replenish the lakes (Figure 1.1). This hypothesis is the most plausible, as local groundwater flows are dependant upon both throughflow and recharge. The water table would have been reduced further due to decreased recharge.

6.2 Preliminary Hydrological budgets

Based on the understanding of the surface water system of the Red Rocks area it has been possible to put forward some hydrologic budgets which reflect the interaction of the various input and output components.

As is has been shown that Red Rock lakes were connected to the groundwater system and the scoriated basalt/tuff/ash allows rapid infiltration of precipitation, preliminary hydrological budgets have been devised for the pre-development and current 2002/2003 scenarios. For this preliminary analysis, and to simplify the calculations, it has been assumed that during the pre-development phase there were steady state conditions, and that now, after a period of reduction in groundwater storage, the groundwater levels have stabilized and a new steady state has been established. The hydrological budgets for the individual lakes could not be calculated, as there is no available data on the rate of decline, so the study block as a whole has been considered.

These preliminary hydrological budgets have been estimated to give an indication of the size and interrelationships of the various recharge components for the entire study block area. Calculations are included (Appendix G), so the reader can see the methodology, including assumptions and parameters used, based on the information available at this stage. They are based on the water balance equation discussed in Chapter 1, however it has been modified to reflect the input and outputs of the hydrological cycle that are relevant to the Red Rock Complex area. All units used are consistent with the Australian standards of m^3/yr.

Pre-development

$$R_B + Rs + Q_{T1} = E_L + X_S + Q_{LC1}$$

Where;

Q_{T1} = annual throughflow for the Newer Volcanic aquifer, with saturated thickness 25m

R_S = annual recharge for the Newer Volcanics (scoria) within the study block

Q_{T1} = annual throughflow for the Newer Volcanic aquifer, with saturated thickness 25m

E_L = annual net evaporation from Red Rock lakes

X_S = annual groundwater extraction from stock and domestic bores

Q_{LC1} = annual natural groundwater discharge to Lake Corangamite

Current scenario with the 2002/2003 total metered irrigation extraction volume

$$R_B + Rs + R_L + Q_{T2} + Q_{LC2} = X_S + X_I$$

Where;

Q_{T2} = annual throughflow for the Newer Volcanic aquifer, with saturated thickness 20m

R_S = annual recharge for the Newer Volcanics (scoria) within the study block

R_B = annual recharge for the Newer Volcanics (basalt) within the study block

X_S = annual groundwater extraction from stock and domestic bores

X_I = annual groundwater extraction from irrigation bores

R_L = annual net evaporation from Red Rock lakes

Q_{LC2} = annual groundwater flow from Lake Corangamite

Diagrammatic representation of these hydrological budgets for the pre development and current scenarios are presented in Figure 6.1, and the corresponding calculations are presented in Appendix E.

Main point to emerge from this process is that recharge as a percentage of precipitation is < 10%, and not as high as the 30 %, which was suggested by Thompson (1971), therefore groundwater extraction may not be within the actual PAV limits.

Groundwater throughflow represents ~30% of the inflows to the total Newer Volcanics aquifer of the study block However groundwater extraction of 3680 ML during an average year such as 2002/2003, which represents 80 % of the outflows, and produces a corresponding negative recharge to the aquifer, which manifested as a decline in the water table. The assumption of a current steady state system, suggests that the groundwater system has now stabilized, with inflow from Lake Corangamite and the reversal of flow to the Red Rock lakes, is now balancing what is being artificially extracted. This however indicates that saline intrusion may be a greater threat to sustainability and will have greater environmental and economic repercussions than previously considered.

Table 6: Calculated components (m^3/yr) of the hydrological budget, for the (a) pre-development and (b) current scenarios**.**

Component	**Pre-development**	**Current figures 2002/2003**
$\mathbf{X_S}$ Extraction stock & domestic bores	4.6×10^5	9.2×10^5
$\mathbf{X_I}$ Extraction irrigation bores	N/A	3.7×10^6
$\mathbf{R_B}$ Recharge Basalt	2.8×10^5	2.8×10^5
$\mathbf{R_S}$ Scoria	2.6×10^6	2.6×10^6
$\mathbf{R_L}$ Recharge lake area	N/A	4.0×10^4
$\mathbf{E_L}$ Evaporation lake area	8.4×10^5	N/A
$\mathbf{Q_T}$ Throughflow	1.6×10^6	1.3×10^6
$\mathbf{Q_{LC1}}$ Throughflow	3.2×10^6	N/A
$\mathbf{Q_{LC2}}$ Throughflow	N/A	4.0×10^5

N/A: not applicable   Refer to Appendix F for methodology and calculations.

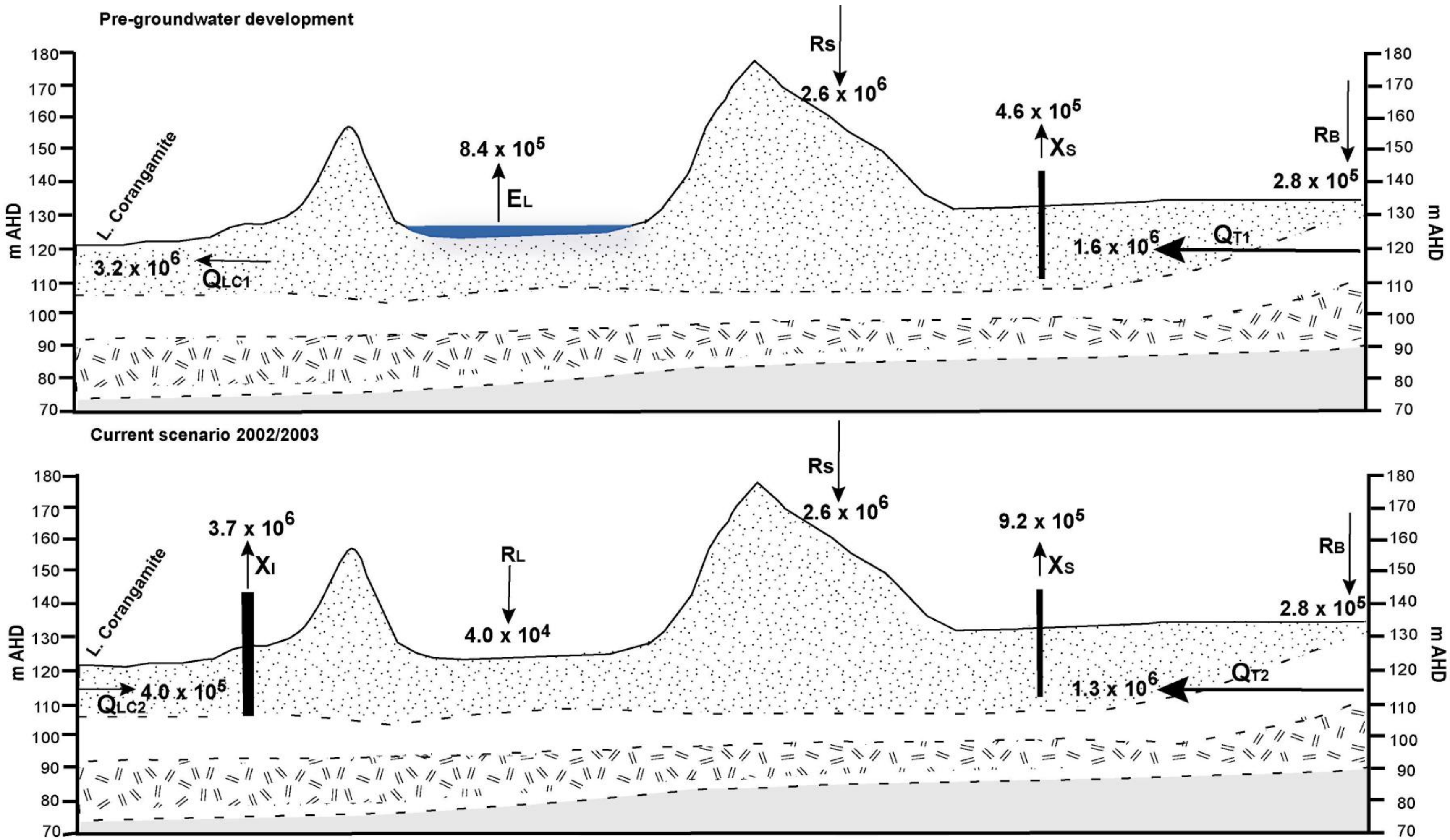

Figure 6.1: Simplified cross-section along A-A' indicating a approximate preliminary estimate of the relative size of the study block components of the hydrological budget (a) Pre-groundwater development (b) Groundwater development during 2002/2003.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

This study of the groundwater-surface water interaction of the Red Rock Complex integrated chemical & physical hydrogeology and meteorology to understand the cause of the drying of the Red Rock lakes. Their decline occurred during a period of substantial groundwater extraction for irrigation, and decreased winter precipitation. The required multi-pronged approach for this study is one that could be applied in other agricultural regions with similar groundwater behavior conflicts. The consideration of groundwater-surface water interactions should be fundamental in all 'sustainable' groundwater management plans.

The conclusions gained from this investigation of the groundwater-surface water interaction of the Red Rock Complex are as follows:

- The Red Rock lakes are a distinct feature in the Western District Plains. They are usually natural groundwater discharge features of the Newer Volcanics flow system in the Red Rock Complex depressions. The lakes have significant social and environmental value and support a rich ecology.

- The Red Rock lakes may be classified as 'discharge' zones when the water table is higher than the lake level, and they receive groundwater inflows. Currently, the depressions simply allow diffuse recharge to the Newer Volcanics aquifer

- Recharge to the Newer Volcanics aquifer and local flow systems is rapid due to the highly permeable pyroclastic and 'stony rise' hummocky topography.
  Regional groundwater flow is from the northeast, however local flow is reflective of the topography and occurs from the northwest, northeast and southwest. Within the Red Rock Complex, there is radial flow toward and away from the depressions, and is reflective of the steep scoria cones and mounds of tuff/ash.

- An increasing EC is observed along the flow path, towards the discharge zones, where evaporative concentration greatly increases the salinity. The lakes' shallow depths and large surface areas made them prone to evaporation, however the absence of halite precipitation implies there was a continual groundwater inflow.

- The Newer Volcanics aquifer is the principal- developed aquifer in the Warrion Parish, with the groundwater used for stock, domestic and irrigation purposes. The tuff/ash/scoria deposits produced from the volcanic activity at Red Rock Complex, Mt Alvie and Mt Warrion locations, form thick fertile soils suitable for crops and there is a concentration of irrigation bores surrounding these eruption centers to take advantage of these rich soils. As a result, 62 % of the total extractions within the WGSPA occur within the study block, which however only represents ~25 % of the total WGSPA surface area.

  The total metered groundwater extraction during 2002/2003 was 3680 ML in the study block. Although this was below the estimated PAV for the WGSPA, a preliminary hydrological budget using a more conservative estimate of the inputs, than Thompson (1971), highlights that the percentage of ground water throughflow is considerable. In addition, this 2002/2003 metering may not be representative of extractions during the drying period as the 2000-03 hydrographs indicate the development of a new steady state system. Recharge would have actually increased compared to the drying period, as the adjoining shoreline of Lake Corangamite and the Red Rock Complex lake depressions have changed from groundwater discharge areas to areas that allow recharge of the Newer Volcanics aquifer.

- Development of the Newer Volcanics aquifer has threatened the sustainability of groundwater-surface water system by lowering the water table. Active saline intrusion has occurred nearby Lake Corangamite, due to the development of a regional cone of depression.

- The cause of the drying of the lakes is due to this lowering of the water table primarily by groundwater extraction for irrigation. Decreased recharge and input from the lakes' surface water catchment, has been a minor contributing factor.

This investigation into the groundwater-surface water interaction of the Red Rock Complex and the cause of the drying of the lakes had to be based on minimal data, as SOB and lake level monitoring was limited. In addition the proposed new SOBs in the remaining lakes had not been completed during this study period. Consequently anecdotal evidence with its vagueness and inconsistencies has had to be used more than one would have liked.

The groundwater system in the study area has explicit economic values, which can be calculated by the associated agricultural profits. However, the environmental/aesthetic value of the groundwater-surface water system cannot be measured as simply. In general, historically, the economic value of groundwater systems have been considered over the associated inherent values. However, changes in attitudes by recent governments have seen a shift back towards environmental focus. This shift is evident by the increasing production of management plans, and environmental publications, including "Securing our water future"(Vic. Gov. 2003) aimed at informing the community about the vulnerable nature of Victoria's diverse water resources.

FURTHER WORK

Sustainability of the groundwater resource should be a great importance in the Red Rock Complex/ Warrion Hill area, as it has both high economic and environmental value. The quantification and prediction of future groundwater behaviour with respect to current practices, was out of the scope of this study. The following recommendations for further study are considered essential for an informed prediction and implementation of a corresponding management plan:

- Construction, monitoring and chemical analysis of the remaining proposed SOBs within the Red Rock Complex. Would also be beneficial to monitor a SOB that represents the full thickness of the Newer Volcanics aquifer.

- Metering of all irrigation bores in the Red Rock Complex/Warrion Hill area, including representation of dairy, stock and domestic bores.

- Enhancement of the existing bore network to include SOBs close to Lake Corangamite. These would monitor the salt wedge position and its future migration, if groundwater extraction continues adjacent to Lake Corangamite.
  Salinity monitoring of all irrigations bores < 200m from Lake Corangamite, including sampling at least at the start and end of every irrigation season.

- Refinement of hydraulic parameters and detailed geologic mapping for inclusion in modelling to simulate groundwater behaviour and better estimate the sustainable yield. This numerical modelling could include a stratified random approach where by hydraulic conductivity, bore yields and recharge is considered in each grid cell.

- To better decide on the relative value of the lakes, with a thriving ecosystem versus the economic benefit of agricultural production from the irrigation. This information combined with the numeric modelling will allow amore representative PAV and management of separate zones in the WGSPA.

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- 1969-2003 monthly evaporation, Wuriboluc Reservoir met. station (87126)
- 1982-2002 monthly temperature, Weearoinah temperature station (90083)

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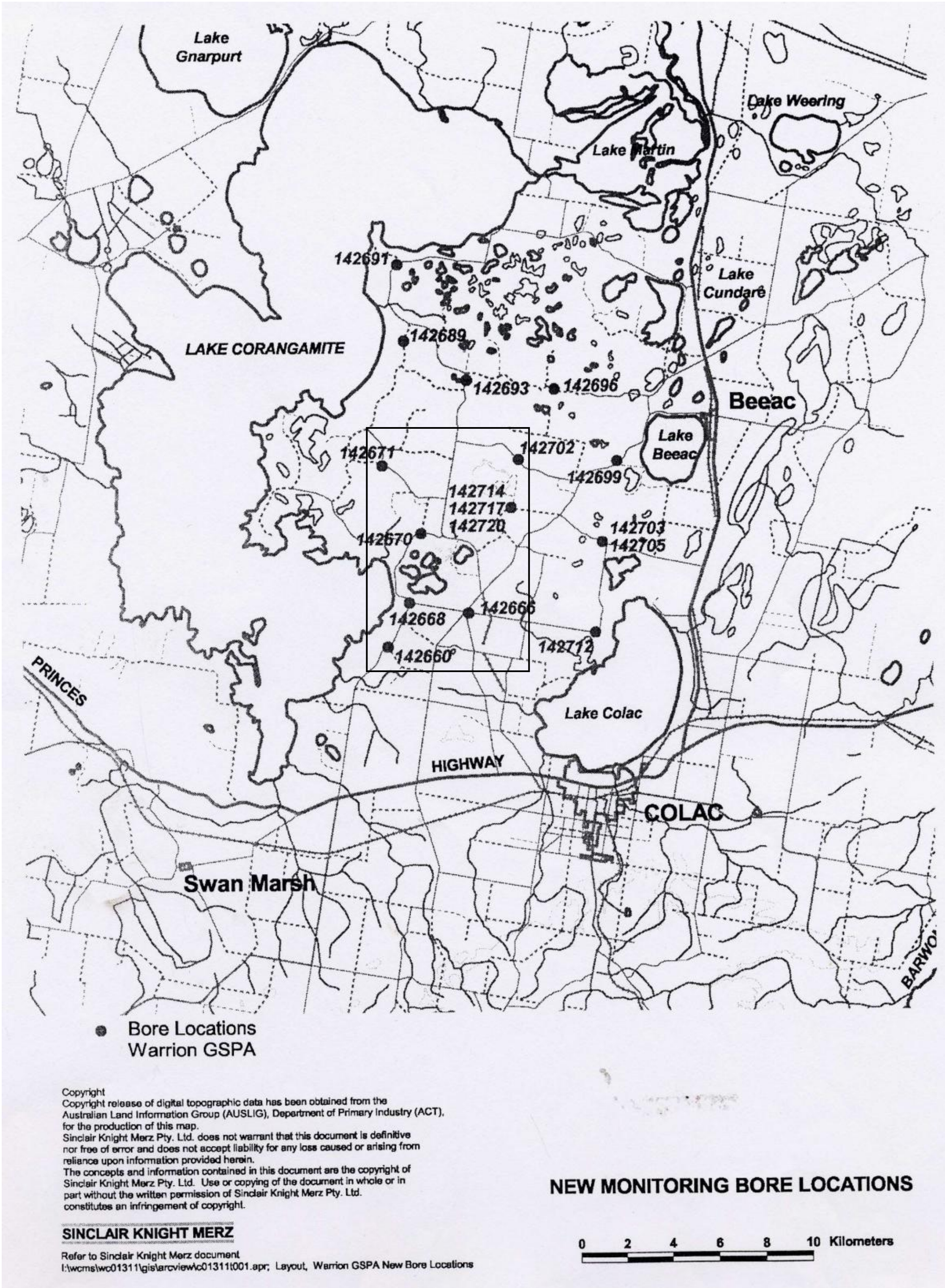
Appendix A: Details of the Warrion Groundwater Supply Protection Area

In 2000 the Warrion Groundwater Management Area was declared a Groundwater Supply Protection Area. Consequently a series of documents were produced addressing the threat of the following sustainability issues (Nolan ITU 2001; WGSPACC 2002):

1. Saline intrusion
2. Unsustainable use of groundwater (mining)
3. Impact of declining levels on bore performance
4. Impact of declining levels on baseflow in significant surface water systems.

The following diagram shows the extent of the WGSPA- which encompasses The Red Rock Complex.



Warrion Groundwater Supply Protection Area, after SRW (2003)

Appendix B: Warrion 5 Borehole Data

The Warrion 5 is closest deep borehole to the study area, located on the eastern side of the study block beside Rayns Rd. The stratigraphic summary of Warrion 5 bore hole is given in the following table. The local geological depositional history is considered comparable to this lithology (Tickell et al. 1991).

The stratigraphic profile of Warrion 5 (Tickell et al. 1991).

Geological Unit	Newer Volcanics (Qvs)	Gellibrand Marl (Tmi)	Demons Bluff Formation (Ted)	Otway Group (K)
Depth to top of formation (m AHD)	0	32	396	469

Appendix C: Construction of the State Observation Bores

Drilling Preliminaries

SKM developed a specification for the bore construction and tenders were invited from reputable, experienced water well drilling contractors. From the tenders received Western District Drilling (based in Terang) was awarded the drilling contract.

Prior to mobilization of the drilling plant, bore construction license applications (BCLs) were obtained from Southern Rural Water Authority (SRW). BCLs are a mandatory requirement of the Water Act (1989), and a copy of the BCL is given following the bore construction diagram.

Field Program/Drilling Investigation

Western District Drilling Company mobilized their truck mounted, 'table-drive drilling rig' to the Lake Purdiguluc site on 11th August, 2003. The bores were drilled using conventional rotary drilling methods, with compressed air as the drilling fluid. Initially the boreholes were to be spudded in using a blade bit, and completed using a downhole pneumatic hammer should competent rock be intersected. However, the scoriaceous basalt was rapidly drilled with the blade bit and hence the downhole hammer was not used during the drilling process.

During the drilling, a foam additive was injected to facilitate flushing and removal of cuttings from the borehole. This drilling method was selected as it was considered the most rapid means of drilling and completing the bores.

A drill bit is attached to the end of a drill rod (i.e. a hollow hardened steel pipe 4.6 m in length). The drill bit is rotated against the bottom the hole causing fracturing, digging and scraping actions of the geologic material. Pressure is applied to the rods and bit to progress the borehole. Compressed air is fed down the drill rods through the drill bit (and drilling foam) to clear and remove the cuttings from the hole. Cutting samples from every meter of drilling were collected and logged. Refer to Appendix D for the lithological logs of all the SOBs in the study block.

Bore Construction

Following intersection of the water table, which can be deduced from the water blown from the hole by the compressed air, the bore was flushed to enable installation of the casing. The borehole was cased with 50 mm internal diameter machine slotted Class 12 uPVC pipe. The interval screened was selected on-site by the supervising hydrogeologist following a review of the lithological cuttings. Following installation of the screen and casing, a gravel pack comprising of washed quartz gravel was tremmied into the borehole. The gravel pack extended 0.5m above the uppermost screen slots. A bentonite seal was placed above the gravel pack to prevent the migration of water in the annulus.

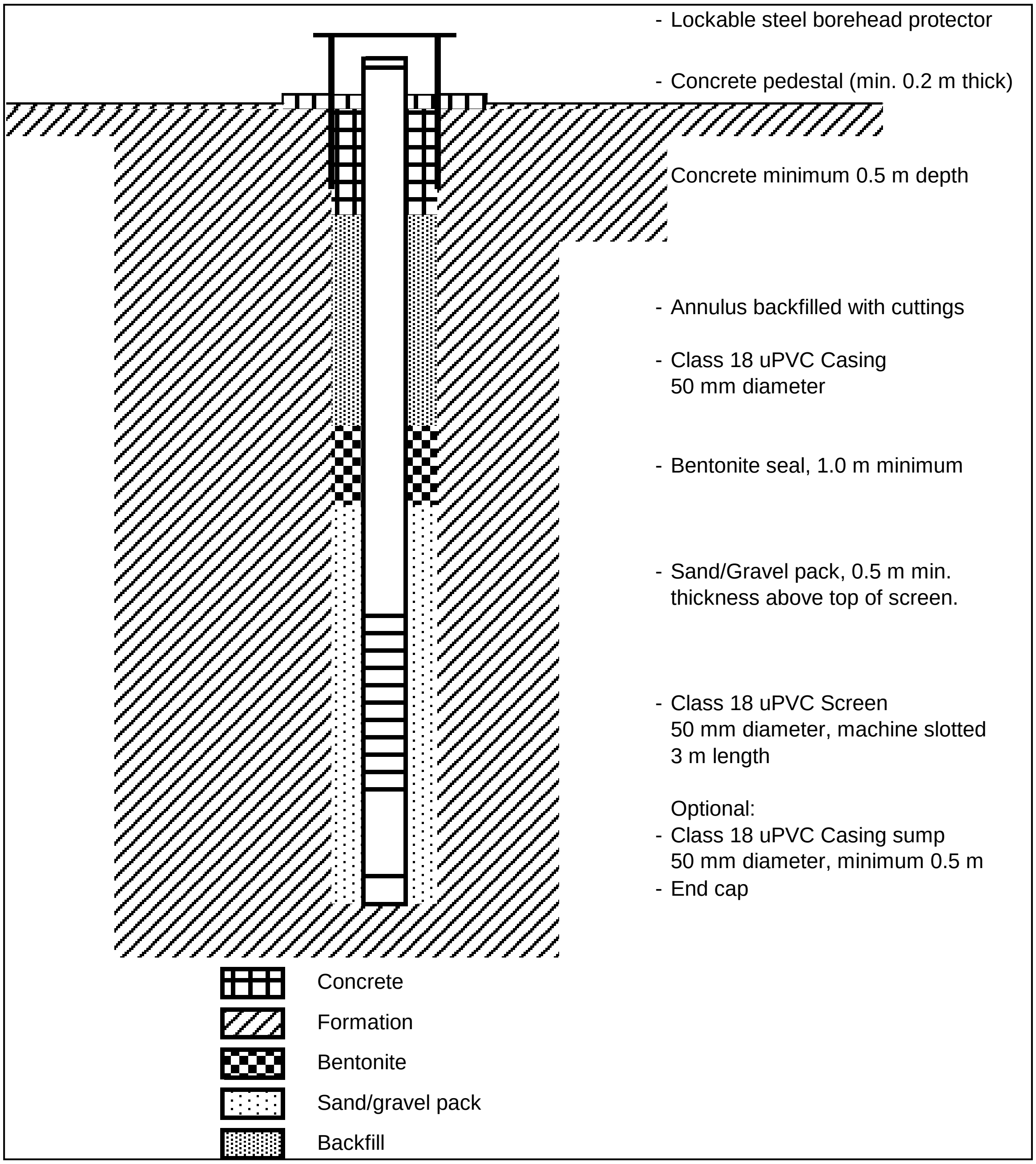
Each bore was subsequently developed using compressed air (airlifting) to remove residual drilling fines, drilling foam, settle the gravel pack and maximize the hydraulic connection with the aquifer. Development was terminated after visual inspection of the water evacuated from the bore. The bores were completed at the surface with lockable steel monuments that were grouted at the surface.

At the time of writing, these SOBs had not been surveyed or given an official SOB identification, hence, for the purpose of this thesis SOB 142AAA is considered to represent ground water adjacent to Lake Purdiguluc, and 142 BBB the groundwater beneath the lake.

Summary of the SOBs characteristics in the Red Rock Complex

Bore ID /location	**142 (AAA)**	**142 (BBB)**
Total depth	12 m	7m
screen lithology	Scoriated basalt	Scoriated basalt
Screen From	7	4
Screen to	11	7

The specified bore design



The Bore Construction License.

GW3

Southern Rural Water JUNE 1994

WATER ACT 1989
Section 67

BORE CONSTRUCTION LICENCE No 61936
(Licence to construct and operate a bore)

Southern Rural Water authorises:

DEPT OF SUSTAINABILITY & ENVIR, C- SINCLAIR KNIGHT MERZ
590 ORRONG RD
ARMADALE 3143

To Construct / Alter and operate a bore on the land described below and subject to the conditions stated.

Lot(s)		**Plan of subdivision no.**	
Allotment(s)	LAKES PURDIGULUC, CORAGUL	**Section**	
Parish	WARRION	**Township**	

for the purpose specified in the application namely: Observation,

This licence is issued for a period of twelve months and expires on 02.06.2004
Date of issue 03.06.2003

CONDITIONS

1. If the bore is considered unsatisfactory, it may be decommissioned and a replacement bore may then be constructed provided that the unwanted bore is decommissioned prior to the drilling rig leaving the site.(C04)
2. This licence authorises the construction of 6 bore(s) at the site(s) provided by the licensee.(C09)
3. The location of each bore must be given to the Authority as AMG co-ordinates listing 1:100,000 AMG map number, easting and northing.(C10)
4. An airline or piezometer for the measurement of water levels must be installed in the bore.(C20)
5. A sample of every water proposed to be extracted for use must be taken after suitable development time and sent to Australian Laboratory Services, Clayton 03 95384444. [C22]
6. The bore shall be constructed to a standard not less than the standard specified in the minimum construction requirements for water bores in Australia (ARMCANZ, 1997), and to the satisfaction of the Authority. (C23)
7. Decommissioning of the bore(s) shall be carried out in accordance with the "Standard for decommissioning test bores, partially completed and completed bores".(D01)
8. IMPORTANT NOTICE
   On your application for these bores you indicated a proposed depth of 20 metres. As a result, these bores must be drilled by a Class 1, Class 2 or Class 3 driller licensed under the Water Act 1989. Please note that for this area a Class 1 driller is only licensed to drill to a depth of 60 metres.

See over for further conditions and additional information. **Authorising Officer**

All communications should be addressed to :

Chief Executive Officer,
Southern Rural Water
PO Box 153, MAFFRA, 3860
Telephone (03) 51393 152
Fax (03) 51393 150

All communication should be addressed to:

Chief Executive Officer,
Southern Rural Water
PO Box 153, MAFFRA 3860
Telephone (03) 5139 3152
Fax (03) 5139 3150

OTHER CONDITIONS

1. The well head of the bore shall be constructed in such a manner as to prevent the introduction of pollutants.

2. The Licensee must ensure that the bore is constructed at the site as indicated on the licence application form.

3. The location of the bore must be indicated on a map which will be sent to the Licensee after the bore has been constructed. The map must be promptly returned to the SRW.

4. The person responsible for the work is required to send a copy of a bore completion report to the SRW and to the Licensee within fourteen (14) working days after the bore is completed.

5. If the bore is to be located close to a septic tank system and is for domestic use the Licensee is advised to contact the local Municipal Authority to meet any requirements of that local Authority.

6. If a bore is unsuccessful, it is necessary to take action to protect the groundwater resource from wastage or pollution. This may be done by decommissioning the bore in accordance with approved methods.

7. If the bore has not been completed prior to the licence expiring the Licensee may apply to renew the licence.

8. This bore cannot be operated until such time as SRW acknowledges that a duly completed and acceptable Bore Completion Report has been received from you or your driller under the Water Act 1989.

9. Water taken under this licence should not be used for human consumption without appropriate treatment.

10. Bore casing wall thickness shall be sufficient to withstand the anticipated formation and hydrostatic pressures imposed on the casing during its installation, bore development and use - as set out in section 9 'Casing' within the Agriculture and Resource Management Council of Australia and New Zealand's Minimum Construction Requirements for Water Bores in Australia.

Disclaimer:
Due to varying environmental conditions the quality of water taken under this licence is not guaranteed. It is the responsibility of the licensee to establish the adequacy of the water quality as fit for the licensed purpose.

PLEASE NOTE: It is an offence to operate a bore unless all conditions are met.

Appendix D: Drillers Logs for State Observation Bores

BORE ID	LITHOLOGY FROM (m)	LITHOLOGY TO (m)	LITHOLOGY DESCRIPTION
142660	0	1.5	BLACK CLAY
142660	1.5	18	BLACK BASALT
142660	18	24	GREEN CLAY & ROCK PATCHES
142666	0	1	BLACK SILT
142666	1	2	BLACK CLAY
142666	2	11	BROWN CLAY & SILT
142666	11	31	BLACK BASALT
142668	0	1	BLACK CLAY
142668	1	2	BROWN SILT
142668	2	7	BLACK SILT
142668	7	9	BROWN CLAY
142668	9	14	BLACK BASALT
142668	14	15	RED SCORIER
142668	15	17	BLACK BASALT
142668	17	18	RED SCORIER
142668	18	24	BLACK BASALT
142670	0	1	BROWN CLAY
142670	1	4	BROWN SILT
142670	4	5	LIGHT BROWN SILT
142670	5	17	BLACK BASALT
142670	17	18	RED SCORIA
142670	18	19	BLACK BASALT
142671	0	1	ROAD FILL
142671	1	3	BROWN CLAY
142671	3	11	BLACK BASALT
142671	11	19	RED SCORIA
142702	0	2	BROWN CLAY
142702	2	3	BROWN WEATHERED BASALT
142702	3	22	BLACK BASALT
142702	22	31	RED SCORIA
142714	0	1	BROWN CLAY
142714	1	3	BROWN CLAY & BASALT
142714	3	15	BLACK BASALT
142714	15	18	BLACK WEATHERED BASALT
142714	18	25	BLACK BASALT

142717	0	1	BROWN CLAY
142717	1	3	BROWN CLAY & BASALT BOULDERS
142717	3	15	BLACK BASALT
142717	15	18	BASALT
142717	18	50	BLACK BASALT
142717	50	52	GREY CLAY
142720	0	1	GREY CLAY
142720	1	3	RED SILT
142720	3	9	BLACK BASALT
142720	9	18	BROWN CLAY & SCORIA
142720	18	49	BLACK BASALT
142720	49	56	BLACK CLAY
142720	56	59	GREY SAND 7 CLAY
142720	59	72	GREEN GREY CLAY

Appendix E: Characteristics of SOBs

SOB Id. No.	Total Bore Depth (m)	Bore location		Bore Elevation (m AHD)
		Easting	Northing	
142660	24	716810	5759325	135.82
142666	31	720270	5760770	134.95
142668	24	717740	5761215	127.60
142670	19	718270	5764230	125.30
142671	19	716640	5767160	134.46
142702	31	722490	5767400	143.83
142703	18	726150	5763810	128.34
142705	54	726150	5763810	128.34
142712	23	725810	5759885	122.14
142714	25	722140	5765325	137.25
142717	52	722140	5765325	137.25
142720	72	722140	5765325	136.98

Appendix F: Preliminary Hydrological budgets

These preliminary hrydrological budgets were constructed to provide a link to further modeling, and are considered to be the first step towards quantitative analysis. The available data on which these budgets were constructed was limited, thus sensitivity analysis was used to estimate values of unknowns, including recharge via the scoria and 'stony rise' basalt. It is considered that the 30% recharge estimate by Thompson (1971) is too high.

The most important assumption made for these hydrological budgets is that for both scenarios the groundwater system was/is in steady state, where inflows equal the outflows.

For both the pre-development and current scenario, the study block is considered to have the following constants:

Study Block Area	80000000.00	m^2
Total Lake Area[1]	965984.63	m^2
Study Block- Lake Area	79034015.37	m^2
(P) Precipitation/yr	**0.59**	m
(E) Potential Evaporation/yr	**1.34**	m
(El) E-P x lake area	**847500.15**	m^3

[1] Total lake area estimated after Timms (1983)

The following parameters are assumed have changed between of two scenarios, and their respective values are given in the following table.

SYMBOL	DESCRIPTION	PRE-DEVELOPMENT (m^3)	2002/2003 (m^3)
E_L	Evaporation from lakes	8.4×10^5	N/A
X_s	stock bores	4.6×10^5	9.2×10^5
X_I	irrigation bores (actual)	N/A	3.7×10^6
R_B	Recharge from basalt (0.03*(0.25*SB)*P)	2.8×10^5	2.8×10^5
Rs	Recharge from scoria (0.07*(0.75*SB)*P)	2.6×10^6	2.6×10^6
R_L	Recharge from lake area	N/A	4.0×10^4
Q_T	Throughflow (Q): K x **I** x A	1.6×10^6	129232.01
Q_{LC1}	Throughflow to Lake Corangamite	3.2×10^6	N/A
Q_{LC2}	Throughflow from Lake Corangamite	N/A	4.0×10^5

[a] SRW 2003; b Assumed saturated thickness 25 m

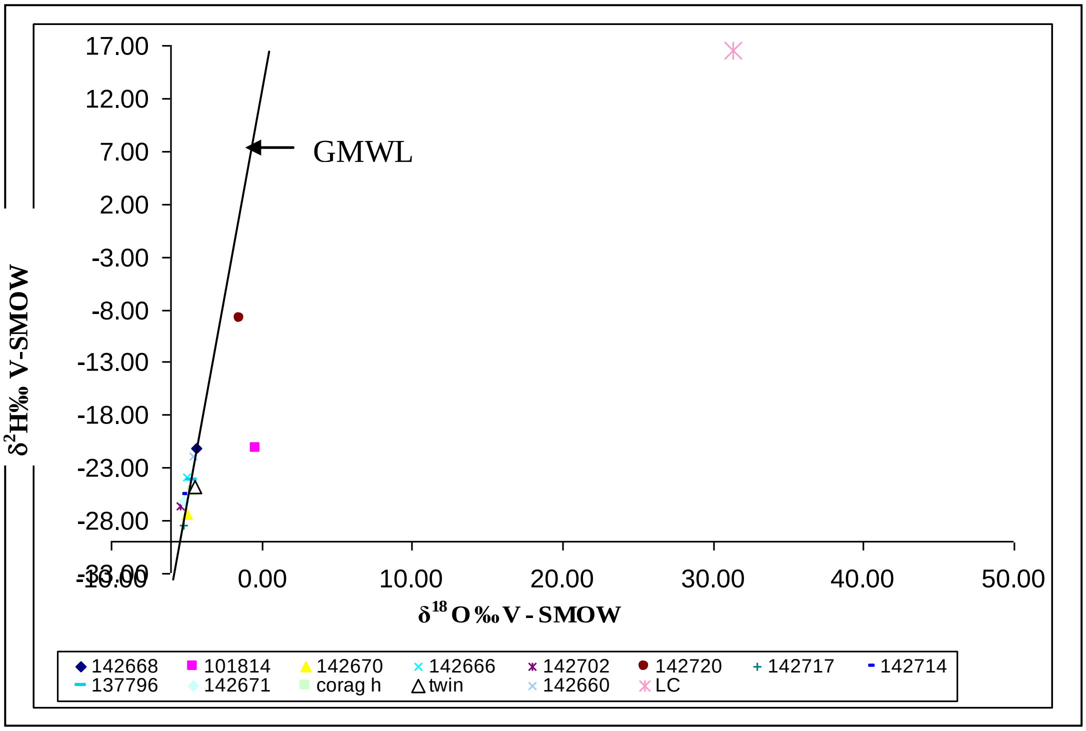
There is only minor metering of extraction from stock and domestic bores (Xs), and no historical volumes. Xs during pre-development period is estimated to be half of what the 2002/2003 estimation from SRW (2003). The 'actual' extraction volume for the 2002/2003 period in the study block was taken from SRW (2003).

It was estimated that basalt ('stony rises') make up 25 % of the surface geology, and the scoria (which includes all pyroclastics) make up the remaining 75% of the surface geology of the study block. The percentage of precipitation that recharges the Newer Volcanics aquifer was estimated using sensitivity analysis. The resultant recharge figure is < 10% (7% for the scoria and 3 % for the basalt) which is considerably less than previously considered. These were determined firstly for the pre-development period, and then applied to the current. Throughflow of the aquifer (Q_T) was calculated using Darcy's Law (Fetter 1994); a hydraulic gradient (I) of 0.0016 (Coram 1996); hydraulic conductivity of 1 x 10^{-5} m/sec (Coram 1995); and an cross sectional area (A) of 384180 m^2 for Q_{T1}, and a subsequent A of 320150 m^2 for Q_{T2}, as the saturated thickness would have decreased by ~ 5m. The length of the cross section corresponds to the hypotenuse of the study block, 12806 m.

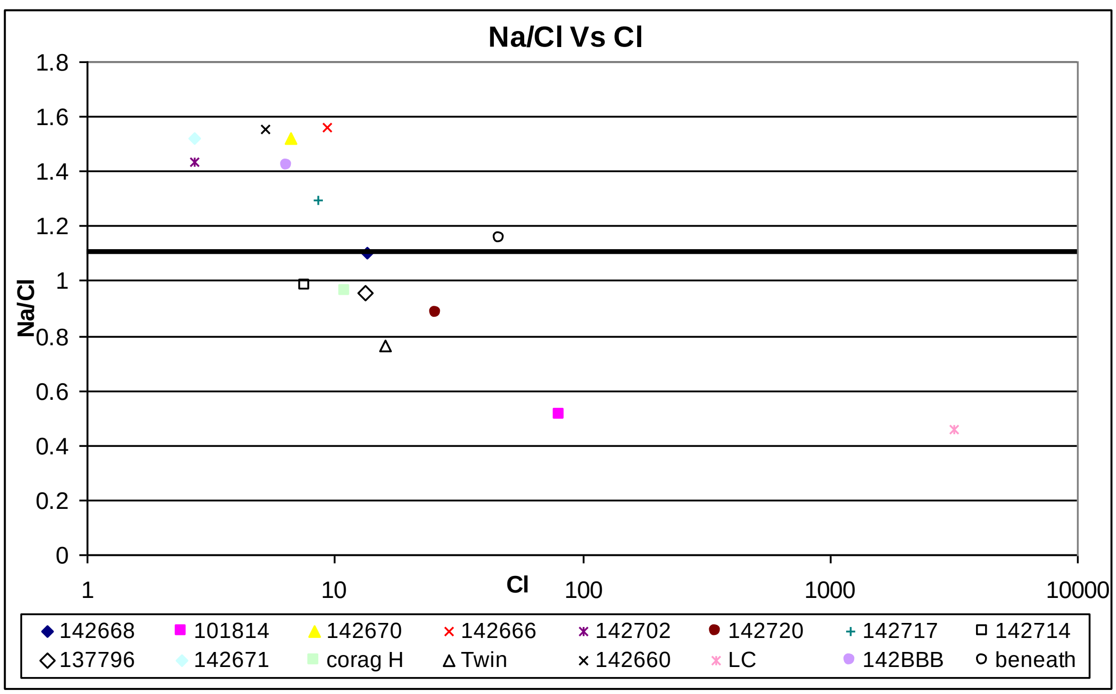
The volume of throughflow to Lake Corangamite (Q_{LC1}) is the resultant difference between the inputs and outputs for the pre-development scenario. The assumed throughflow from Lake Corangamite (Q_{LC2}) is the difference for the current scenario.

It is acknowledged that these components have been based on limited data sets, nevertheless the resultant hydrological budget gives an indication of the relative magnitude of the components. Furthermore, it can be considered that recharge to the aquifer must be less than 30 % of precipitation primarily because otherwise the reduction of the water table would not have occurred.

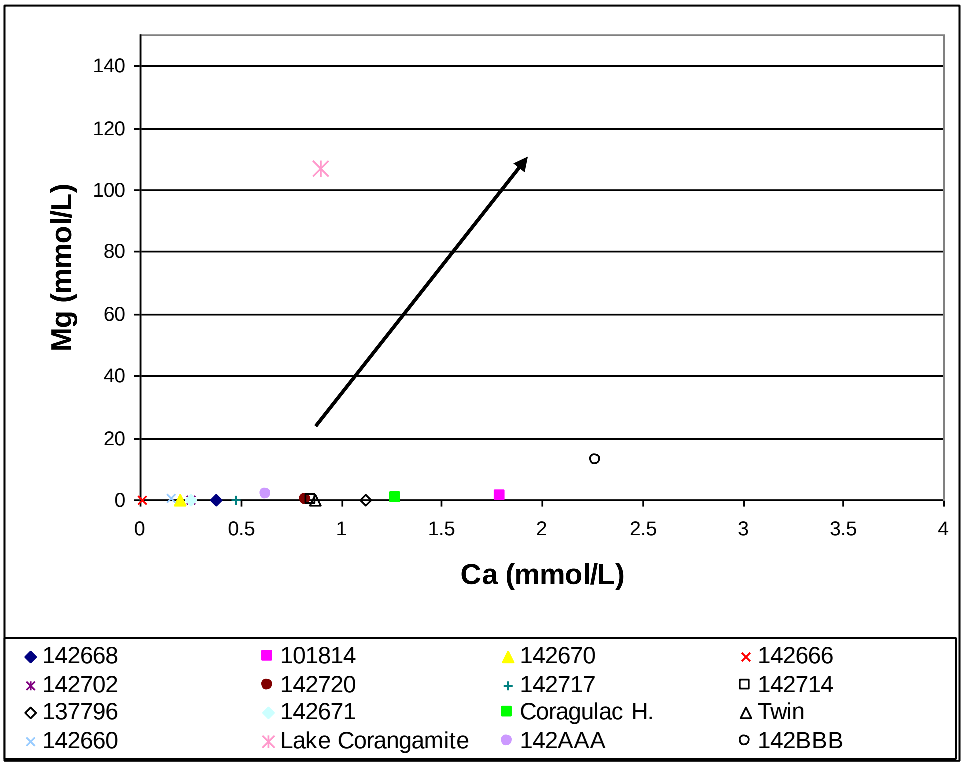
Appendix G Graphs which include Lake Corangamite data points



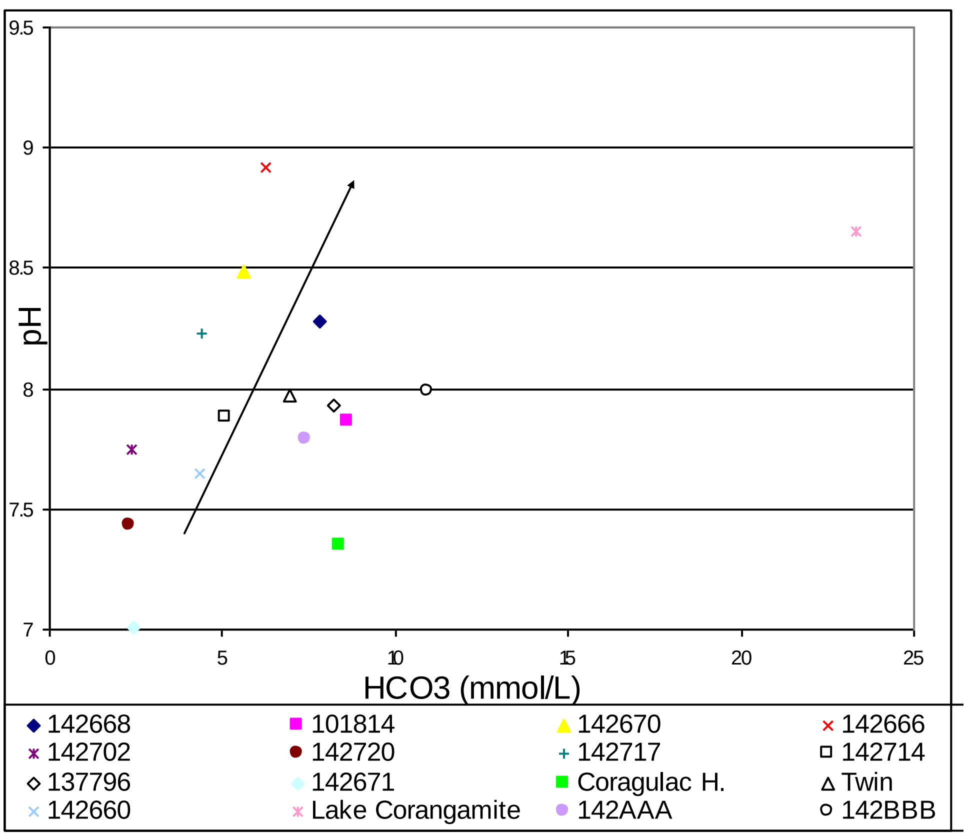
Stable isotopic ratios, GMWL (Craig 1961)



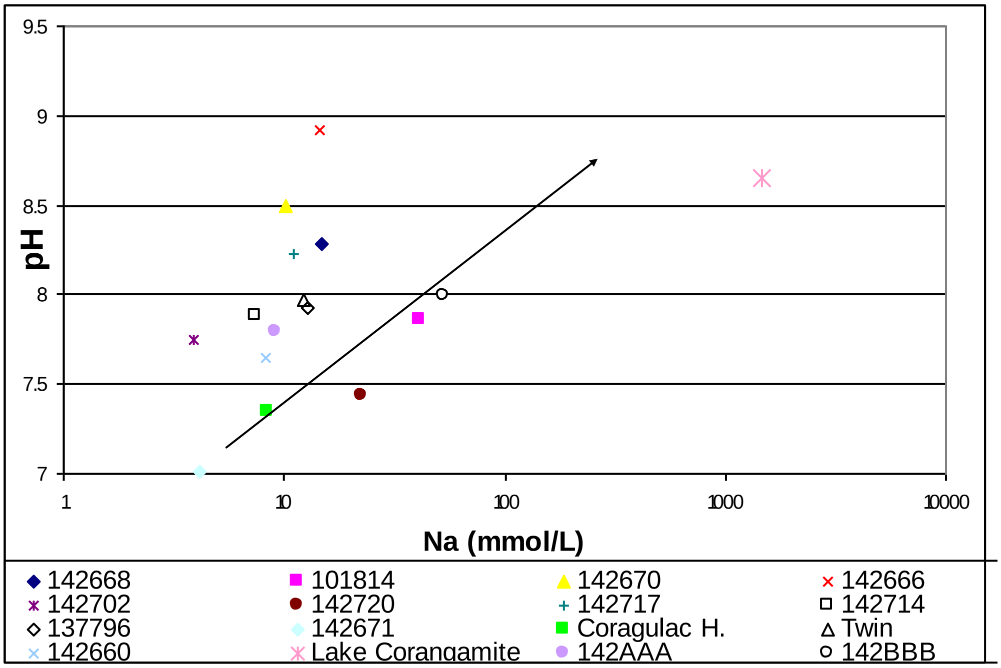
Molar Na/Cl vs Cl



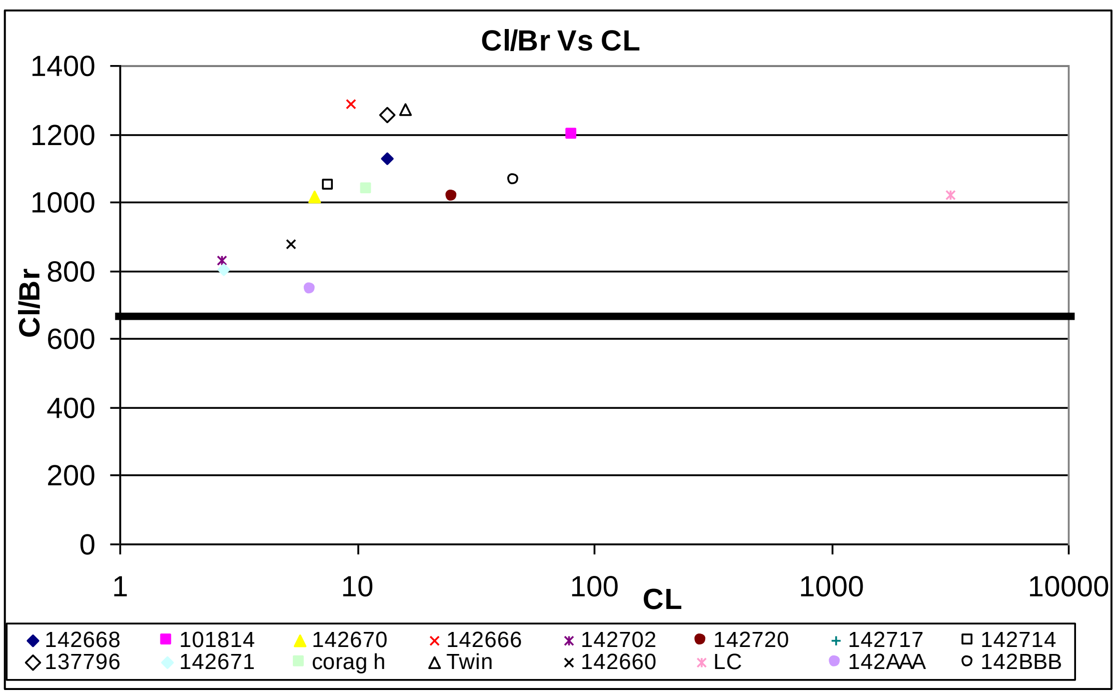
Mg^{2+} vs Ca^{2+} (mmol)



pH vs HCO_3^- (mmol/L)



pH vs Na^+ (mmol/L)



Cl/Br vs Cl^- (mmol)