A HYDROGEOCHEMICAL INVESTIGATION OF THE SURFACE WATER AND GROUNDWATER INTERACTIONS OF A SEMI-ARID WETLAND SYSTEM, WESTERN AUSTRALIA

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[1] This thesis applies the format of the Journal of Hydrology

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Fretwell's law: "Warning! Stable isotope data may cause severe and contagious stomach upset if taken alone. To prevent upsetting reviewers' stomachs and your own, take stable isotope data with a healthy dose of other hydrologic, geologic, and geochemical information. Then, you will find stable isotope data very beneficial" (p52, Kendall and McDonnell, 1998).

Abstract

A 932 ha subcatchment and its associated wetland suite, located in the semi-arid wheatbelt region Western Australia, was investigated in this study. The lower part of the subcatchment exhibits environmental degradation due to altered hydrology resulting from clearing of deep-rooted perennial vegetation. Two main potential threats exist; firstly, upgradient migration of hypersaline groundwater from a regional primary saline valley floor; secondly, increased water and solute loads due to enhanced recharge within the local subcatchment. The hydrological function of the subcatchment and individual wetlands, and uncertainties relating to spatial scales of influence was investigated through combing physical hydrological and hydrochemical methods.

A long-term trend of rising groundwater levels within the study area is evident since the clearing of vegetation, and levels have continued to rise since 2006 at about +0.06 m/yr. A ten-fold increase in the TDS at a hyposaline wetland since 1970 indicates active discharge of both stored and replenished water and solutes to the lower catchment. These trends are occurring in spite of a declining regional rainfall trend since the mid 1970's. The aquifers in the lower discharge area appear to be near full capacity although the subcatchment is yet to reach a post-clearing hydrological equilibrium.

Significant groundwater TDS and density gradients occur across the study area, increasing rapidly down gradient in both the unconfined and semi-confined aquifers. The ionic compositions of groundwater, surface water and rainfall are dominated by Cl^- and Na^-, with overall composition being largely proportional to seawater. Cl^-/Br^- weight ratios indicate that halite dissolution is unlikely to be a primary factor in elevated ionic concentration. Hence, solutes are chiefly sourced from marine-derived aerosols in rainfall. Elevated nutrient concentrations (high N and lower P) were observed, although the absence of algal blooms in wetlands indicates that P is likely a limiting nutrient.

Fractionation enriched stable isotopes (δD and $\delta^{18}O$) and greater ion concentrations are observed in the deep hypersaline semi-confined aquifer compared to the regional primary saline valley floor aquifer. This indicates the occurrence of reflux brines beneath the hypersaline wetland, resulting in the export of solutes to the underlying aquifers. Seasonal changes in both ionic and stable isotope (δD and $\delta^{18}O$) composition within the deep hypersaline semi-confined aquifer further suggest that water and solute exchange is driven by both groundwater head and density gradients.

Excess recharge in the upper recharge domain is expressed down gradient at the lower discharge domain as both groundwater discharge and enhanced surface water flows. This causes persistent shallow water tables, waterlogging, and evapo-concentration of salts in the unsaturated zone and shallow aquifers. The current rate of ET from wetlands, ET losses from shallow water tables and vegetation does not meet recharge excess, resulting in a continuation of rising shallow saline water tables and increased groundwater discharge via wetlands. These processes will continue under the current climate and landuse regime, hence continued biological decline is likely.

The hypersaline groundwater underlying the hypersaline wetland has not migrated significantly up gradient of its area of origin. This suggests that recharge excess in the upper areas of the subcatchment leading to enhanced groundwater discharge, runoff excess, and evapo-concentration of salts in the lower areas is a likely cause of recent post-clearing salinisation, rather than up gradient migration of primary saline regional groundwater. Thus there is potential for management intervention (such as revegetation and engineering) at the local subcatchment scale to mitigate threats to biodiversity assets. This study provides the scientific basis on which that can begin.

CHAPTER 1:

1 Introduction

1.1 Background

The wheatbelt region is located within the Southwest Australian Floristic Region (SWAFR) of Western Australia (Lyons et al., 2004, Keighery et al., 2001, Keighery et al., 2004, Horwitz et al., 2008). The climate within this region is typical of semi-arid environments with annual rainfall deficits due to low rates of precipitation (250-500 mm/yr) and high potential evapotranspiration[2] (ET) rates (typically >2,000 mm/yr) (Hatton et al., 2003, Martínez Alvarez et al., 2008, Luke et al., 1987, Peel et al., 2007). Rainfall is also highly variable and episodic with frequent deviations from long-term averages evident as drought and floods (McEwan et al., 2006, Jolly et al., 2008). The combination of this water limiting environment, variable climate with its frequent episodic events, and long-term geological stability and geographical isolation has lead to very high biological diversity. The area has such high floristic diversity that the wheatbelt region is part of the only global biodiversity hotspot in Australia (Myers et al., 2000, Prober and Smith, 2009). This high diversity includes importantly a high degree of local endemism and persistence of relictual lineages of diverse aquatic and subterranean fauna within groundwater and wetlands connected to these ancient systems (Humphreys, 2009, Humphreys, 2006). Wetlands in the wheatbelt are vitally important refuges during dry periods and often contain endemic and rare flora and fauna. These areas are also important habitats for migratory waterbirds, particularly after significant flooding (Froend et al., 1997, Lyons et al., 2007, Cale et al., 2004, Jaensch et al., 1988, Cale et al., 2011).

The diverse ecosystems of the SWAFR are in many cases under threat from the extensive clearing of native perennial vegetation for agriculture that occurred last century (George et al., 1995, Myers et al., 2000, Beresford et al., 2001). This land clearing has altered the hydrological balance of the region leading to rising saline water tables, waterlogging and salinisation, impacting many wetlands, waterways, and

[2] The physical and biological processes of evaporation, interception and transpiration are often combined together in the literature however this is not always the case and sometimes evapotranspiration may only represent the biological process. Throughout this study, ET refers to the combined physical and biological processes.

woodlands (Short and McConnell, 2001, Clarke et al., 2002, Hatton et al., 2003, McFarlane et al., 2004, Wood, 1924, Cramer and Hobbs, 2002, Froend et al., 1997, Cale et al., 2010, Pinder et al., 2004, Lyons et al., 2004). Altered hydrology[3] is one of the major threats to about 450 plant and 400 animal species in the wheatbelt which are at direct risk from extinction (Keighery et al., 2004). Wheatbelt wetlands and their associated biodiversity assets are particularly vulnerable to impacts from altered hydrology due to their position low in the landscape (Cramer and Hobbs, 2002, Lyons et al., 2004).

1.2 Altered hydrology, the Western Australian story

In the late 1800's and early 1900's, following the clearing of native vegetation, Wood (1924) observed a rapid deterioration of the water quality in reservoirs throughout many areas of the Darling Scarp and wheatbelt region. Wood speculated that the removal of native perennial vegetation caused increased rates of recharge to the shallow soil profile and subsequent recharge of the deeper horizons through confining layers via preferred pathways. The recharge and subsequent rise in groundwater levels of this deeper horizon then mobilised salt-laden groundwater to, or near to the surface. Wood also proposed that the source of the salts was not from decomposing bedrock, but rather the long-term deposition of marine derived aerosols. This theory has been the basis on which much of the current understanding of this issue has been developed over the last 50 years (Bettenay et al., 1964, Speed, 2002, George, 1992c, George et al., 2004, Salama et al., 1993b, Short and McConnell, 2001). In 1996 the extent of broadacre farm land affected by dryland salinity in Western Australia was about 1.8 million hectares (Mha) with two-to-three times this area threatened by salinity unless measures are implemented (George et al., 1999). This figure is likely to be even higher when non-agricultural land is taken into consideration.

1.3 Significance and aims of this study

The Buntine-Marchagee Natural Diversity Recovery Catchment (BMNDRC), located within the wheatbelt region, was selected to focus government and community investment to protect regionally significant biodiversity assets, especially wetlands threatened by altered hydrology (Department of Environment and Conservation, 2008).

[3] The term altered hydrology is used in this document to describe anthropogenic induced changes to any part of the hydrological cycle and the subsequent biological, chemical or physical impacts. Dryland salinity and waterlogging are forms of altered hydrology.

A number of studies have focussed on biodiversity assets of the BMNDRC including vegetation surveys (Huggett et al., 2004, Richardson et al., 2005), aquatic invertebrate studies (Lynas et al., 2006, Storey et al., 2004a, Storey et al., 2004b) and bird surveys (Huggett et al., 2004). Importantly, to assess the threat to biodiversity there were hydrology studies including groundwater (Speed and Strelein, 2004, URS, 2008) and surface water investigations (Short et al., 2006, Sinclair Knight Merz, 2003). These studies have been followed up with extensive and ongoing hydrological monitoring by the Department of Environment and Conservation (DEC).

Research over the last three decades has resulted in an improved understanding of the impact of altered hydrology upon wetlands and their associated biodiversity (Prober and Smith, 2009), although in many cases site-specific hydrological data of sufficient quality, particularly in semi-arid environments, is often lacking. Management intervention in the absence of adequate data can be implemented using “best practice” or “no regrets” principles (George et al., 1995) but must be implemented carefully. Failure to adequately understand the hydrological function of a wetland, including the environmental water requirements (EWR) of resident biota, can result in the adoption of ineffective or in some instances inappropriate management strategies (Walshe, 2005, Walshe et al., 2007).

In spite of the growing knowledge-base in the BMNDRC there are significant gaps in our understanding of the current and future threat from altered hydrology to its wetlands and associated ecosystems. In order to undertake a site-specific threat assessment and implement management options a more robust hydrological analysis (this study) is required. The research area, which lies near the BMNDRC’s western boundary, was selected for this study because the biological values of this suite of wetlands were determined to be at the greatest threat from altered hydrology (URS, 2008). Recent vegetation health surveys (DEC, Unpublished data) and remote sensed vegetation health data (Zdunic and Behn, 2010) identified continued decline in vegetation health in the study area. The aims of this study are to:

Objective 1: Determine the hydrogeological, hydrochemical and stable water isotopic characteristics of a suite of wetlands and subcatchment (the study area) located in a semi-arid environment;

Objective 2: Apply these hydrogeochemical characteristics to elucidate the current (2009) hydrological function of the study area, specifically the relative proportions of different water fluxes to individual wetlands; and

Objective 3: Assess the threat of altered hydrology to a high biodiversity wetland system and review potential options for management intervention to mitigate identified threats.

1.4 Thesis structure

This thesis contains eight main chapters, which are discussed individually below:

Chapter 1, the “Introduction” provides a general background on semi-arid environments, the wheatbelt region and its associated biodiversity. An introduction to the development of altered hydrology and its impacts upon biodiversity in the wheatbelt are also provided. The justification, objectives and scope of the research are presented.

Chapter 2, the “Literature Review” summarises hydrological studies of wetlands in semi-arid climates with a focus on conceptual and applied water and solute balances. This chapter also contains a brief discussion of the use of physical hydrological methods coupled with hydrochemical and stable water isotope data, identifying crucial knowledge gaps. Case studies are used to elucidate common complexities.

Chapter 3, the “Site Description” provides an overview of the field area at both the regional and local scale. The study areas current and historical physical and biological characteristics are described and conceptual hydrological models are presented to provide a foundation for the following chapters.

Chapter 4, the “Materials and Methods” provides summaries of the monitoring infrastructure, sampling, analysis and interpretation methods.

Chapter 5 details the physical hydrogeological characteristics of the study area in detail. The simple conceptual understanding of groundwater flow processes in the subcatchment and suite of wetlands presented in Chapter 3 are expanded significantly. The presentation of historical rainfall trends and those observed throughout the study period provide context to the observed groundwater and surface water trends (water flows and stores). Additionally, total dissolved solids (TDS), will be included to allow the influence of density-dependant flow on the physical flow regime and water balance of individual wetlands to be accounted for.

Chapter 6 details the hydrochemical and stable water isotope characteristics of both fluxes and stores of groundwater, surface water, and rainfall to provide additional detail on the hydrogeological regime of the study area. The analysis of stable water isotopic data in combination with the often conservative tracer of chloride will be used to gain insight into the key processes driving degradation at individual wetlands.

In Chapter 7, hydrogeological, hydrochemistry and stable water isotope data are combined to solve a water and solute balance at monthly and annual time scales. These data are then applied to estimate the pre-clearing water balance to quantify the magnitude of hydrological changes which have subsequently led to decline of its biodiversity values.

Chapter 8 provides a synthesis of this investigation with concluding remarks. Uncertainties identified in this study are highlighted and suggestions are then made to improve the conceptual hydrological understanding of the study area and its wetlands. Results from this study are then applied to identify potential options for management intervention to mitigate threats to biodiversity from altered hydrology.

CHAPTER 2:

2 Literature Review

2.1 Water balance of wetlands in a semi-arid climate

A water balance is a quantification of water (and solute) stores and fluxes that is spatially and temporally bound (Dogramaci et al., 2003, Marimuthu et al., 2005a, Peck, 2000, Salama et al., 1993b, Turner et al., 1984). A water balance is typically undertaken within a defined catchment, with a nominal annual, monthly or daily time period, although seasonal or sub-daily temporal boundaries are also commonly used. Three main components comprise a water balance; inputs – precipitation (rainfall, snowfall etc), surface water or groundwater inflows (if present), imported irrigation water etc; outputs – including groundwater, surface water, and ET, water abstraction etc; and changes in storage flux.

The choice of spatial and temporal scales of analysis requires careful consideration because results obtained at one scale are rarely applicable at another scale (Klemes, 1983, Farmer et al., 2003). For example the analysis of water use for an individual plant cannot be simply up-scaled to represent water use of a large plantation without consideration of a greater number of factors (Salama et al., 1994, Engel et al., 2005). There are however examples, such as the use of the index-lake method (Walker and Krabbenhoft, 1998), where results from one area can be extrapolated to another if the appropriate scale of analysis is used.

A simple water balance for a system for which surface water and groundwater catchment divides coincide can be expressed as (Equation 2-1):

Equation 2-1

$$P = Q + ET + \Delta S + \Delta G$$

Where P is precipitation, Q is runoff out of the catchment, ET the evapotranspiration, ΔS the change in storage of surface water, and ΔG the change in groundwater storage (Freeze and Cherry, 1979).

A mass balance relationship for a wetland at steady-state can also be expressed as (Krabbenhoft et al., 1990b, Marimuthu and Reynolds, 2005, Marimuthu et al., 2005a) (Equation 2-2):

Equation 2-2

$$\frac{\Delta V}{\Delta t} = G_i + S_i + P - G_o - S_o - ET = 0$$

> Where $\Delta V/\Delta t$ is the change in lake volume (V) over time (t), G_i and S_i are groundwater and surface water inflow rates, G_o and S_o are groundwater and surface water outflow rates and P and ET are precipitation and evapotranspiration respectively.

In Equation 2-1 and Equation 2-2, all of the terms balance for the system in question, however in most situations it is rarely that simple. Inputs and outputs are typically not easily quantified therefore residual terms are often introduced, which creates uncertainty in storage and flux calculation and in turn overall uncertainty in the analysis (Winter, 1981, Hunt et al., 1996). These residual terms frequently incorporate groundwater inflows and outflows, as well as ET losses therefore making it difficult to separate individual components. This leads to errors and unrealistic values for water balance terms (Walker and Krabbenhoft, 1998), which makes it difficult to apply these calculations in wetland management.

Regardless of the size of a wetland or catchment and the length or resolution of available data, a degree of uncertainty and error will always be present in a water balance (Krabbenhoft et al., 1990b, Turner et al., 1984, Marimuthu et al., 2005b, Smithers et al., 1995). This uncertainty means that at worst a catchment water balance may be only a rough approximation (Dogramaci et al., 2003). However the error margins and redundant combined residual terms can be significantly reduced by combining and comparing the results from different methods. The following provides a summary of physical hydrological methods, hydrochemistry and stable water isotopic methods, which when combined using a multidisciplinary approach can provide a sound foundation to understand dynamic and transient hydrological systems, particularly wetlands in semi-arid climates.

2.2 Quantifying water fluxes of a wetland

2.2.1 Physical hydrological methods

Quantification of a wetlands input and output fluxes of surface water, groundwater precipitation, and evaporation through the more commonly applied physical hydrological methods is theoretically relatively simple. However in practice in semi-arid environments, which are typically ephemeral and episodic, it is logistically difficult. For example surface water flows can be accounted for through time-series measurement of water flow rate (gauging) and volume of flow for various depths (rating) allowing us to quantify water inputs and outputs (Ladson, 2008). Although semi-arid environments with low rainfall and low topographic relief result in the common occurrence of low flows which are difficult to measure with conventional methods, whilst periods of extremely high flows can lead to damage of monitoring infrastructure (Marimuthu et al., 2005a). Consequently, surface water data is largely either absent or incomplete. This is particularly the case across most of the wheatbelt region of Western Australia. In the absence of data, runoff volumes are often estimated from rainfall-runoff empirical relationships (i.e. Manning's equation, rational method etc) (Ladson, 2008) which require knowledge of long-term rainfall delivery patterns (De Groen and Savenije, 2000, De Groen and Savenije, 2006).

A sound understanding of temporal trends in wetland water level and the interrelationship with wetland area and volume is required to determine wetland storage and solute storage terms. Knowledge of these relationships can be extrapolated from field water level data combined with detailed bathymetry surveys of wetlands (Department of Land Information, 2004), interpolations derived from aerial photography, or other remote sensed data such as Light Detection And Ranging (LiDAR) collected from an aerial platform. Remote sensed data, which often covers large areas with relatively fine spatial resolution, is becoming more readily available and hence is becoming increasingly popular for large-scale water balance studies (Huang et al., 2010). Tweed et al (2009) for example combined field data with remote sensing (Landsat) data to analyse water budgets and salt loads for 28 lakes in the Corangamite catchment, South-east Australia.

Groundwater inflow and outflow fluxes are especially important for those wetlands with no surface water inlets or outlets (Krabbenhoft et al., 1990a). These fluxes however are the most difficult to quantify in a wetland water balance (McCutcheon et al., 1993, Hunt et al., 1996). Groundwater fluxes can be directly measured through the use of seepage meters (Krabbenhoft et al., 1990a, Krabbenhoft et al., 1990b), or shallow bore networks along a seepage face (Lyons et al., 1995), although these methods require extensive instrumentation, intensive sampling and careful placement of monitoring locations to ensure representativeness of broader conditions (Winter, 1981). These methods are largely unsuitable in clayey or organic-rich sediments due to significant heterogeneity (Winter, 1981). Additionally these methods cannot account for groundwater/surface water exchange occurring within the wetland sediments. More commonly the net groundwater inflow is usually calculated as a residual term to balance a water budget (Winter, 1981). The use of residuals may provide a balanced solution however combining unknown parameters together provides little information on the magnitudes of inflows or outflows. Understanding this information is particularly important when trying to manage solutes, nutrients or other contaminants which are mobilised by groundwater (Turner and Townley, 2006).

Groundwater fluxes can be quantified through analysis of flow nets provided that the aquifers characteristics are well understood (Fetter, 2001, Freeze and Cherry, 1979). Values of hydraulic conductivity, hydraulic gradients, and other aquifer properties such as soil moisture retention characteristics can be routinely collected (Scanlon and Goldsmith, 1997, Dogramaci et al., 2003, George, 1992c). However natural systems are inherently heterogeneous (Harrington et al., 2008, Winter, 1999), hence caution is required when extrapolating these values across broad areas (Hunt et al., 1996, Peck, 1983). Careful consideration of solute gradients is also required because failure to account for variations in density (temperature and ionic concentration) can lead to erroneous interpretations of groundwater flow (Massmann et al., 2006, Sophocleous, 2002, Bachu, 1995, Post et al., 2007, Lusczynski, 1961, Alkalali and Rostron, 2003, Oude Essink, 2001).

In addition to density, temporal variability of barometric pressure can influence groundwater levels in some aquifers (Spane, 1999, Toll and Rasmussen, 2007). Changes in atmospheric pressure can affect the aquifer via pressure changes on the overlying material, or directly on the open bore, with rising barometric pressure reducing groundwater levels (Freeze and Cherry, 1979). This barometric effect on groundwater needs to be accounted for, particularly in areas where hydraulic gradients are minor and barometric gradients large (Rasmussen and Crawford, 1997, Spane, 1999). For example in Bakers Hill, Western Australia, Salama et al (1994) determined that barometric effects accounted for up to 0.03 m/day change in water levels.

In semi-arid climates, groundwater recharge predominantly occurs during those months where rainfall exceeds ET demands. In the wheatbelt region, this occurs most often over winter and early spring although high recharge has been observed subsequent to episodic rainfall events associated with ex-tropical cyclones during summer and early autumn (Lefroy et al., 2001, Marshall et al., 1997). The episodic nature of groundwater recharge in semi-arid environments has significant implications for the genetic and phenotypic evolution of native vegetation.

Considerable information is available on plant water use in semi-arid climates for a large range of annual and perennials species (Robertson et al., 2005, Cramer et al., 1999, Mitchell et al., 2009, Singh and Kumar, 1993, Ward and Dunin, 2001, Marshall et al., 1997, Lefroy et al., 2001, Raper, 1998). The strategies of native and introduced plant species which enable survival and reproductive success in the semi-arid climate include; stomatal conductivity control (Carter and White, 2009); leaf and stem configurations (Nulsen et al., 1986, Mitchell et al., 2009); leaf loss during periods of high evaporative demand (Lefroy et al., 2001); and extensive lateral roots and deep sinker roots, which often extend many tens of metres through the profile (Wildy et al., 2004, Marshall et al., 1997, Bennett and Goodreid, 2009, Burgess and Bleby, 2006). In some cases, these roots extend through relatively impermeable layers (Lefroy et al., 2001). A certain level of salt tolerance within many plant species also enables the uptake of saline groundwater in water limited environments (Cramer et al., 1999). The adoption of these strategies enables the persistence of perennial vegetation in water-limited environments and potentially leads to higher plant water use than is made available through incident rainfall (Marshall et al., 1997, Mitchell et al., 2009, Lefroy, 2003, Wildy et al., 2004).

In some instances groundwater use by vegetation, particularly phreatophytic vegetation in contact with the water table, is detectible in high resolution groundwater level data. Analysis of groundwater hydrographs may therefore enable an interpretation of ET. This area is gaining greater attention given the increasing use of electronic data logging devices in field studies (Gribovszki et al., 2010). Diurnal water table fluctuations, indicative of ET, differ from barometric pressure signals as they typically reach their minimum level during the day due to phreatophytic consumption and their maximum level in early morning due to recovery of the groundwater during the night during respiration (Freeze and Cherry, 1979, Gribovszki et al., 2010). The methods of White (1932) combine rates of water level recovery with knowledge of aquifer properties to derive daily ET rates. This method integrates various water balance components (transpiration, interception, evaporation and recharge) at the stand scale, therefore overcoming problems associated with up-scaling measurements from individual trees (Salama et al., 1994). Over time these methods have been slightly modified, however by-in-large are still widely adopted (Engel et al., 2005, Loheide, 2008). This is predominantly due to the methods requiring very few parameters, are simple to use, and they can be applied at a range of time scales (Gribovszki et al., 2010).

Salama et al (1994) applied hydrograph separation techniques to determine ET rates of vegetation within a plantation of eucalypts. ET rates were assumed to be represented by differences between seasonal groundwater level recession curves both within and outside the plantation. Results derived from this method were comparable to sap-flow measurements of individual trees in the same plantation therefore providing a simple alternative for the measurement of stand-level ET. This method was further extended to the Durokoppin and Kodj Kodjin nature reserves in order to determine ET rates of native vegetation. The methods applied in their study appear to be a useful alternative to the White (1932) method, although it is recommended that site conditions minimise groundwater inflows (i.e. located close to the catchment divide and aquifers having low hydraulic conductivity). Consequently these conditions limit the broader adoption of this method elsewhere.

2.2.2 Hydrochemical methods

Mann (1983) describes a process where a "*chemical imprint*" is left on groundwater which interacts with the weathering environment along an evolutionary flow path. The influence of weathering upon the hydrochemistry of Australian groundwater however is less significant than on other continents due to its long period of geological stability (Herczeg et al., 2001, Herczeg and Lyons, 1991). Other processes such as the deposition of marine-derived aerosols from precipitation (Hingston, 1958, Hingston and Gailitis, 1976, Bettenay et al., 1964); dissolution and precipitation of evaporites (Salama et al., 1993b, Davis et al., 1998); exclusion of chloride during plant water uptake (Bennetts et al., 2006); and cation exchange (Cartwright et al., 2009); in many cases play a more important role in the ionic composition of groundwater than the weathering of aquifer minerals (Herczeg et al., 2001).

In contrast to continents with high inland topographical relief, rainfall gradients across Australia decline with distance from the coast. The ionic composition and concentration trends of rainfall in Australia reflects its marine origin, being dominated by sodium (Na^+) and chloride (Cl^-) and these geographical gradients lead to solute concentrations decreasing with increased distance from the coast (Hingston, 1958, Hingston and Gailitis, 1976, Bettenay et al., 1964). Distinct geographic trends in ionic ratios are also notable, with ratios such as Cl^- to Bromide (Br^-) decreasing with distance from the coast due to Cl^- depletion in rainout (Cartwright et al., 2006). The hydrochemical characteristics of surface water are initially determined by precipitation characteristics, however alterations to the chemical properties occur in a similar fashion to groundwater through processes such as ET, dissolution and precipitation of evaporites and interaction with other water sources (i.e. groundwater and interflow). As a consequence of these processes different water sources typically have varying water chemistries. These differences can be used to define distinct end-members which is benefitial when applying a mass balance approach to water balance studies. Therefore chemical analysis of water fluxes can provide an invaluable insight into a wetlands hydrological functioning by advancing an understanding of groundwater-surface water interactions and the evolution of water sources and mineral-water interactions.

The most common form of hydrochemical analysis is the field measurement of electrical conductivity (EC) and pH, while the more accurate laboratory analysis of the major cations (Na^+, K^+, Mg^{2+}, Ca^{2+}), and anions (Cl^-, HCO^{3-}, SO_4^{2-}, NO^{3-}) is also prominent (Appelo and Postma, 2007). The analysis of major ions and other additional individual ions, such as Br^- and Sulphate (SO_4^{2-}) provide some useful information on the origin and evolution of a water flux however these tools are most powerful when interpreted in combination as ionic ratios (Salama et al., 1993b, Davis et al., 1998, Cartwright et al., 2009).

Chloride (Cl^-) most often behaves as a conservative ion and is therefore frequently used as a hydrochemical tracer of water movement, particularly groundwater flows (Peck and Hatton, 2003, Peck and Williamson, 1987), recharge (Allison and Hughes, 1978, Cook et al., 1989, Edmunds and Gaye, 1994, Gates et al., 2008, Salama et al., 1993b) and groundwater/surface water interactions (Dutkiewicz et al., 2000). One of the limitations of using Cl^- to determine recharge rates is the difficulty in accounting for other processes that may influence its concentration, such as terrestrial recycling, the dissolution of halite, and anthropogenic inputs (Cartwright et al., 2006). Interpretations of recharge rates with Cl^- nearly is therefore impossible in primary or secondary saline areas due to mixing of different sources, although the relationship between Cl^- and Br^- within water is well understood and can provide a useful indicator of the origins of Cl^- at a given site (Salama et al., 1993b, Cartwright et al., 2006).

The hydrochemical properties of surface water and groundwater fluxes are also influenced by biotic factors. These include respiration by tree roots leading to dissolution of base cations, and the consumption of H^+, which increases HCO_3^- in soil water (Herczeg et al., 1993). The uptake of water by tree roots can result in the exclusion of solutes, particularly Na^+ and Cl^- which subsequently leads to increased salinisation of the groundwater beneath the root zone (Cramer et al., 1999, Herczeg et al., 1993, Herczeg et al., 2001, Cartwright et al., 2009, Bennetts et al., 2006, Heuperman, 1999). Additionally the presence of different functional groups of microorganisms in surface water and the underlying saturated and vadose zone can influence reduction-oxidisation (redox) processes (Maring and Harris, 1982). Microorganisms and redox conditions determine nitrificatation and denitrification processes (Fetter, 1993).

2.2.3 Stable water isotopic methods

Isotopes have been used extensively in groundwater studies primarily because processes such as radioactive decay, and fractionation (see next section) enable the determination of the age and the geographical source of water, which is difficult to determine with other means (Kendall and Caldwell, 1998). Some of the most common isotopes used in hydrogeological studies are tritium (^3H), ^{14}C, ^{32}Si, and ^{36}Cl, which are often used for aging water, whilst deuterium (^2H), radon (^{222}Rn), ^{18}O, ^{13}C, and ^{34}S are often used to differentiate water, based on its exposure to different climatic or geological conditions.

Oxygen (^{18}O and ^{16}O) and hydrogen (^{1}H and ^{2}H) stable isotopes are commonly applied in conjunction with hydrogeological investigations because they are integral components of natural water molecules (Kendall and Caldwell, 1998); their fractionation processes throughout the environment are well understood (Craig and Gordon, 1965, Gat, 1996, Gat and Airey, 2006); and they complement physical hydrology and hydrochemical studies well (Marimuthu et al., 2005b, Krabbenhoft et al., 1990a, Krabbenhoft et al., 1990b).

2.2.4 Stable isotopic fractionation

The stable isotope protium (^{1}H) represents 99.984% of hydrogen in water in the hydrological cycle, whilst deuterium (^{2}H) represents 0.016% and tritium (^{3}H) the remainder (Freeze and Cherry, 1979). Equally, Oxygen-16 (^{16}O) represents 99.97%, ^{18}O represents about 0.2% and ^{17}O the remainder (Rao, 2006). Isotopic fractionation is a process whereby the ratio of heavy and light isotopes of a certain element is altered (Craig and Gordon, 1965, Dawson et al., 2002). This is because atomically lighter species of isotopes form weaker bonds than the heavier isotopes, therefore they are more reactive and are preferentially concentrated in products of the fractionation processes (Rao, 2006).

Isotopic fractionation is temperature dependant and occurs when water shifts from one phase to another (i.e. water to vapour, vapour to ice) (Gat, 1996). For example the evaporation of water from a wetland preferentially removes the lighter stable isotopes ^{16}O and ^{1}H which results in the product (evaporation) being enriched in the lighter isotopes, but depleted in the heavier isotopes (^{18}O and ^{2}H). The remaining water in the wetland is therefore enriched in the heavier isotopes. The more significant the extent of evaporation experienced by the wetland, the greater the enrichment of heavier isotopes will be within the remaining water. With the exception of high temperature waters (Kendall and Caldwell, 1998), ^{2}H and ^{18}O stable isotopes are not affected by water/rock interactions. In the majority of instances[4] the uptake of groundwater by plants does not alter the isotopic signature of the groundwater (Cramer et al., 1999, Twining et al., 2006, Dawson et al., 2002). Therefore in the context of a water balance analysis, the isotopic signature of a wetland should be largely determined by the isotopic signature of

[4] Fractionation is known to occur in some plants such as a marine, salt excluding plant which fractionates ^{2}H but not ^{18}O (see Dawson et al, 1993 for more information).

the source water and subsequent changes caused by evaporation. This concept assumes steady-state conditions, where the water source, whether it be precipitation, groundwater or surface water inflows, remain constant over time. Temporal variability however is evident in all water sources in all climates therefore a sound conceptual understanding of a wetland hydrological function and the stable isotopic characteristics of a wetlands source waters is required.

Oceanic water is considered relatively homogenous and is therefore used as the standard reference for analysis of water samples. The current standard is the Vienna-Standard Mean Ocean Water (or V-SMOW) (Dawson et al., 2002). The conventions for calculating isotope values are based on the following equation:

Equation 2-3

$$\delta = \frac{R_{sample}}{R_{stamdard}} \times 1000$$

Where *R* is the ratio between the heavy and light isotope for the *sample*, divided by the *R standard*.

All isotope results are reported in the conventional notation ($\delta^{18}O$ and δD) as per mil (‰) deviation from the V-SMOW standard (Coplen, 1993). A more negative value implies that the target sample is depleted in the heavier isotope relative to the standard and a more positive value denotes enrichment of the heavier isotope (Gat, 1996). Samples with high concentrations of solutes may influence the $\delta^{18}O$ and δD values due to the effect of ion hydration (Horita, 1989). This "salt effect" can be accounted for using the methods of Horita (1989), which are discussed in more detail in Chapter 4 and Chapter 6. The correction to the isotope activity for $\Delta\delta D$ (activity differentiated from concentration using Δ) for water approaching ionic saturation may be in the order of 6‰ to 15‰, whilst the correction for $\Delta\delta^{18}O$ activity is commonly less than 1‰ (Dutkiewicz et al., 2000, Marimuthu et al., 2005b, Cartwright et al., 2009).

2.2.5 Global Meteoric Water Line

The stable isotopic signature (δD and $\delta^{18}O$) of precipitation varies considerably over both time and space. This variation can be explained by the geographical and temporal variability of source waters and the cooling and heating processes, rainout and recycling of condensation occurring within the atmosphere (Gat, 1996, Gat, 2000, Dansgaard, 1964, Gat et al., 2001, Rich, 2004). The isotopic signature of precipitation at any location is inversely related to temperature. Detailed analysis of varying water sources across the globe since early to mid-last century has revealed that there is a distinct linear correlation between δD and $\delta^{18}O$ in precipitation across latitudes (Gat, 1996). This relationship is called the Global Meteoric Water Line (GMWL) and can be described by the following equation (Gat, 1996).

Equation 2-4

$$\delta D = (8 \times \delta^{18} O) + 10‰$$

> Where the 10‰ constant is referred to as the *d-excess* which represents non-equilibrium conditions that occur during evaporation and 8 is the slope of the line, representing the fractionation relationship between δD and $\delta^{18}O$.

Deviations in the isotopic signature from the GMWL for local precipitation can occur, generating a Local Meteoric Water Line (LMWL). For the LMWL a variation in both the *d-excess* and the slope of the line occurs. A lower *d-excess* value reflects an increasing influence of evaporation on the stable isotope signature of the residual water (Barton et al., 2007). In Perth precipitation, *d-excess* is generally higher in winter and lower in summer (Liu et al., 2010). Several studies have used a LMWL to assist with estimations of water fluxes (Krabbenhoft et al., 1990b, Herczeg et al., 1993, Herczeg et al., 2001, Turner and Townley, 2006, Mayo et al., 2010, Marimuthu et al., 2005b).

Evaporative losses from wetlands are a key component of their water balance which requires intensive sampling in order to quantify (Rich, 2004), therefore it is often derived as a residual term (Winter, 1981). In order to reduce error associated with the use of residual terms, particularly in semi-arid climates where rainfall deficits occur throughout much of the year, the evaporative flux requires specific attention. This can be achieved using a range of methods, such as interpretations based on regional potential evaporation data (via pan-to-lake coefficients); computation of aerodynamic equations (Webb, 1966); or applying an energy budget (Winter, 1981, Allison, 1974). The most accurate method for determining wetland evaporation is the energy budget method (Winter, 1981), although this method requires detailed measurement of in-situ parameters such as long and short wave radiation, air temperature, dew point, and water temperatures of the wetland and all input and output fluxes (Winter, 1981, Zhang and

Dawes, 1998, Rich, 2004). The use of a pan-to-lake (E_{lake}/E_{pan}) coefficient is widely applied to water balance studies because it uses existing meteorological data, which is readily available (Winter, 1981). An annual E_{lake}/E_{pan} coefficient value of 0.7 is generally used (Allison, 1974, Marimuthu et al., 2005b), however the nature of Class-A evaporation pans (Ladson, 2008); the distance of pan from the area of interest (Winter, 1981); and wetland characteristics, particularly temporal variation of solute concentration, water depth, and temperature can all cause deviations from the coefficient (Marimuthu et al., 2005b, Rich, 2004).

Krabbenhoft et al (1990b) measured the stable water isotopic signature (δD and $\delta^{18}O$) of atmospheric vapour to determine the evaporative flux from a wetland. This approach is unusual because atmospheric and evaporative fluxes are typically estimated upon theoretical mass balance relationships based upon the Craig and Gordon (1965) model. They found that measured atmospheric moisture closely resembled the theoretical vapour in isotopic equilibrium with precipitation, except during the warmest months. The proximity of nearby lakes may provide some explanation for this result however the small spatial variation at the lake of interest indicated that local conditions had little influence on the atmospheric vapour composition. Rich (2004) went to greater lengths to quantify evaporation from Perry Lakes in Western Australia. In his study, daily measurements of pan evaporation (evaporate to dryness and volume constant methods) for a period of 23 months were complimented with direct measurement of atmospheric (δ_A) and evaporative (δ_E) isotopic signatures (predominantly using δD). Rich (2004) found that theoretical estimations of δ_E derived from measured values of δ_A were similar to measured δ_E and noted that the results were identical using the equations of Allison and Leaney (1982) and Craig and Gordon (1965). However the former were compromised by the difficulties associated with the measurement of humidity at the water/air interface.

The measurement of δ_A is easily sampled, whilst δ_E is very difficult, therefore it is logistically impractical to undertake on a regular basis (Rich, 2004). Theoretical estimates appear to adequately represent likely values consequently the terms of δ_E and δ_A are more commonly estimated (Fellman et al., 2011, Gibson, 2002, Gat and Airey, 2006, Twining et al., 2006, Rozanski et al., 2001). However, large water balance uncertainties, up to 50%, can be introduced due to uncertainties in estimations of δ_E (Zimmerman & Ehhalt, 1970 cited in Rich, 2004).

2.3 Application of a multidisciplinary approach to water balance studies

Physical hydrological, hydrochemical and stable water isotopic methods can be applied to calculate individual components of a wetland water balance however, each of these methods has its limitations and levels of uncertainty. These methods are most effective when combined because error and uncertainty can be reduced.

Cartwright et al (2009) used hydrochemical and stable isotope data in the absence of detailed hydrological data to better understand surface water and groundwater interactions in wetlands from the Willaura region in south-eastern Australia. Major ions, Br^- and stable isotopes (δD and $\delta^{18}O$) were sampled from groundwater monitoring bores and wetlands over a 12 month period. The "salt effect" (section 2.2.4) was applied to stable isotopic signatures to account for the high solute concentration in water fluxes. The use of ionic ratios, particularly Cl^-/Br^- provided an important insight into the role of halite precipitation and dissolution and the influence of evaporation of lake water upon the shallow saline groundwater. The dataset gained from their study enabled a rapid and qualitative assessment of wetland type (i.e. groundwater recharge, discharge, or flow-through), and hydrological function. Ionic ratios, particularly Cl^-/Br^-, were useful in differentiating between ET losses and discharge losses to the underlying shallow groundwater. In spite of wetland volumes appearing to be relatively static, the stable isotopic and hydrochemical trends in the wetlands were dynamic, therefore highlighting the shortcomings of basing a water balance upon physical hydrology characteristics alone. This study also recognised the context of the dry climate which preceded their study and the potential implications of return to average or wetter periods upon the development of salinity in the future.

Herczeg et al (2001) analysed major ions, Br^- and stable water isotopes (δD and $\delta^{18}O$) in groundwater and pore water (connate water) in the Murray Basin in South-eastern Australia. Over 100 locations were sampled over a ten-year period along a 350 km flow path. This data was combined with published literature in order to test various hypotheses on the origin and evolution of salt in groundwater. Analysis of major ions indicated that ET increased Na^+ and Cl^- concentrations, whilst changes in ratios and concentrations of other ions were largely due to cation exchange, reverse weathering, and carbonate dissolution and precipitation. A catchment-scale salt balance discounted the weathering of minerals as a source of the salts and Cl^-/Br^- ratios were used to discount the contribution of halite dissolution. Stable isotope signatures of δD and $\delta^{18}O$ were typical of mean winter rainfall therefore indicating meteoric sources of salt rather than a dilution of remnant sea water. The multidisciplinary approach taken in this study provided "compelling" evidence that the source of salts in the Murray Basin in South-eastern Australia was due to the long-term deposition of airborne oceanic aerosols transported inland by precipitation, combined with ET and long periods of relative aridity.

Evaporation of water from a wetland results in increased Na^+ and Cl^- concentrations and enrichment of the stable isotopes δD and $\delta^{18}O$. Conceptually, the groundwater outflow from a wetland influenced by evaporation therefore represents a solute and isotopically enriched plume, analogous to a mobile contaminant. In a study of Sparkling Lake in northern Wisconsin, USA (Krabbenhoft et al., 1990a, Krabbenhoft et al., 1990b), physical hydrological methods were complimented with analysis of δD and $\delta^{18}O$. The resulting datasets were used to calibrate a steady-state finite difference, three-dimensional groundwater flow and solute transport model to determine groundwater flows. The two companion studies (Krabbenhoft et al., 1990a, Krabbenhoft et al., 1990b) successfully derived groundwater inflow and outflow rates for a lake with comparable results, therefore leading to a greater confidence. In recognition of the success of their methods, the use of natural tracers to calibrate solute transport models are now more commonly applied (Reynolds and Marimuthu, 2007, Marimuthu and Reynolds, 2005).

Physical hydrological, hydrochemical and stable water isotopic methods were applied to the Lake Warden coastal wetlands near Esperance, Western Australia, to clearly define the hydrological functioning of the ecosystem (Marimuthu and Reynolds, 2005, Marimuthu et al., 2005a, Marimuthu et al., 2005b, Reynolds and Marimuthu, 2007). Groundwater, surface water from creeks and wetlands, plus rainfall data was compiled to resolve an annual water cycle for the areas wetlands. The key methodologies applied in these studies included the use of a theoretical single-batch evaporation model to determine the residual isotopic signature for each of the wetlands using the Craig and

Gordon (1965) model; “salt effect” corrections on stable isotopic data to account for high solute concentrations; stable isotopic data in mass-balance mixing models to determine relative contributions from surface water, groundwater, and precipitation to wetland water balances; and the calibration of a coupled solute transport model (FEFLOW) with stable water isotopic data. The outcomes from investigations on the Lake Warden coastal wetlands system resolved hydrological uncertainties relating to the interrelationship between wetlands. Previous interpretations of bathymetry survey data indicated that the suite of wetlands operated as a single water body, however the multidisciplinary approach revealed that this was not the case and each of the wetlands are geochemically separate entities. This finding has implications for the development of management actions to address the threat from altered hydrology as a consequence of historical land use changes (Robertson et al., 2005, Robertson and Massenbauer, 2005).

2.4 Summary

Physical hydrological methods can be used to describe wetland functioning in semi-arid environments. However the episodic and variable nature of such a climate and its complex interaction with the physical, chemical and biotic elements means that many terms required for a water balance are rarely well quantified and are therefore combined together into a residual term. This residual term can be a significant source of error because considerable components of the water balance are not individually accounted for.

Error margins and redundant combined residual terms can be significantly reduced by applying a multidisciplinary approach. Hydrochemical and stable water isotopic methods are complimentary to physical hydrological studies and can be easily integrated into existing sampling programs. The hydrochemical properties of Australian precipitation are well understood and the interaction with minerals and other processes such as fractionation of stable isotopes are also well founded. Therefore the combination of methods in a multidisciplinary approach is best suited to adequately describe the hydrological function of a wetland system.

Strategies to reduce error and improve accuracy of interpretations also include the representation of local conditions (including rainfall and evapotranspiration where practical); compensation for density-dependant flow due to temperature and solute driven differences; correction for the “salt effect’ in stable isotopic interpretations; and correction for barometric efficiency.

Regardless of the location and size of a wetland or catchment, and the length or resolution of available data, a degree of uncertainty and error will be present in a water balance. This uncertainty means that at worst a catchment water balance may only be a rough approximation, however a multidisciplinary approach will significantly reduce error and improve the accuracy of water and solute balances. This will in turn enhance the development and implementation of appropriate management strategies to address altered hydrology for wetlands occurring in semi-arid environments.

CHAPTER 3:

3 Site description

3.1 Regional setting

The Buntine-Marchagee Natural Diversity Recovery Catchment (BMNDRC) is located approximately 280 km north-northeast of Perth within the northern agricultural region (NAR) of the wheatbelt region of Western Australia. This investigation focuses on a suite of wetlands and groundwater seeps (sites W015, W016, W017, W026, W051, W735 and W736), located within a 932 ha subcatchment in the western section of the BMNDRC (Figure 3-1). All wetlands and seeps in the study area subcatchment (Nabappie), exhibit signs of physical and biological degradation associated with altered hydrology. Altered hydrology has resulted from land clearing within the catchment for agriculture. The study area is privately owned land and broad acre farming, specifically cropping of wheat, canola and lupins, is the dominant landuse (758 ha or 81%).

3.2 Physiography

3.2.1 Climate

The BMNDRC climate is Mediterranean, characterised by warm to hot summers with long-term average daily temperatures ranging from 16^{o}C to 35^{o}C. On average 10 days per year experience temperatures equal to or exceeding 40^{o}C (Bureau of Meteorology, 2011). Winters are cool to mild with long-term average temperatures ranging from 6.5^{o}C to 18^{o}C with minimum temperatures being on average less than or equal to 2^{o}C around 3 days. The long-term average rainfall at the nearby town of Coorow (BoM site number 8037) is 381 mm and the "break of season" rainfall generally occurs in May. The highest monthly rainfall generally occurs in winter although significantly high daily rainfall totals can occur from December to March (summer to early autumn) resulting from intense thunderstorms or rain bearing depressions associated with remnants of tropical cyclones (Short et al., 2006). A plot of the long term annual rainfall trends for Coorow can be found in Appendix 3A.

Since the very wet year of 1999 the area has experienced a very dry period with only the year 2003 (391 mm) exceeding the long-term average (Appendix 3A). Average annual Class-A pan evaporation rates (based on interpolation from Three Springs, Goodlands and Wongan Hills), are approximately 2,600 mm and largely exceed average rainfall throughout the year (Luke et al., 1987). Average monthly potential evaporation rates vary from about 410 mm in January to 75 mm in June (Luke et al., 1987).

3.3 Regional overview of the geology, hydrogeology, and hydrology of the BMNDRC

The BMNDRC lies within the zone of ancient drainage where Archaean (generally 3,000 to 2,600 mega-annum (Ma)) granites and gneisses of the Yilgarn Craton predominate (Carter and Lipple, 1982, Baxter and Lipple, 1985, Trendall, 1990). The Darling Fault, which marks the western edge of the Yilgarn Craton, is about 17 kilometres west of the BMNDRC boundary (Speed and Strelein, 2004). The BMNDRC contains series of Proterozoic (2,500 to 543 Ma) dolerite dykes that intrude the Archaean basement and increase in abundance westwards towards the Darling fault (McConnell and Pillai, 1995, Speed and Strelein, 2004). These dykes range in thickness between 1 and 10 m, and are generally of a north to north-westerly orientation, the same as the prevailing fracture/joint pattern (Carter and Lipple, 1982). Less prominent are the perpendicular E-W trending dykes of the Widgiemooltha dyke swarm. Basement rock exposures are generally limited to high elevation areas within the BMNDRC, although some isolated outcrops of granite and dolerite are also evident on the valley floor.

The Yilgarn Cratons' surface has been weathered over time resulting in a subdued relief (Geological Survey of Western Australia, 1990). Glaciation of inland Western Australia during the Carboniferous-Early Permian period (~280 Ma) planed off surface features and widespread palaeochannel formation is believed to have begun beneath ice sheet melt waters (Commander et al., 2001). The most recent wide-spread erosion of the Yilgarn Craton occurred in the Cainozoic (<65 Ma) (Geological Survey of Western Australia, 1990) associated with a period of intense fluvial activity and drainage due to the cessation of glaciation (Beard, 1999).

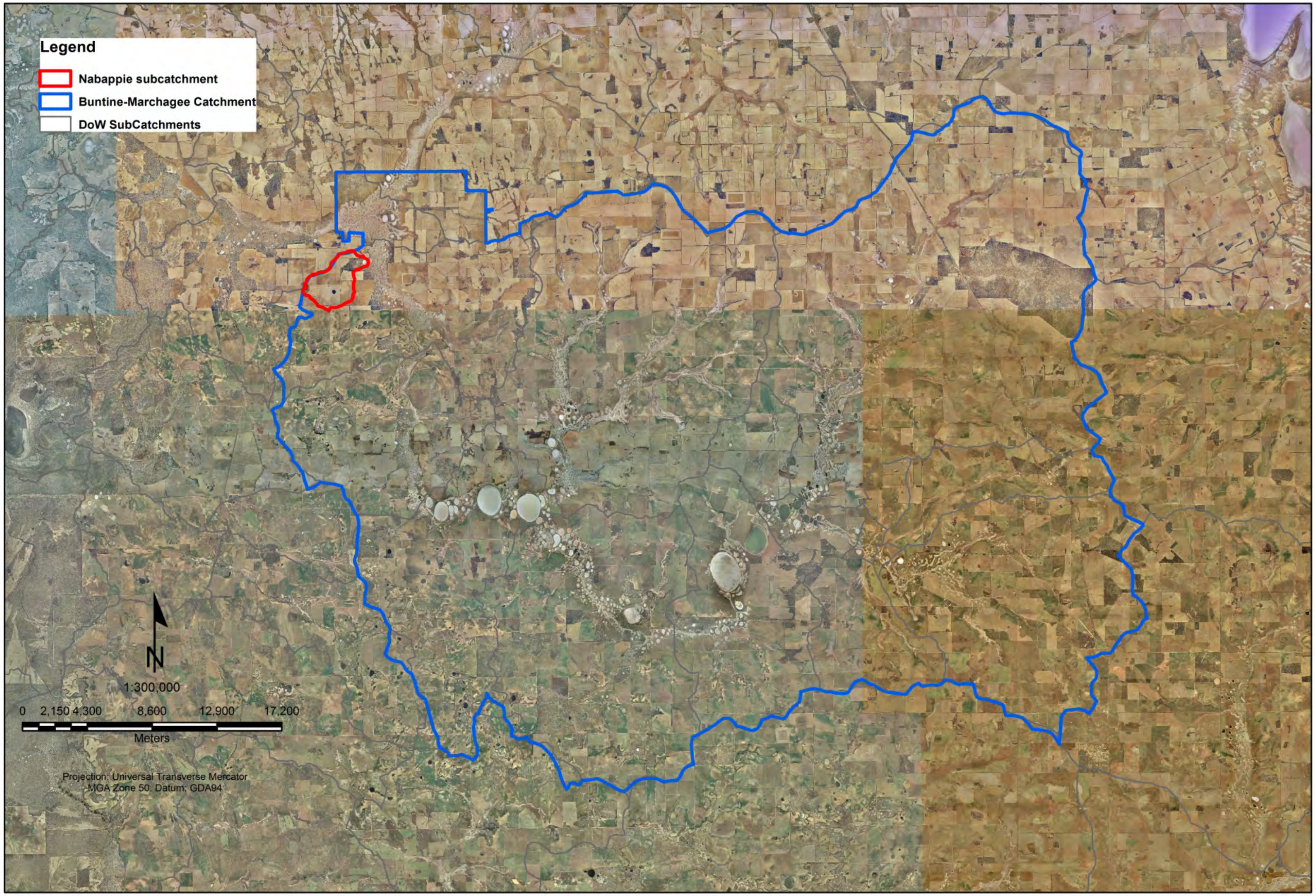

Figure 3-1. Location of the Nabappie subcatchment within the western section of the BMNDRC, approximately 280km north-east of Perth

The conceptual geological block model of a typical wheatbelt valley detailed by Commander et al (2001) is provided in Figure 3-2. This model suitably represents the braided, naturally saline, drainage channels of the BMNDRC. The laterite outcrop and tributary valley in the left of the figure equally represents the study area (Nabappie wetland suite). The alluvial/fluvial deposits within the BMNDRC's palaeodrainage channels are thought to be Eocene (54-36 Ma) or Pliocene (5 Ma) age (URS, 2008) which is consistent with known sediments from the Yarra Yarra Lakes (Commander et al., 2001). Many sections of palaeodrainages in the BMNDRC are still active fluvial systems and have been intermittently reworked. As a result they contain Quaternary (2.6 Ma to present) colluvial, alluvial and lacustrine sediments, particularly associated with salt lakes. The exact location and nature of palaeochannels in the BMNDRC is currently unclear although they are likely to occur predominantly in proximity with the modern valley floor (Magee, 2009).

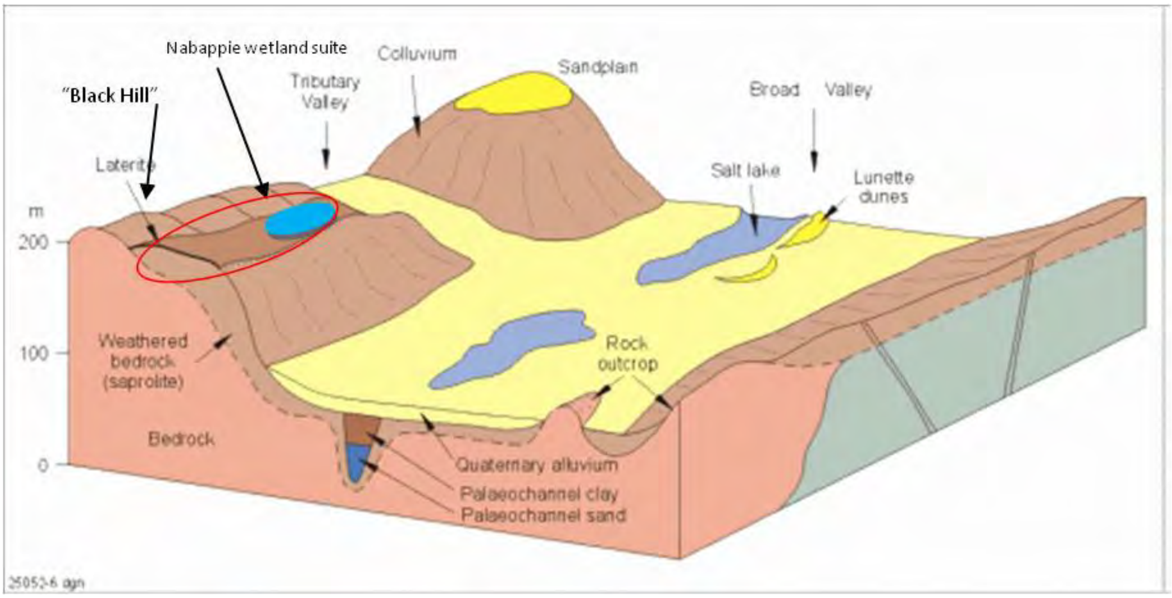

Figure 3-2. A geological block diagram typical of a wheatbelt valley from Commander et al (2001) and the conceptual representation of the location of the Nabappie subcatchment (red oval) and suite of wetlands (blue oval) adjacent to the valley floor.

The BMNDRC lies within the Moore-Hill River basin (Basin 617) and the Moore River subcatchment. The BMNDRC is predominantly internally draining with rainfall and surface water flows being internally redistributed. Regional-scale, whole of catchment flows within the BMNDRC occur only in very wet years or after high magnitude, high intensity rainfall events typically associated with monsoonal lows or remnants of tropical cyclones. The last occurrence of such catchment-scale flow events was in 1999 and 2000 (Short et al., 2006).

3.4 Study area geology, hydrogeology and hydrology

The geological characteristics of the Nabappie subcatchment is considered to be typical of that described for the wheatbelt (George, 1992c, Salama et al., 1993a). The stratigraphy is characterised by competent to fractured basement, overlain by a sequence of weathered bedrock (saprock and saprolite), less permeable pallid zones, and variable sequences of alluvial, colluvial and fluvial sediments often interspersed with mottled zones and ferricrete, calcrete, or silcrete hardpans. The Nabappie subcatchment is situated within an area where an increasing density of dykes and faults significantly influences the movement of groundwater, particularly in the vicinity of its wetlands (Figure 3-3).

The western subcatchment divide occurs at an elevation of 326 mAHD at a locality called "Black Hill", an exposed laterite outcrop overlying highly weathered bedrock (saprock) and coarse-grained Archaean Amphibolite, Leucocratic granite and Para-gneiss (Baxter and Lipple, 1985). The subcatchment slopes (at a gradient of ~2%) eastwards from the outcrop of "Black Hill" through a surficial blanket of deep yellow sands to the break of slope, where there is an abrupt change in gradient and soil type. Below the break of slope (<1% gradient), transported (fluvial, alluvial and aeolian) and lacustrine deposits of sand, silt and clay predominate (Griffin and Goulding, 2004). Shallow and exposed cemented layers of calcrete, silcrete[5], and iron-rich ferricrete or lateritic (pisolithic gravels and duricrust) hardpans occurs throughout this lower area.

The above mentioned geological features of the Nabappie subcatchment produce a number of aquifers, with highly variable and complex hydro-stratigraphic relationships. Heterogeneity within the regolith is reflected in the heterogeneity of hydrochemical and hydraulic properties with considerable anisotropy occurring at both the macro (kilometres) and micro scale (centimetres) (URS, 2008). Five types of aquifers are identified in the study area; a fresh surficial unconfined aquifer within permeable sands, which predominantly overlies silcrete, ferricrete, and calcrete hardpans; a hyposaline unconfined aquifer within less permeable transported sequences of unconsolidated clayey-sands and variably cemented horizons; a saline unconfined aquifer within a sequence of transported unconsolidated sandy-clays, clays, and variably cemented

[5] Silcrete is a term used here to describe a hardpan composed of quartz grains which are predominantly cemented by silica. The term is often used elsewhere interchangeably with calcrete and ferricrete (Bennett et al, 2005).

horizons in close proximity to wetland W017 (Figure 3-3); a hyposaline semi-confined aquifer within weathered bedrock (includes saprolite, saprock and fractured-bedrock); and a saline to hypersaline semi-confined aquifer typical of the regional primary saline aquifer. Palaeochannel sands interpreted in a previous study (URS, 2008) were not extensively intersected. The conceptual model developed in this study assumes that palaeochannel sediments are spatially isolated or disconnected therefore contribute little to the water balance of individual wetlands.

Semi-confined conditions are thought to occur due to the mottled and pallid zones which lay within the deeply weathered profile, consisting of highly weathered and leached clay-rich material (George, 1992c). Hardpans of silcrete, ferricrete or calcrete mark the transition between the weathered regolith, transported sequences and the overlying surficial sediments. Hardpans are typically less permeable than the overlying surficial sediments therefore enhancing lateral interflow[6] and groundwater flow along their margins (Clarke et al., 2000, George, 1992c). Fractures and other preferential flow paths, such as root channels, within hardpans however allow for some vertical movement and exchange of groundwater between the surficial aquifer and the underlying transported sequences and semi-confined aquifers (Bennett et al., 2005, Wildy et al., 2004). The general direction of groundwater flow within the study area is from the catchment divides eastwards towards the valley floor (Figure 3-3).

[6] Interflow is defined as the lateral movement of water in the vadose zone during and immediately after a rainfall event (Fetter, 2001).

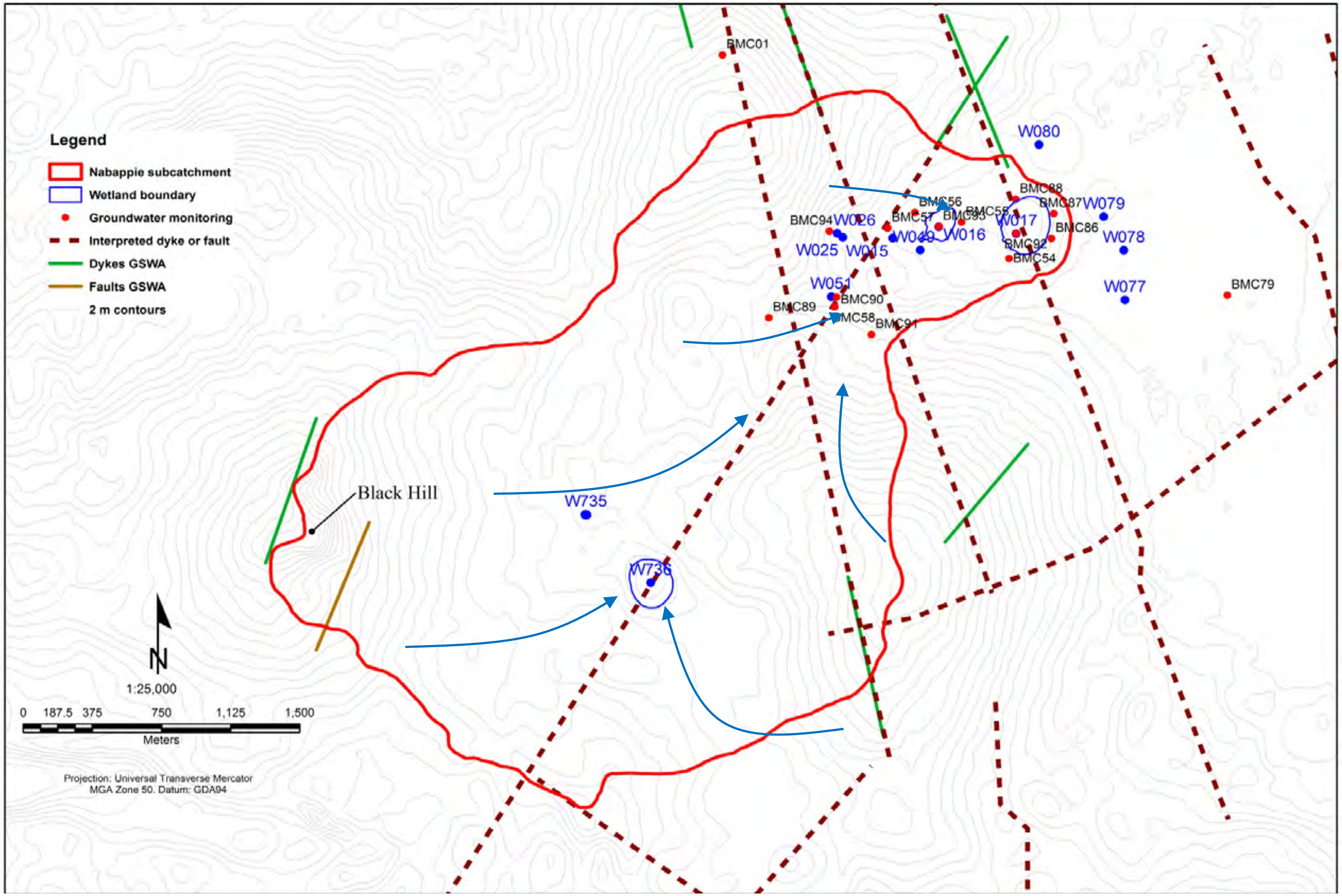

Figure 3-3. Plan view of study area subcatchment with wetland (W*xx*) and groundwater monitoring (BMC*xx*) locations, dykes and faults from maps published by Geological Survey Western Australia (Baxter and Lipple, 1985, Carter and Lipple, 1982) and interpretations by the author based on aerial photographs, airborne geophysics data (Independence Group NL, 2008) and field observations. Blue arrows indicate the general groundwater flow direction.

3.4.1 Vegetation and landuse

Perennial vegetation covers about 120 ha or 13% of the study area[7]. Most (81 ha) of the native vegetation surrounds three wetlands W015, W016, and W017 while a further 15 ha occurs at the top of the catchment on "Black Hill" (Figure 3-4). The remainder is restricted to narrow corridors along fence lines. There are also 25.5 ha of planted perennial vegetation which includes a 21 ha stand of tagasaste (*Chamaecytisus palmensis*) and river red gums (*Eucalyptus camaldulensis*) upgradient of W051. These were planted in 1988 by the previous landholder to control a rising fresh water table. An additional 4.5 ha of river red gums were planted along fence lines (Figure 3-4).

At the break of slope near wetland W051 the vegetation is dominated by native sandplain species. Vegetation composition changes down gradient from W051 from banksia and other sandplain species to casuarina and melaleuca species better suited to increased clay content of soils, increased soil salinity and reduced depth to groundwater. Farther down slope the dense, near-closed canopy gives way to clustered patches of river red gum, native and introduced rushes around groundwater seeps, and samphire flats occurring within drainage lines immediately to the north and south of wetland W015. The drainage line down-gradient of wetland W016 is dominated by dead and dying swamp oak (*Casuarina obesa*) woodlands and samphire (Richardson et al., 2005). These vegetation types continue along the western and north-western edges of wetland W017. The southern, and eastern areas of the lunette around wetland W017 hosts a mix of mallee, melaleuca, acacia, grevillea and sandplain species such as Sandplain Cypress (*Callitris arenarius*) and native grasses (Huggett et al., 2004).

3.5 History of vegetation clearing and development of altered hydrology

The suite of wetlands and springs within the lower reaches of the study area are in the vicinity of the colloquially known Nabappie Spring. Nabappie Spring and others, such as the nearby Jun Jun Spring, were vitally important as a source of fresh water for the early settlers (Doley, 2009). The land containing the Nabappie Spring was purchased in 1869 (Doley, 2009) and was surveyed by John Forrest in 1872 then again by A.J. Lewis in 1876 (Doley, 1979).

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[7] The area listed as native remnant vegetation also includes significant bare areas and introduced weeds such as *Juncus acutus*.

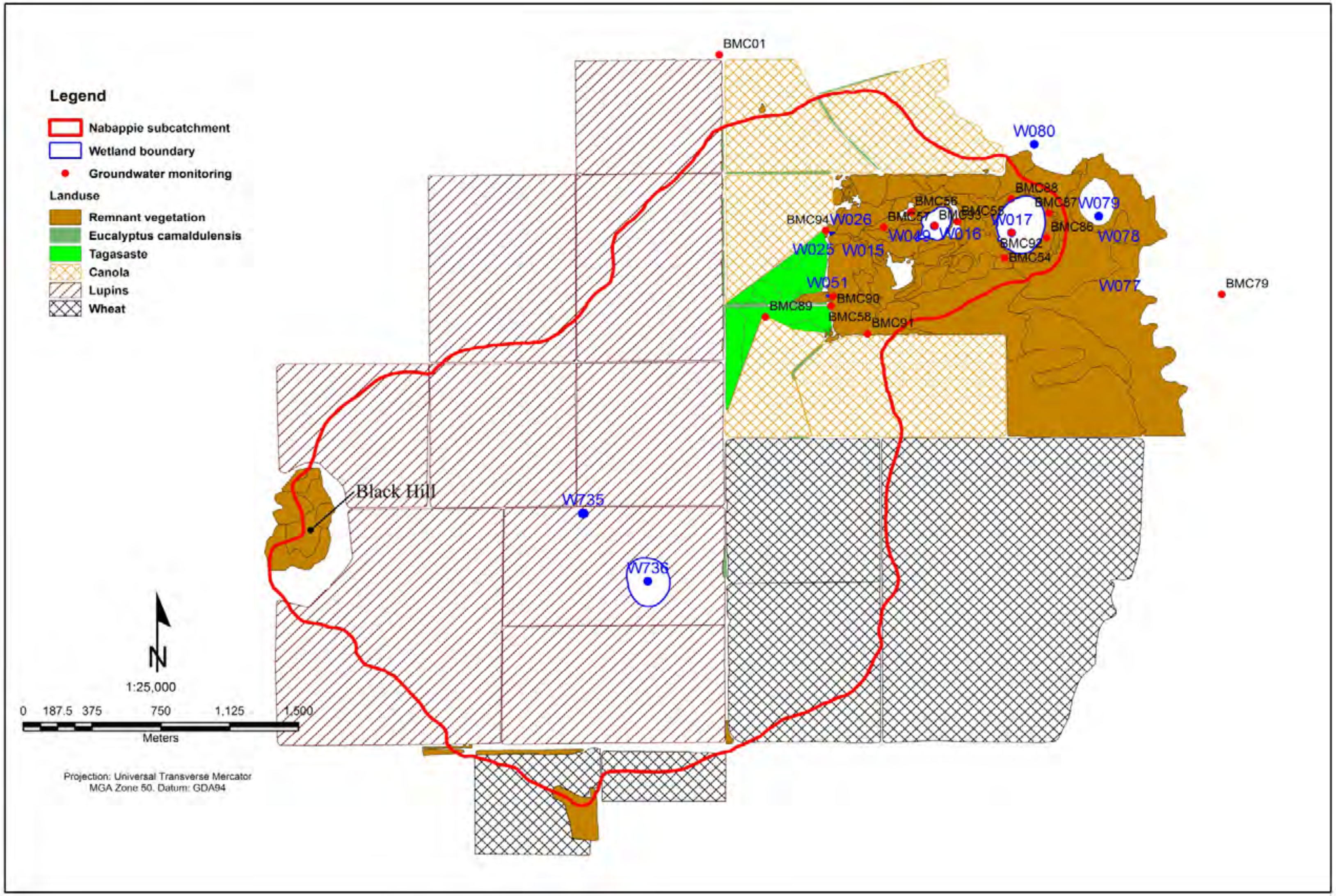

Figure 3-4. Landuse for the study area in 2009, categorised broadly as annual broad-acre crops (canola, lupins and wheat), remnant native vegetation, and planted perennial vegetation (tagasaste and *Eucalyptus camaldulensis*). Blank areas are interpreted as bare soil.

Historical aerial photographs indicate that at least 70% of the natural overstorey vegetation still remained in 1959 (Appendix 3B). Many fire scars appeared in these aerial photographs and the reduced density of the understorey across much of the area may be evidence of livestock grazing. The fire history is undocumented, however it is understood that deliberate burning of native vegetation ceased in 1983 (pers. comm. T. Officer). Clearing largely occurred from 1966 to 1968 (pers. comm. T. Officer), with the current extent of clearing evident in 1969 aerial photographs (Appendix 3C). Groundwater levels are understood to have risen dramatically within 10-years of clearing around wetland W051 due to increased groundwater recharge. Vegetation clearing also coincided with a period of significantly higher than average rainfall during the 1960's therefore further escalating the hydrological impacts. Aerial photographs from 1969 onwards provide evidence of rising water tables in the form of significant loss of vegetation in the lower parts of the study area, particularly the drainage lines nearby wetlands W015, W016, and W017.

Dead river red gums in the drainage lines of the lower areas of Nabappie have abundant epicormic growth scars indicating stress prior to mortality. Vegetation stress can be induced by various means (Souter et al., 2010) however the spread of samphire and other salt-tolerant species, such as the introduced weed spiny rush and slender ice plant, within the drainage lines supports the theory that altered hydrology (elevated water levels and salinity) is the major cause of vegetation mortality and ongoing decline.

Localised variations in geology, topography, and hydrogeology have enabled some vegetation to remain healthy and in some cases regenerate. For example a mass recruitment of river red gums occurs west of wetland W015 (Richardson et al., 2005). These trees are up to 6m tall and may be up to 20 years old. These recruits are now declining in health due to a calcrete hardpan that is limiting their root depth and hence restricting water availability. A ferricrete hardpan within the drainage inlet of W017 may also be having a similar indirect impact to vegetation.

3.6 Wetland description

Wetlands in the study area were classified according to their current characteristics (Table 3-1), rather than their pre-clearing "natural" state which in most cases has changed significantly. Classification was based on geomorphology and hydroperiod

(Semeniuk and Semeniuk, 1995); wetland geometry; and observations of water pH and salinity from 2003 to 2009[8] (Table 3-1). Salinity was classified following guidelines by Davis et al (2003) which are fresh (<1,000 mg/L TDS); hyposaline (1,000 to 10,000 mg/L TDS), saline (10,000 to 100,000 mg/L TDS), and hypersaline (>100,000 mg/L TDS). Further details are provided below, whilst photographs are at the end of this chapter (Figure 3-5).

Table 3-1. Summary of the geomorphology classification and historical water quality for each of the wetlands investigated in the study area.

Wetland ID	Wetland shape	Salinity classification (Davis et al, 2003)	EC (mS/cm)	pH	Semeniuk (1995) classification	Maximum observed (2003-2009) depth (m)
W735	Round	Hyposaline	3 to 6	6.8 to 8.9	Sumpland	0.35
W736	Round	Saline	20 to 28	8.9 to 9	Lake	1.5
W051	Ovoid	Hyposaline	3 to 11	6.3 to 8	Sumpland	0.60
W026	Round	Hyposaline to saline	8 to 31	8 to 8.7	Sumpland	0.20
W015	Irregular	Fresh to hyposaline	4 to 13	6.2 to 8.1	Lake	0.20
W016	Irregular	Saline	17 to 117	7.8 to 9.5	Sumpland	0.20
W017	Round	Saline to hypersaline	57 to 217	6 to 8.6	Sumpland	0.20

3.6.1 W735

Wetland W735 is a round, hyposaline, neutral to alkaline sumpland (i.e. seasonally inundated basin). It is approximately 0.1 ha in size and has a covering of rushes on the western boundary providing an occasional refuge for birdlife. Water level depth has been observed to be <0.35 m and annual broad-acre cropping is the dominant surrounding landuse. There is no groundwater monitoring bores within the vicinity of wetland W735. It is currently thought that this wetland lies on a less permeable layer of silcrete, although connected to the water table and are therefore not perched, as a number of similar wetlands in a neighbouring subcatchment exhibit this characteristic (URS, 2008).

3.6.2 W736

Wetland W736 is a round, saline, alkaline lake (i.e. permanently inundated basin) approximately 5 ha in size and depth is estimated at 1.5 m. Wetland W736 is devoid of

[8] The period from 2003 to 2009 represents a very dry period, hence water levels and water quality may not be representative of long-term trends or trends during significantly wetter years/periods, for example most recently in the very wet year of 1999.

perennial vegetation and is surrounded by annual broad-acre cropping. Like wetland W735, W736 is assumed to be underlain by a hardpan, although interpretations of geological maps and airborne geophysics (Independence Group NL, 2008) indicate that a south-west to north-east trending dyke sub-crops this wetland. This interpretation however is highly speculative and requires further investigation.

3.6.3 W051

Wetland W051 is an ovoid, hyposaline, slightly acidic to alkaline sumpland (i.e. seasonally inundated basin), located at the break of slope. It occurs as a depression in a surficial deposit of deep yellow sands underlain by silcrete and deeply weathered regolith. Maximum depth of surface water in the wetland observed is at approximately 0.6 m. Wetland W051 dries out over summer however the shallow water table can be clearly seen in the concrete well casing. This well was installed to a depth of 3.7 m in 1968 and in 1970 it produced 22.73 m^3/day with a salinity of 262 mg/L TDS (Department of Water, 2009).

3.6.4 W026

Wetland W026 is located at the break of slope 360 m north of W051 at a similar elevation. It is a round, hyposaline to saline, neutral to alkaline sumpland (i.e. seasonally inundated basin). Surface water depths of 0.20 m have been observed. Groundwater and interflow discharge is clearly visible within the wetland and down-gradient during wetter winter months. Wetland W026 is at the head of a drainage line which links wetlands W015 and W016.

3.6.5 W015

Wetland W015 is an irregular, fresh to hyposaline, slightly acid to neutral lake (permanently inundated basin) and is located down-gradient from W051 and W026, where groundwater perennially discharges through fractures in exposed calcrete hardpans. Wetland W015 has an outflow level of ~0.15 m with outflows continuing down the drainage line to wetland W016. The maximum wetland depth observed is ~0.20 m. Deep sands are absent and shallow clay-rich alluvial and fluvial sediments overlie cemented hardpans and deeply weathered regolith. During the winter months the shallow soils surrounding W015 become saturated and surface water flows are obvious. Dark tannin-stained groundwater discharges near W051 flowing eastwards downslope through wetland W015.

3.6.6 W016

Wetland W016 is an irregular, saline, alkaline sumpland (i.e. seasonally inundated basin) with a substrate characterised by cracking clays. The wetland is predominantly dry, filling only during wetter periods or years of average or above rainfall. The maximum observed surface water depth is ~0.20 m. Surface water typically enters the wetland from two poorly defined shallow drainage lines located on the northwest and southwest sides. A sandy lunette on the eastern bank of wetland W016 appears capable of transmitting water when the profile approaches saturation. Surface water outflows have not been observed but may occur, only in very wet years, via the south-western inlet into wetland W017. A sulphurous odour and bubbling of gasses has been noted when the wetland filled in 2008 after an extended dry phase. Previous surveys of wetland W016 (Aquatic Research Laboratory, 2009) recorded elevated levels of nitrogen (7.7 mg/L) and phosphorus (0.87 mg/L).

3.6.7 W017

Wetland W017 is a round, saline to hypersaline, slightly acidic to alkaline sumpland (i.e. seasonally inundated basin) with features, such as a flat base devoid of vegetation and a sandy aeolian lunette, typical of primary saline wetlands of the wheatbelt region. The wetland substrate is composed of fine clays to a depth of ~2m, underlain by well sorted alluvial sands to an unknown depth. A thin salt crust may form on the wetland base over summer months, although this rarely exceeds three mm. W017 has been observed to fill to depths of ~0.20 m. The wetland has a number of inflowing shallow drainage lines to the west and no surface water outlets.

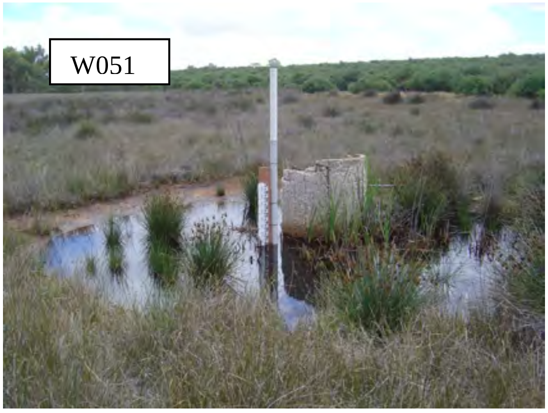

Figure 3-5. Photographs of the major wetlands and groundwater seeps investigated in this study. Wetlands are ordered from left to right, top to bottom commencing at W735 then W736, W051, W026, W015, W016, then lastly W017 on the bottom left.

CHAPTER 4:

4 Materials and Methods

4.1 Background

Groundwater monitoring bores were installed near the study area in 2002 to obtain a regional perspective of the hydrogeology of the BMNDRC (Speed and Strelein, 2004). In 2006, groundwater monitoring bores were installed within the Nabappie subcatchment to provide a preliminary assessment of the areas hydrogeological function and water balance (URS, 2008). Tipping bucket rain gauges (TBRG) were also installed in the study area and neighbouring catchments at the same time. Surface water depth data logging devices, and additional TBRG's and groundwater monitoring bores were added in subsequent years. This historical data provides the foundation for this study.

4.2 Monitoring infrastructure

4.2.1 Groundwater infrastructure

Sixteen groundwater monitoring bores located within the study area (Table 4-1) consist of five deep bores drilled to granitic basement (BMC54d, BMC55d, BMC56d, BMC57d, and BMC58d); one intermediate bore (BMC58i); and ten shallow observation bores (BMC56ob to BMC94ob). Three additional bores (BMC01d, BMC02d, and BMC02ob) within the neighbouring subcatchment were used to evaluate recharge in the upper catchment, whilst a nest of three bores (BMC64d, BMC64i and BMC64ob), located within the valley floor, 3.2 km from the study area, are used as a reference for the regional primary saline aquifer. Full construction details and lithology descriptions for all bores are contained elsewhere (URS, 2008, Speed and Strelein, 2004).

Upon commissioning, all bores within the study area were fitted with a capacitance probe-type electronic data logger (Odyssey 64k) to record water levels. Hourly water level data was recorded during the study period and 6-hourly water level data recorded for historical data (Table 4-1). Hourly data was considered an appropriate interval for; analysis of water level recovery following sampling (section 4.5.5); to determine the influence of barometric pressure upon water levels (section 4.5.6); and to detect diurnal water level changes associated with phreatophytic vegetation ET (section 4.6.1.1).

Logged water levels are subject to inaccuracies associated with calibration drift due to probe fouling (such as precipitation of iron oxides), however the regular cleaning of probes and post-processing of data ensured that values were estimated to be within an error of ±0.02m. Data exceeding this threshold was omitted from analysis. All groundwater levels were corrected to Australian Height Datum (mAHD) (Bourke, 2009, Department of Land Information, 2006).

Table 4-1. Summary of network of sixteen groundwater monitoring bores in the study area subcatchment and additional sites in the adjacent subcatchment (BMC01d, BMC02d, and BMC02ob) and a nested site in the valley floor (BMC64d, BMC64i and BMC64ob) representing the regional groundwater.

Site ID	Casing depth (m)	Ground elevation (mAHD)	Closest wetland	Record commenced	PVC casing diameter (mm)	Drill method
*BMC01d	23.09	291.15	N/A	01/07/2002	50	Air core
*BMC02d	21.88	273.29	N/A	01/07/2002	50	Air core
*BMC02ob	6.42	273.21	N/A	01/07/2002	50	Air core
BMC54d	21.59	258.81	W017	27/06/2006	50	Air core
BMC55d	38.62	260.12	W017	28/06/2006	50	Air core
BMC56d	24.79	260.62	W016	28/06/2006	50	Air core
BMC56ob	5.82	260.58	W016	6/08/2006	50	Hollow-stem auger
BMC57d	25.42	262.55	W015	29/06/2006	50	Air core
BMC58d	19.03	269.55	W051	30/06/2006	50	Air core
BMC58i	13.31	269.80	W051	30/06/2006	50	Air core
BMC86ob	4.29	258.33	W017	5/08/2006	50	Hollow-stem auger
BMC87ob	3.45	258.30	W017	5/08/2007	50	Hollow-stem auger
BMC88ob	5.38	258.16	W017	6/08/2006	50	Hollow-stem auger
BMC89ob	3.50	273.74	W051	16/10/2008	50	Hand auger
BMC90ob	2.17	268.55	W051	16/10/2008	50	Hand auger
BMC91ob	4.40	270.77	W051	16/10/2008	50	Hand auger
BMC92ob	2.00	257.29	W017	15/06/2009	90	Hand auger
BMC93ob	2.11	259.44	W016	15/06/2009	90	Hand auger
BMC94ob	1.92	268.37	W051	15/06/2009	90	Hand auger
*BMC64d	43.03	261.70	N/A	5/07/2006	50	Air core
*BMC64i	24.75	261.64	N/A	5/07/2006	50	Air core
*BMC64ob	5.92	261.67	N/A	5/07/2006	50	Push probe

*** Monitoring bores located outside the Nabappie subcatchment boundary.**

4.2.2 Surface water infrastructure

Manual water level measurements were made at depth gauge boards within wetlands W015, W016, W017, and W051 (Table 4-2) in conjunction with hourly data recorded at these sites using capacitance probe data loggers (Scott Parsons Electronics). Accuracy of logged measurements is likely to be similar to those reported above. Wetlands W015, W016, W017 and W051 were surveyed to mAHD, whilst wetlands W026, W735, and W736 were estimated from high resolution LiDAR data (0.5m DEM ±0.15m at 95% confidence level) (Fugro Spatial Solutions, 2008). Monitoring infrastructure was absent from wetlands W026, W735, and W736.

Table 4-2. Summary of wetland monitoring sites and associated monitoring infrastructure

Site ID	Gauge board present	Ground elevation (mAHD)	Closest bore	Record commenced
W015	Yes	262.10	BMC57d	30/01/2003
W016	Yes	259.44	BMC93ob	7/11/2003
W017	Yes	257.29	BMC92ob	7/11/2003
W026	No	*266.20	BMC94ob	15/06/2009
W051	Yes	267.75	BMC90ob	7/11/2003
W735	No	*279.38	N/A	19/05/2009
W736	No	*277.93	N/A	22/04/2009

*Elevation estimated from LiDAR data

4.2.3 Climate infrastructure

Three TBRG's (sites Rain1, Rain2, and Rain 3) located in the study area provide 0.2 mm depth interval time-series rainfall data. Historical rainfall data for Bureau of Meteorology (BoM) site Koobabbie (station 8067) located 5.5 km east of the study area, and the BoM site at the Coorow Post Office (station 8037) located 16 km north-west were used for analysis of long-term correlations between groundwater level and rainfall. The BoM sites have a standard 203 mm rain galvanised steel gauge with a plastic graduated flask. The limited availability of other climate datasets within the study area meant that data was acquired from a number of different locations. Barometric pressure, air temperature and relative humidity were acquired from Dalwallinu automated weather station (BoM station 8297), and daily Class-A pan evaporation data Wongan Hills (BoM station 8138). Corrections (sections 4.5.6 and 4.7.1) were applied to represent the local subcatchment conditions.

4.3 Sampling methods

4.3.1 Groundwater and surface water sampling

Shallow bores were purged and then sampled with a 12-volt submersible pump (Proactive, 12m Super Twister), or stainless steel bailer (Dormer, 1.0m x 38mm, model SLR3810). Deep bores (>12m) were sampled with a 12-volt submersible pump (Proactive, 45m Hurricane). Bores were considered purged once key water quality parameters (pH ± 0.1, EC ± 5% and temperature ± 0.2°C) stabilised.

The sampled wetlands were considered well mixed hence only one representative sample was collected at each site, per visit. Each sample was taken from the middle of the water column near the water level gauge or, if no gauge was present, at the centre of the wetland. In the case of wetland W736, which was ~1.5 m deep, the sample collection point was approximately 15 m from the eastern edge of the wetland.

Basic water quality parameters, pH, Electrical Conductivity (EC), Oxidation-Reduction Potential (ORP), Dissolved Oxygen (DO) and temperature were measured (TPS, model 90-FLMV) in the field prior too and during sample collection. ORP measurements (Eh) were corrected for the standard hydrogen electrode (SHE) relative to water temperature. Alkalinity ($CaCO_3$) was measured immediately prior to sample collection (Hanna, model HI3811) with results averaged from two titrations. Carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) representation was based on the pH driven carbonate speciation theory discussed by Appelo and Postma (2007). All field equipment was decontaminated (0.3% Decon-90 solution and deionised water) and calibrated where appropriate to manufacturer's specifications prior at the start of each sampling day.

An unfiltered groundwater sample for each bore was collected in a 100mL amber bottle for stable water isotope (δD and $\delta^{18}O$) analysis. Samples were refrigerated at 4^0C prior to being sent to the Natural Isotopes Laboratory, Edith Cowan University School of Natural Sciences, for analysis. Samples for ion and nutrient analysis were field-filtered (Advantec MFS, model KP-47S with 0.45μm paper filters) and stored in both 500 mL and 50 mL plastic bottles, the 50 mL being preserved with nitric acid. Samples were refrigerated at 4^0C, until analysis by Edith Cowan University (ECU) Analytical Services Laboratory or the Chemistry Centre of Western Australia. A minimum of one field duplicate was taken per sampling round (approximately a ratio of 1:20) to test the quality control standards of all three laboratories used in this study.

4.3.2 Rainfall sampling

The conical funnel and measuring flask of the two BoM rain gauges (BoM sites 8037 and 8067) were washed with Decon-90 and deionised water prior to the onset of winter. At 9am each morning, the BoM rain gauges were sampled and transferred to 500 mL unpreserved plastic bottles and stored at 4^0C refrigerator at the respective sites. At the end of each month, daily rainfall samples were transferred to 100 mL amber bottles and dispatched for analysis of stable water isotopes (δD and $\delta^{18}O$). Excess rainfall samples from individual BoM sites were aggregated into 500 mL unpreserved plastic bottles and dispatched monthly for laboratory analysis of major ions. A 5-litre sample container was also attached to the outlets of the TBRG at site Rain 1 located within the study area to provide monthly composite (major ions, δD and $\delta^{18}O$) samples.

4.4 Laboratory methods

4.4.1 Chemical analysis

All groundwater, surface water and composite rainfall samples were analysed in the laboratory for major ions (Ca^{2+}, Cl^-, K^+, Mg^{2+}, Na^+, Br^- and SO_4^{2-}), EC, and Total Dissolved Solids (TDS). Water samples taken in April, May and November were sent to the Chemistry Centre of Western Australia (CCWA) for analysis, whereas water samples collected in June to October were sent to the Edith Cowan University (ECU), School of Natural Sciences Analytical Services Laboratory. Samples collected in April, and May were analysed for nitrate (NO_3) and November samples analysed for NO_3, Total N, Soluble P, and Total P by the CCWA. Similar methods of analysis of major ions were used at both laboratories following the procedures and guidelines outlined in APHA (2005). A summary of the laboratory reporting limits for major ions can be found in Appendix 4A.

The CCWA analysed Br^- and SO_4^{2-} using single column ion chromatography (Dionex Ion Chromatograph), Cl^- using a discrete auto analyser (Labmetics/Therm Fisher Aquakem), EC using a conductivity meter corrected to 25°C; Ca^{2+}, Mg^{2+}, Na^+, and K^+ by inductive coupled emission spectroscopy (Varian VISTA ICPAES); nutrients (N_NO_3, PO_4, TN and TP) were measured colormetrically (Lachat FIA); TDS was determined from the total concentration of calculated individual ions. Measurement uncertainty ranged from 5% for SO_4^{2-} and EC to 21% for Br^- (Appendix 4A).

The Edith Cowan University, School of Natural Sciences Analytical Services Laboratory measured cations using a Varian Pro ICP-OES. Anions were analysed by ion chromatography using a Metrohm 761 Compact Ion Chromatograph with Metrosep A supp 5 column (150mm x 4.0mm) and auto sampler. EC was measured with an Orion Model 140 conductivity meter with 014010 conductivity cell. TDS was determined by adding a measured volume of filtered water in a pre-weighed borosilicate container and oven drying at 103°C and the residue was then heated to 180°C to remove occluded water (i.e. water molecules trapped in mineral matrix). The remaining weight post-drying represents TDS.

4.4.2 Stable water isotope analysis

The Natural Isotopes Laboratory analysed stable water isotopes (δD and $\delta^{18}O$) with a DLT-100 Liquid-Water Isotope Analyser (Los Gatos Research Inc., Mountain View, CA, USA). Each sample was analysed six times, with the first two being discarded and the last four averaged. Working standard waters, calibrated against IAEA reference waters (Vienna Standard Mean Ocean Water-2 (VSMOW2), Greenland Ice Sheet Precipitation (GISP) and Standard Light Antarctic Precipitation-2 (SLAP2)), were interspaced with the samples for calibration. Data were normalised following Coplen (1988) and are expressed as $\delta^{18}O$ and δD per mille (‰) relative to V-SMOW where $\delta^{18}O$ and δD values of SLAP are –55.5‰ and –427.5‰ respectively. The analytical precision was 0.04‰ for $\delta^{18}O$, 0.3‰ for δD. Stable isotope abundances are expressed as relative to V-SMOW (Equation 2-3). Event-based rainfall stable isotopic values were converted to monthly and annual rainfall weighted δ-values (δ_P) using the following (Equation 4-1) (Liu et al., 2010):

Equation 4-1

$$\delta_P = \frac{\sum_{i=1}^{n} \delta \times P_i}{\sum_{i=1}^{n} P_i}$$

Where δ refers to the isotopic value of precipitation (δD or $\delta^{18}O$) and *P* is the depth of rainfall occurring at interval *i*.

4.4.3 "Salt effect" correction for stable water isotopes

The presence of high concentrations of cations can cause hydration of ions, which result in substantial fractionation of δD and $\delta^{18}O$ between the hydrated ion sphere and the free water molecules. This is particularly a problem during the preparation of samples for determination of δD (Horita, 1989). Given the high ionic concentrations of groundwater and surface water within the study area (URS, 2008), all stable isotope values were corrected using the following (Horita, 1989, Marimuthu et al., 2005b) (Equation 4-2 and Equation 4-3):

Equation 4-2

$$\Delta\delta^2 H = mNaCL.(-2.4) + mMgCl_2(-5.1) + mCaCl_2.(-6.1) + mKCl.(-2.4)$$

Equation 4-3

$$\Delta\delta^{18} O = mMgCl_2(0.8) + mCaCl_2.(0.5) + mKCl.(-0.1)$$

4.5 Hydrogeology data analysis and interpretation

4.5.1 Catchment delineation

Surface water catchment boundaries were manually interpreted using ESRI ArcMap (version 9.2) populated with LiDAR elevation data. It is assumed that no major cross boundary faults were present therefore the subcatchment surface water divide is a no-flow boundary with respect to groundwater.

4.5.2 Depth to wetland volume area relationships

LiDAR elevation data was applied using Surfer (version 9.0) with the “contarea2.bas” script to calculate the relationship for depth to volume and surface area at 0.01 m interval for wetlands W016, W017, W051, and W735. A range of grid sizes (1 m, 2 m, 10 m and 20 m) were used to assess the sensitivity of bathymetry interpolations to sampling resolution.

LiDAR has limited ability to penetrate water (Huang et al., 2010) therefore wetland W736, which is a permanent wetland, was analysed through a process of digitising the time-series changes in surface area from decadal historical aerial photographs from 1959 (dry) to 2010 (~1.5 m deep). The bank slope was extrapolated for each contour using neighbouring topographical depressions as a guide. Wetland bathymetry and depth to volume and area relationships were then interpolated using Surfer (version 9.0) with the “contarea2.bas” script as above. Wetlands W015 and W026 are relatively small and largely under canopy cover therefore not suitable for LiDAR interpolation. Depth to volume relationships were not completed for these wetlands.

The accuracy of depth to volume relationships in this study is largely influenced by the limitations of LiDAR methods to adequately capture topographic variations within wetlands which are either very flat (W016 and W017), and/or vegetated (W015, W016, W051 and W735) or contained water during data capture (W736). Accuracy of depth to volume relationships for wetlands is therefore estimated to be <20%, whilst a large error (>20%) is likely at W736 therefore interpretations here are considered qualitative.

4.5.3 Density correction

Aquifer heterogeneity observed in a previous study (URS, 2008) highlighted the potential for vertical density gradients to occur. Consequently density corrections were applied using the methods of Post et al (2007). Field temperature (T) and salinity (S)

(defined here as TDS) were used to calculate the density of groundwater using the following equations (Equation 4-4 to Equation 4-6) (McCutcheon et al., 1993):

Equation 4-4

$$\rho = 1000 \times \frac{(1-(T+288.9414)}{(508929.2 \times (T+68.12963)} \times (T-3.9863)^2$$

Where ρ equals density in kg/m^3 as a function of temperature (T) only.

Equation 4-5 and Equation 4-6 were applied to calculate point water density as a function of temperature (T) and salinity (S), measured as TDS:

Equation 4-5

$$\rho_i = \rho + AS + BS^{\frac{3}{2}} + CS^2$$

Equation 4-6

$$A = (8.24493 \times 10^{-1}) - (4.0899 \times 10^{-3}) \times T + (7.6438 \times 10^{-5}) \times (T^2) - (8.2467 \times 10^{-7}) \times (T^3) + (5.3675 \times 10^{-9}) \times (T^4)$$

$$B = (-5.724 \times 10^{-3}) + (1.0227 \times 10^{-4}) \times T - (1.6546 \times 10^{-6}) \times T^2$$

$$C = 4.8314 \times 10^{-4}$$

Wetland elevations and bore casing depths vary considerably along hydraulic gradients therefore it was essential that a suitable reference depth (z_r) was selected in order to calculate horizontal flow. Groundwater and surface water levels h_i were measured relative to elevation head z_i for each site. Density ρ_i was corrected to fresh water heads relative to a reference density ρ_f (1,000 kg/m^3). An average density (ρ_a) between the reference depth (z_r) and elevation head (z_i) for each bore and wetland was determined and a sensitivity analysis was completed using a range of reference depths (z_r) and average vertical density gradients (ρ_a). The following (Equation 4-7) was used to calculate the fresh water head at the reference depth z_r ($h_{f,r}$) (Post et al., 2007):

Equation 4-7

$$h_{fr} = z_r + \frac{\rho_i}{\rho_f}(h_i - z_i) - \frac{\rho_a}{\rho_f}(z_r - z_i)$$

4.5.4 Flow net analysis

All groundwater levels were converted to mAHD and then corrected to equivalent fresh water heads to account for density (detailed above). Density-corrected heads were hand contoured for both May and August of 2009 to examine the seasonal trough and peak variations in the water table. Plan-view water table maps were geo-referenced and digitised in ArcMAP then processed in Surfer using the "GridMath" function to convert to metres below ground level (mbgl).

4.5.5 Aquifer testing

Slug test analysis was undertaken to characterise the aquifer properties (K_{hoz}) for each aquifer. Sites with highly permeable sands had water added (slug-in or falling-head test), whereas those with low permeability clays had water removed (slug-out or rising-head test). The rate of recovery of the groundwater head was measured using an Odyssey (64k) capacitance probe type data logger set to log at 5-second intervals. Sites with recovery times in excess of 12-hours were logged on an hourly basis and data was recovered the following month. Slug test analysis was performed between one and nine times on each bore. Results from bores BMC89ob, BMC91ob, BMC93ob and BMC94ob were excluded due to a significant proportion of the screened interval being above the water table, meaning that slug tests are likely to over-estimate hydraulic conductivities (Bouwer, 1989). Hydraulic conductivity for these sites was obtained from the relevant literature.

Analysis was performed using the Bouwer and Rice (1976) method for unconfined aquifers with completely or partially penetrating wells (Halford and Kunianski, 2002). When plotting the water level recovery over time (log Yo/t (metres/seconds)) it is recognised that a double straight-line effect can occur (Bouwer, 1989). An initial straight-line can represent a higher permeability zone proximal to the bore which can be due to higher permeability soils around the bore, drainage of the gravel pack, or development zone which is formed around the bore after lowering of the water table (Weeber and Narasimhan, 1997). In this study the double straight-line effect was overcome by using the second straight line to calculate hydraulic conductivity (K_{hoz}) of the aquifer (Bouwer, 1989).

4.5.6 Barometric efficiency

Mean Sea Level Pressure (MSLP) data from the automated weather station (AWS) from Dalwallinu (BoM site 8297) was corrected to station level pressure for the study area using the following equation (Equation 4-8) detailed in Kinkela (2009):

Equation 4-8

$$P = P_O \exp - \frac{Mgz}{RT}$$

> Where P is the station level pressure (Pa); P_o the hourly mean sea level pressure (Pa) from the AWS in Dalwallinu; M the molar mass of air; g the gravitational acceleration; z is the height of the station above sea level (257.29 mAHD) at wetland W017; R is the universal gas constant; and T is temperature. Station level pressure was converted to the SI units of m H^2O using P * 0.0102.

Graphical methods are a rapid way to estimate barometric efficiency (*BE*) because they are simple to apply, have a low error compared to other mathematical methods, and are resistant to other factors which are independent of barometric pressure (Gonthier, 2007). Hourly groundwater hydrographs and hourly station pressure were plotted against time for all groundwater and surface water monitoring sites. Plots were then used to qualitatively assess the relative influence of barometric pressure upon water levels for each of the groundwater monitoring sites.

4.5.7 Groundwater trends

Groundwater trends were analysed by graphically applying a linear line of best fit to long-term water level records. Additionally, the temporal relationship between groundwater fluctuations and long-term rainfall trends were analysed using Hydrograph Analysis: Rainfall and Time Trends (HARTT) software (Ferdowsian et al., 2005, Ferdowsian and Pannell, 2001). HARTT analysis explicitly details the effect of rainfall upon groundwater recharge. It is however least effective for analysis of shallow water tables (<5 m below ground level) where other factors, such as ET influence groundwater trends (Ferdowsian et al., 2000). Water levels within bores are all <5 m, however given the application in similar conditions elsewhere (Robertson et al., 2010, Dogramaci et al., 2003) it was considered an appropriate tool for analysis of bores screened within semi-confined aquifers. HARTT was populated with historical daily rainfall data from the BoM stations Koobabbie (1911 to 2009) and Coorow Post Office (1912 to 2009).

4.5.8 EM38 soil salinity

Electromagnetic (EM) surveys of the low lying areas near wetlands W015, W016 and W051 were conducted by Melissa Cundy of DEC Geraldton, in November 2008 using a Geonics EM38, electromagnetic inductor meter. Equipment was calibrated as per Bennett *et al* (1995) and EM38 surveys were conducted in horizontal and vertical mode at approximate 100 m x 25 m grid intervals.

The EM38 measures apparent electrical conductivity (EC_a) in units of mill Siemens per metre (mS/m). In a uniform soil, about 75% of the signal response in horizontal mode can be attributed to the top 1.0 m of the soil profile (Bennett and George, 1995). In vertical mode the depth of penetration extends to about 1.8 m below the surface (Bennett and George, 1995). While soil salinity is the major parameter influencing EC_a, clay content, soil moisture, bulk density and temperature can also affect EC_a (Bennett et al., 2000, Wong et al., 2008). Thus EM38 results are treated here as qualitative estimates of soil salinity.

4.6 Catchment-scale water balance methods

Water balance analysis was based on the assumption that on an annual basis there is no net change in storage. The following steady-state equation (Equation 2-2) was applied to determine the water balances at both the wetland and catchment-scale:

Equation 4-9

$$\frac{\Delta V}{\Delta t} = G_i + S_i + P - G_o - S_o - ET = 0$$

> Where ΔV is the change in lake volume over time (t), P is precipitation inflow volumes, G_i and S_i are groundwater and surface water inflow volumes, G_o and S_o are groundwater and surface water outflow volumes and evapotranspiration (ET) outflow.

George (1992a) calculated a pre-clearing water balance by applying a conceptual boundary, or hinge-line, between the groundwater recharge zone and discharge zone occurring adjacent to playas and halophytic (saline) areas. While it is recognised that recharge and discharge occurs both within the upper and lower slopes of Nabappie, discharge predominantly occurs in the lower slopes. Consequently for the purpose of a catchment-scale water balance, the Nabappie subcatchment was divided into an upper slope recharge domain and lower slope discharge domain with the conceptual hinge-line occurring at the break of slope near wetlands W051 and W026.

4.6.1 Recharge and ET

Groundwater recharge rates were determined for areas aggregated according to vegetation type and landuse. The distribution of bare soil and annual cropping was interpreted from aerial photographs, whilst soil types and native vegetation boundaries were obtained from spatial datasets (Griffin and Goulding, 2004, Huggett et al., 2004). Vegetation type was intersected with interpolated depth to water table (DTW) maps to predict areas of groundwater availability for deep-rooted perennial vegetation. ET rates were allocated to each vegetation type under the assumption that plant water use in the recharge domains is optimal, including annual agricultural crops in the upper slopes, whilst the prevalence of waterlogging and elevated salinity in the lower discharge area means that ET is likely to be suboptimal. The nitrogen-fixing perennial, tagasaste is assumed to be accessing GW where DTW was <6 mbgl. Details on the specific recharge rates and ET rates allocated to each vegetation type and landuse are tabulated in Chapter 7.

4.6.1.1 Direct measurement of ET

Short-term fluctuations in shallow water table levels can be used to directly measure ET rates from phreatophytic vegetation (Gribovszki et al., 2010, Freeze and Cherry, 1979). Hourly groundwater level data in shallow groundwater monitoring bores was assessed for evidence of diel, or diurnal water table fluctuations. In cases where diurnal signals is evident the modified version of the White method (cited in Freeze and Cherry, 1979), was applied to determine ET (Equation 4-10).

Equation 4-10

$$ET = Sy(24r \pm s)$$

> Where *r* is the rate of change over a 24-hour period defined by slope from midnight to 4am, *Sy* the readily available specific yield (~50% of true specific yield), and *S* the net rise or fall of water table over 24 hours (Figure 4-1).

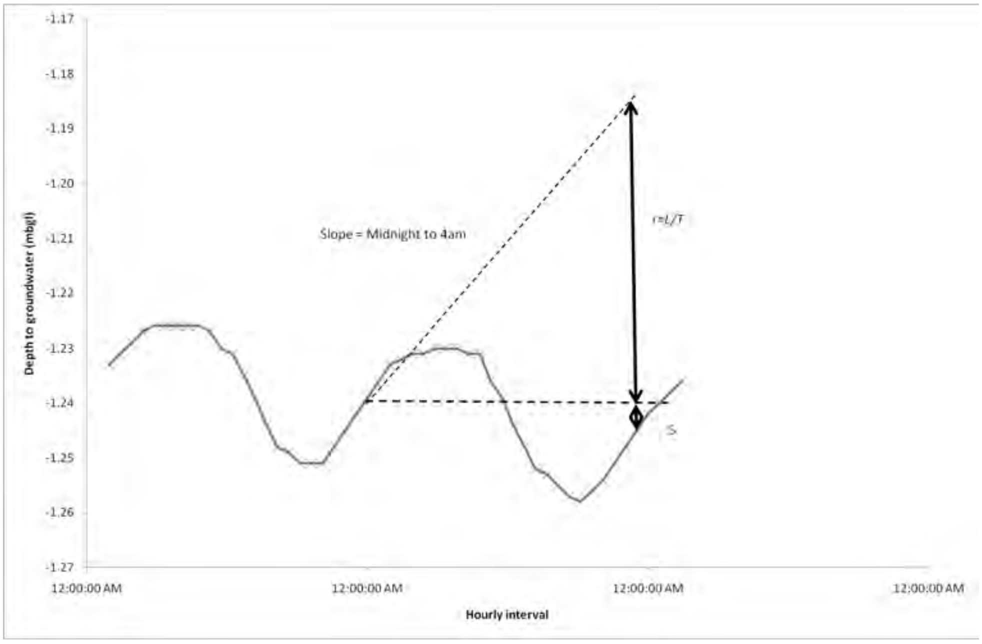

Figure 4-1. Calculation of evapotranspiration in a discharge area from water table fluctuations induced by phreatophytic consumptive over a 24-hour period (after Freeze and Cherry, 1979)

4.6.1.2 Recharge - Chloride mass balance

Rainfall is assumed to occur uniformly across the entire subcatchment with groundwater recharge rates dependent upon soil type/depth, vegetation and topographic relief. Mean annual recharge (MAR) was assessed using average Cl^- in precipitation and groundwater, based on the assumption that Cl^- is sourced only from precipitation and dry fallout occurring on the surface and no contribution from weathering (Allison and Hughes, 1978). Other sources of Cl^-, such as applied fertilizers were considered negligible. Cl^- methods were therefore applied only to bores occurring in the recharge domain, specifically bores BMC89ob, BMC91ob, and BMC94ob plus three additional bores located in the adjacent catchment (BMC01d, BMC02d, and BMC02ob). The following equation (Equation 4-11) was applied:

Equation 4-11

$$R = P \times \frac{Cl_p}{Cl_{gw}}$$

Where R is recharge (mm), P is precipitation (mm) and Cl_p refers to average Cl^- in precipitation (mg/L) and Cl_{gw} is Cl^- in groundwater (mg/L). Upper and lower rainfall Cl^- concentrations applied by George (1992a) (4 mg/L and 8 mg/L) were used.

4.6.1.3 Recharge - Hydrograph analysis method (specific yield method)

If the specific yield of an aquifer is known then groundwater recharge rates can be estimated by analysis of the annual fluctuation of groundwater levels (Salama et al., 1993b, George, 1992a). Specific yield for the study area are not well quantified, however the use of values from the literature (George, 1992c, Fetter, 2001, Halford and Kunianski, 2002, George, 1992a) enabled an analysis of recharge using the upper and lower bound specific yield values (Chapter 5).

4.7 Wetland-scale water balance methods

4.7.1 Evaporation

Wetland-scale water balances for wetlands W016, W017, and W051 were completed. A fixed-area wetland boundary was used for water balances, based on the maximum wetland extent in 2009. Monthly surface water depths observed in 2009 were translated to temporally variable water volume, water body surface area and the area of bare soil. These were then used to calculate monthly precipitation inputs, as well as outputs from both bare soil and open water body ET.

Daily Class-A pan evaporation data from Wongan Hills Research Station (BoM site 8138) was interpolated from pan evaporation isolines from Luke et al (1987) to represent Nabappie (E_{pan}=x*1.0549). Evaporation from open water bodies was calculated using the following (Equation 4-12 and Equation 4-13):

Equation 4-12

$$ET = E_{pan} \times \frac{E_{pan}}{E_{lake}} \times aw \times A$$

Equation 4-13

$$aw = \frac{1}{(1 + TDS \times 10^{-6})}$$

Where ET is evapotranspiration from an open water body; E_{pan} is pan evaporation; E_{pan}/E_{lake} is an evaporation coefficient range of 0.6 to 0.8; A is the surface area of the wetland; aw is the correction factor for water activity, where the wetland TDS accounts for salinity effects upon evaporation rates (Equation 4-13) (Tweed et al., 2009, Jones et al., 2001).

Temporally variable ET-driven surface salt mineralisation (or crusting) and rainfall dissolution has a significant influence on bare soil ET rates (Chen, 1992, Tyler et al., 1997). Two distinctly different patterns occur, which Chen (1992) describes as E_1, which is a very low rate (<70 mm/yr or 2.4% of pan evaporation) occurring during the salt-encrusted phase; and E_2, which is as a higher rate, although lower than annual rainfall, which occurs after the surface salts are dissolved by rainfall. In this study, the E_1 state was considered to occur from 1st January through to 21st May (break of season), the E_2 state from 22nd May through 30th September, thereafter returning to the E_1 state. Three values (low, middle and upper) were selected for the E_1 state which was 50 mm/yr ($0.02*E_{pan}$), 60 mm/yr ($0.024*E_{pan}$), and 70 mm/yr ($0.28*E_{pan}$); and three values for the E_2 state of 760 mm/yr ($0.3*E_{pan}$), 1013 mm/yr ($0.4*E_{pan}$), and 1266 mm/yr ($0.5*E_{pan}$). On an annual basis this equates to 309 mm/yr (1.1*P), 407 mm/yr (1.45*P), and 506 mm/yr (1.8*P) bare soil ET. Bare soil ET rates were reduced slightly at wetland W051 due the presence of organic matting and reeds. This simple bi-modal method was applied rather than explicitly model sub-annual time-steps due to the paucity of time-series soil moisture data.

4.7.2 Darcy's groundwater flux calculation

Daily groundwater water levels were used to calculate horizontal discharge from the unconfined aquifer and vertical discharge from the semi-confined aquifer at wetlands W051, W016 and W017. Wetland W051 is a flow-through wetland therefore the principles of Townley et al (1993) were applied to determine the groundwater capture and release zones. The capture zone of W051 is twice the diameter of the wetland (10 m) and the depth of the capture zone being half of the aquifer thickness (5.63 m). Capture zone widths of wetlands W016 and W017 were considered equal to the diameter, and the capture zone depth equal to the aquifer thickness due to the small ratio of wetland diameter to aquifer thickness (2a/B) (Townley et al., 1993). It was assumed that there is no vertical inflow from the semi-confined aquifer to wetland W016. Uncertainties relating to the width or depth of capture zone for wetlands are likely to contribute error in calculated groundwater inflows.

A sensitivity analysis of groundwater fluxes in the water balance was completed using a range of three lower middle and upper hydraulic conductivity values from both this study (Chapter 5) and the published literature (Bennett and Goodreid, 2009, George, 1992c, George, 1992b).

4.7.3 Surface water flows

Except during the highest magnitude rainfall events (perhaps 1:50 to 1:100 ARI), the area of deep yellow sands in the upper catchment will not generate overland flows. Any water which doesn't infiltrate in typical years will be redistributed locally resulting in additional recharge (Short et al., 2006). Conversely, the lower area of the subcatchment has shallow groundwater and is waterlogged for much of the year allowing for the generation of surface water.

A monthly time-step model was used to estimate runoff inflows to wetlands W051, W016, and W017, in the absence of continuous surface water flow data. It was assumed that surface water flows were generated only within the drainage lines where the DTW was <1 mbgl (Figure 4-2), and the immediate vicinity of W051. The contribution area for wetland W051 was 81 m^2, 88,139 m^2 for W016, and 231,233 m^2 W017 (Figure 4-2). Runoff was calculated using the monthly interception method described by De Groen and Savenije (2006), as applied by Marimuthu et al (2005a) (Equation 4-14 and Equation 4-15).

Equation 4-14

$$S_i = C(P_m - I_m)A$$

Equation 4-15

$$I_m = P_m(1 - \exp(\frac{-Dn_r}{P_m})$$

> Where S_i is surface water runoff; C is the runoff coefficient (0.1 to 0.3); P_m is the monthly rainfall; I_m is the monthly interception (includes leaf interception and wet surface evaporation); A is the catchment area; D is a daily threshold, defined as 4 mm/d (Savenije, Undated); and n_r is number of rain days per month observed at Nabappie in 2009.

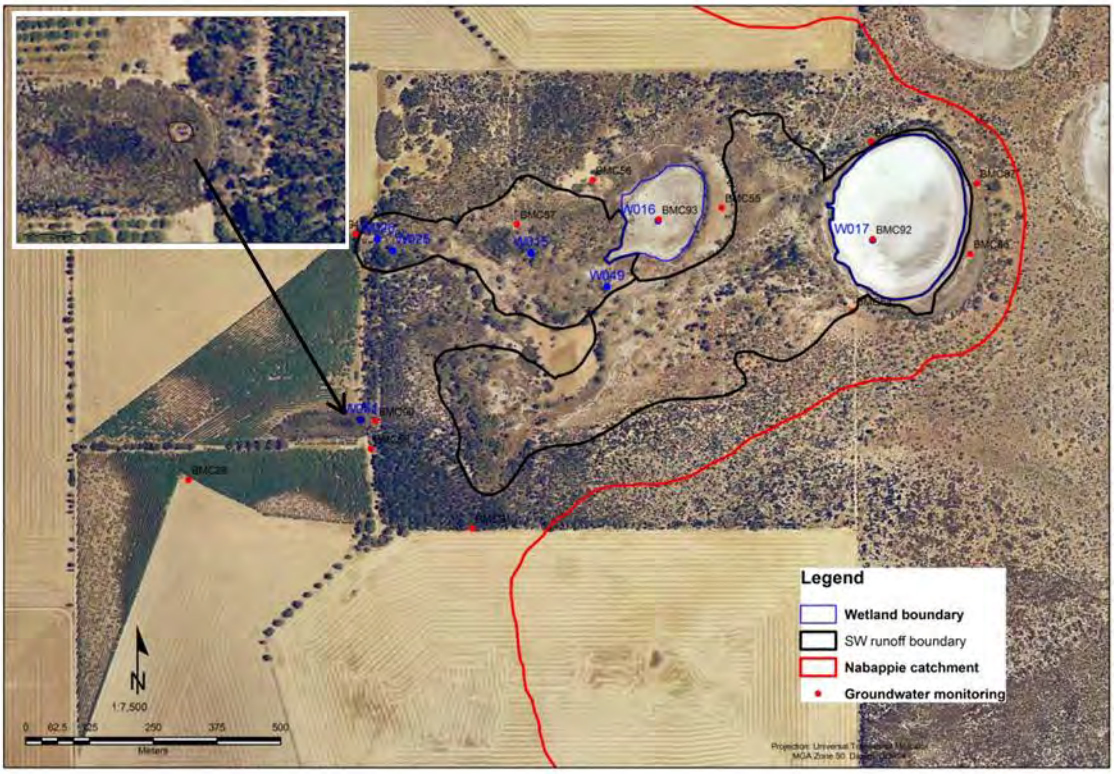

Figure 4-2. Boundary of surface water contribution areas for wetlands W016 and W017, with an inset showing the surface water boundary for wetland W051.

4.7.4 Hydrochemical and stable water isotope methods

Precipitation, groundwater, surface water fluxes, bare soil ET, and wetland ET were cumulated into sampling periods for application to stable water isotope and Cl^- mass-balance methods. Conceptual models for each of the wetlands were used to allocate the most appropriate end-member (δD, $\delta^{18}O$, and Cl^-) representing the groundwater and surface water input fluxes. Mass balances were undertaken on the assumption that wetlands were well mixed and the isotopic signature of the groundwater outflow was equal to that of the wetland. The volumes of fluxes and their isotopic signatures were then applied to steady-state mass balance equations (Equation 4-16 to Equation 4-24) to determine groundwater inflows and outflows (Krabbenhoft et al., 1990b).

Equation 4-16

$$Gi = \frac{P(\delta_L - \delta_P) + S_I(\delta_L - \delta_{SI}) + E(\delta_E - \delta_L)}{(\delta_{GI} - \delta_L)}$$

Equation 4-17

$$G_o = G_I + S_I + P - E - \Delta V$$

Where δ denotes the isotopic signature of the water flux precipitation (δ_P), wetland surface water (δ_L), groundwater inputs (δ_{GI}); surface water inputs (δ_{SI}) and evaporation outputs (δ_E) determined from Equation 4-18 (Rozanski et al., 2001, Kendall and Caldwell, 1998, Craig and Gordon, 1965, Horita and Wesolowski, 1994); and *P*, *S*, *G* and *E* represent the volume of each flux. Equation 4-16 as applied to the conservative tracer Cl^-, although the δ_E was excluded from the equation due to Cl^- concentration in the evaporate equalling zero (Kendall and Caldwell, 1998).

Equation 4-18

$$\delta_E = \frac{(\alpha^* \delta_w - h'\delta_a - \varepsilon)}{\left[(1-h') + \Delta\varepsilon / 1000\right]}$$

Equation 4-19

$$\varepsilon = \varepsilon^* + \Delta\varepsilon$$

Equation 4-20

$$\varepsilon^* = (1-\alpha^*).10^3$$

Equation 4-21

$$\Delta\varepsilon = (1-h') \times \theta \times n \times \varepsilon_k$$

Equation 4-22

$$\delta_a = (\delta_p \times \alpha^*) - \varepsilon$$

Equation 4-23

$$(\ln \delta^{18}O)\alpha = 2.0667 \cdot 10^{-3} + \frac{0.4156}{T} - \frac{1.137 \cdot 10^3}{T^2}$$

Equation 4-24

$$(\ln \delta D)\alpha = -52.612 \cdot 10^{-3} + \frac{76.248}{T} - \frac{24.844 \cdot 10^3}{T^2}$$

Where α (>1) is the equilibrium isotope fractionation factor at the temperature of the water/atmosphere interface, whilst α* is 1/α therefore <1; *T* is the average monthly atmospheric temperature (degrees Kelvin); δ is the stable isotope signature of evaporation (δ_E), lake water (δ_L) atmosphere (δ_A) and weighted monthly mean precipitation (δ_P); Δε is the diffusion controlled or kinetic fractionation factor; ε_k is the kinetic enrichment constant with values 25.1‰ for δD and 28.5‰ for $\delta^{18}O$; ε* is the equilibrium fractionation; θ is a weighting term which can be assumed to be 1, and *n* is 0.5 for an open water body; *h* is the average monthly relative humidity for 2009 from Dalwallinu (BoM site 8297) normalised (*h'*) to the salinity of the water (Equation 4-13 and Equation 4-25).

Equation 4-25

$$h' = \frac{h}{aw}$$

A sensitivity analysis was conducted using the stable water isotope (δD and $\delta^{18}O$) and Cl^- mass balance approach. This provided an independent method for validating the conceptual models and to segregate the inflow sources applied in the water balance. The sensitivity analysis included applying a range of input parameters to represent the range of likely and extreme volumes (*P, E,* and *Si*), concentrations (Cl^-, δD, and $\delta^{18}O$), and climate (relative humidity) values. The appropriateness of the local isotopic signature (LMWL) of precipitation was also tested by applying both the weighted monthly mean, annual weighted mean, and also the weighted long-term annual isotopic signature for Perth (δD -16.69‰, and $\delta^{18}O$ -4.09‰) (Liu et al., 2010).

CHAPTER 5:

5 Physical hydrology

5.1 Precipitation and evaporation trends

Rainfall recharge, groundwater discharge via ET and surface water inflows are the critical drivers of the hydrogeological function of the Nabappie wetland suite. The annual rainfall for the Nabappie subcatchment for 2009 was 280 mm (Figure 5-1), which was comparable to 2008 (285 mm), and more than 2007 (230 mm). In 2009 the nearby town of Coorow (BoM site 8067) received 314 mm and the Koobabbie homestead 286 mm (BoM site 8037) (Bureau of Meteorology, 2010), which were below the long-term averages by 66.7 mm and 50.2 mm respectively. Measurement error at Nabappie is anticipated with be within ±10% (~30mm) due to site specific factors such as proximity of rain gauges to vegetation, and inherent measurement errors associated with tipping bucket rain gauges such as non-linear responses (Canterford, 1997, Winter, 1981). The 2009 Class-A pan evaporation, interpolated from the Wongan Hills Research Station, was 2,533 mm (Figure 5-1). Rainfall was greater than potential evaporation for 34 days in 2009, largely during winter (Figure 5-1).

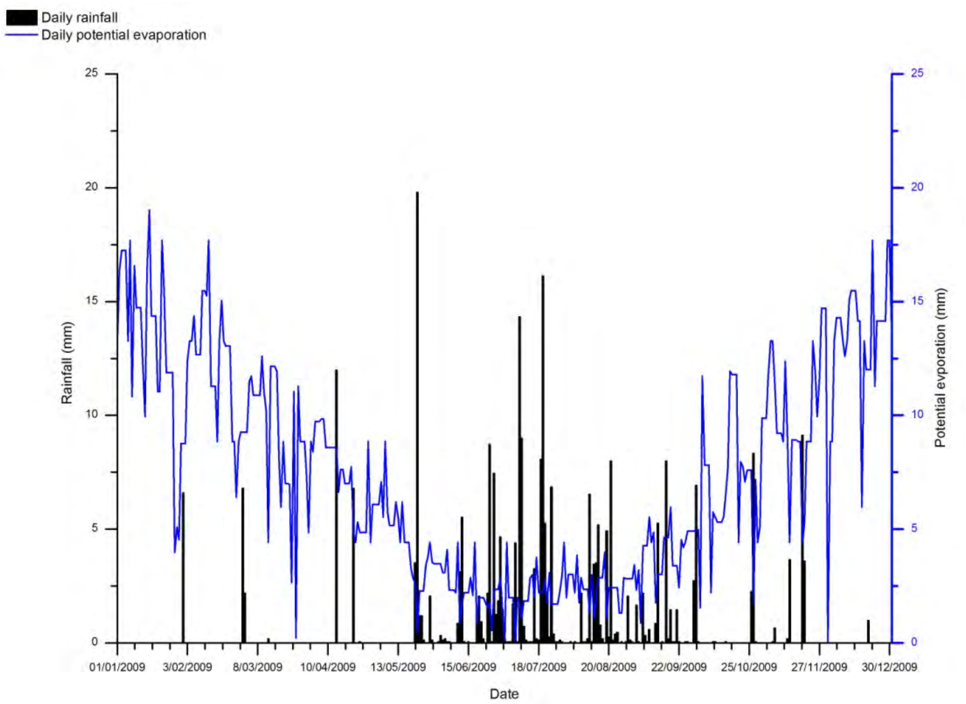

Figure 5-1. Daily 9am rainfall and interpolated daily Class-A pan evaporation for the Nabappie subcatchment in 2009.

5.2 Field observations

Discharge of tannin-stained groundwater was observed in winter months down gradient of wetlands W051 and W026 across a broad area, although was concentrated within the poorly defined drainage lines (Figure 5-2). Saturated conditions persisted throughout winter, resulting in rapid generation of surface water inflows to wetland W017 following rainfall. The mixing of groundwater discharge, surface water and rainfall was evident with surface water flows of varying EC and colour. Inflows to wetland W017 in July and August (sample name W017_inlet) were analysed to assist with water balance analysis (Chapter 7). Surface water flows were not observed entering wetland W016, or on the deep yellow sands of the upper catchment.

Figure 5-2. Photograph by the author in July 2009 of tannin-stained surface water flows occurring south-east of wetland W016. Water was flowing in an easterly direction from top of picture to the bottom along poorly defined drainage lines into wetland W017.

5.3 Hydrogeology

5.3.1 Aquifer testing

Analysis of slug test results from November 2008 to November 2009 yielded a large range of hydraulic conductivity values across bores tested (Table 5-1 and Appendix 5A). At sites BMC89ob, BMC91ob, and BMC94ob a large proportion of the screen was above the water table, therefore a locally relevant K_{hoz} value for sandplain soils of 0.15 m/day (±0.5 m/day) was adopted (Bennett and Goodreid, 2009, George, 1992b). This value is comparable to results from BMC90ob (0.13 m/day). Ratios of K_{hoz} to vertical hydraulic conductivity (K_{vert}) are dependant upon the aquifer material and anisotropy therefore can range from 1:100 to 1:<0.002. Reported K_{hoz}:K_{vert} ratios for sand, silt and clay are typically in the order of 1:10 (Papadopulos and Larson, 1978) and were assumed as the first approximation of the likely values. Table 5-1 provides a summary of the K_{hoz} values and approximated K_{vert} for the five aquifers at Nabappie.

Table 5-1.Summary of average hydraulic conductivity values (m/day) for the five interpreted aquifers in the Nabappie subcatchment

Aquifer	Bore	K_{hoz} (m/day)	K_{vert} (m/day)
Fresh surficial unconfined	BMC89ob, BMC90ob, BMC91ob, BMC94ob	0.15	0.015
Hyposaline unconfined	BMC56ob	0.024	0.0024
Saline unconfined	BMC86ob, BMC87ob, BMC88ob	0.019	0.0019
Hyposaline semi-confined	BMC56d, BMC57d, BMC58d, BMC58i	0.009	0.0009
Saline to hypersaline semi-confined	BMC54d, BMC55d	0.003	0.0003

Note: Values for bores located in the base of wetlands (BMC92ob and BMC93ob) are excluded from this table.

5.3.2 Barometric efficiency corrections

Time-series hydrographs of barometric pressure versus depth to groundwater were plotted for all bores (two examples provided in Appendix 5B). While a barometric pressure signal within groundwater levels was present for all bores, it was considered to have an insignificant influence on water levels. Consequently a detailed analysis of barometric efficiency (BE) was not necessary therefore negating the need to correct water levels for barometric pressure. These results contrast with other studies within the wheatbelt region where barometric efficiency (BE) was in the order of 50% (Salama et al., 1994, George, 1992b).

5.3.3 Density corrections

An analysis of the effects of density on groundwater and wetland surface water levels revealed corrections were sensitive to density and reference depth (z_r). The range of parameters tested encompassed two average density (ρ_a) ranges (90% and 100% of point density (ρ_i)), and four different reference depths (z_r), which represented 7m, 2m, 1m and 0m below the base of wetland W017.

Given the short screen lengths for all bores (typically 2m), the range of casing depths, and wetland elevations, it was not possible to keep z_r within the range of employed screens as recommended by Post et al (2007). To try and replicate an appropriate reference datum within the screened interval, a depth of 1m below wetland W017 (256.29mAHD) was used (Table 5-2). The average density (ρ_a) equal to the measured density (ρ_i) was also used in combination with this z_r to achieve a conservative, yet "realistic" density correction. All of the results derived from the different parameters can be found in Appendix 5C, whilst Table 5-2 contains average corrected heads for the adopted reference depth (z_r=256.29 mAHD) and ρ_a equal to measured density (ρ_i). Density corrected heads derived from these parameters are applied throughout the remainder of this study.

The effects of density corrections on freshwater equivalent heads were greatest for wetland W736 (+0.23m) (Table 5-2). W736 is located in the upper slopes of the catchment; hence the relatively large difference is more related to the choice of reference datum rather than density and should be considered an anomaly. In the lower slopes, where density corrections are more critical, the difference between measured and corrected heads was greatest (+0.19 m, average +0.17 m) at bore BMC55d (Table 5-2). The largest corrections (+0.28 m to +0.36 m) were observed in the regional primary saline aquifer. This is an artefact of the distance from the study area and difference in ground elevation consequently density corrected data from these bores has been excluded from flow net interpretations.

Table 5-2. Summary of average water level (h_i) and density-corrected (h_{fr}) water levels for groundwater and wetlands using reference depth (z_r) of 256.29mAHD, 257.29mAHD, and an average vertical density (ρ_a) equal to measured density.

Site ID	Average h_i (mAHD)	Average Density (kg/m^3)	StdDev (kg/m^3)	h_{fr} (zr=256.29)	Difference (m)
BMC54D	257.31	1097.07	9.65	257.41	0.10
BMC55D	259.67	1049.85	2.63	259.84	0.17
BMC56D	262.26	1000.02	0.05	262.26	0.00
BMC56OB	259.91	1003.00	1.35	259.92	0.01
BMC57D	262.70	1000.00	0.00	262.70	0.00
BMC58d**	268.15	1000.10	-	268.12	0.00
BMC58I	268.11	1000.10	0.17	268.11	0.00
BMC64D*	260.70	1081.94	-	261.06	0.36
BMC64I*	260.42	1073.24	-	260.72	0.30
BMC64OB*	260.56	1066.41	-	260.84	0.28
BMC86OB	257.03	1059.09	-	257.07	0.04
BMC87OB	257.30	1060.83	2.92	257.36	0.06
BMC88OB	257.26	1075.19	11.73	257.33	0.07
BMC89OB	270.38	1000.00	0.00	270.38	0.00
BMC90OB	267.87	1000.55	0.41	267.88	0.01
BMC91ob**	266.83	1000.00	-	266.83	0.00
BMC92OB	257.30	1134.71	64.82	257.43	0.13
BMC93OB	258.78	1006.40	0.53	258.79	0.02
BMC94OB	267.32	1000.00	-	267.32	0.00
W015	262.27	1001.69	1.95	262.28	0.01
W016	259.57	1012.09	6.89	259.61	0.04
W017	257.39	1105.10	82.34	257.50	0.11
W026***	-	-	-	-	-
W051	268.01	1001.15	1.47	268.03	0.01
W735	279.63	1001.10	0.34	279.66	0.03
W736	280.37	1009.74	1.45	280.61	0.23

*Not in the study area but used as a reference for the regional hypersaline aquifer.
** TDS data extrapolated from established TDS/E.C. relationship using historical field water quality (E.C.) data.
*** Water depth data not available.

5.3.4 Groundwater historical trend analysis

HARTT analysis of groundwater level data from 2006 to 2009 indicated that groundwater trends were more strongly correlated to rainfall trends from Coorow PO (BoM site 8067) than the Koobabbie homestead (BoM site 8037) therefore all results are reported with respect to the Coorow PO rainfall. Plots of HARTT analysis and daily time-series hydrographs are contained in Appendix 5E and Appendix 5F, whilst Table 5-3 provides a summary of HARTT analysis from the deep and intermediate bores[9].

The strongest correlations were observed in those deep bores screened within the hyposaline semi-confined aquifer (BMC56d, BMC57d, BMC58d), and intermediate

[9] Shallow bores excluded as per comments in Chapter 4 (methods).

bore BMC58i, whilst the lowest correlations were observed for those bores within the hypersaline semi-confined aquifer nearest to the valley floor. In all cases HARTT analysis indicated, with respect to the long-term average rainfall, that groundwater levels are rising between 0.25 m/yr and 0.34 m/yr (Table 5-3). The use of HARTT in shallow groundwater sites (<5m DTW) is not recommended (Ferdowsian and Pannell, 2001, Ferdowsian et al., 2000) so the shallow sites have been excluded from this analysis. Manual linear interpolation of groundwater trends produced more conservative values and ranged from 0.04 m/yr to 0.08 m/yr (Table 5-3). These latter interpretations are based on the observed data rather than inference from the long-term climate trends.

Table 5-3. Summary of Hydrograph Analysis: Rainfall and Time Trends (HARTT) with respect to the long-term Accumulative Annual Residual Rainfall (AARR) trends of Coorow (BoM site 8037) and manually interpreted linear trends. Groundwater records are from 2006 to 2009 and rainfall from 1912 to 2009.

Bore ID	Length of record (years)	Number of readings	Best fit delay (months)	Correlation (R^2)	HARTT Trend (m/year)	Linear trend (m/year)
BMC54d	4	34	1	0.64	0.25	0.065
BMC55d	4	33	0	0.40	0.27	0.083
BMC56d	4	30	1	0.92	0.25	0.059
BMC57d	4	34	1	0.90	0.22	0.040
BMC58d	4	33	0	0.86	0.30	0.067
BMC58i	4	33	0	0.76	0.34	0.063
Minimum	4.00	30.00	0.00	0.40	0.22	0.040
Maximum	4.00	34.00	1.00	0.92	0.34	0.083
Mean	4.00	32.83	0.50	0.75	0.27	0.063
STDEV	0.00	1.47	0.55	0.20	0.04	0.014

5.3.5 Wetland depth to volume relationships

Plots of depth to volume relationships for wetlands W016, W017, W051, W735 and W736 determined from LiDAR topographical data are detailed in Appendix 5G. Given the low topographical relief of wetlands at Nabappie, the error is estimated to be greatest when wetland water levels are at their lowest. The following table (Table 5-4) provides a summary of the maximum depths and volumes of water stored in each of the wetlands in 2009 and interpolations from orthophotos in the very wet year of 1999.

Time-series wetland surface water levels were extrapolated from historical aerial photographs for wetland W736 (Figure 5-3). In 1959 this wetland was dry and likely ephemeral however it appeared as a permanent water body thereafter. Analysis of time-series aerial photographs indicates that wetland water levels in W736 have risen by ~0.04 m/yr from dry in 1959 to ~1.5 m in 2009/2010. In the very wet year of 1999, the water levels were about 1.9 m deep, which is approximately 0.4 m higher than current levels, hence contained an additional 17,347 m^3 of water.

Table 5-4. Summary of depth to volume relationships interpreted for 1999 and 2009. With the exception of W736, error for depth and volume values is likely to be in the order of ±20% for 2009.

Wetland ID	Year	Depth (m)	Volume (m^3)
W015	1999	Unknown	-
	2009	0.20	-
W016	1999*	0.75	13,620
	2009	0.18	302
W017	1999*	1.40	93,220
	2009	0.18	1,562
W026	1999*	Unknown	-
	2009	0.20	-
W051	1999*	1.28	24
	2009	0.60	15
W735	1999*	0.60	771
	2009	0.35	211
W736*	1999*	1.86	75,463
	2009	1.50	56,614

*Error associated with depth to volume relationships likely to be >20%

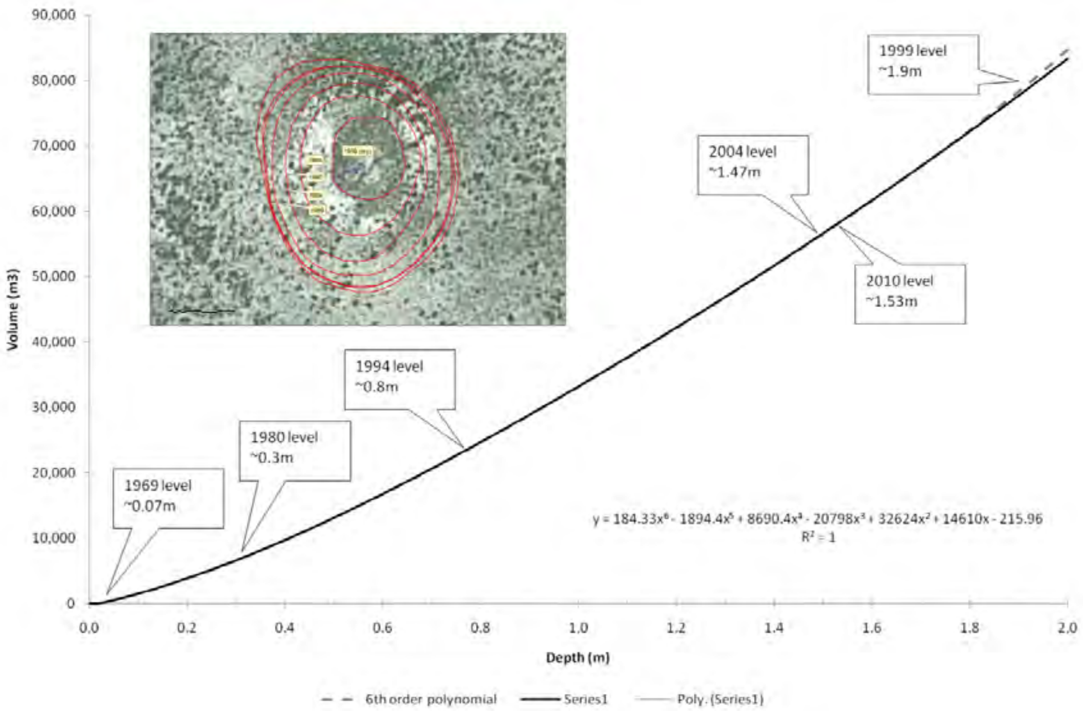

Figure 5-3. Historical water levels for wetland W736 from 1959 to 2010, determined from historical aerial photographs and bathymetry interpolated from LiDAR topographical data. Error bounds on interpretations are >20%. Inset image of wetland in 1959 with red rings indicative of surface area of wetland in 1969, 1990, 1994, 1999, 2004 and 2010.

5.3.6 Groundwater/surface water interactions

Hydrographs of logged daily rainfall, surface water and groundwater levels, combined with manual monthly measurements of water level and TDS are presented for wetlands W051, W015, W016, and W017 (Figure 5-4 to Figure 5-7). Observations from wetland W735 and W736 are omitted due to the paucity of groundwater data and lack of accurate time-series water level data.

5.3.6.1 Wetland W051

Water levels in W051 were below ground level (267.75 mAHD) from the start of 2009 until successive rainfall events in late May (~25 mm) led to a rise in water levels in early June (Figure 5-4). Water level responses to rainfall were notable thereafter and continued to rise to a depth of 268.35 mAHD (0.60 m) in late August. Water levels subsequently fell, although rose immediately following rainfall events occurring in October and November. Water levels at down-gradient bore BMC90ob responded to seasonal variability of rainfall in a similar pattern to wetland W051 although were ~0.25m lower in elevation. This suggests a continuous flow-through discharge of wetland water (when present) to the unconfined aquifer.

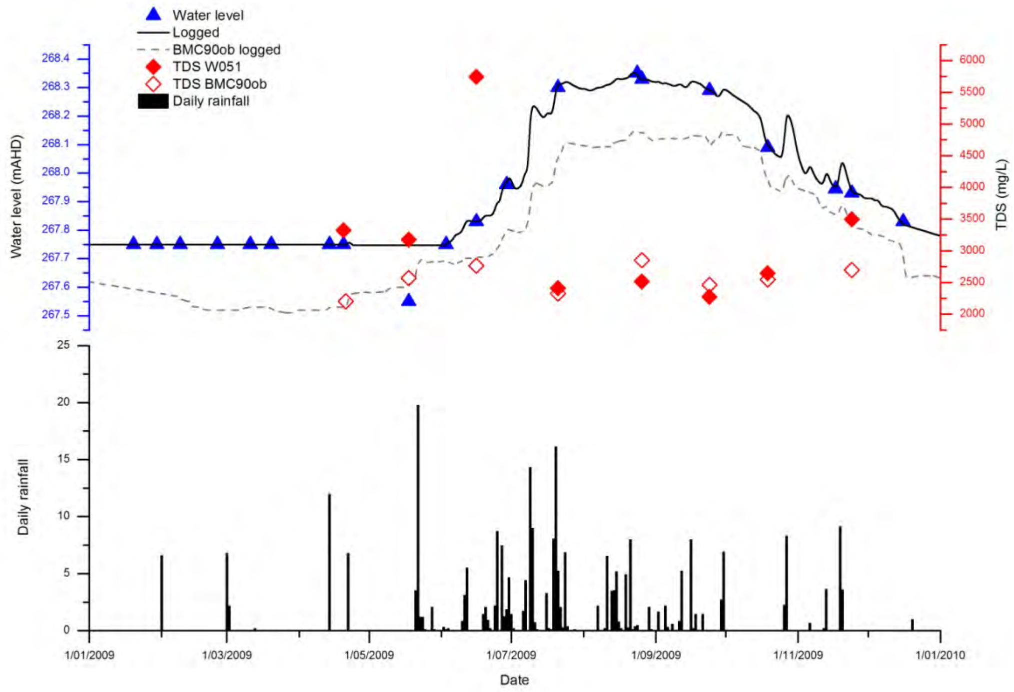

Figure 5-4. Logged daily water levels (black line) and manual measurements (blue triangle) for wetland W051 with daily average rainfall for Nabappie (black bars) and logged daily water levels for bore BMC90ob (grey dashed line), which is located immediately down-hydraulic gradient. TDS values are provided for wetland W051 (solid red diamond) and bore BMC90ob (hollow red diamond). The wetland base occurs at 267.75mAHD

TDS of wetland W051 in April 2009 was 3,326 mg/L (Figure 5-4), falling slightly to 3,178mg/L in May then rising to 5,742 mg/L in June. The relatively high TDS values in June could reflect the previous year's precipitated salt in the wetland being mobilised or a first flush inflow of local groundwater or interflow. The lowest TDS (~2,500 mg/L) was observed from July through October as rainfall diluted the TDS and rose to pre-winter concentrations in November as the wetland begun to dry. Groundwater TDS in down-gradient bore BMC90ob displayed only minor variability with the highest TDS observed in August at 2,853 mg/L. TDS concentrations at W051 were ten-fold higher than records from 1970 (262 mg/L TDS) (Department of Water, 2009).

5.3.6.2 Wetland W015

Wetland W015 occurs as a small sump which is readily overtopped by surface water or groundwater inputs, with the excess discharging down gradient. Water level responses to rainfall were therefore immediate, although very small, with levels varying only 0.03m, from 262.26 mAHD to 262.29 mAHD (0.16 m to 0.19 m deep) (scale exaggerated on Figure 5-5). The greatest evidence of response to rainfall was observed from early to mid June. The piezometric head of adjacent deep bore BMC57d was consistently higher than the base of wetland W015 by more than 0.40m throughout the year (data not shown) which is a potential source of baseflow during summer. Hence this wetland is interpreted as a groundwater discharge system.

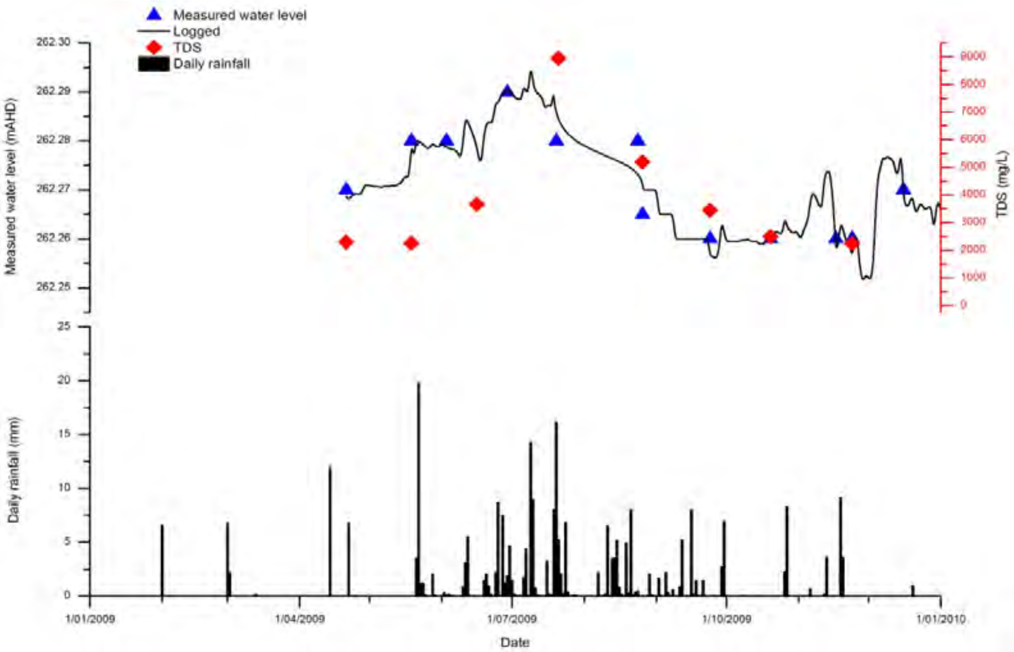

Figure 5-5. Logged daily water levels (black line) and manual measurements (blue triangle) (exaggerated scale) for wetland W015 with daily average rainfall for Nabappie (black bars).TDS values are provided for wetland W015 (solid red diamond). The wetland base occurs at 262.1 mAHD.

TDS (Figure 5-5) in W015 in April 2009 was 2,299 mg/L and increased over subsequent months, peaking at 8,955 mg/L in July. This peak was followed by a decreasing trend of TDS over successive months to 2,240 mg/L which is only moderately higher than the adjacent deep bore BMC57d (1,900 to 2,045 mg/L). TDS returned to pre-winter concentration by October. The highest TDS occurs during the period of highest water levels, suggesting a mobilisation of nearby soil salts or interflow discharging at the wetland.

5.3.6.3 Wetland W016

In contrast to wetland W051, there was a noticeable slower groundwater response to recharge with unsaturated conditions persisting until late June when the water table and surface water body appear to be in hydraulic connection (Figure 5-6). The greater antecedent depth to groundwater also contributes to the greater time taken for the unsaturated zone to fill and connection to be achieved. Wetland W016 filled to a maximum of 0.18m (259.62mAHD) in late August and thereafter water levels gradually declined, with only minor water level responses observed corresponding to rainfall occurring in September and October. During late September and October the groundwater levels fell below the level of surface water therefore disconnecting groundwater and surface water. Wetland W016 was dry by mid to late October and no response was observed to rainfall occurring in November and December. Groundwater levels beneath wetland W016 fell to pre-winter levels by mid December 2009.

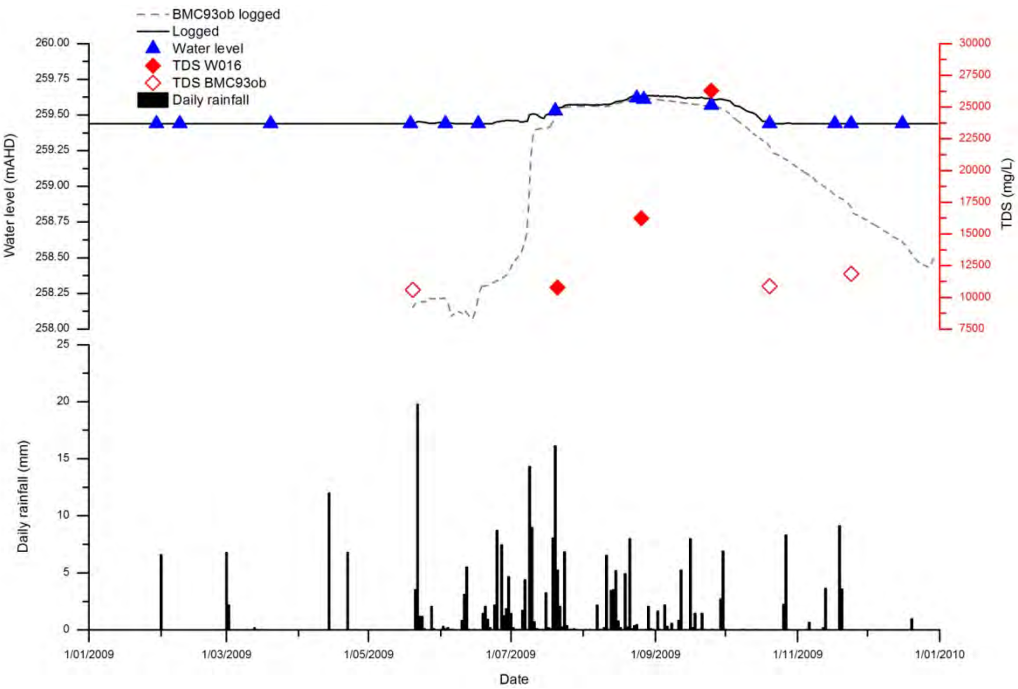

Figure 5-6. Logged daily water levels (black line) and manual measurements (blue triangle) for wetland W016 with daily average rainfall for Nabappie (black bars) and logged daily water levels for bore BMC93ob (grey dashed line), which is located within the wetland base. TDS values are provided for wetland W016 (solid red diamond) and bore BMC93ob (hollow red diamond). The wetland base occurs at 259 44 mAHD.

TDS of bore BMC93ob, located within the base of wetland W016 was 10,589 mg/L in May 2009 (Figure 5-6). In July, the TDS concentration within W016 was equivalent to groundwater in May at 10,763 mg/L, providing further evidence of connection between groundwater and surface water. TDS rose to 16,223 mg/L in W016 when the water level peaked in August, then continued to rise to a maximum of 26,284 mg/L in September as the wetland levels were receding and evapo-concentration of salts occurred. By October the wetland was dry. There was no apparent change in groundwater TDS beneath wetland W016 throughout the sampling period.

5.3.6.4 Wetland W017

Unlike wetland W016, unsaturated conditions were short-lived beneath wetland W017 and an immediate response was evident in groundwater levels following rainfall occurring on 21-22nd May (Figure 5-7). Saturated conditions persisted from late May 2009 until March of the following year, consequently throughout much of the study period wetland water levels responded instantaneously to rainfall. The maximum water level of 0.18m (257.47mAHD) was observed in late August 2009. In following months as the wetland dried, groundwater levels were consistently higher than surface water levels therefore indicating groundwater discharge.

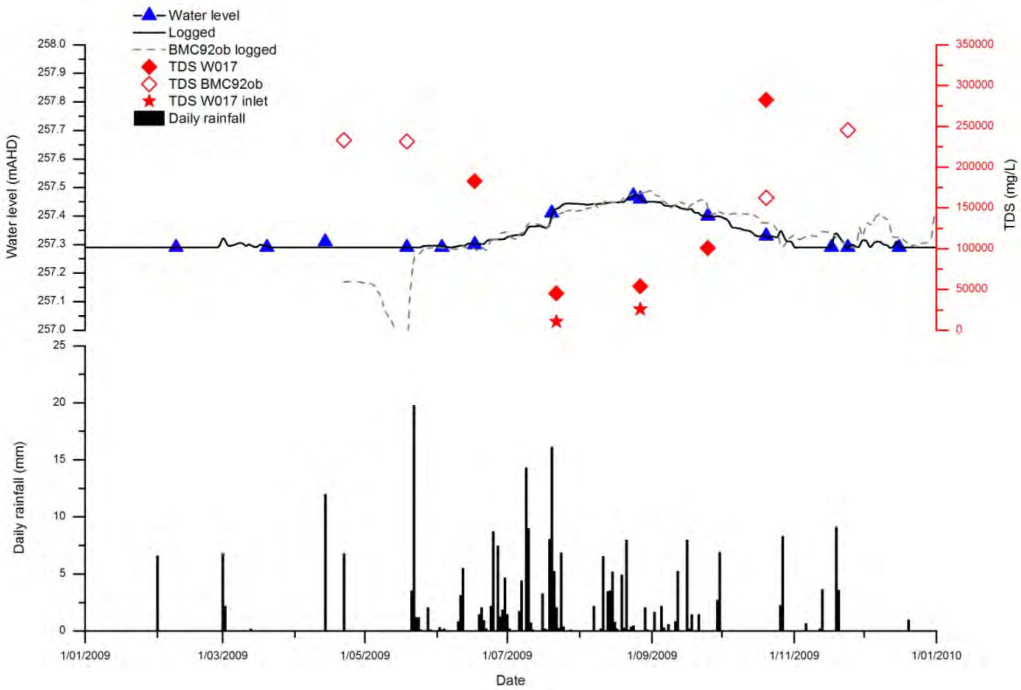

Figure 5-7. Logged daily water levels (black line) and manual measurements (blue triangle) for wetland W017 with daily average rainfall for Nabappie (black bars) and logged daily water levels for bore BMC92ob (grey dashed line), which is located within the wetland base. TDS values are provided for wetland W017 (solid red diamond), bore BMC92ob (hollow red diamond) and wetland inflows (red star). The wetland base occurs at 257.29 mAHD.

Groundwater TDS concentrations at bore BMC92ob beneath wetland W017 were below halite precipitation (~300,000 mg/L (Tweed et al., 2009, Simmons and Narayan, 1998)) in April and May 2009 at 232,931 mg/L, and 231,562 mg/L respectively (Figure 5-7). In June, the wetland TDS concentrations were observed to be lower than groundwater in May (182,722 mg/l) indicating inflows of fresher sources. In July and August, observed surface water inflows and other likely sources (i.e. rainfall and local-scale surface water inflows), caused dilution of the wetland. After achieving the peak water level in August, TDS of wetland W017 increased as it dried with TDS peaking at 282,490 mg/L in October. In October the groundwater beneath the wetland was fresher than the surface water further supporting hydraulic evidence of groundwater actively discharging, and also indicating the prevalence of unstable conditions which may lead to density-driven flow. Groundwater TDS returned to pre-winter concentrations (245,408 mg/L) in November.

5.3.7 Catchment-scale groundwater levels and flow

Given the limited number of bores in the upper catchment, groundwater contours were interpolated assuming a linear change in head between known water table elevations. The density-corrected catchment-scale water table map (Appendix 5H and Figure 5-9) indicates that groundwater flow mimics topography and flows from the topographical divides in the west, north and south, towards the valley floor in the east. Depth to the water table (DTW) ranged from >20 mbgl in the upper catchment (if a water table was present at all), to <2 mbgl around wetlands W735 and W736 and other inter-dunal depressions (Figure 5-8). Many lower-lying areas were <1 mbgl particularly around the wetlands at the base of the catchment, which persisted throughout the year (Figure 5-9). The interpreted discharge area within the Nabappie subcatchment (where the water table is <2 mbgl) is 152 ha or 16% of the whole catchment (Figure 5-8).

The water table in the upper parts of the catchment is interpreted to have an annual fluctuation of <0.2 m. Larger fluctuations in the order of 0.5 m to 0.8 m is common in the surficial aquifer in lower areas due to the greater specific yield in the sandy sediments and the great seasonal exchange between groundwater and atmosphere (rainfall and evaporation). These fluctuations are less distinct in bores within the semi-confined aquifer (see hydrographs in Appendix 5E).

Lateral movement of groundwater within the surficial aquifer throughout the year occurs due to the greater horizontal hydraulic conductivity relative to the underlying strata (Figure 5-10 and Appendix 5J). During winter, rainfall recharge leads to elevated discharge from both the unconfined and semi-confined aquifers at the break of slope down gradient of wetlands W051 and W026 (Figure 5-10). This is evidenced by changes to both the water table and water quality as discussed in previous sections. The piezometric head of the deep bores in the lower catchment were consistently above the water table or land surface indicating upward discharge. Artesian heads were most notable in bore BMC56d (+2.6 m) located adjacent to wetland W016, and BMC57d (+0.25 m above ground level) located adjacent to wetland W015.

5.3.8 Groundwater TDS gradients

Groundwater TDS gradients are significant with variations of several orders of magnitude evident across the study area. Cross sections (Figure 5-11 and Appendix 5K) illustrate the convergence occurring in proximity to BMC54d, and BMC55d between the hypersaline regional aquifer and the fresher unconfined and semi-confined aquifers. The observed seasonal changes to both head and density, particularly at BMC55d, provide evidence of a complex interaction between shallow and deep, fresh and hypersaline groundwater fluxes. Seasonal variability is highest within wetland W017 due to the interaction between groundwater and surface water.

5.3.9 Soil salinity and waterlogging

In the lower catchment area the shallow depth to the water table (DTW) enhances bare soil ET and groundwater discharge, resulting in elevated soil salinity and waterlogging. The highest apparent soil salinities (EC_a=190 mS/m), determined from EM38 measurements, occurred within the boundaries of wetland W016 and continue eastwards to wetland W017 (Appendix 5H). These correlate well with observed salinity trends in groundwater, down-hole EM39 data (Appendix 5I) and spatial trends of vegetation decline (Richardson et al., 2005).

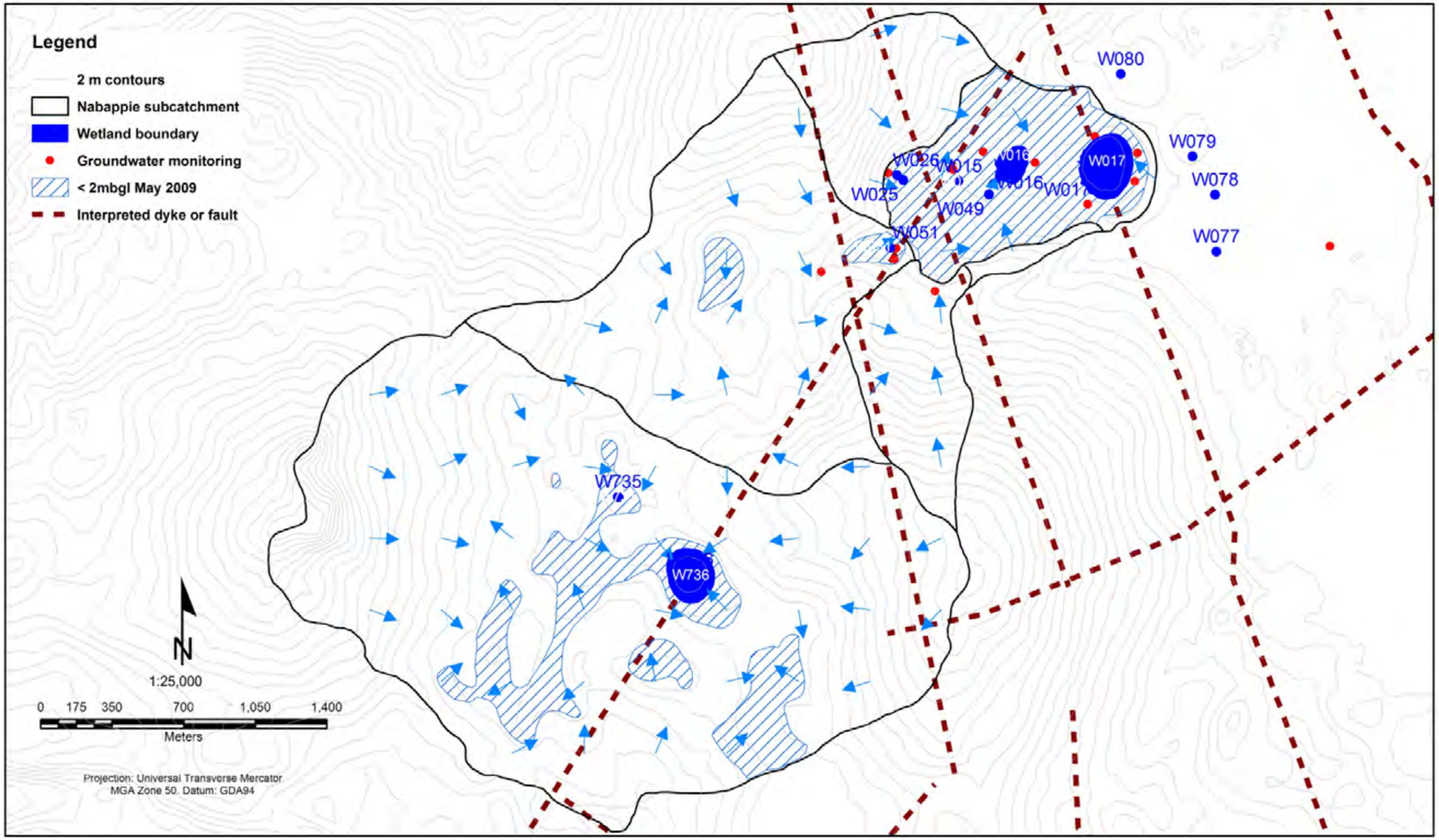

Figure 5-8. Nabappie catchment and surface water subcatchments divides with surface water flow vectors, wetlands and areas where the depth to groundwater is interpreted to be less than 2 mbgl during the water table low in May 2009.

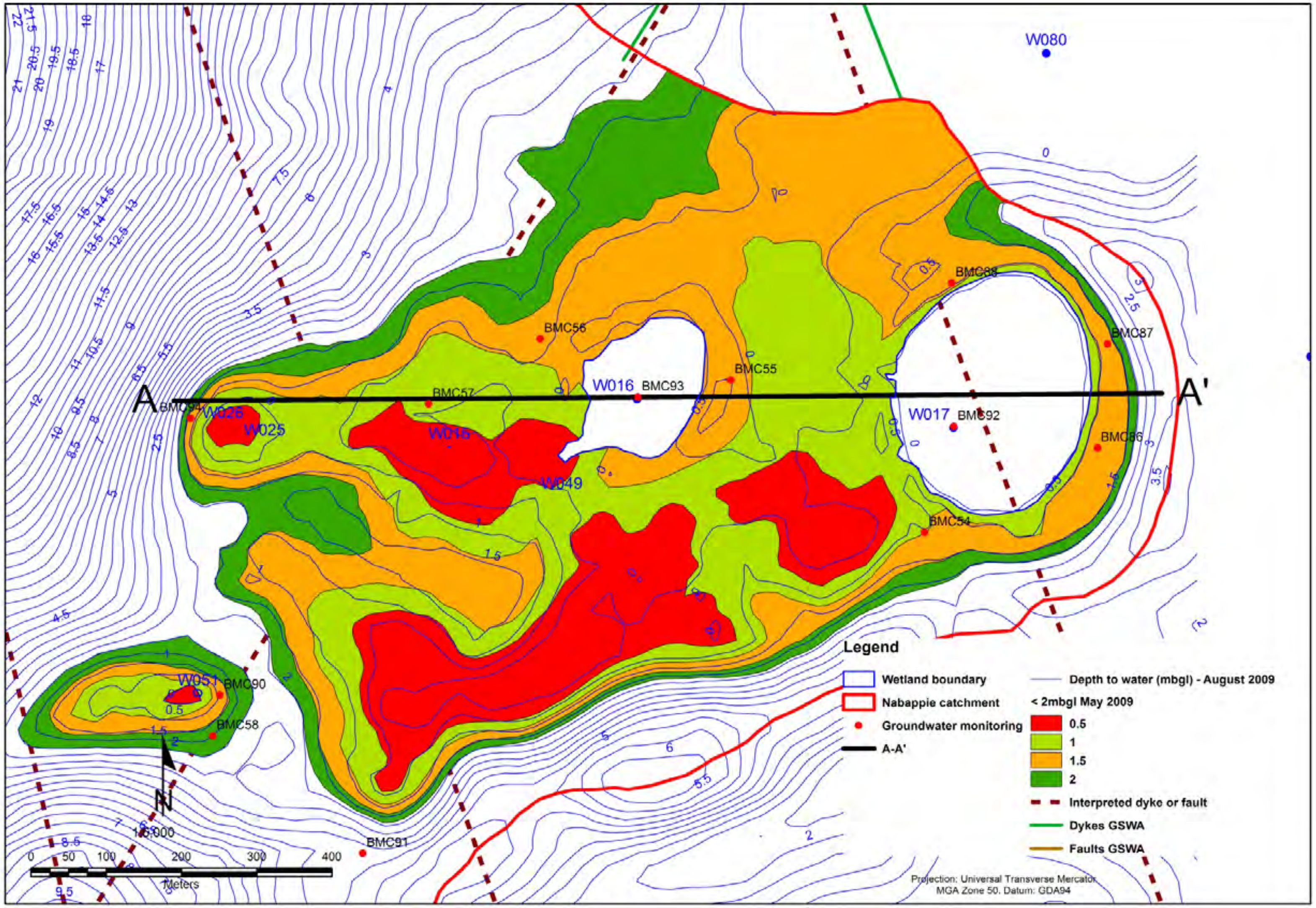

Figure 5-9. Density corrected depth to the water table (mbgl) interpreted from the water table low in May (shaded areas), and water table high in August 2009 (blue 0.5 m contours) with location of cross section A-A'.

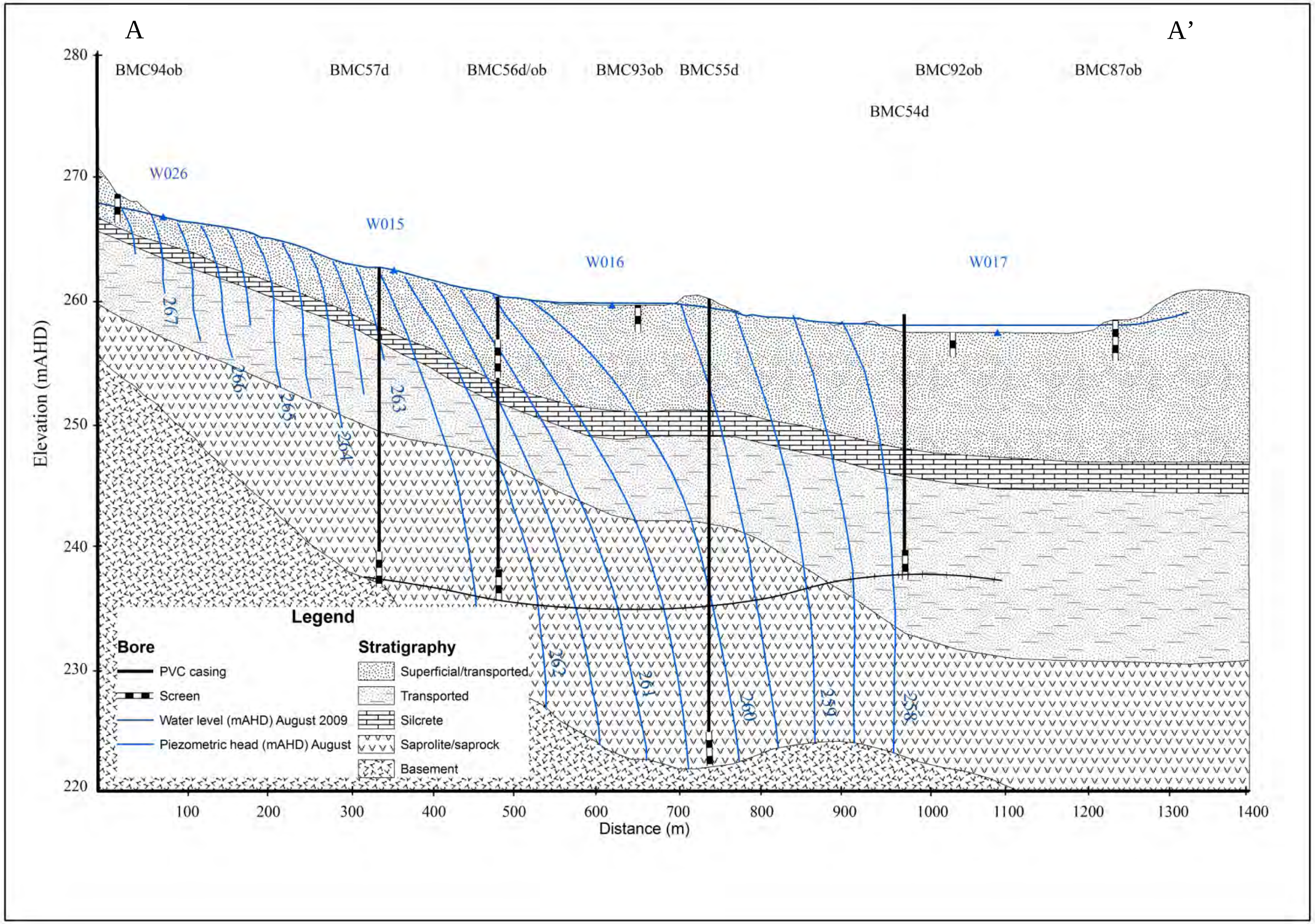

Figure 5-10. Cross section A-A’ representing the density-corrected water table surface and piezometric head (mAHD) for August 2009. The depth of the interpreted boundary of bedrock along the valley flank is represented by a black dashed line.

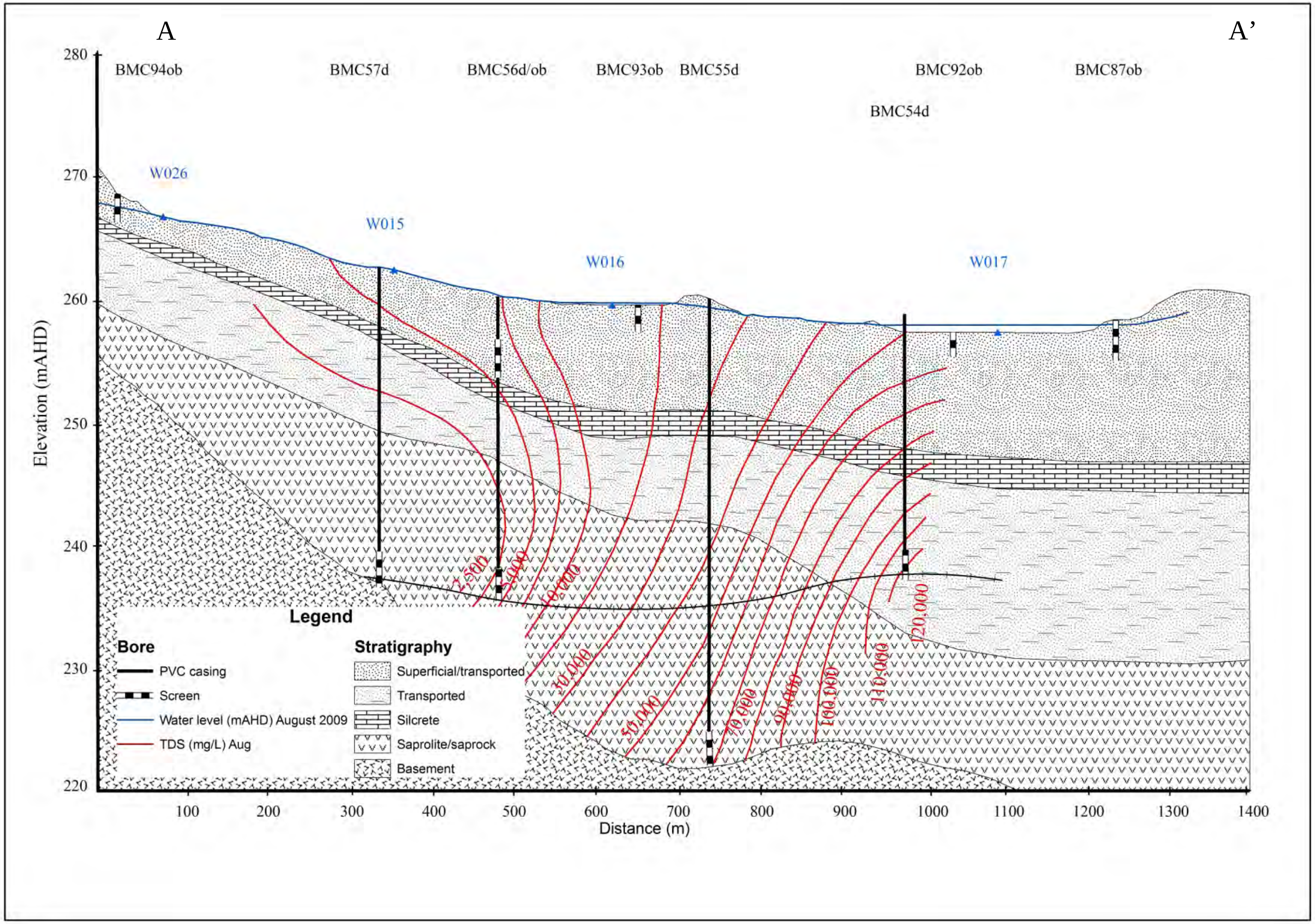

Figure 5-11. Cross section A-A' representing the density-corrected water table surface (mAHD) and total dissolved solids (TDS mg/L) for August 2009. The depth of the interpreted boundary of bedrock along the valley flank is represented by a black dashed line.

5.4 Discussion

The hydraulic conductivity (K_{hoz}) values determined from aquifer testing in sands (0.15 m/day) and clayey sediments (0.019 to 0.024 m/day) were within the expected range (Fetter, 2001, Bennett and Goodreid, 2009, George, 1992b). However the values for bores situated in the saprolite grits and pallid zone (0.003 to 0.009 m/day) were considerably lower than a previous investigation in the study area (URS, 2008) and generally reported for the wheatbelt (Clarke et al., 2000, George, 1992c, George, 1992b, George, 1992a). The consistently long recovery times of water levels after sampling, which were sometimes more than 90 hours, are further evidence of a significantly low permeability as is the repeated nature of the testing. Drilling methods can have a considerable influence on hydraulic properties of developed bores (Peck et al., 1980), however the drilling techniques adopted in the study area (URS, 2008) are unlikely to be responsible for the low K_{hoz} values.

Observations of hydraulic head, surface water levels and TDS show a high amount of spatial and temporal variability. Despite the persistence of shallow water tables in topographical depressions in the upper catchment, particularly proximal to wetlands W735 and W736, this area is predominantly a groundwater recharge domain. It feeds water (primarily via the permeable surficial sandy sediments) into the discharge area affecting the wetlands at the break of slope and in the lower catchment proximal to the valley floor. The prevalence of shallow water tables and waterlogging throughout these lower reaches is due to the greater amounts of surface water flows and groundwater discharge than would be under natural (vegetated) conditions. The continuing mortality of vegetation located in the lower landscape leads to additional rise in water tables, waterlogging and enhanced surface water flows. Additionally, the heads in the deep semi-confined aquifer throughout these lower reaches are consistently higher than the water table, implying upward discharge. The presence of a low permeability pallid zone within the weathered regolith will somewhat limit this discharge. However the likely presence of preferential pathways for groundwater movement, for example macropores formed by roots (Scanlon and Goldsmith, 1997, George, 1992c), or other geological controls such as faults or fractures (Peck and Hatton, 2003) could lead to areas of greater groundwater discharge. Dolerite dykes or faults interpreted as north-south trending are thought to preferentially move groundwater from recharge domains to the lower slopes along contacts. These combined processes are thought to be responsible for the observed perennial baseflow at wetland W015. This could also provide explanation for the presence of fresh water seeps prior to the clearing of native vegetation.

In recent decades a prolonged reduction in rainfall has resulted in a decline in groundwater levels in many parts of the northern agricultural region (NAR) (Speed and Kendle, 2008). In spite of this change in climate, there are still areas where groundwater levels are rising. The general groundwater decline in the NAR is in contrast with the South Coast and Central regions of the wheatbelt, where groundwater levels are predominantly rising, due primarily to the occurrence of several large recent episodic rainfall events (George et al., 2008). Historically, episodic recharge events such as those recently experienced in the south coast are thought to cause significant expansion of salinity affected areas (Robertson et al., 2010). These non-linear pulses of salinity development were observed in the BMNDRC during a wet period in the mid 1960's (pers. comm. B. Fowler, 2007) and after the significantly wet year of 1999 (pers. comm A. Doley, 2010).

Longer-term groundwater observations at the neighbouring Koobabbie farm (Bourke, 2010) show that water levels in the BMNDRC were the most elevated immediately following the very wet year of 1999 and within 8 to 10 years returned to their previous levels. In contrast, analysis of groundwater levels and historical wetland water levels at Nabappie indicate a continuing rise, on average 0.06 m/yr, in spite of the recent drying climate trend. This is likely due to the combination of a more recent clearing history than the Koobabbie farm, relatively high topographic relief, and the prevalence of deep yellow sands in the upper catchment which are more conducive to recharge and groundwater transmission (George, 1992b, Bennett and Goodreid, 2009).

In conjunction with rising groundwater levels, a ten-fold increase in the TDS of groundwater discharging at wetland W051 since 1970 indicates the subcatchment is actively discharging both stored and replenished water and solutes. These trends have been accompanied by a decline in vegetation health. The aquifers in the lower discharge domain appear near full, therefore are approaching a hydrological equilibrium. However it is likely that the current trend of rising groundwater levels and increasing solute discharge will continue, hence additional vegetation impacts are expected in the future.

CHAPTER 6:

6 Hydrochemistry, and stable water isotopes

6.1 Sampling frequency summary

Nine, monthly field sampling events were undertaken from April to December 2009, eight of which (April to November), were submitted for laboratory analysis. In total there were 135 water samples analysed for major ions and 249 analysed for stable isotopes (δD and $\delta^{18}O$), which included 65 event-based rainfall samples from the Koobabbie homestead (BoM site 8037) and 56 rainfall samples from the Coorow PO (BoM site 8067).

6.2 Field water quality results

A broad range of groundwater qualities were observed throughout the sampling period. Seasonal effects were evident at all sites, with the largest temporal variability observed at wetland sites and shallow bores located in close proximity to wetlands. The lowest variability was observed for deep bores in the hyposaline semi-confined aquifer. A general trend was observed with EC increasing exponentially down catchment gradient, although EC was observed to decrease slightly at BMC57d and BMC56d compared to upgradient at the break of slope near wetland W051.

Groundwater was freshest with the lowest pH (BMC89ob; 0.38 mS/cm, pH 4.3) in the unconfined deep yellow sand aquifer's recharge area with higher EC and higher pH in discharge areas of the same soil type (BMC94ob; 2.3 mS/cm, pH 6.4). Fresher and higher pH (3.5 to 5.1 mS/cm; pH 6.1 to 6.4) groundwater was also observed in an intermediate bore located at the break of slope (BMC58i) and deep bores within the semi-confined aquifer (BMC57d and BMC56d) proximal to wetlands W015 and W016. Bores in close proximity to wetlands W051 (BMC90ob; 5.43 mS/cm, pH 6.4) and W016 (BMC56ob; 11.56 mS/cm, pH 6 and BMC93ob; 19.34 mS/cm, pH 6.9) indicate an increase in EC and general increase in pH in the unconfined aquifer down slope. EC values significantly increase down gradient of wetland W016 within the semi-confined aquifer (BMC55d; 92.08 mS/cm, pH 6.2), and unconfined aquifer (BMC92ob; 197.06 mS/cm, pH 7.1) at the base of wetland W017.

Surface water EC was variable across the subcatchment with a general trend of increasing EC down gradient, although EC in wetland W736 was higher than many down-gradient wetlands. EC was lowest in wetland W735 (4.91 mS/cm ±1.35), followed by W015 (5.57 mS/cm ±2.58), W051 (6.27 mS/cm ±2.68), W026 (15.49 mS/cm ±9.16), W736 (24.57 mS/cm ±2.98), then W016 (27.9 mS/cm ±11.14). The highest surface water EC was observed at wetland W017 (126.72 mS/cm ±62.99). Surface water inflows into W017 in both July and August were saline (16.60 mS/cm and 34.10 mS/cm respectively). The pH of surface water in wetlands and associated groundwater, particularly in the lunette surrounding wetland W017, was higher (pH 6.5 to 7.3) than deeper groundwater, whilst surface water in wetlands W735 and W736 in the upper catchment were alkaline, pH 7.7 to 8.9 and W735 and W736 respectively.

6.3 Laboratory quality control results

Analytical accuracy in the form of electrical neutrality (<5% deviation between anions and cations) is suggested via an electrical charge balance (Appelo and Postma, 2007). Ionic balances for samples analysed were in most cases (n=116 of 138 or 86%) <10% and more than half of the samples (n=69 or 51%) were less than 5% and therefore within acceptable limits (Appelo 2007). The lower analytical precision was concentrated in the fresher sites (e.g. site BMC89ob), and occurred on occasions where nutrients (N and P) were omitted from analysis, which proved to be in relatively high concentrations. Precision could not be calculated for rainfall samples due to lack of sample volume to determine field alkalinity and hence HCO_3^-.

6.4 Hydrochemistry results

6.4.1 Overview of major ions

Major ion concentrations (April to November 2009) for all samples are presented in Appendix 6B. Plots of the ion weight ratios of Na^+, K^+, Mg^{2+}, Ca^{2+}, SO_4^{2-} and HCO_3^- (field alkalinity), as a function of Cl^- for groundwater, surface water and rainfall are presented in Appendix 6K. The ion weight ratio combinations of Ca^{2+}+Mg^{2+}/HCO_3^- versus Cl^-, and EC versus TDS are also presented. The ionic weight ratios representing the southwest central and southwest coastal rainfall (Hingston and Gailitis, 1976), average rainfall for the central wheatbelt (Table 6-1) (Mazor and George, 1992), and seawater (Hingston and Gailitis, 1976) are plotted in figures where applicable.

Table 6-1. Major ion weight ratios relative to Cl^- for rainfall and seawater as detailed in *Mazor and George (1992), and **Hingston and Gailitis (1976).

Ion (mg/L)	*Central wheatbelt rainfall	**Southwest central rainfall	**Southwest coastal rainfall	**Seawater
Cl^-	1.000	1.000	1.000	1.000
Na^+	0.575	0.520	0.540	0.556
Mg^{2+}	0.113	0.100	0.067	0.067
Ca^{2+}	0.100	0.400	0.083	0.021
K^-	2.000	0.065	0.044	0.020
SO_4^{2-}	0.375	0.400	0.200	0.140
HCO_3^-	0.375	1.100	0.130	0.007
Br^-	0.00375			
Cl^-/Mg^{2+}	0.100	0.100	0.070	14.930
Mg^{2+}/Ca^{2+}	0.250	0.250	0.810	3.190
Cl^-/Br^-	267			

Cl^- and Na^+ dominates (>85% TDS) the major ion composition of all waters as represented in the piper diagram Figure 6-1. A strong correlation between TDS and EC (y=0.0051$x^{0.8788}$, $r^2$0.996) is also observed. A generally positive linear relationship between these dominant ions (Figure 6-2) and all other major ions was observed. The sequences of decreasing ionic concentration for the most saline groundwater, BMC54d and BMC55d, was $Cl^->Na^+>SO_4^{2-}>Mg^{2+}>Ca^{2+}>K^->Br^-$>total alkalinity, which was consistent with the regional, primary saline groundwater system (site BMC64d). The TDS concentration for these sites was 127,834 mg/L (stdev 12,061), and 68,486 mg/l (stdev 3,809) respectively. Similar $Cl^->Na^+>SO_4^{2-}$ ionic concentration sequences were observed at most other saline sites. In the fresher groundwater sites the ionic concentration sequences were the most variable. At the freshest site BMC89ob (TDS 118 mg/L, stdev 22) the ionic concentration sequence was most often $Cl^->Na^+$ however $Cl^->Mg^{2+}>Na^+$ was observed in April 2009. At this site Ca^{2+} and Br^- were close to or below detectible limits.

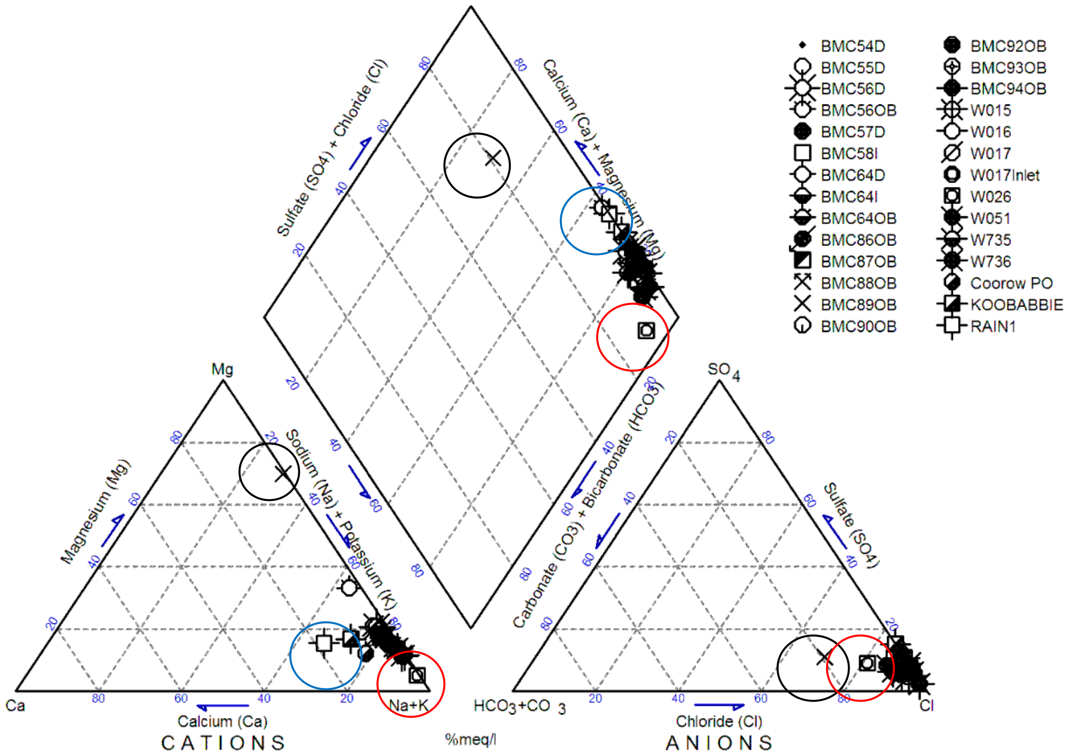

Figure 6-1. Piper diagram showing the average chemical composition of groundwater, surface water and rainfall for the period April to November 2009. Outliers are BMC89ob (black circle), W026 (red circle), and rainfall (blue circle) from Koobabbie, Coorow PO and site Rain1.

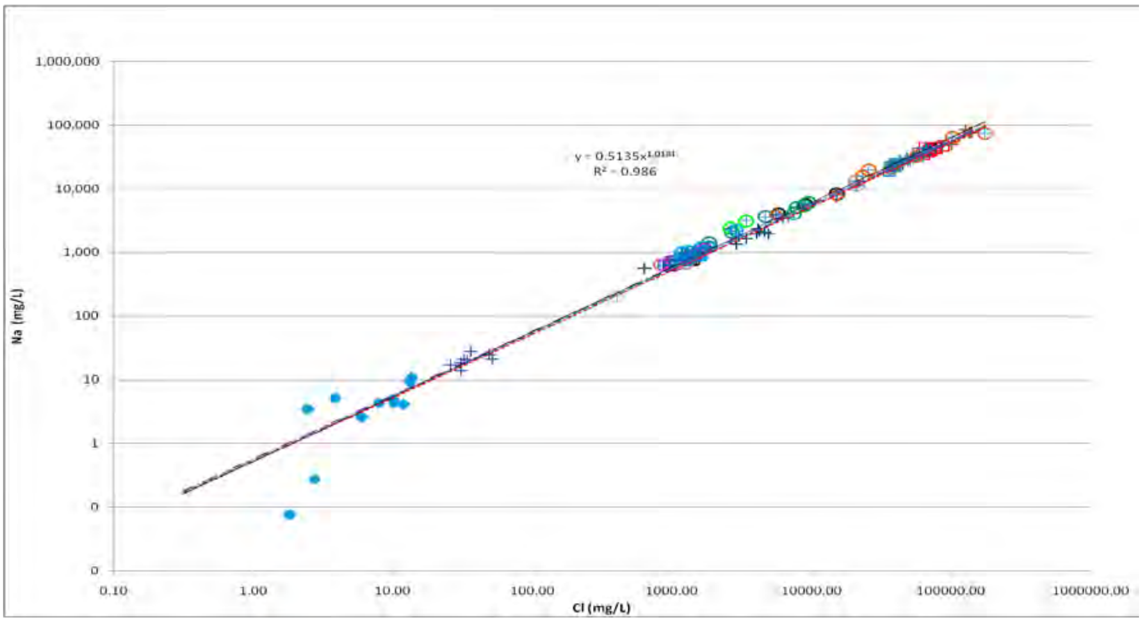

Figure 6-2. Log/log scaled plot of Na versus Cl for rainfall, groundwater and surface water data for Nabappie. The average Na/Cl ratio observed was 0.62 (stdev 0.15) with a power relationship of y=0.5135$x^{1.0184}$ ($r^2$0.986). The greatest variation was observed in rainfall samples, whilst the highest ratios were observed in the fresher sites (W026=0.76 to 0.92). All values plot along the average Na^+/Cl^- ratios for seawater (Hingston and Gailitis, 1976), coastal and central rainfall (Hingston and Gailitis, 1976), and rainfall of the central wheatbelt (Mazor and George, 1992).

Surface water ionic concentrations reflected the variable influence of rainfall, groundwater and surface water inflows and subsequent ET losses (discussed in Chapter 5). Hypersaline wetland W017 (TDS 132,934 mg/L, stdev 99,851) and saline wetland W736 (TDS 14,524 mg/L, stdev 1,868) were similar in composition ($Cl^- > Na^+ > Mg^{2+} > SO_4^{2-} > Ca^{2+}$>or<$K^-$ etc), whereas the fresher wetlands W015 (TDS 3,818, stdev 2,314 mg/L), W051 (TDS 3,198 mg/L, stdev 1,123) and W735 (TDS 2,590, stdev 1,123) were $Cl^- > Na^+ > SO_4^{2-}$>total alkalinity>$Mg^{2+} > Ca^{2+}$>or<$K^- > Br^-$; wetland W016 (TDS 17,757 mg/L, stdev 7,873) and surface water flows at site W017_inlet were similar ($Cl^- > Na^+ > SO_4^{2-} > Mg^{2+}$ etc) although W016 was more enriched with Ca^{2+} relative to total alkalinity. During the period when an alkaline pH was observed at wetland W026 the ionic concentration sequence was $Cl^- > Na^+$>total alkalinity>$SO_4^{2-} > Mg^{2+} > Ca^{2+} > K^- > Br^-$.

Major ion concentrations in rainfall were variable with TDS ranging from <1 to 53 mg/L with Br^- generally below detection limits. Rainfall was dominated by Cl^- and Na^+ ions, with remaining ion concentrations similar to those reported for Western Australia (Hingston and Gailitis, 1976, Hingston and Gailitis, 1977).

6.4.2 Cl/Br weight ratios

The Cl^-/Br^- weight (mg/L) ratios can provide a useful indication whether halite dissolution is occurring. Weight (mg/L) ratios of 290 are generally indicative of rainfall (Davis et al., 1998), with ratios of 267 observed in the central wheatbelt (Mazor and George, 1992). Very low ratios indicate the enrichment of Br^- in residual water during mineralisation of halite whilst dissolution of halite results in Cl^-/Br^- ratios rising significantly due to the high Cl^- composition. Dissolution of halite typically results in Cl^-/Br^- ratios above 1,000 and as high as 10,000 (Davis et al., 1998).

The lowest Cl^-/Br^- ratios were observed in rainfall at the Coorow PO and Koobabbie sites, at 5.3 and 6.9 respectively. The very low Cl^-/Br^- ratios observed in rainfall are likely due to high analytical error for analysis of Br^- at low ionic concentration (Cartwright et al., 2006). Temporal variability was evident in Cl^-/Br^- ratios across all sites, as evidenced in Figure 6-3 to Figure 6-6 however there was no systematic or seasonal trend.

Cl^-/Br^- weight ratios for groundwater and surface water samples were all <1,000 and generally 300 to 600 with the greatest variation observed in the freshest sites, again most likely due to Br^- concentrations in these samples being close to detection limits. Temporal variability observed in more saline sites, such as wetlands W016 (Figure 6-5) and W017 (Figure 6-6), during periods of fresher inflow could potentially be due to the mobilisation of halite stored within the unsaturated zone. Although the dissolution of only a small amount of halite can make a significant difference to Cl^-/Br^- ratios (Cartwright et al., 2006) hence it is likely that halite plays only a minor role. During the period when the ionic concentration of surface water in wetland W017 exceeded halite saturation (>300,000 mg/L TDS) (Simmons and Narayan, 1998), the Cl^-/Br^- ratio (261) was still equivalent of rainfall for the wheatbelt (267) (Mazor and George, 1992).

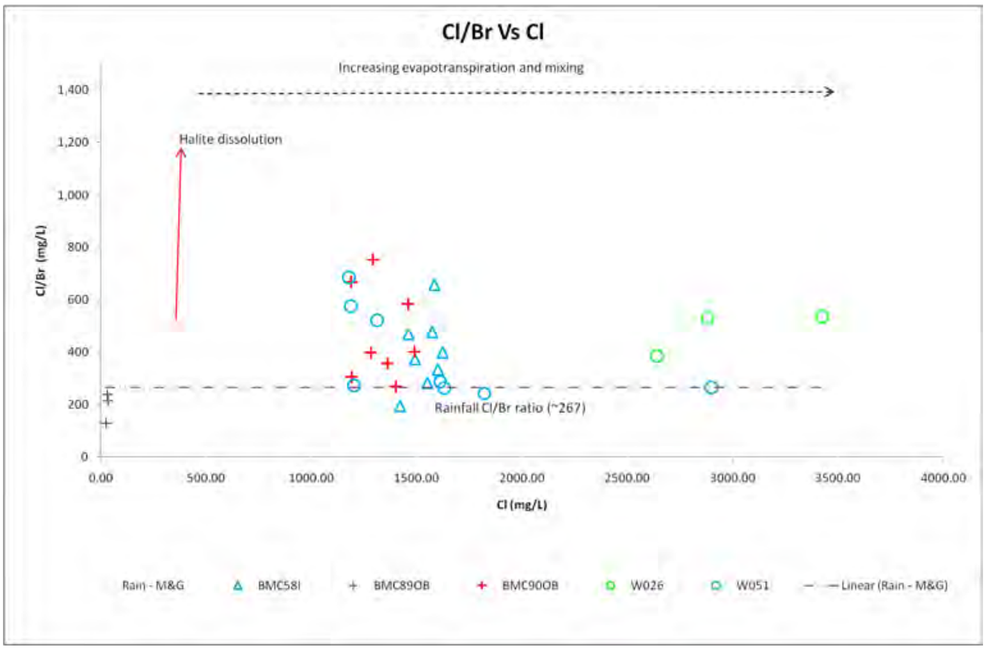

Figure 6-3. Plot of Cl^- versus Cl^-/Br^- weight (mg/L) ratios for wetlands W051, W026, and groundwater at sites BMC58i, BMC89ob, and BMC90ob.

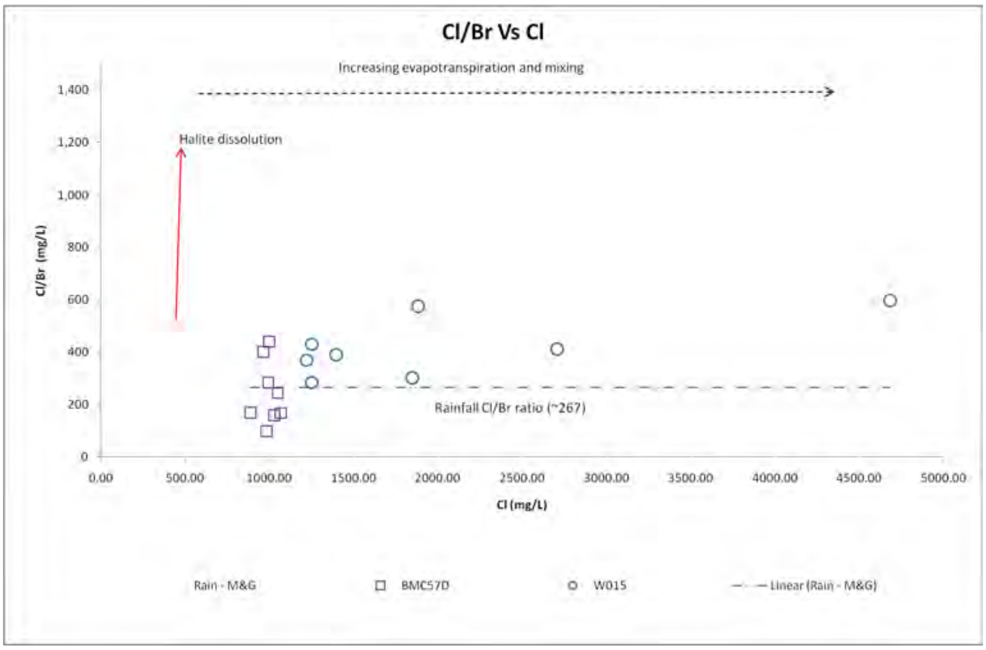

Figure 6-4. Plot of Cl⁻ versus Cl⁻/Br⁻ weight (mg/L) ratios for wetland W015 and groundwater at site BMC57d.

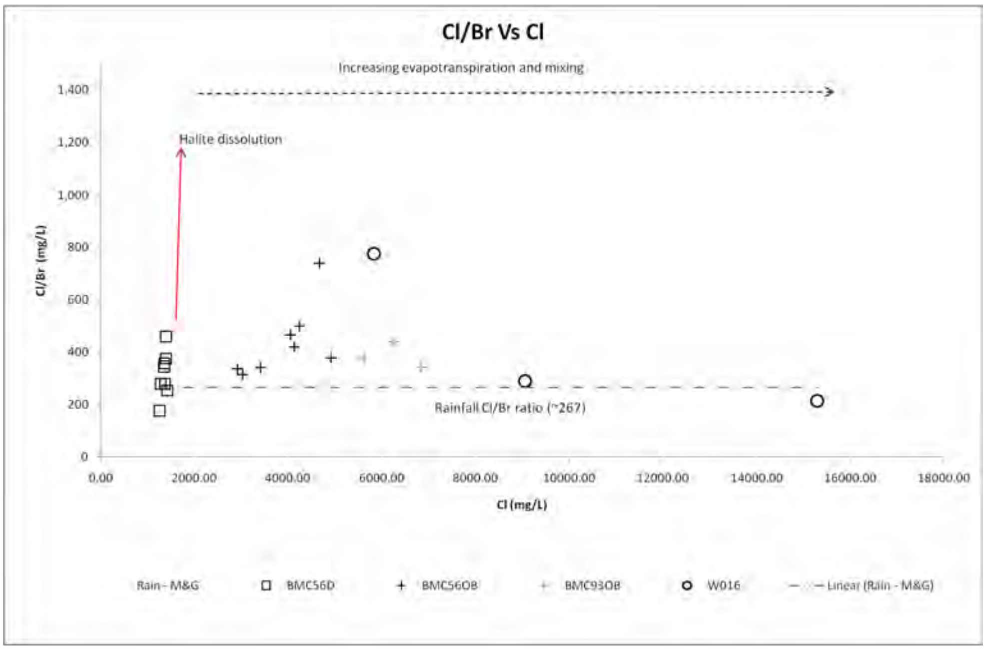

Figure 6-5. Plot of Cl⁻ versus Cl⁻/Br⁻ weight (mg/L) ratios for wetland W016 and groundwater sites BMC56d, BMC56ob, and BMC93ob.

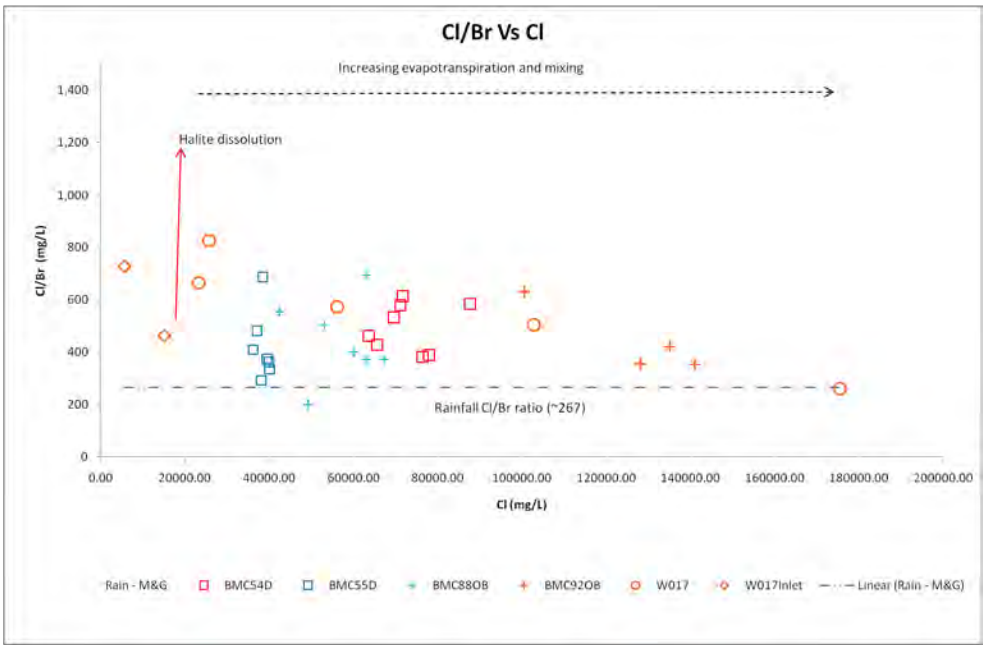

Figure 6-6. Plot of Cl^- versus Cl^-/Br^- weight (mg/L) ratios for wetland W017, surface water inflows (W017_inlet) and groundwater sites BMC54d, BMC55d, BMC88ob, and BMC92ob.

6.4.3 Nutrients

Observed levels of nitrate (NO_3) in April, and May as well as the total nitrogen (TN) and total phosphorus (TP) in November shows elevated nutrient levels occur across the subcatchment. Nitrogen concentrations are generally greater than phosphorus and dominated by inorganic forms of nitrogen (NO_3) in the fresher groundwater and wetlands than in the saline groundwater (Table 6-2). Nitrate levels (TN in brackets) in groundwater ranged from below detection limits to a maximum of 26.7 mg/L (35 mg/L) at BMC89ob, whilst phosphorus (TP in brackets) was generally below detection limits although was 0.03 mg/L (0.04 mg/L) at bore BMC90ob. Maximum nitrate levels (TN in brackets) in wetlands ranged from 0.14 mg/L (3.3 mg/L) at wetland W051 to 2.2 mg/L (3.3 mg/L) at wetland W015, whilst phosphorus (TP in brackets) were 0.05 mg/L (0.08 mg/L) in wetland W051 to 0.06 mg/L (0.09 mg/L) in wetland W015. Nutrients were not analysed at wetlands W016, W017, W026, or W735 although elevated nutrient concentrations were observed from 2003 to 2008 (Aquatic Research Laboratory, 2009) at wetland W015 and W016 with total nitrogen levels up to 2.7 mg/L and 7.7 mg/L respectively; and total phosphorus concentrations up to 0.03 mg/L and 0.87 mg/L respectively (Table 6-2).

Table 6-2. Maximum nitrogen (NO3 and Total N), and phosphorus (soluble P and Total P) observed for all groundwater and surface water from April to November 2009.

Row Labels	NO3 (mg/L)	TN (mg/L	P soluble (mg/L)	TP (mg/L)
BMC54D	0.02	-	-	-
BMC55D	0.02	0.96	<0.01	<0.01
BMC56D	1.6	1.9	0.01	0.03
BMC56OB	3	4	0.01	0.01
BMC57D	1.8	2.5	0.01	0.04
BMC58I	4	4.4	0.01	0.02
BMC58D	-	-	-	-
BMC86OB	0.02	-	-	-
BMC87OB	0.04	-	-	-
BMC88OB	0.01	-	-	-
BMC89OB	26.7	35	<0.01	0.02
BMC90OB	4	2.8	0.03	0.04
BMC91OB	-	-	-	-
BMC92OB	0.09	8.3	0.21	0.24
BMC93OB	-	1.6	0.01	0.04
BMC94OB	-	-	-	-
Coorow PO	-	-	-	-
Koobabbie	-	-	-	-
RAIN1	-	-	-	-
W015	2.2 (*2.7)	3.3 (*2.7)	0.06	0.09 (*0.03)
W016	-	*7.7	-	*0.87
W017	-	-	-	-
W026				
W017Inlet	-	-	-	-
W051	0.14	3.4	0.05	0.08
W735	-	-	-	-
W736	1.3	-	-	-

* Nutrient values from 2003 to 2008 (Aquatic Research Laboratory, 2009)

6.5 Stable water isotopes

6.5.1 "Salt effect" correction

Corrections for the "salt effect" for δD ranged from below the analytical precision of data (<0.1 ‰) for the freshest sites (i.e. rainfall and BMC89ob) to 12.8 ‰ at wetland W017 when salinity was at its highest. Salt effect corrections for δ^{18}O were much lower and ranged from no change at the freshest sites to -0.67 ‰ at the hypersaline wetland W017. Interpretations were based on both the uncorrected concentrations (δD and δ^{18}O) and the "salt effect" corrected activities (ΔδD and $\Delta\delta^{18}$O) (Horita, 1989).

6.5.2 Local Meteoric Water Line

Rainfall δ-values weighted by annual precipitation amounts for the Coorow PO were δD -11.94 ‰, δ^{18}O -3.7‰; Koobabbie δD -12.04 ‰, δ^{18}O -3.7 ‰; and for site Rain1 δD -9.2 ‰, δ^{18}O -3.1 ‰. These values are more enriched than the long-term record of Perth rainfall (δD -16.69 ‰, δ^{18}O -4.09 ‰), although their analysis excluded data from January, April and September (Liu et al., 2010). Event-based δ-values from the Coorow PO and Koobabbie were used to define the Local Meteoric Water Line (LMWL), which is $\delta D = 5.59\ (\pm 0.24) * \delta^{18}O + 9.61\ (\pm 0.94)$. The use of event-based values (i.e. rather than weighted values) and results from only one year may skew the slope of the LMWL (Vodila et al., 2011) however the plot of local data is similar to the long-term Perth LMWL (Figure 6-7). Isotopic signatures (δ^{18}O and δD) for all groundwater and surface water were plotted to derive an Evaporation Line (EL) which is $\delta D = 4.58\ (\pm 0.14) * \delta^{18}O - 3.35\ (\pm 0.52)$ (Figure 6-8).

High temporal variability of δD and δ^{18}O was evident (Appendix 6O), although a general trend of depleted δ-values is observed in winter months and enrichment in October and November. This trend represents temporal trends in atmospheric flow paths, temperatures and conditions, precipitation origins etc (Dansgaard, 1964, Turner et al., 1987b), and is consistent with other sites in Australia (Liu et al., 2010). Recharge events are more prominent during these months therefore the groundwater δ-values should reflect an isotopic signature more depleted than the weighted annual average values (Turner et al., 1987b).

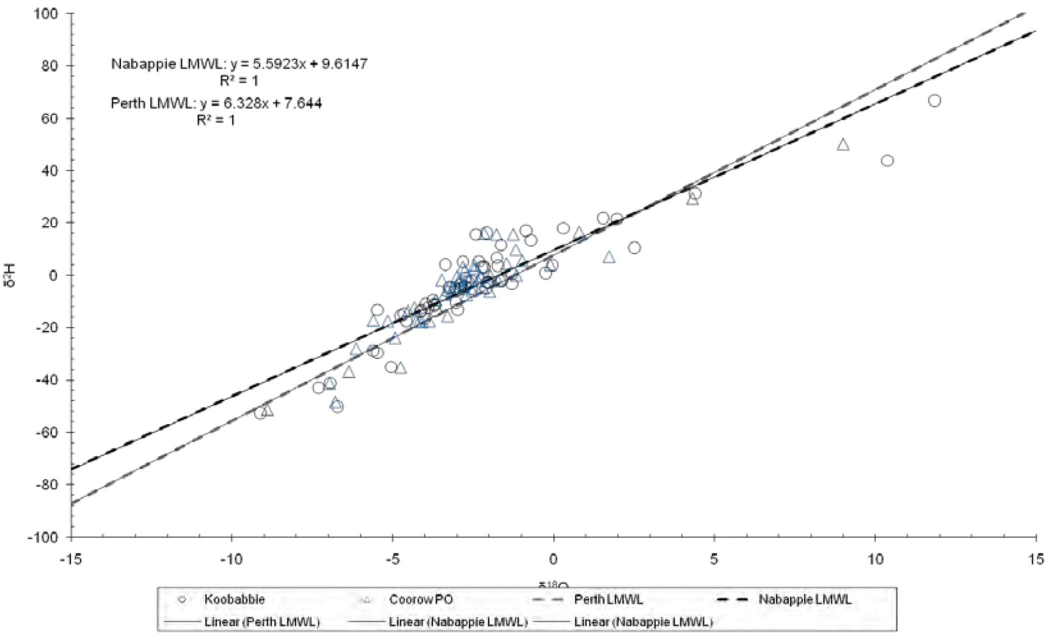

Figure 6-7. Stable isotope concentration ratios (δ^{18}O and δD) for the Coorow Post Office (blue triangles), Koobabbie (black circles) and the Local Meteoric Water Line (LMWL) for Nabappie (n=127) (black dashed line) $\delta D=5.5923*\delta^{18}O+9.6147$, and the LMWL for Perth (grey dashed line) from 1962 to 2000 (n=254) $\delta D=6.328*\delta^{18}O+7.644$ (IAEA/WMO, 2006).

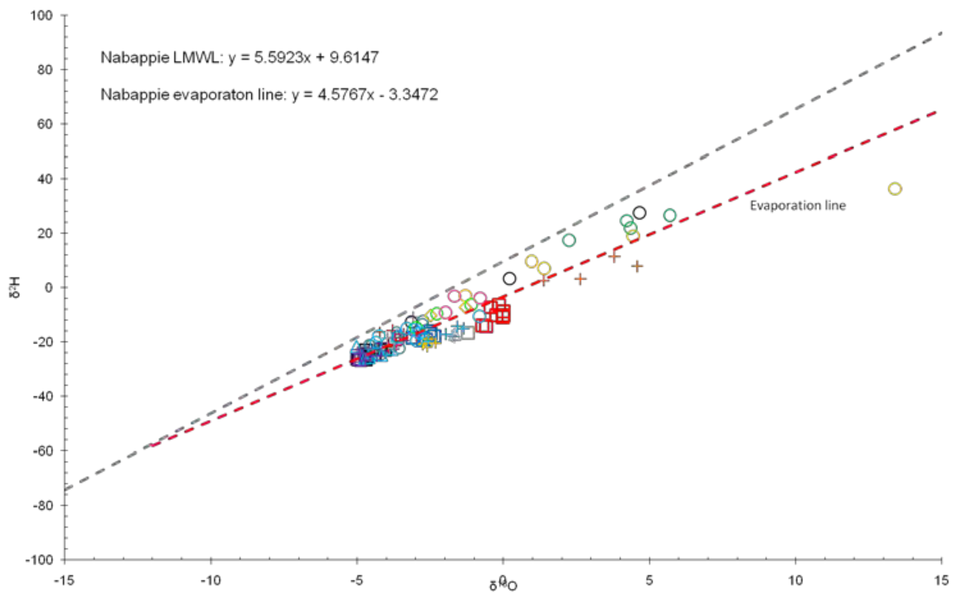

Figure 6-8. Stable isotope concentration ratios ($\delta^{18}O$ and δD) for all groundwater and surface water collected throughout the study period with the Local Meteoric Water Line (LMWL) for Nabappie (grey dashed line) $\delta D=5.5923*\delta^{18}O+9.6147$ and Evaporation Line (EL) for Nabappie (n=131) (red dashed line) $\delta D=4.58*\delta^{18}O-3.35$.

6.5.3 Chloride and stable isotope results

Plots of $\delta^{18}O$ versus Cl^- were used to understand groundwater and surface water processes. Figure 6-9 provides a summary of $\delta^{18}O$ and Cl^- for all groundwater and surface water sites sampled from April through November 2009. Additional plots of δD and $\delta^{18}O$, $\delta^{18}O$ and Cl^-, and *d-excess* (Dansgaard, 1964) are provided in Appendix 6O.

The $\delta^{18}O$ and Cl^- ratios in the saline unconfined aquifer (BMC86ob, BMC87ob, BMC8ob and BMC92ob), and saline to hypersaline semi-confined aquifer (BMC54d, and BMC55d) displayed a strong positive linear relationship between $\delta^{18}O$ enrichment and increasing Cl^- (Figure 6-9). The deep bore at site BMC54d was more saline and enriched (δD and $\delta^{18}O$) relative to the regional primary saline aquifer in the valley floor (BMC64d) (Figure 6-10). The enrichment was more noticeable when considering "salt corrected" activities ($\Delta\delta$). In May 2009, BMC54d was $\Delta\delta D$= -0.51‰, $\Delta\delta^{18}O$= -0.3‰; and BMC64d was $\Delta\delta D$= -11.8‰, $\Delta\delta^{18}O$= -1.4‰. This suggests that quick recharge of rainfall is not a dominant process and those other processes such as evaporation, and aquifer mixing is affecting the isotopic signature of these groundwaters.

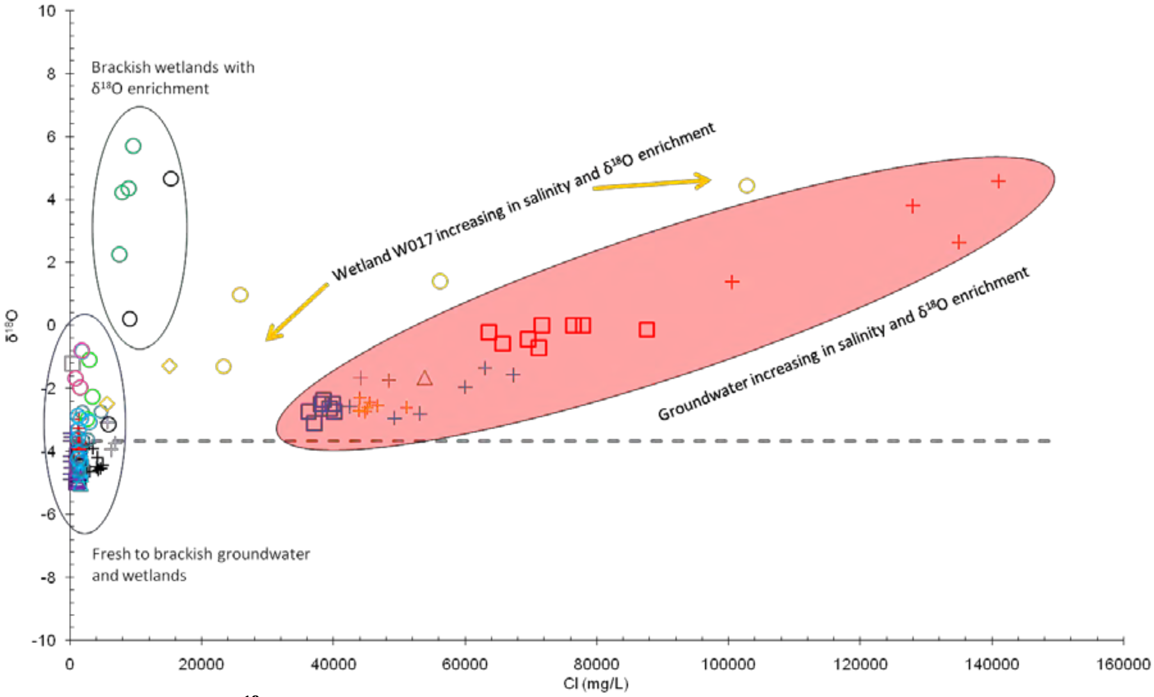

Figure 6-9. Plot of $\delta^{18}O$ versus Cl for all sampled sites from April to November 2009 and the weighted average isotopic signature $\delta^{18}O$ -3.68 for Nabappie. Crosses depict shallow observation bores, triangles are intermediate depth bores, deep bores are squares and wetlands are circles.

Bores BMC56d and BMC57d, within the hyposaline semi-confined aquifer, display a depletion of δ-values corresponding to a minor decrease in salinity following winter rains. This indicates relatively quick mixing between isotopically depleted rainfall and the aquifer waters, implying quick recharge rates. A notable depletion from May to June of δD (-22.5‰ to -17.6‰) and $\delta^{18}O$ (-3.95‰ to -3.64‰) of groundwater was observed in intermediate bore BMC58i with only a minor (72 mg/L) reduction of Cl^-, although the Cl^-/Br^- decreased from 372 to 194. This event coincided with an observed doubling of TDS at nearby wetland W051 (Chapter 5). The isotopic trend was not evident in wetland W051, however the isotopic enrichment was evident in down-gradient shallow observation bore BMC90ob and wetland W015. The cause of the episodic enrichment of groundwater observed at BMC58i and BMC90ob and surface water within wetland W015 is unknown, although it does indicate a rapid aquifer response to rainfall recharge and an interconnection between these three sites.

Isotopic enrichment was most evident in wetlands W016, W017 and W736 (Figure 6-10 to Figure 6-12). Wetland W736 is located in the upper catchment and is significantly fresher than W017, however the δ-values (ΔδD = 25.2, $\Delta\delta^{18}O$ = 4.2‰, TDS 13,803 mg/L) at this wetland plot along the evaporation line and are only slightly less enriched than wetland W017 (ΔδD = 27.2, Δδ ^{18}O = 4.7‰, TDS 182,721 mg/L) indicating that evaporation is a dominant process occurring at both wetlands. Surface water inflows to wetland W017 (site W017_inlet) also lay along the evaporation line and were isotopically enriched in July and August at ΔδD = -9.8, Δδ^{18}O = -2.5‰; and ΔδD = -6.2, Δδ^{18}O = -1.3‰, respectively. This indicates that water has been directly influenced by evaporation, or it contains a proportion of a water flux which has.

There was little evidence of isotopic enrichment (δD and δ^{18}O) in groundwater associated with observed increases in salinity in the unconfined aquifer underlying wetland W016 (BMC93ob), or nearby (BMC56ob). In most cases the isotopic signature of groundwater was depleted relative to the LMWL (Figure 6-12), hence there is no evidence of evaporation effects on these groundwaters.

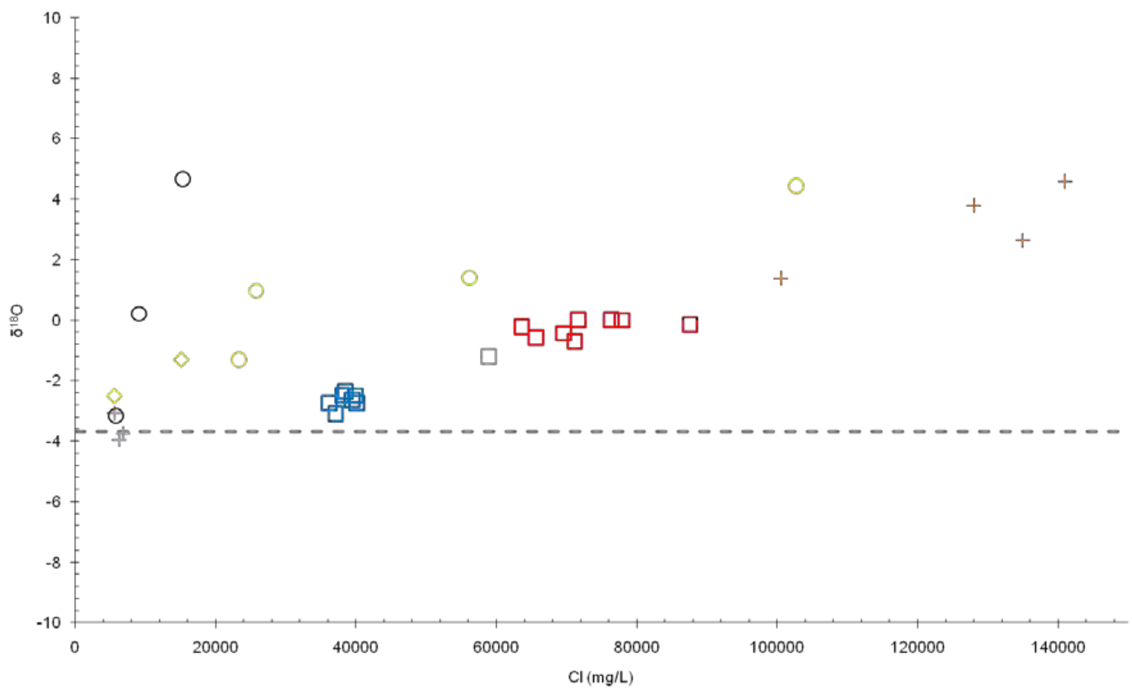

Figure 6-10. Plot of δ^{18}O versus Cl^{-} from April to November 2009 for wetlands W016 (black circles), W017 (orange circles), wetland W017_inlet (orange diamonds), and groundwater from BMC54d (red square), BMC55d (blue square), BMC92ob (red cross), BMC93ob (violet cross), the regional aquifer at BMC64d (grey square), and the weighted average isotopic signature δ^{18}O -3.68 ‰ for Nabappie.

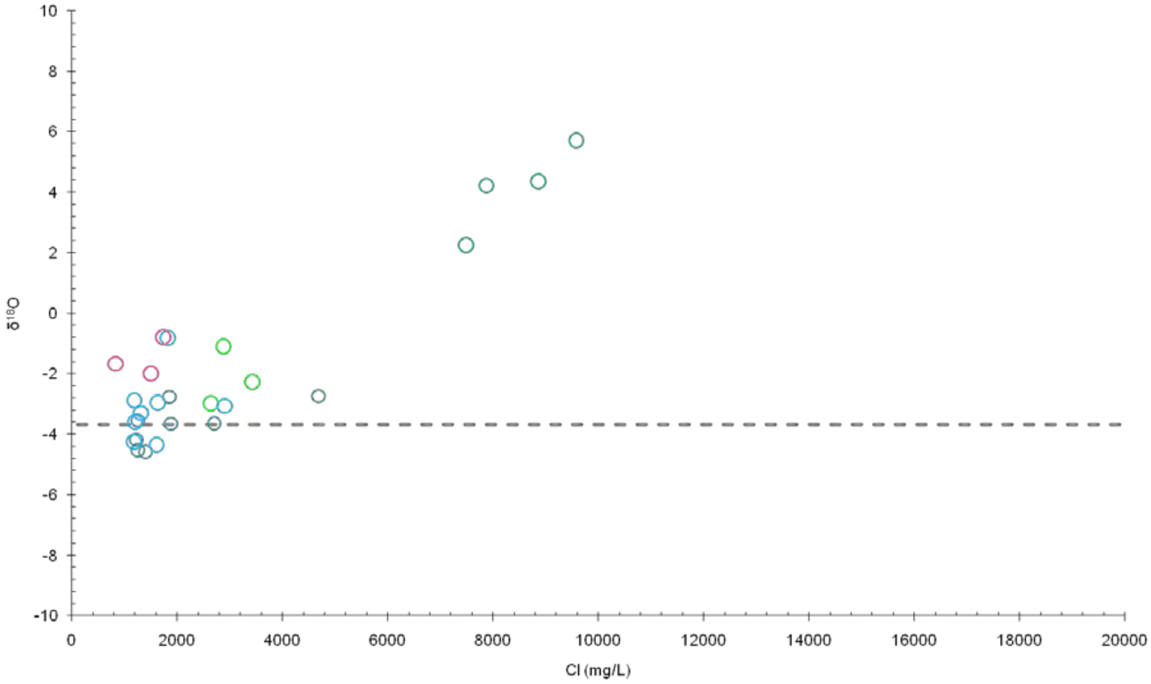

Figure 6-11. Plot of δ^{18}O versus Cl$^-$ from April to November 2009 for wetlands W015 (blue circles), W026 (light green circles), W051 (light blue circles), W735 (pink circles), and W736 (dark green circles) and the long-term (1962-2000) weighted average isotopic signature δ^{18}O -3.68 ‰ for Nabappie.

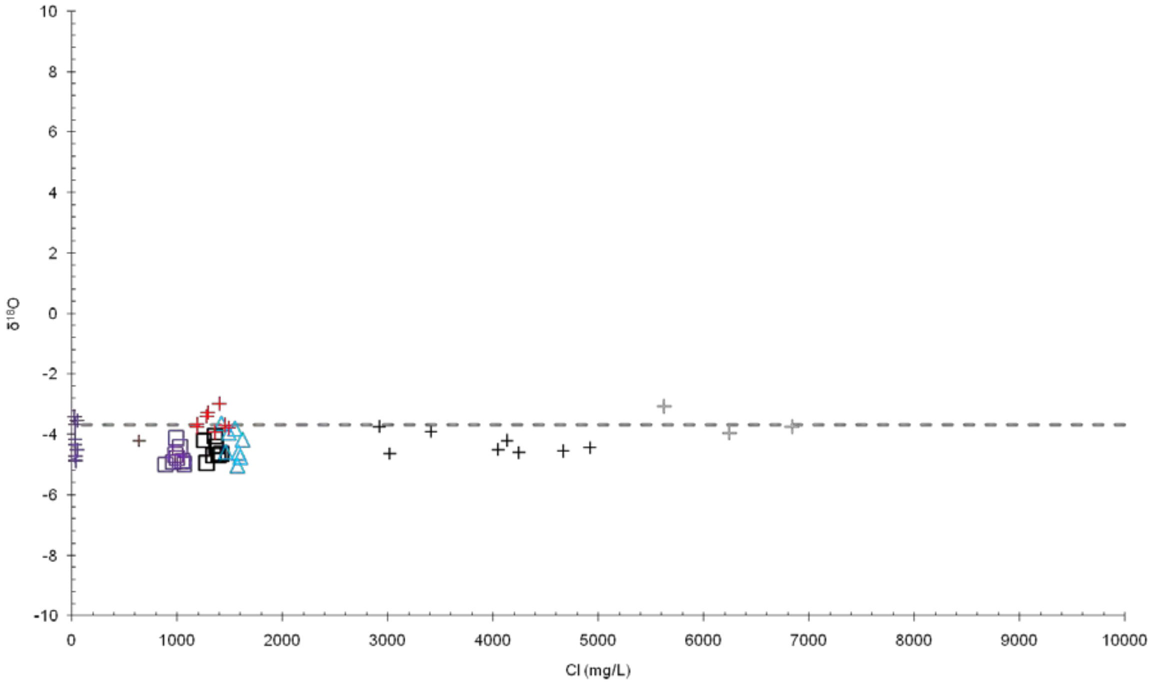

Figure 6-12. Plot of δ^{18}O versus Cl$^-$ from April to November 2009 for shallow observation bores BMC56ob (black cross), BMC89ob (purple cross), BMC90ob (red cross), BMC93ob (violet cross) and BMC94ob (brown cross); intermediate bore BMC58i (blue triangle); and deep bores BMC57D (purple square), and BMC56d (black square). δ^{18}O versus Cl$^-$ plotted with the long-term (1962-2000) weighted average isotopic signature δ^{18}O -3.68 ‰ for Nabappie.

6.6 Discussion

The dominance by Cl^- and Na^+ was observed in all surface waters and groundwaters, with concentrations of other major ions being largely proportional to seawater. This indicates that major ions are predominantly sourced from marine-derived ions deposited by rainfall (Hingston and Gailitis, 1976, Hingston and Gailitis, 1977, Herczeg et al., 2001). Major ion concentration in both groundwater and surface waters increased exponentially down-gradient to wetland W017 near the valley floor. As concentrations increased, the variability of major ions and stable isotope signatures decreased. This trend of increasing homogeneity with increasing distance along a flow path can most likely be attributed to mixing of multiple water sources (Cartwright et al., 2004, Turner et al., 1987a). Groundwater processes such as dissolution and precipitation of minerals (Dutkiewicz et al., 2000), weathering (Bennetts et al., 2006, Bettenay et al., 1964), plus anthropogenic influences such as the application of fertilisers (Cartwright et al., 2006, Davis et al., 2001), can modify groundwater composition during mixing and transportation down-gradient and thus need to be considered.

The Cl^-/Br^- ratio provided a well-founded means to assess the relative importance of halite to the hydrochemistry of water (Cartwright et al., 2006, Davis et al., 1998, Davis et al., 2001). However the application of Br^- was restricted due to the presence of concentrations near or below the laboratory detection limits in rainfall and fresh groundwater, thus likely increasing the associated error margin for these low concentration samples (Cartwright et al., 2006). With the exception of sites proximal to wetland W017 the ionic concentrations of groundwater were well below the precipitation threshold of halite (Tweed et al., 2009, Herczeg et al., 2001, Mazor and George, 1992, Simmons and Narayan, 1998). Additionally, the Cl^-/Br^- ratios were below those likely to indicate halite dissolution (Davis et al., 1998) therefore it is doubtful that halite dissolution is a primary factor in surface water composition.

The concentration and distribution of nutrients (higher N and lower P) in groundwater and surface water provides an insight into nutrient fluxes and their likely sources. Elevated nitrogen (up to 35 mg/L TN), predominantly consisting of inorganic forms of N (NO_3) was observed in groundwater adjacent to broad acre cropping and a stand of nitrogen-fixing tagasaste (*Chamaecytisus proliferus*), whilst phosphorus was <0.01 mg/L. The sandy soils of the upper subcatchment are inherently nutrient-poor, hence the observed elevated N concentrations, particularly in groundwater at site BMC89ob, indicates an external source. One potential source is the application of fertilisers for improved crop yields, although a less obvious source is from N-fixing plants. Tagasaste for example was observed in the nearby area of Moora to have very high rates of nitrogen fixing (up to 587 kg N/ha), which combined with decomposition of nitrogen-rich litter is potentially a major source of inorganic-N in the soil (Unkovich et al., 2000). Significant stores of N also occur under annual crops, particularly lupins, due to the accumulation of above-ground and below-ground (roots and nodules) residuals (Anderson et al., 1998a, Anderson et al., 1998b). Seasonal and episodic recharge can leach these N-stores below the root zone which may lead to groundwater contamination (Hasson and Wiley, 2010). In this study the relative contribution from each of these potential sources of N was unable to be determined due to insufficient data. However should elevated nutrient concentrations persist in wetlands and groundwater in the future then it is recommended that investigations be undertaken which specifically quantify rates of nutrient mineralisation and leaching for different land uses in the sandy soils of the upper subcatchment.

The concentration of TN decreased significantly down-gradient to ≤4 mg/L at BMC90ob, with similar concentrations observed in groundwater further down-gradient both within the unconfined and semi-confined aquifers. Although these concentrations are near the threshold (5 mg/L) suggested by Prober and Smith (2009) for the protection of native vegetation. Observed TN concentrations in wetland W015, and W051, and historical data from wetlands W015, and W016 (Aquatic Research Laboratory, 2009) indicate that TN concentrations are likely to exceed the ANZECC/ARMCANZ (2000) guidelines for “slightly disturbed wetlands from Southwest Australia” (1.5 mg/L TN). Phosphorus (TP) concentrations were significantly lower and below the suggested thresholds (5 mg/L TP) by Prober and Smith (2009), although observed concentrations at wetlands W016 (0.15 – 0.87 mg/L TP), and W051 (0.08 mg/L TP) were above the ANZECC/ARMCANZ (2000) guidelines (0.06 mg/L). The generally low concentrations of phosphorus and absence of algal blooms indicates that phosphorus is likely a limiting nutrient (Aquatic Research Laboratory, 2009). However in the past elevated phosphorus has been observed at wetland W016 therefore it has the greatest potential for elevated nutrient concentrations to impact upon its aquatic biodiversity values.

The analysis of the wheatbelt rainfall ionic chemistry data is limited to several keystone studies (Hingston and Gailitis, 1976, Hingston and Gailitis, 1977, Mazor and George, 1992, Bettenay et al., 1964). In this study there was an opportunity to assess temporal trends of major ions. Average ionic results in rainfall of this study were comparable to the published literature for other locations in the wheatbelt region at similar distances from the coast (Hingston and Gailitis, 1977, Mazor and George, 1992). Analysis of stable isotopic (δD and $\delta^{18}O$) data derived from event-based rainfall samples enabled the interpretation of a Local Meteoric Water Line (LMWL). While no direct comparison of the isotopic signature of Perth rainfall for 2009 and the Nabappie LMWL was possible the Nabappie LMWL is similar to the long-term dataset collected from Perth (IAEA/WMO, 2006, Liu et al., 2010).

The integration of stable isotopes and hydrochemistry with physical hydrogeological methods enabled an insight into groundwater and surface water processes, including salinisation. Groundwater heads (Chapter 5) indicate general groundwater flow is from the western boundary catchment divides discharging in the lower eastern areas. However, the δD and $\delta^{18}O$ enrichment evident in groundwater and elevation of ion concentrations at bore BMC54d, above the levels of the regional primary saline aquifer (BMC64d), indicates that wetland W017 is not only behaving as groundwater discharge lake but it is also recharging the underlying aquifers with hypersaline, isotopically enriched water. The occurrence of reflux brines is common beneath playa lakes (Macumber, 1991, Chen, 1992) and is thought to be the dominant influence upon the presence of highly fractionated and hypersaline groundwaters at BMC54d. It also explains why only minor salt crusting occurs on the lakebed of W017. Seasonal changes in both ionic and stable isotope (δD and $\delta^{18}O$) composition in bores BMC54d and BMC55d further suggests that water and solute exchange within the semi-confined aquifer is driven by both groundwater head and density gradients.

The hypersaline groundwater at BMC54d and W017 does not appear to have migrated upgradient of BMC55d in the hyposaline semi-confined or unconfined aquifer respectively. TDS concentrations within the hyposaline unconfined aquifer and its associated wetlands are greater than the underlying semi-confined aquifer (BMC56d and BMC57d). This suggests that evapo-concentration of salts from increased catchment surface water and groundwater flows are a likely cause of recent salinisation as opposed to migration of regional hypersaline groundwater. Validation of this theory is more difficult because evidence of evaporative enrichment in δD and $\delta^{18}O$, evident in wetlands and surface water, is not evident in the underlying unconfined water table. This observed trend, for example at bore BMC93ob (base of wetland W016), is due to the preferential recharge of isotopically light rainfall which tends to overwhelm the evaporation-enriched signature (Hsieh et al., 1998, Shurbaji et al., 1995, Harrington et al., 2002, Wenninger et al., 2010, Robertson and Gazis, 2006). Consequently the separation between evaporation and transpiration cannot be distinguished using the adopted parameters because the neither process modifies the isotopic signature (δD and $\delta^{18}O$) of groundwater, whilst both can lead to an increased ion concentration (Cramer et al., 1999, Bennetts et al., 2006, Dawson et al., 2002).

CHAPTER 7:

7 Water Balance

7.1 Conceptual hydrological models and assumptions

Born (1979) developed a system to describe the conceptual hydrogeological function of wetlands into recharge, discharge and flow-through types. Nield et al (1994) further described eleven subtypes of recharge and discharge regimes and seventeen subtypes of flow-through regimes. It is acknowledged by these authors and others (Tóth, 1970, Winter et al., 1998, Townley et al., 1993, Turner and Townley, 2006) that simple, stylised models do not represent accurately the spatial and temporal complexity inherent in wetland systems. However it is recognised that the level of complexity in model conceptualisation must be appropriate for the scale of interest (Klemes, 1983, Farmer et al., 2003).

The primary classification suggested by Born et al (1979) is used here where a wetland is classified as a "recharge lake" if water from the wetland recharges the underlying aquifer over the entire lakebed; a "discharge lake" if the underlying aquifer discharges over the entire lakebed; and a "flow-through lake" if water moves into and out of the lakebed in different areas. This classification is consistent with the classification system used on the Swan Coastal Plain (Townley et al., 1993).

A mass water balance was constructed for the entire Nabappie subcatchment as well as independent mass water balances for wetlands W051, W016 and W017. Wetland-scale water balances were attempted using both physical hydrogeology parameters and also Cl^- and stable isotopic (δD and $\delta^{18}O$) data. The Cl^- and stable isotope mass balance method however proved problematic for wetland-scale water balances and were discarded and as such this chapter will focus on the mass water balances derived using physical hydrogeological methods. Additionally, the Cl^- mass balance and hydrograph analysis (specific yield) methods were used to assess site-specific recharge rates.

Based on interpretations and conceptual models discussed in Chapters 5 and 6, several assumptions are made relating to the Nabappie subcatchment. The catchment is a closed catchment, except in the vicinity of wetland W017, where hydrological connectivity exists between wetland W017 and groundwaters from both the Nabappie subcatchment and regional hypersaline semi-confined aquifer.

Wetland W051 is designated a flow-through wetland with groundwater conditions at bore BMC89ob representing inflows from the unconfined aquifer (Gi Q_{hoz}) and bore BMC58d representing inflows from the semi-confined aquifer (Gi Q_{vert}) (Table 7-1). The prevalence of unsaturated conditions beneath wetland W016 during summer months (Chapter 5), suggests that the semi-confined (Gi Q_{vert}) aquifer does not contribute to the wetlands water balance. This is in spite of a high potential for vertical discharge evidenced at bore BMC56d. Bore BMC90ob was used to determine the volume of groundwater inflows (Gi Q_{hoz}) to W016, whereas BMC56ob was used as a representation of inflow hydrochemistry. Groundwater outflow volumes (Go Q_{hoz}) are unable to be determined from existing monitoring infrastructure.

Table 7-1. Summary of sites and horizontal and vertical hydraulic conductivity (K_{hoz} and K_{vert}) values and groundwater input (Gi) and output (Go) fluxes from the unconfined (Qhoz), and semi-confined (Qvert) aquifers for wetlands W051, W016, and W017.

Parameter	W051	W016	W017
Gi - Qhoz - Bore 1	BMC89ob	BMC90ob	BMC93ob
Gi - Qhoz - Bore 2	W051	BMC93ob	BMC92ob
Length (m)	355	685	420
Aquifer area (m^2)	56 to 62	2,111 to 2,363	3,604 to 3,786
Range of K_{hoz} (m/day)	0.09, 0.15, 0.29	0.02, 0.1, 0.2	0.02, 0.1, 0.2
Gi - Qvert - Bore 1	BMC58d	BMC56d	BMC54d
Gi - Qvert - Bore 2	BMC90ob	BMC93ob	BMC93ob
Length (m)	16.03	12.22	19.29
Discharge area (m^2)	81	12,145	35,746
Range of K_{vert} (m/day)	0.0003, 0.001, 0.01	0.0003, 0.001, 0.01	0.0003, 0.001, 0.01
Go - Qhoz - Bore 1	W051		
Go - Qhoz - Bore 2	BMC90ob		
Length (m)	25		
Aquifer area (m^2)	55 to 58		
Range of K_{vert} (m/day)	0.09, 0.15, 0.29		

Hydrochemical evidence from bores BMC54d and BMC55d (Chapter 6) indicate that in spite of very low hydraulic conductivities (K_{hoz} and K_{vert}), density-driven downward flow of reflux brines occurs from wetland W017. This flow can occur against hydraulic gradients resulting in a loss of solutes to the underlying aquifer (Tyler et al., 1997, Allison and Barnes, 1985, Simmons et al., 1999, Nield et al., 2008, Van Dam et al., 2009). Inflow volumes from the unconfined aquifer to wetland W017 were determined from bore BMC93ob (Gi Q_{Hoz}), and vertical discharge determined from bore BMC55d (Gi Q_{vert}) within the semi-confined aquifer (Table 7-1). Bores BMC54d and BMC55d are assumed to represent a mixture of the regional primary saline aquifer, groundwater inflows from the Nabappie subcatchment, and reflux brines sourced from wetland W017.

7.2 Recharge and evapotranspiration estimates

7.2.1 Recharge by chloride mass balance

The mean annual recharge (MAR) calculated based on the possible ranges in precipitation Cl^- concentrations (4 and 8 mg/L) are provided for each analysed bore (Table 7-2). The highest recharge rates (32 to 64 mm/year) were calculated for bore BMC89ob, which is located within an area of bare deep (4 m) yellow sandy soil adjacent to broadacre cropping. Much lower recharge rates (3 to 6 mm/yr) are observed for BMC91ob, a bore screened within a similar profile to BMC89ob and located in native vegetation adjacent to broadacre cropping. Similar recharge rates (2 to 6 mm/yr) were observed for three bores (BMC01d, BMC02d, and BMC02ob) with similar land uses, located in the adjacent catchment within approximately 800 m of the catchment divide. Bore BMC94ob is located within a discharge zone resulting in elevated Cl^- concentrations therefore exhibits possible erroneous recharge rates.

Table 7-2. Annual recharge rate calculated using the Chloride mass balance approach for bores within groundwater recharge domains.

Site ID	Aquifer	Recharge (Cl precipitation 4mg/L)	Recharge (Cl precipitation 8mg/L)
BMC01D	Fresh, superficial unconfined	2.0	4.1
BMC02D	Fresh, superficial unconfined	1.1	2.3
BMC02OB	Fresh, superficial unconfined	2.8	5.6
BMC89OB	Fresh, superficial unconfined	32.1	64.1
BMC91OB	Fresh, superficial unconfined	2.8	5.6
BMC94OB	Fresh, superficial unconfined	1.7	3.5

7.2.2 Recharge estimate from hydrograph analysis

Results from hydrograph analysis (specific yield method) for bores in the upper slopes (BMC01d, BMC02d, and BMC02ob) were comparable to those from Cl^- mass balance at <5 mm/yr (Table 7-3). Recharge rates at BMC89ob ranged from 7 to 26 mm/yr, whilst the range of rates at bores BMC91ob and BMC94ob, was higher, ranging from 12 to 71 mm/yr.

Recharge on the lunette east of wetland W017 (bores BMC86ob, BMC87ob, and BMC88ob) ranged from <1 to 33 mm/yr with calculation using the middle parameter set yielding about 10 mm/yr (Table 7-3). Recharge to the deep weathered aquifer (hyposaline semi-confined aquifer and saline to hypersaline semi-confined aquifer) was in the order of 10 mm/yr (5 to 20 mm/yr). Recharge within the base of wetland W016 (BMC93ob) was 26 mm/yr (1.3 to 66 mm/yr), and 12 mm/yr at W017 (0.6 to 31 mm/yr).

Table 7-3. Summary of groundwater recharge in 2009 determined from hydrograph analysis using a range of specific yield values.

Site ID	Specific yield (dimensionless)			Water level range (m)	Recharge (mm/yr)		
	Lower	Middle	Upper		Lower	Middle	Upper
BMC01d	0.01	0.02	0.03	0.08	0.8	1.6	2.4
BMC02d	0.01	0.02	0.03	0.15	1.5	3.0	4.5
BMC02ob	0.01	0.02	0.03	0.11	1.1	2.2	3.3
BMC54d	0.01	0.02	0.03	0.52	5.2	10.4	15.6
BMC55d	0.01	0.02	0.03	0.64	6.4	12.8	19.2
BMC56d	0.01	0.02	0.03	0.36	3.6	7.2	10.8
BMC56OB*	0.03	0.07	0.12	0.75	22.5	52.5	90.0
BMC57d	0.01	0.02	0.03	0.35	3.5	7.0	10.5
BMC58d	0.01	0.02	0.03	0.4	4.0	8.0	12.0
BMC58i	0.01	0.02	0.03	0.6	6.0	12.0	18.0
BMC86ob**	0.001	0.02	0.05	0.48	0.5	9.6	24.0
BMC87ob**	0.001	0.02	0.05	0.49	0.5	9.8	24.5
BMC88ob**	0.001	0.02	0.05	0.66	0.7	13.2	33.0
BMC89ob*	0.03	0.07	0.12	0.22	6.6	15.4	26.4
BMC90ob*	0.03	0.07	0.12	0.62	18.6	43.4	74.4
BMC91ob*	0.03	0.07	0.12	0.59	17.7	41.3	70.8
BMC92ob**	0.001	0.02	0.05	0.625	0.6	12.5	31.3
BMC93ob**	0.001	0.02	0.05	1.32	1.3	26.4	66.0
BMC94ob*	0.03	0.07	0.12	0.41	12.3	28.7	49.2

Values for deep bores within the weathered regolith were obtained from George (1992c), whilst values for shallow bores representing sandy clay (*), or clay (**) were obtained from Johnson (1967, cited in Halford, 2002).

7.2.3 Evapotranspiration

A review of high resolution (hourly) groundwater hydrographs revealed the presence of a consistent diurnal ET signal at bore BMC94ob (Figure 7-1). This site, located nearby a stand of tagasaste and mature eucalypt trees, was the only site to exhibit such diurnal characteristics. Daily ET rates from analysis of the BMC94ob hydrograph for a range of Sy values were; 1.1 mm/d (Sy 0.015); 2.5 mm/d (Sy of 0.035); and 4.35 mm/d (Sy of 0.06). The results from lowest Sy value are within the range considered typical of this vegetation whilst the middle value was about three times rainfall, or 36% of pan evaporation which is still within the likely range. The upper value was about 5.6 times rainfall or 60% pan evaporation, and therefore represents the upper limit or above for a particularly dry year (Salama et al., 1994, Lefroy et al., 2001, Raper, 1998).

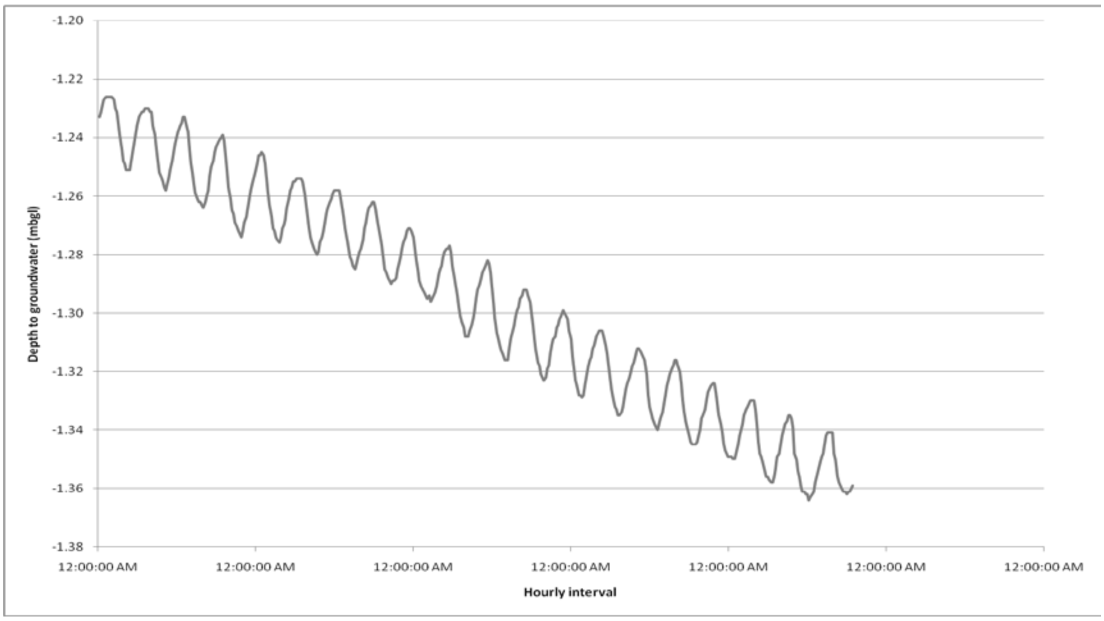

Figure 7-1. Hourly hydrograph of bore BMC94ob from 26/11/2009 to 15/12/2009. Note the presence of a diurnal groundwater fluctuation indicative of an evapotranspiration signal.

7.3 Catchment-scale water balance results

Analysis of the range of water balance parameters (Table 7-4) indicated that on an annual time-scale the Nabappie subcatchment ranged from a loss of -0.4 mm/yr (~3.6 ML/yr) to a gain of +4.8 mm/yr (~45 ML/yr) (lower and upper range). Recharge was greatest (76 to 151 ML/yr) in the upper recharge domain beneath broad acre cropping, whilst recharge per landuse was greatest beneath bare sandy soils at 50 to 110 mm/yr. ET estimations from wetlands W735 and W736 accounted for a large proportion of recharge excess (~92 ML/yr), which is expected as excess recharge will flow into these wetlands laterally via the unconfined aquifer. Excess recharge down-gradient of these wetlands is largely accounted for by ET of deep-rooted perennial vegetation in the recharge domain (21 to 75 ML/yr). These high ET losses were largely attributed to the 13.4 ha proportion of tagasaste with access to fresh groundwater resources (DTW <6 mbgl). Total recharge in the lower area (discharge domain) was estimated to range from 3.3 to 16.7 ML/yr, and the water balance was estimated to be in excess of 1.2 ML to 6.8 ML/yr (1.3 to 7.2 mm/yr). Significant ET losses occurred in wetlands W016 and W017 however the results indicate that there is insufficient discharge through bare soil ET or open water body ET to account for all the excess groundwater or interflow contributed from the recharge domain.

A range of recharge values, indicative of the pre-clearing vegetation, were assigned across the whole catchment to assess the changes that have occurred to the water balance as a result of agricultural development. For this analysis a discharge area of 5 ha was assumed for wetlands W016 and W017, as was a range of 0.02 to 3 mm/yr recharge under pristine pre-clearing conditions (George, 1992a, Salama et al., 1993b) across the remaining catchment area (927 ha). Annual recharge under these pre-clearing conditions was estimated to range between 0.2 to 28 ML/yr. Estimates of ET losses from wetlands W016 and W017 are sufficient to account for these ranges of pre-clearing recharge excess estimates. These results indicate that recharge excess has increased by at least four-fold, and perhaps greater than 30-fold due to the clearing of native deep-rooted vegetation.

Table 7-4. Summary of a catchment-scale water balance for 2009 with precipitation (P), recharge (R), and surface water (Si) inputs and evapotranspiration (E) outputs.

Parameter	Lower (mm/yr)	Middle (mm/yr)	Upper (mm/yr)	Area (ha)	Lower volume (m3)	Middle volume (m3)	Upper volume (m3)	Reference	Comments
Whole catchment									
Precipitation	280.30	280.30	280.30	932.00	2,612,396.00	2,612,396.00	2,612,396.00		
Evaporation	2,532.70	2,532.70	2,532.70						
Upslope recharge area	**280.30**	**280.30**	**280.30**	**837.59**	**2,347,750.76**	**2,347,750.76**	**2,347,750.76**		
E - Bare soil, upper sands	230.30	200.30	170.30	35.38	-81,480.14	-70,866.14	-60,252.14		
R - Bare soil, upper sands	50.00	80.00	110.00		17,690.00	28,304.00	38,918.00	1	
E - E. camaldulensis fence line	392.42	560.60	756.81	4.08	-15,998.96	-22,855.66	-30,855.14	2, 3	1.4*P, 2*P, 2.7*P
R - E. camaldulensis fence line	-112.12	-280.30	-476.51		-4,571.13	-11,427.83	-19,427.31		Negative recharge
E - Tagasaste, access to GW	392.42	560.60	644.69	13.37	-52,466.55	-74,952.22	-86,195.05	4	1.4*P, 2.0*P, 2.3*P
R- Tagasaste, access to GW	-112.12	-280.30	-364.39		-14,990.44	-37,476.11	-48,718.94		Negative recharge
E - Tagasaste, no access to GW	294.32	336.36	364.39	7.66	-22,544.53	-25,765.18	-27,912.27	2	1.05*P, 1.2*P, and 1.3*P
R - Tagasaste, no access to GW	-14.02	-56.06	-84.09		-1,073.55	-4,294.20	-6,441.29		Negative recharge
E - Wheat	270.30	265.30	260.30	147.06	-397,503.18	-390,150.18	-382,797.18		
R - Wheat	10.00	15.00	20.00		14,706.00	22,059.00	29,412.00		
E - Canola	270.30	265.30	260.30	119.13	-322,008.39	-316,051.89	-310,095.39		
R - Canola	10.00	15.00	20.00		11,913.00	17,869.50	23,826.00		
E - Lupins	270.30	265.30	260.30	491.81	-1,329,362.43	-1,304,771.93	-1,280,181.43		
R - Lupins	10.00	15.00	20.00		49,181.00	73,771.50	98,362.00		
E - Native vege, upslope	280.28	280.24	280.16	13.89	-38,930.89	-38,925.34	-38,914.22	5	
R - Native vege, upslope	0.02	0.06	0.14		2.78	8.33	19.45	5	
E - Wetland W735 and W736	1,772.89	1,772.89	1,772.89	5.21	-92,332.11	-92,332.11	-92,332.11		
SI - Wetland W735 and W736	0.00	0.00	0.00		0.00	0.00	0.00		
Subtotal (m3)	-	-	-	-	**-4,876.43**	**11,080.11**	**38,215.81**		
Subtotal (mm)	-	-	-	-	**-0.58**	**1.32**	**4.56**		
Downslope discharge area				**94.42**	**264,645.27**	**264,645.27**	**264,645.27**		
E - Wetland W051				0.18	-22.30	-26.22	-30.26		
SI - Wetland W051					0.45	0.89	1.34		
E - Wetland W015				0.00	-0.37	-0.37	-0.37		
SI - Wetland W015					0.00	0.00	0.00		
E - Wetland W016				1.21	-3,629.00	-4,691.84	-5,754.53		
SI - Wetland W016					484.77	969.55	1,454.30		
E - Wetland W017				3.57	-10,150.00	-12,955.00	-15,761.00		
SI - Wetland W017					1,271.80	2,543.61	3,815.41		
E - Bare soil, lower clays	308.33	308.33	308.33	7.94	-24,486.64	-24,486.64	-24,486.64		1.1*P
R - Bare soil, lower clays	-28.03	-28.03	-28.03		-2,226.06	-2,226.06	-2,226.06		No recharge
E - Lower strata vegetation	275.30	270.30	255.30	66.47	-182,991.91	-179,668.41	-169,697.91		E=P
R - Lower strata vegetation	5.00	10.00	25.00		3,323.50	6,647.00	16,617.50		Recharge based on hydrograph analysis
E - Native overstorey vege, downslope	280.30	280.30	280.30	15.03	-42,129.09	-42,129.09	-42,129.09	5	
R - Native overstorey vege, downslope	0.00	0.00	0.00		0.00	0.00	0.00	5	
Subtotal					**1,235.96**	**687.70**	**6,785.47**		
Subtotal (mm)					**1.31**	**0.73**	**7.19**		
Balance (m3)				0.00	**-3,640.48**	**11,767.81**	**45,001.28**		
Balance (mm)					**-0.39**	**1.26**	**4.83**		

Reference: 1 - Argent 1999; 2 - Eastham et al 1993, 3 - Marshall et al 1997; 4 - Lefroy 2004; 5 - George 1992a

7.4 Wetland-scale water balance results

7.4.1 Wetland W051

Analysis of the lower, middle and upper range of parameters for wetland W051 indicate that annual water balance estimates ranged from an excess of +7% to a deficit of -13% (Table 7-5). The inputs for wetland W051 were dominated by rainfall (50%) and groundwater from the unconfined aquifer (47%) (Table 7-5 and Appendix 7A) with inflows from surface water and the semi-confined aquifer being minor. However, the low Cl^- concentration of rainfall meant that it was the least significant contributor to the solute balance (0.2 kg/yr or 0.7%), whilst contributions via groundwater inflows from the unconfined aquifer were the greatest (26 kg/yr or 95%). It was estimated that about 27 kg/yr of Cl^- was exported via groundwater outflows, and there was no net gain of solutes, and therefore the wetland was in steady-state with respect to Cl^- on an annual basis.

Table 7-5. Wetland W051 lower, middle and upper annual estimates of volumes and Cl^- concentration (kg) of precipitation (P), surface water inflows (Si), groundwater inputs from the unconfined (Gi_{hoz}) and semi-confined aquifers (Gi_{vert}), groundwater outputs from the unconfined aquifer (Go_{hoz}), and bare soil and evaporation outputs.

Parameter	Lower (mm/yr)	Middle (mm/yr)	Upper (mm/yr)	Cl^- concentration (mg/L)	Lower Cl^- (kg)	Middle Cl^- (kg)	Upper Cl^- (kg)
P	22.7	22.7	22.7	8.0	0.2	0.2	0.2
Si	0.5	0.9	1.3	500.0	0.2	0.4	0.7
Gi (hoz)	13.0	21.6	41.8	1,200.0	15.6	25.9	50.1
Gi (vert)	0.2	0.7	1.5	2,000.0	0.4	1.4	2.9
Go (hoz)	12.5	20.9	40.4	1,300.0	16.3	27.2	52.5
Bare soil E	5.5	6.8	8.0		0.0	0.0	0.0
Wetland E	16.8	19.5	22.2		0.0	0.0	0.0
ΔS	0.0	0.0	0.0		0.0	0.0	0.0
Balance	0	-2	-4		0.1	0.8	1.4
% residual	7%	-6%	-13%				

Monthly water balance summaries (including the unknown residuals) were compiled to assess potential areas of uncertainty (Figure 7-2). These were used to identify seasonal processes which were not well captured in the annual water balance. Low residuals (<1 KL/month) from January through March and December occurred during a “water limited” period where rainfall and surface water inputs were minor and groundwater inflows were met by groundwater outflows and bare soil and wetland ET. From April through June rainfall increased and residuals were in excess up to 2 KL/month indicating that output fluxes (ET or groundwater out (Go)) were likely under estimated.

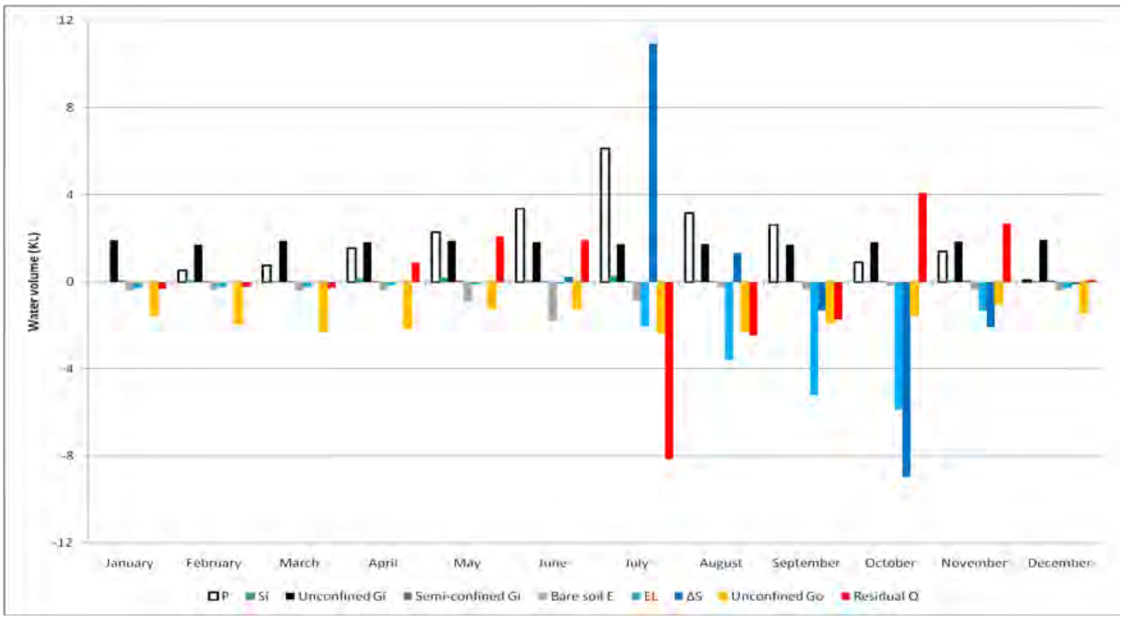

Figure 7-2. Wetland W051 monthly water balance with inputs of precipitation (P), surface water inflow (Si), groundwater inflows from the unconfined aquifer (Gi), semi-confined aquifer, outputs of bare soil evaporation, evaporation from open water (E_L), change in wetland storage (ΔS), and the residual (Q).

In July a shift to highly negative residuals (8 KL/month) resulted from an increase in wetland storage, which was not accounted for by estimated inflows. July is representative of a "water excess" period when observed interflow discharge and surface water flows down-gradient from wetland W051 were most significant. Hence potential error indicated by negative residual may be due to the occurrence of interflow discharge which is not accounted for in the water balance. Additionally, residuals may have occurred due to the conversion of wetland depth to wetland area and volume.

ET outputs increased in August and September, rainfall inputs declined, and wetland storage consequently decreased and negative residuals were observed. Significant decline in storage was also observed in October and November, although residuals were positive. This period from August through November is considered a "drying phase" when it is expected decreases in rainfall and wetland storage levels and increased ET losses occur. Hence the monthly time-step analysis suggests that there is at least one parameter not being adequately represented in the water balance during the "water excess" and "drying phase" periods.

7.4.2 Wetland W016

The analysis of the lower, middle and upper range of parameters for wetland W016 all indicate that residuals were positive for annual water balance estimates, in the order of between +13% and +22% (Table 7-6). This suggests that the input fluxes are an overestimation, however observed interflow discharge occurring down gradient of wetland W016 indicates that the residual may be indicative of unaccounted groundwater outflow volumes. This theory is further supported by the similarity between the hydrochemical properties of surface water within W016, and interflow discharge which is evident as surface water inflows to down-gradient wetland W017 (Chapter 6).

Rainfall was the dominant input source (62%) for wetland W016, with contributions from the unconfined aquifer (20%) and surface water inflows (18%) being less considerable (Table 7-6 and Appendix 7A). As expected, rainfall with its comparatively minor Cl^- was the lowest contributor to the Cl^- balance (27 kg/yr or 0.4%). Inflows from the unconfined aquifer were the highest (4,187 kg/yr or 68%), with the remaining consisting of surface water inflows (1,966 kg/yr or 32%). If there were no groundwater outflows from the wetland then Cl^- was estimated to increase by 1,848 to 11,351 kg/yr, which is contrary to observed trends (Chapters 5 and 6). However if the estimated residual of 473 to 1,240 KL can be attributed to groundwater outflows, and assuming a mean Cl^- concentration of 6,200 mg/L (mean Cl^- of BMC93ob), then the Cl^- balance for the lower, middle and upper ranges would be a loss of 1,086 kg/yr, a gain of 1,532 kg/yr and 3,663 kg/yr respectively, which provides a closer representation of observed conditions.

Table 7-6. Wetland W016 lower, middle and upper annual estimates of volumes and Cl^- concentration (kg) of precipitation (P), surface water inflows (Si), groundwater inputs from the unconfined (Gi_{hoz}) and semi-confined aquifers (Gi_{vert}), and bare soil and evaporation outputs.

Parameter	Lower (m^3)	Middle (m^3)	Upper (m^3)	Cl^- concentration (mg/L)	Lower Cl^- (kg)	Middle Cl^- (kg)	Upper Cl^- (kg)
P	3,404	3,404	3,404	8	27	27	27
Si	485	970	1,454	2,028	983	1,966	2,949
Gi (hoz)	214	1,068	2,136	3,920	837	4,187	8,375
Gi (vert)	0	0	0	996	0	0	0
Bare soil E	3,064	4,032	5,001				
Wetland E	565	659	754				
ΔS	0	0	0				
Balance	473	750	1240		1,848	6,181	11,351
% residual	13%	16%	22%				

Monthly water balance summaries (including the residuals) were compiled to assess potential areas of uncertainty (Figure 7-3). Positive value residuals were observed in all months except June, August and September. This may be due largely to the failure to account for groundwater outflows in the water balance, although it may also be due to overestimates of surface water inflows or systematic underestimations of bare soil ET or a combination of these.

On an annual basis, it is apparent that surface water storage changes for wetland W016 are minor, relative to input and output fluxes. The majority of the period from January through May, November and December were interpreted to be “water limited” due to low inputs of rainfall and surface water and little or no change to surface water storage in wetland W016. June through August represented a “water excess” period where wetland storages increased due to increased rainfall and surface water inflows, even though there were significant increases in bare soil ET. Storage decline, decreased rainfall and ET increases were observed in September and October creating a “drying phase”.

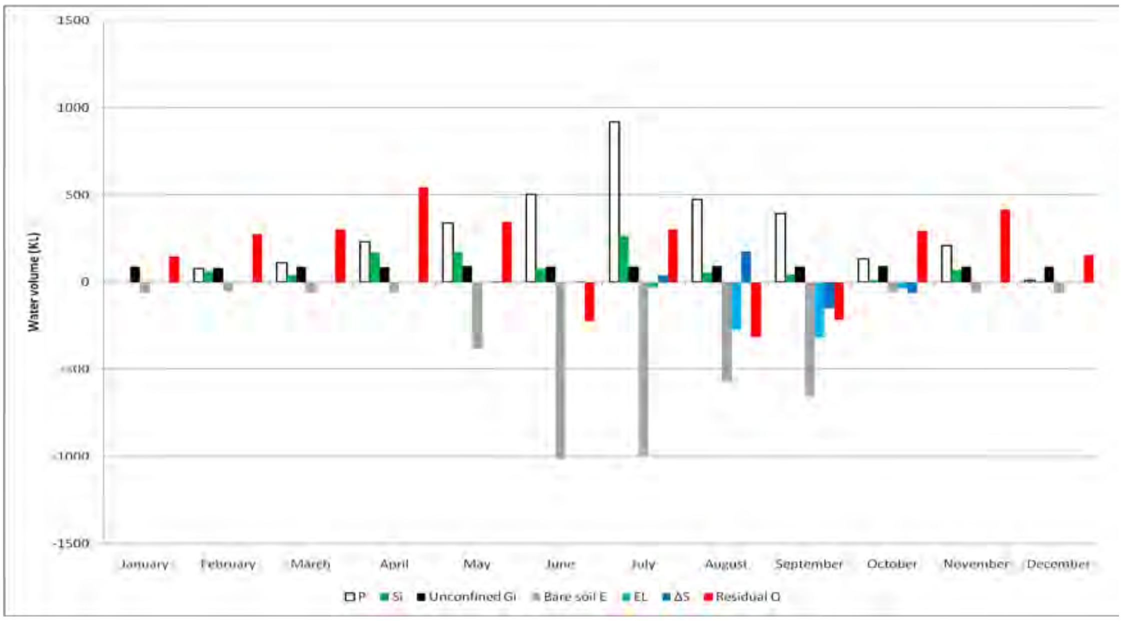

Figure 7-3. Wetland W016 monthly water balance with inputs of precipitation (P), surface water inflow (Si), groundwater inflows from the unconfined aquifer, semi-confined aquifer, outputs of bare soil evaporation, evaporation from open water, change in wetland storage (ΔS), and the residual (Q).

7.4.3 Wetland W017

The analysis of the lower, middle and upper range of parameters for wetland W017 indicate that annual water balance estimates ranged from an excess of +12% to a deficit of -7%. However the middle range indicates an approximate balance (Table 7-7). Rainfall (77%) was the dominant input flux for wetland W017, with the semi-confined aquifer (loss of -1%) being the lowest due to a net loss of water from the wetland to the underlying aquifer (Table 7-7 and Appendix 7A).

Table 7-7. Wetland W017 lower, middle and upper annual estimates of volumes and Cl^- concentration (kg) of precipitation (P), surface water inflows (Si), groundwater inputs from the unconfined (Gi_{hoz}) and semi-confined aquifers (Gi_{vert}), and bare soil and evaporation outputs.

Parameter	Lower	Middle	Upper	Cl^- concentration (mg/L)	Lower Cl^- (kg)	Middle Cl^- (kg)	Upper Cl^- (kg)
P	10,018	10,018	10,018	8	80	80	80
Si	1,272	2,544	3,815	5,000	6,359	12,718	19,077
Gi (hoz)	92	459	919	10,000	919	4,595	9,190
Gi (vert)	-4	-14	-27	60,000	-244	-812	-1,624
Bare soil E	7,604	9,985	12,366		0		0
Wetland E	2,546	2,970	3,395		0		0
ΔS	0	0	0		0		0
Balance	1,228	53	-1,035		7,115	16,581	26,723
% residual	12%	0.4%	-7%				

Again the low Cl^- concentration of rainfall mean that it is the lowest contributor to the Cl^- balance (80 kg/yr or 0.5%) in wetland W017, whilst surface water inflows were the highest (12,718 kg/yr or 77%) (Table 7-7). This is contrary to hydrochemical analysis (Chapter 6), which suggested that groundwater discharge contributes a significant proportion of the solutes to wetland W017. Water loss from the wetland to the underlying semi-confined aquifer resulted in an estimated 1,600 kg/yr of Cl^- being exported. Despite this loss, there was an estimated gain of 7,115 kg/yr to 26,723 kg/yr of Cl^-. These estimates were based upon an assumption of a constant Cl^- concentration of 60,000 mg/L for water entering and leaving the wetland via the semi-confined aquifer. Hence this model fails to account for the differences in Cl^- concentration of groundwater inflows, versus the export of more concentrated reflux brines occurring due to evaporative enrichment within the wetland. Therefore this simple Cl^- mass balance method is likely to be in error.

Monthly water balance summaries (including the residuals) were compiled to assess potential areas of uncertainty which were not well captured in the annual water balance (Figure 7-4). Significant seasonality was evident most notably in the semi-confined aquifer. This is due to the area immediately surrounding wetland W017 being topographically and hydrostatically flat (Chapter 5), resulting in groundwater flow being highly sensitive to subtle changes in hydraulic gradients and density (Post et al., 2007, Freeze and Cherry, 1979). For example, wetland W017 was a groundwater "recharge lake" from April through July when groundwater recharge was driven by rainfall and surface water inflows. From August through November, during the "drying phase" W017 became a "discharge lake" when groundwater head and/or density gradients overwhelmed the conditions within the wetland. These results are in agreement with interpretations of hydraulic gradients (Chapter 5), which were made independent of the analysis of surface water or precipitation inflows.

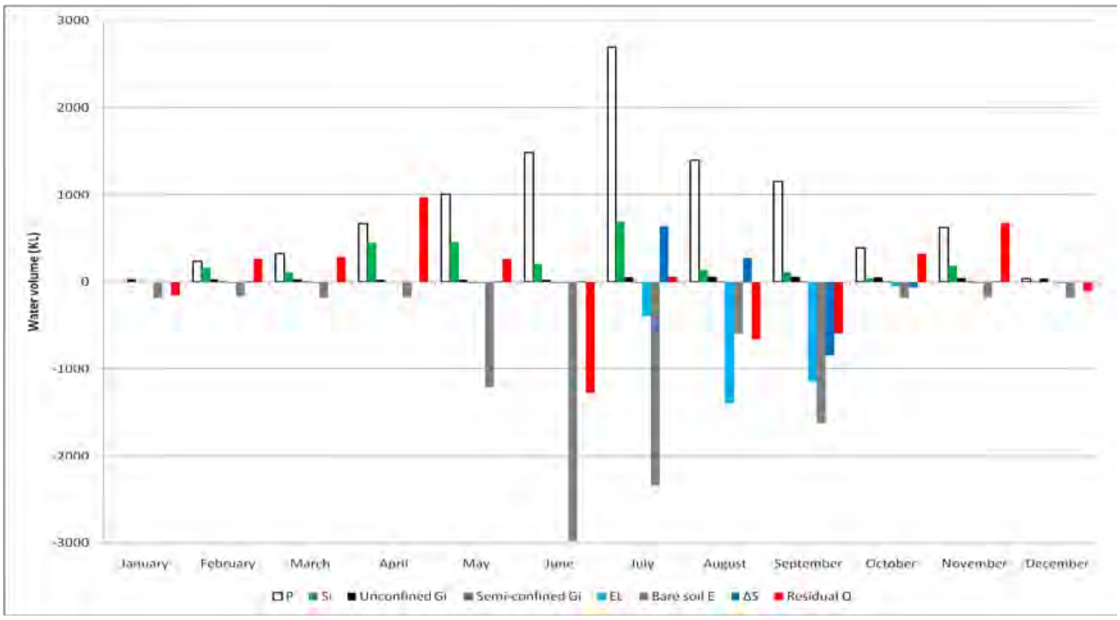

Figure 7-4. Wetland W017 monthly water balance with inputs of precipitation (P), surface water inflow (Si), groundwater inflows from the unconfined aquifer, semi-confined aquifer, outputs of bare soil evaporation, evaporation from open water, change in wetland storage (ΔS), and the residual (Q).

The unaccounted volumes or residuals apparent throughout the record altered in a similar seasonal fashion to wetland W016. The periods January to May, and November to December were interpreted to be "water limited" due to low inputs of rainfall and surface water and little or no change to surface water storage. June through August represented a "water excess" period where wetland storages increased due to increased rainfall and surface water inflows, even though bare soil ET increased due to the wetting of surface soils and dissolution of surface salt-crusting (Chen, 1992). In August, groundwater inflows also contributed to the excess water balance. A decline in storage was observed during September and October representing a "drying phase" when rainfall decreased, wetland storage levels declined, ET losses increased. The fact that groundwater discharge continued until November suggests that ET was significant during this period.

7.5 Wetland-scale hydrochemical and stable water isotope mass balance results

The stable isotope mass balance approach was found to be sensitive to all input parameters. In general, inflow volumes derived from water balance analysis, particularly surface water inflows, appeared to have less influence on the results than the choice of isotopic signatures for individual fluxes. The analysis was most sensitive to isotopic signatures (δD and $\delta^{18}O$) of the allocated groundwater inflows and least sensitive to surface water inflow volumes. Sensitivity to relative humidity and precipitation was variable. The stable water isotope mass balance method failed to reproduce similar results to the mass balance derived from the physical hydrogeology. The reasoning for this variation is discussed at the conclusion of this chapter. Given the limitations of the mass balance approach the results are not discussed further, although the raw data and plots generated from the mass balance approach are presented in the appendices (Appendix 7B).

7.6 Discussion

7.6.1 Recharge and ET

The analysis of recharge determined by Cl^- mass balance and hydrograph analysis (specific yield) methods provided consistent results in recharge areas within the catchment and hence insights into the unconfined aquifer recharge characteristics. Significant differences were observed between the two methods for other components of the catchment system. This is because the Cl^- mass balance method can only be applied where groundwater Cl^- is sourced only from precipitation and dry fallout (Allison and Hughes, 1978). However many of the discharge areas in the Nabappie subcatchment have considerable stores of solutes within unsaturated/saturated aquifers. Hence the hydrograph analysis method was more suitable to these areas, as evident in a similar study by George (1992b), although the potential of this method was limited by the paucity of specific yield values. Greater knowledge of the aquifer properties would improve the results derived from this method, additionally this would enhance confidence in the analysis of ET rates derived from high-resolution (hourly) water level data.

7.6.2 Catchment-scale water balance

The Nabappie subcatchment water balance was determined to be close to an annual steady-state (gain of +1.3mm/yr) based on middle range parameters. Although estimates did range from a loss of -0.4 mm/yr for the lower range parameters to a gain of +4.8 mm/yr when the high range parameters were used. Assuming a specific yield of 0.02 then this range reflect a variation in the water table of between -0.02 m/yr (lower end parameters) and +0.24 m/yr (high end parameters). These values are within the range of observed rising groundwater trends (+0.06 m/yr) since 2006 and are similar to the long-term trend interpreted from historical aerial photographs since 1959 (Chapter 5).

The groundwater system in the Nabappie subcatchment was separated into the upper recharge and lower discharge domains. This divide was located at the break of slope near wetlands W026 and W051. Groundwater recharge was greatest under broad-acre cropping (114 ML/yr) in the upper recharge domain, with recharge excess greatest per unit area for bare soil areas (28 ML/yr across 36 ha or 80 mm). ET losses from surface water in wetlands W735 and W736 and the 21 ha stand of tagasaste proximal to wetland W051 reduced much of the total recharge leaving up to 38 ML/yr (4.6 mm/yr) recharge excess unaccounted for.

Excess recharge in the upper catchment is transported down-gradient to the lower discharge domain. It creates increased interflow discharge, enhanced surface water flows, shallow water tables, waterlogging, and evapo-concentration of salts. These increased salt stores accumulate on the surface and within the unsaturated profile and are readily mobilised by active groundwater discharge and surface water flow into low lying areas and wetlands. Much of the water excess in the lower areas of the subcatchment is largely met by ET losses from numerous seeps and open water bodies, predominantly wetlands W016 and W017. Enhanced bare soil ET due to the prevalence of shallow water tables also plays a role in reducing water excess. However ET from the current extent of open water or shallow water tables is unable to meet the current recharge excess originating in the recharge domain. Consequently rising shallow water tables and increased groundwater discharge via wetlands will continue under the current climate and landuse regime.

In 1988, the previous landholder planted the 21 ha area of tagasaste upgradient of wetland W051 to try and lower a rising fresh water table. Water use by tagasaste in suitable areas is an effective method for lowering water tables as ET can be significantly higher than incident rainfall. Lefroy et al (2001) for example observed water use by this species at 55-63% of Penman-Montieth ET or ~2.3 times annual rainfall (>1,000 mm/yr). They also demonstrated high water use over summer months following episodic rainfall, which is an important characteristic of perennial vegetation as a strategy to address excess recharge during periods when annual crops are absent. Estimated transpiration loss of 16 ML/yr to 55 ML/yr occurring during a below average rainfall year indicates that this strategy has been effective at reducing some of the excess recharge that otherwise would have impacted on the lower discharge area.

Other native species are known to be effective in reducing shallow water tables, in particular eucalypts (Wildy et al., 2004, Brooksbank et al., 2011a, Brooksbank et al., 2011b, Marshall et al., 1997). For example water use by river red gums (Eastham et al., 1994, Marshall et al., 1997) are seen to be similar to tagasaste, however the rooting depth of this species are significantly higher. In this study, higher biomass production, hence greater water use, was observed for tagasaste in the areas where DTW was <6 mbgl, the inferred effective rooting depth of this species. There is therefore potential to increase water use by replacing tagasaste in areas where DTW is >6 mbgl with deeper-rooted eucalypt species, particularly given that water quality within this area is relatively fresh (i.e. <5,000 mg/L TDS).

ET from open water is an effective means for addressing excess recharge and runoff in semi-arid climates, but this process can accumulate solutes, particularly salt (Na^+Cl^-). Limited data in the upper catchment suggests ET losses from wetlands W735 and W736 (~92 ML/yr) can account for the majority of excess recharge in the vicinity of these wetlands (Figure 7-5). However wetland W736 appears to be expanding in area and accumulating salts over time (Chapter 5), therefore ET losses may not meet the current recharge excess. Additionally, about 69 ha of the subcatchment surrounding these wetlands has a DTW <2 mbgl (Figure 7-5), therefore there is potential for additional evaporative losses and evapo-concentration of salts. Increased vigour of annual crops (observed in aerial photographs in 1999) confirms the distribution of the mapped shallow DTW. It is hypothesised that this 514 ha subcatchment contributes little to the water balance of the lower discharge area except in the highest magnitude rainfall events or years of high rainfall (i.e. 1999). Additional monitoring infrastructure and data is required in order to substantiate this theory.

A pre-clearing water balance, based on a recharge rate of 0.02 to 3 mm/yr for pristine native vegetation, resulted in an estimated recharge excess of 0.2 to 28 ML/yr. Analysis indicated that this recharge excess can be easily accounted for by surface water ET from wetlands W016 and W017. The recharge excess in the 2009 water balance was estimated to have increased to between 73 to 116 ML/yr, which is at least a four-fold, perhaps greater than 30-fold increase in recharge. While the large range suggests some uncertainty in the analysis, other studies have identified similar (25-fold) post-clearing increase in recharge in wheatbelt catchments (Salama et al., 1993b).

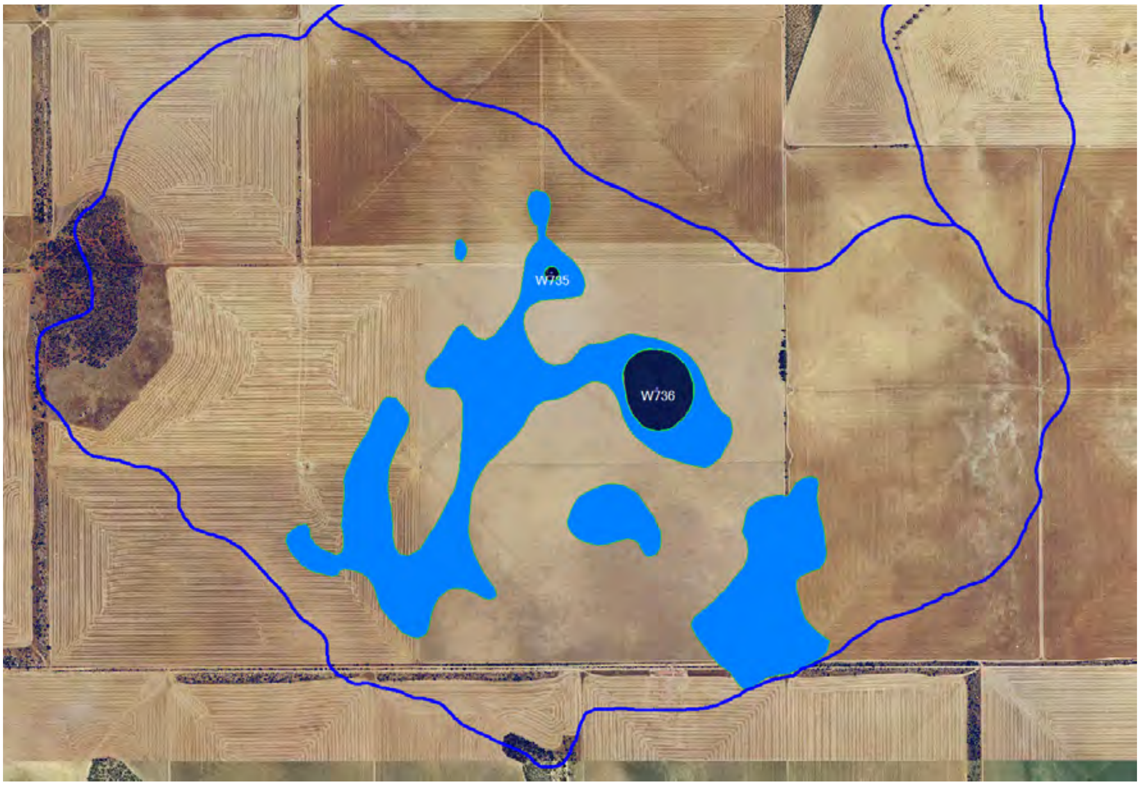

Figure 7-5. Wetlands W735 and W736 and their 514 ha subcatchment which includes a 69 ha area where the DTW is interpreted to be < 2mbgl (blue shaded area).

7.6.3 Review of hydrochemical and stable water isotope mass-balance methods

Steady-state mass balance analysis for wetland-scale analysis using both Cl^- and stable water isotope (δD and $\delta^{18}O$) methods yielded comparable results for estimation of groundwater inputs, however these results were at least an order of magnitude different than those derived from physical hydrogeological methods. Limitations of stable water isotope and Cl^- methods (Kendall and Caldwell, 1998) may provide some explanation for the observed differences between the mass balance approach and the physical hydrological approach. However the predominantly dry, ephemeral characteristics of the wetlands investigated means that the assumption of steady-state conditions did not hold true for sub-annual analysis. Consequently the Cl^- and stable water isotope mass balance analysis did not perform as well as expected. The full potential of the mass balance approach may however be achieved through higher resolution sampling, perhaps weekly, and adoption of non-steady-state solutions.

7.7 Wetland-scale water balance

On an annual basis, given the range in parameters analysed, the wetland-scale water balances were all within 22% of balancing, although were more commonly <13% and at wetland W017 it was <1%. The ephemeral nature of wetlands W016, W017 and W051 means that bare soil comprises the majority of the wetland area throughout the year. During the dry months in wetlands W016 and W017, the ET losses from bare soil within the interpreted wetland boundary are likely to be significantly reduced due to the formation of surface crusting of salts, where even thin crusts reduce ET to almost nil (Tyler et al., 1997, Chen, 1992, Allison and Barnes, 1985). The subsequent dissolution of these salts by rainfall results in significant increases in bare soil ET. Failure to explicitly model the temporal variability of bare soil ET in semi-arid climates can introduce significant error. However in this study a simple bi-modal method was applied to represent the two distinctly different patterns of bare soil ET described by Chen (1992); where E_1 occurs when surface salt crusting is present, and E_2.when rainfall dissolves these salts. The adopted methods have reduced some error and uncertainty, however the complex process of bare soil ET is an important component of a wetland-scale water balance therefore deserves greater attention in future studies.

Precipitation constituted a significant proportion of the water balance in each of the wetlands analysed. While the contribution from both surface water and groundwater was variable, they contributed the majority of Cl^-. A general trend was observed where groundwater was the largest contributor of Cl^- (95%) at the break of slope at wetland W051, and surface water became increasingly important down gradient, as evident at wetland W017 where surface water contributed 77% of Cl^-.

7.7.1 Wetland W051

Wetland W051 is a flow-through lake, with groundwater from the unconfined aquifer and rainfall contributing the majority (97%) of inflows. Contributions from the semi-confined aquifer are considered insignificant. The unconfined aquifer is estimated to contribute the majority (92%) of inflow solutes (Cl^-). A short-lived seasonal pulse of higher solute concentrations observed in June (Chapters 5 and 6) suggests the mobilisation of a local source of stored solutes after the first flush of rainfall. This is likely due to elevated salt stores in the root zone excluded during transpiration by the stand of deep-rooted perennial vegetation immediately upgradient. The key drivers of altered hydrology at wetland W051 are therefore inflows from the unconfined aquifer and seasonal pulses of locally derived solutes.

On an annual basis there was no net change in salinity due to the export of solutes down-gradient via groundwater to the lower discharge domain, however historical records indicate that groundwater salinity has increased in 40 years by an order of magnitude (Chapter 5). While the longer-term threat from altered hydrology is unknown, should the historical trend of increasing groundwater salinity in the vicinity of wetland W051 exceed the tolerance of the surrounding vegetation then water use by this vegetation will decline. A decline in water use by surrounding vegetation will result in elevated water tables, increased bare soil ET, continued rises in groundwater salinity and enhanced interflow discharge down-gradient to wetland W015.

7.7.2 Wetland W016

The water balance of wetland W016 is dominated by precipitation (62%), whilst surface water and groundwater inflows from the unconfined aquifer make up the remainder. Inflows from the semi-confined aquifer were assumed to be nil. Elevated salinity in the unconfined aquifer meant that this contributed over half (68%) of the Cl^- load on an annual basis and surface water the other dominant Cl^- source (32%). Groundwater outflows were unable to be determined due to an absence of down-gradient shallow monitoring infrastructure. Analysis of the Cl^- balance however indicates that a large proportion of the water balance residual can be attributed to groundwater outflow. However uncertainty in other areas, particularly bare soil ET, means that it would be erroneous to assume that all the residual can be attributed to groundwater outflow.

The enrichment of stable water isotopes (δD and $\delta^{18}O$) suggests that ET is a dominant process within the water body, therefore contributing to elevated surface water salinity during the “drying phase”. Although, elevated salinity (>10,000 mg/L TDS) when the wetland first filled in May (Chapter 5) and the underlying groundwater indicates a significant store of solutes within the unsaturated/saturated aquifers underlying the wetland. Bare soil ET is thought to drive the elevation of salinity in the unsaturated zone, although this process is unable to be verified with stable isotope (δD and $\delta^{18}O$) data due the tendency of isotopically light recharge events to overwhelm evidence of ET in shallow groundwater (Chapter 6) (Shurbaji and Phillips, 1995, Hsieh et al., 1998, Harrington et al., 2002).

There was no dominant, or consistent hydrological condition observed, with wetland W016 seasonally switching between groundwater recharge or discharge states and considering the likely high groundwater outflow it represents a flow-through regime. The key drivers of altered hydrology at wetland W016 are inflows of saline groundwater from the unconfined aquifer, with contributions from mobilised stores of solutes within the underlying unsaturated aquifer. Inflows of saline surface water and evapo-concentration processes within the water body also play a major role in salinisation of the wetland. On an annual basis it is likely that a proportion of solutes are recycled between the surface and the underlying sediments. In 2009, there was no net change in groundwater salinity beneath wetland W016 however a lack of data means there is no long-term trend to compare with. Ongoing decline of vegetation and increased prevalence of halophyte plant communities nearby although suggests a net annual gain in water and solutes is likely.

7.7.3 Wetland W017

Results from the hydraulic-based water balance for wetland W017 indicate that precipitation inputs are dominant (77%), whilst surface water inflows contribute the largest proportion of solutes (77% of Cl^-). The hypersaline semi-confined aquifer is only a minor contributor. The isotopic signature of wetland surface water indicates that ET is dominant. This process leads to increased solute concentration which approaches saturation during the “drying phase”.

Prior to this investigation wetland W017 was thought to be typical of a terminal discharge lake where groundwater from the local and regional aquifers discharge via ET (Cartwright et al., 2009). Detailed analysis however indicates that the process is more complex due to the prevalence of very flat, unstable hydrostatic conditions where minor changes to hydraulic head or density, such as the influx of surface water, results in the wetland switching from states of a groundwater discharge lake to a recharge lake. Additionally, the hydrochemical and stable water isotope evidence suggests the presence of reflux brines (Chapter 6), which are driven by dispersive and convective gradients leading to the downward fingering of dense, saline, isotopically enriched brines (Tyler et al., 1997, Allison and Barnes, 1985, Simmons et al., 1999, Nield et al., 2008, Van Dam et al., 2009). This downward flux results in a loss of solutes to the underlying aquifer which can occur against hydraulic gradients. This conceptual model helps to explain the poor explanatory power of Cl^- as a conservative tracer in Cl^- balance analysis and also provides explanation for the short-lived nature of surface-crusting of salts on the base of this wetland.

The semi-confined and unconfined aquifers underlying wetland W017 are essentially full, with little apparent potential for additional storage. The addition of inflows can only be met through ET losses from the open water body, bare soil ET, or downward flow of reflux brines. The prevalence of hydrostatically flat and unstable conditions within the vicinity of wetland W017 means that only minor changes to hydraulic head or density can readily alter the direction of groundwater flow. The key drivers of altered hydrology at wetland W017 are therefore surface water inflows and groundwater inflows of the unconfined aquifer from the upper catchment. Contribution by the regional semi-confined aquifer was unable to be determined due to the absence of infrastructure within the valley floor. However the water balance of wetland W017 was estimated to be in approximate steady state, therefore potentially the regional primary saline aquifer contributes little to the water or solute balance. The apparent connectivity between wetland W017 and the underlying semi-confined aquifer evidenced in upgradient bores BMC54d and BMC55d means that evapo-concentration within this wetland is the dominant process leading to salinisation of the underlying semi-confined aquifer. The potential for additional storage, particularly in very wet years is unknown, however extensive areas of surface water ponding observed in aerial photographs in the very wet year of 1999 indicate there is little available.

CHAPTER 8:

8 Synthesis

The study area experiences a semi-arid climate with low rainfall and high ET. The rainfall observed throughout the study period was 280 mm, and Class-A pan evaporation of 2,533 mm, which is consistent with recent trends being ~20% dryer than the long term-average. Contrary to the rainfall trends, the groundwater levels are rising at rates of about +0.06 m/yr since records commenced in 2006. This rising trend is consistent with the long-term increases in wetland area since 1959 (observed in aerial photographs) at wetland W736. Additionally, a ten-fold increase in the TDS at wetland W051 since 1970 indicates the upper catchment is actively discharging groundwater and solutes at elevated concentrations compared to pre-clearing conditions. The groundwater system of the Nabappie catchment is near full although it is yet to achieve a post-clearing hydrological equilibrium.

Significant groundwater TDS gradients are evident across the study area, increasing rapidly in both the semi-confined and unconfined aquifers down gradient toward the primary saline valley floor. Given the highly saline conditions it was necessary to correct groundwater levels for density. Density corrections were greatest in the lower saline area, where the difference between measured and corrected heads was up to +0.19 m. This is significant in the context of very flat gradients in the lower part of the study area. Wetland surface water salinity generally increased down gradient, although wetland W736 in the upper catchment was higher than some down-gradient wetlands. Differences in water quality of individual wetlands can be attributed to their water and solute balances and the differential influence of ET, which is in turn influenced by wetland salinity and hydroperiod.

Ionic composition of groundwater, surface water and rainfall is dominated by Cl^- and Na^+, with overall composition being largely proportional to seawater. As TDS concentrations increased down-gradient towards the valley floor, the variability of major ions (and stable isotope signatures) decreased. This trend of increasing homogeneity with increasing distance along a flow path can most likely be attributed to mixing of multiple water sources (Cartwright et al., 2004, Turner et al., 1987a). Cl^-/Br^-

weight ratios were temporally variable, although generally in a range of 300 to 600 which is below those (>1,000) likely to indicate halite dissolution, therefore it is doubtful that halite dissolution is a primary factor in elevated salt (Na^+Cl^-) concentration. Hence ionic content is chiefly sourced from marine-derived aerosols in rainfall.

Elevated concentrations of predominantly inorganic forms of nitrogen were observed in the freshest groundwater adjacent to broad acre cropping and the nitrogen-fixing tagasaste (*Chamaecytisus proliferus*), decreasing rapidly down-gradient. Phosphorus concentrations were significantly lower than nitrogen, although elevated concentrations were previously observed in wetland W016 (Aquatic Research Laboratory, 2009). The generally low concentrations of phosphorus and absence of algal blooms indicates that phosphorus is likely a limiting nutrient (Aquatic Research Laboratory, 2009). Although given that elevated phosphorus concentrations were observed in the past, there is potential for algal blooms and eutrophication to occur. Consequently it is recommended that nutrient levels (P and N) be measured on a regular (perhaps annual) basis at the fresher wetlands at Nabappie. Should elevated nutrient concentrations persist in the future then it is recommended that investigations be undertaken which specifically quantify rates of nutrient mineralisation and leaching for different land uses in the sandy soils of the upper subcatchment.

Analysis of stable isotopic (δD and $\delta^{18}O$) data derived from event-based rainfall samples enabled the derivation of a Local Meteoric Water Line (LMWL) for Nabappie. No direct comparison to the isotopic signature of Perth rainfall for 2009 was possible, however it is similar to the long-term Perth dataset (IAEA/WMO, 2006, Liu et al., 2010). High temporal variability of δD and $\delta^{18}O$ was evident with a general trend of depleted δ-values observed in winter and enrichment in October and November, consistent with other sites in Australia (Liu et al., 2010).

Stable water isotope corrections for the “salt effect” (Horita, 1989) were applied and changed values up to δD 12.8 ‰ and $\delta^{18}O$ -0.67 ‰ at the hypersaline wetland W017. The isotopic signature of surface water in wetlands plot along the local evaporation line and were found to be highly enriched during spring. The linear enrichment of stable water isotopes and increased Cl^- concentration evident during spring, particularly at wetlands W016, W017 and W736, indicates that ET is a dominant process. A similar strong linear relationship between Cl^- and isotopic enrichment also exists in the shallow saline unconfined aquifer, the semi-confined hyposaline and hypersaline semi-confined aquifers, again indicating ET as a dominant process. It also indicates that significant amounts of aquifer mixing are occurring, altering the isotopic signature of these groundwaters. Conversely there was little evidence of isotopic enrichment in the fresher shallow unconfined aquifer underlying and adjacent to wetland W016. This is likely due to the preferential recharge of isotopically light rainfall which tends to overwhelm the evaporation-enriched signature occurring at the evaporating front within the unsaturated zone (Hsieh et al., 1998, Shurbaji et al., 1995, Harrington et al., 2002, Wenninger et al., 2010, Robertson and Gazis, 2006).

Groundwater flow generally mimics topography and flows from the western catchment divides to the lower eastern areas where groundwater and ET discharge is dominant. The stable water isotope enrichment in groundwater and elevation of ion concentrations at bore BMC54d, above the levels of the regional primary saline aquifer (BMC64d), indicates that wetland W017 is not only behaving as groundwater discharge lake but it is also recharging hypersaline, isotopically enriched water to the underlying aquifer. The occurrence of reflux brines is common beneath playa lakes (Macumber, 1991, Chen, 1992) and this explains the presence of highly fractionated and hypersaline deep groundwaters at BMC54d. It also explains why only minor seasonal salt crusting occurs on the lakebed of W017. Seasonal changes in both ionic and stable water isotope values in bores BMC54d and BMC55d further suggests that water and solute exchange within the semi-confined aquifer is driven by both groundwater head and density gradients.

The hypersaline groundwater at BMC54d and W017 does not appear to have migrated upgradient of BMC55d in the hyposaline semi-confined and unconfined aquifers respectively. TDS concentrations within the hyposaline unconfined aquifer and associated wetlands W015 and W016 are greater than the underlying semi-confined aquifer (BMC56d and BMC57d). This suggests that evapo-concentration of salts from increased catchment surface water flows and groundwater discharge are a likely cause of recent post-clearing salinisation as opposed to migration of regional primary saline groundwater.

8.1 Catchment-scale water balance

The Nabappie catchment-scale water balance was in a quasi steady-state with an estimated gain of +1.3mm/yr, although estimates ranged from a loss of -0.4 mm/yr to a gain of +4.8 mm/yr. This represents a catchment-scale change in water table elevation between a decline of -0.02 m/yr to a rise of +0.24 m/yr with a middle value of +0.06 m/yr. These values are within the range of long-term trends discussed above.

Actual net groundwater recharge was observed to occur during a lower than average rainfall year, predominantly in upper areas of broad acre cropping and bare soil areas. ET losses from wetlands W735 and W736 and the 21 ha stand of tagasaste near wetland W051 accounted for a significant proportion however there is still an excess of up to 38 ML/yr (4.6 mm/yr). This excess is expressed down-gradient at the break of slope in the lower discharge domain as groundwater discharge and enhanced surface water flows. This causes persistence of shallow water tables, waterlogging, and evapo-concentration of salts in the unsaturated zone and shallow aquifers. This has led to increased salt stores within the unsaturated zone and soil surface, which are readily mobilised by seasonal groundwater discharge and surface water flow into low lying areas and wetlands. The excess water entering the lower part of the study area is discharged by ET losses from numerous seeps, shallow water tables, and open water bodies, predominantly wetlands W016 and W017. However it appears that the current extent of open water or ET losses from shallow water tables is unable to meet recharge excess occurring in the recharge domain. Consequently the rising of shallow, saline water tables and increased groundwater discharge via wetlands will continue under the current climate and landuse regime.

Analysis of a pre-clearing catchment-scale water balance indicates that recharge has increased at least four-fold, and perhaps greater than 30-fold as a consequence of land clearing and agricultural development. While the large range suggests some uncertainty in the analysis, other studies have identified similar (25-fold) post-clearing increase in recharge in wheatbelt catchments (Salama et al., 1993b).

8.2 Wetland-scale water balance

Conceptual hydrogeological models and water balances were developed for individual wetlands within the lower discharge area. These models were aided by high resolution (hourly) water level data and regular (monthly) analysis of hydrochemical and stable water isotope (δD and δ^{18}O) data. These methods proved complimentary and provided important insights into the hydrological functioning of individual wetlands, which would not have been achieved using any individual method in isolation.

Steady-state mass balance analysis using both Cl^- and stable water isotopes (δD and δ^{18}O) yielded comparable results for estimation of groundwater inputs, although an order of magnitude greater to those derived from physical hydrological methods. Error in the Cl^- mass balance can be attributed to the presence of significant salt stores within both the unsaturated/saturated aquifers. Whilst δD and δ^{18}O mass balance methods were hampered by the lack of site-specific time-series climate data (barometric pressure, temperature and relative humidity) and high-resolution (hourly) surface water temperature. Additionally the ephemeral nature of the wetlands mean the assumption of steady-state conditions did not hold true for sub-annual analysis. Consequently the hydrochemical and stable water isotope mass balance analysis did not perform as well as expected. The full potential of the mass balance approach may however be achieved through higher resolution sampling, perhaps weekly, collection of site-specific climate data, and adoption of non-steady-state solutions.

8.3 Water balance summary

Absolute knowledge of complex systems, such as those which occur in the Nabappie subcatchment, is unobtainable (Walshe et al., 2007), hence error and uncertainty is inherent in all water balances. In this study, water balance error margins were significantly reduced by applying a multidisciplinary approach. The study also avoided the use of combined residual terms for stores and fluxes which are difficult to quantify, improving the robustness and usefulness of the analysis.

A subjective and qualitative review of the water balance (Table 8-1) captures the degree of certainty in the conceptual models for each of the wetlands analysed and the relative confidence in the water and salt balance results. Additionally, results from these wetlands were used to infer the water and Cl^- balances for the remaining wetlands within the Nabappie subcatchment.

The highest level of certainty (0.9) is attributed to the water balance of wetland W051 where surface water inflows and bare soil ET was the lowest (Table 8-1). Reduced certainty at wetlands W016 (0.6) and W017 (0.7) can be largely attributed to the increased importance of these two parameters. The absence of down-gradient shallow groundwater monitoring infrastructure at wetland W016 is the justification for certainty being reduced to 0.6. The higher levels of certainty (0.7) predicted at wetlands W026, W735 and W736 are due to bare soil ET and surface water contributing less to the water and solute balances than in wetlands W016 and W017. Bare soil ET and surface water flows are important components of a wetland-scale water balance in a semi-arid environment therefore deserve greater attention in future studies.

The highest level of certainty in the Cl^- balance (Table 8-1) was again allocated to wetland W051 where surface water and groundwater inflows and groundwater outflows appeared to be well accounted for. The lowest level of certainty was allocated to W017, where reflux brines are thought to export solutes to the underlying semi-confined aquifer. Certainty can be significantly increased at this wetland by applying a fully density and head coupled solute transport model (such as SUTRA and FEFLOW), although higher temporal resolution hydrochemical and stable water isotope data will be required.

Table 8-1. Summary of the water balance, salt balance and a qualitative assessment of level of certainty for the suite of wetlands in the Nabappie subcatchment.

ID	Landscape position	Type	Proportion of water flux in water balance	Level of certainty	Salt balance	Level of certainty	Greatest knowledge gap(s)
W735	Upper slope	Ephemeral, round, hyposaline sumpland	50% P 49% Unconfined Gi <1% Si <1% Semi-confined Gi	0.7	95% Unconfined Gi <2% Si <2% Semi-confined Gi <1% P	0.6	No geological or historical hydrological data available in order to define water/salt balance.
W736	Upper slope	Permanent, round, saline lake	50% P 49% Unconfined Gi <1% Si <1% Semi-confined Gi	0.7	95% Unconfined Gi <2% Si <2% Semi-confined Gi <1% P	0.6	No geological or historical hydrological data available in order to define water/salt balance.
W026	Break of slope	Round, hyposaline to saline sumpland	50% P 48% Unconfined Gi 2% Si <1% Semi-confined Gi	0.7	95% Unconfined Gi 3% Semi-confined Gi <2% Si <1% P	0.6	No long-term GW or solute trends available in order to predict impacts of GW discharge down-stream to wetlands W015 and W016.
W051	Break of slope	Ephemeral, ovoid, hyposaline sumpland	50% P 48% Unconfined Gi 2% Si <1% Semi-confined Gi	0.9	95% Unconfined Gi 3% Semi-confined Gi <2% Si <1% P	0.8	Long-term salinity and GW level data required in order to make long-term projections of impacts of GW discharge down-stream to wetlands W015 and W016.
W015	Lower slope	Permanent, irregular, fresh to hyposaline lake	40% Semi-confined Gi 20% P 20% Si 20% Unconfined Gi	0.7	50% Si 40% Unconfined Gi 9% Semi-confined Gi <1% P	0.7	Long-term viability of currently healthy remnant vegetation surrounding W015 (ecological water requirements, thresholds etc).
W016	Lower slope	Ephemeral, irregular, saline sumpland	62% P 20% Unconfined Gi 18% Si 0% Semi-confined Gi	0.6	68% Unconfined Gi 32% Si <1% P 0% Semi-confined Gi	0.6	Long-term salinity and GW level projections. What will the implications be in the future of increased head within the semi-confined aquifer? Is there potential for hypersaline conditions to extend upgradient of BMC55d?
W017	Valley floor	Ephemeral, round, saline to hypersaline sumpland	77% P 20% Si <4% Unconfined Gi <1% Semi-confined Gi	0.7	77% Si 28% Unconfined Gi 5% Semi-confined Gi <1% P	0.5	Solute balance poorly defined due to the occurrence of reflux brines. Unknown capacity for additional water/solute storage should GW levels continue to rise, or capacity to be used as a disposal basin for future management.

Salinity classification (Davis et al, 2003): Fresh = <1,000 mg/L TDS; hyposaline = 1,000 to 10,000 mg/L; saline = 10,000 to 100,000 mg/L; hypersaline = >100,000 mg/L. The proportion of each flux in the water balance of each wetland is provided for groundwater contributions for precipitation (P) the unconfined and semi-confined aquifers (Gi) and surface water inflows (Si).

8.4 Future management

The Nabappie suite of wetlands lies on private property, therefore the feasibility of any one or number of management actions will depend upon whether economic or other goals of the landholder can be met simultaneously with biodiversity conservation goals (Department of Environment and Conservation, 2008). Management action feasibility requires that a number of factors are specifically defined and considered (Sparks et al., 2006), these include; defining the asset(s) where management is to be targeted (i.e. spatial boundary of specifically described assets); undertaking a threat assessment which considers not only altered hydrology, but other factors (i.e. weeds, feral animals, problem native animals etc); defining the end-point (i.e. setting management targets); assessment of the technical and economic capacity to manage the asset(s); and assessment of the socio-political will/capacity to apply the required resources to achieve the goal for the asset(s). Within the context of the Natural Diversity Recovery Catchment (NDRC) program the biodiversity assets within the Nabappie subcatchment have not been fully assessed, nor have discussions commenced with the landholders to assess the social and economic feasibility of any potential management actions.

8.4.1 Potential management options

Analysis of historical aerial photographs, since 1959, and anecdotal information indicates that the hydrological response to clearing at Nabappie was rapid with evidence of impacts appearing within a few years. More extensive clearing in years following led to the development of permanent wetlands and shallow water tables in the upper catchment. The revegetation of an area upgradient of wetland W051 was an important step in addressing the altered hydrology, however this level of intervention is insufficient to mitigate all impacts to the lower part of the catchment where biodiversity values and impacts are greatest.

Maximum potential hydrological benefit, through direct groundwater use, by deep-rooted perennial vegetation can only be achieved through strategic planting in areas with suitable soil structure, water quality, and depth to groundwater (Brooksbank et al., 2011b). For example, George et al (1999) observed >2 m lowering of the water table in discharge areas only where groundwater salinity is <5,000 mg/L TDS. Enhanced plant water use can also be achieved through active surface water management (Brooksbank et al., 2011b), or artificial irrigation (Lefroy et al., 2001).

Given the prevalence of relatively fresh and shallow groundwater conditions at Nabappie in the upper slopes near wetlands W735 and W736, and also at the break of slope near wetlands W026 and W051, there is opportunity to address excess recharge with deep-rooted perennial vegetation. There may also be potential for planting of perennial pastures or alternative high water use crops only if these options are available and economically viable. In the lower discharge areas however the presence of saline soils and shallow saline groundwater means that only minimal benefits are likely to be achieved through enhancing ET through revegetation (George et al., 1999). Consequently engineering solutions, such as groundwater pumping, surface water conveyances and groundwater interceptor drains, are likely to be more effective at addressing shallow, saline water tables and excess surface water flows. Engineering solutions although require environmentally responsible options for disposal of saline effluent (George and Frantom, 1990, George et al., 2005).

Even without well-defined biodiversity assets or precise knowledge of the ecological water requirements (EWR) for all individual species, estimates of the volume of groundwater required to be managed can be made. If we assume a critical depth to the water table of 1.8 mbgl is required in the lower discharge domain to disconnect groundwater from the process of bare soil ET and improve plant growth (Nulsen, 1981) and apply this to the depth to water in May 2009 (Figure 5-9) then about 8 ML of water needs to be removed. Disposal of this water directly into wetland W017 would raise the water level to ~0.30 m. In years of average or above average rainfall there will additional inflows to address. However there appears to be little additional storage capacity available within wetland W017, particularly in very wet years as observed in 1999, therefore W017 is unlikely to be a suitable disposal site. Therefore alternative solutions for effluent disposal or increased water use are required.

8.5 Future research opportunities and ongoing monitoring

A simple qualitative analysis was undertaken to assess the threat of altered hydrology on individual wetlands (Table 8-2), including an estimate of the level of certainty. A review of potential research opportunities and recommendations for future monitoring is provided in Table 8-3. Analysis of level of certainty indicates that the two areas which require greatest attention are; the continued gathering of water level and water quality data to determine long-term trends; and knowledge of the link between these hydrological/hydrochemical attributes and the biological assets. Knowledge of the EWR, specifically the tolerance of deep-rooted vegetation to the combined influence of waterlogging, salinity and nutrients, is the most pressing issue at the Nabappie wetland suite. Without adequate knowledge of the EWR then management targets cannot be set.

8.6 Conclusions

The hydrogeological functioning the Nabappie subcatchment and its high biodiversity wetland system were investigated using physical hydrological methods combined with hydrochemistry and stable water isotopes (δD and $\delta^{18}O$). As a result, the key drivers of altered hydrology, particularly excess water and solutes, were described.

The current discharge area (i.e. extent of open water or ET losses from shallow water tables) appears unable to meet recharge excess consequently rising shallow, saline water tables and increased groundwater discharge via wetlands will continue under the current climate and landuse regime. On an annual basis the aquifers in the lower discharge area appear to be in a quasi steady-state and are approaching full capacity, although are yet to reach a post-clearing hydrological equilibrium.

The deep, hypersaline semi-confined aquifer is more saline and isotopically enriched than the regional primary saline aquifer indicating the occurrence of reflux brines which redistribute dense, hypersaline water from wetland W017 to the underlying aquifers. Hydraulic and hydrochemical evidence and the presence of confining layers however appear to prevent migration of this hypersaline water further upgradient. Consequently the threat from altered hydrology upon the lower reaches of Nabappie originates from the local subcatchment and not from the regional primary saline aquifer. Thus there is potential for management intervention (such as revegetation and engineering) at the local subcatchment scale to mitigate threats to biodiversity assets.

An improved hydrogeochemical understanding of the Nabappie subcatchment is an important step in our understanding of not only the impact of altered hydrology at this site, but at many other similar sites in the BMNDRC. The social and economic feasibility of management now requires stakeholder consultation combined with further investigations which link this new hydrogeochemical understanding with the long-term health of the biodiversity assets of the Nabappie subcatchment.

Table 8-2. Summary of physical processes and a qualitative assessment of the probability and level of certainty of biological decline for the suite of wetlands in the Nabappie subcatchment.

ID	Threatening processes	Level of certainty	Probability of threat causing biodiversity loss.	Greatest knowledge gap(s)
*W735	Rising water tables Salinisation of GW and SW Eutrophication Increased hydroperiod	0.5 0.5 0.8 0.2	0.5 1.0 0.8 1.0	There is no historical biological or hydrogeological data in order to undertake a robust threat assessment.
*W736	Rising water tables Salinisation Eutrophication Increased hydroperiod	0.5 0.8 0.8 1.0	0.2 0.7 0.8 1.0	There is no historical biological or hydrogeological data in order to undertake a robust threat assessment.
*W026	Rising water tables Salinisation Eutrophication Increased hydroperiod	0.8 0.8 0.8 1.0	0.1 0.7 0.5 1.0	There is no historical biological or hydrogeological data in order to undertake a robust threat assessment.
*W051	Rising water tables Seasonal pulses of elevated solutes in GW Eutrophication Increased hydroperiod	0.5 0.5 0.8 0.8	1.0 0.3 0.2 1.0	Ecological water requirements of down-gradient vegetation unknown therefore difficult to make robust link between continued increases in GW levels and solutes.
W015	Rising water tables. Salinisation of shallow water table. Eutrophication Increased hydroperiod	1.0 1.0 0.5 1.0	1.0 1.0 0.5 1.0	Ecological water requirements of deep-rooted surrounding vegetation required to make robust link between continued increases in shallow water table levels and solutes. Ecological thresholds (solutes and hydroperiod) for aquatic biodiversity requires assessment.
W016	Rising water tables Salinisation Eutrophication Increased hydroperiod	1.0 1.0 0.7 1.0	1.0 1.0 0.7 1.0	Ecological thresholds (solutes and hydroperiod) for aquatic biodiversity requires assessment.
W017	Rising water tables Salinisation Eutrophication Increased hydroperiod	1.0 1.0 0.8 0.5	0.2 0.1 0.1 0.5	Fringing vegetation in lower areas has already undergone significant loss, or decline. The future risk to deep rooted vegetation along the eastern lunette is unknown.

***Wetland appeared after clearing therefore the biodiversity values are significantly different than pre-clearing.**

Table 8-3. Summary of the potential future research opportunities, ongoing monitoring, and the priority and ranking for these tasks in the Nabappie subcatchment.

Parameter	Descriptor	Specific detail	Reasoning	Priority	Rank
Climate	High resolution climate	High resolution (hourly or better), site specific climate data, particularly barometric pressure, relative humidity (RH), atmospheric temperature and wetland temperature. Data required to calculate normalised RH.	Site-specific climate data is essential for water balance analysis, specifically for determining evapotranspiration rates and the application of stable isotopes in mass-balance analysis.	High	1
Hydrological trends	Water levels	High resolution (hourly to 6-hourly) data in groundwater and wetlands	Groundwater data from specific sites can be used to assess recharge and evapotranspiration. Wetland levels required to asses responses to rainfall and surface water inflow events.	High	2
Hydrogeology	Geological mapping	Airborne, or ground-based remote sensing (radiometrics and magnetics).	An understanding of the occurrence of dolerite dykes and other structure controls, such as faults, is required to better understand the movement of groundwater in order to better target specific areas for recharge/discharge management.	Low	12
	Soil salinity	Catchment-scale and wetland-scale remote sensing mapping (EM) of soil salinity.	Airborne, or ground-based EM surveys can be used to better define the current extent of shallow saline soils, plus be used as a tool for long-term monitoring of change.	Low	14
	Aquifer properties	Investigation to determine vertical hydraulic conductivity and specific yield.	The accuracy of vertical discharge rates will be significantly improved through analysis of K_{vert}. Estimates of recharge based on hydrograph analysis will be significantly improved with site-specific data.	Medium	9
	Unsaturated zone processes	Bare soil evapotranspiration	Significant improvements can be made to the wetland-scale water balances with an improved understanding of evaporation processes occurring within shallow, saline, unsaturated soils proximal to wetlands.	Medium	5
	Density dependant flow	High-resolution (hourly to 6-hourly) logging of EC, temperature and water level within wetland W017 and bore BMC54d and BMC55d.	A sound understanding of reflux brines within the vicinity of W017, BMC54d and BMC55d, is required in order to determine the fate of solutes at the fresh/hypersaline groundwater interface.	Low	8
Hydrochemistry	Rainfall - major ion and stable isotope	Long-term, event-based, or cumulative (monthly) rainfall to be sampled and analysed for major ion chemistry and stable isotope (δD and δ18O).	Sufficient detail collected from this current study to apply local rainfall characteristics to mass-balance analysis, however a long-term analysis will provide higher certainty to analysis within the Nabappie subcatchment and the broader BMNDRC. Additionally, there are no recent, or long-term datasets in the wheatbelt.	Low	10
	Groundwater, surface water and wetlands - nutrients	Annual (end of winter), or monthly, analysis of organic and inorganic species of nitrogen and phosphorus.	Elevated nitrogen concentrations were identified in this study, particularly at BMC89ob. The source needs to be identified due to the potential negative impacts of eutrophication.	Low	11
	Groundwater, surface water and wetlands - major ions and stable isotopes	Regular (annual, seasonal, or monthly) analysis of major ions and stable isotopes in groundwater, surface water and wetlands.	A better long-term understanding of seasonal trends will be required to better understand the hydrological function of the wetlands and their associated groundwater.	Low	13
	Water quality	Groundwater - Annual field water quality (EC, pH, Redox, DO, temp)	Assess relative changes over time. High resolution (hourly, 6-hourly or monthly) may be required in order to assess influence of management actions.	Medium	7
		Wetlands - Regular (monthly) field water quality during winter and spring	The episodic and dynamic nature of the climate means that regular (ideally monthly) monitoring of water quality is required to better understand the importance of different water sources to individual wetlands.	High	3
		Surface water - Opportunistic field water quality from flowing water	Analysis of surface water flows can be used to better understand water and solute sources for specific areas.	Medium	6
Ecohydrology	Ecological water requirements	Determine the tolerances/thresholds and ecological water requirements of defined species, or communities of vegetation.	A sound understanding of the ecological water requirements, including tolerances to waterlogging, salinity and nutrients is required in order to set management targets. These targtets can be used to evaluate potential and implemented management actions.	High	4

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APPENDICES:

A HYDROGEOCHEMICAL INVESTIGATION OF THE SURFACE WATER AND GROUNDWATER INTERACTIONS OF A SEMI-ARID WETLAND SYSTEM, WESTERN AUSTRALIA

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B.Sc. (Hons).

A Thesis submitted in partial fulfil of the requirements for Master of Science (Hydrogeology) Research Project SCIE9722.

At the Faculty of Natural and Agricultural Sciences

The University of Western Australia

THE UNIVERSITY OF WESTERN AUSTRALIA

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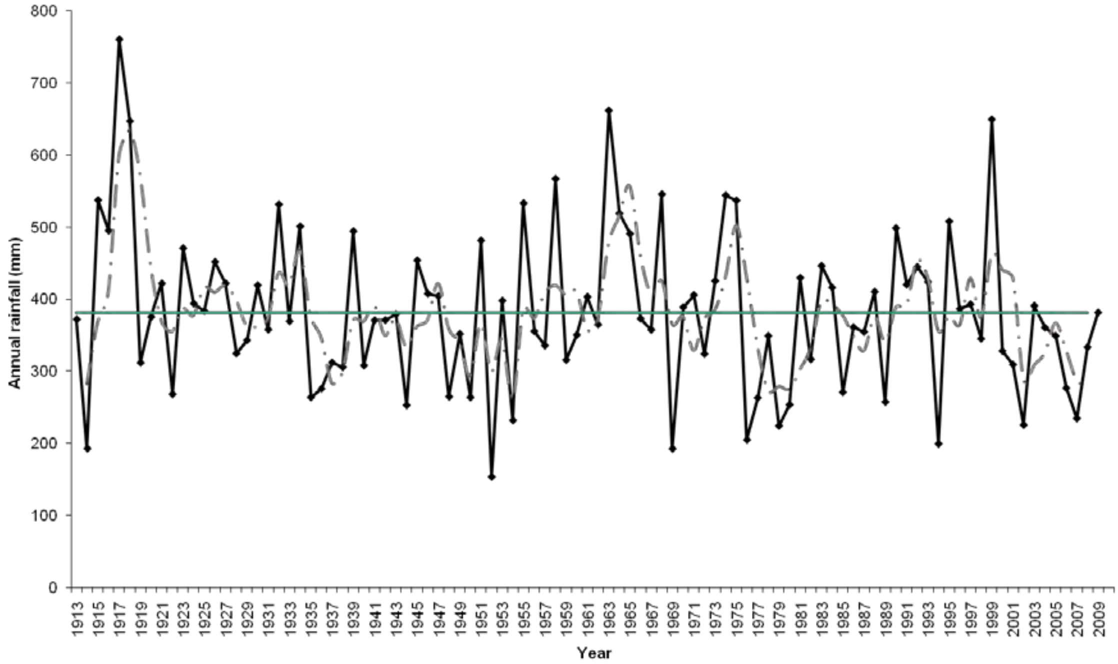
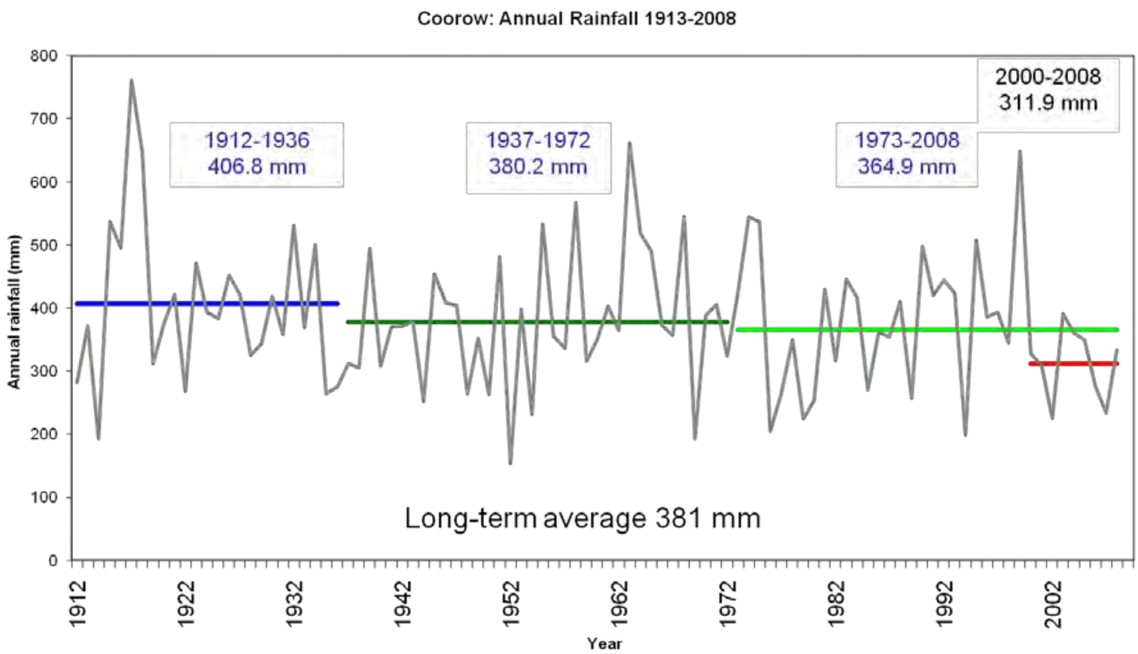
Appendix Chapter 3

Appendix 3A Long-term annual rainfall for Coorow post Office (BoM site 8037)



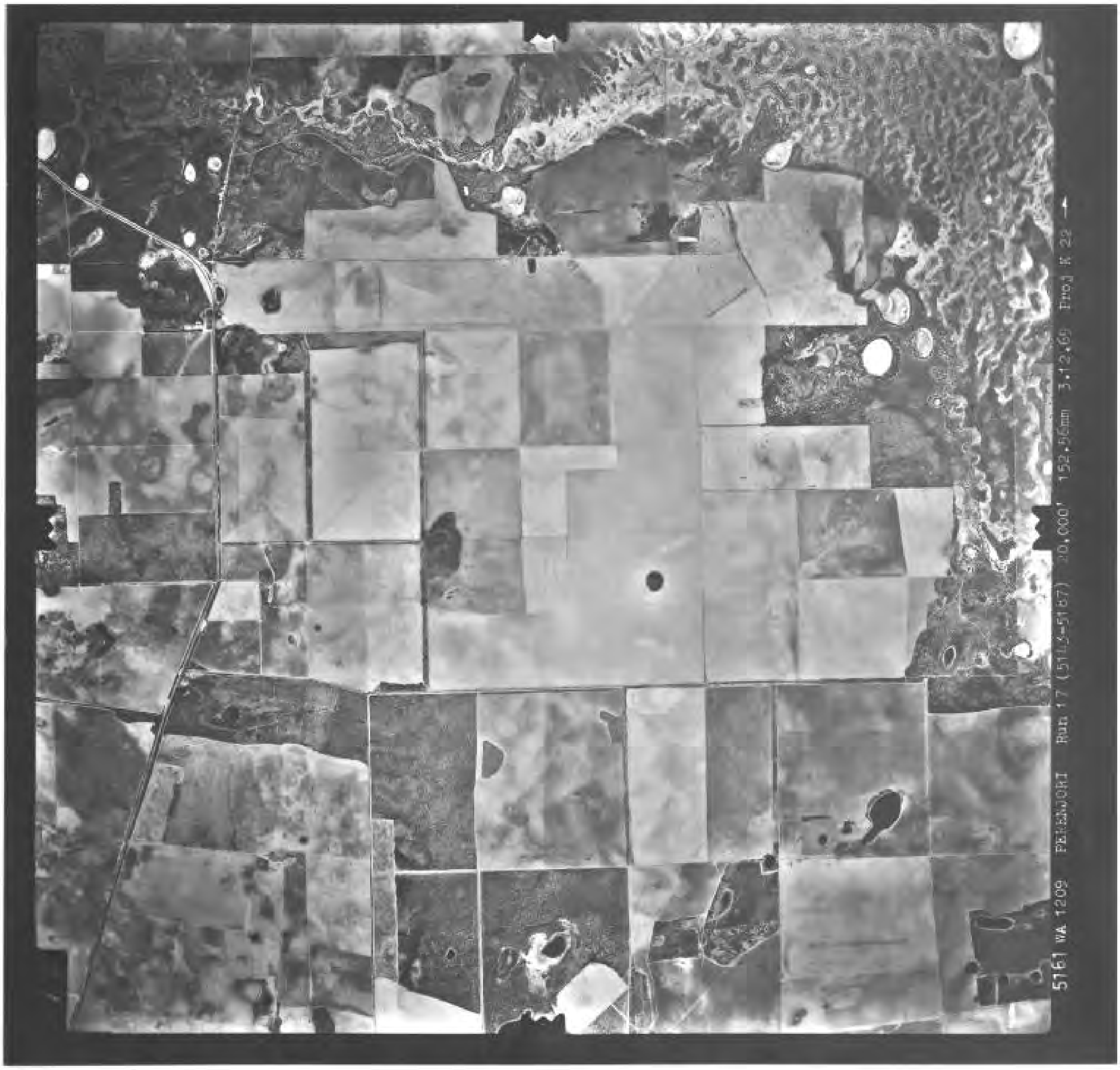
Appendix Fig 3-1. Annual rainfall at Coorow post Office (BOM site 8037) from 1913 to 2009. The black solid line represents the annual rainfall totals, the dotted grey line indicates the 10-year moving average and the solid green line the long-term average.



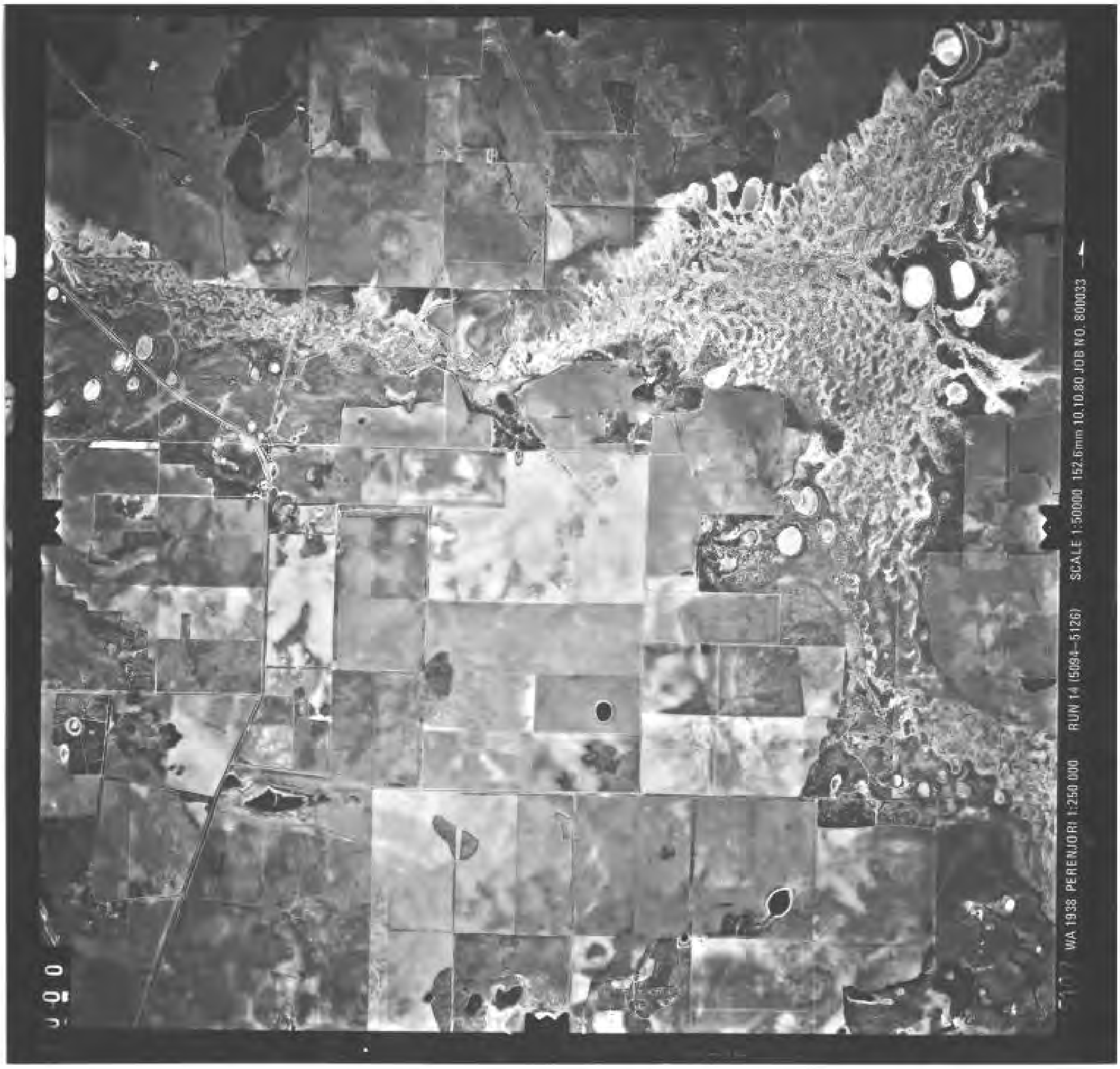
Appendix Fig 3-2. Annual rainfall at Coorow post Office (BOM site 8037) from 1913 to 2008. The grey solid line represents the annual rainfall totals, whilst the blue, dark green, light green lines represent the 35-year average rainfall whilst the red line represents the average rainfall from 2000 to 2008.

Appendix 3B Aerial photograph 26/08/1959

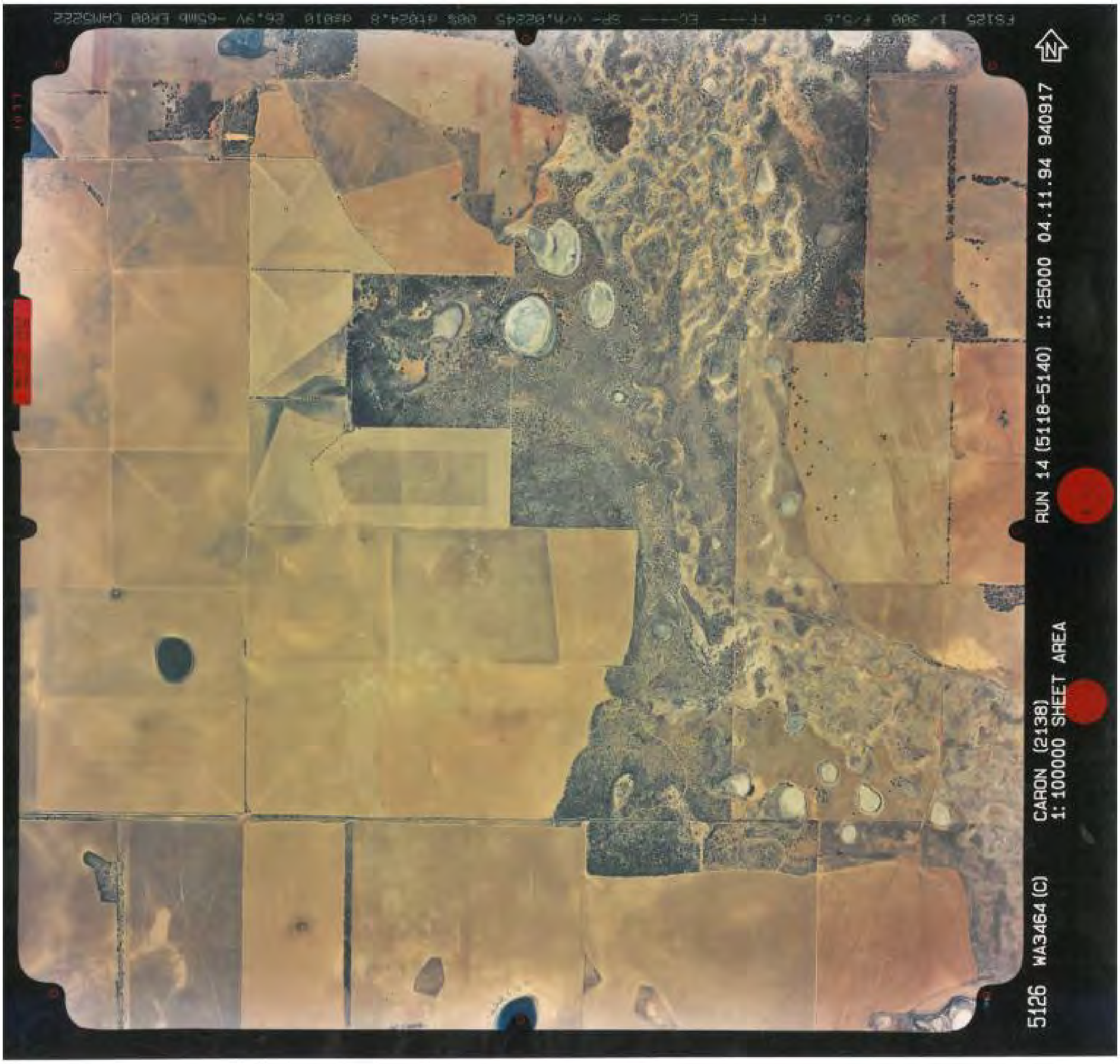
Appendix 3C Aerial photograph 03/12/1969



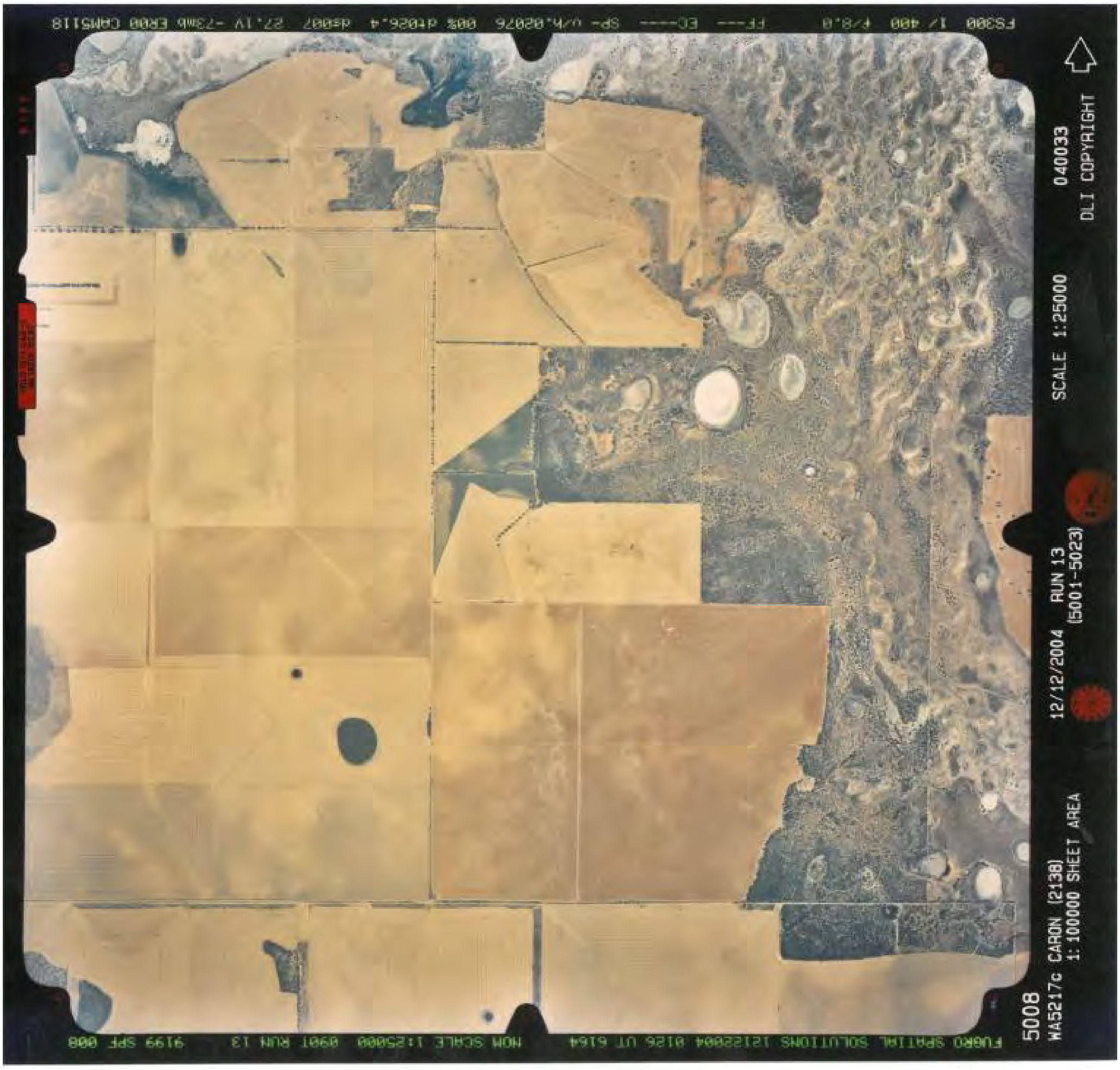
Appendix 3D Aerial photograph 10/10/1980



Appendix 3E   Aerial photograph 04/11/1994



Appendix 3F Aerial photograph 12/12/2004



Appendix Chapter 4

Appendix 4A Laboratory analysis reporting limits and uncertainty

Appendix Table 4-1. Reporting limits (mg/L) and list of major ion and nutrient analysed by the CCWA and ECU laboratories.

Analyte	April	May	June	July	August	September	October	November
Br	0.10	0.10	0.50	0.05	0.05	0.05	0.05	0.02
Ca	0.10	0.10	0.05	0.05	0.05	0.05	0.05	0.10
Cl	1.00	1.00	0.01	0.01	0.01	0.01	0.01	1.00
CO3	1.00	1.00	N/A	N/A	N/A	N/A	N/A	1.00
ECond	0.20	0.20	0.01	0.001	0.001	0.001	0.001	0.20
HCO3	1.00	1.00	N/A	N/A	N/A	N/A	N/A	1.00
K	0.10	0.10	0.50	0.50	0.50	0.50	0.50	0.10
Mg	0.10	0.10	0.05	0.05	0.05	0.05	0.05	0.10
Na	0.10	0.10	0.50	0.50	0.50	0.50	0.50	0.10
SO4_S	0.10	0.10	0.50	0.50	0.50	0.50	0.50	0.10
N_NO3	0.01	0.01	N/A	N/A	N/A	N/A	N/A	0.01
N_total	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.01
P_SR	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.01
P_total	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.01
TDS_180C	N/A	N/A	1.00	1.00	1.00	1.00	1.00	1.00
Lab Name	CCWA	CCWA	ECU	ECU	ECU	ECU	ECU	CCWA

Appendix Table 4-2. Chemistry Centre of Western Australia summary of measurement uncertainty

Analyte	Method Code	Limit of Reporting	Measurement Uncertainty
Units		mg/L	%
Br	iANIO1WAIC	0.1	21
Ca	iMET1WCICP	0.1	10.6
Cl	iCO1WCDA	1	7
CO3	iALK1WATI	1	10
ECond	iEC1WZSE	0.2	5
HCO3	iALK1WATI	1	10
K	iMET1WCICP	0.1	13.4
Mg	iMET1WCICP	0.1	10.8
N_NO3	iNTAN1WFIA	0.01	18
N_total	iNP1WTFIA	0.02	22
Na	iMET1WCICP	0.1	8.8
SO4_S	iMET1WCICP	0.1	8
SO4	iANIO1WAIC	0.1	5
P_SR	iP1WTFIA	0.01	16
P_total	iPP1WTFIA	0.01	18
TDS_180C	iSOL1WDGR	10	10
TDS sum	ixTDS_Sum	1	not applicable
aION_BAL	ixIONBAL	0.1	not applicable

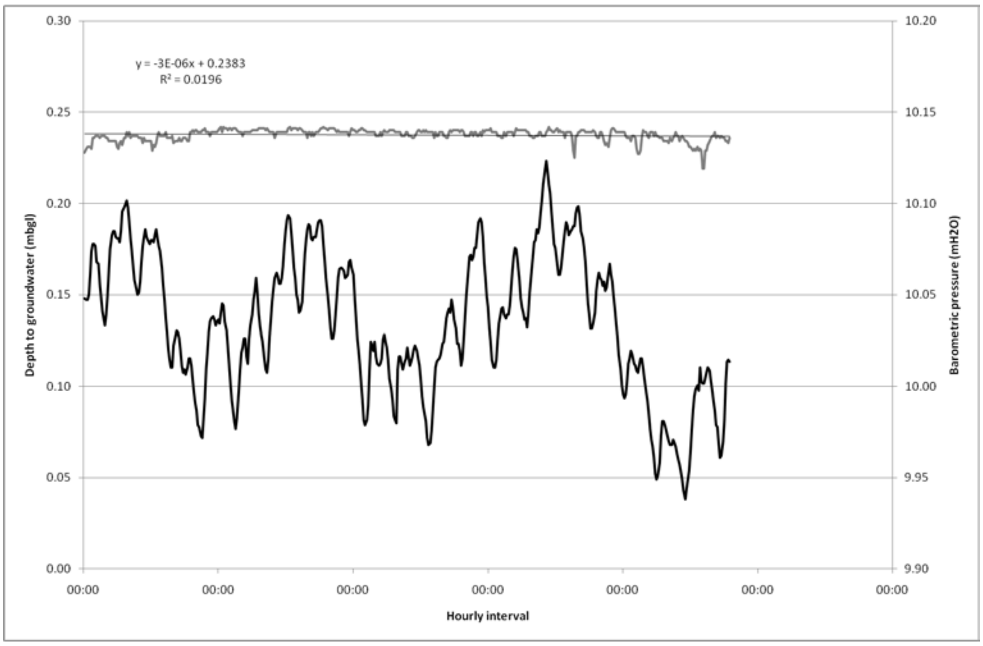
Appendix Chapter 5

Appendix 5A Hydraulic conductivity results

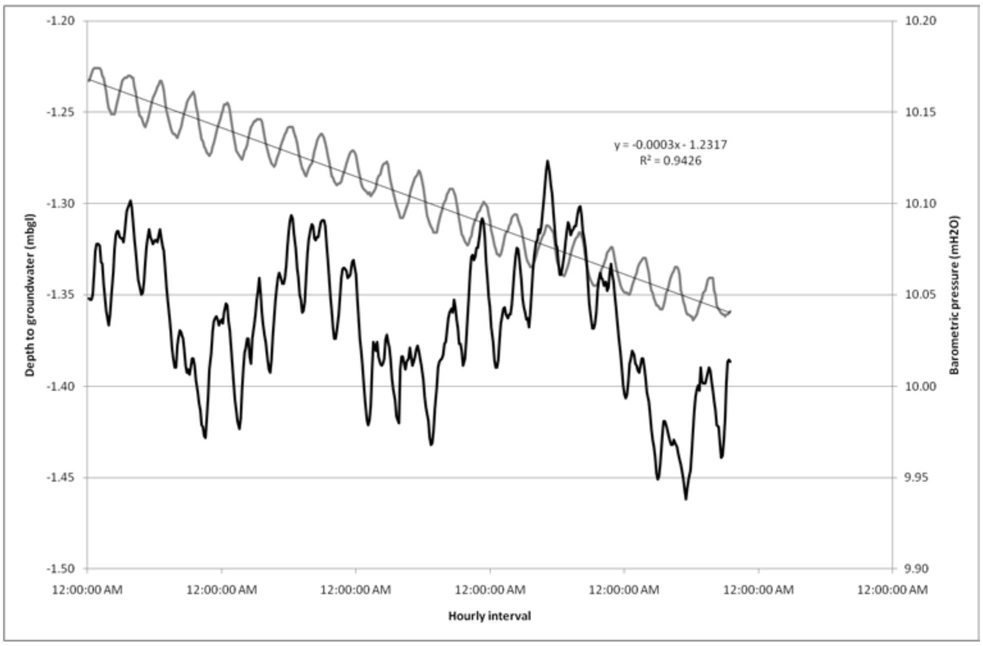
Appendix Table 5-1. Hydraulic conductivity derived from analysis of slug test data using the Bouwer and Rice (1976) method for unconfined aquifers with completely or partially penetrating wells.

Date	BMC54d K (m/day)	BMC55d K (m/day)	BMC56d K (m/day)	BMC56ob K (m/day)	BMC57d K (m/day)	BMC58d K (m/day)	BMC58i K (m/day)	BMC86ob K (m/day)	BMC87ob K (m/day)	BMC88ob K (m/day)	BMC89ob K (m/day)	BMC90ob K (m/day)	BMC91ob K (m/day)	BMC92ob K (m/day)
URS 2006				0.60000					0.02300	0.06600				
1/11/2008				0.08300							3.20000		0.79000	
1/12/2008				0.01300		0.00450	0.02200	0.01200	0.04100	0.01700	3.70000	0.13000	1.80000	
1/04/2009	0.00500	0.00064	0.00450	0.00640	0.00510		0.01600	0.01300	0.01300					0.00190
1/05/2009	0.00310	0.00069	0.00160	0.00490	0.00570		0.00770							0.00065
1/06/2009	0.00410	0.00074	0.00310	0.01200			0.01500							
1/07/2009	0.00420	0.00043	0.00160		0.00660		0.01900							
1/08/2009	0.00410	0.00056	0.00430		0.00680		0.02300							
1/09/2009	0.00410		0.00410		0.00750		0.01200							
1/10/2009	0.00470		0.00430		0.00640		0.01800							0.00120
1/11/2009	0.00410		0.00430		0.00640		0.01800							0.00082
Mean	**0.00418**	**0.00061**	**0.00348**	**0.02386**	**0.00636**	**0.00450**	**0.01674**	**0.01250**	**0.02700**	**0.01700**	**3.45000**	**0.13000**	**1.29500**	**0.00114**
Stdev	**0.00055**	**0.00012**	**0.00123**	**0.03324**	**0.00077**	**#DIV/0!**	**0.00478**	**0.00071**	**0.01980**	**#DIV/0!**	**0.35355**		**0.71418**	**0.00055**
Median	**0.00410**	**0.00064**	**0.00420**	**0.01200**	**0.00640**	**0.00450**	**0.01800**	**0.01250**	**0.02700**	**0.01700**	**3.45000**	**0.13000**	**1.29500**	**0.00101**
No. of observations	**8**	**5**	**8**	**5**	**7**	**1**	**9**	**2**	**2**	**1**	**2**	**1**	**2**	**4**
min	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.01	0.02	3.20	0.13	0.79	0.00
max	0.01	0.00	0.00	0.08	0.01	0.00	0.02	0.01	0.04	0.02	3.70	0.13	1.80	0.00

Appendix 5B Barometric pressure corrections



Appendix Fig 5-1. Hourly Mean Sea Level Pressure data (BOM site 8297, Dalwallinu) (black line) from 26/11/2009 to 15/12/2009 converted to 257.29 mAHD and metres H_2O for the study area versus hourly depth to groundwater at site BMC57d (grey line), which is a bore drilled to basement in a semi-confined aquifer.



Appendix Fig 5-2. Hourly Mean Sea Level Pressure data (BOM site 8297, Dalwallinu) (black line) from 26/11/2009 to 15/12/2009 converted to 257.29 mAHD and metres H_2O for the study area versus hourly depth to groundwater at site BMC94ob (grey line), which is a shallow bore drilled in an unconfined aquifer adjacent to a stand of perennial vegetation.

Appendix 5C Density corrected heads

Appendix Table 5-2. Average density corrected heads based on three reference elevations (zr) of 255.29 mAHD, 257.29mAHD, and 256.29 mAHD and an average density equal to measured density.

Site ID	Average h_i (mAHD)	Average Density (kg/m3)	StdDev (kg/m3)	h_{fr} (zr=250.29)	Difference (m)	h_{fr} (zr=255.29)	Difference (m)	h_{fr} (zr=256.29)	Difference (m)	h_{fr} (z_r=257.29)	Difference (m)	h_{fr} (z_r=257.29, Pa=0.9)	Difference (m)
BMC54D	257.31	1097.07	9.65	257.99	0.68	257.51	0.20	257.41	0.10	257.31	0.00	257.51	0.20
BMC55D	259.67	1049.85	2.63	260.14	0.47	259.89	0.22	259.84	0.17	259.79	0.12	259.97	0.30
BMC56D	262.26	1000.02	0.05	262.26	0.00	262.26	0.00	262.26	0.00	262.26	0.00	262.26	0.00
BMC56OB	259.91	1003.00	1.35	259.94	0.03	259.92	0.01	259.92	0.01	259.92	0.01	259.92	0.01
BMC57D	262.70	1000.00	0.00	262.70	0.00	262.70	0.00	262.70	0.00	262.70	0.00	262.70	0.00
BMC58I	268.11	1000.10	0.17	268.11	0.00	268.11	0.00	268.11	0.00	268.11	0.00	268.11	0.00
BMC64D*	260.70	1081.94	-	261.55	0.85	261.14	0.44	261.06	0.36	260.98	0.28	261.30	0.60
BMC64I*	260.42	1073.24	-	261.16	0.74	260.80	0.38	260.72	0.30	260.65	0.23	260.80	0.38
BMC64OB*	260.56	1066.41	-	261.24	0.68	260.91	0.35	260.84	0.28	260.78	0.22	260.79	0.23
BMC86OB	257.03	1059.09	-	257.43	0.40	257.13	0.10	257.07	0.04	257.01	-0.02	257.03	0.00
BMC87OB	257.30	1060.83	2.92	257.72	0.43	257.42	0.12	257.36	0.06	257.30	0.00	257.31	0.02
BMC88OB	257.26	1075.19	11.73	257.78	0.52	257.40	0.15	257.33	0.07	257.25	0.00	257.28	0.03
BMC89OB	270.38	1000.00	0.00	270.38	0.00	270.38	0.00	270.38	0.00	270.38	0.00	270.38	0.00
BMC90OB	267.87	1000.55	0.41	267.88	0.01	267.88	0.01	267.88	0.01	267.88	0.01	267.88	0.01
BMC91ob	-	-	-	-	-	-	-	-	-	-	-	-	-
BMC92OB	257.30	1134.71	64.82	258.24	0.94	257.56	0.26	257.43	0.13	257.30	-0.01	257.32	0.02
BMC93OB	258.78	1006.40	0.53	258.83	0.05	258.80	0.02	258.79	0.02	258.79	0.01	258.79	0.01
BMC94OB	267.32	1000.00	-	267.32	0.00	267.32	0.00	267.32	0.00	267.32	0.00	267.32	0.00
W015	262.27	1001.69	1.95	262.29	0.02	262.28	0.01	262.28	0.01	262.28	0.01	262.27	0.01
W016	259.57	1012.09	6.89	259.68	0.11	259.62	0.05	259.61	0.04	259.60	0.03	259.60	0.03
W017	257.39	1105.10	82.34	258.13	0.74	257.60	0.22	257.50	0.11	257.39	0.01	257.39	0.01
W026	-	-	-	-	-	-	-	-	-	-	-	-	-
W051	268.01	1001.15	1.47	268.03	0.02	268.03	0.01	268.03	0.01	268.02	0.01	268.02	0.01
W735	279.63	1001.10	0.34	279.66	0.03	279.66	0.03	279.66	0.03	279.65	0.02	279.65	0.02
W736	280.42	1009.74	1.45	280.72	0.29	280.67	0.24	280.66	0.23	280.65	0.22	280.63	0.20

* Bores sampled within the valley floor to represent the regional hypersaline aquifer.

Appendix 5D Density corrected heads continued.

Appendix Table 5-3. Monthly density corrected heads based on a reference elevation (zr) of 256.29 mAHD and an average density equal to measured density.

PR_KEY	Date	ELEV	DEPTHTO	Depth_mbgl	Raw Density (kg/m3)	Density (kg/m3)	Zi	Hi	Pa	Zr	Hfr	Difference	Comment
BMC54D	21/04/2009	258.81	21.59	1.65	1101.86	1101.86	237.22	257.16	1101.86	256.29	257.25	0.09	
BMC54D	19/05/2009	258.81	21.59	1.73	1114.81	1114.81	237.22	257.08	1114.81	256.29	257.17	0.09	
BMC54D	17/06/2009	258.81	21.59	1.74	1082.33	1082.33	237.22	257.07	1082.33	256.29	257.13	0.06	
BMC54D	22/07/2009	258.81	21.59	1.56	1095.74	1095.74	237.22	257.25	1095.74	256.29	257.34	0.09	
BMC54D	27/08/2009	258.81	21.59	1.22	1093.23	1093.23	237.22	257.59	1093.23	256.29	257.71	0.12	
BMC54D	25/09/2009	258.81	21.59	1.28	1095.50	1095.50	237.22	257.53	1095.50	256.29	257.65	0.12	
BMC54D	20/10/2009	258.81	21.59	1.37	1090.33	1090.33	237.22	257.44	1090.33	256.29	257.54	0.10	
BMC54D	24/11/2009	258.81	21.59	1.43	1102.73	1102.73	237.22	257.38	1102.73	256.29	257.49	0.11	
BMC55D	21/04/2009	260.12	38.62	0.58	1049.38	1049.38	221.50	259.54	1049.38	256.29	259.70	0.16	
BMC55D	19/05/2009	260.12	38.62	0.73	1053.54	1053.54	221.50	259.39	1053.54	256.29	259.56	0.17	
BMC55D	17/06/2009	260.12	38.62	0.76	1044.86	1044.86	221.50	259.36	1044.86	256.29	259.50	0.14	
BMC55D	21/07/2009	260.12	38.62	0.43	1050.70	1050.70	221.50	259.69	1050.70	256.29	259.86	0.17	
BMC55D	26/08/2009	260.12	38.62	0.12	1049.70	1049.70	221.50	260.00	1049.70	256.29	260.18	0.18	TDS estimated/broken pump
BMC55D	25/09/2009	260.12	38.62	0.21	1051.48	1051.48	221.50	259.91	1051.48	256.29	260.10	0.19	
BMC55D	20/10/2009	260.12	38.62	0.33	1047.81	1047.81	221.50	259.79	1047.81	256.29	259.96	0.17	
BMC55D	24/11/2009	260.12	38.62	0.44	1051.30	1051.30	221.50	259.68	1051.30	256.29	259.85	0.17	
BMC56D	21/04/2009	260.62	24.79	-1.47	999.21	1000.00	235.83	262.09	1000.00	256.29	262.09	0.00	
BMC56D	19/05/2009	260.62	24.79	-1.45	999.21	1000.00	235.83	262.07	1000.00	256.29	262.07	0.00	
BMC56D	17/06/2009	260.62	24.79	-1.46	999.51	1000.00	235.83	262.08	1000.00	256.29	262.08	0.00	
BMC56D	21/07/2009	260.62	24.79	-1.58	1000.15	1000.15	235.83	262.20	1000.15	256.29	262.20	0.00	
BMC56D	26/08/2009	260.62	24.79	-1.77	999.56	1000.00	235.83	262.39	1000.00	256.29	262.39	0.00	
BMC56D	24/09/2009	260.62	24.79	-1.81	999.54	1000.00	235.83	262.43	1000.00	256.29	262.43	0.00	
BMC56D	20/10/2009	260.62	24.79	-1.81	999.50	1000.00	235.83	262.43	1000.00	256.29	262.43	0.00	
BMC56D	24/11/2009	260.62	24.79	-1.77	999.28	1000.00	235.83	262.39	1000.00	256.29	262.39	0.00	
BMC56OB	21/04/2009	260.58	5.82	1.06	1000.68	1000.68	254.76	259.52	1000.68	256.29	259.52	0.00	
BMC56OB	19/05/2009	260.58	5.82	1.09	1001.75	1001.75	254.76	259.49	1001.75	256.29	259.50	0.01	
BMC56OB	17/06/2009	260.58	5.82	0.87	1002.00	1002.00	254.76	259.71	1002.00	256.29	259.72	0.01	
BMC56OB	21/07/2009	260.58	5.82	0.44	1003.91	1003.91	254.76	260.14	1003.91	256.29	260.16	0.02	
BMC56OB	26/08/2009	260.58	5.82	0.34	1003.66	1003.66	254.76	260.24	1003.66	256.29	260.25	0.01	
BMC56OB	24/09/2009	260.58	5.82	0.46	1004.54	1004.54	254.76	260.12	1004.54	256.29	260.14	0.02	
BMC56OB	20/10/2009	260.58	5.82	0.50	1003.93	1003.93	254.76	260.08	1003.93	256.29	260.09	0.01	
BMC56OB	24/11/2009	260.58	5.82	0.60	1003.52	1003.52	254.76	259.98	1003.52	256.29	259.99	0.01	
BMC57D	21/04/2009	262.55	25.42	0.05	998.52	1000.00	237.13	262.50	1000.00	256.29	262.50	0.00	
BMC57D	19/05/2009	262.55	25.42	-0.01	999.12	1000.00	237.13	262.56	1000.00	256.29	262.56	0.00	
BMC57D	16/06/2009	262.55	25.42	-0.02	999.38	1000.00	237.13	262.57	1000.00	256.29	262.57	0.00	
BMC57D	21/07/2009	262.55	25.42	-0.12	999.61	1000.00	237.13	262.67	1000.00	256.29	262.67	0.00	
BMC57D	26/08/2009	262.55	25.42	-0.28	998.65	1000.00	237.13	262.83	1000.00	256.29	262.83	0.00	
BMC57D	24/09/2009	262.55	25.42	-0.30	999.10	1000.00	237.13	262.85	1000.00	256.29	262.85	0.00	
BMC57D	20/10/2009	262.55	25.42	-0.30	999.28	1000.00	237.13	262.85	1000.00	256.29	262.85	0.00	
BMC57D	24/11/2009	262.55	25.42	-0.25	998.71	1000.00	237.13	262.80	1000.00	256.29	262.80	0.00	

PR_KEY	Date	ELEV	DEPTHTO	Depth_mbgl	Raw Density (kg/m3)	Density (kg/m3)	Zi	Hi	Pa	Zr	Hfr	Difference	Comment
BMC58I	21/04/2009	269.80	13.31	1.98	999.96	1000.00	256.49	267.82	1000.00	256.29	267.82	0.00	
BMC58I	18/05/2009	269.80	13.31	1.93	999.96	1000.00	256.49	267.87	1000.00	256.29	267.87	0.00	
BMC58I	16/06/2009	269.80	13.31	1.82	999.98	1000.00	256.49	267.98	1000.00	256.29	267.98	0.00	
BMC58I	21/07/2009	269.80	13.31	1.42	1000.38	1000.38	256.49	268.38	1000.38	256.29	268.38	0.00	
BMC58I	26/08/2009	269.80	13.31	1.54	999.91	1000.00	256.49	268.26	1000.00	256.29	268.26	0.00	
BMC58I	24/09/2009	269.80	13.31	1.55	1000.06	1000.06	256.49	268.25	1000.06	256.29	268.25	0.00	
BMC58I	19/10/2009	269.80	13.31	1.61	1000.38	1000.38	256.49	268.19	1000.38	256.29	268.19	0.00	
BMC58I	24/11/2009	269.80	13.31	1.69	999.40	1000.00	256.49	268.11	1000.00	256.29	268.11	0.00	
BMC64D	19/05/2009	261.70	43.03	1.00	1081.94	1081.94	218.67	260.70	1081.94	256.29	261.06	0.36	
BMC64I	19/05/2009	261.64	24.75	1.22	1073.24	1073.24	236.89	260.42	1073.24	256.29	260.72	0.30	
BMC64OB	19/05/2009	261.67	5.92	1.11	1066.41	1066.41	255.75	260.56	1066.41	256.29	260.84	0.28	
BMC86OB	22/04/2009	258.33	4.29	1.30	1059.09	1059.09	254.04	257.03	1059.09	256.29	257.07	0.04	
BMC87OB	22/04/2009	258.30	3.45	1.25	1058.06	1058.06	254.85	257.05	1058.06	256.29	257.09	0.04	
BMC87OB	19/05/2009	258.30	3.45	1.32	1062.91	1062.91	254.85	256.98	1062.91	256.29	257.02	0.04	
BMC87OB	21/07/2009	258.30	3.45	1.00	1058.85	1058.85	254.85	257.30	1058.85	256.29	257.36	0.06	
BMC87OB	27/08/2009	258.30	3.45	0.83	1060.73	1060.73	254.85	257.47	1060.73	256.29	257.54	0.07	
BMC87OB	24/09/2009	258.30	3.45	0.83	1059.85	1059.85	254.85	257.47	1059.85	256.29	257.54	0.07	
BMC87OB	20/10/2009	258.30	3.45	0.88	1059.00	1059.00	254.85	257.42	1059.00	256.29	257.49	0.07	
BMC87OB	24/11/2009	258.30	3.45	0.92	1066.38	1066.38	254.85	257.38	1066.38	256.29	257.45	0.07	
BMC88OB	22/04/2009	258.16	5.38	1.24	1084.56	1084.56	252.78	256.92	1084.56	256.29	256.97	0.05	
BMC88OB	19/05/2009	258.16	5.38	1.31	1092.29	1092.29	252.78	256.85	1092.29	256.29	256.90	0.05	
BMC88OB	21/07/2009	258.16	5.38	0.76	1079.31	1079.31	252.78	257.40	1079.31	256.29	257.49	0.09	
BMC88OB	27/08/2009	258.16	5.38	0.65	1059.39	1059.39	252.78	257.51	1059.39	256.29	257.58	0.07	
BMC88OB	24/09/2009	258.16	5.38	0.72	1070.74	1070.74	252.78	257.44	1070.74	256.29	257.52	0.08	
BMC88OB	20/10/2009	258.16	5.38	0.80	1062.79	1062.79	252.78	257.36	1062.79	256.29	257.43	0.07	
BMC88OB	24/11/2009	258.16	5.38	0.85	1077.28	1077.28	252.78	257.31	1077.28	256.29	257.39	0.08	
BMC89OB	20/04/2009	273.74	4.50	3.47	997.31	1000.00	269.24	270.27	1000.00	256.29	270.27	0.00	
BMC89OB	18/05/2009	273.74	4.50	3.47	997.51	1000.00	269.24	270.27	1000.00	256.29	270.27	0.00	
BMC89OB	15/06/2009	273.74	4.50	3.43	998.06	1000.00	269.24	270.31	1000.00	256.29	270.31	0.00	
BMC89OB	21/07/2009	273.74	4.50	3.36	998.51	1000.00	269.24	270.38	1000.00	256.29	270.38	0.00	
BMC89OB	26/08/2009	273.74	4.50	3.29	998.70	1000.00	269.24	270.45	1000.00	256.29	270.45	0.00	
BMC89OB	24/09/2009	273.74	4.50	3.27	998.61	1000.00	269.24	270.47	1000.00	256.29	270.47	0.00	
BMC89OB	19/10/2009	273.74	4.50	3.28	998.51	1000.00	269.24	270.46	1000.00	256.29	270.46	0.00	
BMC89OB	24/11/2009	273.74	4.50	3.30	998.17	1000.00	269.24	270.44	1000.00	256.29	270.44	0.00	
BMC90OB	21/04/2009	268.55	2.17	0.99	999.43	1000.00	266.38	267.56	1000.00	256.29	267.56	0.00	
BMC90OB	18/05/2009	268.55	2.17	0.93	1000.00	1000.00	266.38	267.62	1000.00	256.29	267.62	0.00	
BMC90OB	16/06/2009	268.55	2.17	0.85	1000.65	1000.65	266.38	267.71	1000.65	256.29	267.71	0.01	
BMC90OB	21/07/2009	268.55	2.17	0.49	1000.81	1000.81	266.38	268.06	1000.81	256.29	268.07	0.01	
BMC90OB	26/08/2009	268.55	2.17	0.41	1001.10	1001.10	266.38	268.14	1001.10	256.29	268.15	0.01	
BMC90OB	24/09/2009	268.55	2.17	0.45	1000.82	1000.82	266.38	268.10	1000.82	256.29	268.11	0.01	
BMC90OB	19/10/2009	268.55	2.17	0.59	1000.72	1000.72	266.38	267.96	1000.72	256.29	267.97	0.01	
BMC90OB	24/11/2009	268.55	2.17	0.70	1000.29	1000.29	266.38	267.85	1000.29	256.29	267.85	0.00	

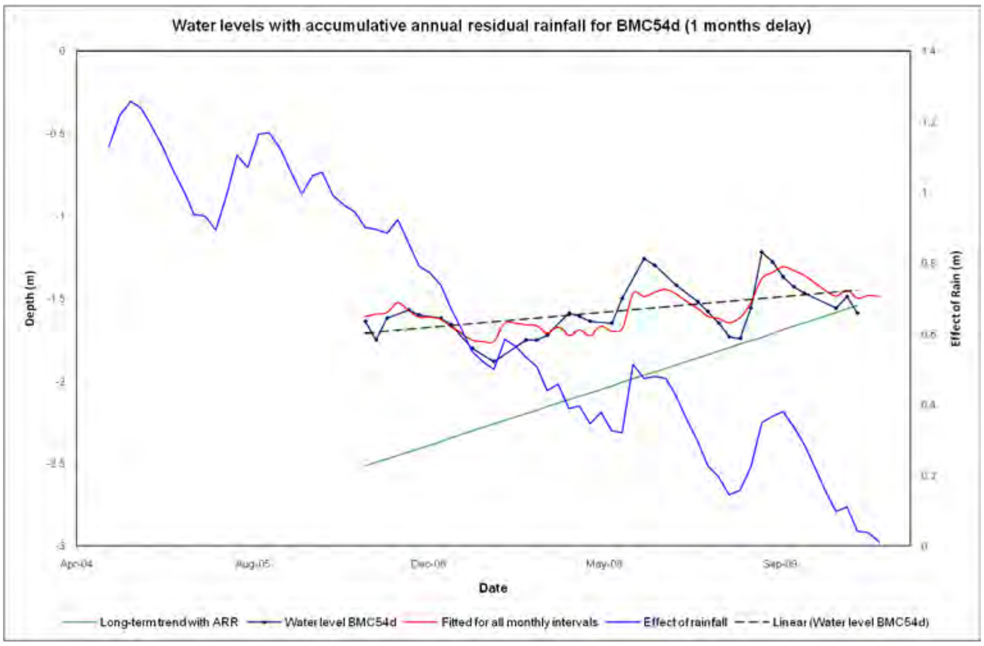
PR_KEY	Date	ELEV	DEPTHTO	Depth_mbgl	Raw Density (kg/m3)	Density (kg/m3)	Zi	Hi	Pa	Zr	Hfr	Difference	Comment
BMC92OB	22/04/2009	257.29	2.00	-0.02	1185.36	1185.36	255.29	257.31	1185.36	256.29	257.50	0.19	
BMC92OB	19/05/2009	257.29	2.00	0.43	1184.46	1184.46	255.29	256.86	1184.46	256.29	256.97	0.11	
BMC92OB	27/08/2009	257.29	2.00	-0.20	1040.12	1040.12	255.29	257.49	1040.12	256.29	257.54	0.05	WQ not measured; values based on density from W017
BMC92OB	25/09/2009	257.29	2.00	-0.16	1077.47	1077.47	255.29	257.45	1077.47	256.29	257.54	0.09	
BMC92OB	20/10/2009	257.29	2.00	-0.09	1125.61	1125.61	255.29	257.38	1125.61	256.29	257.52	0.14	
BMC92OB	24/11/2009	257.29	2.00	-0.03	1195.24	1195.24	255.29	257.32	1195.24	256.29	257.52	0.20	
BMC93OB	20/05/2009	259.44	2.11	1.14	1005.80	1005.80	257.33	258.30	1005.80	256.29	258.31	0.01	
BMC93OB	20/10/2009	259.44	2.11	0.22	1006.64	1006.64	257.33	259.22	1006.64	256.29	259.24	0.02	
BMC93OB	24/11/2009	259.44	2.11	0.63	1006.78	1006.78	257.33	258.81	1006.78	256.29	258.83	0.02	
BMC94OB	22/07/2009	268.37	1.92	1.05	999.72	1000.00	266.45	267.32	1000.00	256.29	267.32	0.00	
W015	21/04/2009	262.10	0.00	-0.17	998.76	1000.00	262.10	262.27	1000.00	256.29	262.27	0.00	
W015	19/05/2009	262.10	0.00	-0.18	1001.15	1001.15	262.10	262.28	1001.15	256.29	262.29	0.01	
W015	16/06/2009	262.10	0.00	-0.16	1002.07	1002.07	262.10	262.26	1002.07	256.29	262.27	0.01	
W015	21/07/2009	262.10	0.00	-0.18	1005.98	1005.98	262.10	262.28	1005.98	256.29	262.32	0.04	
W015	26/08/2009	262.10	0.00	-0.17	1002.58	1002.58	262.10	262.27	1002.58	256.29	262.28	0.02	
W015	24/09/2009	262.10	0.00	-0.16	1000.73	1000.73	262.10	262.26	1000.73	256.29	262.26	0.00	
W015	20/10/2009	262.10	0.00	-0.16	1001.00	1001.00	262.10	262.26	1001.00	256.29	262.27	0.01	
W015	24/11/2009	262.10	0.00	-0.16	999.73	1000.00	262.10	262.26	1000.00	256.29	262.26	0.00	
W016	21/07/2009	259.44	0.00	-0.10	1006.60	1006.60	259.44	259.54	1006.60	256.29	259.56	0.02	
W016	26/08/2009	259.44	0.00	-0.17	1009.86	1009.86	259.44	259.61	1009.86	256.29	259.64	0.03	
W016	25/09/2009	259.44	0.00	-0.13	1019.82	1019.82	259.44	259.57	1019.82	256.29	259.63	0.07	
W017	17/06/2009	257.29	0.00	-0.01	1144.52	1144.52	257.29	257.30	1144.52	256.29	257.44	0.15	
W017	22/07/2009	257.29	0.00	-0.15	1033.79	1033.79	257.29	257.44	1033.79	256.29	257.48	0.04	
W017	27/08/2009	257.29	0.00	-0.17	1040.12	1040.12	257.29	257.46	1040.12	256.29	257.51	0.05	
W017	25/09/2009	257.29	0.00	-0.11	1077.47	1077.47	257.29	257.40	1077.47	256.29	257.48	0.09	
W017	20/10/2009	257.29	0.00	-0.04	1229.57	1229.57	257.29	257.33	1229.57	256.29	257.57	0.24	
W051	20/04/2009	267.75	0.00	0.00	998.98	1000.00	267.75	267.75	1000.00	256.29	267.75	0.00	
W051	18/05/2009	267.75	0.00	0.20	1000.94	1000.94	267.75	267.55	1000.94	256.29	267.56	0.01	
W051	16/06/2009	267.75	0.00	-0.08	1004.45	1004.45	267.75	267.83	1004.45	256.29	267.88	0.05	
W051	21/07/2009	267.75	0.00	-0.55	1001.57	1001.57	267.75	268.30	1001.57	256.29	268.32	0.02	
W051	26/08/2009	267.75	0.00	-0.58	1001.32	1001.32	267.75	268.33	1001.32	256.29	268.35	0.02	
W051	24/09/2009	267.75	0.00	-0.54	999.90	1000.00	267.75	268.29	1000.00	256.29	268.29	0.00	
W051	19/10/2009	267.75	0.00	-0.34	999.81	1000.00	267.75	268.09	1000.00	256.29	268.09	0.00	
W051	24/11/2009	267.75	0.00	-0.18	1000.96	1000.96	267.75	267.93	1000.96	256.29	267.94	0.01	
W735	18/05/2009	279.38	0.00	-0.35	1000.76	1000.76	279.38	279.73	1000.76	256.29	279.75	0.02	
W735	17/06/2009	279.38	0.00	-0.20	1001.09	1001.09	279.38	279.58	1001.09	256.29	279.61	0.03	
W735	22/10/2009	279.38	0.00	-0.20	1001.44	1001.44	279.38	279.58	1001.44	256.29	279.61	0.03	
W736	22/04/2009	278.87	0.00	-1.50	1011.51	1011.51	278.87	280.37	1011.51	256.29	280.65	0.28	
W736	18/05/2009	278.87	0.00	-1.50	1009.65	1009.65	278.87	280.37	1009.65	256.29	280.61	0.23	
W736	17/06/2009	278.87	0.00	-1.50	1009.86	1009.86	278.87	280.37	1009.86	256.29	280.61	0.24	
W736	22/10/2009	278.87	0.00	-1.50	1007.95	1007.95	278.87	280.37	1007.95	256.29	280.57	0.19	

Appendix 5E Hydrograph Analysis and Time Trends (HARTT) rainfall (AMRR) results

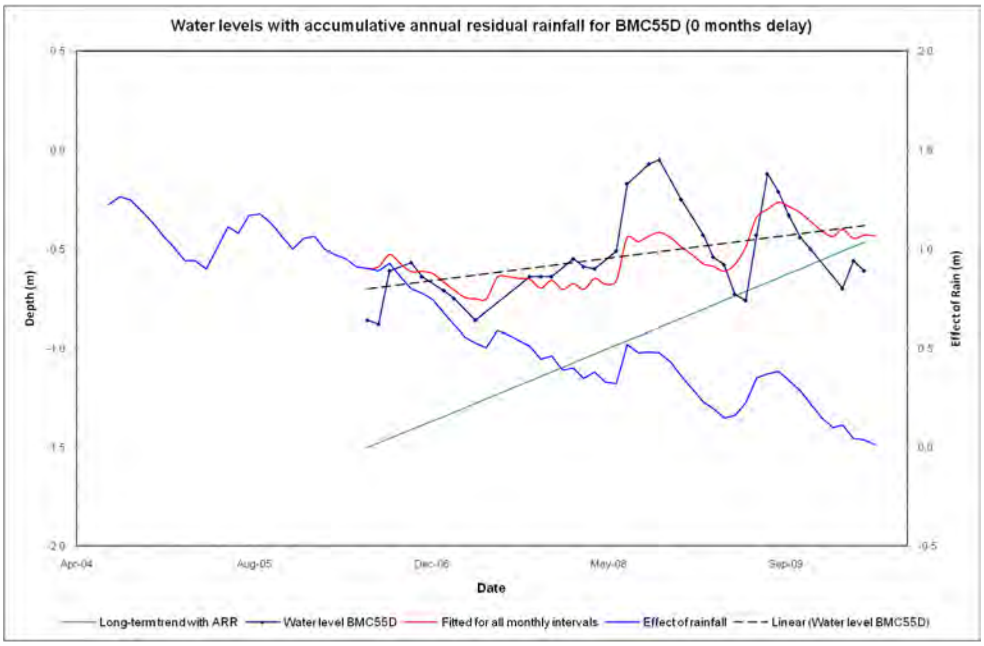
Appendix Fig 5-1. Accumulative monthly residual rainfall (AMRR) from 1912 to 2010 for Coorow (BoM site 8037). Values calculated as the sum of the monthly total minus the long-term monthly average.

Appendix Fig 5-2. Accumulative monthly residual rainfall (AMRR) from 1911 to 2010 for Coorow (BoM site 8067). Values calculated as the sum of the monthly total minus the long-term monthly average.

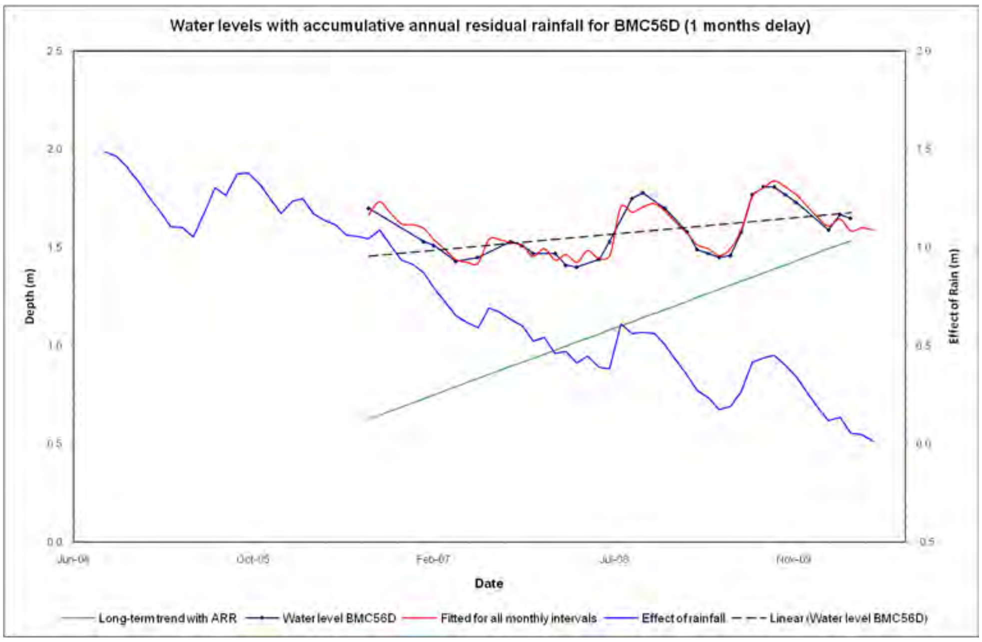
Appendix 5F   HARTT analysis results



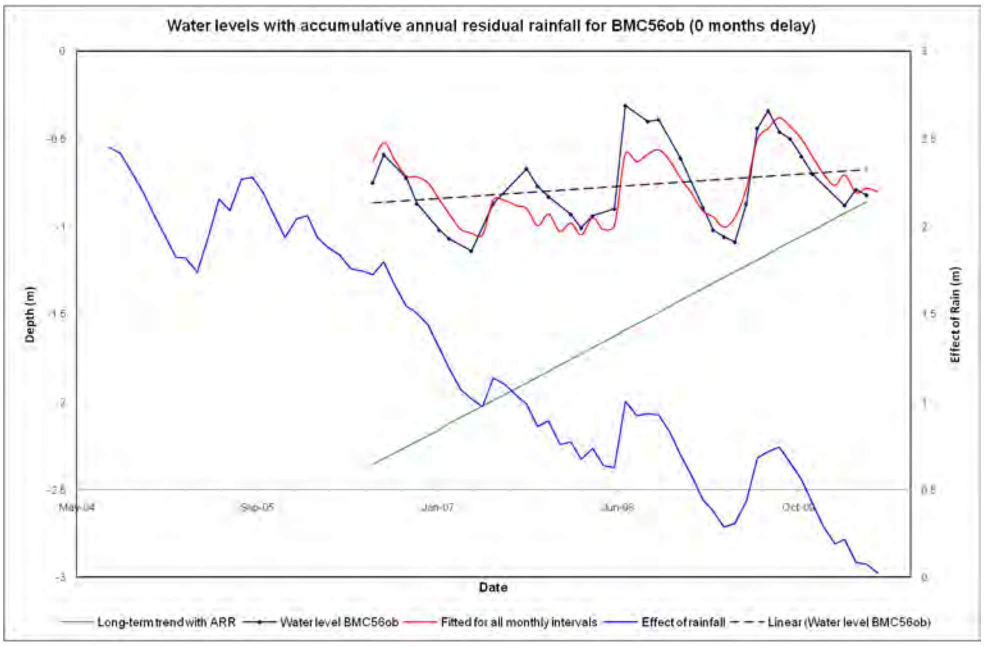
Appendix Fig 5-3. Groundwater levels for BMC54d and the long-term trend fitted using HARTT analysis to the accumulative annual residual rainfall (1 month delay) of the Coorow Post Office (BoM site 8037) and the linear trend.



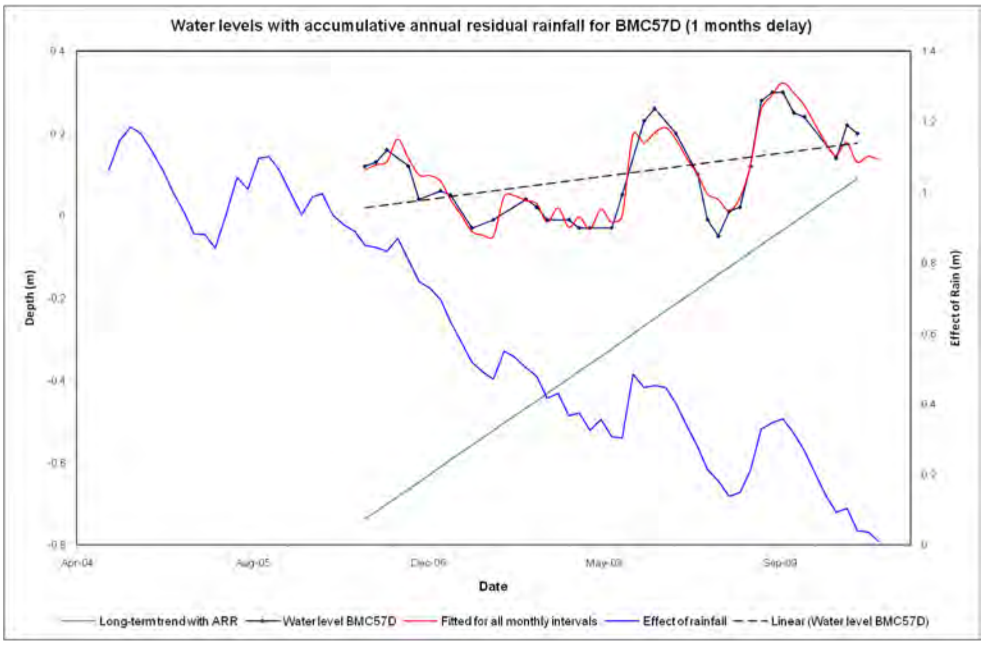
Appendix Fig 5-4. Groundwater levels for BMC55d and the long-term trend fitted using HARTT analysis to the accumulative annual residual rainfall (0 months delay) of the Coorow Post Office (BoM site 8037) and the linear trend.



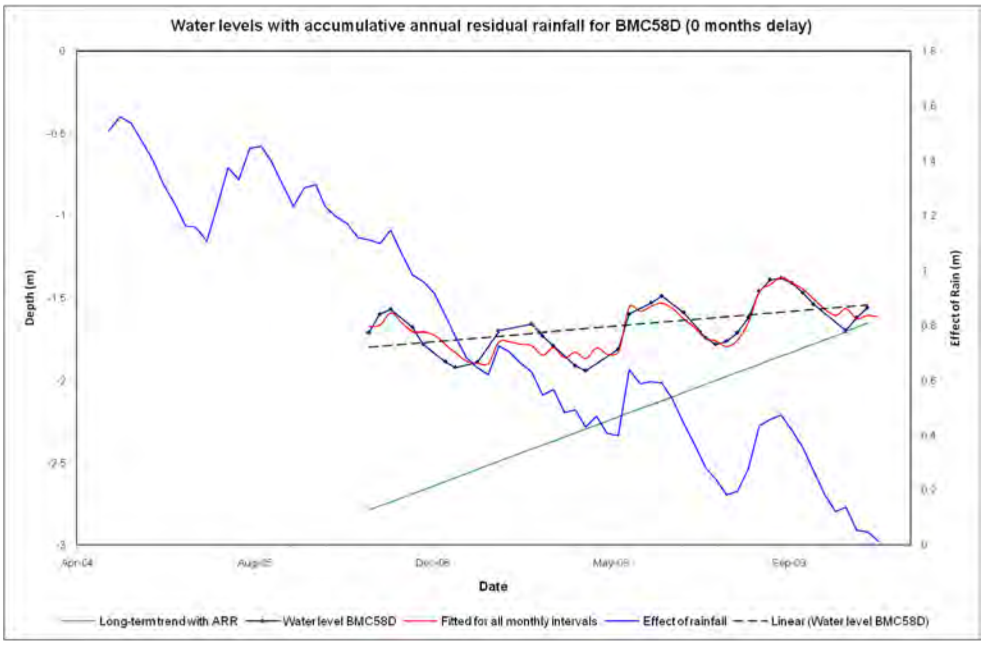
Appendix Fig 5-5. Groundwater levels for BMC56d and the long-term trend fitted using HARTT analysis to the accumulative annual residual rainfall (1 month delay) of the Coorow Post Office (BoM site 8037) and the linear trend.



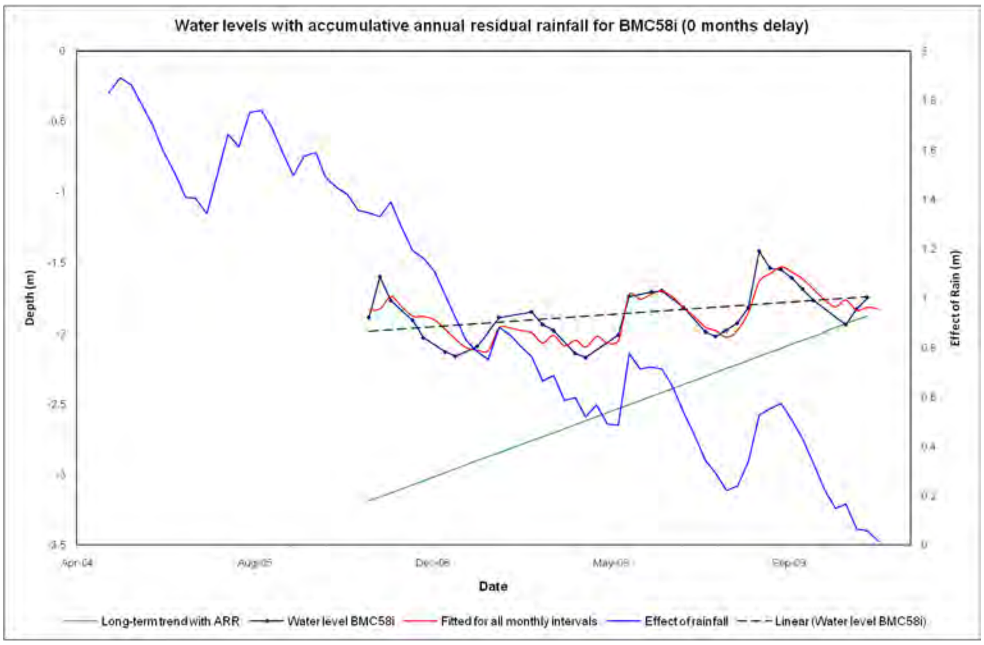
Appendix Fig 5-6. Groundwater levels for BMC56ob and the long-term trend fitted using HARTT analysis to the accumulative annual residual rainfall (0 months delay) of the Coorow Post Office (BoM site 8037) and the linear trend.



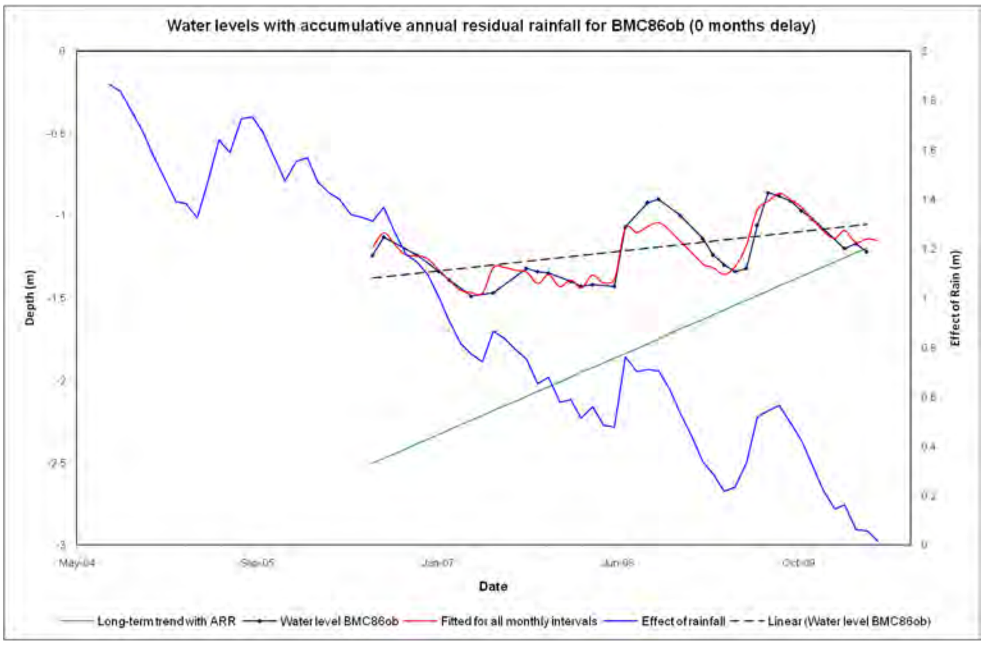
Appendix Fig 5-7. Groundwater levels for BMC57d and the long-term trend fitted using HARTT analysis to the accumulative annual residual rainfall (1 month delay) of the Coorow Post Office (BoM site 8037) and the linear trend.



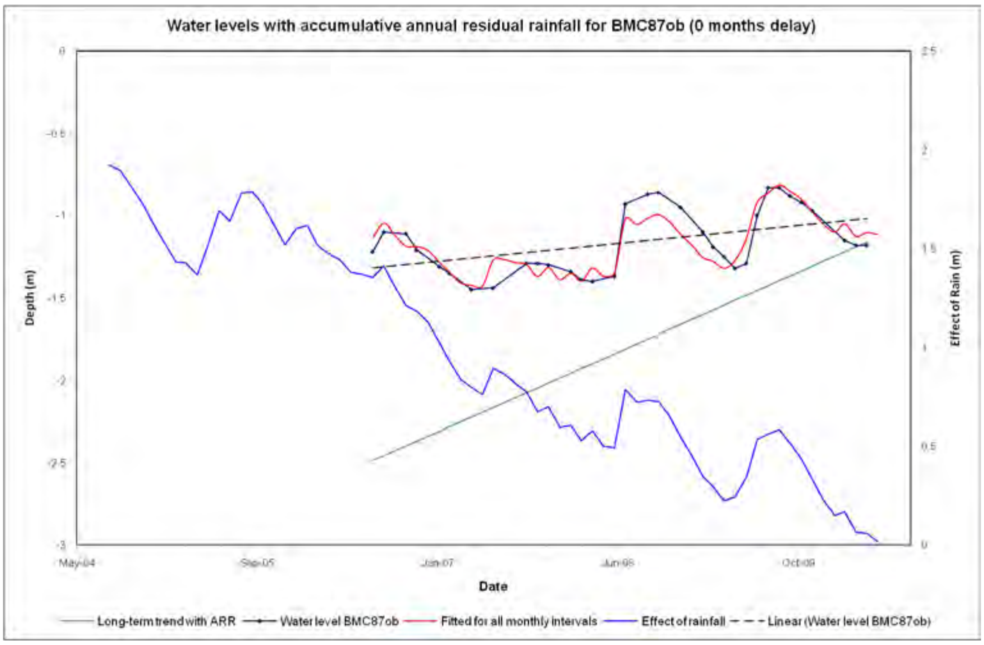
Appendix Fig 5-8. Groundwater levels for BMC58d and the long-term trend fitted using HARTT analysis to the accumulative annual residual rainfall (0 months delay) of the Coorow Post Office (BoM site 8037) and the linear trend.



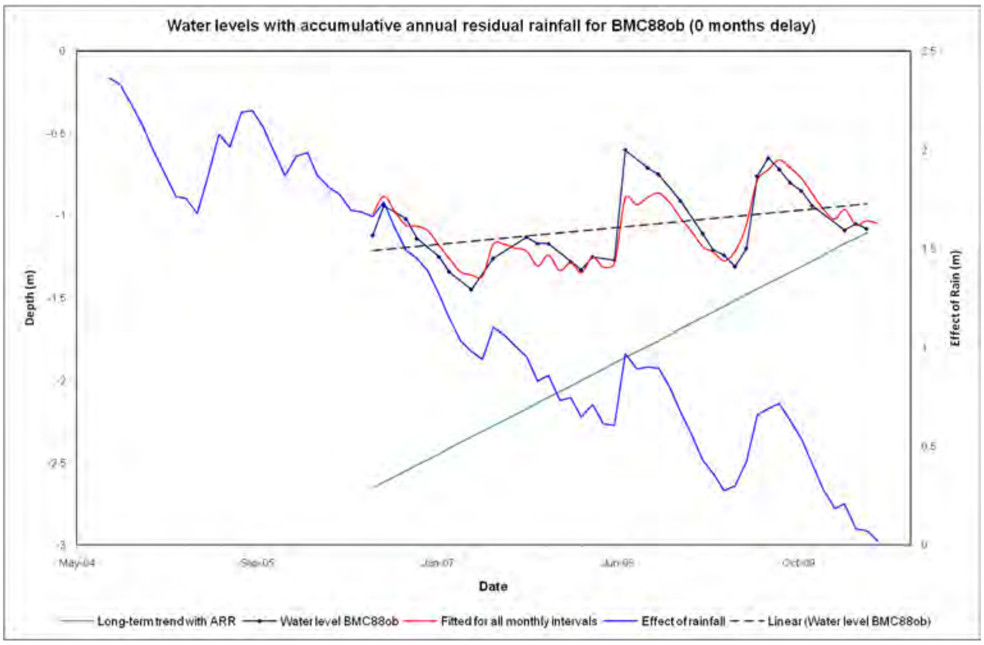
Appendix Fig 5-9. Groundwater levels for BMC58i and the long-term trend fitted using HARTT analysis to the accumulative annual residual rainfall (0 months delay) of the Coorow Post Office (BoM site 8037) and the linear trend.



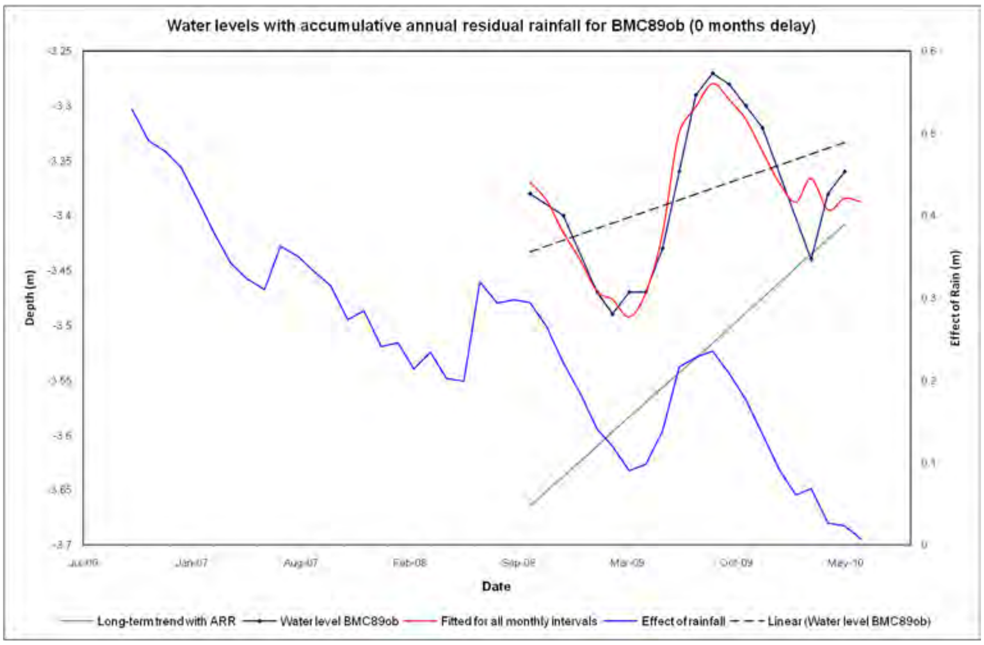
Appendix Fig 5-10. Groundwater levels for BMC86ob and the long-term trend fitted using HARTT analysis to the accumulative annual residual rainfall (0 months delay) of the Coorow Post Office (BoM site 8037) and the linear trend.



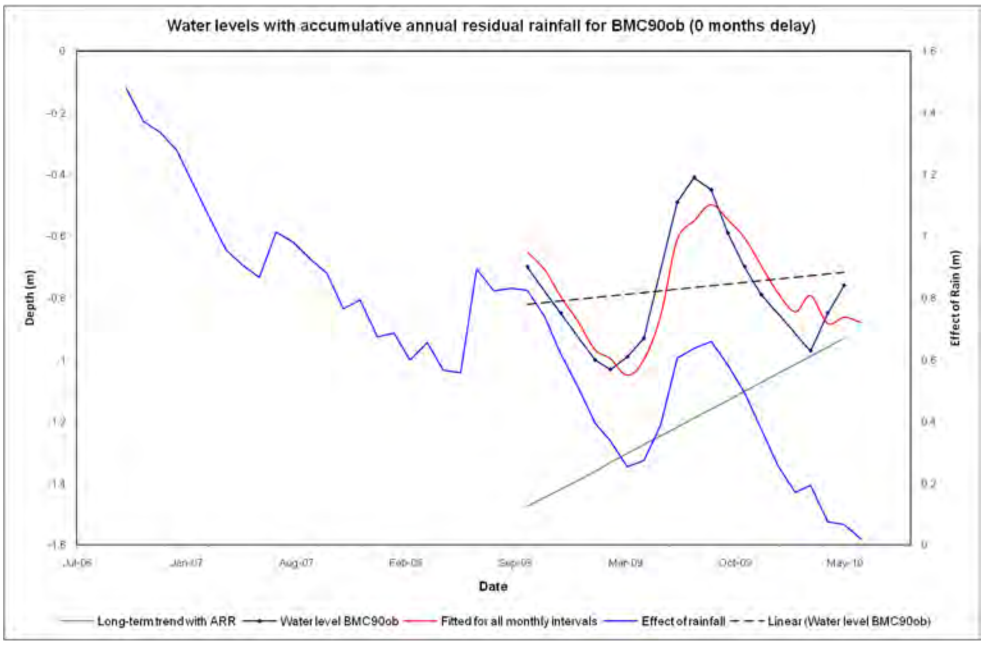
Appendix Fig 5-11. Groundwater levels for BMC87ob and the long-term trend fitted using HARTT analysis to the accumulative annual residual rainfall (0 months delay) of the Coorow Post Office (BoM site 8037) and the linear trend.



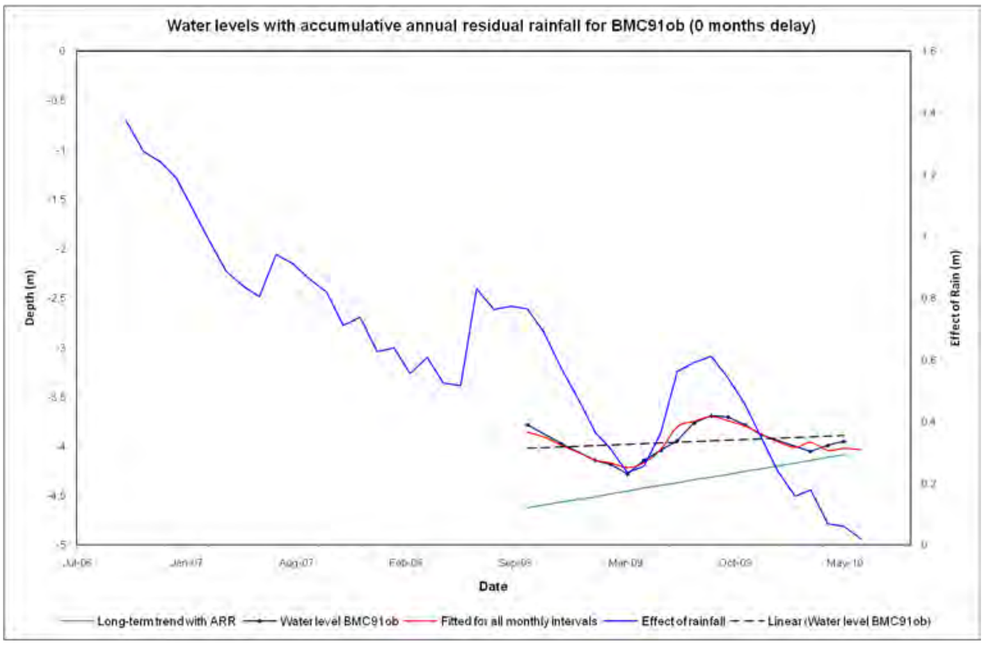
Appendix Fig 5-12. Groundwater levels for BMC88ob and the long-term trend fitted using HARTT analysis to the accumulative annual residual rainfall (0 months delay) of the Coorow Post Office (BoM site 8037) and the linear trend.



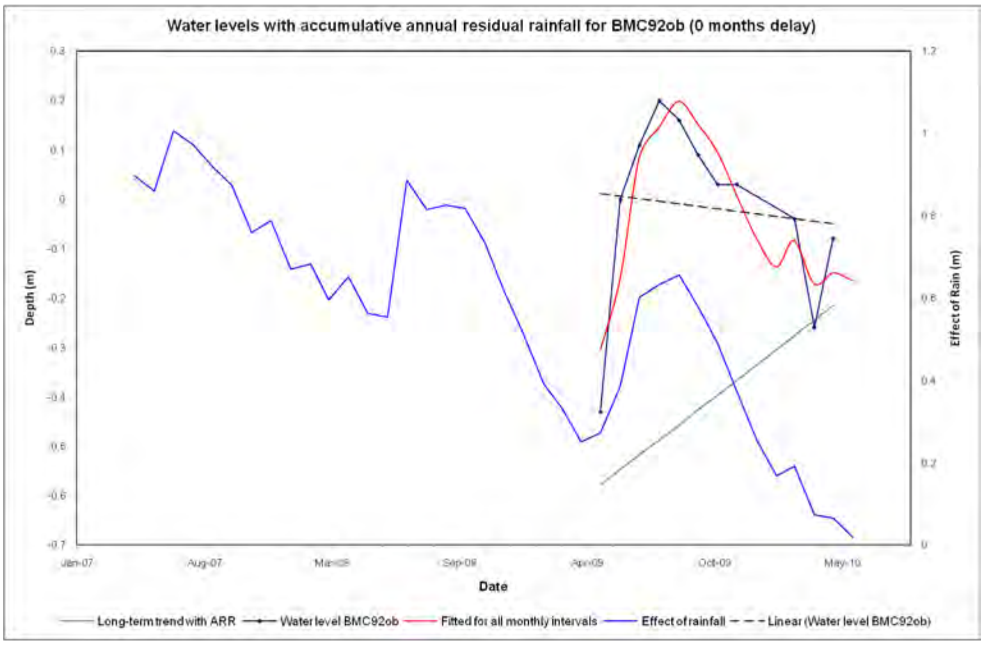
Appendix Fig 5-13. Groundwater levels for BMC89ob and the long-term trend fitted using HARTT analysis to the accumulative annual residual rainfall (0 months delay) of the Coorow Post Office (BoM site 8037) and the linear trend.



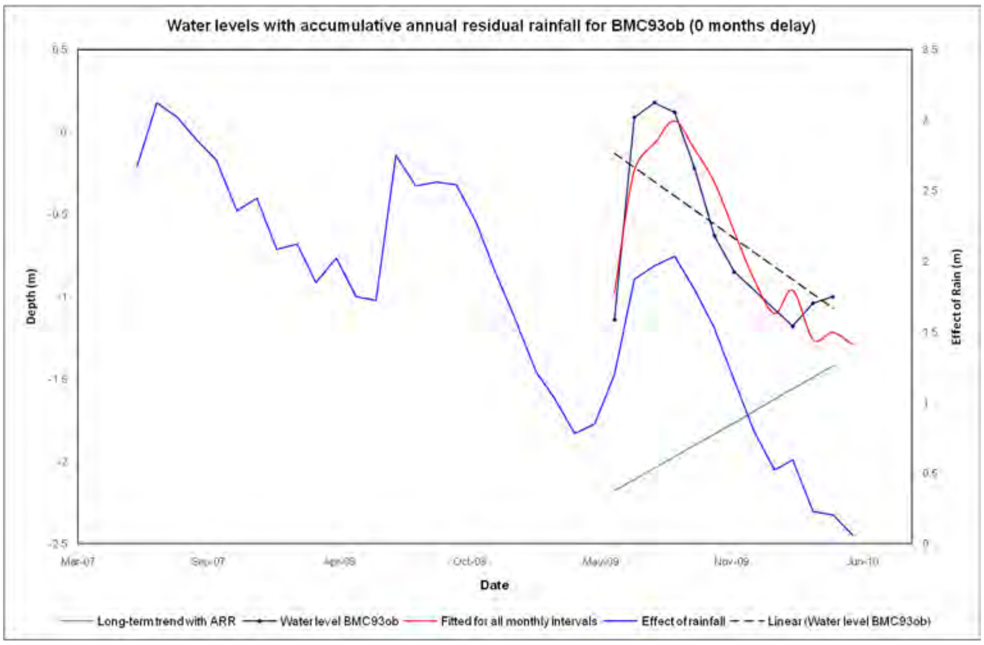
Appendix Fig 5-14. Groundwater levels for BMC90ob and the long-term trend fitted using HARTT analysis to the accumulative annual residual rainfall (0 months delay) of the Coorow Post Office (BoM site 8037) and the linear trend.



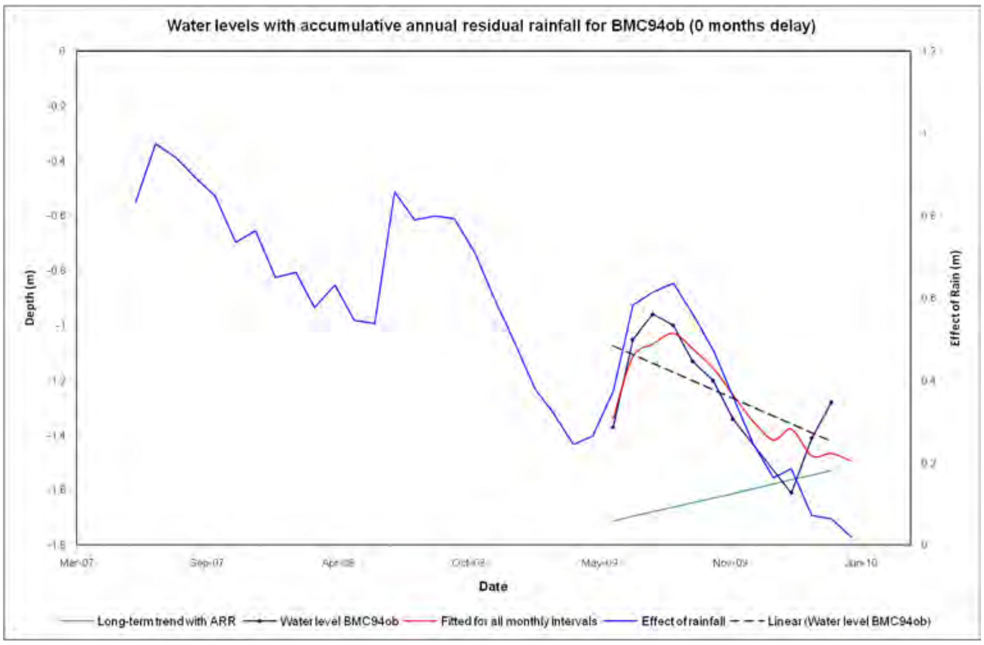
Appendix Fig 5-15. Groundwater levels for BMC91ob and the long-term trend fitted using HARTT analysis to the accumulative annual residual rainfall (0 months delay) of the Coorow Post Office (BoM site 8037) and the linear trend.



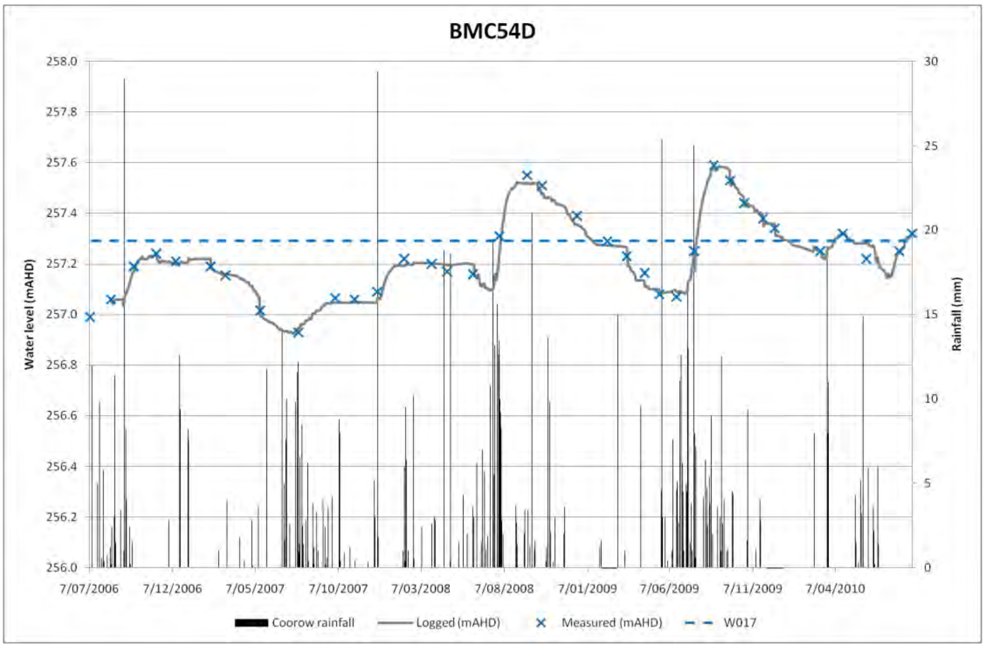
Appendix Fig 5-16. Groundwater levels for BMC92ob and the long-term trend fitted using HARTT analysis to the accumulative annual residual rainfall (0 months delay) of the Coorow Post Office (BoM site 8037) and the linear trend.



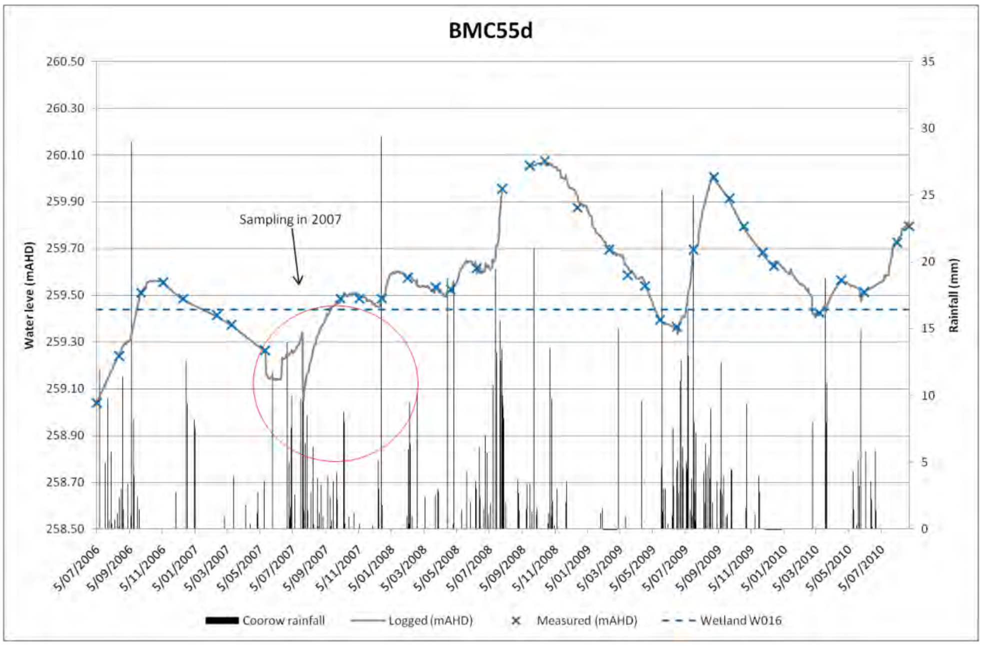
Appendix Fig 5-17. Groundwater levels for BMC93ob and the long-term trend fitted using HARTT analysis to the accumulative annual residual rainfall (0 months delay) of the Coorow Post Office (BoM site 8037) and the linear trend.



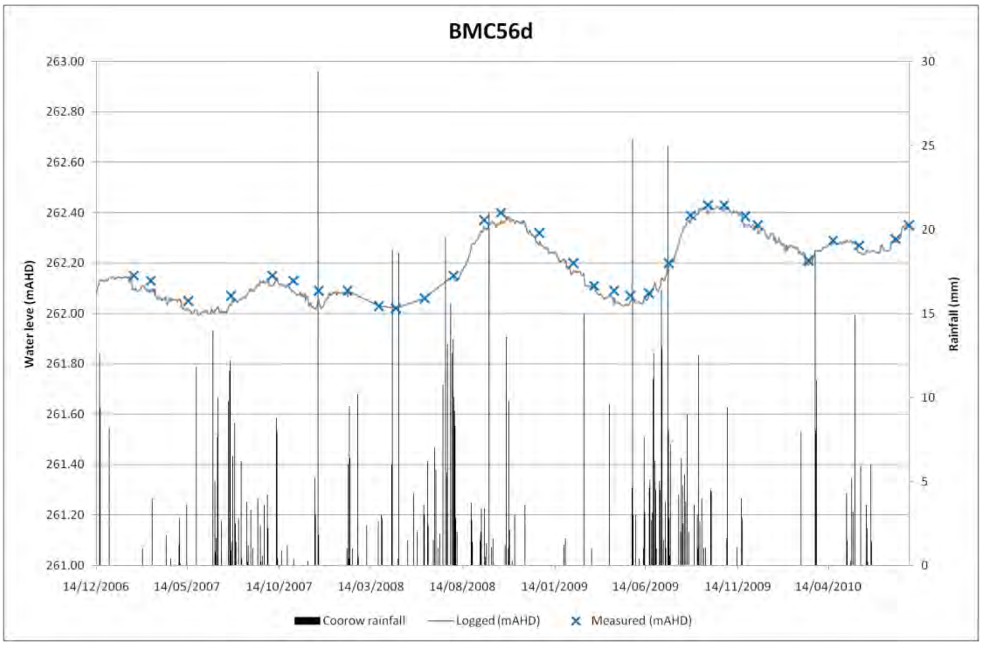
Appendix Fig 5-18. Groundwater levels for BMC94ob and the long-term trend fitted using HARTT analysis to the accumulative annual residual rainfall (0 months delay) of the Coorow Post Office (BoM site 8037) and the linear trend.



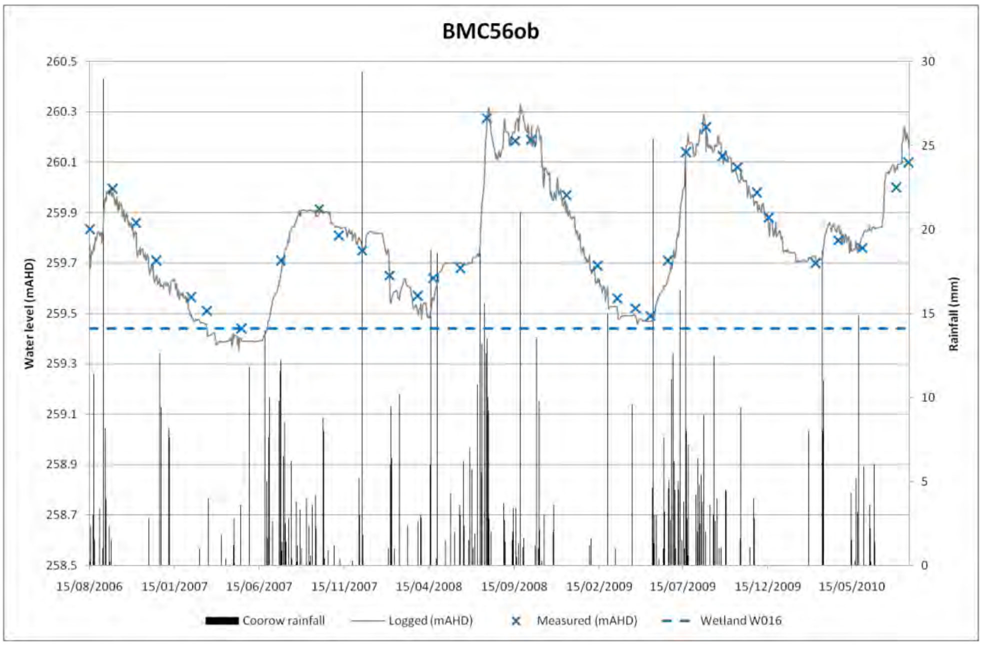
Appendix Fig 5-19. Measured and logged daily groundwater levels (mAHD) for bore BMC54D from 2006 to 2010 and daily rainfall from Coorow.



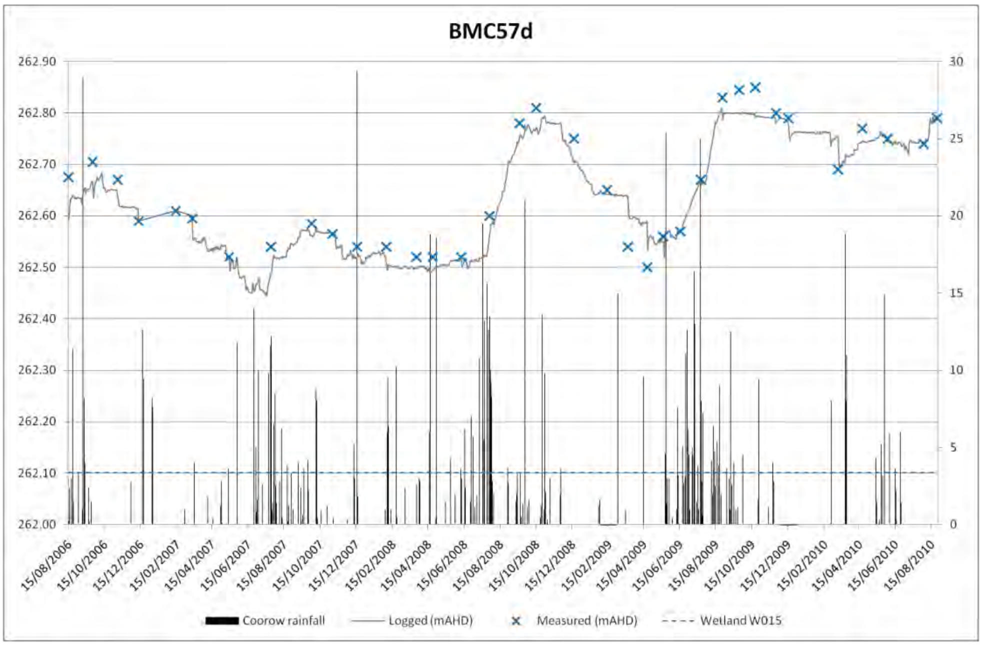
Appendix Fig 5-20. Measured and logged daily groundwater levels (mAHD) for bore BMC55D from 2006 to 2010 and daily rainfall from Coorow.



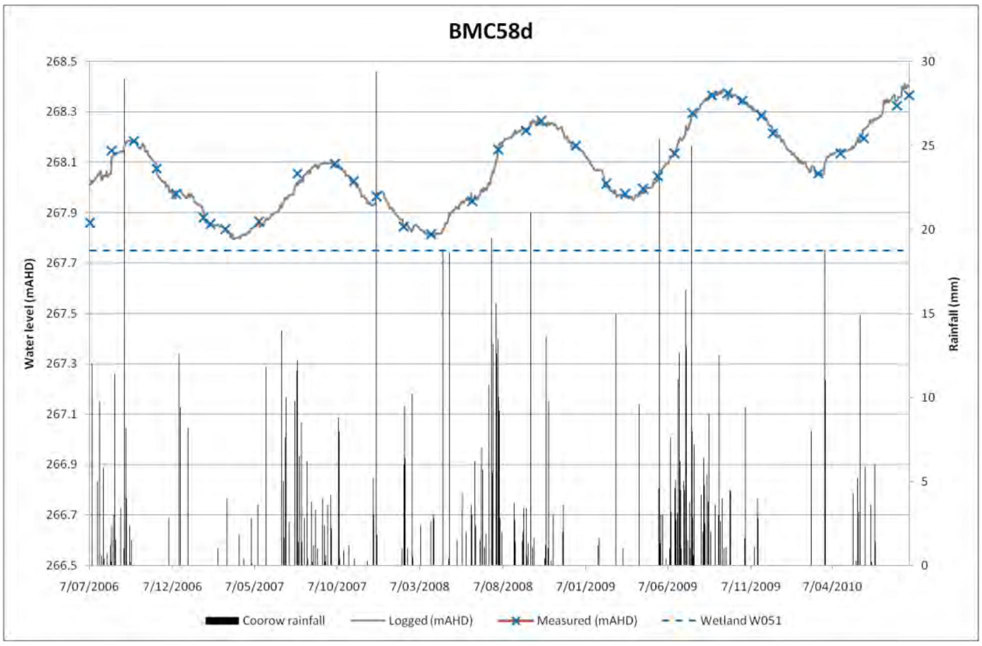
Appendix Fig 5-21. Measured and logged daily groundwater levels (mAHD) for bore BMC56D from 2006 to 2010 and daily rainfall from Coorow.



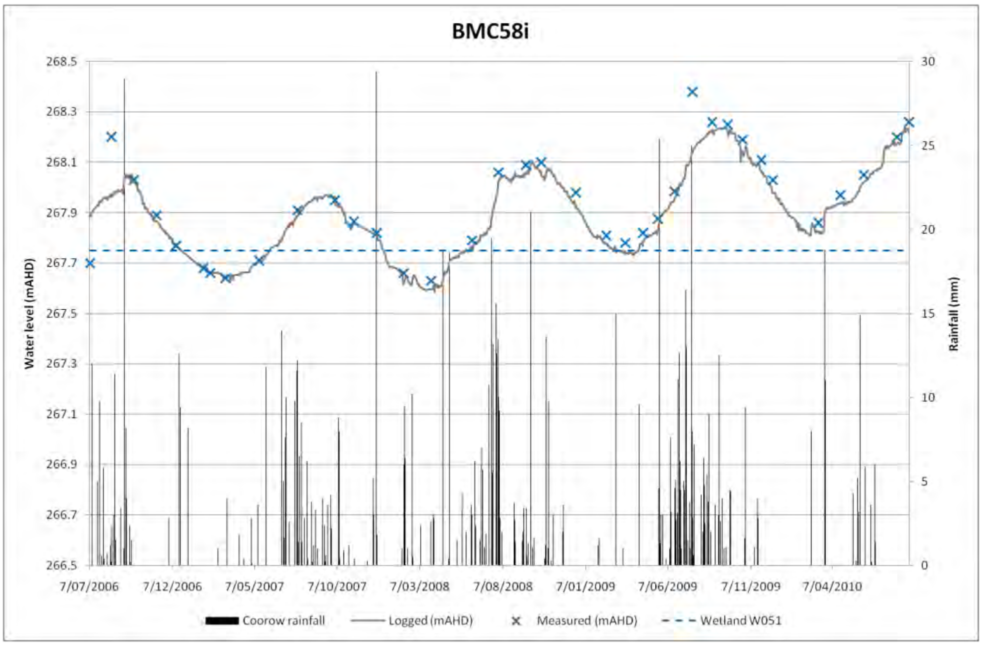
Appendix Fig 5-22. Measured and logged daily groundwater levels (mAHD) for bore BMC56ob from 2006 to 2010 and daily rainfall from Coorow.



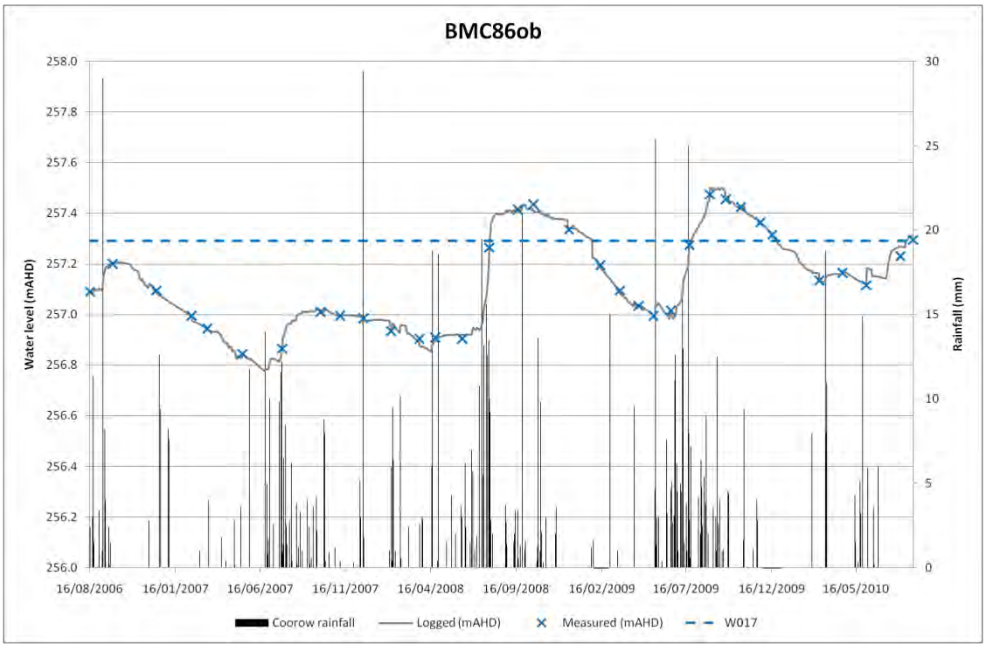
Appendix Fig 5-23. Measured and logged daily groundwater levels (mAHD) for bore BMC57D from 2006 to 2010 and daily rainfall from Coorow.



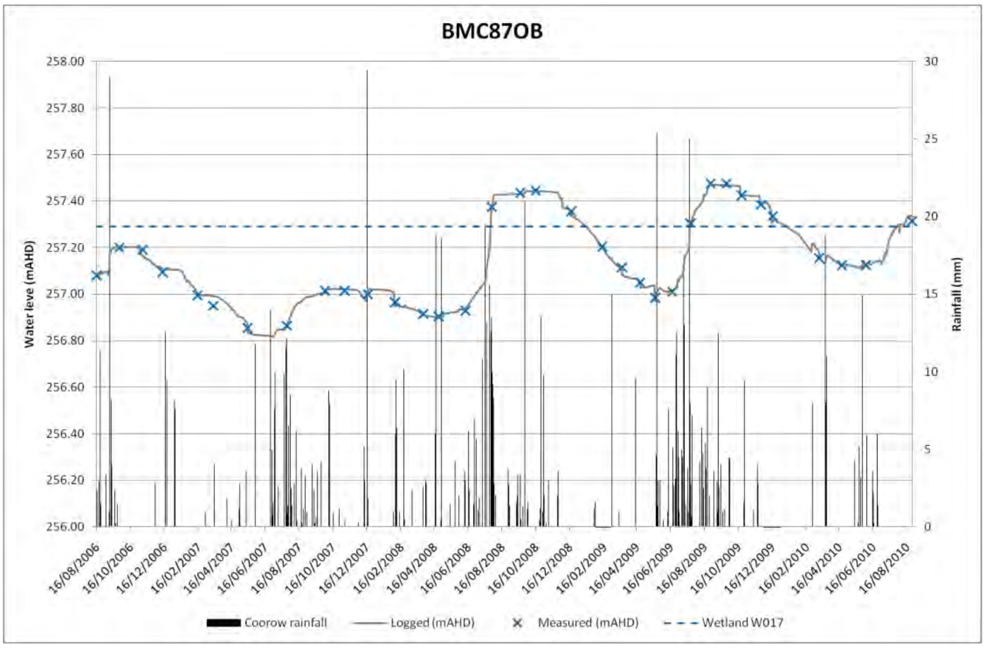
Appendix Fig 5-24. Measured and logged daily groundwater levels (mAHD) for bore BMC58D from 2006 to 2010 and daily rainfall from Coorow.



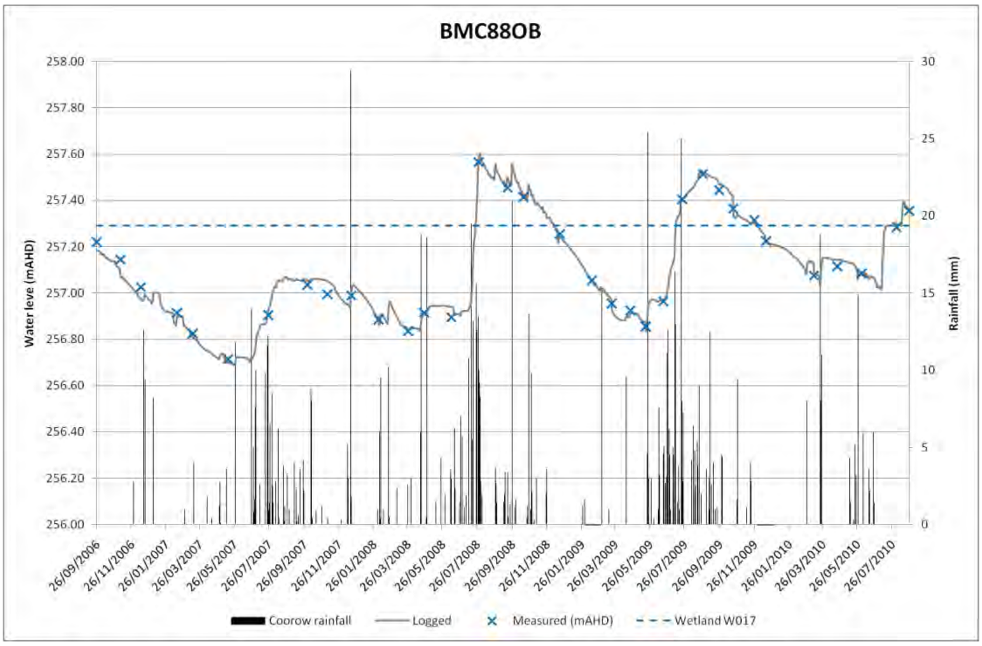
Appendix Fig 5-25. Measured and logged daily groundwater levels (mAHD) for bore BMC58i from 2006 to 2010 and daily rainfall from Coorow.



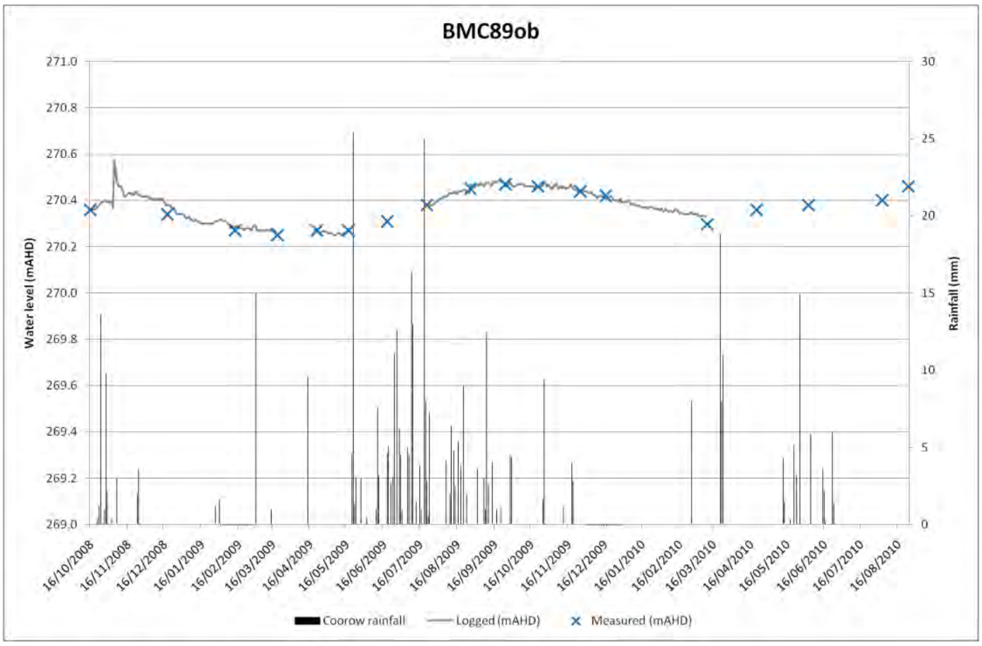
Appendix Fig 5-26. Measured and logged daily groundwater levels (mAHD) for bore BMC86ob from 2006 to 2010 and daily rainfall from Coorow.



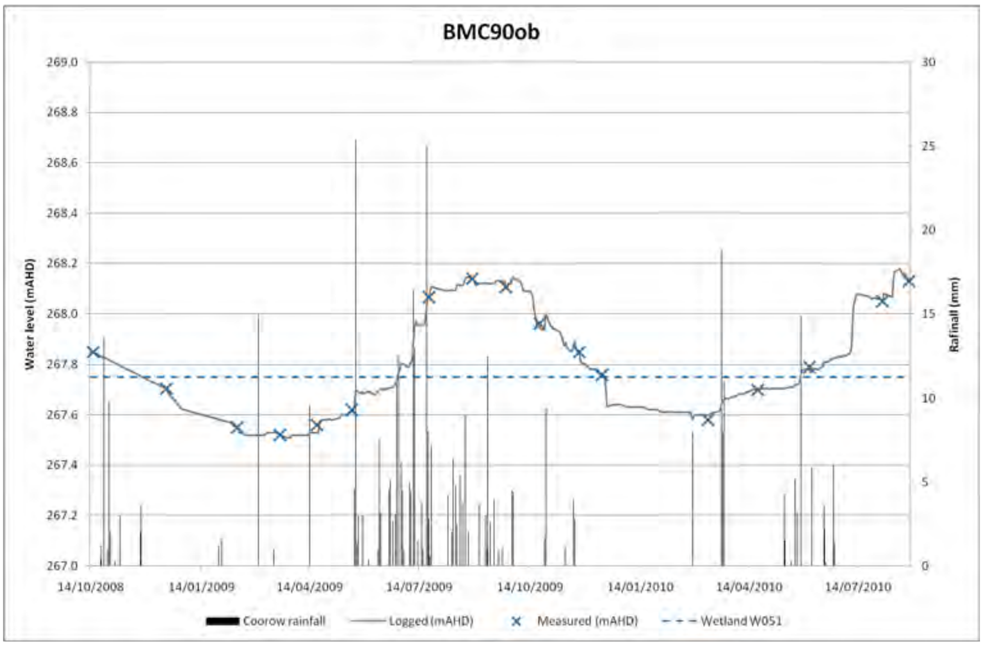
Appendix Fig 5-27. Measured and logged daily groundwater levels (mAHD) for bore BMC87ob from 2006 to 2010 and daily rainfall from Coorow.



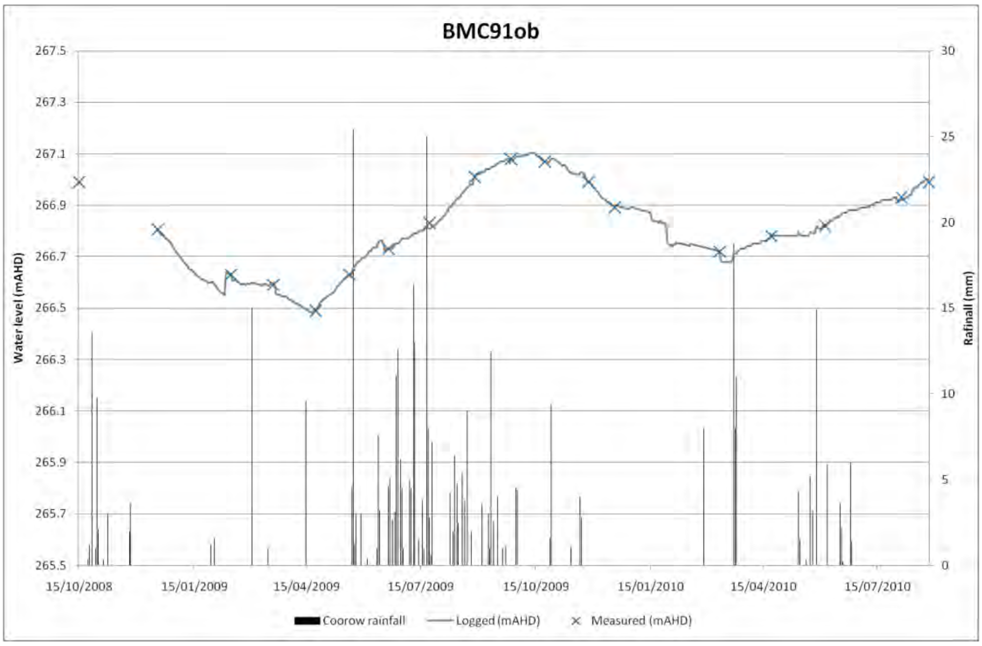
Appendix Fig 5-28. Measured and logged daily groundwater levels (mAHD) for bore BMC88ob from 2006 to 2010 and daily rainfall from Coorow.



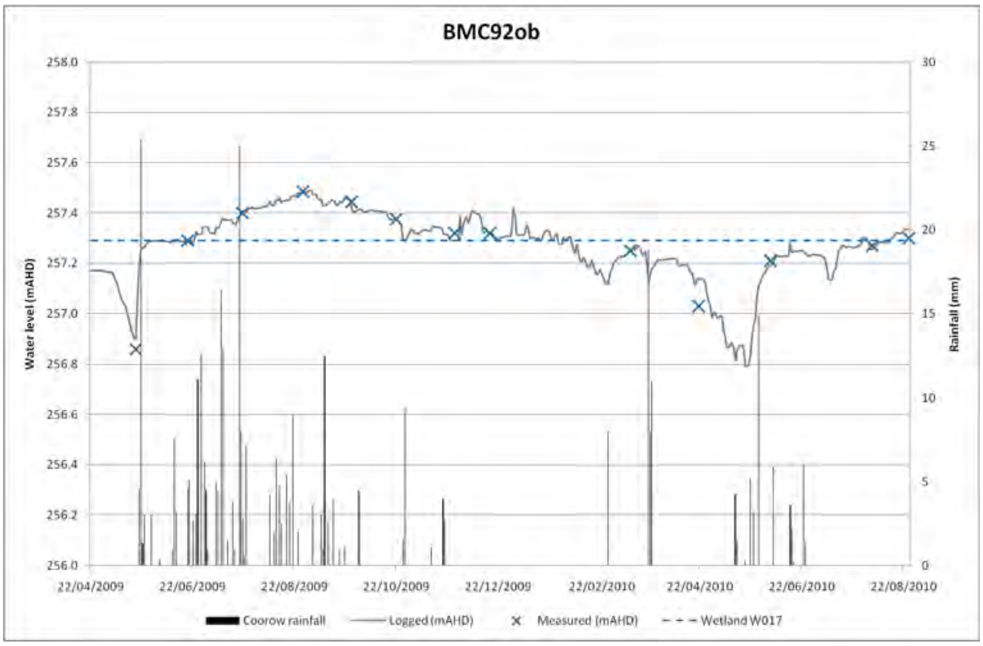
Appendix Fig 5-29. Measured and logged daily groundwater levels (mAHD) for bore BMC89ob from 2008 to 2010 and daily rainfall from Coorow.



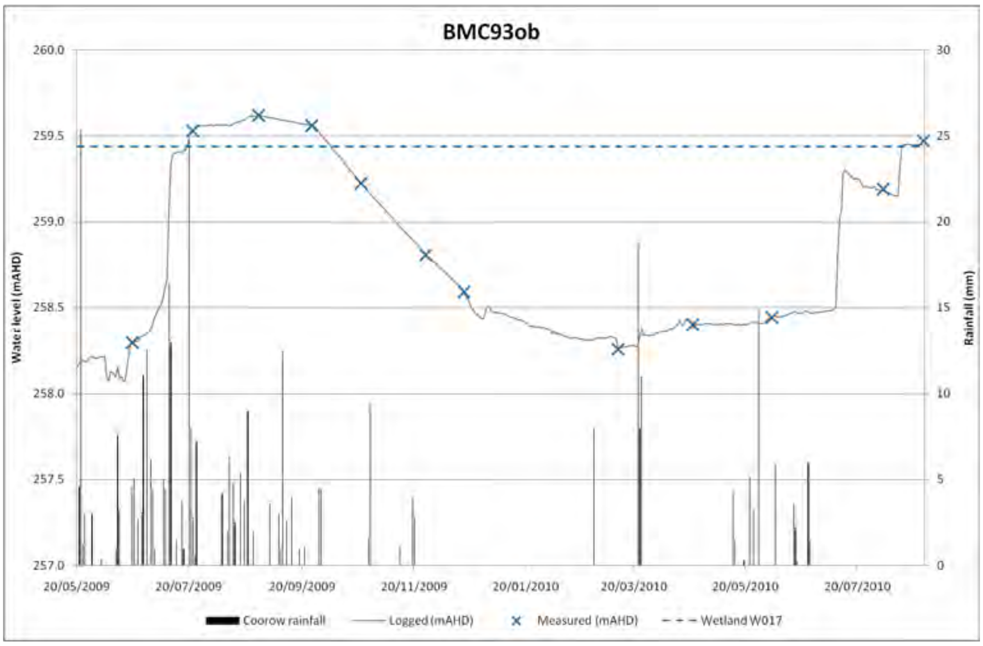
Appendix Fig 5-30. Measured and logged daily groundwater levels (mAHD) for bore BMC90ob from 2008 to 2010 and daily rainfall from Coorow.



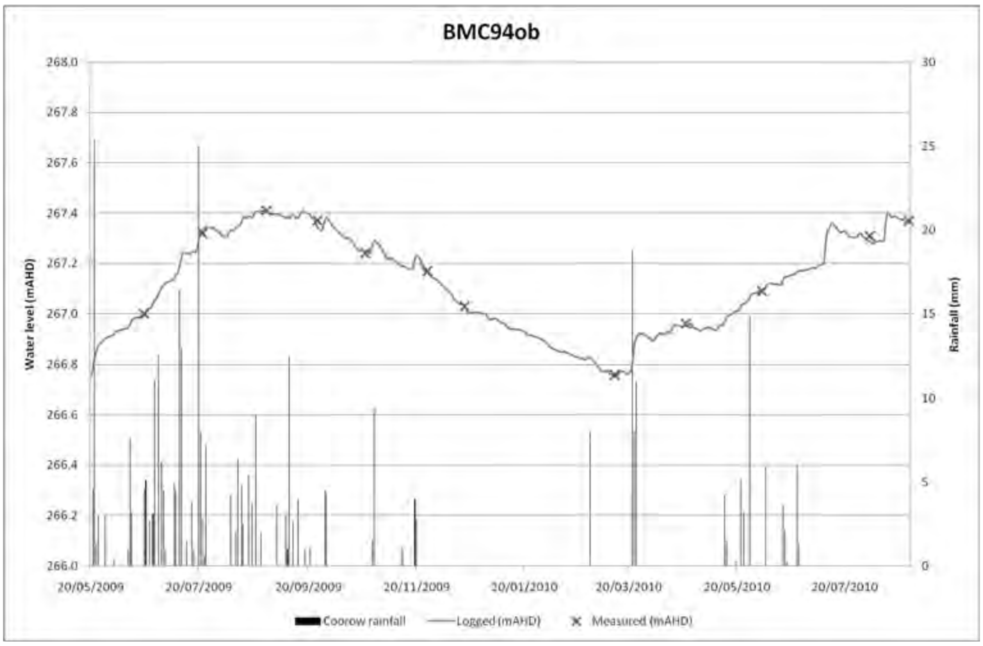
Appendix Fig 5-31. Measured and logged daily groundwater levels (mAHD) for bore BMC91ob from 2008 to 2010 and daily rainfall from Coorow.



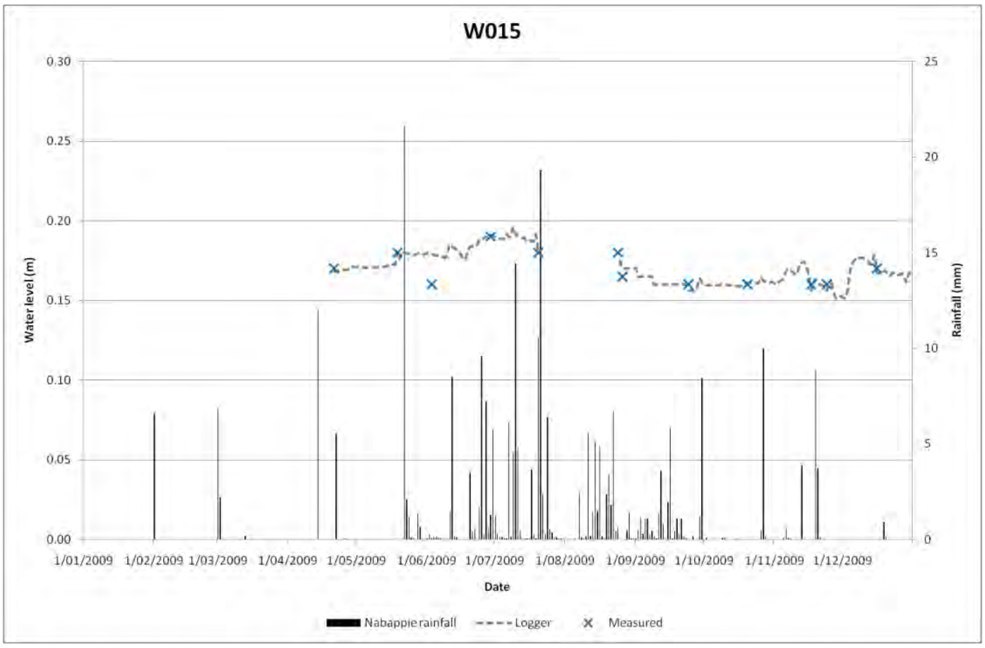
Appendix Fig 5-32. Measured and logged daily groundwater levels (mAHD) for bore BMC92ob from 2009 to 2010 and daily rainfall from Coorow.



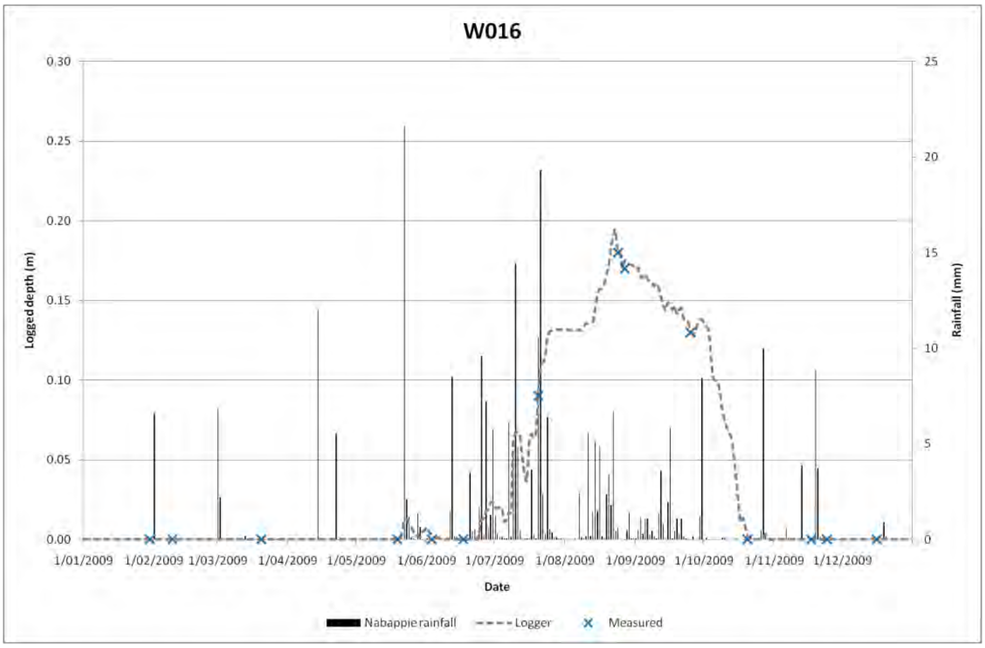
Appendix Fig 5-33. Measured and logged daily groundwater levels (mAHD) for bore BMC93ob from 2009 to 2010 and daily rainfall from Coorow.



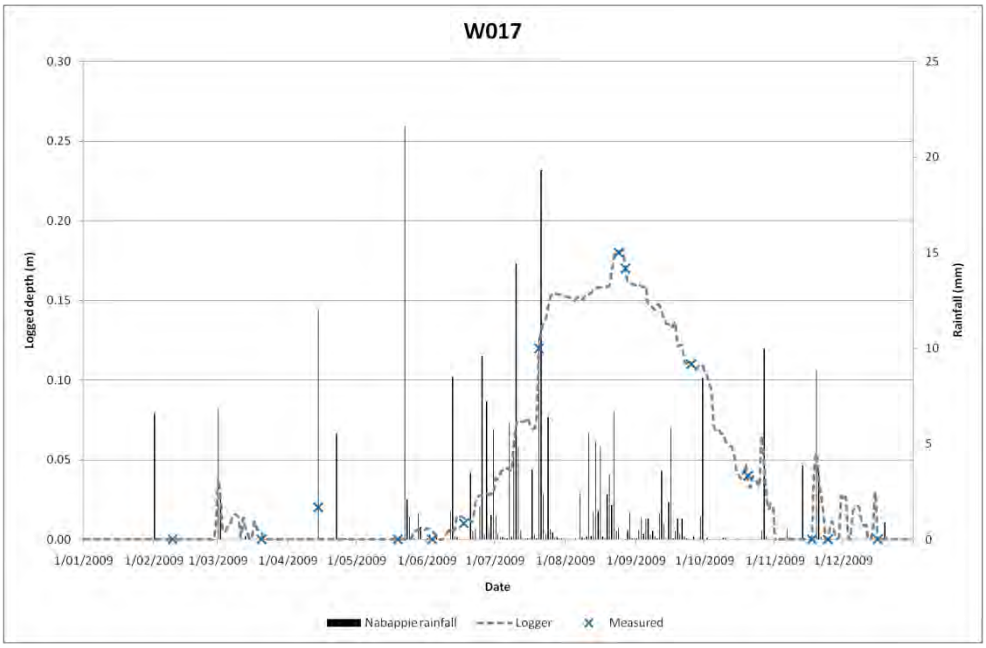
Appendix Fig 5-34. Measured and logged daily groundwater levels (mAHD) for bore BMC57D from 2009 to 2010 and daily rainfall from Coorow.



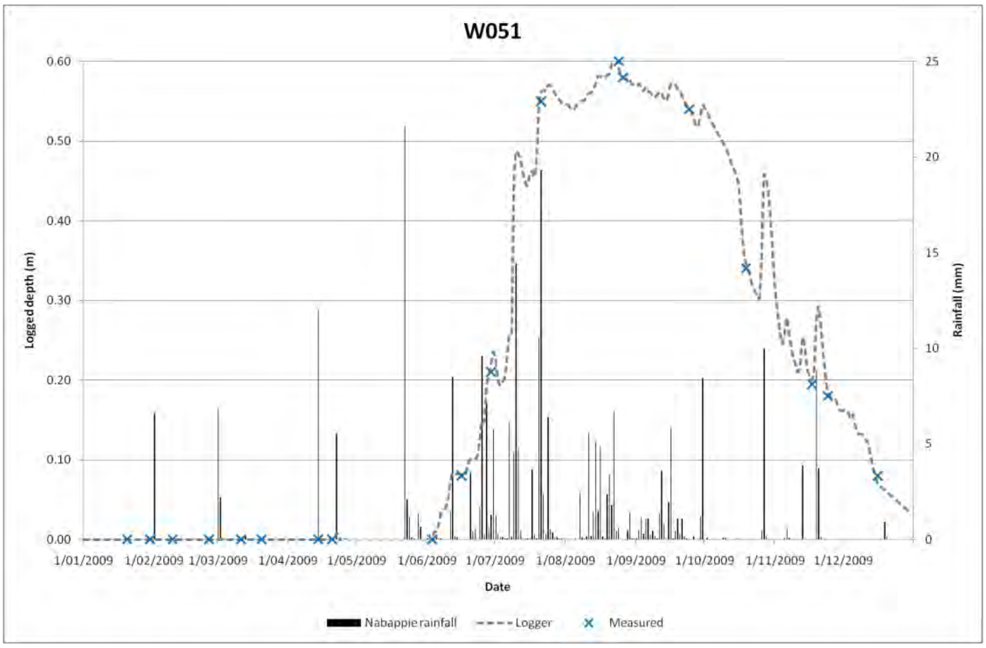
Appendix Fig 5-35. Wetland W015 daily average logged water level (grey dashed line), measured water level (blue cross) and average daily rainfall recorded at Nabappie (black bars) in 2009. Due to logger error, data was missing from 20th July through 24th August.



Appendix Fig 5-36. Wetland W016 daily average logged water level (grey dashed line), measured water level (blue cross) and average daily rainfall recorded at Nabappie (black bars) in 2009.

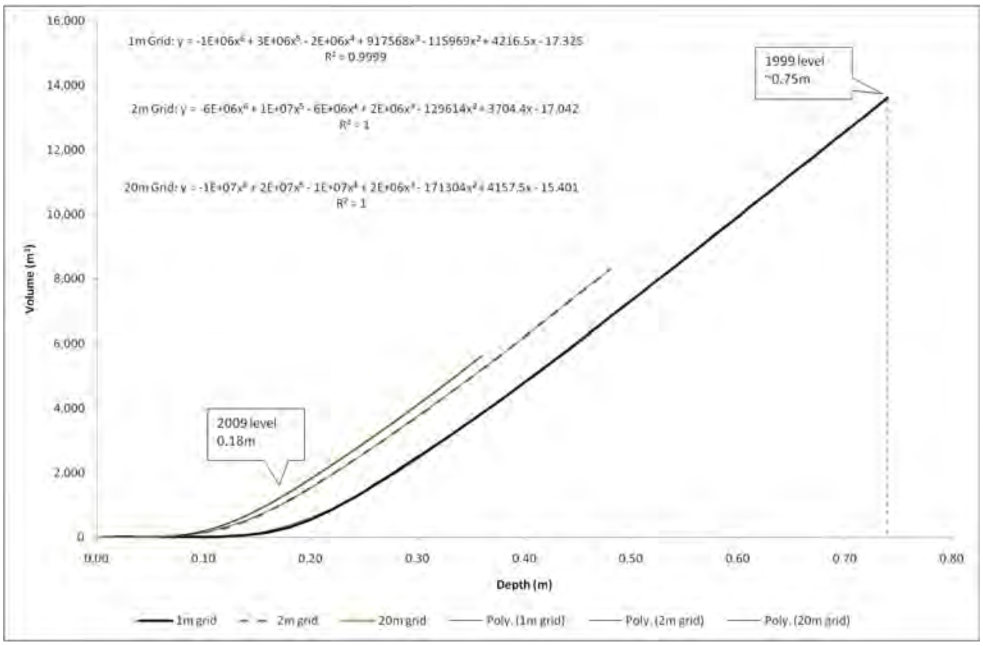


Appendix Fig 5-37. Wetland W017 daily average logged water level (grey dashed line), measured water level (blue cross) and average daily rainfall recorded at Nabappie (black bars) in 2009.

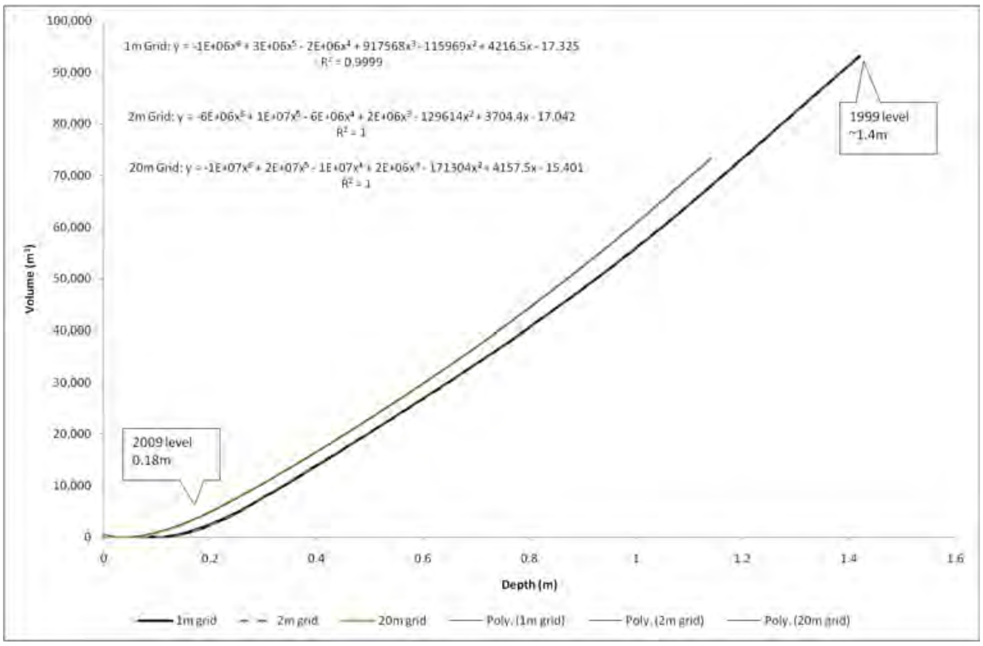


Appendix Fig 5-38. Wetland W051 daily average logged water level (grey dashed line), measured water level (blue cross) and average daily rainfall recorded at Nabappie (black bars) in 2009.

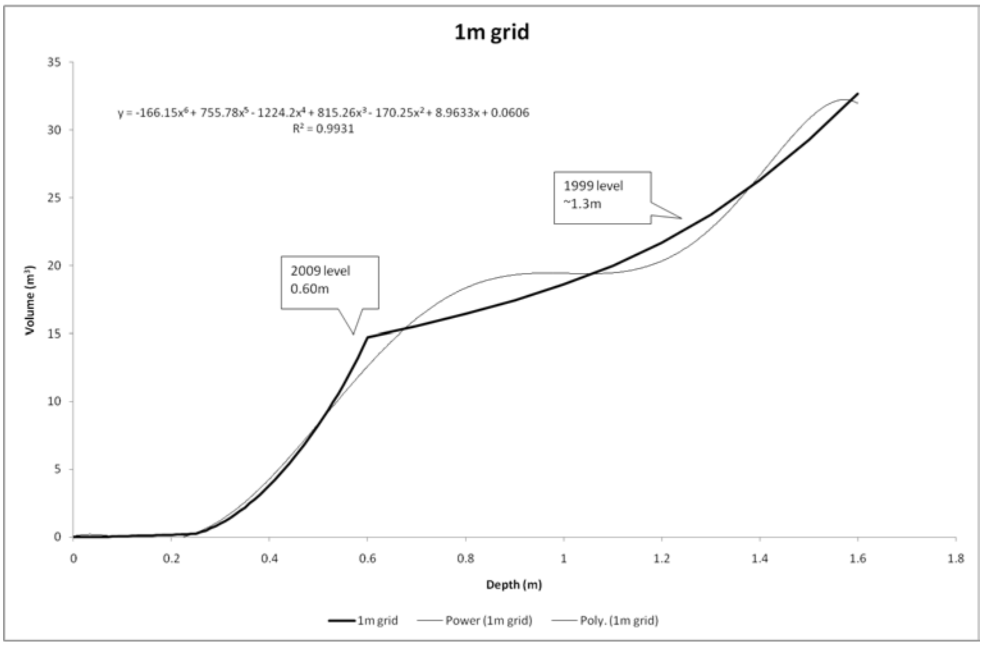
Appendix 5G Depth to volume relationship for wetlands



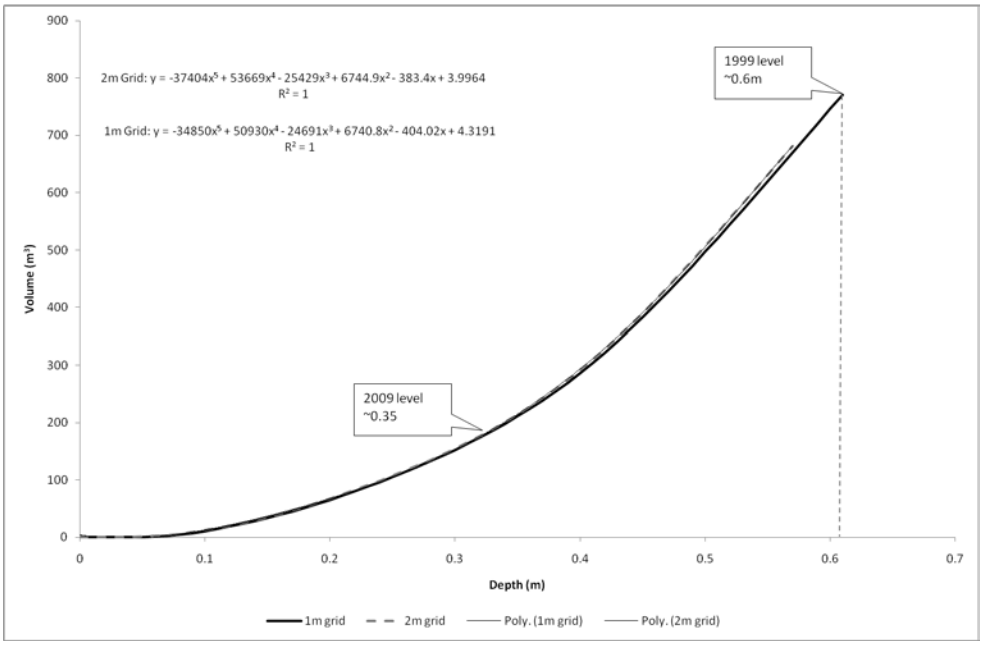
Appendix Fig 5-39. Depth to volume relationships for wetland W016 interpolated for a range of grid sizes (1m, 10m, and 20m) from LiDAR topographical data.



Appendix Fig 5-40. Depth to volume relationships for wetland W017 interpolated for a range of grid sizes (1m, 10m, and 20m) from LiDAR topographical data.

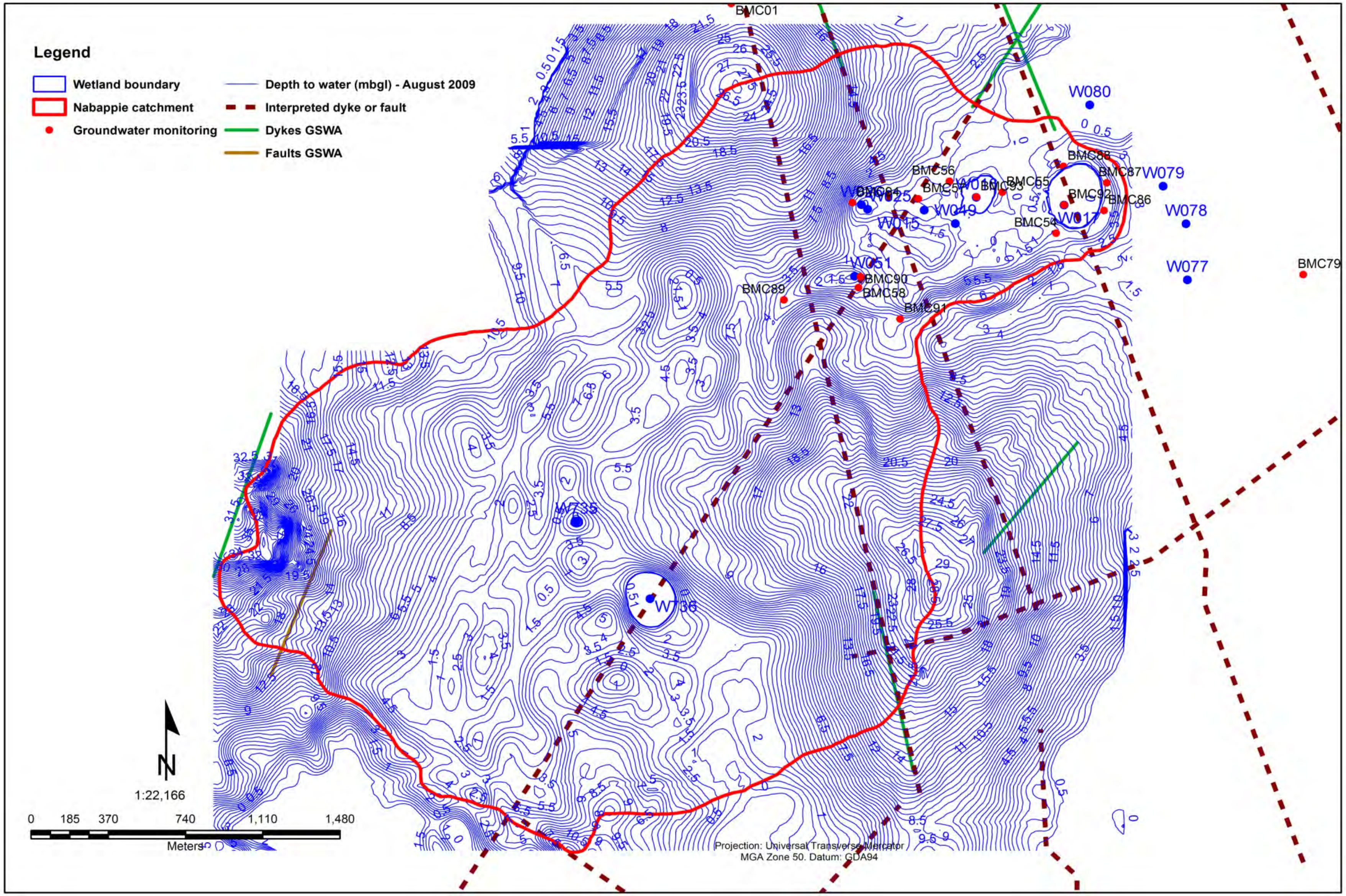


Appendix Fig 5-41. Depth to volume relationships for wetland W051 interpolated for a 1m grid sizes from LiDAR topographical data.

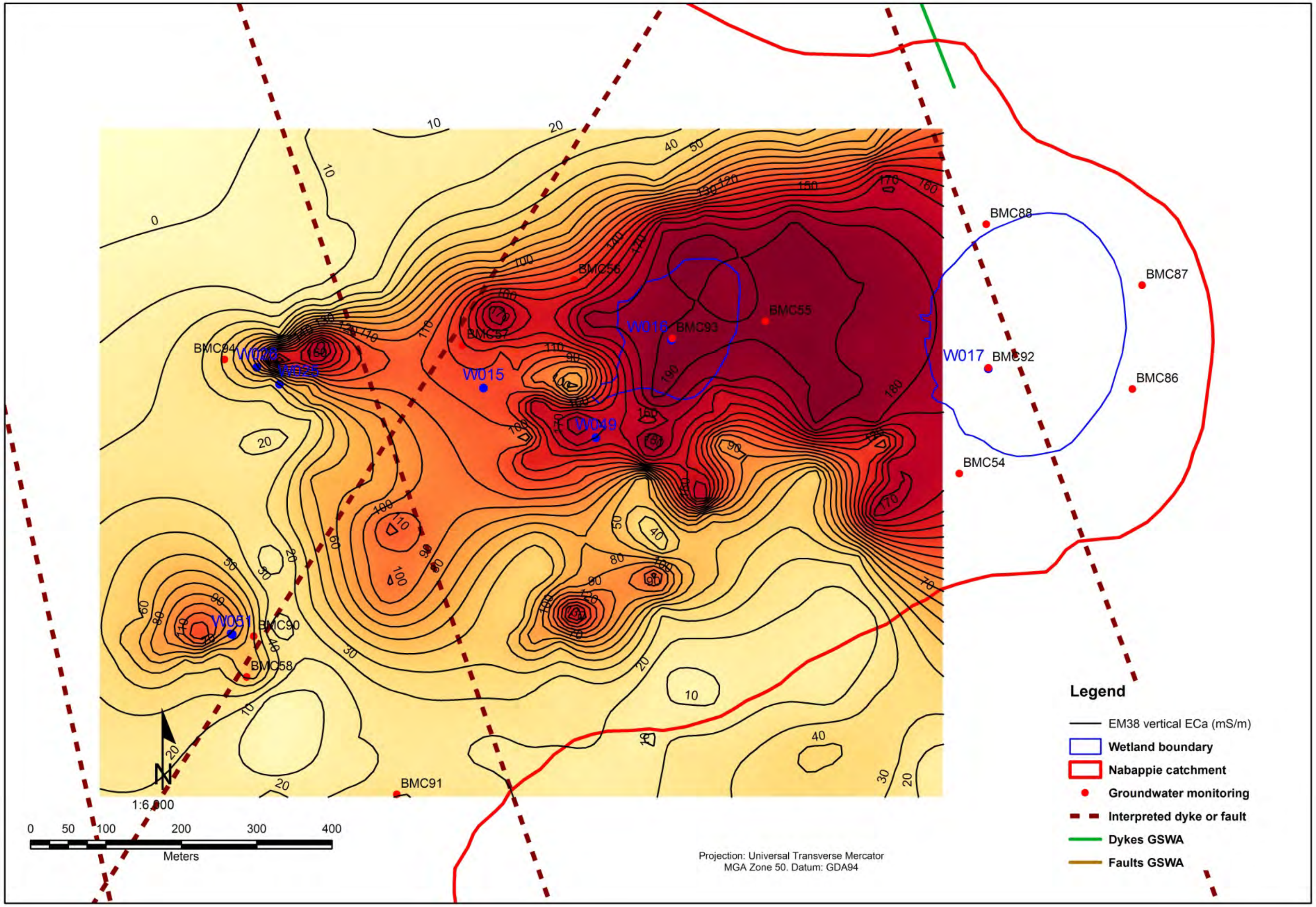


Appendix Fig 5-42. Depth to volume relationships for wetland W735 interpolated for a range of grid sizes (1m, and 2m) from LiDAR topographical data.

Appendix 5H Depth to the water table and EM38 maps

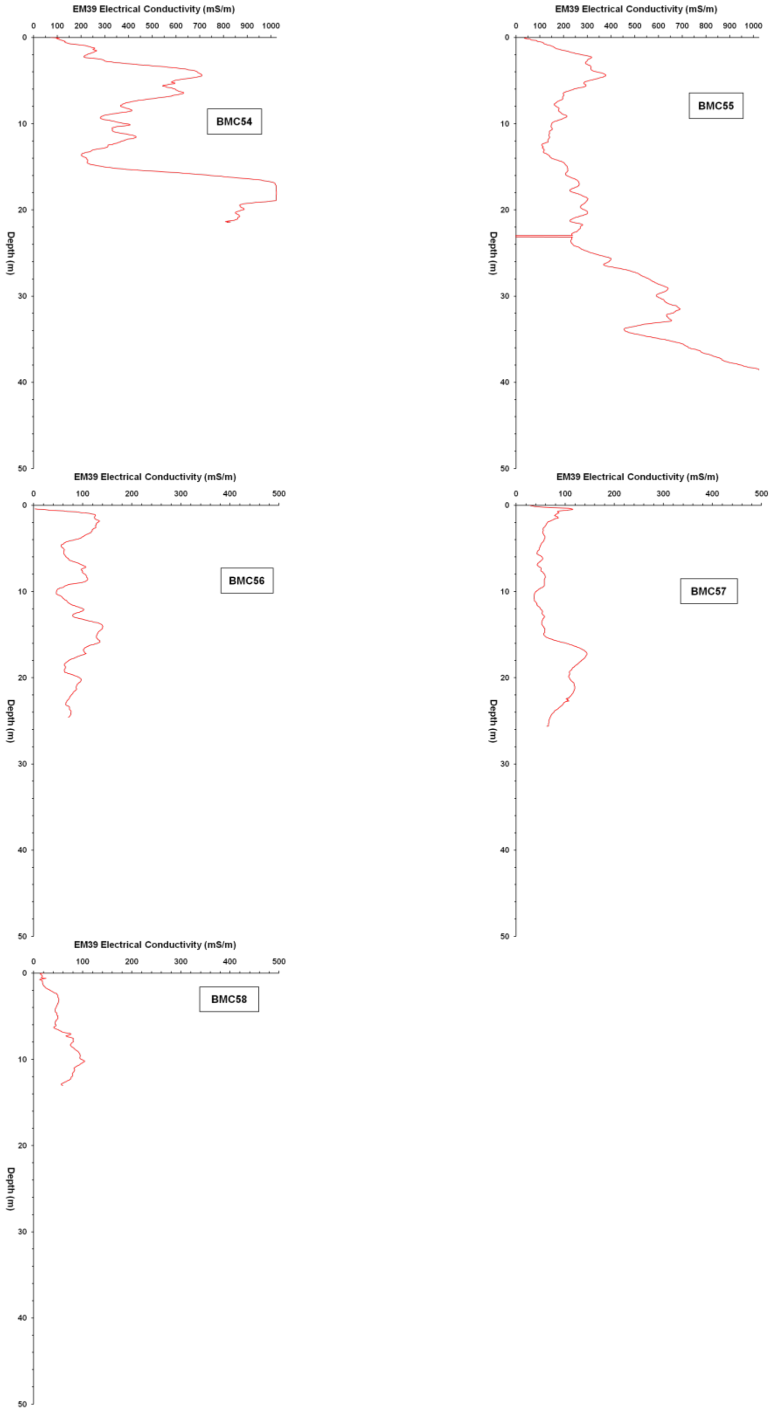


Appendix Fig 5-43. Density-corrected depth to the water table (mbgl) for August 2009 in the Nabappie subcatchment



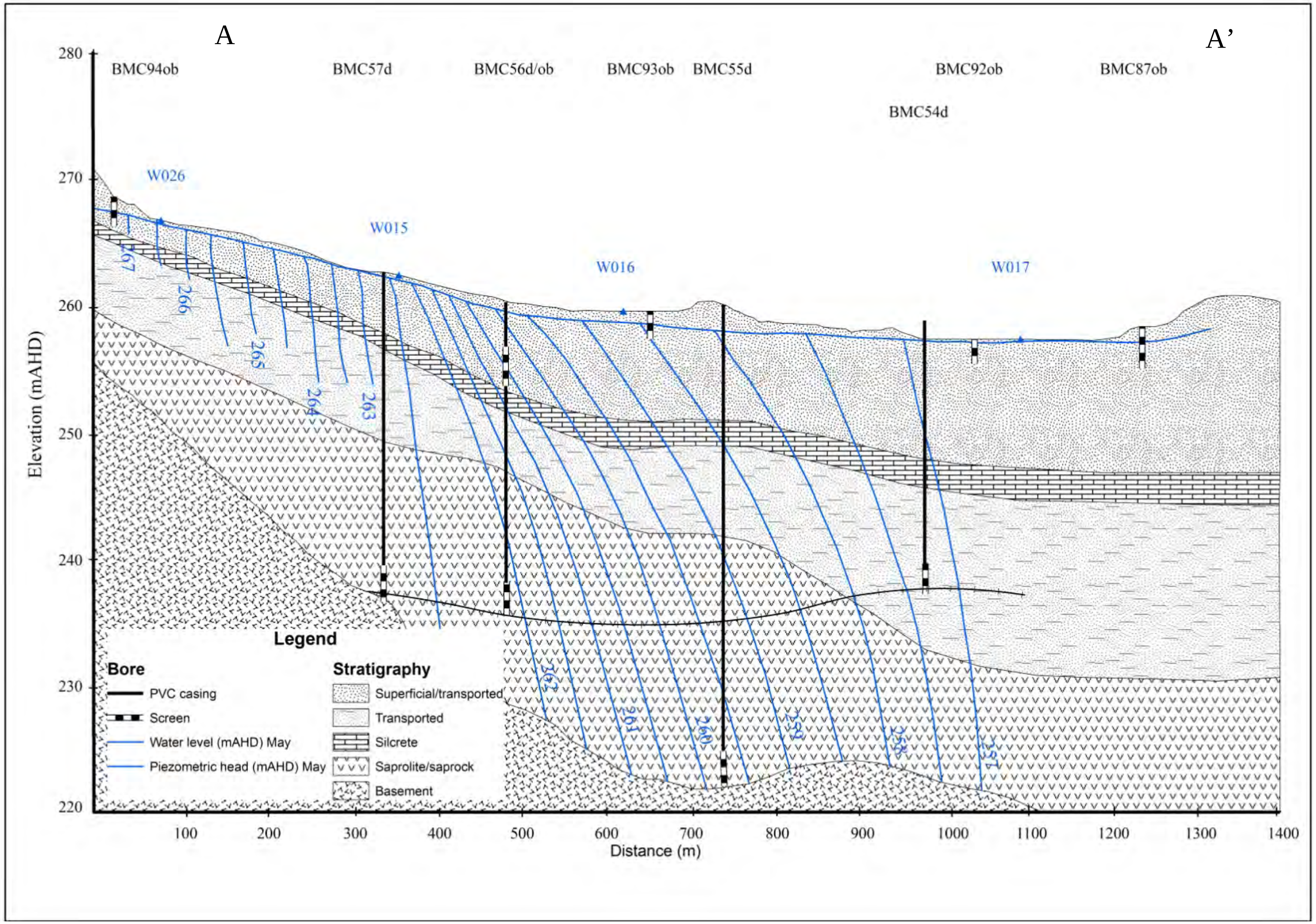
Appendix Fig 5-44. Interpolated EM38 (vertical mode) apparent soil salinity (EC_a), which ranges from <10 mS/m to 190mS/m, plotted with dykes mapped by Geological Survey of Western Australia (Baxter and Lipple, 1985) and dykes and faults interpreted by the author.

Appendix 5I Down-hole EM39



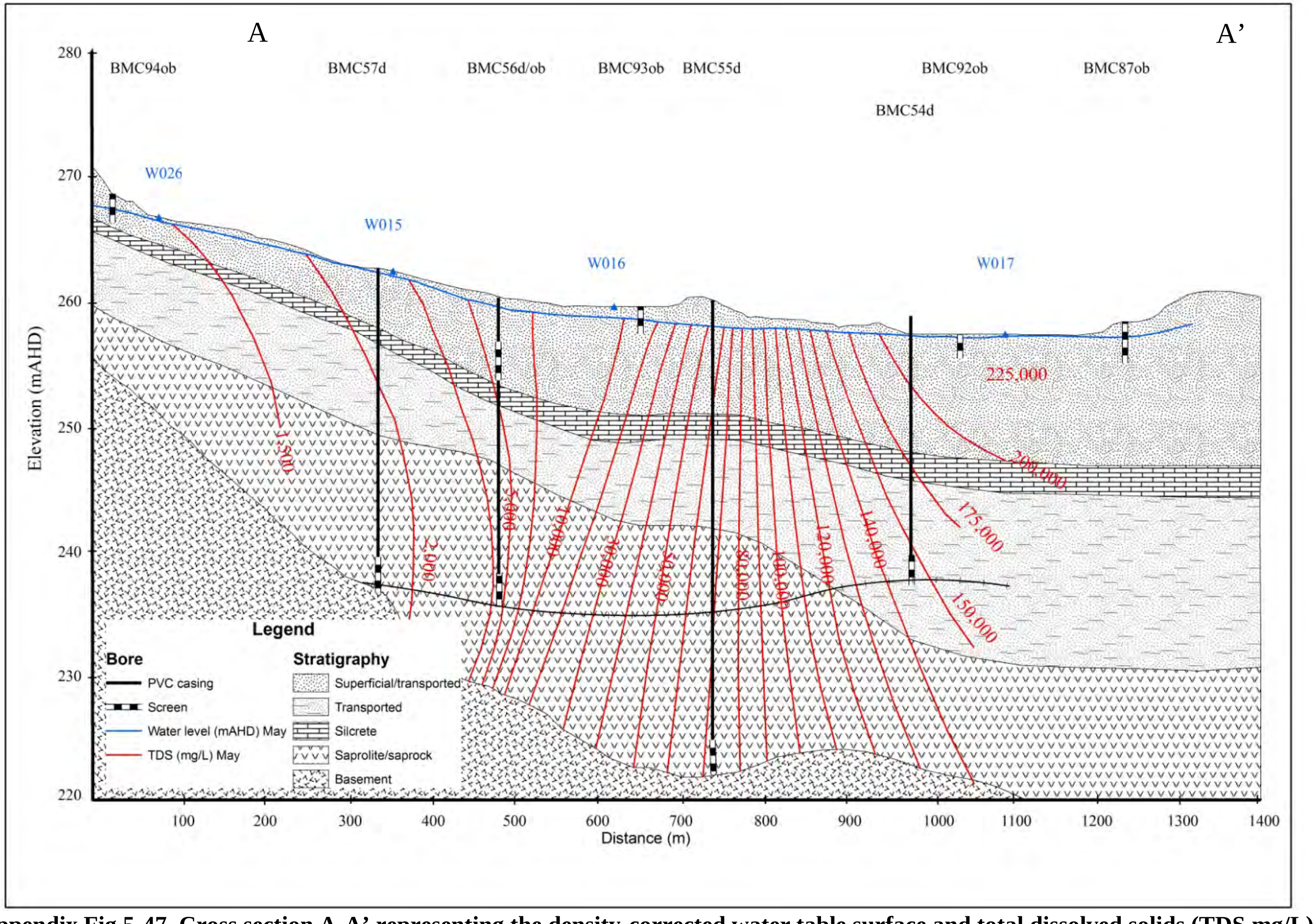
Appendix Fig 5-45. Down-hole EM39 salinity versus depth profiles for bore BMC54d (top left), BMC55D (top right), BMC56d (middle left), BMC57d (middle right), and BMC58d (bottom left) (Kendle and Speed, 2008). BMC54d and BMC55d are scaled at 0 to 1,000mS/m, whilst the remainder are 0 to 500mS/m.

Appendix 5J Water table and piezometric head cross section A-A’ May 2009



Appendix Fig 5-46. Cross section A-A’ representing the density-corrected water table surface and piezometric head for May 2009. The depth of the interpreted boundary of bedrock along the valley flank is represented by a black dashed line.

Appendix 5K Water table and TDS at cross section A-A' May 2009



Appendix Fig 5-47. Cross section A-A' representing the density-corrected water table surface and total dissolved solids (TDS mg/L) for May 2009. The depth of the interpreted boundary of bedrock along the valley flank is represented by a black dashed line

Appendix Chapter 6

Appendix 6A Field water quality data

Data available on request

Appendix 6B Laboratory data (raw), major ions

Appendix Table 6-1. Major ion results from the Chemistry Centre, Western Australia for April 2009

ChemCentre ID	Method Code	Limit of Reporting	Units	08E1841/001	08E1841/002	08E1841/003	08E1841/004	08E1841/005	08E1841/006	08E1841/007	08E1841/008	08E1841/009	08E1841/010	08E1841/011	08E1841/012	08E1841/013	08E1841/014	08E1841/015	08E1841/016	08E1841/017
Client ID				QC1	QC2	BMC89ob	W051	BMC90ob	BMC58i	GS017	BMC57d	BMC56d	BMC56ob	BMC55d	BMC54d	BMC86ob	BMC87ob	BMC88ob	W736	BMC92ob
Sampled				20/04/2009	20/04/2009	20/04/2009	20/04/2009	21/04/2009	21/04/2009	21/04/2009	21/04/2009	21/04/2009	21/04/2009	21/04/2009	21/04/2009	22/04/2009	22/04/2009	22/04/2009	22/04/2009	22/04/2009
Br	iANIO1WAIC	0.1	mg/L	0.5	0.2	0.2	6.2	3.9	5.5	4.4	3.5	4.9	8.7	130	200	130	120	170	34	360
Ca	iMET1WCICP	0.1	mg/L	9.4	0.3	<0.1	8.4	6.8	22	11.5	15.8	21.1	45.2	376	685	921	906	877	52	883
Cl	iCO1WCDA	1	mg/L	196	27	26	1630	1190	1550	1250	993	1370	2920	38100	76400	44100	44000	63000	9580	128000
CO3	iALK1WATI	1	mg/L	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	147	<1
ECond	iEC1WZSE	0.2	mS/m	75.8	36.5	36.5	647	425	531	431	357	454	901	9370	15000	11100	11000	14000	2800	22000
HCO3	iALK1WATI	1	mg/L	61	<1	<1	137	70	40	79	88	52	73	122	113	268	262	210	302	146
K	iMET1WCICP	0.1	mg/L	5.8	5.1	4.9	16.9	9.2	15.5	12.6	13.7	15.8	13.6	327	583	393	386	582	91.8	1280
Mg	iMET1WCICP	0.1	mg/L	9.8	23.3	22.8	95.7	64.6	103	67.1	63.3	99.9	354	2210	3680	3290	3250	3680	506	7430
N_NO3	iNTAN1WFIA	0.01	mg/L	0.34	25	25	0.03	4	3.2	1.1	1.8	1.6	1.6	<0.01	<0.01	0.02	<0.01	<0.01	0.77	0.09
Na	iMET1WCICP	0.1	mg/L	143	18.7	17.2	1180	755	898	772	623	743	1340	22200	43900	26100	25600	38400	6030	83600
SO4_S	iMET1WCICP	0.1	mg/L	29.4	5.5	5.2	301	138	168	130	130	110	472	4980	8470	5460	5450	6440	360	11300
TDS sum	ixTDS_Sum	1	mg/L	430	190	190	3300	2200	2800	2300	1900	2400	5200	68000	130000	80000	80000	110000	17000	230000
aION_BAL	ixIONBAL	-50	%	3.2	4.3	2.3	4.9	1.1	0.9	0.9	1.7	0	-1.9	-0.2	-1.6	3.4	2.9	2.9	3.6	5.8

Appendix 6C Laboratory data (raw), major ions

Appendix Table 6-2. Major ion results from the Chemistry Centre, Western Australia for May 2009

ChemCentre ID	Method Code	Limit of Reporting	Units	08E1942/001	08E1942/002	08E1942/003	08E1942/004	08E1942/005	08E1942/006	08E1942/007	08E1942/008	08E1942/009	08E1942/010	08E1942/011	08E1942/012	08E1942/013	08E1942/014	08E1942/015	08E1942/016	08E1942/017	08E1942/018	08E1942/019
Client ID				QC3	BMC58I	BMC89OB	BMC90OB	W051	W735	W736	BMC54D	BMC55D	BMC56D	BMC56OB	BMC57D	BMC64D	BMC64I	BMC64OB	BMC87OB	BMC88OB	BMC92OB	W015
Sampled				18/05/2009	18/05/2009	18/05/2009	18/05/2009	18/05/2009	18/05/2009	18/05/2009	19/05/2009	19/05/2009	19/05/2009	19/05/2009	19/05/2009	19/05/2009	19/05/2009	19/05/2009	19/05/2009	19/05/2009	19/05/2009	19/05/2009
Br	iANIO1WAIC	0.1	mg/L	3.8	4	<0.2	3.8	5.6	5	31	150	110	3.8	10	2.4	150	140	120	120	180	320	2.9
Ca	iMET1WCICP	0.1	mg/L	23.3	22.6	<0.1	9.2	8.8	12.9	48.1	749	386	21.4	61.9	13.8	904	819	873	979	983	1120	10.7
Cl	iCO1WCDA	1	mg/L	1540	1490	52	1360	1610	1500	8860	87600	39900	1360	3410	963	58900	53800	48400	46700	67300	135000	1250
CO3	iALK1WATI	1	mg/L	<1	<1	<1	<1	<1	<1	144	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
ECond	iEC1WZSE	0.2	mS/m	540	540	48	500	589	536	2690	15300	9600	467	1120	362	14100	13000	11600	11200	15100	21800	429
HCO3	iALK1WATI	1	mg/L	43	31	<1	92	183	134	281	110	122	55	85	79	140	73	31	256	189	153	79
K	iMET1WCICP	0.1	mg/L	16.3	15.7	5.6	11.3	14.5	15.4	84.7	669	355	15.9	15.2	12.7	538	469	443	411	623	1270	11.4
Mg	iMET1WCICP	0.1	mg/L	113	108	30.7	97.1	79.1	96.7	458	3940	2370	101	487	62.7	4830	4260	3480	3450	4080	6870	66.2
N_NO3	iNTAN1WFIA	0.01	mg/L	3.9	3.9	30	2	0.03	<0.01	1.3	0.02	<0.01	1.6	1.6	1.8	0.01	<0.01	0.69	0.04	0.01	<0.01	2.1
Na	iMET1WCICP	0.1	mg/L	1010	941	21	864	1110	939	5390	47000	25000	751	1650	610	36200	31700	30100	28000	42300	75900	748
SO4_S	iMET1WCICP	0.1	mg/L	182	181	5.1	181	276	185	338	9320	5500	106	623	129	7840	7150	6190	5980	7290	11000	128
TDS sum	ixTDS_Sum	1	mg/L	2900	2800	240	2600	3200	2800	15000	150000	74000	2400	6300	1800	110000	98000	89000	86000	120000	230000	2300
aION_BAL	ixIONBAL	0.1	%	6.5	5	-1.2	2.9	1.3	1.6	1.9	-4.8	2.8	0.9	2	2.2	5.3	3.4	4.9	3.9	4.4	-1	-0.8

Appendix 6D Laboratory data (raw), major ions

Appendix Table 6-3. Major ion results from Edith Cowan University for June 2009

ECU School of Natural Sciences
Analytical Services

Date of Issue:12/07/2009
Reference:Bourke 09-01
Your Reference:Water Samples
Customer:Lindsay Bourke

Analysis Report

Sample Code	Date	Ca	K	Mg	Na	Cl⁻	Br	SO_4^{2-}	Conductivity	TDS
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mS.cm	mg/L
Reporting Limit		<0.05	<0.5	<0.05	<0.5	<0.01	<0.5	<0.5	<0.001	<1
1MilliQ		0.14	0.11	<0.05	1.2	8.7	<0.5	0.5	0.004	2.0
2Rain 1	15-Jun-09	0.95	0.12	0.33	4.1	12	<0.5	1.2	0.030	2.0
3QC4		394	310	1690	19702	38408	90	4568	95.2	75003
4Koobabbie	22-May-09	0.36	0.35	0.26	4.3	10.3	<0.5	1.5	0.021	34
5Coorow PO	22-May-09	0.28	0.17	0.33	4.9	10.1	<0.5	1.2	0.019	20
6BMC54d	17-Jun-09	732.8	562	2956	34592	63610	137	6685	151.3	135862
7BMC55d	17-Jun-09	381.6	305	1668	18700	36218	88	4203	95.1	75268
8BMC56d	17-Jun-09	22.4	12.5	106	795	1253	7.1	95	4.56	2719
9BMC56ob	17-Jun-09	57.4	12.4	398	1784	3020	9.6	454	10.65	6993
10BMC57d	16-Jun-09	16.2	12.2	65.9	730.9	1068	6.3	106	3.64	2091
11BMC58i	16-Jun-09	21.4	11.9	95	1013	1419	7.3	135	5.32	3161
12BMC89ob	15-Jun-09	0.24	3.9	29.2	20.4	34	0.2	5.2	0.383	311
13BMC90ob	16-Jun-09	11.48	8.328	87.5	978.2	1488	3.7	152	4.93	2806
14BMC93ob	20-May-09	72.3	51.3	350	3845	5625	15	487	19.01	12077
15W015	16-Jun-09	16.8	14.1	107	1411	1846	6.1	188	6.85	3964
16W017	17-Jun-09	1723.6	1134	4526	63980	102739	204	8351	201	220002
17W051	16-Jun-09	11.5	22.6	128	2198	2897	11	366	10.79	6431
18W735	17-Jun-09	10.0	11.2	74.6	639	834	6.2	100	3.42	1978
19W736	17-Jun-09	47.2	70.9	393	5106	7871	35	240	25.7	16377
		0.236	3.859	34.17	24.39					

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Appendix 6E Laboratory data (raw), major ions

Appendix Table 6-4. Major ion results from Edith Cowan University for July 2009

School of Natural Sciences
Analytical Services

Date of Issue:12/08/2009
Reference:Bourke 09-02
Your Reference:Water Samples
Customer:Lindsay Bourke

Analysis Report

Sample Code	Date	Ca	K	Mg	Na	Cl⁻	Br	Br	SO_4^{2-}	Conductivity	TDS
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mS.cm	mg/L
Reporting Limit		<0.05	<0.5	<0.05	<0.5	<0.01	<0.05	<0.2	<0.5	<0.001	<1
1Rain 1	20-Jul-09	0.48	0.07	0.17	5.2	3.89	<0.05		0.86	0.031	4.0
2Coorow PO	20-Jul-09	0.04	<0.5	<0.05	3.5	2.45	<0.05		0.95	0.020	10.0
3QC6	20-Jul-09	0.47	<0.5	0.17	5.0	3.88	<0.05		0.83	0.031	8.0
4BMC54d	22-Jul-09	747	645	3916	40290	71687		117	8317	150.7	135262
5BMC55d	21-Jul-09	388	343	2206	22812	38501		56.0	4949	94.20	73294
6BMC56d	21-Jul-09	25.7	14.6	130	893	1393		3.7	84.6	13.29	2703
7BMC56ob	21-Jul-09	84.9	15.5	258	2326	4134		9.8	617	13.26	8865
8BMC57d	21-Jul-09	16.4	14.2	80.0	718	1028		6.4	98.9	3.58	2076
9BMC58i	21-Jul-09	26.4	16.0	126.3	986	1623		4.1	135	5.31	3155
10BMC87ob	21-Jul-09	910	362	2883	24384	44841		59.6	5151	105.7	85394
11BMC88ob	22-Jul-09	870	584	3010	30872	63059		90.6	5974	136.8	117935
12BMC89ob	21-Jul-09	0.25	4.83	31.5	18.29	31.1	<0.05		6.97	0.363	215
13BMC90ob	21-Jul-09	8.59	12.5	100	835	1189		1.78	141	4.19	2466
14BMC94ob	22-Jul-09	1.70	2.95	39.3	580	638		0.98	68.8	2.47	1428
15W015	21-Jul-09	29.6	37.5	152	3629	4681		7.83	334	14.72	9226
16W016	21-Jul-09	104	56.8	201	4030	5827		7.50	451	17.71	11257
17W017	22-Jul-09	1059	268	1545	15630	23310		35.0	3270	64.90	48053
18W017 inlet	22-Jul-09	63	42.5	198	3883	5624		7.72	473	17.32	11094
19W051	21-Jul-09	4.49	17.8	49.3	963	1178		1.72	143	4.29	2538
20seep 10	22-Jul-09	16.5	14.5	69.5	3145	3424		6.37	566	12.17	8120

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Appendix 6F Laboratory data (raw), major ions

Appendix Table 6-5. Major ion results from Edith Cowan University for August 2009

School of Natural Sciences
Analytical Services

Date of Issue:25/09/2009
Reference:Bourke 09-03
Your Reference:Water Samples
Customer:Lindsay Bourke

Analysis Report

Sample Code	Date	Ca	K	Mg	Na	Cl^-	Br^-	Br	SO_4^{2-}	Conductivity	TDS
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mS.cm	mg/L
Reporting Limit		<0.05	<0.5	<0.05	<0.5	<0.01	<0.05	<0.2	<0.5	<0.001	<1
1Nitric acid		0.22	<0.5	<0.05	<0.5						
2Rain 1	26-Aug-09	0.78	<0.5	0.34	0.27	2.76	<0.05		<0.5	0.035	47
3Coorow PO	21-Aug-09	0.26	<0.5	<0.05	<0.5	0.32	0.06		<0.5	0.011	<1
4Coorow PO	24/07 to 20/08/09	0.58	<0.5	0.08	0.06	1.83	<0.05		0.6	0.024	<1
5Koobabbie	26-Aug-09	0.26	<0.5	<0.05	<0.5	1.36	0.20		<0.5	0.020	<1
6BMC89ob	26-Aug-09	0.25	4.7	31.1	21	32.6	<0.05		5.7	0.39	237
7BMC54d	27-Aug-09	731	634	3722	44352	65665		153	7858	150.80	132705
8BMC56d	26-Aug-09	24.4	14.4	119	834	1277		4.6	84	4.59	2574
9BMC56ob	26-Aug-09	92.7	14.8	688	1976	4049		8.7	558	13.64	8754
10BMC57d	26-Aug-09	15.5	12.7	72.6	631	888		5.2	84	3.48	1922
11BMC58i	26-Aug-09	25.6	14.2	118	988	1460		3.1	120	5.31	3032
12BMC87ob	27-Aug-09	994	377	3341	27214	43901		70	4761	108.600	86623
13BMC88ob	27-Aug-09	723	443	2539	28597	42482		76	3844	107.40	84136
14BMC90ob	26-Aug-09	11.0	16.2	109	1052	1457		2.5	166	5.53	3291
15QC7	26-Aug-09	11.3	16.6	101	1156	1451		2.8	168	5.54	3308
16W015	26-Aug-09	21.8	20.8	139	2031	2706		6.5	164	9.43	5627
17W016	26-Aug-09	160	88.7	540	5652	9053		31	690	28.30	18248
18BMC92OB	27-Aug-09	1491	346	1823	19798	25783		31	4245	80.20	61021
19W017 inlet	27-Aug-09	210	100	1005	7837	15073		33	1297	44.50	30684
20W051	26-Aug-09	5.4	14.6	66.5	1012	1202		4.4	135	4.67	2757
21seep 10	26-Aug-09	10.4	9.0	70.9	2385	2638		6.8	400	10.39	6743

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Appendix 6G Laboratory data (raw), major ions

Appendix Table 6-6. Major ion results from Edith Cowan University for September 2009

School of Natural Sciences
Analytical Services

Date of Issue:5/11/2009
Reference:Bourke 09-04
Your Reference:Water Samples
Customer:Lindsay Bourke

Analysis Report

Sample Code	Date	Ca	K	Mg	Na	Cl	Br	Br	SO_4^{2-}	Conductivity	TDS
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mS.cm	mg/L
Reporting Limit		<0.05	<0.5	<0.05	<0.5	<0.01	<0.05	<0.2	<0.5	<0.001	<1
1BMC89ob	24-Sep-09	0.64	3.8	26.4	24.9	49	<0.05		16	0.460	312
2QC8	24-Sep-09	0.58	3.6	23.2	25.8	50	<0.05		8	0.460	341
3Rain 1	24-Sep-09	1.08	0.6	1.03	9.4	13	<0.05		2	0.073	26
4COOROW + Koobabbie	29/08 to 21/09/09	0.95	0.5	1.24	10.9	14	<0.05		3	0.081	53
5W001	23-Sep-09	1796	397	2527	20790	37280		385	6807	101	77822
6W002	23-Sep-09	1498	209	1392	11185	21180		167	3392	63.2	47976
7W011	22-Sep-09	15.1	14.4	65	1154	1605		2.8	105	6.59	3456
8W012	22-Sep-09	26.9	144	503	13085	21006		170	611	62.0	37874
9W013	22-Sep-09	26.3	24.3	108	1236	1893		3.6	120	7.11	3795
10W015	24-Sep-09	15.1	11.2	112	1217	1881		3.3	115	7.02	3835
11W016	25-Sep-09	249	94	1025	8343	15297		71	1031	46.7	30025
12W017	25-Sep-09	2155	458	3362	31620	56156		98	6612	137	112091
13W023	22-Sep-09	57.2	16.3	136	681	1264		1.4	11	5.00	2624
14W024	22-Sep-09	15.2	6.7	60	205	402		3.7	14	1.62	911
15W051	24-Sep-09	5.94	9.8	75	793	1186		2.1	124	4.83	2627
16SEEP 10	24-Sep-09	8.51	4.6	81	2182	2880		5.4	394	10.9	6532
17BMC54d	25-Sep-09	715	504	4043	41420	71163		123	6979	164	74812
18BMC55d	25-Sep-09	410	261	2748	22410	39437		105	3961	104	139532
19BMC56d	24-Sep-09	25.1	13.2	140	781	1347		3.9	51	5.00	2779
20BMC56ob	24-Sep-09	90.1	10.7	697	2101	4665		6.3	653	15.3	10287
21BMC57d	24-Sep-09	15.8	8.9	86	651	983		9.9	101	3.84	2036
22BMC58i	24-Sep-09	26.1	11.8	139	986	1584		2.4	119	5.79	3214
23BMC87ob	24-Sep-09	959	277	3740	24290	45505		82	4212	120	94860
24BMC88ob	24-Sep-09	843	486	3252	30484	53110		106	4710	131	101508
25BMC90ob	24-Sep-09	5.71	9.8	68	878	1292		1.7	127	5.12	2801

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Appendix 6H Laboratory data (raw), major ions

Appendix Table 6-7. Major ion results from Edith Cowan University for October 2009

School of Natural Sciences
Analytical Services

Date of Issue: 10/11/2009
Reference: Bourke 09-05
Your Reference: Water Samples
Customer: Lindsay Bourke

Analysis Report

Sample Code	Date	Ca	K	Mg	Na	Cl	Br	Br	SO_4^{2-}	Conductivity	TDS
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mS.cm	mg/L
Reporting Limit		<0.05	<0.5	<0.05	<0.5	<0.01	<0.05	<0.2	<0.5	<0.001	<1
1BMC54d	20-Oct-09	717.5	534.8	3827	38860	69578		131	6182.70	165	137558
2BMC55d	20-Oct-09	405.1	264.2	2520	22260	37124		77	3415.13	103	77244
3BMC56d	20-Oct-09	25.9	13.43	130	876.8	1392		3.0	77.76	5.01	2873
4BMC56ob	20-Oct-09	91.99	11.61	677.2	2137	4245		8.5	565.1	15.0	10291
5BMC57d	20-Oct-09	16.29	9.952	74.95	711.9	998		2.3	89.65	3.90	2157
6BMC58i	19-Oct-09	26.86	12.57	128	1020	1573		3.3	123.4	5.78	3371
7BMC87ob	20-Oct-09	989	292.8	3508	25250	45153		82	3762	120	93884
8BMC88ob	20-Oct-09	728.8	363	2879	27030	49248		245	3393	128	99704
9BMC89ob	19-Oct-09	0.478	3.29	35.06	27.7	36.2	<0.05		12	0.432	317
10BMC90ob	19-Oct-09	5.515	10.09	65.46	976	1281		3.2	118	5.06	2850
11BMC92ob	20-Oct-09	1275	782.2	4394	49260	100518		159	5835	208	195343
12BMC93ob	20-Oct-09	77.2	54.25	412.8	3471	6245		14.2	428	21.3	12939
13W015	20-Oct-09	12.27	7.404	81.6	843.6	1396		3.6	103	5.56	3133
14W017	20-Oct-09	446.6	3244	20240	73380	175348		671	8795	214	365189
15W051	19-Oct-09	6.86	11.42	75.64	1033	1311		2.5	87	4.59	2522
16W735	22-Oct-09	40.14	5.97	136.6	1121	1729		3.8	106	6.48	3607
17W736	22-Oct-09	54.49	64.65	402.1	4088	7485		19.8	185	24.8	15017

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Appendix 6I Laboratory data (raw), major ions

Appendix Table 6-8. Major ion quality control results from Edith Cowan University for November 2009

School of Natural Sciences
Analytical Services

Date of Issue:10/12/2009
Reference:Bourke 09-06
Your Reference:Water Samples
Customer:Lindsay Bourke

Analysis Report

Sample Code	Date	Ca	K	Mg	Na	Cl	Br	Br	SO_4^{2-}	Conductivity	TDS
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mS.cm	mg/L
Reporting Limit		<0.05	<0.5	<0.05	<0.5	<0.01	<0.05	<0.2	<0.5	<0.001	<1
1Y21	27-Nov-09	45.9	5.1	22.17	107	147		0.27	10.2	1.006	214
2Y22	27-Nov-09	7.9	3.8	25.66	62.3	68.2		0.40	15.0	0.560	284
3QC14	24-Nov-09	0.15	4.8	25.29	22.5	29.2		0.80	19.0	0.395	500
4QC15	24-Nov-09	24.3	15.3	92.1	816	1229		2.82	73.6	5.000	2529

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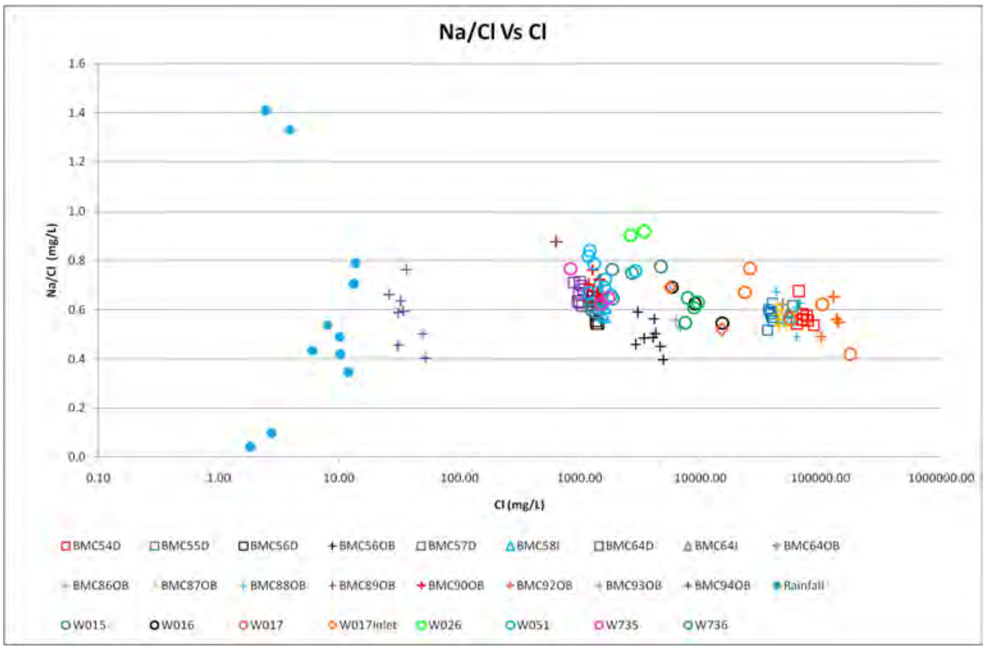
Appendix 6J Laboratory data (raw), major ions

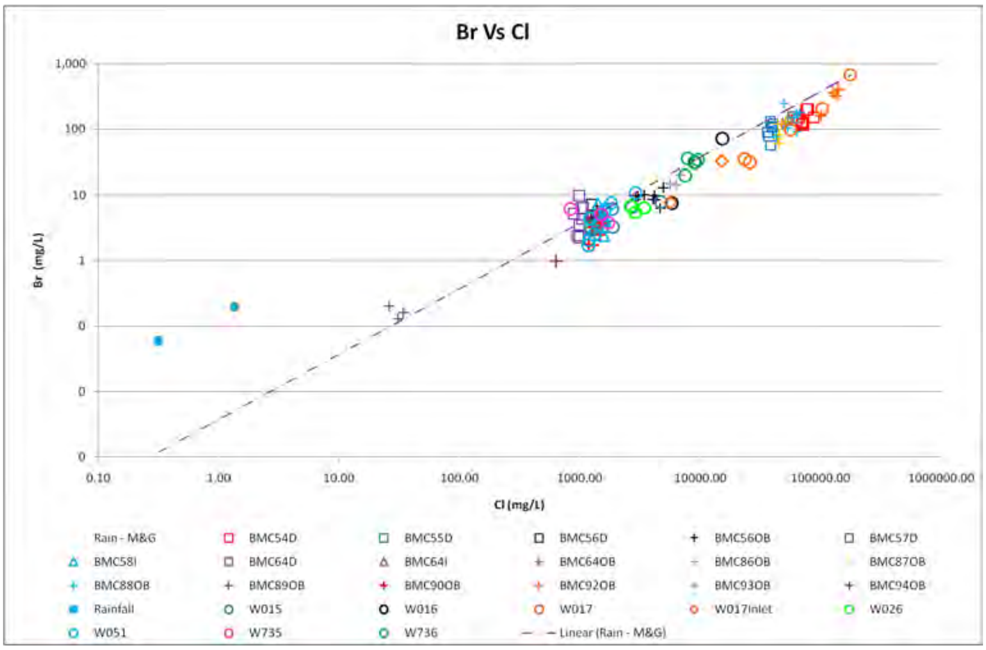
Appendix Table 6-9. Major ion results from the Chemistry Centre, Western Australia for November 2009

CCWA ID			09E0860/001	09E0860/002	09E0860/003	09E0860/004	09E0860/005	09E0860/006	09E0860/007	09E0860/008	09E0860/009	09E0860/010	09E0860/011	09E0860/012	09E0860/013	09E0860/014	09E0860/015	09E0860/016	09E0860/017	09E0860/018	09E0860/019
Client ID			BMC54D	BMC55D	BMC56D	BMC56OB	BMC57D	BMC58I	BMC87OB	BMC88OB	BMC89OB	BMC90OB	BMC92OB	BMC93OB	Rain 1	W015	W051	QC9	QC10	QC11	Koobabbie
Sampled On			24/11/2009	24/11/2009	24/11/2009	24/11/2009	24/11/2009	24/11/2009	24/11/2009	24/11/2009	24/11/2009	24/11/2009	24/11/2009	24/11/2009	24/11/2009	24/11/2009	24/11/2009	19/10/2009	19/10/2009	20/10/2009	
Br	iBRLOW1WAI	mg/L	200	120	5.6	13	4.3	4.8	130	150	0.13	5.2	400	20	<0.02	3.3	7.5	0.17	6.6	210	<0.02
Ca	iMET1WCICP	mg/L	676	314	20.2	75.3	13.4	21.5	976	766	0.1	5.5	848	68.3	1.3	9.7	7.7	0.4	4.6	682	0.5
Cl	iCO1WCDA	mg/L	77900	40100	1420	4920	1050	1600	51100	60000	31	1400	141000	6840	8	1220	1820	43	1300	76000	6
ECond	iEC1WZSE	mS/cm	151	95.6	4.69	14.2	3.72	5.41	111	126	0.383	4.92	212	20	0.088	4.29	6.32	0.412	4.71	151	0.08
K	iMET1WCICP	mg/L	652	404	15.2	15.7	12.4	15	403	548	4.2	14.3	1720	63.1	1.6	11.2	18.8	4.3	12.7	667	2.4
Mg	iMET1WCICP	mg/L	3820	2170	105	647	65.5	106	3530	3120	23.3	62.5	9480	399	1	63.5	81.7	27.4	53.3	3910	0.8
N_NO3	iNTAN1WFIA	mg/L		0.02	1.5	3	1.8	4			25	<0.10	0.07	<0.01		2.2	0.14				
N_total	iNP1WTFIA	mg/L		0.96	1.9	4	2.5	4.4			35	2.8	8.3	1.6		3.3	3.4				
Na	iMET1WCICP	mg/L	43300	22200	770	1950	646	911	27300	32900	14.1	937	77300	3630	4.3	752	1200	19	913	44100	2.6
P_SR	iP1WTFIA	mg/L		<0.01	0.01	0.01	0.01	0.01			<0.01	0.03	0.21	0.01		0.06	0.05				
P_total	iPP1WTFIA	mg/L		<0.01	0.03	0.01	0.04	0.02			0.02	0.04	0.24	0.04		0.09	0.08				
SO4	iANIO1WAIC	mg/L	9650	5520	127	860	142	194	6460	6050	6.7	160	14500	676	2.2	142	254	6.8	184	10100	2.7
TDS_180C	iSOL1WDGR	mg/L	120000	75000	2700	9000	2100	3100	92000	100000	290	2900	260000	12000	41	2300	3700	270	2700	140000	38

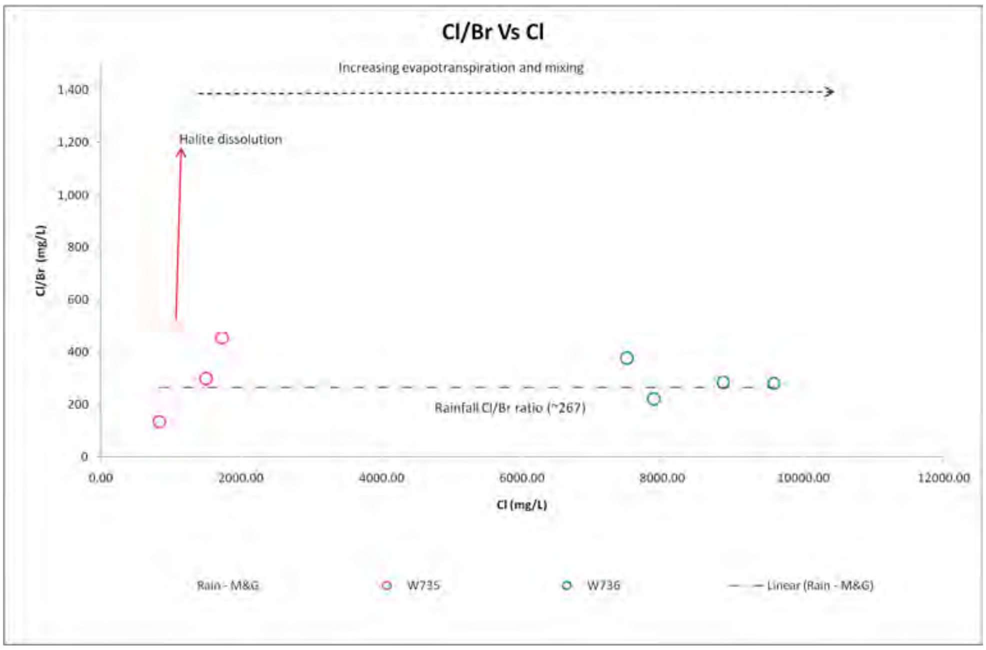
Appendix 6K Plots of major ion weight ratios



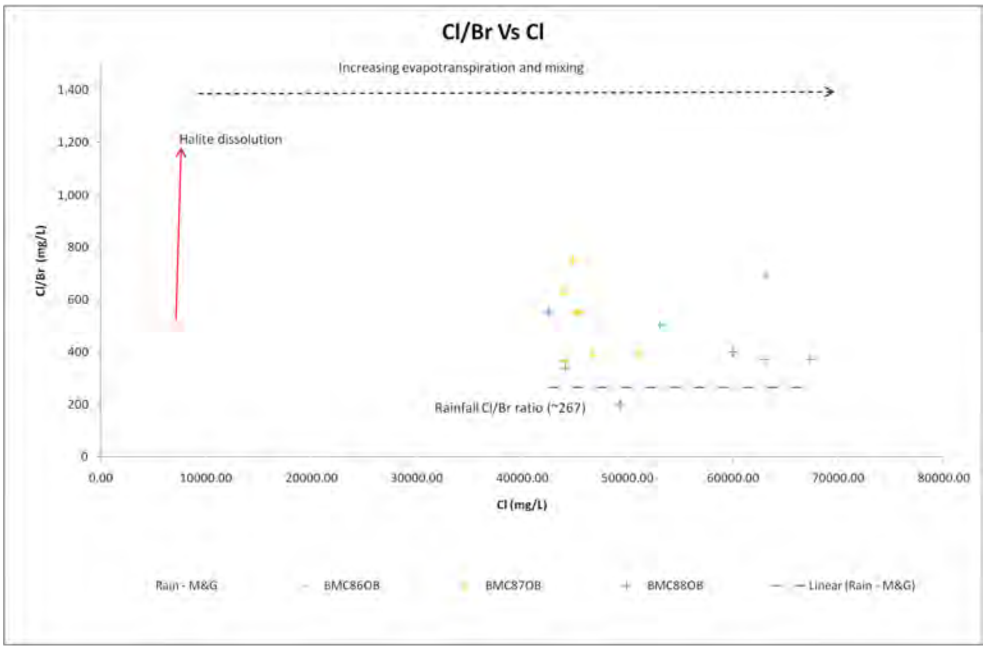
Appendix Fig 6-1. Linear/log scaled plot of Na/Cl versus Cl of Na/Cl versus Cl for groundwater, surface water and rainfall. The greatest variation was observed in rainfall samples and fresh groundwater at BMC89ob, whilst the lowest range was observed in the most saline groundwater at BMC92ob. The most depleted with respect to Na was site BMC56ob, located adjacent to wetland W016 and wetland W017, whilst the most enriched was wetland W026.



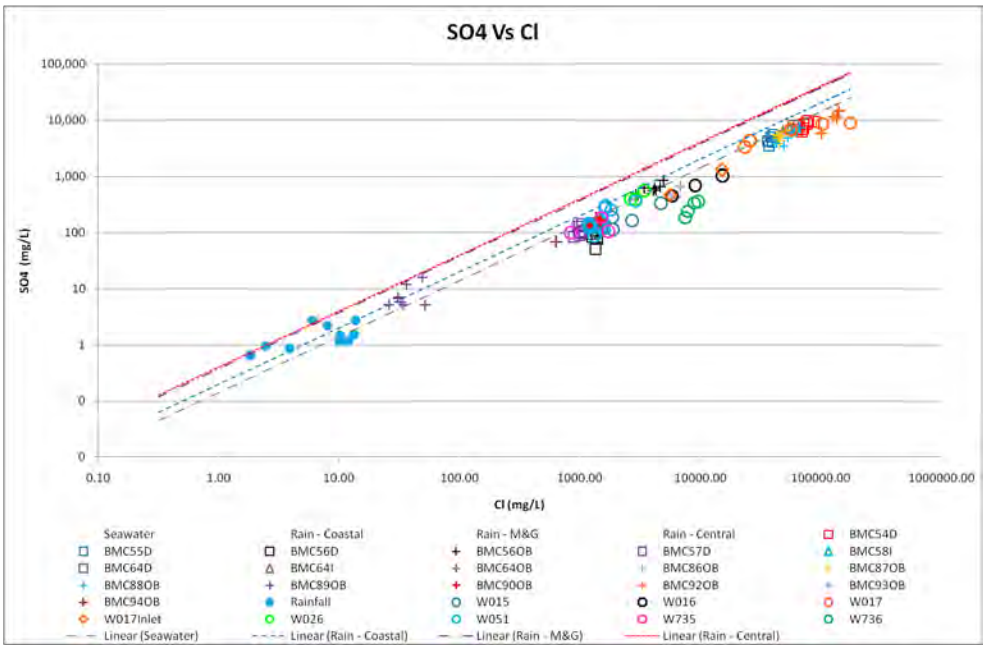
Appendix Fig 6-2. Log/log scaled plot of Br versus Cl for rainfall, groundwater and surface water data for Nabappie. The greatest variation was observed in rainfall samples and the freshest bore BMC89ob. All values plot along the Cl/Br ratio for rainfall of the central wheatbelt (Mazor & George, 1992).



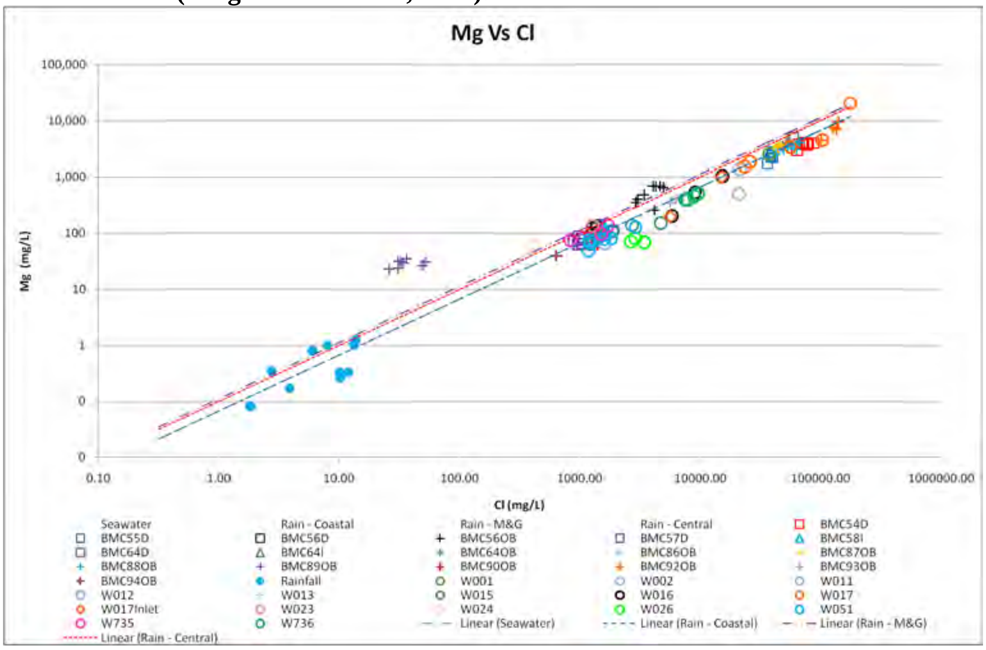
Appendix Fig 6-3. Linear scaled plot of Cl/Br versus Cl for wetlands W735 and W736 and the mean Cl/Br ratio (267) of rainfall (Mazor & George, 1992). Wetland W735 Cl/Br ratio lay above the mean rainfall Cl/Br ratio in October (455), below in June (135), and approximating the line in May, 2009 (300). Wetland W736 Cl/Br ratio lay above the mean rainfall Cl/Br line in April (282), May (286), and June (222) and lay above the line in October (378), 2009.



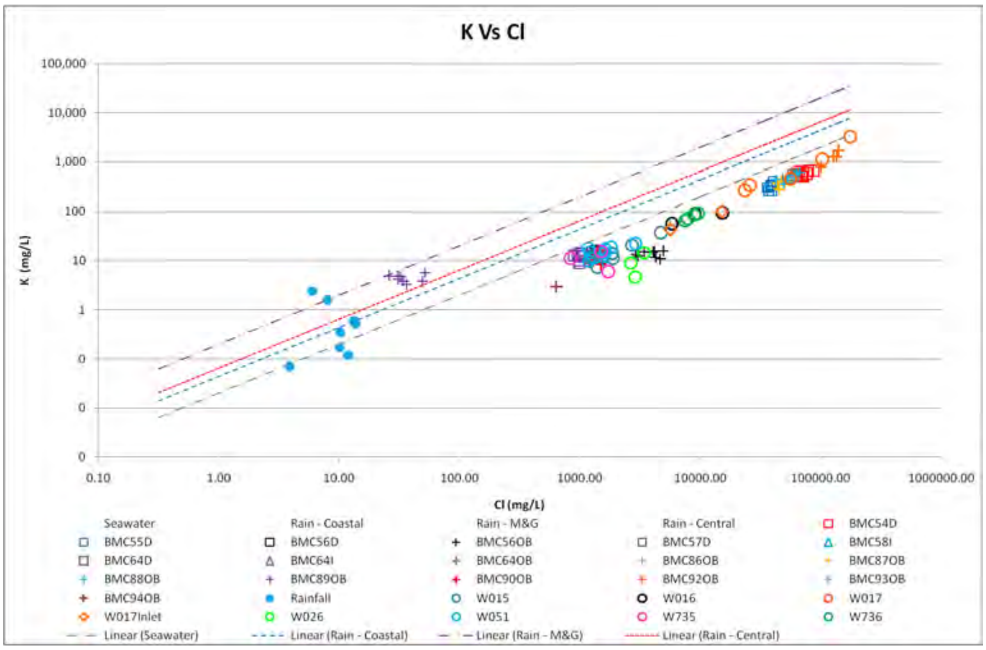
Appendix Fig 6-4. Linear scaled plot of Cl/Br versus Cl for shallow observation bores BMC86ob, BMC87ob, and BMC88ob, located on the banks of wetland W017, and the mean Cl/Br ratio (267) of rainfall (Mazor & George, 1992). The Cl/Br ratio for BMC88ob (201) in October lay below the mean rainfall Cl/Br ratio. The remaining observations all lay above the mean Cl/Br ratio of rainfall (Mazor & George, 1992). Cl/R ratios were similar for all sites, whilst a higher temporal variability of Cl was observed for BMC88ob.



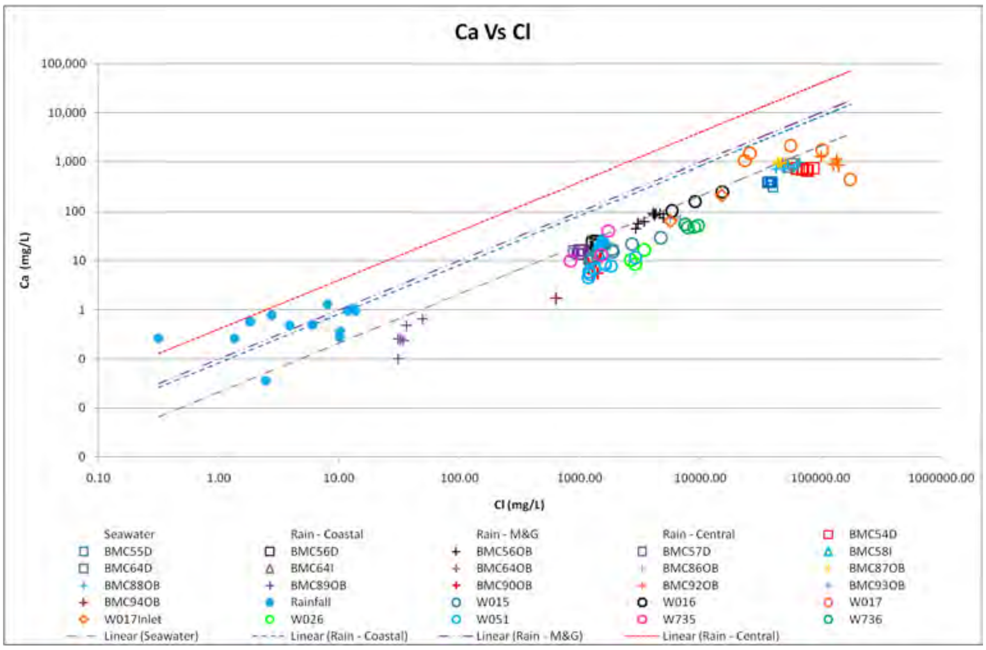
Appendix Fig 6-5. Log/log scaled plot of SO4 versus Cl for rainfall, groundwater and surface water data for Nabappie. The average SO4/Cl ratio observed was 0.12 (stdev 0.06). The greatest variation was observed in rainfall samples, whilst the lowest ratios were observed at wetland W736 (0.02 to 0.04), wetland W017 in October (0.05) and bore BMC56d (0.04) in September 2009. With the exception of rainfall and the freshest bore BMC89ob, all values plot below the SO4/Cl ratio for central rainfall (Hingston & Gailitis, 1976), and rainfall of the central wheatbelt (Mazor & George, 1992) and on or below the average SO4/Cl ratios for seawater (Hingston & Gailitis, 1976) and coastal rainfall (Hingston & Gailitis, 1976).



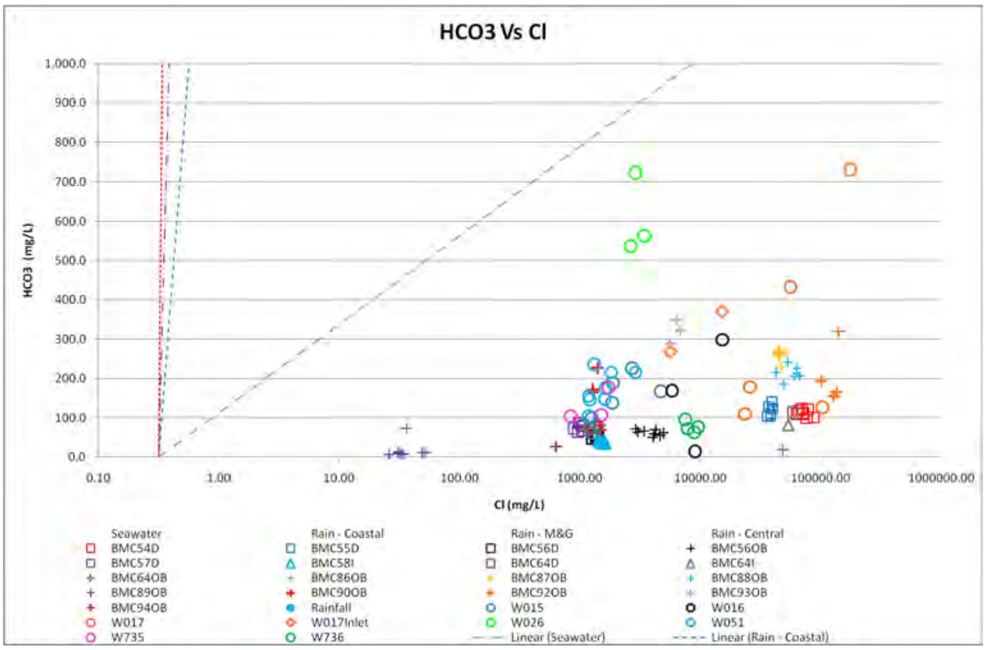
Appendix Fig 6-6. Log/log scaled plot of Mg versus Cl for rainfall, groundwater and surface water. A positive linear relationship was observed between Mg and Cl with the freshest sites BMC56d, BMC56ob, BMC57d, BMC58i and wetland W736, laying closest to the linear reference for central rainfall (Hingston & Gailitis, 1976), and the central wheatbelt rainfall (Mazor & George, 1992). The majority of the wetlands and saline groundwater lay along or below the linear reference for coastal rainfall and seawater (Hingston & Gailitis, 1976). Site BMC89ob was notably enriched with Mg relative to other water samples.



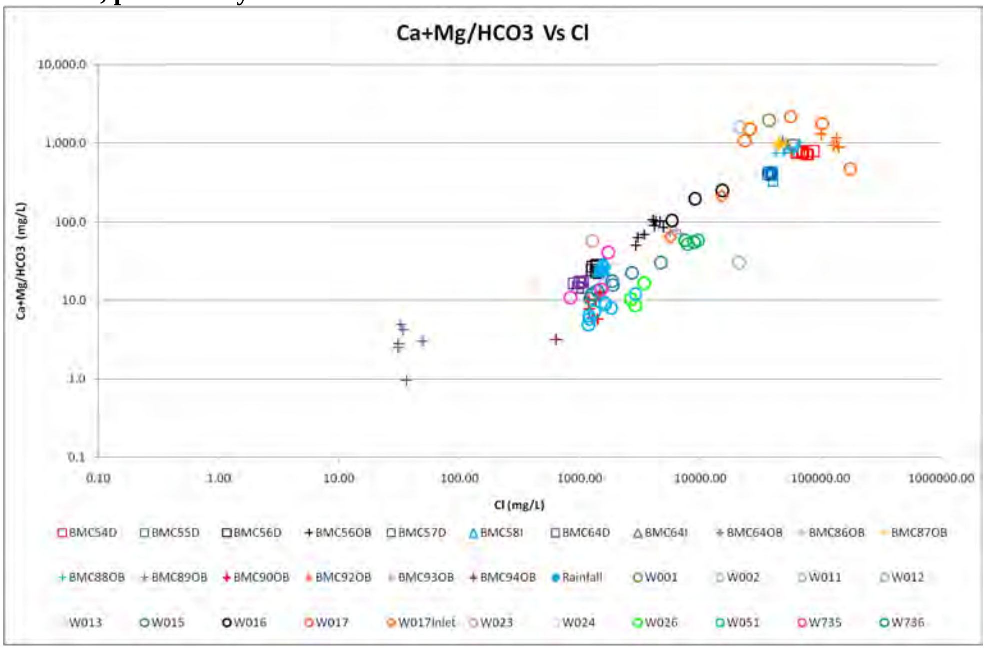
Appendix Fig 6-7. Log/log plot of K versus Cl for rainfall, groundwater and surface water. A positive linear trend was observed between K and Cl with rainfall being the most variable and the freshest groundwater site (BMC89ob) laying above the line for central rainfall (Hingston & Gailitis, 1976). The remainder of sites lay on or below the linear reference for seawater (Hingston & Gailitis, 1976).



Appendix Fig 6-8. Log/log plot of Ca versus Cl for rainfall, groundwater and surface water. A positive linear trend was observed between Ca and Cl with rainfall being the most variable. In July, August and September wetland W017 lay above the linear reference for seawater (Hingston & Gailitis, 1976), whilst the remaining samples and sites all lay on or below this reference.



Appendix Fig 6-9. A linear plot of HCO3 versus Cl for rainfall, groundwater and surface water. There was a general trend of increasing alkalinity with increasing Cl with the lowest HCO3 values at the freshest bore BMC89ob and the highest at W017. Increases in alkalinity were most notable at wetlands, particularly wetland W026.



Appendix Fig 6-10. Log/log scaled plot of Ca+Mg/HCO3 versus Cl of groundwater and surface water (rainfall excluded). A positive linear trend was observed with Ca+Mg/HCO3 increasing with Cl. The greatest range of Ca+Mg/HCO3 in groundwater was observed for freshest groundwater site (BMC89ob) followed by BMC90ob. Whilst wetland W017 was observed to have the largest range for wetlands.

Appendix 6L   Laboratory data (raw), stable water isotopes (δD and $\delta^{18}O$)

Natural Isotopes

ABN 25 410 057 226

Stable Isotope Results

Notes: Nil.

Laboratory Check Standard (NIWLCS-2)

	n	δ^2H_{VSMOW} (permil)	δ^2H_{VSMOW} Standard Deviation (permil)	$\delta^{18}O_{VSMOW}$ (permil)	$\delta^{18}O_{VSMOW}$ Standard Deviation (permil)
Reported	40	-18.4	0.7	-3.93	0.07
Expected	n/a	-18.7	n/a	-3.90	n/a

Samples

Sample Code	Date	δ^2H_{VSMOW} (permil)	δ^2H_{VSMOW} Standard Deviation (permil)	$\delta^{18}O_{VSMOW}$ (permil)	$\delta^{18}O_{VSMOW}$ Standard Deviation (permil)
Coorow PO	21/05/2009	-7.1	0.6	-3.39	0.08
Coorow PO	23/05/2009	3.1	0.6	-2.83	0.03
Coorow PO	24/05/2009	-17.6	0.8	-4.28	0.01
Coorow PO	28/05/2009	16.6	0.6	0.79	0.02
Coorow PO	2/06/2009	4.6	0.6	-1.47	0.02
Coorow PO	10/06/2009	-1.9	0.7	-2.65	0.04
Coorow PO	11/06/2009	-3.9	0.4	-2.80	0.07
Coorow PO	12/06/2009	-5.7	0.9	-3.30	0.05
Coorow PO	19/06/2009	-0.4	0.9	-3.01	0.04
Coorow PO	20/06/2009	-12.3	0.5	-4.33	0.08
Coorow PO	22/06/2009	-1.8	0.9	-3.48	0.02
Coorow PO	24/06/2009	-15.6	0.4	-3.30	0.08
Coorow PO	25/06/2009	-17.4	1.0	-5.16	0.02
Coorow PO	27/06/2009	-13.6	0.5	-4.53	0.07
Coorow PO	29/06/2009	2.1	0.6	-2.76	0.01
Coorow PO	30/06/2009	-6.1	0.8	-3.19	0.08
Coorow PO	1/07/2009	15.6	0.8	-1.78	0.01
Coorow PO	6/07/2009	-48.4	0.7	-6.79	0.01
Coorow PO	9/07/2009	-17.2	0.3	-4.17	0.07
Coorow PO	16/07/2009	16.0	0.7	-2.16	0.05
Coorow PO	17/07/2009	-4.2	0.7	-3.09	0.10
Coorow PO	21/07/2009	-17.2	0.6	-5.61	0.05
Coorow PO	22/07/2009	-9.4	0.4	-3.66	0.01
Koobabbie	21/05/2009	-9.6	0.9	-3.76	0.08
Koobabbie	22/05/2009	-7.8	0.3	-3.49	0.05
Koobabbie	23/05/2009	5.1	0.7	-2.82	0.07
Koobabbie	24/05/2009	-12.3	0.4	-3.89	0.05
Koobabbie	28/05/2009	21.9	0.5	1.54	0.06

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Appendix 6M

Stable Isotope Results

	n	δ^2H_{VSMOW} (permil)	δ^2H_{VSMOW} Standard Deviation (permil)	$\delta^{18}O_{VSMOW}$ (permil)	$\delta^{18}O_{VSMOW}$ Standard Deviation (permil)
Koobabbie	2/06/2009	13.4	1.0	-0.70	0.05
Koobabbie	4/06/2009	2.8	0.9	-2.16	0.04
Koobabbie	10/06/2009	6.7	0.6	-1.77	0.02
Koobabbie	11/06/2009	-4.3	0.3	-2.77	0.06
Koobabbie	12/06/2009	-11.1	1.0	-3.71	0.02
Koobabbie	19/06/2009	-4.3	0.4	-2.74	0.04
Koobabbie	20/06/2009	-13.6	0.4	-3.67	0.06
Koobabbie	21/06/2009	-4.5	0.9	-3.22	0.02
Koobabbie	24/06/2009	-3.3	0.9	-1.30	0.03
Koobabbie	25/06/2009	-14.8	0.6	-4.66	0.08
Koobabbie	27/06/2009	-10.9	0.8	-3.98	0.08
Koobabbie	28/06/2009	5.3	0.3	-2.32	0.05
Koobabbie	29/06/2009	-11.5	0.7	-3.70	0.03
Koobabbie	30/06/2009	-3.6	0.7	-2.91	0.07
Koobabbie	1/07/2009	15.6	0.3	-2.42	0.02
Koobabbie	6/07/2009	-50.3	0.9	-6.72	0.05
Koobabbie	7/07/2009	-16.6	0.4	-4.01	0.01
Koobabbie	9/07/2009	-13.9	0.9	-4.15	0.09
Koobabbie	10/07/2009	-17.5	0.7	-4.58	0.09
Koobabbie	11/07/2009	-1.0	0.4	-2.73	0.05
Koobabbie	16/07/2009	16.3	0.7	-2.09	0.10
Koobabbie	17/07/2009	-2.6	0.6	-2.66	0.01
Koobabbie	19/07/2009	-13.2	0.6	-5.48	0.02
Koobabbie	20/07/2009	-28.8	0.9	-5.61	0.05
Koobabbie	21/07/2009	-15.4	0.3	-4.75	0.09
Koobabbie	22/07/2009	-13.4	0.9	-4.11	0.06
BMC56d	26/08/2009	-26.4	1.0	-4.94	0.01
BMC56ob	26/08/2009	-24.4	0.5	-4.51	0.09
BMC57d	26/08/2009	-26.3	0.8	-5.00	0.02
BMC58i	26/08/2009	-24.6	0.7	-4.58	0.08
BMC87ob	27/08/2009	-20.5	0.6	-2.71	0.08
BMC88ob	27/08/2009	-19.7	0.7	-2.58	0.09
BMC89ob	26/08/2009	-27.0	1.0	-4.73	0.06
BMC90ob	26/08/2009	-18.4	0.6	-3.70	0.06
QC7		-17.8	0.3	-3.48	0.03
W015	26/08/2009	-18.3	0.4	-3.64	0.04
W016	26/08/2009	3.3	0.3	0.21	0.07
BMC92ob	27/08/2009	9.7	1.0	0.97	0.02
W017_INLET	27/08/2009	-7.3	0.6	-1.29	0.09
W051	26/08/2009	-18.0	0.6	-3.59	0.05
SEEP10	26/08/2009	-14.7	0.7	-2.98	0.09
Coorow PO	13/08/2009	-0.4	0.4	-2.29	0.00
Coorow PO	23/07/2009	15.6	0.4	-1.26	0.06
Coorow PO	24/08/2009	-5.8	0.3	-2.54	0.01
Coorow PO	7/08/2009	0.0	0.8	-1.16	0.07
Coorow PO	10/08/2009	5.6	0.6	-0.98	0.05

Natural Isotopes
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Stable Isotope Results

	n	δ^2H_{VSMOW} (permil)	δ^2H_{VSMOW} Standard Deviation (permil)	$\delta^{18}O_{VSMOW}$ (permil)	$\delta^{18}O_{VSMOW}$ Standard Deviation (permil)
Coorow PO	11/08/2009	-7.5	0.5	-2.71	0.08
Coorow PO	14/08/2009	-4.8	0.3	-2.80	0.02
Coorow PO	17/08/2009	-4.5	0.5	-2.20	0.06
Coorow PO	20/08/2009	-2.1	1.0	-2.35	0.03
Coorow PO	21/08/2009	-36.8	0.7	-6.37	0.02
Coorow PO	24/07/2009	-41.3	0.8	-6.97	0.07
Koobabbie	24/07/2009	-42.9	0.7	-7.31	0.07
Koobabbie	25/07/2009	4.0	0.8	-3.37	0.05
Koobabbie	7/08/2009	3.9	0.9	-0.04	0.06
Koobabbie	10/08/2009	-10.4	0.6	-3.04	0.09
Koobabbie	11/08/2009	-5.0	0.5	-2.56	0.03
Koobabbie	12/08/2009	3.2	0.6	-2.18	0.02
Koobabbie	13/08/2009	-5.0	0.3	-3.06	0.04
Koobabbie	14/08/2009	3.1	0.8	-2.24	0.04
Koobabbie	15/08/2009	-2.7	0.3	-2.04	0.05
Koobabbie	16/08/2009	16.9	0.6	-0.86	0.03
Koobabbie	19/08/2009	-5.7	0.6	-2.99	0.09
Koobabbie	20/08/2009	-2.6	1.0	-2.03	0.04
Koobabbie	21/08/2009	-29.7	0.5	-5.48	0.09
Koobabbie	22/08/2009	-2.2	0.7	-1.66	0.00
Koobabbie	23/08/2009	-1.9	0.3	-1.60	0.09
Rain 1	26/08/2009	-11.9	0.9	-3.41	0.05
BMC54d	27/08/2009	-14.3	0.6	-0.58	0.04
W001	23/09/2009	29.6	0.8	4.98	0.07
W002	23/09/2009	19.0	0.8	2.33	0.00
W011	22/09/2009	8.4	0.3	1.73	0.02
W012	22/09/2009	16.2	0.5	1.25	0.04
W013	22/09/2009	11.1	0.8	2.12	0.05
W015	24/09/2009	-16.5	0.6	-3.65	0.04
W016	25/09/2009	27.6	0.5	4.66	0.00
W023	22/09/2009	31.4	0.5	5.80	0.01
W017	25/09/2009	7.1	0.7	1.40	0.07
W024	22/09/2009	-7.3	0.4	-1.81	0.03
W051	24/09/2009	-16.7	1.0	-2.88	0.00
Seep 10	24/09/2009	-6.3	0.7	-1.10	0.04
BMC54d	25/09/2009	-13.9	0.7	-0.71	0.08
BMC55d	25/09/2009	-19.2	0.8	-2.64	0.02
BMC56d	24/09/2009	-24.8	0.3	-4.70	0.10
BMC56ob	24/09/2009	-24.0	0.4	-4.55	0.09
BMC57d	24/09/2009	-24.8	0.3	-4.69	0.04
BMC58i	24/09/2009	-25.6	0.6	-4.60	0.07
BMC87ob	24/09/2009	-19.9	0.7	-2.45	0.05
BMC88ob	24/09/2009	-17.0	0.4	-2.81	0.08
BMC89ob	24/09/2009	-25.1	0.5	-4.52	0.07
BMC90ob	24/09/2009	-17.2	0.6	-3.27	0.04
QC8	24/09/2009	-27.2	0.7	-4.96	0.10

Natural Isotopes

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Stable Isotope Results

	n	$\delta^{2}H_{VSMOW}$ (permil)	$\delta^{2}H_{VSMOW}$ Standard Deviation (permil)	$\delta^{18}O_{VSMOW}$ (permil)	$\delta^{18}O_{VSMOW}$ Standard Deviation (permil)
Rain1	24/09/2009	-2.9	0.7	-2.23	0.07
Koobabbie	29/08/2009	-41.2	0.8	-6.94	0.06
Koobabbie	2/09/2009	-2.3	0.6	-2.54	0.07
Koobabbie	5/09/2009	-3.1	0.3	-2.86	0.01
Koobabbie	6/09/2009	11.5	0.9	-1.64	0.03
Koobabbie	8/09/2009	21.5	0.4	1.97	0.03
Koobabbie	11/09/2009	18.0	0.9	0.30	0.09
Koobabbie	12/09/2009	0.8	0.3	-0.25	0.00
Koobabbie	16/09/2009	-5.2	0.3	-2.11	0.06
Koobabbie	18/09/2009	-2.7	0.4	-2.09	0.09
Koobabbie	21/09/2009	3.6	0.8	-1.74	0.09
Coorow PO	7/09/2009	3.9	0.7	-2.47	0.07
Coorow PO	14/09/2009	4.1	0.6	-0.11	0.06
Coorow PO	2/09/2009	-17.7	0.9	-4.09	0.04
Coorow PO	8/09/2009	-0.3	0.6	-1.97	0.02
Coorow PO	11/09/2009	9.8	0.5	-1.18	0.02
Coorow PO	16/09/2009	-17.4	0.3	-3.87	0.06
Coorow PO	18/09/2009	-0.6	0.7	-2.26	0.03
Coorow PO	21/09/2009	2.6	0.4	-2.46	0.05
W015	20/10/2009	-21.2	0.9	-4.58	0.05
W017	20/10/2009	36.4	0.7	13.40	0.00
W051	19/10/2009	-15.0	1.0	-3.30	0.07
W735	22/10/2009	-3.8	0.3	-0.80	0.08
W736	22/10/2009	17.5	0.6	2.25	0.01
Coorow PO	29/09/2009	-25.6	0.9	-6.02	0.08
Coorow PO	30/09/2009	-49.5	0.6	-8.81	0.10
Koobabbie	29/09/2009	-3.6	1.0	-3.14	0.05
Koobabbie	30/09/2009	-51.2	0.3	-9.16	0.09
QC9		-22.1	0.7	-4.59	0.09
QC10		-17.3	0.9	-3.25	0.03
QC11		-8.2	0.4	-0.22	0.03
BMC54D	20/10/2009	-7.3	0.3	-0.44	0.06
BMC55D	20/10/2009	-18.4	0.8	-3.10	0.05
BMC56D	20/10/2009	-23.2	0.8	-4.70	0.04
BMC56OB	20/10/2009	-22.9	0.3	-4.60	0.04
BMC57D	20/10/2009	-24.1	0.3	-4.79	0.03
BMC58I	19/10/2009	-21.6	0.9	-5.03	0.08
BMC87OB	20/10/2009	-20.2	0.5	-2.63	0.07
BMC88OB	20/10/2009	-16.5	0.6	-2.95	0.06
BMC89OB	19/10/2009	-24.0	0.3	-4.88	0.00
BMC90OB	19/10/2009	-17.0	0.4	-3.40	0.05
BMC92OB	20/10/2009	2.6	1.0	1.38	0.03
BMC93OB	20/10/2009	-18.6	0.3	-3.95	0.08
Rain 1		-24.6	0.4	-5.49	0.04

Natural Isotopes

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Stable Isotope Results

Notes: Nil.

Laboratory Check Standard (NIWLCS-2)

	n	δ^2H_{VSMOW} (permil)	δ^2H_{VSMOW} Standard Deviation (permil)	$\delta^{18}O_{VSMOW}$ (permil)	$\delta^{18}O_{VSMOW}$ Standard Deviation (permil)
Reported	32	-18.8	0.4	-3.89	0.03
Expected	n/a	-18.7	n/a	-3.90	n/a

Samples

Sample Code	Date	δ^2H_{VSMOW} (permil)	δ^2H_{VSMOW} Standard Deviation (permil)	$\delta^{18}O_{VSMOW}$ (permil)	$\delta^{18}O_{VSMOW}$ Standard Deviation (permil)
GS017	21/04/2009	-22.4	0.4	-3.55	0.03
KAU_220409	22/04/2009	-32.4	0.8	-5.98	0.09
QC2	20/04/2009	-19.0	0.7	-3.23	0.07
W051	20/04/2009	-19.4	0.3	-2.96	0.10
W736	22/04/2009	26.6	0.7	5.70	0.06
BMC54d	21/04/2009	-8.7	0.8	0.00	0.10
BMC55d	21/04/2009	-17.0	0.0	-2.49	0.09
BMC56d	21/04/2009	-24.6	0.0	-4.40	0.05
BMC56ob	21/04/2009	-22.6	0.3	-3.75	0.01
BMC57d	21/04/2009	-22.8	1.0	-4.12	0.08
BMC58i	21/04/2009	-22.6	0.8	-3.81	0.03
BMC86ob	22/04/2009	-18.1	0.1	-1.66	0.04
BMC87ob	22/04/2009	-20.4	0.5	-2.31	0.04
BMC88ob	22/04/2009	-15.1	0.6	-1.36	0.00
BMC89ob	20/04/2009	-19.5	0.7	-3.42	0.04
BMC90ob	21/04/2009	-21.0	0.0	-3.75	0.09
BMC92ob	22/04/2009	11.4	0.1	3.80	0.07
BMC54d	22/07/2009	-10.2	0.1	0.00	0.04
BMC55d	21/07/2009	-18.0	0.4	-2.36	0.00
BMC56d	21/07/2009	-26.4	0.5	-4.70	0.06
BMC56ob	21/07/2009	-24.3	0.7	-4.20	0.04
BMC57d	21/07/2009	-24.7	0.5	-4.43	0.10
BMC58i	21/07/2009	-24.8	1.0	-4.17	0.03
BMC87ob	22/07/2009	-21.0	0.7	-2.75	0.01
BMC88ob	22/07/2009	-16.4	0.3	-1.97	0.12
BMC89ob	21/07/2009	-23.0	0.9	-4.15	0.02
BMC90ob	21/07/2009	-20.9	0.4	-3.66	0.08
BMC94ob	22/07/2009	-16.4	1.0	-4.21	0.10

Natural Isotopes

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Stable Isotope Results

	n	δ^2H_{VSMOW} (permil)	δ^2H_{VSMOW} Standard Deviation (permil)	$\delta^{18}O_{VSMOW}$ (permil)	$\delta^{18}O_{VSMOW}$ Standard Deviation (permil)
Coorow PO	20/07/2009	-23.9	0.1	-4.93	0.12
QC6	20/07/2009	-9.5	0.8	-3.11	0.00
RAIN1	20/07/2009	-10.6	0.6	-3.50	0.12
SEEP10	22/07/2009	-9.6	0.2	-2.27	0.09
W015	21/07/2009	-12.1	0.0	-2.74	0.10
W016	21/07/2009	-12.7	0.2	-3.15	0.08
W017	22/07/2009	-2.9	0.6	-1.30	0.10
W017_INLET	22/07/2009	-10.3	0.2	-2.49	0.00
W051	21/07/2009	-17.7	0.7	-4.25	0.09
BMC54d	17/06/2009	-10.2	0.6	-0.23	0.11
BMC55d	17/06/2009	-18.5	0.6	-2.74	0.12
BMC56d	17/06/2009	-22.7	1.0	-4.20	0.11
BMC56ob	17/06/2009	-24.9	0.3	-4.64	0.03
BMC57d	16/06/2009	-25.1	0.2	-4.99	0.01
BMC58i	16/06/2009	-17.6	0.5	-3.64	0.03
BMC89ob	15/06/2009	-21.4	1.0	-3.68	0.03
BMC90ob	16/06/2009	-15.8	0.8	-3.79	0.11
BMC93ob	20/05/2009	-10.9	0.7	-3.08	0.07
W015	16/06/2009	-13.3	0.2	-2.76	0.08
W017	17/06/2009	19.0	0.8	4.44	0.06
W051	16/06/2009	-15.5	0.1	-3.07	0.09
W735	17/06/2009	-3.1	0.3	-1.67	0.11
W736	17/06/2009	24.6	0.2	4.22	0.04
Rain 1	15/06/2009	-3.6	0.9	-2.90	0.04
QC4	-	-18.5	0.8	-2.92	0.06
MilliQ	-	No Sample Provided			
Koobabbie	22/05/2009	-2.4	0.9	-2.99	0.11
Coorow PO	22/05/2009	-2.4	0.3	-2.97	0.12
BMC54d	19/05/2009	-6.4	0.8	-0.14	0.09
BMC55d	19/05/2009	-16.0	0.8	-2.50	0.07
BMC56d	19/05/2009	-23.0	0.3	-4.05	0.01
BMC56ob	19/05/2009	-20.8	0.2	-3.91	0.07
BMC57d	19/05/2009	-26.2	0.4	-4.92	0.12
BMC58i	18/05/2009	-22.5	0.4	-3.95	0.07
BMC64d	19/05/2009	-16.7	0.7	-1.21	0.10
BMC64i	19/05/2009	-17.2	0.5	-1.66	0.07
BMC64ob	19/05/2009	-17.8	0.8	-1.75	0.11
BMC87ob	19/05/2009	-19.0	0.8	-2.55	0.11
BMC88ob	19/05/2009	-14.3	0.3	-1.58	0.08
BMC89ob	18/05/2009	-17.4	0.8	-3.55	0.06
BMC90ob	18/05/2009	-21.7	0.7	-3.94	0.02
BMC92ob	19/05/2009	3.2	0.9	2.64	0.11
BMC93ob	20/05/2009	No Sample Provided			
W015	19/05/2009	-21.3	0.0	-4.53	0.08
W051	18/05/2009	-20.1	0.0	-4.35	0.00
W735	18/05/2009	-9.1	0.3	-1.98	0.02

Natural Isotopes

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Stable Isotope Results

Notes: Nil.

Laboratory Check Standard (NIWLCS-2)

	n	$\delta^{2}H_{VSMOW}$ (permil)	$\delta^{2}H_{VSMOW}$ Standard Deviation (permil)	$\delta^{18}O_{VSMOW}$ (permil)	$\delta^{18}O_{VSMOW}$ Standard Deviation (permil)
Reported	92	-18.8	0.7	-3.96	0.13
Expected	n/a	-18.7	n/a	-3.90	n/a

Samples

Sample Code	Date	$\delta^{2}H_{VSMOW}$ (permil)	$\delta^{2}H_{VSMOW}$ Standard Deviation (permil)	$\delta^{18}O_{VSMOW}$ (permil)	$\delta^{18}O_{VSMOW}$ Standard Deviation (permil)
BMC54D	24/11/2009	-10.8	0.7	-0.01	0.11
BMC55D	24/11/2009	-19.3	0.4	-2.74	0.05
BMC56D	24/11/2009	-25.6	0.7	-4.65	0.07
BMC56OB	24/11/2009	-25.1	1.0	-4.44	0.20
BMC57D	24/11/2009	-26.7	1.0	-4.88	0.14
BMC58I	24/11/2009	-25.8	0.9	-4.74	0.04
BMC87OB	24/11/2009	-21.9	0.4	-2.61	0.11
BMC88OB	24/11/2009	-17.2	1.0	-1.96	0.06
BMC89OB	24/11/2009	-25.2	0.3	-4.33	0.07
BMC90OB	24/11/2009	-17.8	1.2	-2.98	0.11
BMC92OB	24/11/2009	7.9	0.6	4.58	0.09
BMC93OB	24/11/2009	-22.5	1.2	-3.75	0.18
Rain 1	24/11/2009	-3.5	0.9	-1.24	0.16
W015	24/11/2009	-24.8	1.2	-4.19	0.16
W051	24/11/2009	-10.6	1.8	-0.82	0.19
Coorow PO	20/11/2009	-35.2	2.7	-4.76	0.25
Coorow PO	29/09/2009	-30.4	1.0	-6.25	0.25
Coorow PO	30/09/2009	-53.1	1.9	-8.99	0.16
Coorow PO	12/11/2009	50.2	1.0	8.99	0.09
Coorow PO	27/10/2009	-2.1	0.5	-1.73	0.18
Coorow PO	19/11/2009	-6.2	1.1	-1.99	0.31
Coorow PO	26/10/2009	7.2	0.7	1.72	0.17
Coorow PO	13/11/2009	29.4	1.6	4.31	0.13
Koobabbie	12/11/2009	43.8	0.8	10.37	0.10
Koobabbie	26/10/2009	10.6	0.4	2.52	0.09
Koobabbie	30/09/2009	-54.0	1.0	-9.06	0.17
Koobabbie	29/09/2009	-7.1	1.2	-2.65	0.09
Koobabbie	13/11/2009	31.3	1.5	4.40	0.11

Natural Isotopes

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Stable Isotope Results

	n	$\delta^{2}H_{VSMOW}$ (permil)	$\delta^{2}H_{VSMOW}$ Standard Deviation (permil)	$\delta^{18}O_{VSMOW}$ (permil)	$\delta^{18}O_{VSMOW}$ Standard Deviation (permil)
Koobabbie	6/11/2009	66.8	1.1	11.84	0.14
Koobabbie	27/10/2009	0.7	1.4	-1.30	0.17
Koobabbie	19/11/2009	-13.1	0.8	-2.98	0.16
Koobabbie	20/11/2009	-35.0	0.4	-5.05	0.08
QC14	24/11/2009	-23.6	0.8	-4.27	0.16
QC15	24/11/2009	-24.8	1.3	-4.53	0.12

Natural Isotopes

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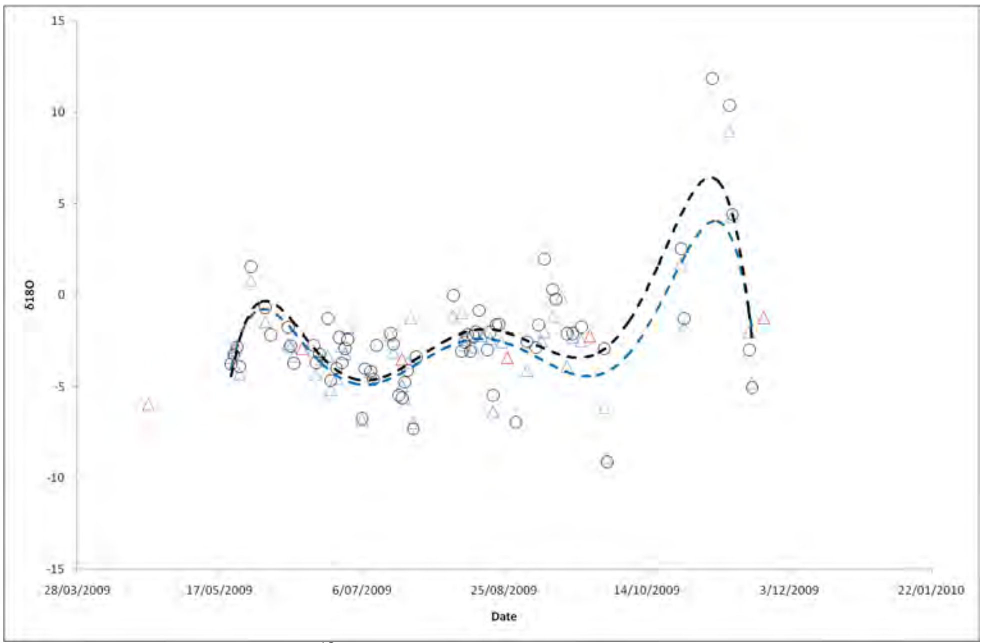
Stable Isotope Results

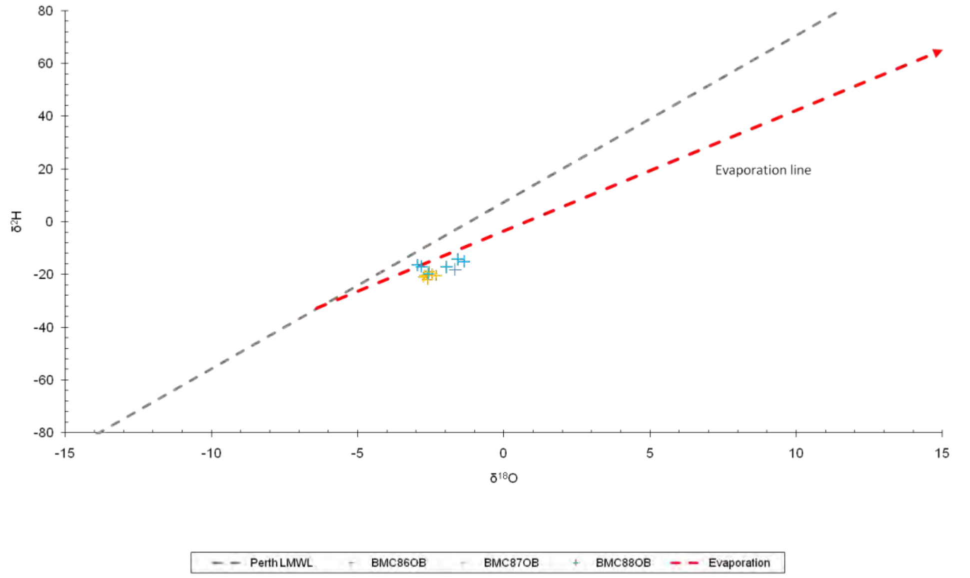
	n	$\delta^{2}H_{VSMOW}$ (permil)	$\delta^{2}H_{VSMOW}$ Standard Deviation (permil)	$\delta^{18}O_{VSMOW}$ (permil)	$\delta^{18}O_{VSMOW}$ Standard Deviation (permil)
W736	18/05/2009	22.0	0.6	4.36	0.07
QC3	18/05/2009	-26.6	0.5	-4.21	0.00

Appendix 6N

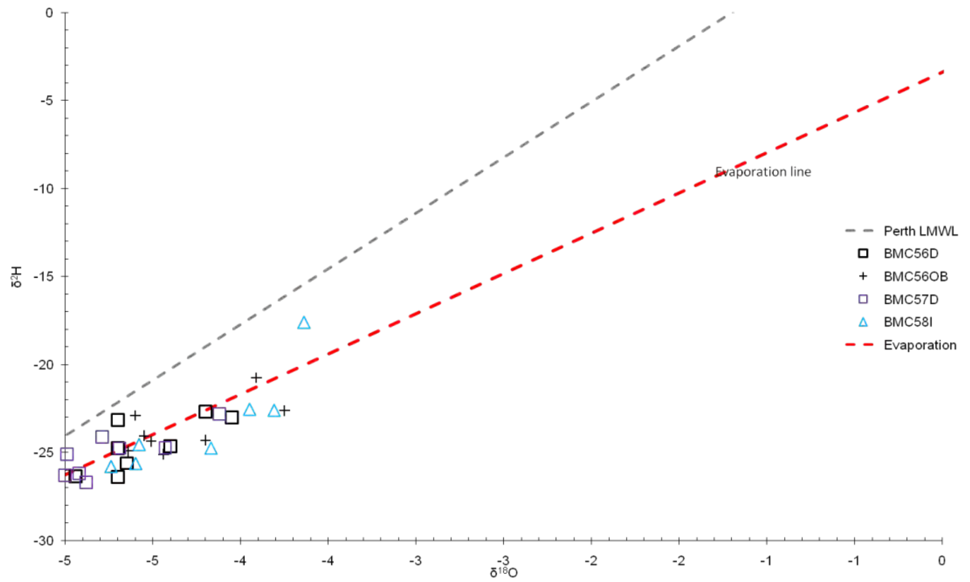
Appendix 6O Stable isotope plots



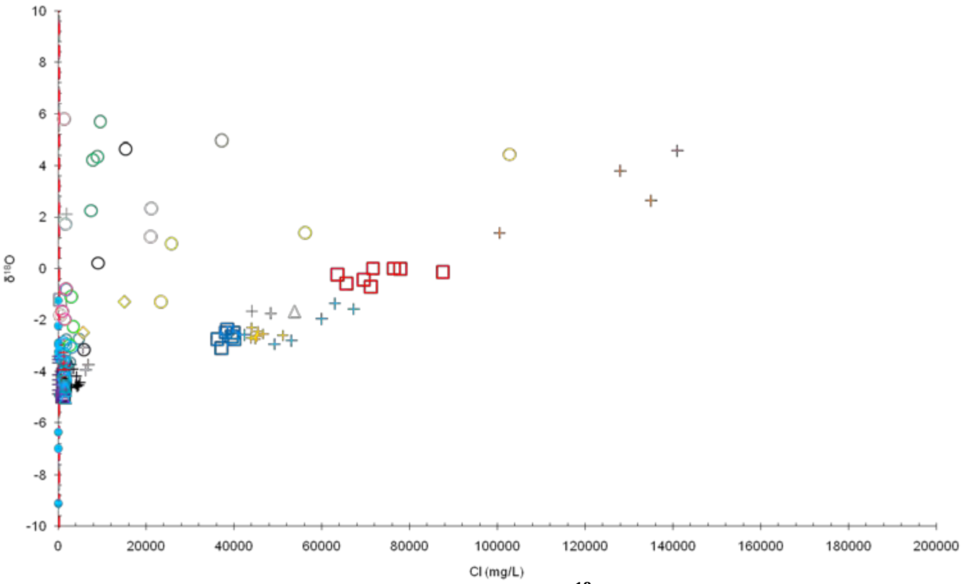
Appendix Fig 6-11. Plot of $\delta^{18}O$ stable isotope values over time for Coorow Post Office (blue triangles), Koobabbie (black circles) and site RAIN1 (red triangles). A 6th order polynomial trend-line was fitted to Coorow (blue dashed line) and Koobabbie (black dashed line) data.



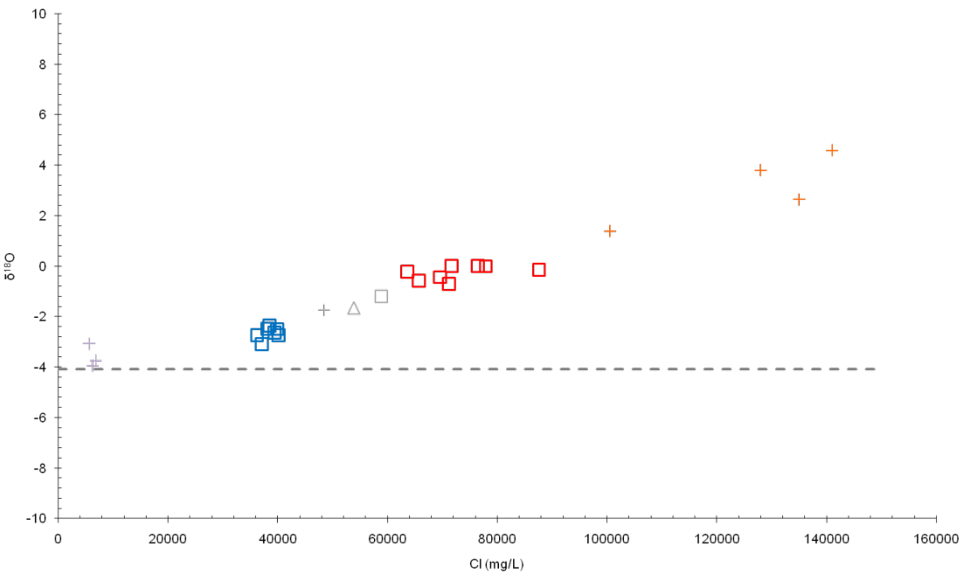
Appendix Fig 6-12. Stable isotope concentration ratios (δ^{18}O and δD) observed throughout the study for the shallow, saline unconfined aquifer at bores BMC86ob, BMC87ob, and BMC88ob period.



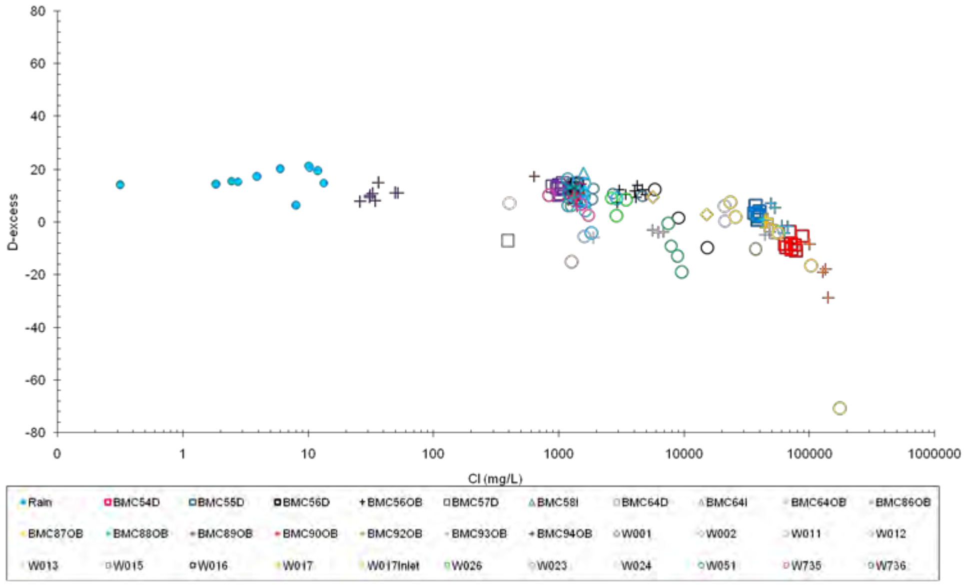
Appendix Fig 6-13. Stable isotope concentration ratios (δ^{18}O and δD) observed throughout the study period for the shallow hyposaline aquifer at bore BMC56ob, and the hyposaline semi-confined aquifer at bores BMC56d, BMC57d, and BMC58i.



Appendix Fig 6-14. Plot of aqueous stable isotope δ^{18}O versus Cl for all rainfall, groundwater and surface water sites.



Appendix Fig 6-15. δ^{18}O versus Cl for saline to hypersaline groundwater at bores BMC93ob (violet cross), BMC55d (blue square), BMC64ob (grey cross), BMC64i (grey triangle), BMC64d (grey square), BMC54d (red square) and BMC92ob (dark-orange cross). δ^{18}O versus Cl plotted with the long-term (1962-2000) weighted average isotopic signature δ^{18}O -4.09‰ for Perth rainfall 1962-2000 (Liu et al, 2010).



Appendix Fig 6-16. D-excess versus Cl$^-$ for all surface water, groundwater and rainfall samples for Nabappie from April through November 2009.

Appendix 6P “Salt effect” correction for stable isotope values

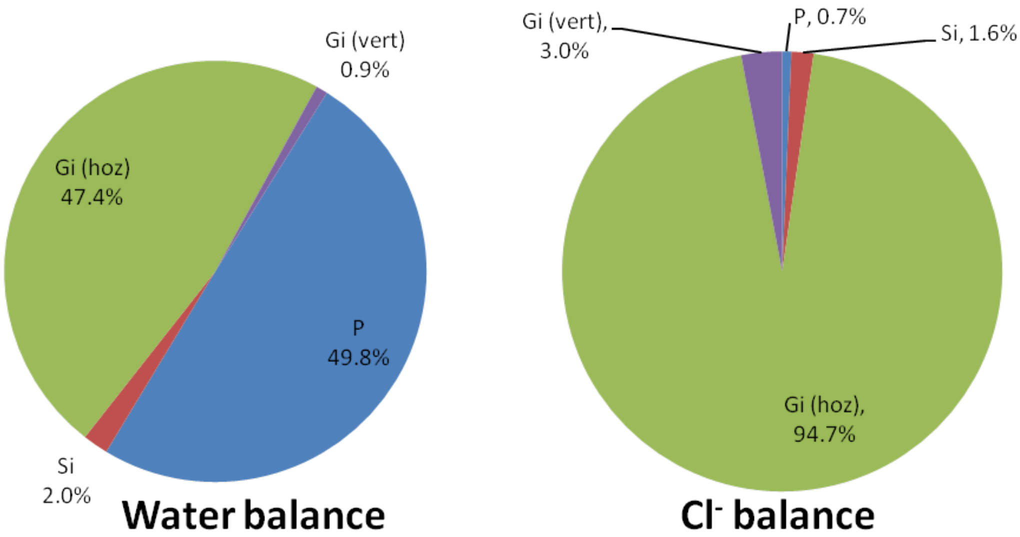
PR_KEY	Date	δ2HVSMOW (permil)	δ2HVSMOW STDV (permil)	δ18OVSMOW (permil)	δ18OVSMOW STDV (permil)	D-excess	δ2H_activity	δ2H_difference	δ18O_activity	δ18O_difference
BMC54D	21/04/2009	-8.70	0.8	0.00	0.10	-8.70	-3.22	5.48	-0.13	-0.13
BMC54D	19/05/2009	-6.40	0.8	-0.14	0.09	-5.28	-0.51	5.89	-0.28	-0.14
BMC54D	17/06/2009	-10.20	0.6	-0.23	0.11	-8.36	-5.85	4.35	-0.33	-0.10
BMC54D	22/07/2009	-10.20	0.1	0.00	0.04	-10.20	-5.04	5.16	-0.14	-0.14
BMC54D	27/08/2009	-14.30	0.6	-0.58	0.04	-9.66	-8.79	5.51	-0.71	-0.13
BMC54D	25/09/2009	-13.90	0.7	-0.71	0.08	-8.22	-8.63	5.27	-0.85	-0.14
BMC54D	20/10/2009	-7.30	0.3	-0.44	0.06	-3.78	-2.31	4.99	-0.57	-0.13
BMC54D	24/11/2009	-10.80	0.7	-0.01	0.11	-10.72	-5.36	5.44	-0.14	-0.13
BMC55D	21/04/2009	-17.00	0	-2.49	0.09	2.92	-14.18	2.82	-2.57	-0.08
BMC55D	19/05/2009	-16.00	0.8	-2.50	0.07	4.00	-12.85	3.15	-2.58	-0.08
BMC55D	17/06/2009	-18.50	0.6	-2.74	0.12	3.42	-16.16	2.34	-2.80	-0.06
BMC55D	21/07/2009	-18.00	0.4	-2.36	0.00	0.88	-15.12	2.88	-2.44	-0.08
BMC55D	25/09/2009	-19.20	0.8	-2.64	0.02	1.92	-16.25	2.95	-2.73	-0.09
BMC55D	20/10/2009	-18.40	0.8	-3.10	0.05	6.40	-15.52	2.88	-3.19	-0.09
BMC55D	24/11/2009	-19.30	0.4	-2.74	0.05	2.62	-16.50	2.80	-2.81	-0.07
BMC56D	21/04/2009	-24.60	0	-4.40	0.05	10.60	-24.50	0.10	-4.40	0.00
BMC56D	19/05/2009	-23.00	0.3	-4.05	0.01	9.40	-22.90	0.10	-4.05	0.00
BMC56D	17/06/2009	-22.70	1	-4.20	0.11	10.90	-22.59	0.11	-4.20	0.00
BMC56D	21/07/2009	-26.40	0.5	-4.70	0.06	11.20	-26.28	0.12	-4.70	0.00
BMC56D	26/08/2009	-26.40	1	-4.94	0.01	13.12	-26.29	0.11	-4.94	0.00
BMC56D	24/09/2009	-24.80	0.3	-4.70	0.10	12.80	-24.69	0.11	-4.70	0.00
BMC56D	20/10/2009	-23.20	0.8	-4.70	0.04	14.40	-23.08	0.12	-4.70	0.00
BMC56D	24/11/2009	-25.60	0.7	-4.65	0.07	11.60	-25.50	0.10	-4.65	0.00
BMC56OB	21/04/2009	-22.60	0.3	-3.75	0.01	7.40	-22.38	0.22	-3.76	-0.01
BMC56OB	19/05/2009	-20.80	0.2	-3.91	0.07	10.48	-20.52	0.28	-3.93	-0.02
BMC56OB	17/06/2009	-24.90	0.3	-4.64	0.03	12.22	-24.63	0.27	-4.65	-0.01
BMC56OB	21/07/2009	-24.30	0.7	-4.20	0.04	9.30	-24.00	0.30	-4.21	-0.01
BMC56OB	26/08/2009	-24.40	0.5	-4.51	0.09	11.68	-24.04	0.36	-4.53	-0.02
BMC56OB	24/09/2009	-24.00	0.4	-4.55	0.09	12.40	-23.63	0.37	-4.57	-0.02
BMC56OB	20/10/2009	-22.90	0.3	-4.60	0.04	13.90	-22.53	0.37	-4.62	-0.02
BMC56OB	24/11/2009	-25.10	1	-4.44	0.20	10.42	-24.76	0.34	-4.46	-0.02
BMC57D	21/04/2009	-22.80	1	-4.12	0.08	10.16	-22.72	0.08	-4.12	0.00
BMC57D	19/05/2009	-26.20	0.4	-4.92	0.12	13.16	-26.12	0.08	-4.92	0.00
BMC57D	16/06/2009	-25.10	0.2	-4.99	0.01	14.82	-25.01	0.09	-4.99	0.00
BMC57D	21/07/2009	-24.70	0.5	-4.43	0.10	10.74	-24.61	0.09	-4.43	0.00
BMC57D	26/08/2009	-26.30	0.8	-5.00	0.02	13.70	-26.22	0.08	-5.00	0.00
BMC57D	24/09/2009	-24.80	0.3	-4.69	0.04	12.72	-24.71	0.09	-4.69	0.00
BMC57D	20/10/2009	-24.10	0.3	-4.79	0.03	14.22	-24.01	0.09	-4.79	0.00
BMC57D	24/11/2009	-26.70	1	-4.88	0.14	12.34	-26.62	0.08	-4.88	0.00
BMC58I	21/04/2009	-22.60	0.8	-3.81	0.03	7.88	-22.48	0.12	-3.81	0.00
BMC58I	18/05/2009	-22.50	0.4	-3.95	0.07	9.10	-22.38	0.12	-3.95	0.00
BMC58I	16/06/2009	-17.60	0.5	-3.64	0.03	11.52	-17.47	0.13	-3.64	0.00
BMC58I	21/07/2009	-24.80	1	-4.17	0.03	8.56	-24.67	0.13	-4.17	0.00
BMC58I	26/08/2009	-24.60	0.7	-4.58	0.08	12.04	-24.47	0.13	-4.58	0.00
BMC58I	24/09/2009	-25.60	0.6	-4.60	0.07	11.20	-25.47	0.13	-4.60	0.00
BMC58I	19/10/2009	-21.60	0.9	-5.03	0.08	18.64	-21.46	0.14	-5.03	0.00
BMC58I	24/11/2009	-25.80	0.9	-4.74	0.04	12.12	-25.68	0.12	-4.74	0.00
BMC64D	19/05/2009	-16.70	0.7	-1.21	0.10	-7.02	-11.80	4.90	-1.38	-0.17
BMC64I	19/05/2009	-17.20	0.5	-1.66	0.07	-3.92	-12.90	4.30	-1.81	-0.15

PR_KEY	Date	δ2HVSMOW (permil)	δ2HVSMOW STDV (permIl)	δ18OVSMOW (permil)	δ18OVSMOW STDV (permIl)	D-excess	δ2H_activity	δ2H_difference	δ18O_activity	δ18O_difference
BMC64OB	19/05/2009	-17.80	0.8	-1.75	0.11	-3.80	-13.82	3.98	-1.87	-0.12
BMC86OB	22/04/2009	-18.10	0.1	-1.66	0.04	-4.82	-14.57	3.53	-1.78	-0.12
BMC87OB	22/04/2009	-20.40	0.5	-2.31	0.04	-1.92	-16.94	3.46	-2.43	-0.12
BMC87OB	19/05/2009	-19.00	0.8	-2.55	0.11	1.40	-15.24	3.76	-2.67	-0.12
BMC87OB	21/07/2009	-21.00	0.7	-2.75	0.01	1.00	-17.75	3.25	-2.85	-0.10
BMC87OB	27/08/2009	-20.50	0.6	-2.71	0.08	1.18	-16.85	3.65	-2.83	-0.12
BMC87OB	24/09/2009	-19.90	0.7	-2.45	0.05	-0.30	-16.47	3.43	-2.58	-0.13
BMC87OB	20/10/2009	-20.20	0.5	-2.63	0.07	0.84	-16.72	3.48	-2.76	-0.13
BMC87OB	24/11/2009	-21.90	0.4	-2.61	0.11	-1.02	-18.20	3.70	-2.74	-0.13
BMC88OB	22/04/2009	-15.10	0.6	-1.36	0.00	-4.22	-10.20	4.90	-1.49	-0.13
BMC88OB	19/05/2009	-14.30	0.3	-1.58	0.08	-1.66	-8.89	5.41	-1.72	-0.14
BMC88OB	27/08/2009	-19.70	0.7	-2.58	0.09	0.94	-16.10	3.60	-2.67	-0.09
BMC88OB	24/09/2009	-17.00	0.4	-2.81	0.08	5.48	-13.03	3.97	-2.93	-0.12
BMC88OB	20/10/2009	-16.50	0.6	-2.95	0.06	7.10	-12.99	3.51	-3.05	-0.10
BMC88OB	24/11/2009	-17.20	1	-1.96	0.06	-1.52	-13.02	4.18	-2.07	-0.11
BMC89OB	20/04/2009	-19.50	0.7	-3.42	0.04	7.86				
BMC89OB	18/05/2009	-17.40	0.8	-3.55	0.06	11.00				
BMC89OB	15/06/2009	-21.40	1	-3.68	0.03	8.04	-21.39	0.01	-3.68	0.00
BMC89OB	21/07/2009	-23.00	0.9	-4.15	0.02	10.20	-22.99	0.01	-4.15	0.00
BMC89OB	26/08/2009	-27.00	1	-4.73	0.06	10.84	-26.99	0.01	-4.73	0.00
BMC89OB	24/09/2009	-25.10	0.5	-4.52	0.07	11.06	-25.09	0.01	-4.52	0.00
BMC89OB	19/10/2009	-24.00	0.3	-4.88	0.00	15.04	-23.99	0.01	-4.88	0.00
BMC89OB	24/11/2009	-25.20	0.3	-4.33	0.07	9.44	-25.19	0.01	-4.33	0.00
BMC90OB	21/04/2009	-21.00	0	-3.75	0.09	9.00	-20.91	0.09	-3.75	0.00
BMC90OB	18/05/2009	-21.70	0.7	-3.94	0.02	9.82	-21.59	0.11	-3.94	0.00
BMC90OB	16/06/2009	-15.80	0.8	-3.79	0.11	14.52	-15.68	0.12	-3.79	0.00
BMC90OB	21/07/2009	-20.90	0.4	-3.66	0.08	8.38	-20.79	0.11	-3.66	0.00
BMC90OB	26/08/2009	-18.40	0.6	-3.70	0.06	11.20	-18.27	0.13	-3.70	0.00
BMC90OB	24/09/2009	-17.20	0.6	-3.27	0.04	8.96	-17.09	0.11	-3.27	0.00
BMC90OB	19/10/2009	-17.00	0.4	-3.40	0.05	10.20	-16.88	0.12	-3.40	0.00
BMC90OB	24/11/2009	-17.80	1.2	-2.98	0.11	6.04	-17.69	0.11	-2.98	0.00
BMC92OB	22/04/2009	11.40	0.1	3.80	0.07	-19.00	22.13	10.73	3.55	-0.25
BMC92OB	19/05/2009	3.20	0.9	2.64	0.11	-17.92	12.94	9.74	2.40	-0.24
BMC92OB	20/10/2009	2.60	1	1.38	0.03	-8.44	8.96	6.36	1.22	-0.16
BMC92OB	24/11/2009	7.90	0.6	4.58	0.09	-28.74	18.38	10.48	4.26	-0.32
BMC93OB	20/05/2009	-10.90	0.7	-3.08	0.07	13.74	-10.42	0.48	-3.09	-0.01
BMC93OB	20/10/2009	-18.60	0.3	-3.95	0.08	13.00	-18.14	0.46	-3.96	-0.01
BMC93OB	24/11/2009	-22.50	1.2	-3.75	0.18	7.50	-22.03	0.47	-3.76	-0.01
BMC94OB	22/07/2009	-16.40	1	-4.21	0.10	17.28	-16.33	0.07	-4.21	0.00
Coorow PO	22/05/2009	-2.40	0.3	-2.97	0.12	21.36	-2.40	0.00	-2.97	0.00
Coorow PO	20/07/2009	-23.90	0.1	-4.93	0.12	15.54				
Coorow PO	24/07/2009	-41.30	0.8	-6.97	0.07	14.46				
Coorow PO	21/08/2009	-36.80	0.7	-6.37	0.02	14.16				
Coorow PO	29/08/2009									
KOOBABBIE	22/05/2009	-5.10	0.6	-3.24	0.08	20.82	-5.10	0.00	-3.24	0.00
KOOBABBIE	30/09/2009	-52.60	0.65	-9.11	0.13	20.28	-52.60	0.00	-9.11	0.00
QC02	20/04/2009	-19.00	0.7	-3.23	0.07	6.84	-18.99	0.01	-3.23	0.00
QC03	18/05/2009	-26.60	0.5	-4.21	0.00	7.08	-26.47	0.13	-4.21	0.00

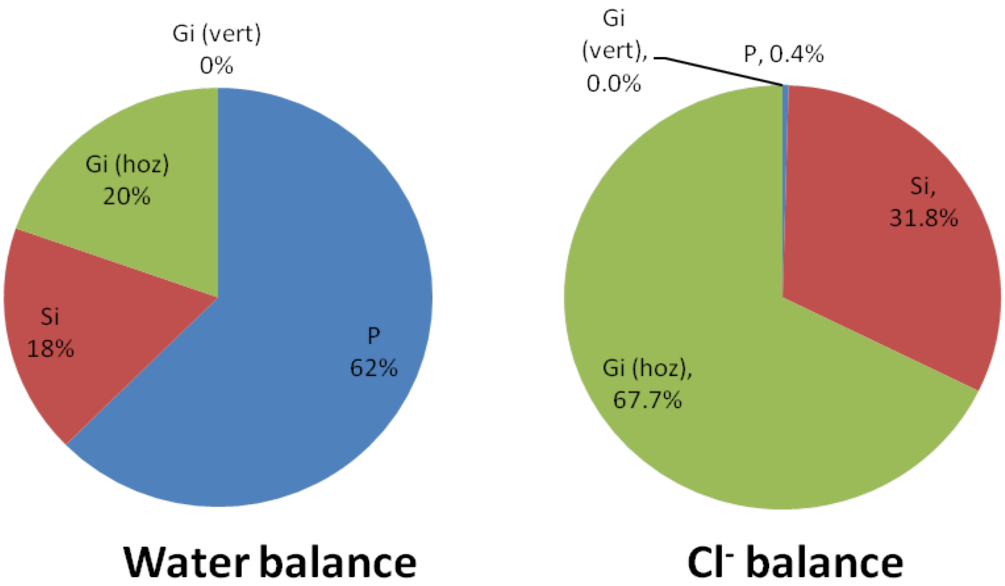
PR_KEY	Date	δ2HVSMOW (permil)	δ2HVSMOW STDV (permll)	δ18OVSMOW (permil)	δ18OVSMOW STDV (permll)	D-excess	δ2H_activity	δ2H_difference	δ18O_activity	δ18O_difference
QC04	17/06/2009	-18.50	0.8	-2.92	0.06	4.86	-16.05	2.45	-2.98	-0.06
QC06	20/07/2009	-9.50	0.8	-3.11	0.00	15.38				
QC07	26/08/2009	-17.80	0.3	-3.48	0.03	10.04	-17.66	0.14	-3.48	0.00
QC08	24/09/2009	-27.20	0.7	-4.96	0.10	12.48	-27.19	0.01	-4.96	0.00
QC09	19/10/2009	-22.10	0.7	-4.59	0.09	14.62	-22.09	0.01	-4.59	0.00
QC10	19/10/2009	-17.30	0.9	-3.25	0.03	8.70	-17.19	0.11	-3.25	0.00
QC11	20/10/2009	-8.20	0.4	-0.22	0.03	-6.44	-2.65	5.55	-0.36	-0.14
QC14	24/11/2009	-23.60	0.8	-4.27	0.16	10.56	-23.59	0.01	-4.27	0.00
QC15	24/11/2009	-24.80	1.3	-4.53	0.12	11.44	-24.69	0.11	-4.53	0.00
RAIN1	15/06/2009	-3.60	0.9	-2.90	0.04	19.60	-3.60	0.00	-2.90	0.00
RAIN1	20/07/2009	-10.60	0.6	-3.50	0.12	17.40	-10.60	0.00	-3.50	0.00
RAIN1	26/08/2009	-11.90	0.9	-3.41	0.05	15.38				
RAIN1	24/09/2009	-2.90	0.7	-2.23	0.07	14.94	-2.90	0.00	-2.23	0.00
RAIN1	24/11/2009	-3.50	0.9	-1.24	0.16	6.42	-3.50	0.00	-1.24	0.00
W015	21/04/2009	-22.40	0.4	-3.55	0.03	6.00	-22.30	0.10	-3.55	0.00
W015	19/05/2009	-21.30	0	-4.53	0.08	14.94	-21.21	0.09	-4.53	0.00
W015	16/06/2009	-13.30	0.2	-2.76	0.08	8.78	-13.13	0.17	-2.76	0.00
W015	21/07/2009	-12.10	0	-2.74	0.10	9.82	-11.69	0.41	-2.75	-0.01
W015	26/08/2009	-18.30	0.4	-3.64	0.04	10.82	-18.06	0.24	-3.64	0.00
W015	24/09/2009	-16.50	0.6	-3.65	0.04	12.70	-16.35	0.15	-3.65	0.00
W015	20/10/2009	-21.20	0.9	-4.58	0.05	15.44	-21.09	0.11	-4.58	0.00
W015	24/11/2009	-24.80	1.2	-4.19	0.16	8.72	-24.71	0.09	-4.19	0.00
W016	21/07/2009	-12.70	0.2	-3.15	0.08	12.50	-12.22	0.48	-3.16	-0.01
W016	26/08/2009	3.30	0.3	0.21	0.07	1.62	4.04	0.74	0.19	-0.02
W016	25/09/2009	27.60	0.5	4.66	0.00	-9.68	28.76	1.16	4.62	-0.04
W017	17/06/2009	19.00	0.8	4.44	0.06	-16.52	27.18	8.18	4.27	-0.17
W017	22/07/2009	-2.90	0.6	-1.30	0.10	7.50	-0.77	2.13	-1.36	-0.06
W017	27/08/2009	9.70	1	0.97	0.02	1.94	12.43	2.73	0.89	-0.08
W017	25/09/2009	7.10	0.7	1.40	0.07	-4.10	11.51	4.41	1.26	-0.14
W017	20/10/2009	36.40	0.7	13.40	0.00	-70.80	49.17	12.77	12.73	-0.67
W017Inlet	22/07/2009	-10.30	0.2	-2.49	0.00	9.62	-9.85	0.45	-2.50	-0.01
W017Inlet	27/08/2009	-7.30	0.6	-1.29	0.09	3.02	-6.24	1.06	-1.33	-0.04
W026	22/07/2009	-9.60	0.2	-2.27	0.09	8.56	-9.26	0.34	-2.27	0.00
W026	26/08/2009	-14.70	0.7	-2.98	0.09	9.14	-14.44	0.26	-2.98	0.00
W026	24/09/2009	-6.30	0.7	-1.10	0.04	2.50	-6.06	0.24	-1.10	0.00
W051	20/04/2009	-19.40	0.3	-2.96	0.10	4.28	-19.26	0.14	-2.96	0.00
W051	18/05/2009	-20.10	0	-4.35	0.00	14.70	-19.97	0.13	-4.35	0.00
W051	16/06/2009	-15.50	0.1	-3.07	0.09	9.06	-15.24	0.26	-3.07	0.00
W051	21/07/2009	-17.70	0.7	-4.25	0.09	16.30	-17.59	0.11	-4.25	0.00
W051	26/08/2009	-18.00	0.6	-3.59	0.05	10.72	-17.88	0.12	-3.59	0.00
W051	24/09/2009	-16.70	1	-2.88	0.00	6.34	-16.60	0.10	-2.88	0.00
W051	19/10/2009	-15.00	1	-3.30	0.07	11.40	-14.88	0.12	-3.30	0.00
W051	24/11/2009	-10.60	1.8	-0.82	0.19	-4.04	-10.46	0.14	-0.82	0.00
W735	18/05/2009	-9.10	0.3	-1.98	0.02	6.74	-8.98	0.12	-1.98	0.00
W735	17/06/2009	-3.10	0.3	-1.67	0.11	10.26	-3.02	0.08	-1.67	0.00
W735	22/10/2009	-3.80	0.3	-0.80	0.08	2.60	-3.65	0.15	-0.80	0.00
W736	22/04/2009	26.60	0.7	5.70	0.06	-19.00	27.37	0.77	5.68	-0.02
W736	18/05/2009	22.00	0.6	4.36	0.07	-12.88	22.69	0.69	4.34	-0.02
W736	17/06/2009	24.60	0.2	4.22	0.04	-9.16	25.24	0.64	4.21	-0.01
W736	22/10/2009	17.50	0.6	2.25	0.01	-0.50	18.03	0.53	2.24	-0.01

Appendix Chapter 7

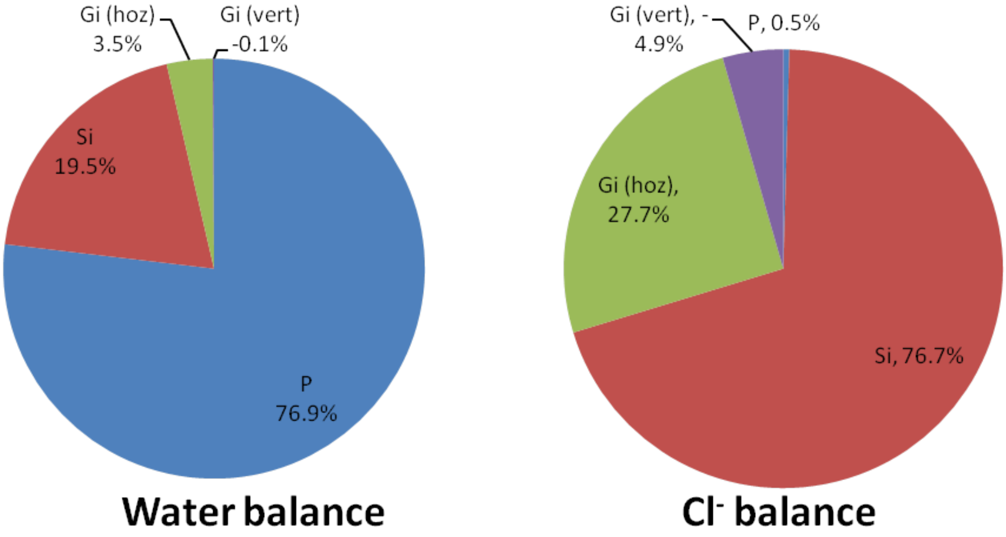
Appendix 7A Water balance and Cl^- balance pie charts



Appendix Fig 7-1Proportion of the water balance for the middle range of tested parameters at wetland W051 (left figure), and the proportion of the solute (Cl^-) balance (right figure).

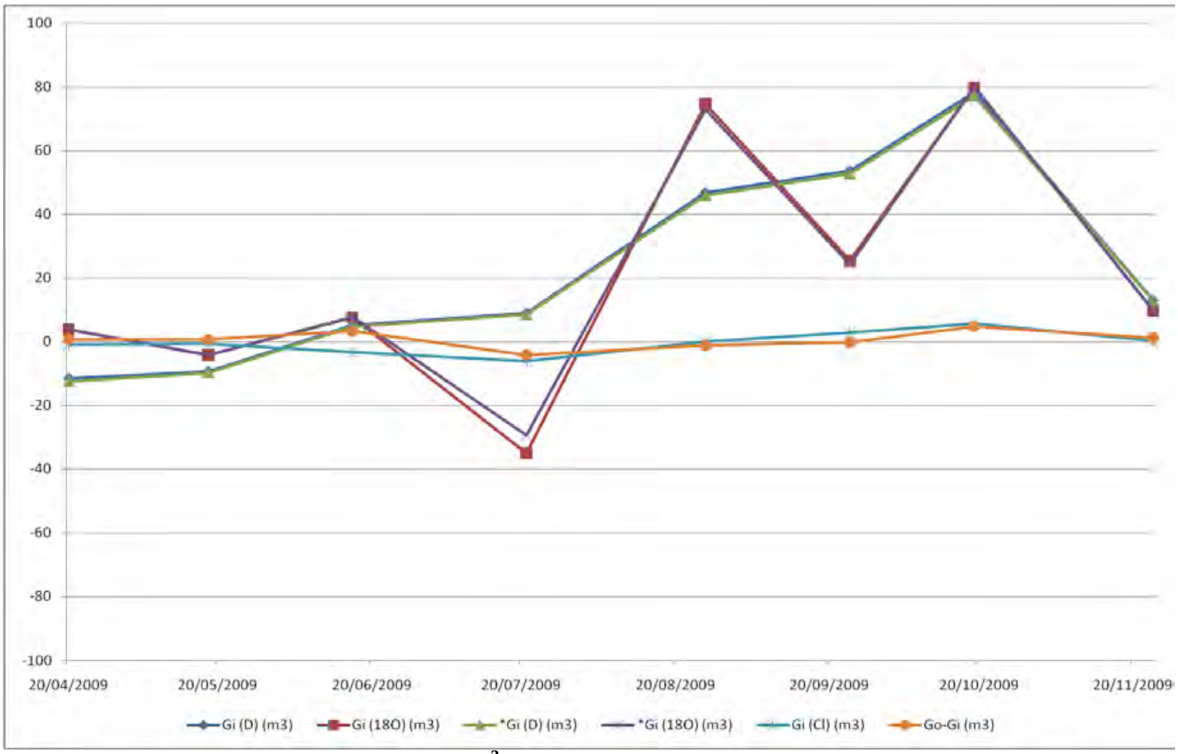


Appendix Fig 7-2. Proportion of the water balance for the middle range of tested parameters at wetland W016 (left figure), and the proportion of the solute (Cl^-) balance (right figure).

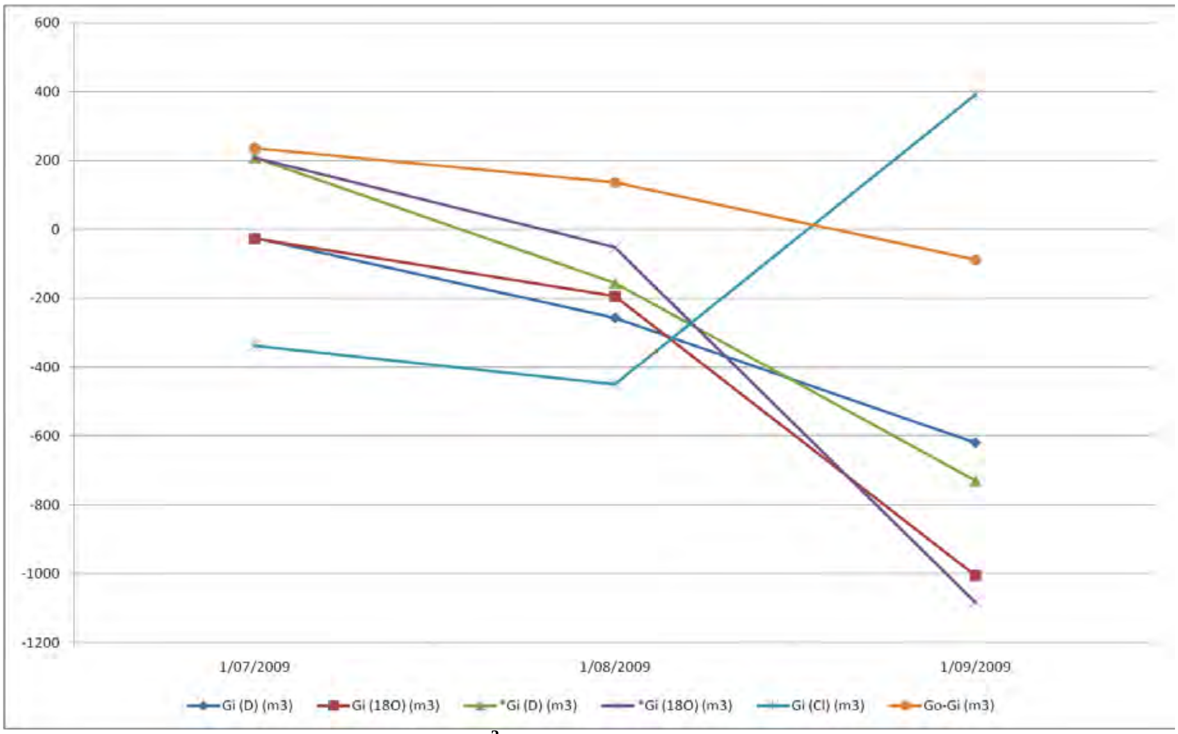


Appendix Fig 7-3. Proportion of the water balance for the middle range of tested parameters at wetland W017 (left figure), and the proportion of the solute (Cl^-) balance (right figure).

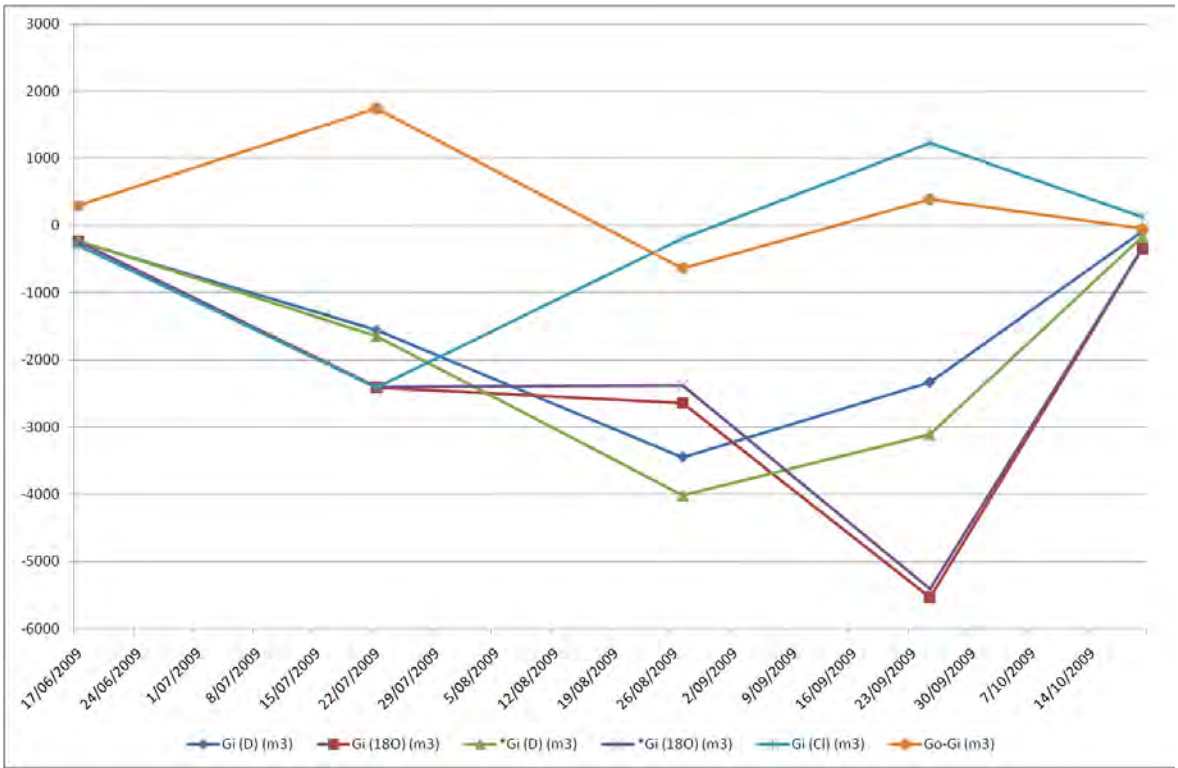
Appendix 7B Stable water isotope and Cl^- mass-balance plots



Appendix Fig 7-4. Groundwater inflows (m^3 per sample period) calculated from stable isotope concentrations (δD and $\delta^{18}O$), activities ($*\delta D$ and $*\delta^{18}O$), and Chloride for wetland W051



Appendix Fig 7-5. Groundwater inflows (m^3 per sample period) calculated from stable isotope concentrations (δD and $\delta^{18}O$), activities ($*\delta D$ and $*\delta^{18}O$), and Chloride for wetland W016



Appendix Fig 7-6. Groundwater inflows (m^3 per sample period) calculated from stable isotope concentrations (δD and $\delta^{18}O$), activities ($*\delta D$ and $*\delta^{18}O$), and Chloride for wetland W016

Appendix 7C Stable water isotope and Cl^- mass-balance, raw data.

PR_KEY	Date	Month	CSIRO - Temp	8297 - RH	Water TEMP	Cl (mg/L)	P-Cl (mg/L)	TDS (mg/L) - calculated	TDS 180C (mg/L)	δD (‰)	δ18O (‰)	*Actvity δD (‰)	*Activity δ18O (‰)	aw - Jones etal 2001
W015	21/04/2009	04	20.02	45.33	25.20	1250.00	8.00	2298.72		-22.40	-3.55	-22.30	-3.55	0.998
W015	19/05/2009	05	16.32	47.77	13.00	1250.00	8.00	2249.80		-21.30	-4.53	-21.21	-4.53	0.998
W015	16/06/2009	06	12.17	75.75	14.20	1846.48	8.00	3658.63	3964.00	-13.30	-2.76	-13.13	-2.76	0.996
W015	21/07/2009	07	10.41	85.85	15.20	4680.63	8.00	8954.91	9226.00	-12.10	-2.74	-11.69	-2.75	0.991
W015	26/08/2009	08	10.69	84.82	18.10	2705.65	8.00	5202.17	5627.00	-18.30	-3.64	-18.06	-3.64	0.995
W015	24/09/2009	09	12.17	79.30	20.60	1881.49	8.00	3449.33	3835.00	-16.50	-3.65	-16.35	-3.65	0.997
W015	20/10/2009	10	16.48	59.52	15.30	1396.07	8.00	2487.86	3133.00	-21.20	-4.58	-21.09	-4.58	0.998
W015	24/11/2009	11	22.18	51.70	21.00	1220.00	8.00	2240.50	2300.00	-24.80	-4.19	-24.71	-4.19	0.998
W016	21/07/2009	07	10.41	85.85	19.10	5827.46	8.00	10763.52	11257.00	-12.70	-3.15	-12.22	-3.16	0.989
W016	26/08/2009	08	10.69	84.82	22.70	9053.25	8.00	16223.42	18248.00	3.30	0.21	4.04	0.19	0.984
W016	25/09/2009	09	12.17	79.30	12.50	15297.10	8.00	26284.54	30025.00	27.60	4.66	28.76	4.62	0.974
W017	17/06/2009	06	12.17	75.75	18.60	102738.99	8.00	182721.61	220002.00	19.00	4.44	27.18	4.27	0.85
W017	22/07/2009	07	10.41	85.85	15.30	23309.85	8.00	45172.72	48053.00	-2.90	-1.30	-0.77	-1.36	0.96
W017	27/08/2009	08	10.69	84.82	16.20	25783.16	8.00	53608.69	61021.00	9.70	0.97	12.43	0.89	0.95
W017	25/09/2009	09	12.17	79.30	16.70	56155.98	8.00	100678.16	112091.00	7.10	1.40	11.51	1.26	0.91
W017	20/10/2009	10	16.48	59.52	26.00	175348.38	8.00	282490.61	365189.00	36.40	13.40	49.17	12.73	0.78
W017Inlet	22/07/2009	07	10.41	85.85	15.90	5623.70	8.00	10428.78	11094.00	-10.30	-2.49	-9.85	-2.50	0.990
W017Inlet	27/08/2009	08	10.69	84.82	22.10	15072.69	8.00	25744.32	30684.00	-7.30	-1.29	-6.24	-1.33	0.975
W026	22/07/2009	07	10.41	85.85	15.10	3423.64	8.00	7530.84	8120.00	-9.60	-2.27	-9.26	-2.27	0.993
W026	26/08/2009	08	10.69	84.82	15.70	2637.86	8.00	5794.24	6743.00	-14.70	-2.98	-14.44	-2.98	0.994
W026	24/09/2009	09	12.17	79.30	15.50	2879.73	8.00	5920.44	6532.00	-6.30	-1.10	-6.06	-1.10	0.994
W051	20/04/2009	04	20.02	45.33	27.20	1630.00	8.00	3326.07		-19.40	-2.96	-19.26	-2.96	0.997
W051	18/05/2009	05	16.32	47.77	18.60	1610.00	8.00	3178.14		-20.10	-4.35	-19.97	-4.35	0.997
W051	16/06/2009	06	12.17	75.75	7.30	2897.25	8.00	5742.32	6431.00	-15.50	-3.07	-15.24	-3.07	0.994
W051	21/07/2009	07	10.41	85.85	10.50	1177.84	8.00	2409.72	2538.00	-17.70	-4.25	-17.59	-4.25	0.998
W051	26/08/2009	08	10.69	84.82	13.30	1202.05	8.00	2513.11	2757.00	-18.00	-3.59	-17.88	-3.59	0.997
W051	24/09/2009	09	12.17	79.30	20.30	1185.74	8.00	2273.64	2627.00	-16.70	-2.88	-16.60	-2.88	0.998
W051	19/10/2009	10	16.48	59.52	22.00	1311.24	8.00	2646.06	2522.00	-15.00	-3.30	-14.88	-3.30	0.997
W051	24/11/2009	11	22.18	51.70	19.70	1820.00	8.00	3497.81	3700.00	-10.60	-0.82	-10.46	-0.82	0.997
W735	18/05/2009	05	16.32	47.77	18.10	1500.00	8.00	2811.88		-9.10	-1.98	-8.98	-1.98	0.997
W735	17/06/2009	06	12.17	75.75	9.90	833.60	8.00	1727.21	1978.00	-3.10	-1.67	-3.02	-1.67	0.998
W735	22/10/2009	10	16.48	59.52	16.10	1728.99	8.00	3231.16	3607.00	-3.80	-0.80	-3.65	-0.80	0.997
W736	22/04/2009	04	20.02	45.33	17.20	9580.00	8.00	16696.00		26.60	5.70	27.37	5.68	0.984
W736	18/05/2009	05	16.32	47.77	20.60	8860.00	8.00	15245.52		22.00	4.36	22.69	4.34	0.985
W736	17/06/2009	06	12.17	75.75	14.20	7871.39	8.00	13803.23	16377.00	24.60	4.22	25.24	4.21	0.986
W736	22/10/2009	10	16.48	59.52	18.40	7485.12	8.00	12351.34	15017.00	17.50	2.25	18.03	2.24	0.988

PR_KEY	Date	h' - normalised h	δP (D)	δP (18O)	ean δP (D	ean δP (18	α* (δD)	α* (δ18O)	ε* (δD)	ε* (δ18O)	ε (δD)	ε (δ18O)	Δε - δD	Δε - δ18O	Slope	*Activity slope	δa - (δD)	δa - (δ18O)	δE - (δD)	δE - (δ18O)
W015	21/04/2009	0.45	-12.27	-3.69	-12.274	-3.6914	0.922	0.990	78.345	9.742	85.193	17.518	6.848	7.776	5.417	5.412	-96.506	-21.173	-112.20	-20.62
W015	19/05/2009	0.48	-3.36	-2.91	-12.274	-3.6914	0.918	0.990	82.133	10.065	88.674	17.492	6.541	7.427	5.547	5.542	-91.759	-20.378	-121.82	-23.12
W015	16/06/2009	0.76	-8.41	-1.98	-12.274	-3.6914	0.913	0.990	86.579	10.442	89.588	13.858	3.009	3.416	6.557	6.520	-97.265	-15.822	-114.48	-18.75
W015	21/07/2009	0.87	-20.05	-4.84	-12.274	-3.6914	0.911	0.989	88.536	10.607	90.216	12.514	1.679	1.907	-69.136	-68.686	-108.494	-17.299	-53.64	-1.77
W015	26/08/2009	0.85	-11.31	-1.54	-12.274	-3.6914	0.912	0.989	88.212	10.579	90.062	12.680	1.850	2.100	5.466	5.405	-100.373	-14.202	-141.84	-27.91
W015	24/09/2009	0.80	-15.26	-3.97	-12.274	-3.6914	0.913	0.990	86.572	10.441	89.135	13.352	2.563	2.911	8.071	8.014	-103.076	-17.277	-107.27	-15.52
W015	20/10/2009	0.60	1.11	-0.83	-12.274	-3.6914	0.918	0.990	81.968	10.051	87.030	15.799	5.062	5.748	5.613	5.604	-86.015	-16.619	-135.09	-25.46
W015	24/11/2009	0.52	-9.83	-1.64	-12.274	-3.6914	0.924	0.990	76.213	9.560	82.260	16.426	6.047	6.866	5.169	5.163	-91.339	-18.050	-118.56	-22.96
W016	21/07/2009	0.87	-20.05	-4.84	-12.274	-3.6914	0.911	0.989	88.536	10.607	90.196	12.491	1.660	1.885	30.419	27.842	-108.475	-17.277	-57.08	-4.59
W016	26/08/2009	0.86	-11.31	-1.54	-12.274	-3.6914	0.912	0.989	88.212	10.579	89.945	12.547	1.733	1.967	2.867	0.197	-100.256	-14.069	-3.72	-1.51
W016	25/09/2009	0.81	-15.26	-3.97	-12.274	-3.6914	0.913	0.990	86.572	10.441	88.908	13.093	2.336	2.653	3.793	4.027	-102.848	-17.019	106.14	28.44
W017	17/06/2009	0.90	-8.41	-1.98	-12.27	-3.69	0.91	0.99	86.58	10.44	87.89	11.92	1.31	1.48	3.28	5.08	-95.56	-13.89	143.14	46.53
W017	22/07/2009	0.90	-20.05	-4.84	-12.27	-3.69	0.91	0.99	88.54	10.61	89.83	12.07	1.29	1.46	2.42	3.54	-108.10	-16.86	43.56	16.97
W017	27/08/2009	0.89	-11.31	-1.54	-12.27	-3.69	0.91	0.99	88.21	10.58	89.55	12.09	1.33	1.52	8.88	12.39	-99.86	-13.62	79.28	9.59
W017	25/09/2009	0.87	-15.26	-3.97	-12.27	-3.69	0.91	0.99	86.57	10.44	88.17	12.25	1.60	1.81	2.32	3.70	-102.11	-16.18	57.81	25.23
W017	20/10/2009	0.76	1.11	-0.83	-12.27	-3.69	0.92	0.99	81.97	10.05	84.94	13.42	2.97	3.37	0.90	2.32	-83.92	-14.24	52.30	44.62
W017Inlet	22/07/2009	0.87	-20.05	-4.84	-12.274	-3.6914	0.911	0.989	88.536	10.607	90.200	12.496	1.664	1.889	-15.035	-14.120	-108.479	-17.281	-40.89	0.23
W017Inlet	27/08/2009	0.87	-11.31	-1.54	-12.274	-3.6914	0.912	0.989	88.212	10.579	89.843	12.431	1.631	1.852	6.408	5.632	-100.154	-13.954	-71.14	-11.89
W026	22/07/2009	0.86	-20.05	-4.84	-12.274	-3.6914	0.911	0.989	88.536	10.607	90.231	12.531	1.695	1.924	-9.673	-9.099	-108.510	-17.316	-37.48	1.47
W026	26/08/2009	0.85	-11.31	-1.54	-12.274	-3.6914	0.912	0.989	88.212	10.579	90.056	12.673	1.844	2.093	5.466	5.391	-100.367	-14.195	-119.91	-23.57
W026	24/09/2009	0.80	-15.26	-3.97	-12.274	-3.6914	0.913	0.990	86.572	10.441	89.111	13.324	2.539	2.883	27.022	26.449	-103.051	-17.249	-61.81	-3.18
W051	20/04/2009	0.45	-12.27	-3.69	-12.274	-3.6914	0.922	0.990	78.345	9.742	85.187	17.511	6.842	7.769	5.430	5.422	-96.500	-21.167	-107.20	-19.56
W051	18/05/2009	0.48	-3.36	-2.91	-12.274	-3.6914	0.918	0.990	82.133	10.065	88.669	17.486	6.536	7.421	5.539	5.532	-91.753	-20.371	-119.75	-22.78
W051	16/06/2009	0.76	-8.41	-1.98	-12.274	-3.6914	0.913	0.990	86.579	10.442	89.568	13.835	2.989	3.394	6.596	6.544	-97.246	-15.799	-122.92	-20.02
W051	21/07/2009	0.86	-20.05	-4.84	-12.274	-3.6914	0.911	0.989	88.536	10.607	90.286	12.594	1.750	1.987	9.335	9.251	-108.565	-17.379	-92.02	-13.03
W051	26/08/2009	0.85	-11.31	-1.54	-12.274	-3.6914	0.912	0.989	88.212	10.579	90.091	12.712	1.878	2.133	5.469	5.439	-100.402	-14.235	-139.41	-27.40
W051	24/09/2009	0.79	-15.26	-3.97	-12.274	-3.6914	0.913	0.990	86.572	10.441	89.147	13.365	2.575	2.924	10.717	10.665	-103.087	-17.290	-108.13	-11.88
W051	19/10/2009	0.60	1.11	-0.83	-12.274	-3.6914	0.918	0.990	81.968	10.051	87.029	15.797	5.061	5.747	5.688	5.677	-86.014	-16.618	-121.16	-22.37
W051	24/11/2009	0.52	-9.83	-1.64	-12.274	-3.6914	0.924	0.990	76.213	9.560	82.252	16.417	6.039	6.857	5.395	5.384	-91.331	-18.041	-91.66	-16.12
W735	18/05/2009	0.48	-3.36	-2.91	-12.274	-3.6914	0.918	0.990	82.133	10.065	88.671	17.489	6.538	7.424	5.656	5.648	-91.755	-20.374	-100.61	-18.34
W735	17/06/2009	0.76	-8.41	-1.98	-12.274	-3.6914	0.913	0.990	86.579	10.442	89.606	13.878	3.027	3.437	5.806	5.782	-97.284	-15.843	-76.24	-14.35
W735	22/10/2009	0.60	1.11	-0.83	-12.274	-3.6914	0.918	0.990	81.968	10.051	87.025	15.792	5.057	5.742	5.974	5.957	-86.010	-16.613	-95.98	-16.31
W736	22/04/2009	0.46	-12.27	-3.69	-12.274	-3.6914	0.922	0.990	78.345	9.742	85.111	17.425	6.766	7.683	5.590	5.512	-96.424	-21.080	-29.60	-3.78
W736	18/05/2009	0.48	-3.36	-2.91	-12.274	-3.6914	0.918	0.990	82.133	10.065	88.596	17.404	6.463	7.339	6.141	6.071	-91.681	-20.289	-45.91	-6.22
W736	17/06/2009	0.77	-8.41	-1.98	-12.274	-3.6914	0.913	0.990	86.579	10.442	89.492	13.748	2.912	3.307	2.580	2.916	-97.169	-15.712	32.35	10.60
W736	22/10/2009	0.60	1.11	-0.83	-12.274	-3.6914	0.918	0.990	81.968	10.051	86.956	15.715	4.988	5.664	5.602	5.519	-85.942	-16.535	-47.48	-8.74

PR_KEY	Date	*Activity δE - (δD)	*Activity δE - (δ18O)	Wetland area (m2)	Total P (m3)	Total wetland area (m2)	Wetland P (m3)	Wetland evaporation (m3)	Lake volume	ΔS (m3)	Si - site	Si (m3)	$\delta Si_{(D)}$	$\delta Si_{(18O)}$
W015	21/04/2009	-111.85	-20.72											
W015	19/05/2009	-121.46	-23.20											
W015	16/06/2009	-113.65	-18.53											
W015	21/07/2009	-50.78	-3.80											
W015	26/08/2009	-140.13	-27.33											
W015	24/09/2009	-106.42	-15.16											
W015	20/10/2009	-134.62	-25.48											
W015	24/11/2009	-118.18	-23.05											
W016	21/07/2009	-53.75	-3.84	768.04	1171.60	12145.00	74.09	2.15	12.28	12.28	W015	216.17	-12.10	-2.74
W016	26/08/2009	1.08	-1.64	7889.29	566.80	12145.00	368.19	223.80	213.23	200.72	W015	219.12	-18.30	-3.64
W016	25/09/2009	111.59	28.07	1901.62	302.00	12145.00	47.29	357.00	35.57	-177.66	W015	43.5	-16.50	-3.65
W017	17/06/2009	213.65	44.20	0.50	1379.80	35746.00	0.02	0.01	0.01	0.01	Estimate	286.43	-12.10	-2.74
W017	22/07/2009	62.14	16.22	19906.34	3448.30	35746.00	1920.30	37.86	413.30	413.29	W017Inle	567.11	-10.30	-2.49
W017	27/08/2009	102.23	8.31	32857.28	1668.15	35746.00	1533.34	1482.00	1562.58	1149.28	W017Inle	338.95	-7.30	-1.29
W017	25/09/2009	88.96	24.09	4771.45	888.88	35746.00	118.65	1335.40	65.82	-1496.76	Estimate	114.13	-12.10	-2.74
W017	20/10/2009	101.05	42.29	3.02	357.46	35746.00	0.03	144.54	0.05	-65.77	Estimate	40.58	-12.10	-2.74
W017Inlet	22/07/2009	-37.74	0.21				#DIV/0!							
W017Inlet	27/08/2009	-63.69	-11.75				#DIV/0!							
W026	22/07/2009	-35.13	1.58				#DIV/0!							
W026	26/08/2009	-118.11	-23.06				#DIV/0!							
W026	24/09/2009	-60.62	-2.86				#DIV/0!							
W051	20/04/2009	-106.78	-19.65	1.13	0.972	81.00	0.972	0.20	0.002	0.00	Rainfall	0.1244	-12.27	-3.69
W051	18/05/2009	-119.32	-22.86	1.13	0.5562	81.00	0.5562	0.11	0.002	0.00	Rainfall	0.1396	-3.36	-2.91
W051	16/06/2009	-121.74	-19.78	1.13	3.1266	81.00	3.1266	0.06	0.038	0.04	Rainfall	0.1055	-8.41	-1.98
W051	21/07/2009	-91.15	-12.40	67.33	7.8138	81.00	7.8138	1.00	11.823	11.79	Rainfall	0.1987	-20.05	-4.84
W051	26/08/2009	-138.46	-26.83	73.08	3.78	81.00	3.78	3.95	13.211	1.39	Rainfall	0.1187	-11.31	-1.54
W051	24/09/2009	-107.52	-11.46	61.42	2.0142	81.00	2.0142	4.89	10.554	-2.66	Rainfall	0.04	-15.26	-3.97
W051	19/10/2009	-120.68	-22.38	26.66	0.81	81.00	0.81	5.41	1.927	-8.63	Rainfall	0.0142	1.11	-0.83
W051	24/11/2009	-91.24	-16.18	1.13	2.268	81.00	2.268	2.71	0.158	-1.77	Rainfall	0.0568	-9.83	-1.64
W735	18/05/2009	-100.23	-18.40				#DIV/0!							
W735	17/06/2009	-75.79	-14.22				#DIV/0!							
W735	22/10/2009	-95.48	-16.31				#DIV/0!							
W736	22/04/2009	-28.25	-3.82				#DIV/0!							
W736	18/05/2009	-44.62	-6.26				#DIV/0!							
W736	17/06/2009	34.79	10.57				#DIV/0!							
W736	22/10/2009	-46.19	-8.78				#DIV/0!							

PR_KEY	Date	*δSi $_{(D)}$	*δSi $_{(18O)}$	Si $_{(Cl)}$	Gi$_{primary}$ - site	δGi $_{(D)}$	δGi $_{(18O)}$	*δGi $_{(D)}$	*δGi $_{(18O)}$	Gi $_{(Cl)}$	Gi 2nd - site	G 2nd m3	δGi 2nd $_{(D)}$	δGi 2nd $_{(18O)}$	*δG 2nd $_{(D)}$	*δGi $_{2nd\ (18O)}$	Gi 2nd $_{(Cl)}$	Gi $_{(D)}$ (m3)
W015	21/04/2009																	0.00
W015	19/05/2009																	0.00
W015	16/06/2009																	0.00
W015	21/07/2009																	0.00
W015	26/08/2009																	0.00
W015	24/09/2009																	0.00
W015	20/10/2009																	0.00
W015	24/11/2009																	0.00
W016	21/07/2009	-11.69	-2.75	4680.63	BMC56OB	-24.30	-4.20	-24.00	-4.21	4134.05	BMC57D	0	-24.70	-4.43	-24.61	-4.43	1028.43	-27.57
W016	26/08/2009	-18.06	-3.64	2705.65	BMC56OB	-24.40	-4.51	-24.04	-4.53	4048.65	BMC57D	0	-26.30	-5.00	-26.22	-5.00	888.16	-308.31
W016	25/09/2009	-16.35	-3.65	1881.49	BMC56OB	-24.00	-4.55	-23.63	-4.57	4664.87	BMC57D	0	-24.80	-4.69	-24.71	-4.69	982.91	-619.87
W017	17/06/2009	-11.69	-2.75	4000.00	BMC56OB	-20.00	-4.64	-24.63	-4.65	3020.04	BMC64D	0.00	-16.70	-1.21	-11.80	-1.38	58900.00	-228.46
W017	22/07/2009	-9.85	-2.50	5623.70	BMC56OB	-24.30	-4.20	-24.00	-4.21	4134.05	BMC64D	0.00	-16.70	-1.21	-11.80	-1.38	58900.00	-1817.62
W017	27/08/2009	-6.24	-1.33	15072.69	BMC56OB	-24.40	-4.51	-24.04	-4.53	4048.65	BMC64D	0.00	-16.70	-1.21	-11.80	-1.38	58900.00	-4137.68
W017	25/09/2009	-11.69	-2.75	10000.00	BMC56OB	-24.00	-4.55	-23.63	-4.57	4664.87	BMC64D	0.00	-16.70	-1.21	-11.80	-1.38	58900.00	-2333.12
W017	20/10/2009	-11.69	-2.75	10000.00	BMC56OB	-22.90	-4.60	-22.53	-4.62	4245.16	BMC64D	0.00	-16.70	-1.21	-11.80	-1.38	58900.00	-71.96
W017Inlet	22/07/2009																	#DIV/0!
W017Inlet	27/08/2009																	#DIV/0!
W026	22/07/2009																	#DIV/0!
W026	26/08/2009																	#DIV/0!
W026	24/09/2009																	#DIV/0!
W051	20/04/2009	-12.27	-3.69	12.00	BMC89ob	-17.40	-3.55	-17.40	-3.55	52.00								-12.69
W051	18/05/2009	-3.36	-2.91	12.00	BMC89ob	-17.40	-3.55	-17.40	-3.55	52.00								-8.37
W051	16/06/2009	-8.41	-1.98	12.00	BMC89ob	-21.40	-3.68	-21.39	-3.68	34.31								4.98
W051	21/07/2009	-20.05	-4.84	12.00	BMC89ob	-23.00	-4.15	-22.99	-4.15	31.12								10.46
W051	26/08/2009	-11.31	-1.54	12.00	BMC89ob	-27.00	-4.73	-26.99	-4.73	32.60								56.19
W051	24/09/2009	-15.26	-3.97	12.00	BMC89ob	-25.10	-4.52	-25.09	-4.52	49.43								53.58
W051	19/10/2009	1.11	-0.83	12.00	BMC89ob	-24.00	-4.88	-23.99	-4.88	36.24								65.33
W051	24/11/2009	-9.83	-1.64	12.00	BMC89ob	-25.20	-4.33	-25.19	-4.33	31.00								15.17
W735	18/05/2009																	#DIV/0!
W735	17/06/2009																	#DIV/0!
W735	22/10/2009																	#DIV/0!
W736	22/04/2009																	#DIV/0!
W736	18/05/2009																	#DIV/0!
W736	17/06/2009																	#DIV/0!
W736	22/10/2009																	#DIV/0!

PR_KEY	Date	Gi $_{(18O)}$ (m3)	*Gi $_{(D)}$ (m3)	*Gi $_{(18O)}$ (m3)	Gi $_{(Cl)}$ (m3)	Go $_{(D)}$ (m3)	Go $_{(18O)}$ (m3)	*Go $_{(D)}$ (m3)	*Go $_{(18O)}$ (m3)	Go $_{(Cl)}$ (m3)	Mean Gi (m3)	Mean Go (m3)	Go-Gi (m3)	#Days
W015	21/04/2009	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7984.80	0.00		
W015	19/05/2009	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7990.40	0.00		
W015	16/06/2009	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7996.00	0.00		
W015	21/07/2009	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8003.00	0.00		
W015	26/08/2009	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8010.20	0.00		
W015	24/09/2009	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8016.00	0.00		
W015	20/10/2009	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8021.20	0.00		
W015	24/11/2009	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8028.20	0.00		
W016	21/07/2009	-31.65	-31.85	-32.11	-393.61	248.26	244.18	243.98	243.72	-117.78	7978.36	245.03	-7733.33	35.00
W016	26/08/2009	-233.38	-350.05	-225.85	-538.53	-145.52	-70.59	-187.26	-63.06	-375.74	7786.68	-116.61	-7903.29	36.00
W016	25/09/2009	-1005.14	-641.57	-993.57	390.75	-708.42	-1093.69	-730.13	-1082.12	302.19	7364.17	-903.59	-8267.76	30.00
W017	17/06/2009	-226.56	-214.94	-225.25	-283.62	57.97	59.86	71.49	61.17	2.80	7817.16	62.62	-7754.53	29.00
W017	22/07/2009	-2813.10	-1918.53	-2803.28	-2810.52	218.64	-776.85	117.73	-767.02	-774.26	6132.69	-301.88	-6434.57	35.00
W017	27/08/2009	-3172.30	-4820.37	-2850.70	-227.37	-4896.67	-3931.29	-5579.36	-3609.69	-986.36	5014.19	-4504.25	-9518.44	36.00
W017	25/09/2009	-5534.49	-3108.95	-5406.00	1224.69	-1938.98	-5140.35	-2714.81	-5011.86	1618.83	4739.69	-3701.50	-8441.19	30.00
W017	20/10/2009	-287.14	-139.04	-282.46	108.88	-110.13	-325.30	-177.20	-320.63	70.72	7865.08	-233.31	-8098.39	25.00
W017Inlet	22/07/2009	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	
W017Inlet	27/08/2009	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	
W026	22/07/2009	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	
W026	26/08/2009	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	
W026	24/09/2009	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	
W051	20/04/2009	4.27	-13.55	4.33	-0.92	-11.79	5.16	-12.65	5.22	-0.03	7981.07	-3.52	-7984.59	33.00
W051	18/05/2009	-3.78	-8.76	-3.78	-0.60	-7.79	-3.20	-8.17	-3.20	-0.02	7985.26	-5.59	-7990.85	27.00
W051	16/06/2009	7.42	4.64	7.46	-3.20	8.12	10.55	7.77	10.59	-0.06	8000.90	9.26	-7991.64	29.00
W051	21/07/2009	-40.79	9.96	-34.37	-7.15	5.69	-45.56	5.19	-39.14	-11.92	7992.05	-18.46	-8010.51	35.00
W051	26/08/2009	89.53	55.09	87.63	0.08	54.75	88.09	53.65	86.19	-1.36	8067.89	70.67	-7997.22	36.00
W051	24/09/2009	25.47	52.69	24.25	2.97	53.40	25.30	52.51	24.07	2.79	8047.20	38.82	-8008.38	30.00
W051	19/10/2009	66.62	64.30	66.70	4.73	69.37	70.66	68.34	70.74	8.76	8073.59	69.78	-8003.81	25.00
W051	24/11/2009	11.27	14.95	11.32	0.40	16.55	12.66	16.34	12.70	1.79	8038.74	14.56	-8024.18	35.00
W735	18/05/2009	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!		
W735	17/06/2009	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!		
W735	22/10/2009	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!		
W736	22/04/2009	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!		
W736	18/05/2009	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!		
W736	17/06/2009	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!		
W736	22/10/2009	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!		