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Padthaway Salt Accession Study Volume Three: Conceptual Models

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Jason Van den Akker, Nikki Harrington and Keith Brown

Knowledge and Information Division
Department of Water, Land and Biodiversity Conservation

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Department of Water, Land and Biodiversity Conservation

25 Grenfell Street, Adelaide

GPO Box 2834, Adelaide SA 5001

Telephone	National	(08) 8463 6946
	International	+61 8 8463 6946
Fax	National	(08) 8463 6999
	International	+61 8 8463 6999
Website	www.dwlbc.sa.gov.au	

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FOREWORD

South Australia's unique and precious natural resources are fundamental to the economic and social wellbeing of the State. It is critical that these resources are managed in a sustainable manner to safeguard them both for current users and for future generations.

The Department of Water, Land and Biodiversity Conservation (DWLBC) strives to ensure that our natural resources are managed so that they are available for all users, including the environment.

In order for us to best manage these natural resources it is imperative that we have a sound knowledge of their condition and how they are likely to respond to management changes. DWLBC scientific and technical staff continues to improve this knowledge through undertaking investigations, technical reviews and resource modelling.

Rob Freeman
CHIEF EXECUTIVE
DEPARTMENT OF WATER, LAND AND BIODIVERSITY CONSERVATION

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1. INTRODUCTION

The following is the third in a series of four reports on the *Padthaway Salt Accession Investigations and Determination of Sustainable Extraction Limits (PAV)* study. Volume 1 of the report series provides a background to the project and details of the study area, project approach, methodology and site instrumentation. Volume 2 is a collation and evaluation of the field data collected throughout the project. This report, Volume 3, concentrates on the development of conceptual models for salt and water movement through the Padthaway Prescribed Wells Area (PWA) using those data. This includes:

- One-dimensional models of drainage, groundwater recharge and flushing of saline soil water from the unsaturated zone following land clearing at field sites in the Naracoorte Ranges.
- The results of an empirical approach used to extrapolate the one-dimensional models across the Naracoorte Ranges, and implications for groundwater salinisation in this area.
- Conceptual models of water and salt movement, and estimations of drainage and salt fluxes, beneath each of the irrigated field sites located on the Padthaway Flat.
- Spatial extrapolation of the one-dimensional site-specific results for the Padthaway Flat to estimate salinity impacts from irrigation development in the PWA.
- A two-dimensional regional conceptual and numerical model describing groundwater flow and changes in groundwater salinity over time in the Padthaway PWA predominantly as a result of salt accessions in the Naracoorte Ranges.

2. METHODOLOGY

The overall project approach, methodology, field site instrumentation and data collection techniques were described in Volume 1 of this report series. However, the following provides details of the data interpretation methodologies used to derive the point and regional scale salt and water balances and conceptual models in this volume.

2.1 MODELLING OF DRAINAGE AND FLUSHING OF SALINE SOIL WATER FROM THE UNSATURATED ZONE IN THE NARACOORTE RANGES

One dimensional models of salt accession processes in the Naracoorte Ranges were developed in collaboration with CSIRO Land and Water, Adelaide, and details of this aspect of the project are presented in a separate report (Wohling et al., 2005). However, the methodology is summarized here and the key results are discussed in Sections 3.1 and 3.2.

Clearing of native vegetation from the majority of the Naracoorte Ranges portion of the Padthaway PWA occurred in the 1960s ~45 yrs ago. It is now well understood that the clearance of native vegetation in semi-arid and temperate parts of Australia, and replacement of this with shallow rooted perennial crops, results in the displacement of highly saline soil water from the unsaturated zone and salinisation of groundwater resources. Thick unsaturated zones (up to 40 m) in the Naracoorte Ranges mean that flushing of the salt that was previously stored in the soil profile there may not yet be complete. It is believed that this process may have at least partially contributed to observed increases in groundwater salinity in the Padthaway Flat Irrigation area, down-gradient of the Naracoorte Ranges.

Increased drainage following land clearing results in the downward movement of a pressure front through the unsaturated zone. When this pressure front reaches the water table, an increase in aquifer recharge occurs (Jolly et al., 1989). The increase in drainage also results in flushing of saline soil water, which has accumulated under native vegetation as a result of large degrees of evapotranspiration of rainfall over long time periods. An analytical model for calculating drainage following land clearing was developed by Walker et al. (1991). This model, known as the chloride front displacement technique, is based on site-specific measurements of the downward displacement of the historic salt store. Hence, although useful for drainage calculations at the point scale, its extrapolation over large areas such as the Naracoorte Ranges requires prohibitive amounts of field data. However, a large body of data now exists on point scale post-clearing drainage rates estimated using this model under different soil types in the 270–470 mm rainfall zones of the Murray Basin. Here, groundwater recharge under native mallee vegetation has been estimated to be negligible at ~0.1 mm/y, but drainage below cleared agricultural land varies from less than 1 mm/y to more than 50 mm/y, depending on factors such as rainfall and soil type (Cook et al., 2001). From this data, a relationship between post-clearing drainage rates and soil type (specifically clay content in the top 2 m of the soil profile) was identified by Kennett-Smith et al. (1994) (Fig. 2.1). Figure 2.1 also shows that the relationship changes with rainfall, with higher rainfall generally resulting in higher post-clearing drainage rates.

As maps of shallow soil type are often readily available, the drainage versus clay content relationship provides a tool for spatially extrapolating estimates of post-clearing drainage.

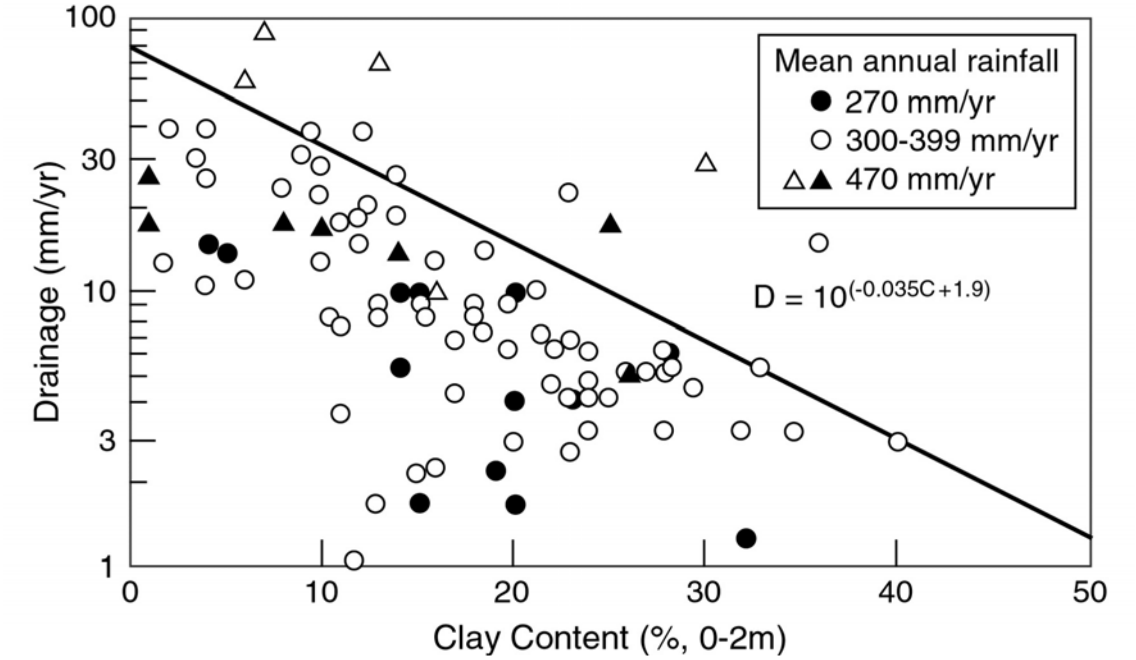


Figure 2.1 Relationship betweens soil texture and drainage under dryland agriculture in the 270 (closed circles), 300–400 (open circles), and 470 (diamond) mm yr^{-1} mean annual rainfall zones (Cook et al., 2004). The line of best fit was determined for data from the 470 mm/yr rainfall sites (Leaney et al., 2004).

This method was used by Cook et al. (2004) as the basis for extrapolating a one-dimensional model of increasing recharge and flushing of saline soil water following an increase in drainage across a 240–300 mm/y rainfall zone in the Murray Basin. The approach of Cook et al. (2004) was subsequently applied to the Tintinara region (rainfall = 470 mm/y) by Leaney et al. (2004), with the drainage versus clay content relationship modified slightly using field data for the higher rainfall conditions (Fig. 2.1).

In the present study, a similar approach to that of Cook et al. (2004) and Leaney et al. (2004) was applied to the Naracoorte Ranges portion of the Padthaway PWA. Field data was collected to determine the relationship that should be used for the Padthaway PWA, where rainfall is significantly higher (510 mm/y) and the soil profile is more clayey and calcareous. Soil property (clay, silt and sand content), water content and pore water chloride concentration data were obtained from soil cores collected at a variety of sites in the Naracoorte Ranges (see Map 1). These results are included in Volume 2 of this report. The data identified (a) some sites located in stands of remnant native vegetation where the original store of saline soil water is still present, (b) sites where the salt store has been partially flushed into the groundwater system and (c) sites where saline soil water has been completely flushed and recharge with fresher water is now occurring. The field data were then used to refine the parameters and empirical relationships used in the model of Cook et al. (2004). Agreement between the model results and interpretation of the field data provided increased confidence in application of the model to the Naracoorte Ranges portion of the study area. Point estimates of recharge and salt flux to the water table were then extrapolated spatially via a GIS interpretation of soil landscape unit (SLU) and water table depth maps to produce maps of potential groundwater salinisation. See Wohling et al. (2005) for a full description of the methodology for this section of the project and Section 3.2 of this report for the results.

2.2 ESTIMATION OF IRRIGATION DRAINAGE RATES FOR THE PADTHAWAY FLAT IRRIGATED SITES

2.2.1 WATER BALANCE TECHNIQUES

Drainage (D) was calculated using a residual water balance approach on a daily basis for each investigation site where:

$$D = (P + I) - (ET + \Delta S) \qquad (2.1)$$

Precipitation (P) and Irrigation (I) are the input components of the water balance, ΔS is the change in stored soil water and ET is the water lost via evapotranspiration from the crop. At the vineyard sites, daily ET was obtained from measurements made by the CSIRO Flux station at sites NAP 6 and NAP1. Estimates of ET at the centre pivot and flood irrigation sites were calculated from Class A Pan Evaporation provided by the Bureau of Meteorology. Crop coefficients for each crop were sourced from Desmier (1992). Changes in soil moisture storage were measured on a fortnightly to monthly basis at the vineyard sites using a neutron moisture meter (NMM) and water balance calculations carried out using this information will be described as the "standard water balance" for the purpose of this report.

In the absence of measured ΔS, a daily soil water balance was calculated using theoretical values for available soil moisture storage following the approach of Penman and Grindley (Penman, 1948, 1949, 1950; Grindley 1967, 1969). This will be known as the Penman-Grindley method for the purposes of this report. Drainage is considered to be a function of effective rainfall, irrigation and ET (P + I – ET) and recharge takes place only when the Soil Moisture Deficit (SMD)[1] is zero (Rushton and Redshaw, 1979). In heterogeneous environments, drainage may occur when SMD > 0 through preferential flow, and applying this method to a heterogenous soil profile may lead to an underestimation of drainage. The heterogeneous texture of the soils at Padthaway, where large cracks, cavities and sediment-filled root channels (below vines) have been observed, may mean that results of this method should be interpreted with caution.

Capacitance probes (c-probes) were used at each site to monitor changes in soil water content. Un-calibrated values from capacitance sensors at depths of 20, 30 and 50 cm were summed together and plotted against the daily soil water balance to give a visual (qualitative) picture of drainage through the soil profile. C–probes can support the daily water balance calculations by verifying individual drainage events and the degree of soil moisture deficit. The comparison allows for a higher confidence in our calculations.

A plot of capacitance vs SMD for the centre pivot site, NAP 3 shows an increase in scatter as the SMD approaches 0 (Fig. 2.2). This suggests that c-probes are only effective at determining soil water volume when a SMD exists and therefore cannot easily resolve the difference between large and small drainage events.

[1] Soil moisture deficit (SMD) = wilting point (WP) x rooting depth (RD). WP was calculated by the method of Hutson and Cass (1987), based on soil particle size distribution.

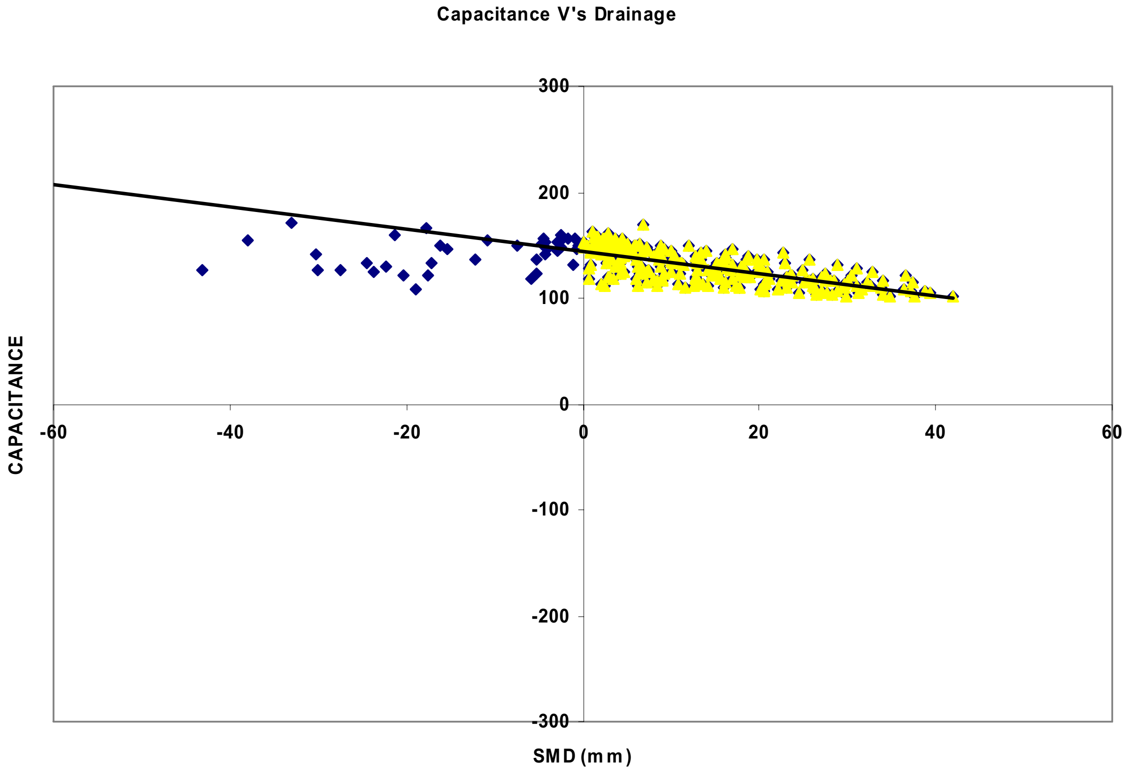


Figure 2.2 Plot of capacitance, measured using c-probes, versus Soil Moisture Deficit (SMD) calculated using the methodology of Rushton and Redshaw (1979)

2.2.2 CHLORIDE MASS BALANCE

The chloride mass balance method is based on the conservation of mass within or below the root zone. The steady-sate model of the US Salinity Laboratory (1954) was used to determine drainage rates in the irrigated fields and background sites. The chloride mass balance is a widely accepted method and has been successfully used to determine drainage under irrigated sites (Frenkel 1984; Oster 1984; Shalhevet 1984; Ayres and Westcott 1985). However, for the method to be valid the system must be in steady state, i.e. there should be no change in chloride storage within the soil profile. If this is not the case, a transient model such as SODICS of Rose et al (1979) should be used. Monthly measurements of chloride concentrations in irrigation water, rainfall and soil water at depth were used to estimate drainage using the following equations:

$$C_A = (C_P + C_I) / (P + I) \quad (2.2)$$

$$D = (P + I) \times C_A / C_D \quad (2.3)$$

Where P = precipitation (mm/y), I = irrigation (mm/y), C_A = average chloride concentration of precipitation (C_P) and Irrigation (C_I) (mg/L) and C_D is the chloride concentration of soil water below the root zone (mg/L).

2.2.3 LEACHM MODEL

A one-dimensional model was created to simulate and quantify the infiltration of rainfall and irrigation water through the unsaturated zone to the water table at vineyard site NAP6. The aim of the model was to increase our confidence by comparing the simulated drainage with our estimates of drainage calculated via the traditional water balance, Penman-Grindley and chloride mass balance methods.

The simulation of the water balance within the unsaturated zone of the soil profile was undertaken using LEACHM (Leaching Estimation and Chemistry Model; Hutson & Wagnet, 1992). The model, written in FORTRAN, simulates vertical water flow based on the solution of the Richards equation.

The multilayer model calculated the water balance on a daily basis over the 2004/05 irrigation season. It is anticipated that additional models could be developed to infer drainage across smaller soil units throughout the PWA, where we lack field data and instrumentation.

The average depth of the unsaturated zone was set at 5 m. The soil profile consists of 50 segments, each of an equal thickness of 100 mm. Each segment contains specific soil physical properties to represent horizons of various thicknesses within the soil profile. The lower boundary condition was set to free draining, giving a unit hydraulic gradient flux at the lowest node.

Input data used in the development of the model includes soil physical properties for each depth increment, weather and crop data outlined below:

- The soil physical properties include particle size distribution, bulk density and matric potential. These properties were obtained from soil cores which were retrieved during an excavation and are summarised in Volume 2. The water flow model in LEACHM requires equations relating volume fractional water content, pressure potential and hydraulic conductivity. The model uses functions based on those proposed by Campbell (1974), and has a sub routine to calculate water retention parameters. Soil parameter estimation software, SOILPAR v.2 was used to calculate soil retentivity (Campbell a and b parameters) based on textural data.
- Daily precipitation/irrigation, total weekly evapotranspiration, mean weekly air temperature, and mean weekly amplitude of air temperature were measured via the CSIRO flux station and climate station.
- Vine information such as canopy growth (crop cover fraction; 0 at bud burst increasing to 0.7 at maturity), date of maturity, date of harvest (May 2005) and rooting depth (2 m) were used to simulate crop water use (transpiration) and crop growth.

2.3 ESTIMATION OF SALINITY IMPACTS FROM IRRIGATION ON THE PADTHAWAY FLAT

Following the estimation of drainage rates, net salinity impacts to the unconfined aquifer were calculated for each field site using the following methodology:

1. Drainage values for each field site were selected from estimates made using the above methods, based on knowledge of the limitations of each method.
2. The salinity of the drainage water was determined using one of the following methods:

a. In the case of the flood irrigation sites (NAP4 and NAP5), the salinity of the drainage water was assumed to be equivalent to that of the soil pore water sampled by the 2 m and 3 m suction lysimeters (i.e. below the root zone).

b. At the centre pivot site, NAP3, suction lysimeter data was not available below 2 m depth and hence, pore water salinities below the root zone could not be confirmed using this method. Salinity of the drainage water was inferred from the average chloride concentration of soil water measured from soil cores, taken below the chloride bulge and above the capillary zone. In addition, the average increase in soil water salinity measured at the 1 and 2 m lysimeters, multiplied by an estimated water content at each depth was used to infer the volume of salt accumulation over one season.

c. In the case of the vineyard sites, the salinity of the soil water sampled by the deepest suction lysimeters, when multiplied by the drainage estimates, caused a large salt imbalance, with the amount of salt calculated to leave the profile via drainage being much greater than that applied at the surface in irrigation water and rainfall. This imbalance, along with the non-steady-state and irregular shapes of pore water chloride versus depth profiles, suggested that preferential flow, particularly of heavy winter rainfall, may be occurring down sediment-filled cracks and root channels observed in the vineyard soils. The occurrence of preferential flow would mean that not all drainage carries a salinity as high as that measured in the suction lysimeters (see Section 4 for a full discussion of this). Little change in the salinity of pore water sampled by the suction lysimeters over the time frame of the project suggested that the majority of the soil profile is at a steady state with respect to chloride over the time scale of a year and hence, the mass of salt entering the soil profile via irrigation and rainfall must equal that exiting the profile in drainage. Based on this assumption, an equivalent salinity of drainage water was calculated by dividing the mass of salt entering the profile over a 12 month period by the estimated volume of drainage occurring during that time.

3. The difference between the estimated salinity of the drainage water and the applied irrigation water was calculated. This gives the net salinity increase caused by the use of groundwater for irrigation, and was done due to the fact that, in many cases, landholders were irrigating with relatively fresh groundwater extracted from adjacent the Naracoorte Ranges, resulting in irrigation drainage water with a lower salinity than the groundwater underlying the irrigation site. Despite the local freshening effect that this may have, a salinity impact to the aquifer is still occurring from irrigation due to the fact that otherwise fresh groundwater through-flow is being intercepted and evapo-concentrated.

4. The net salinity increase (∆sal) was multiplied by the drainage rate (D) to give a net salinity impact to the aquifer (SI), in t/ha/y as follows:

$$SI\ (t/ha/y) = \Delta sal\ (mg/L) \times D\ (mm/y)\ /100\ 000 \qquad (2.4)$$

2.4 ESTIMATION OF VERTICAL DIFFUSION OF SALT BELOW THE DRIP IRRIGATED VINEYARDS

The shapes of the soil water chloride versus depth profiles for the drip irrigated sites suggested that diffusion could be a solute transport mechanism occurring at these sites. Under water-saturated conditions, vertical diffusion of salt to the water table from the point of maximum pore water salinity below the drip irrigated vineyards would be calculated using Fick's Law (Fetter, 1994):

$F = -D_s \, dC/dx$ (2.5)

where F = mass flux of solute per unit area per unit time

D_s = bulk sedimentary diffusion coefficient (area/time)

DC/dx = concentration gradient (mass/volume/distance)

Since the majority of the salt dissolved in groundwater at Padthaway is NaCl, the diffusion coefficient for Cl^- was used. The free solution diffusion coefficient (D_0) of Cl^- is 5.03 x 10^{-2} m^2/y (Robinson & Stokes, 1959). Based on a porosity of 0.33, the bulk sedimentary diffusion coefficient ($D_S = D_0$ x pososity) is 1.66 x 10^{-2} m^2/y (Ullman & Aller, 1982). Na^+ should diffuse at the same rate to maintain charge balance. To convert between [Cl] and TDS, a factor of 2.2 was used. This factor was based on observed TDS/Cl ratios in groundwater on the Padthaway Flat.

However, in unsaturated soils, diffusion of salts becomes much slower and is a less effective solute transport mechanism. In this case, the free solution diffusion coefficient should be modified to an effective diffusion coefficient (D_E) based on the ratio between water content (θ) and saturated water content (i.e. porosity; θ_s) using the relationship (Millington & Quirk, 1961):

$$D_E = D_0 \frac{\theta^{10/3}}{\theta_s} \qquad (2.6)$$

Hence, maximum diffusion occurs in saturated soils, where $\theta = \theta s$ and Equation 2.5 can be used. In unsaturated soils where there is very little mass flow, diffusion may still be an important mass transfer mechanism. For the purpose of the salt balance calculations provided in Sections 4 to 6, the maximum potential contribution from diffusion is calculated using Equation 2.5.

2.5 EXTRAPOLATION OF SALINITY IMPACT ESTIMATES ACROSS THE PADTHAWAY FLAT

The upper and lower limits of drainage and net salinity impact, calculated at each of the 9 investigation sites were extrapolated to other areas on the Padthaway Flat with similar:

- Irrigation practice;
- Crop type;
- Soil type/thickness;
- Climate (rainfall / evapotranspiration); and
- Irrigation water salinity

Based on the above criteria, an ArcMap (GIS) framework was used to create zones containing similar attributes to which the drainage and salt flux terms could be applied.

2.6 GEOCHEMICAL MODELLING OF SALT FLUSHING AND GROUNDWATER FRESHENING IN THE NARACOORTE RANGES

In order to investigate the hypothesis that groundwater salinity and chemistry distributions in the Naracoorte Ranges are the result of (a) flushing of the historical unsaturated zone salt store, and (b) subsequent fresh recharge, a geochemical model simulating the chemical reactions that occur as a result of these processes was created using the PHREEQC geochemical modelling software (Parkhurst & Appelo, 1999). The model was used to simulate the following processes, and results are shown on the chemical diagrams in Sections 3 to 6:

- Evapotranspiration of rainfall (rainfall composition obtained from data for Kybybolite (50 km south-east of Padthaway) (Blackburn & McLeod, 1983)) to a chloride concentration of 6000 mg/L, as observed in soil water below un-cleared native vegetation sites. This simulates the chemical composition of saline soil water in the unsaturated zone under pre-clearing conditions. The reaction was allowed to occur in equilibrium with solid phases of calcite and dolomite and with a CO_2 partial pressure (pCO_2) of $10^{-2.5}$ (to simulated the elevated pCO_2 that occurs in most unsaturated zones).
- Evapotranspiration of rainfall to a chloride concentration of 50 mg/L, to simulate the chemical composition of fresher recharge that is now occurring under post-clearing conditions, as observed in the flushed soil profiles. This reaction was allowed to occur in equilibrium with the same phases as the previous evaporation reaction.
- Mixing of the two resulting groundwater recharge compositions described above with regional groundwater, represented by the composition of groundwater from the deep piezometer PB5. This reaction was again allowed to occur in equilibrium with carbonate minerals, the dissolution of which was thought to be having a profound on the groundwater chemistry observed in the Padthaway PWA. Different mixing fractions were used to simulate the expected trends in groundwater composition with increased mixing with either the fresh or saline recharge compositions. The simulations of mixing with fresher drainage water and saline soil water have been called MixDrainage_PB5 and MixSalt_PB5 respectively.

2.7 DEVELOPMENT OF A TWO-DIMENSIONAL NUMERICAL MODEL OF GROUNDWATER FLOW AND SALT MOVEMENT FROM THE NARACOORTE RANGES TO THE PADTHAWAY FLAT

2.7.1 GENERAL

A two-dimensional groundwater flow and solute transport model was developed along an inferred groundwater flow path running from the eastern Naracoorte Ranges onto the Padthaway Flat (See Map 1 for location of modelled flow path). The aim of the model was to investigate the hypothesis that the majority of the groundwater salinity increase observed on the Padthaway Flat is due to the flushing of saline soil water in the Naracoorte Ranges. It is intended that the results of the model will provide valuable insight for the future construction of a regional three-dimensional groundwater flow model of the Padthaway PWA.

The flow modelling was undertaken using the USGS software MODFLOW (McDonald and Harbaugh, 1988). MODFLOW is a computer generated three-dimensional numerical code that uses finite difference techniques to approximate the governing equations for groundwater flow. The modelling process was enhanced using pre-processors and post-processors from Visual Modflow Version 4.1 (Waterloo Hydrogeologic Incorporated, 2005). The WHS solver was used to solve the flow equation. The mass transport engine MT3DMS (Zheng, 1990) was used to simulate the movement of salt within the aquifer.

A two-dimensional cross section model assumes that all flow occurs parallel to and within the plane of the cross-section (i.e. the cross-section is assumed to be aligned along the direction of flow in an aquifer). Although the model is two-dimensional, it performs in the same way as a three-dimensional regional model, with the exception that any groundwater flow perpendicular to the cross-section is ignored.

2.7.2 CONCEPTUAL MODEL

Figure 2.3 shows the conceptualised model of groundwater flow along the modelled cross-section. Rainfall recharge in the Naracoorte Ranges prior to land clearance is considered to have been small (< 0.1 mm/yr) and was assumed to be zero in the model. Results of the one-dimensional modelling described in Section 2.1 showed that, post land clearance recharge to the aquifer increased until a new steady state recharge rate was reached. For example, site PB5 has an initial recharge rate of 0.1 mm/yr, but this increases to 163.1 mm/yr over a ten-year period following clearing. Groundwater then flows westward from the Naracoorte Ranges and onto the Padthaway Flat beneath the main viticultural area.

A conceptualised solute transport model of the Padthaway PWA is presented in Figure 2.4, and shows the main sources and sinks of salt for the modelled cross-section. Salt fluxes to the aquifer caused by post-clearing flushing of the historical salt store were determined through the one-dimensional modelling described in Section 2.1. Once flushing began, initial salt loads to the aquifer were high (e.g. PB1 had an initial salinity of 11 661 mg/L). The effects of irrigation on groundwater salinity on the Flat were not simulated in this modelling exercise due to limitations in the capability of the two-dimensional model, and the objective of the exercise, which was to investigate the potential impacts on the flats of salt accession processes in the Naracoorte Ranges.

2.7.3 MODEL DESIGN

The model domain consists of one layer, that is 9.5 kilometres long and divided into 95, 100 m x 100 m square cells (Fig. 2.5). The left side of the model represents the beginning of the nominal flow path in the Naracoorte Ranges in the east of the PWA and the right side of the model represents the end of the nominal flow path, on the Padthaway Flat to the west of the starting point (see Map 1; Fig. 2.5). Layer 1 is modelled as an unconfined aquifer, representing both geological units of the Bridgewater and Padthaway formations on the Flat and the Bridgewater Formation in the Ranges. Ground surface elevations were obtained from ArcGIS. The bottom of the layer (or aquifer) was considered to be the top of the Ettrick Formation, and elevations of this were obtained from hydrogeological cross sections. Input recharge rates and salinities are given in Appendix A.

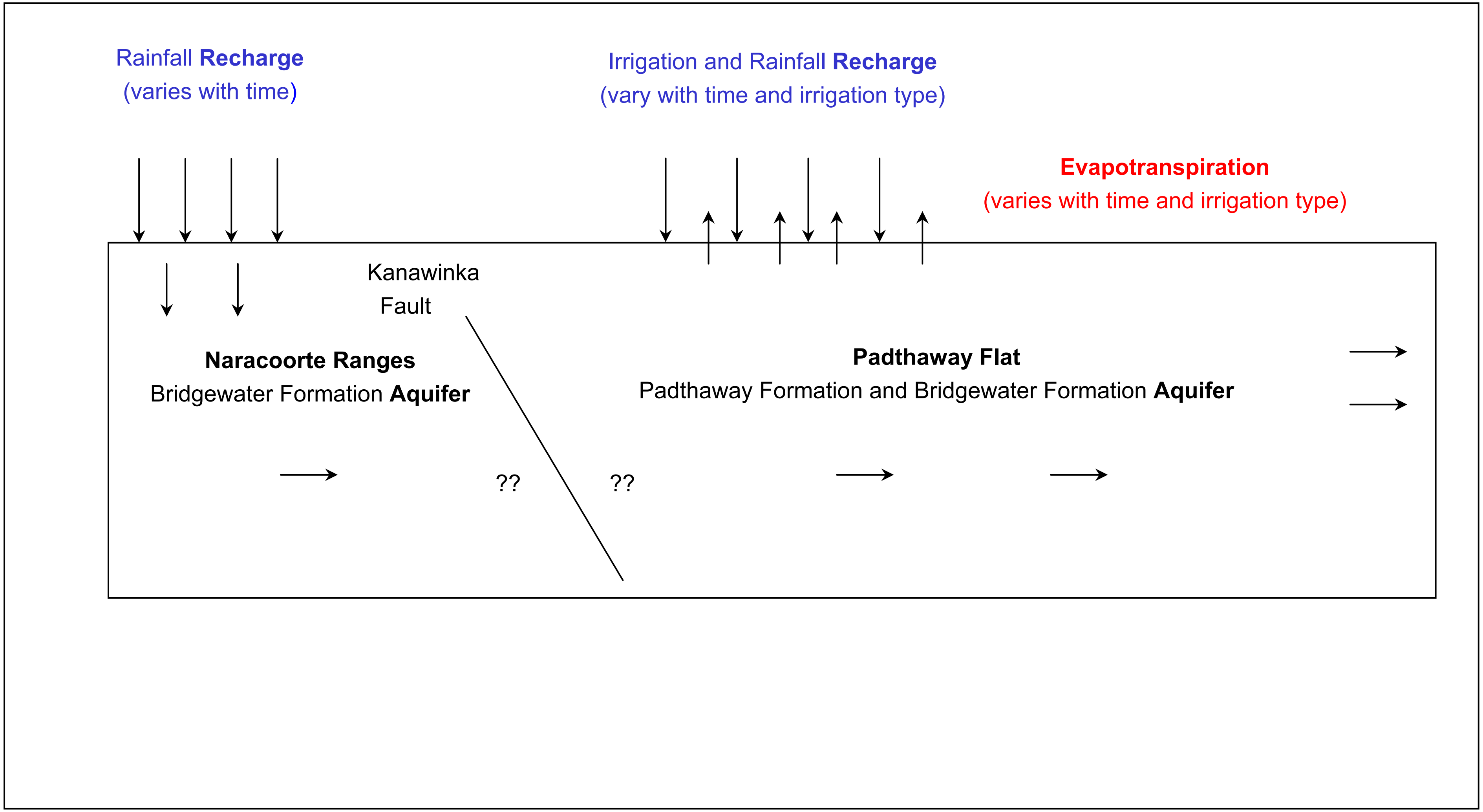


Figure 2.3 Conceptual model of groundwater flow system

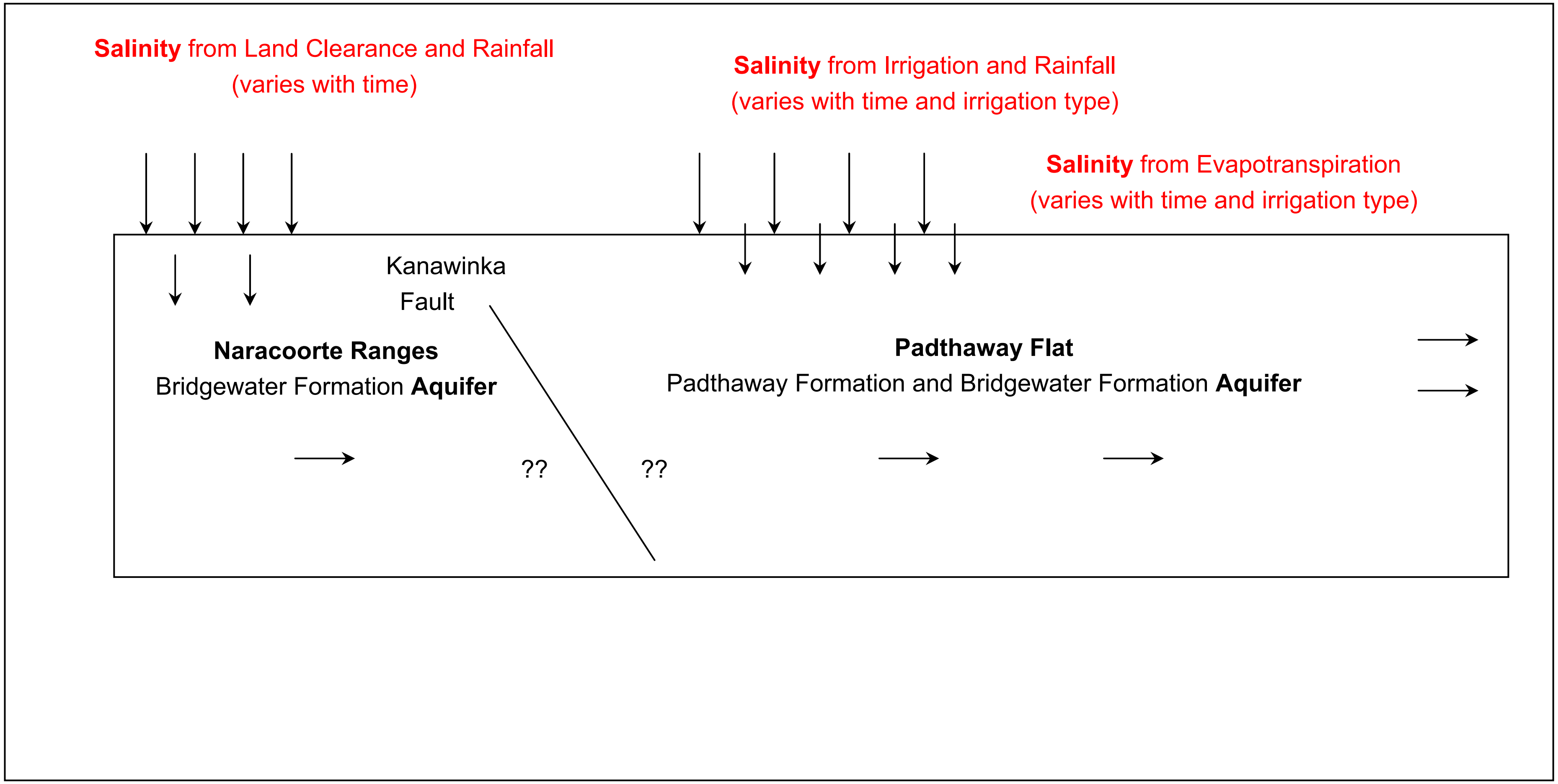


Figure 2.4 Conceptual model of groundwater solute transport system.

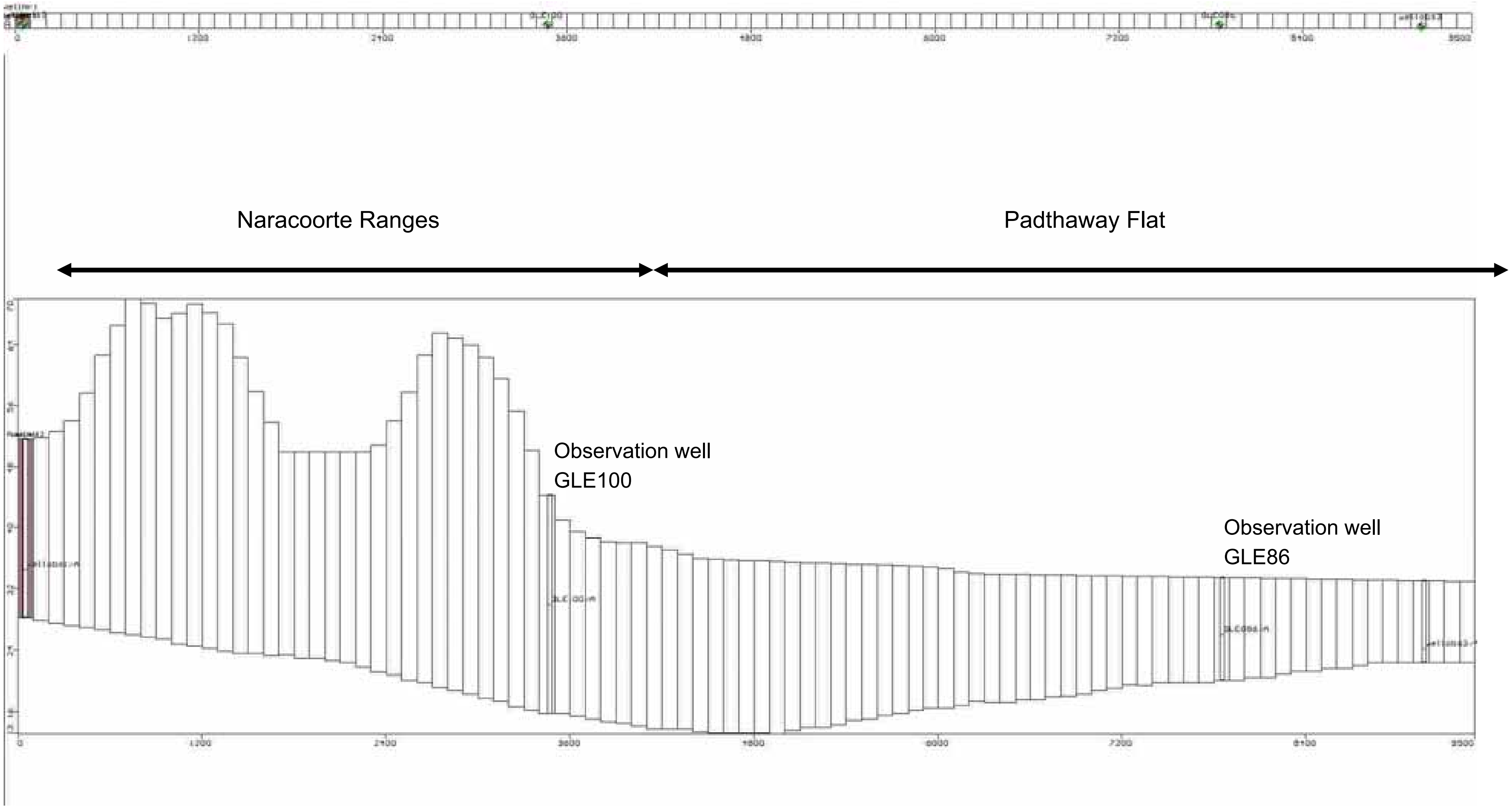


Figure 2.5 Model grid used in the two-dimensional numerical model

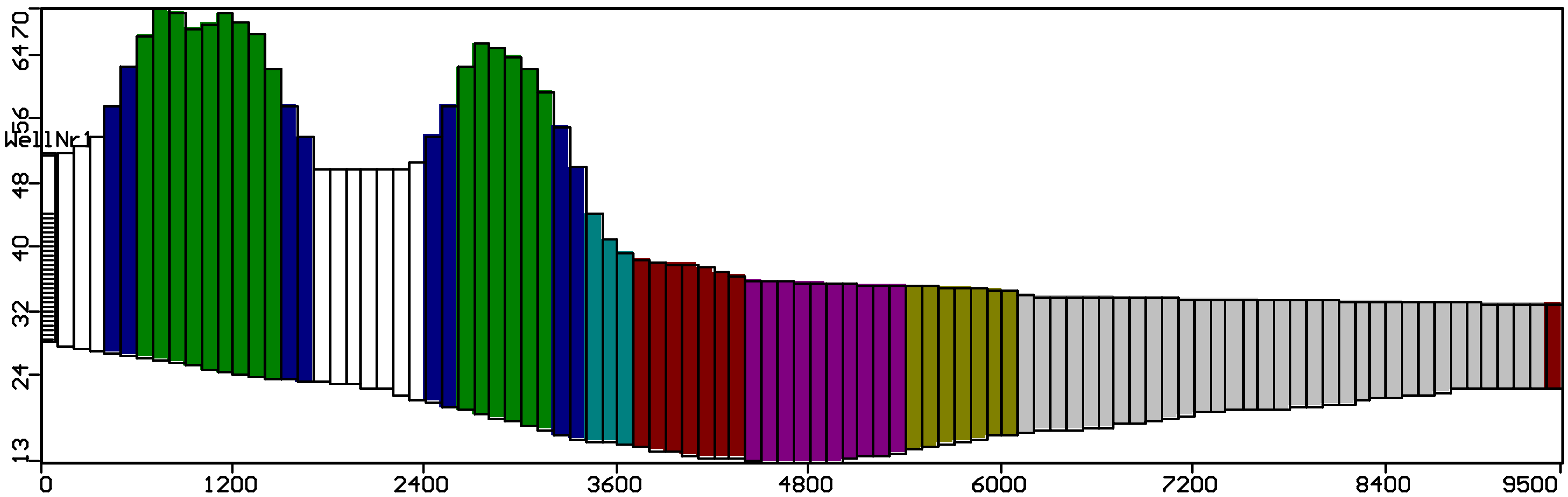
Initial hydraulic head conditions for the flow model were obtained from a steady state simulation that replicated assumed conditions prior to European settlement. A transient model was then run, simulating the period from 1960–2010 and calibrated against hydraulic and salinity data from observation wells GLE100 located at the foot of the Range and GLE086 located near the end of the flow path (Fig. 2.5).

Boundary conditions for the flow model were as follows (Fig. 2.6):

- A pumping well at the left boundary of the model injects water at 7.5 m^3/day, simulating inflow from up-hydraulic gradient of the model in the Naracoorte Ranges.
- A constant head boundary, with an elevation of 32 m AHD, as measured in observation wells in the area, was placed at the right hand end of the model to ensure outflow from the model at the western margin.
- Temporal variations of recharge rates and salinities for each of the Naracoorte Ranges recharge zones were based on the results of the one-dimensional models of our field sites developed using field data. Recharge zones were broadly assigned based on similarities in water table depth and soil type, and numbering corresponds to the field sites upon which the recharge characteristics are based (Fig. 2.6). For the purpose of the modelling exercise, recharge on the Padthaway Flat was assumed to be zero as groundwater extraction is considered to balance recharge in this area and groundwater extraction / evapotranspiration cannot be effectively simulated in two-dimensions. Land clearance in all parts of the Range was assumed to occur in 1960. Commencement of the increase in recharge to the aquifer in each zone varies depending largely on clay content in the unsaturated zone and depth to the water table (see App. A for input recharge rates and salinities). Recharge rates also vary depending on the soil properties.

The aquifer properties used in the model are summarised in Table 2.1 below and their distributions are shown in Figure 2.7. These parameters are consistent with field data obtained by Harris (1972) and used in previous groundwater modelling exercises (e.g. Lisdon Assoc. & Stadter, 1998) Model calibration was obtained by varying the aquifer parameters within acceptable limits, so that a reasonable match between observed and modelled hydraulic head and groundwater salinity data was obtained.

The transport model was applied to simulate the same 100-year period (i.e. 1960–2060). The model was used to simulate salt accessions in the Naracoorte Ranges and the impact this has had on groundwater salinity on the Padthaway Flat. An initial salinity of 1400 mg/L was considered representative of pre-land clearance and irrigation for all cells in the model. The concentration of groundwater inflow at the eastern (left hand) boundary, simulated using an injection well, was assumed to be 1400 mg/L, equivalent to that of the deep well PB5 that is screened in the top of the Gambier Limestone. Similarly to recharge rates, temporal variations in recharge concentrations for the Naracoorte Ranges were also obtained from the one-dimensional modelling described in Section 2.1 (see App. A for input parameters). The minimum chloride concentration of the fresh recharge occurring in the Naracoorte Ranges, as observed in the flushed soil profiles collected during the study, is 50 mg/L. This was multiplied by two to convert to total salinity. However, this does not take into consideration the salts added through calcite dissolution by the fresh water in the calcareous soils present in the Naracoorte Ranges. Therefore, the actual salinity of the fresh recharge water is probably closer to 296 mg/L, which was derived by modelling calcite dissolution by the fresh recharge water using the geochemical modelling package PHREEQC (Parkhurst & Appelo, 1999).



	Variable Recharge Zone
	PB1
	PB5
	PB7
	PB8

Figure 2.6 Boundary conditions used in the two-dimensional numerical model.

The temporal variations of recharge rates and salinities for each of the Naracoorte Ranges recharge zones were based on the results of the one-dimensional models of our field sites developed using field data. Recharge zones were broadly assigned based on similarities in water table depth and soil type, and numbering corresponds to the field sites upon which the recharge characteristics are based. For the purpose of the modelling exercise, recharge on the Padthaway Flat was assumed to be zero as groundwater extraction is considered to balance recharge in this area and groundwater extraction / evapotranspiration cannot be effectively simulated in two-dimensions. A constant head boundary, based on hydraulic head measurements in observation wells, was assigned at the right hand (down-gradient) end of the model to facilitate the movement of water through the Padthaway Flat.

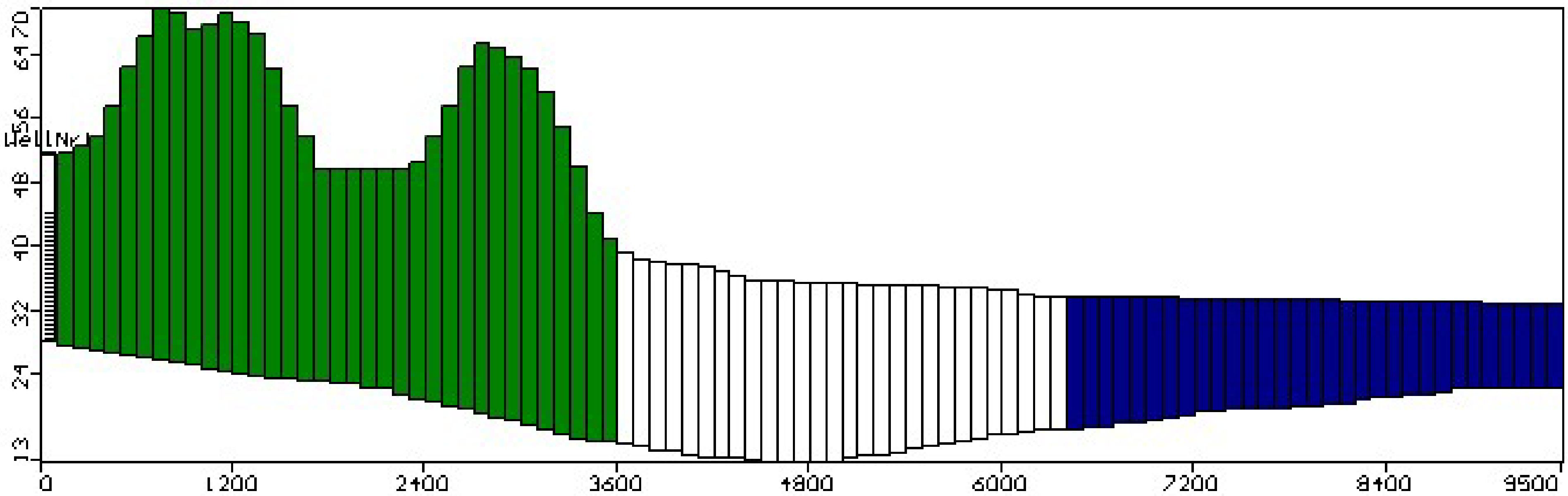


Figure 2.7 Modelled zones of different properties (see Table 2.1).

Table 2.1 Model parameters used in the two-dimensional numerical model. Refer to Figure 2.7 for location of model zones.

	Zone A (Green)	Zone B (White)	Zone C (Blue)
Horizontal hydraulic conductivity (m/d)	10	100	200
Vertical hydraulic conductivity (m/d)	10	100	200
Ss (1/m)	0.0001	0.0001	0.00001
Sy ( )	0.1	0.12	0.12
Effective porosity ( )	0.1	0.12	0.12
Total porosity ( )	0.1	0.12	0.12
Initial heads (m AHD)	69.97	69.97	69.97
Initial concentration (mg/L)	1400	1400	1400
Dispersion (m)	0	0	0

The two-dimensional numerical model was designed to test the conceptual model of the effects of salt accession in the Naracoorte Ranges on groundwater salinity on the Padthaway Flat, therefore no attempt was made to reproduce small fluctuations as observed in the hydrographs. Such fluctuations are considered to be due to seasonal and climatic variability in rainfall (Brown et al., 2005). It was originally envisaged that the model would also reproduce salinity impacts from different irrigations practices undertaken on the Flat. However it was not possible to do this with any confidence using the slice model. The layer was assumed to therefore be in steady state on the Flat and no recharge was applied.

3. SALT ACCESSION PROCESSES IN THE NARACOORTE RANGES

3.1 ONE DIMENSIONAL MODELLING OF DRAINAGE AND FLUSHING OF SALINE SOIL WATER FROM THE UNSATURATED ZONE IN THE NARACOORTE RANGES

3.1.1 THE SALT STORE UNDER NATIVE VEGETATION

Figure 3.1 shows a soil water chloride profile collected under a stand of native vegetation in the Naracoorte Ranges, representing the pre-clearing scenario. This profile shows soil water chloride concentrations of ~6000 mg/L (equivalent to a total salinity of ~15 600 mg/L) occurring below the root zone. Data from sites PA1 and PA4 also showed similarly high pore water chloride concentrations despite being located in fairly open areas (see Volume 2 for data from these sites). It is believed that some small trees and shrubs nearby may have influenced the chloride profiles at these sites despite best efforts to locate the cores away from vegetation. Hence these also represent the pre-clearing scenario. Flushing of small amounts of such highly saline soil water into groundwater that has a salinity of ~1400 mg/L would significantly increase the salinity of that groundwater.

3.1.2 GROUNDWATER SALINISATION IN PROGRESS

The soil profile collected from site PB7 shows a scenario where the saline soil water has been displaced downwards to a depth of ~18 m, but has not yet completely flushed from the unsaturated zone (Fig. 3.2a). The water table at this site is at a depth of ~32 m, meaning that 14 m of the unsaturated zone remains un-flushed. In this scenario, salinisation of the underlying groundwater is in progress, with saline soil water slowly leaching into and mixing with the groundwater that flows underneath. The water that is recharging behind the saline soil water has a much lower Cl concentration of ~100 mg/L (a total salinity of ~260 mg/L). The results of the one-dimensional model are shown in Figure 3.2b, as the predicted salt flux to the groundwater system over time following land clearing at site PB7. Salinisation of the groundwater by the leaching salt is predicted to have commenced about 30 years after clearing (Fig. 3.2b, Table 3.1). If clearing is assumed to have occurred in 1960, groundwater salinisation would have commenced in ~1990. The model predicts that all of the salt would have flushed from the profile after about 80 yrs post-clearing, i.e. by the year 2040 (Fig. 3.2b, Table 3.1). Following this, the salt flux becomes much lower as the water recharging under the higher recharge conditions is much fresher.

A similar situation is shown for site NV1, which was originally selected as a native vegetation site, but was later discovered to be partially flushed due to being located in a slight clearing (Fig. 3.3a). Assuming that NV1 represents a site that was cleared, the model agrees with the data, predicting the saline soil water to have started entering the groundwater about 20 yrs post-clearing (i.e. in about 1980) and this salt flux to continue until about 55 yrs after clearing (i.e. 2015) (Fig. 3.3b, Table 3.1).

Table 3.1 Summary of model results for Naracoorte Ranges field sites.

	Unsat'd Zone Thickness (m)	**Average %clay in top 2 m**	**Year Flushing Starts**	**Peak Salt Flux** (t/ha)	**Year Flushing Ends**	**Total Salt Load** (t/ha)
Part Flushed						
PB7	32	22	1990	3.1	2040	58
NV1	24	21	1980	3.25	2015	45
PA2	10.7	1	1964	8.4	1970	23
Flushed						
PB1	5.75	9	1963	6.1	1970	12.5
PB5	15.6	0.5	1965	8.5	1975	32
PB8	11.4	19	1968	3.7	1985	22
PA3	40	21	1965	4.1	1978	44

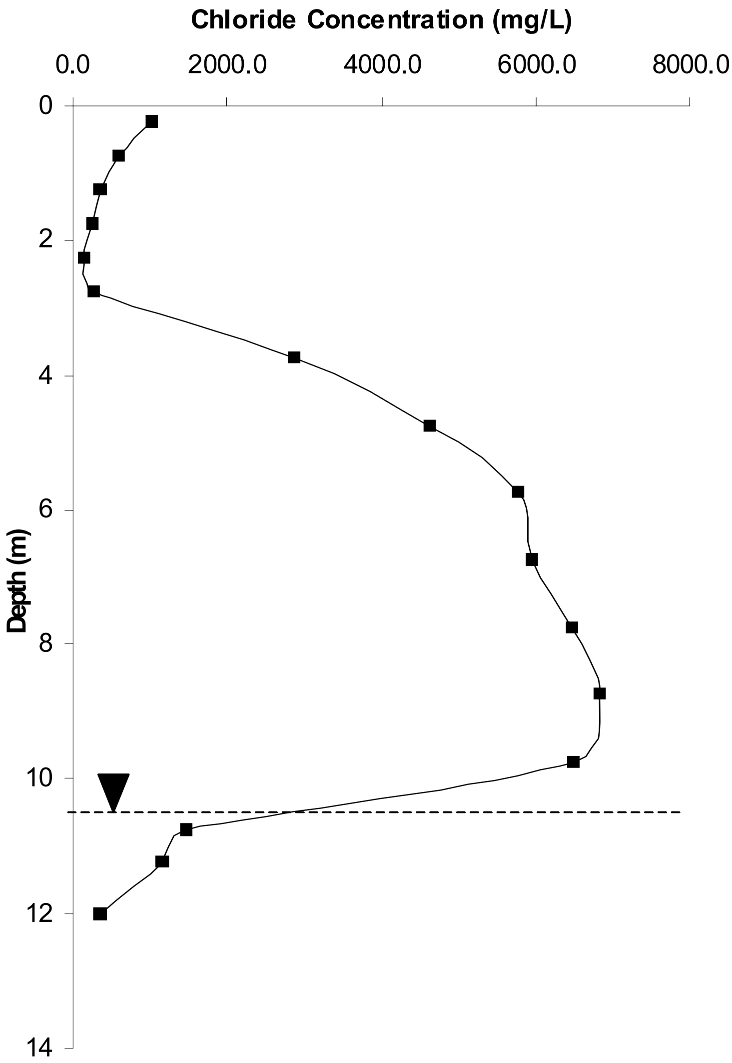


Figure 3.1 Soil water chloride profile collected from below a stand of remnant native vegetation, showing the original store of salt in the unsaturated zone.

Under pre-clearing conditions, soil water has a chloride concentration of ~6000 mg/L, equivalent to a total salinity of ~15 600 mg/L.

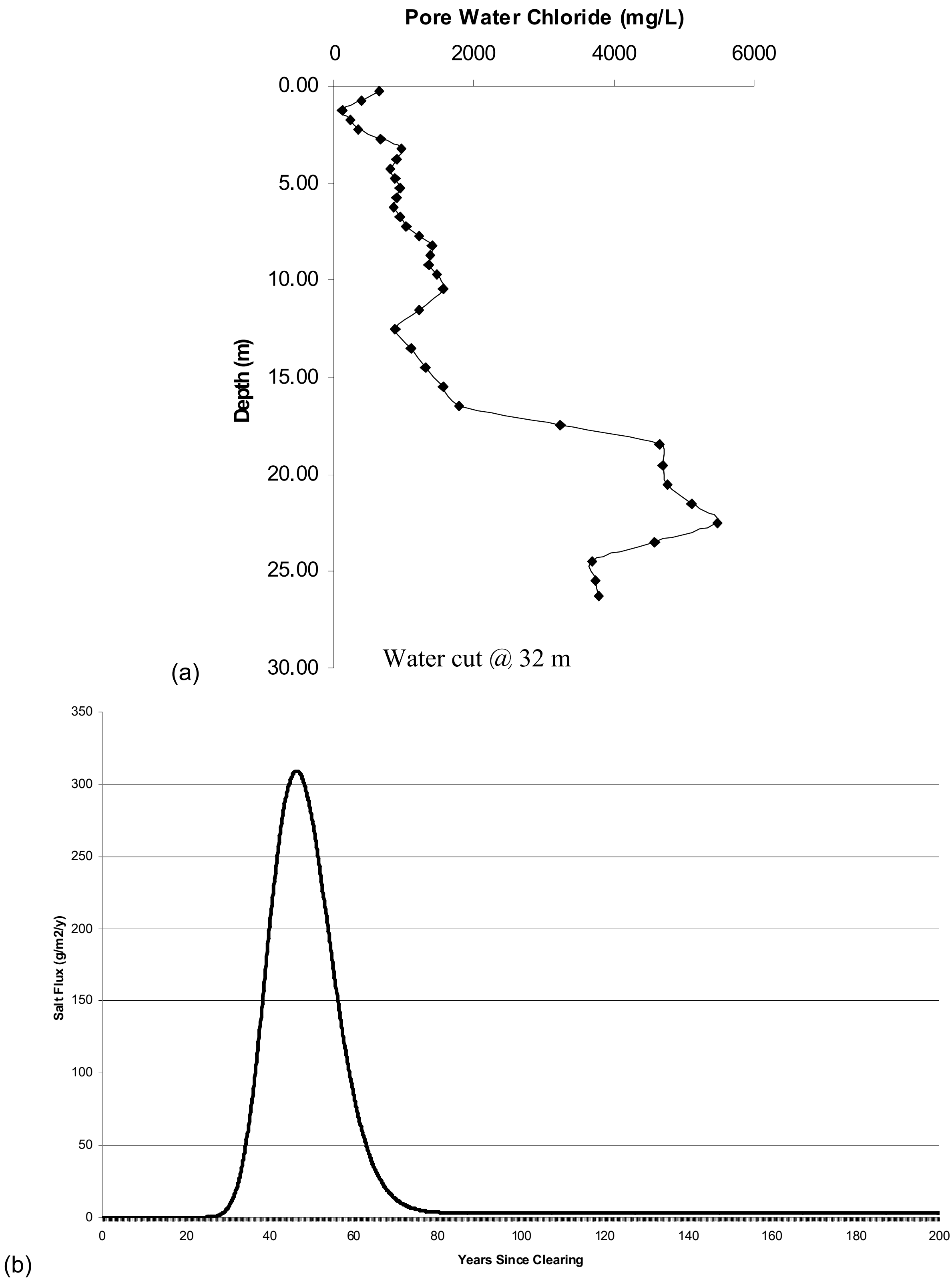


Figure 3.2 (a) Soil water chloride profile from site PB7, where the original saline soil water has been displaced downwards but not yet completely flushed from the unsaturated zone. Groundwater salinisation is in progress at this location. (b) Model results for site PB7, showing the predicted salt flux to groundwater over time since clearing.

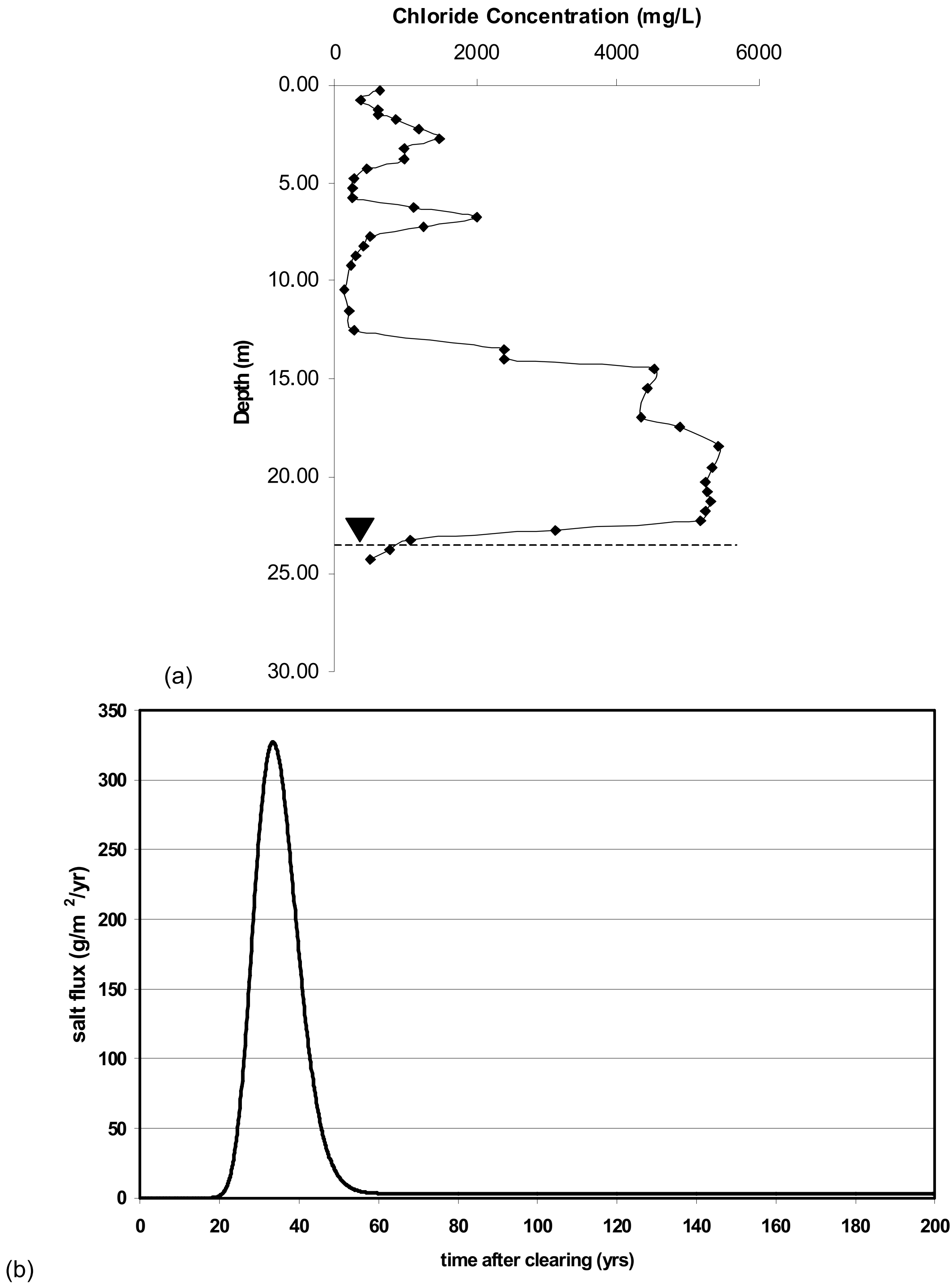


Figure 3.3 (a) Soil water chloride profile from site NV1, where the original saline soil water has been displaced downwards but not yet completely flushed from the unsaturated zone. Groundwater salinisation is in progress at this location. (b) Model results for site NV1, showing the predicted salt flux to groundwater over time since clearing.

Site PA2, which has a thinner unsaturated zone of only 11 m also appears partially flushed (Fig. 3.4a). However, the model predicted flushing at this site to have commenced ~5 yrs after clearing and to be completed within 15 yrs of clearing (Fig. 3.4b, Table 3.1). This discrepancy may suggest that clearing occurred only recently. However, this is not known to be the case and it is more likely that the model has over predicted drainage and recharge at this site, which, being located in an inter-dunal depression, has more clayey soils than accounted for in the model.

3.1.3 FLUSHING COMPLETE: RECHARGE OF FRESHER WATER

The soil water chloride data collected from sites PB1, PB5 and PB8 show soil profiles that have already been flushed of their salt stores (Figs 3.5–3.7). Drainage under the new recharge regime at these sites has a chloride concentration of ~50 mg/L, which is equivalent to a total salinity of ~130 mg/L.[2] Recharge of this comparatively fresh water at locations similar to PB1, PB5 and PB8 is expected to have a significant freshening effect on the groundwater resource. The model results for all of these sites are in agreement with the field data, suggesting that flushing of the saline salt store should have started and been completed within 20 yrs of clearing (i.e. approximately by 1985). The reasons for rapid flushing of the saline soil water at these sites are the comparatively thin unsaturated zones at PB1 and PB8 and a low clay content in the upper 2 m of the soil zone at site PB5.

Figure 3.8a shows the soil water chloride profile from site PA3. The water table at this site is located 40 m below ground level, but sampling could only be carried out to a depth of 25 m. The profile above 25 m is flushed of the highly saline soil water seen below the native vegetation sites, although residual chloride concentrations of ~500 mg/L remain suggesting that flushing has not been as efficient at this site as at the others described above. It is unknown whether some saline soil water remains in the profile below 25 m. However, the results of the model (Fig. 3.8b) suggest that the profile should be completely flushed, with flushing having been completed by 1978, assuming that clearing occurred in 1960.

3.1.4 COMPARISON OF MODEL RESULTS WITH OBSERVATION WELL DATA

Model results were also qualitatively compared with salinity data from wells GLE53 and GLE88 (Figs 3.9–3.10 respectively). Predicted flushing of the historical salt store between 12–32 yrs after clearing at GLE53 (between 1972–92) matches well with an observed TDS increase in the observation well nearby (Fig. 3.9). Subsequent peaks in the groundwater TDS are likely to be due to saline groundwater from up-gradient moving through the area. Likewise, the predicted flushing of the historical salt store between 10–30 yrs after clearing at GLE88 (between 1970–90) matches reasonably well with an observed TDS increase in the groundwater that starts in about 1975 (Fig. 3.10). A delay in observing the salinity increase in the groundwater system may be expected at many sites due to the lag time associated with mixing in the groundwater system. The salinity increase is probably maintained in well GLE88 after flushing was complete at that site due to the arrival of salinised groundwater from up-gradient of the well.

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[2] This total salinity is based on the salinity of rainwater that has simply evaporated to a chloride concentration of 50 mg/L. In reality, this water would then dissolve large amounts of $CaCO_3$ as it moves through the carbonaceous Bridgewater Formation unsaturated zone, resulting in a salinity of closer to 300 mg/L.

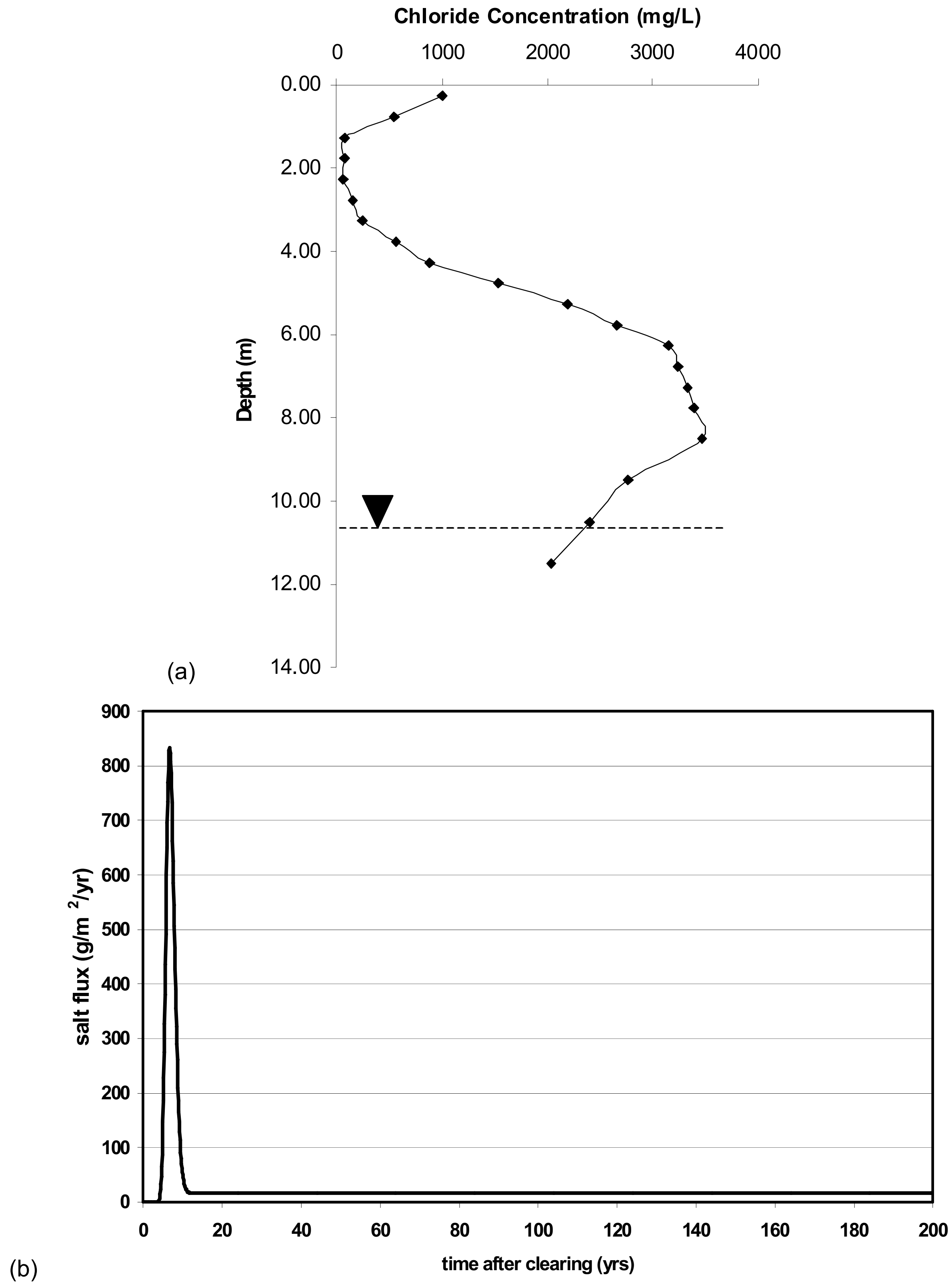


Figure 3.4 **(a) Soil water chloride profile from site PA2, where the original saline soil water appears to have been displaced downwards but not yet completely flushed from the unsaturated zone. Groundwater salinisation is in progress at this location. (b) Model results for site PA2, which show that the salt flux is predicted to have been started and completed within 15 yrs after clearing. The discrepancy between the model and the field data is believed to be due to larger proportions of clay in the profile than accounted for in the model.**

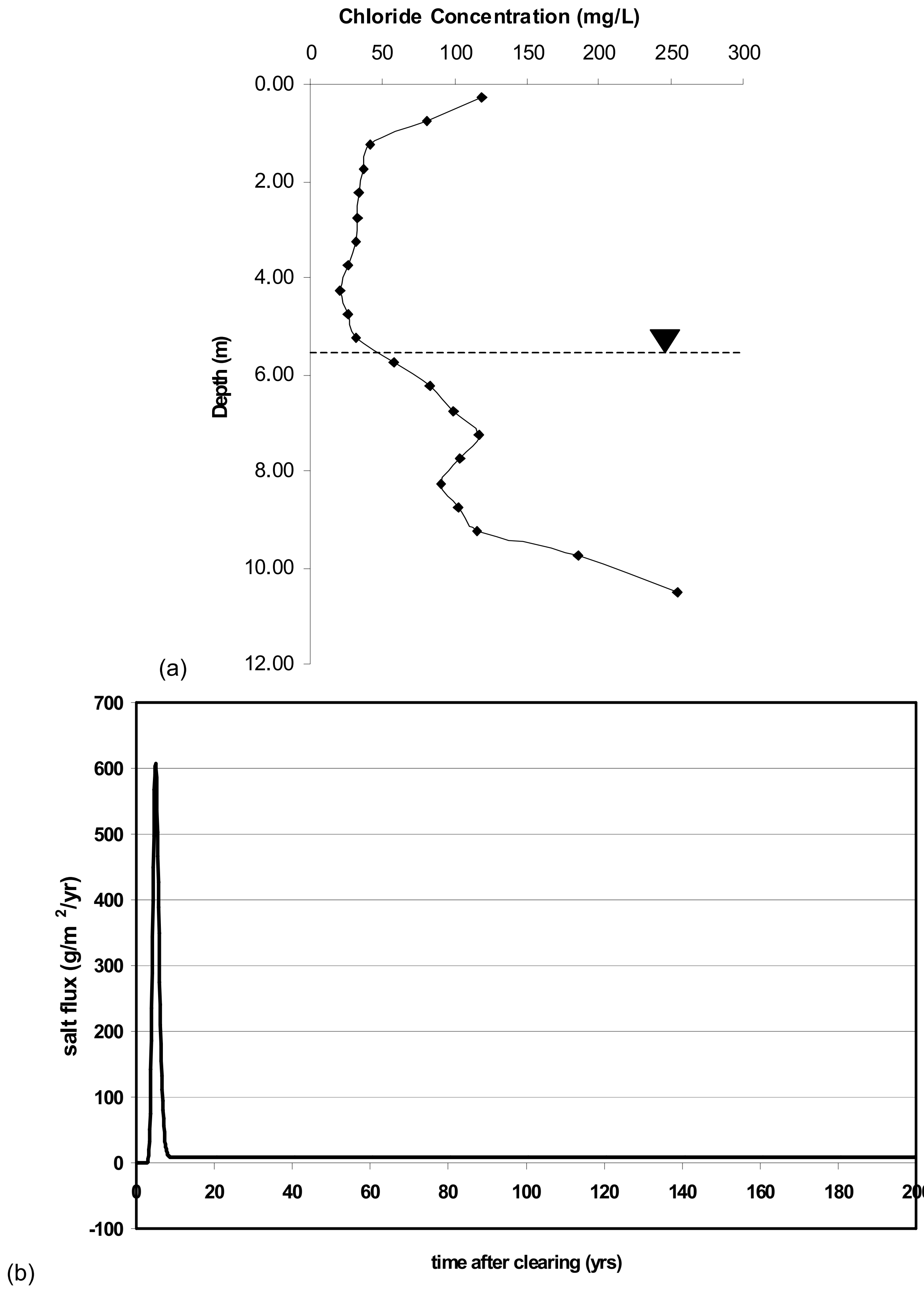


Figure 3.5 (a) Soil water chloride profile from site PB1, where the original saline soil water has been completely flushed from the unsaturated zone and fresher recharge is now occurring. (b) Model results for site PB1, showing the predicted salt flux to groundwater over time since clearing.

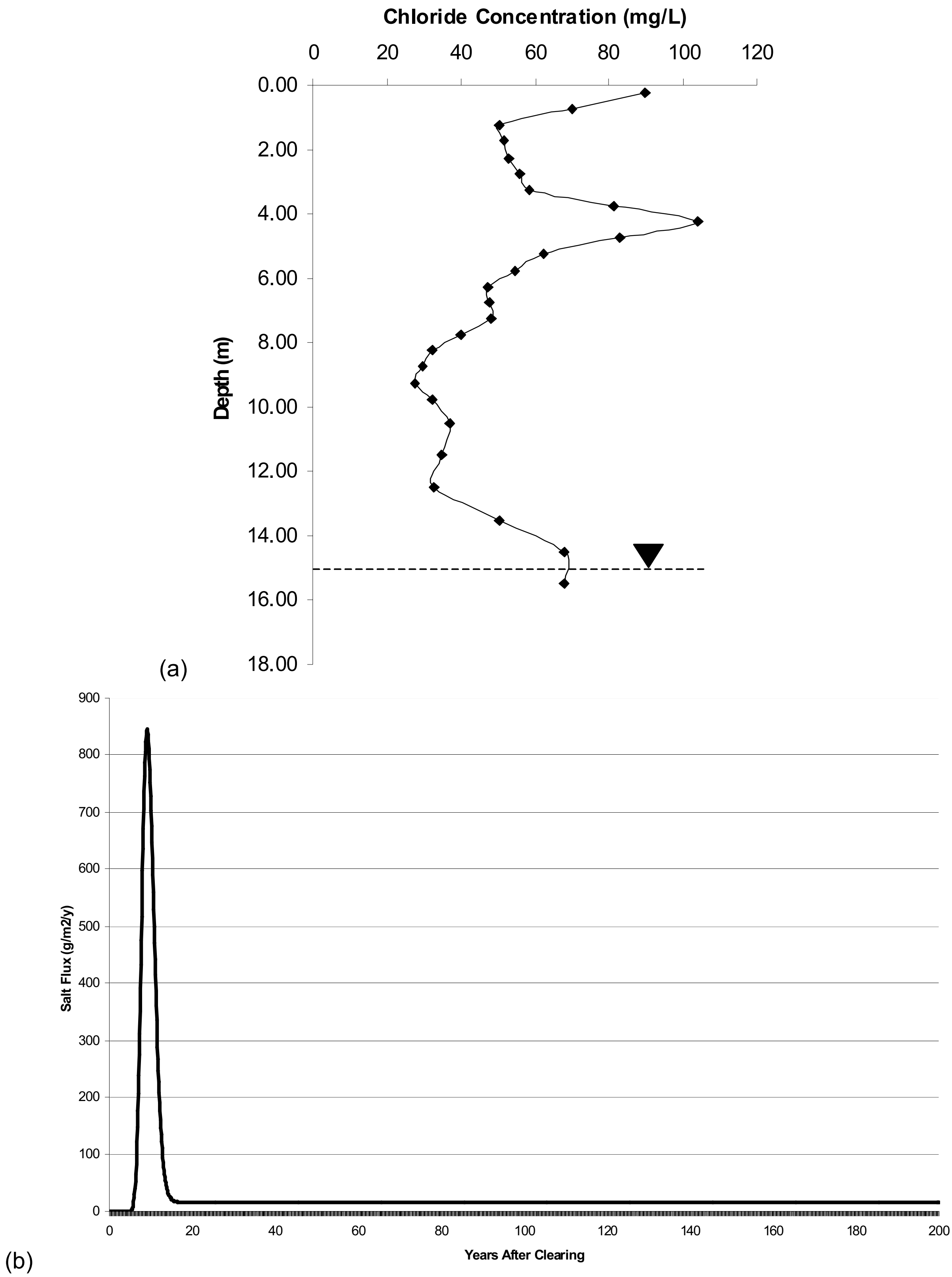


Figure 3.6 (a) Soil water chloride profile from site PB5, where the original saline soil water has been completely flushed from the unsaturated zone and fresher recharge is now occurring. (b) Model results for site PB5, showing the predicted salt flux to groundwater over time since clearing.

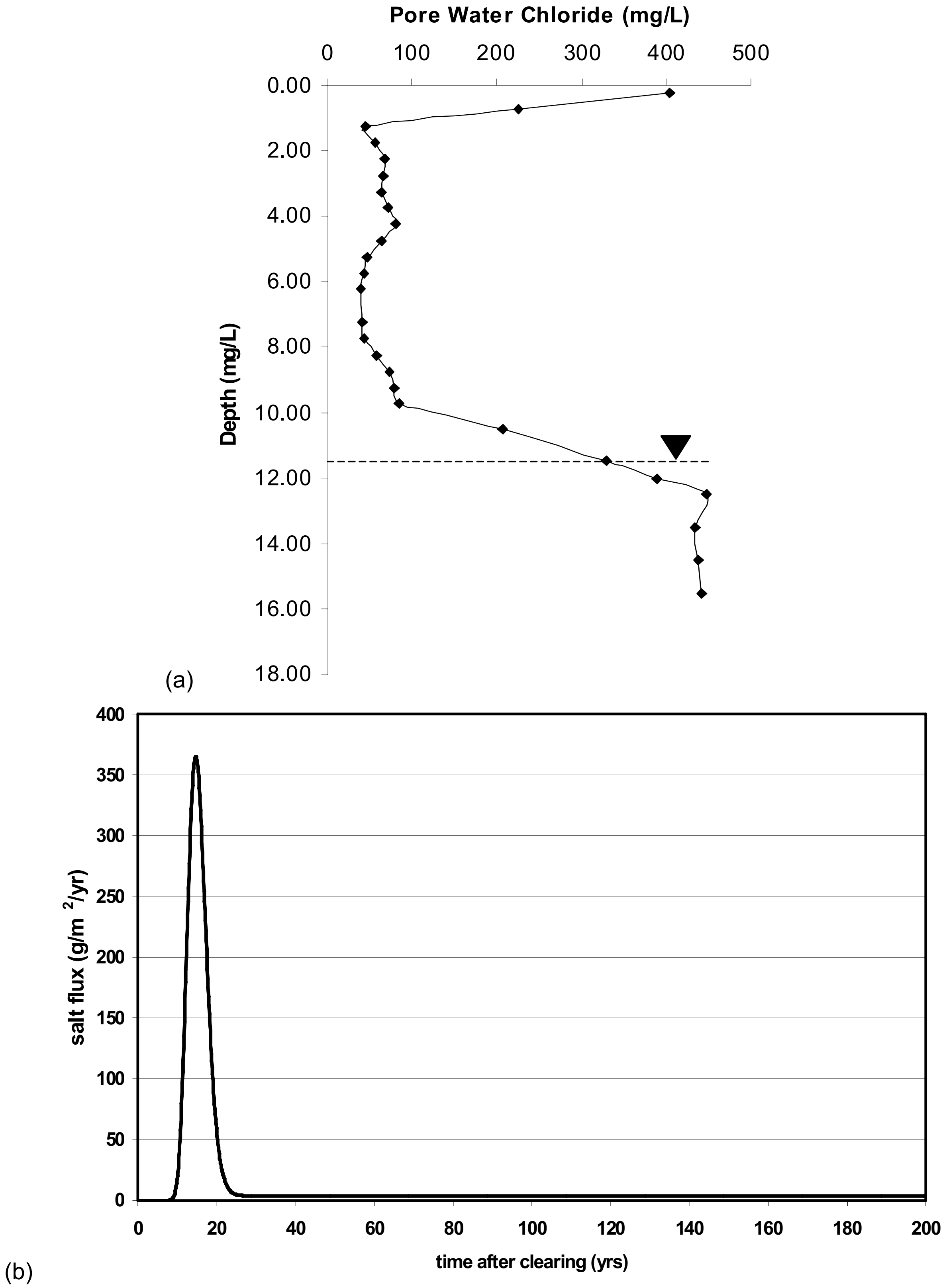
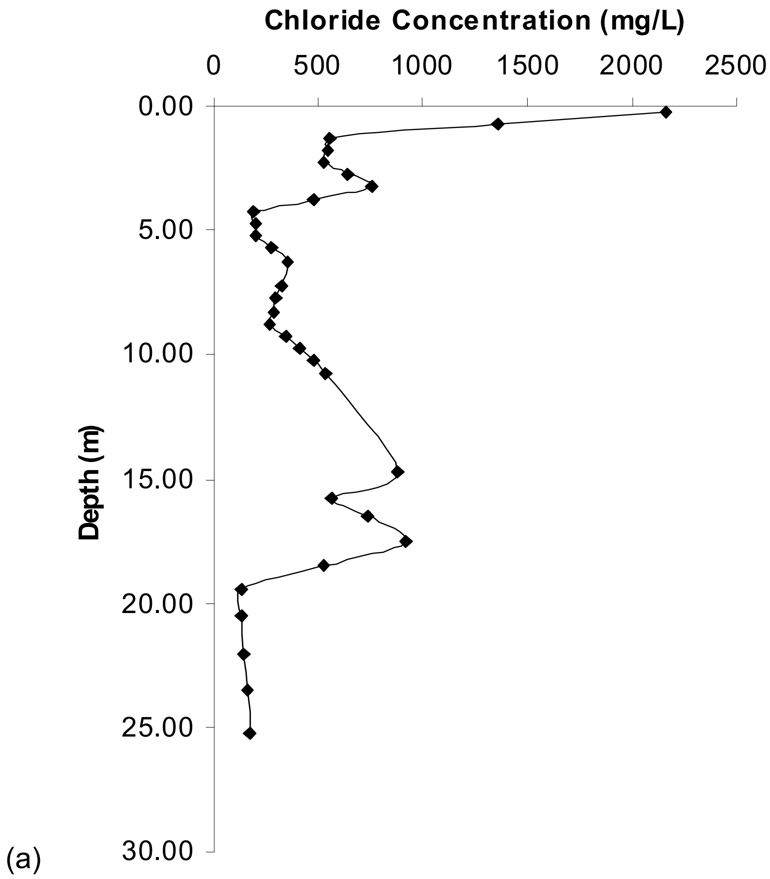


Figure 3.7 (a) Soil water chloride profile from site PB8, where the original saline soil water has been completely flushed from the unsaturated zone and fresher recharge is now occurring. (b) Model results for site PB8, showing the predicted salt flux to groundwater over time since clearing.



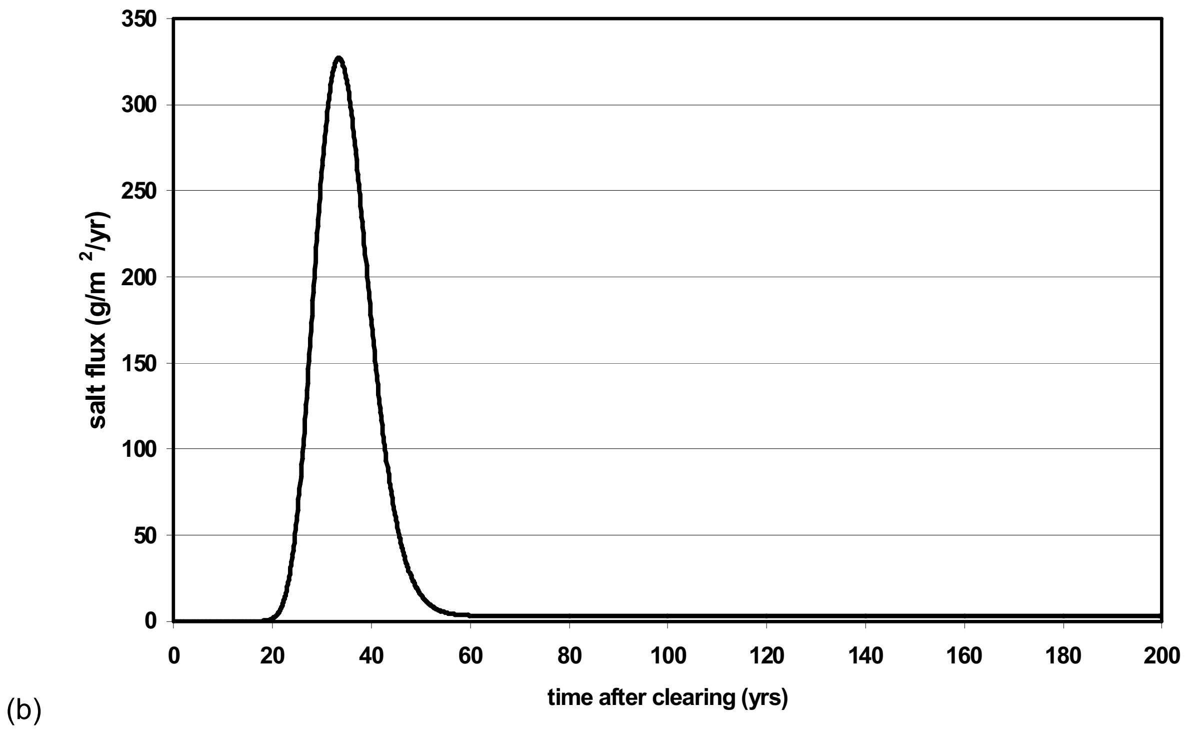
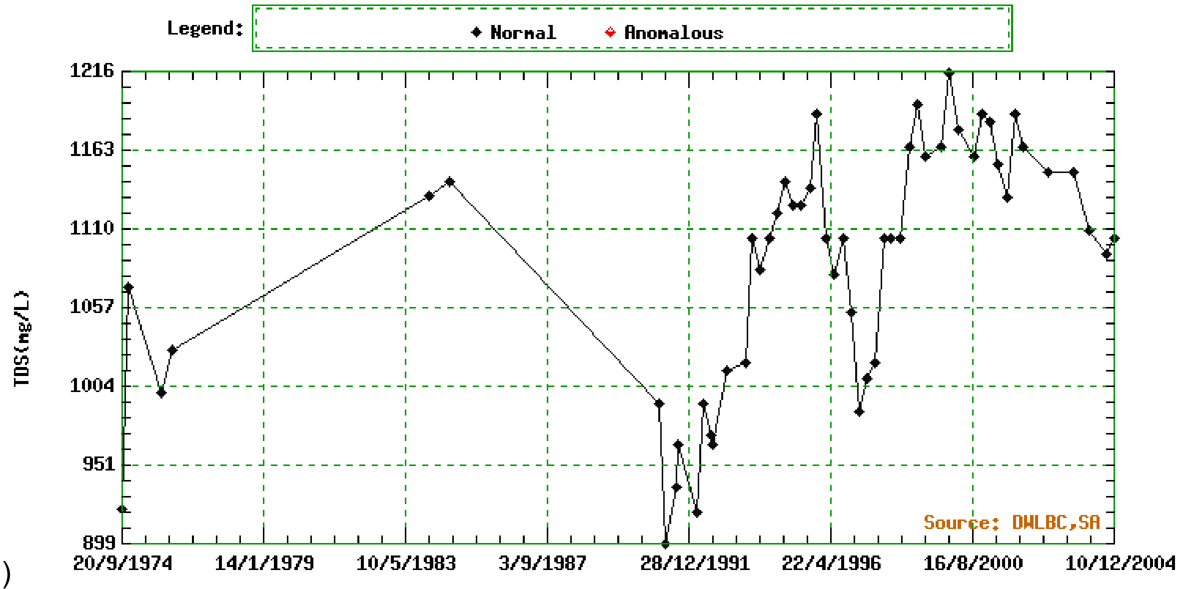
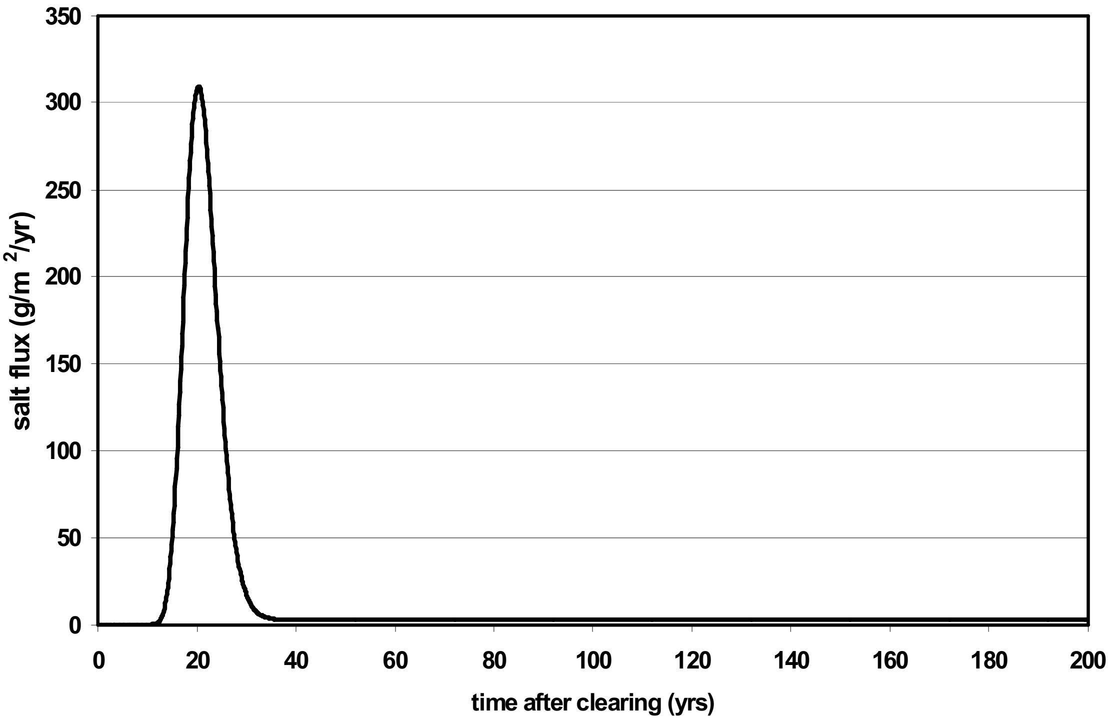


Figure 3.8 (a) Soil water chloride profile from site PA3, where the original saline soil water has been completely flushed from the top 25 m of the unsaturated zone. Sampling was discontinued at this depth and it is unknown whether saline soil water still remains between here and the water table at 40 m. (b) Model results for site PA3, showing that flushing should have been completed by approximately 18 yrs after clearing (i.e. 1978).



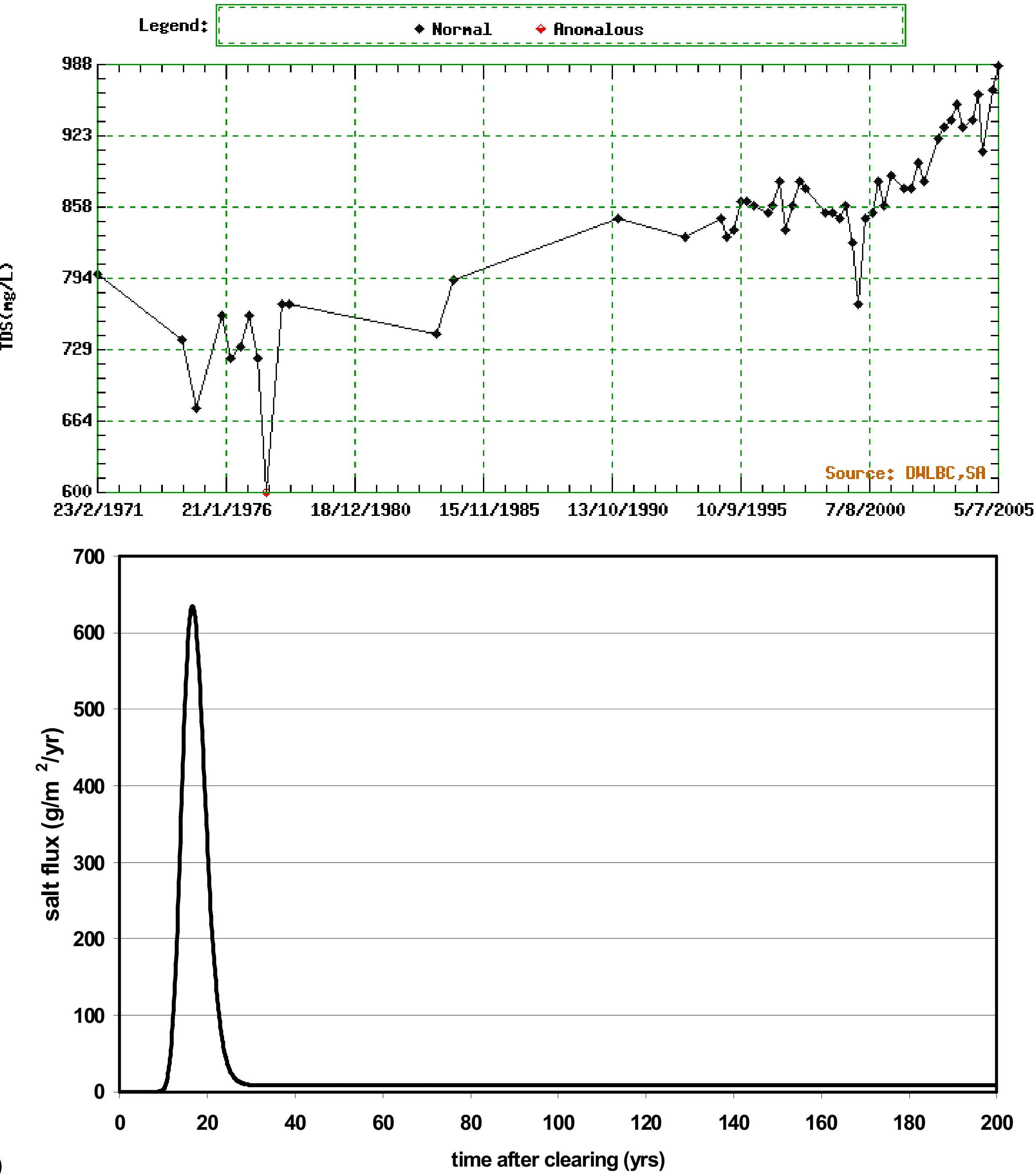
(a)



(b)

Figure 3.9 Comparison of predicted salt flux to the aquifer at observation well GLE53 with measured TDS in the well.

Predicted flushing of the historical salt store between 12–32 yrs after clearing (between 1972–92) matches well with an observed TDS increase. Subsequent peaks in the groundwater TDS are likely to be due to saline groundwater from up-gradient flushing moving through the area.



(a)

(b)

Figure 3.10 Comparison of predicted salt flux to the aquifer at observation well GLE88 with measured TDS in the well.

Predicted flushing of the historical salt store between 10–30 yrs after clearing (between 1970–90) match reasonably well with an observed TDS increase in the groundwater that starts in about 1975. A delay in observing the salinity increase may be expected due to the lag time associated with mixing in the groundwater system. The salinity increase is maintained in well GLE88 due to the arrival of salinised groundwater from up-gradient of the well.

3.1.5 DISCUSSION OF ONE-DIMENSIONAL RESULTS

There is good agreement between the predictions of the model of salt accessions in the Naracoorte Ranges, the unsaturated zone data collected during this study, and some randomly selected observation well salinity trends. The unsaturated zone data collected from the field sites encompass the full spectrum of flushing scenarios, including sites where the saline salt store is still present, where the salt has been partially flushed from the profile and groundwater salinisation is in progress, and sites where all of the saline soil water has been flushed and fresher recharge is now occurring. The field sites include a range of unsaturated zone thicknesses and surface (top 2 m) clay contents (Table 3.1), factors that are known to be important in determining drainage rates and subsequent recharge. There is also a large variability in the predicted peak and total salt loads to the aquifer at the Naracoorte Ranges field sites, ranging between 3.1 t/ha/y and 8.5 t/ha/y and 12.5 t/ha and 58 t/ha respectively.

The above results indicate that, although some flushing of salt is still occurring in the Naracoorte Ranges, this process has finished in many areas and that enhanced recharge of fresher water is now occurring.

3.2 SPATIAL EXTRAPOLATION OF ONE-DIMENSIONAL MODELS ACROSS THE NARACOORTE RANGES

As described in Section 2.1, the one-dimensional model of drainage and salt flux following land clearing was extrapolated across the Naracoorte Ranges portion of the Padthaway PWA using a GIS framework, with soil type and depth to water as input parameters. This work was carried out by CSIRO Land and Water, Adelaide and is presented in more detail in a separate report (Wohling et al., 2005). For the study area, there are 38 Soil Land Units (SLUs) with one sub-unit (soil type) for each. Seven of the 38 SLUs had not been mapped at the time modelling was completed for this project. However, the seven SLUs comprise ~2% of the total study area and are located along the southern boundary of the study area. The mean clay content of the SLUs for the 0–2 m depth interval ranges from 10–55%. Greater than 72% of the area has soils with clay content (0–2 m) of 10%. The key results from this work are shown in Figure 3.11(a-d).

Figure 3.11 shows predicted recharge rates and annual salt fluxes to the aquifer at 10, 20, 45 and 50 yrs after clearing. If clearing was assumed to occur in 1960, the 45 year scenario represents present day conditions. Comparison of the diagrams indicates that:

- a large amount of salt is predicted to have already reached the water table in areas scattered throughout the Ranges.
- significant flushing will continue to occur, particularly from the central portion of the Ranges, approximately over the next 5–10 years. After this, most of the salt store will have reached the water table.
- whilst flushing (and hence groundwater salinisation) is currently occurring and will continue over at least the next 10 years, large areas have already been flushed and fresher water is now recharging the aquifer. This is likely to have a positive impact on the salinity of groundwater that is moving from the Ranges to the Padthaway Flats irrigation area, or at least moderate the salinity increases caused by continued flushing from the unsaturated zone along the flow path and further into the Ranges.

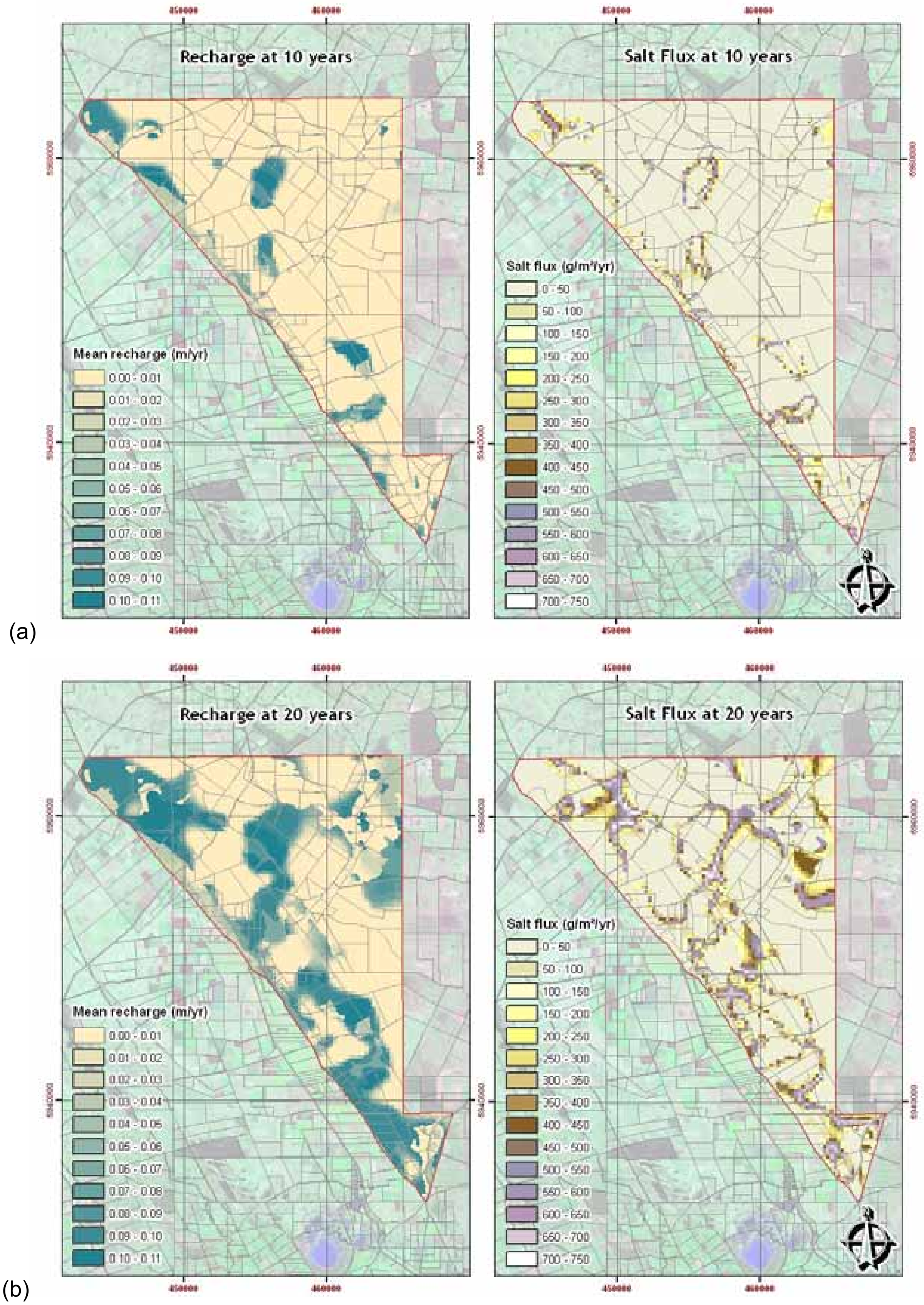
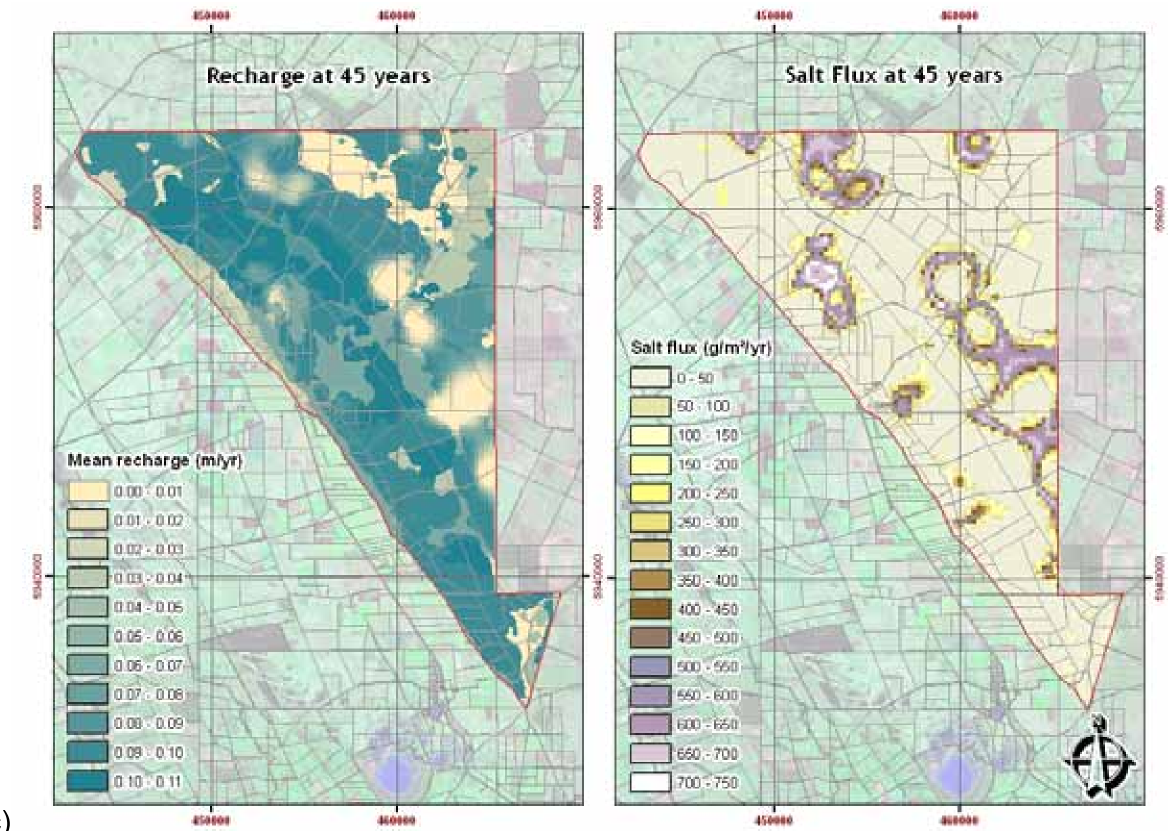
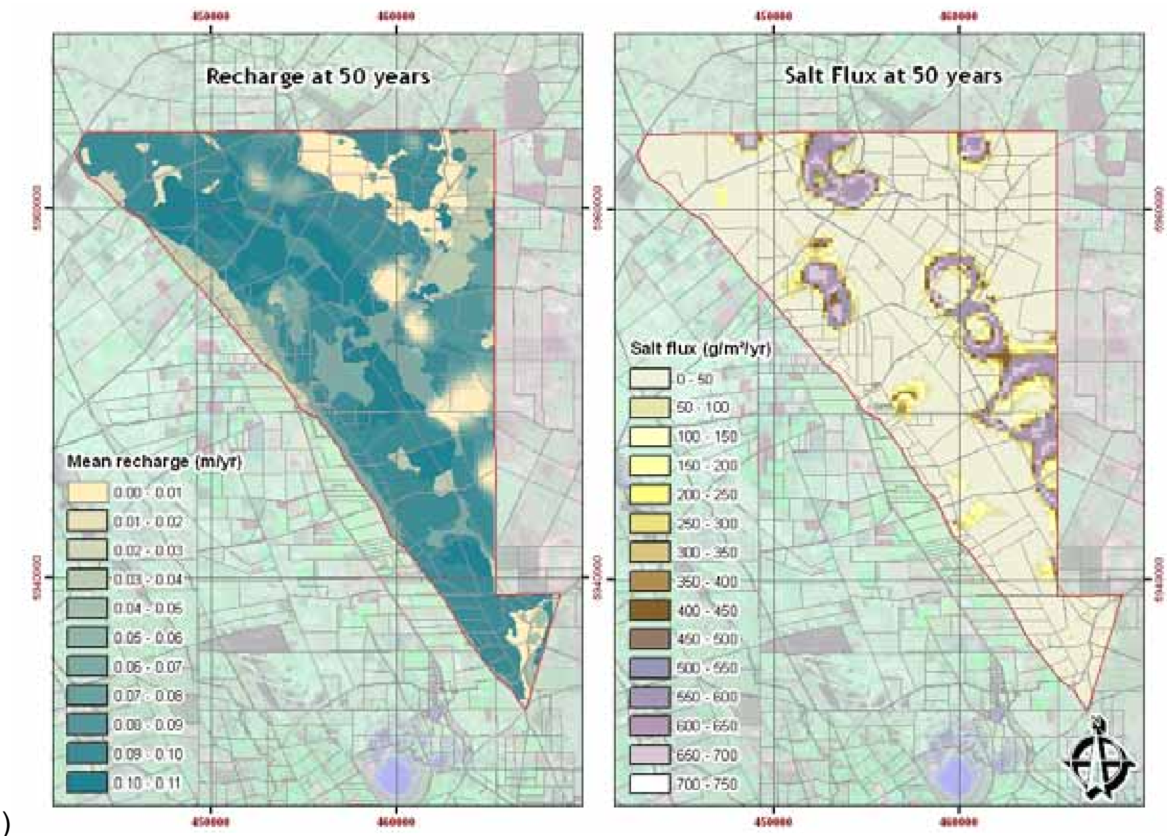


Figure 3.11 Recharge rates and salt fluxes from flushing of saline water from the unsaturated zone predicted by the model of salt accession in the Naracoorte Ranges for (a) 10, (b) 20, (c) 45 and (d) 50 years following clearing.



(c)



(d)

Figure 3.11 continued.

Additional simulations showed that flushing of the historical salt store would continue in increasingly small areas of the Naracoorte Ranges until ~150 yrs post-clearing (i.e. until the year 2110), after which all recharge would be fresh. However, due to the limitations of using an empirical model to determine this, predictions made at this time scale should be considered as indicative only.

3.3 INFORMATION FROM GROUNDWATER GEOCHEMISTRY AND ISOTOPIC SIGNATURES

The objectives of the interpretation of Naracoorte Ranges groundwater chemistry were to:

- Determine whether groundwater chemistry and isotopic signatures can provide additional information on the hydraulic processes occurring in the Naracoorte Ranges, and support or refute the conceptual model of groundwater salinisation/freshening developed above.
- Identify trends in the Naracoorte Ranges data that can be used to identify the impact of salt accessions in the Ranges on groundwater salinity on the Padthaway Flats.

3.3.1 CARBON ISOTOPES AS INDICATORS OF ENHANCED RECHARGE

Both the radioactive carbon content (^{14}C) and stable carbon isotope ratio ($\delta^{13}C$) of dissolved inorganic carbon (DIC) in groundwaters can provide information on groundwater residence times, recharge conditions and interaction with aquifer materials or other water types. At the time of recharge, groundwater has a “modern” ^{14}C signature[3] of ~100 percent modern carbon (pmC) due to being in equilibrium with atmospheric CO_2. The $\delta^{13}C$ signature of the recharging groundwater is largely controlled by the composition of soil CO_2, which in turn is influenced by soil microbiological reactions and plant root respiration. This gives a $\delta^{13}C$ signature that is indicative of recharge environment. As groundwater moves along a flow path, it is no longer in contact with the atmosphere (^{14}C cannot be replenished) and the radioactive ^{14}C decays at a known rate. The $\delta^{13}C$ signature of groundwater also evolves as a result of a variety of reactions, particularly the dissolution of aquifer carbonate minerals.

The $\delta^{13}C$ and ^{14}C signatures of groundwater DIC was found by Leaney and Herczeg (1995) to be extremely useful in identifying and quantifying enhanced recharge caused by land clearing in the area between Bordertown and Naracoorte (~30 km east of Padthaway). Regional groundwater in that area was found to be depleted in ^{14}C (~20 pmC) due to large residence times and the addition of “old” carbon by dissolution of carbonate minerals. It also has a comparatively high (less negative) $\delta^{13}C$ value (-2.2 ‰), which is close to that of the aquifer matrix (Fig. 3.12a). Enhanced recharge due to land clearing contains higher ^{14}C activities (96 pmC) due to equilibration with “modern” CO_2 in the unsaturated zone, as well as a more negative $\delta^{13}C$ value (-12.8 ‰), closer to that of DIC derived from atmospheric carbon (Fig. 3.12a). Because of the large differences in signature between these two end-members, mixing between “older” regional groundwater and “modern” enhanced recharge could be clearly identified.

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[3] The chemical “signature” of groundwater is a term often used to describe its chemical or isotopic composition, which has been influenced by the groundwater’s history, e.g. recharge conditions, interactions with minerals and mixing with other water types. The term chemical “fingerprint” is also often used analogously to “signature”.

Carbon isotope data collected from the Naracoorte Ranges in the Padthaway PWA is shown on Figure 3.12a. The linear trend in this data is extremely similar to that collected by Leaney and Herczeg (1995), with the main difference being that the Padthaway dataset contains some data points with ^{14}C concentrations as low as 5 pmC. The two groundwater samples with the extremely low ^{14}C contents come from piezometers PB5 and PB5a, screened in the top of the Gambier Limestone aquifer. Assuming that the Gambier Limestone and Bridgewater Formation aquifers are hydraulically connected, the chemical composition of the old groundwater from piezometer PB5 may also represent the signature of regional groundwater flowing through the Bridgewater Formation in the Naracoorte Ranges. Plotting the groundwater ^{14}C contents against chloride and various ionic ratios supports this hypothesis that groundwater sampled by piezometer PB5 is an end-member for a mixing process occurring in the Naracoorte Ranges (Figs 3.12b–d).

3.3.2 CHEMICAL EVIDENCE FOR GROUNDWATER SALINISATION AND FRESHENING

Figure 3.12b shows a clear trend of groundwater freshening (decreasing chloride concentration) that correlates with enhanced recharge (increasing ^{14}C). This agrees with the hypothesis that enhanced recharge in the Ranges is leading to freshening of the groundwater resource once flushing of the old salt store has finished. Three samples from Transect A do not follow the main freshening trend. These samples have higher chloride concentrations (and hence salinities) than samples with the same ^{14}C content. The compositions of these samples are a result of mixing with saline recharge at sites where flushing is still in progress. It is important to note that these signatures are not necessarily the result of processes happening in the unsaturated zone directly above the sampling point, but that flushing may have occurred anywhere along the groundwater flow path.

Figures 3.12c–d show additional trends in the chemical signature of groundwater with increasing influence of enhanced recharge. These figures show decreasing Mg/Ca and SO_4/Cl with increasing influence of enhanced recharge. Conversely, an increase in Mg/Ca with increasing groundwater residence time (decreasing ^{14}C) is consistent with a process of incongruent dissolution of carbonate minerals. This involves the dissolution of Mg-carbonate and re-precipitation of the lower solubility Ca-carbonates along a flow path. The process leading to a decrease in SO_4/Cl with increasing influence of enhanced recharge, or increasing SO_4/Cl along the groundwater flow path is currently unknown.

3.3.3 GEOCHEMICAL MODELLING OF THE GROUNDWATER SALINISATION AND FRESHENING PROCESSES IN THE NARACOORTE RANGES

The results of the geochemical modelling described in Section 2.6 are shown on Figure 3.13, along with the groundwater chemistry data collected from the Naracoorte Ranges (Transects A and B). The five graphs selected for Figure 3.13 were considered to be the most diagnostic, with the clearest trends observed in the data. Figure 3.13 shows that the processes accounted for in the geochemical model (Section 2.6) explain the groundwater

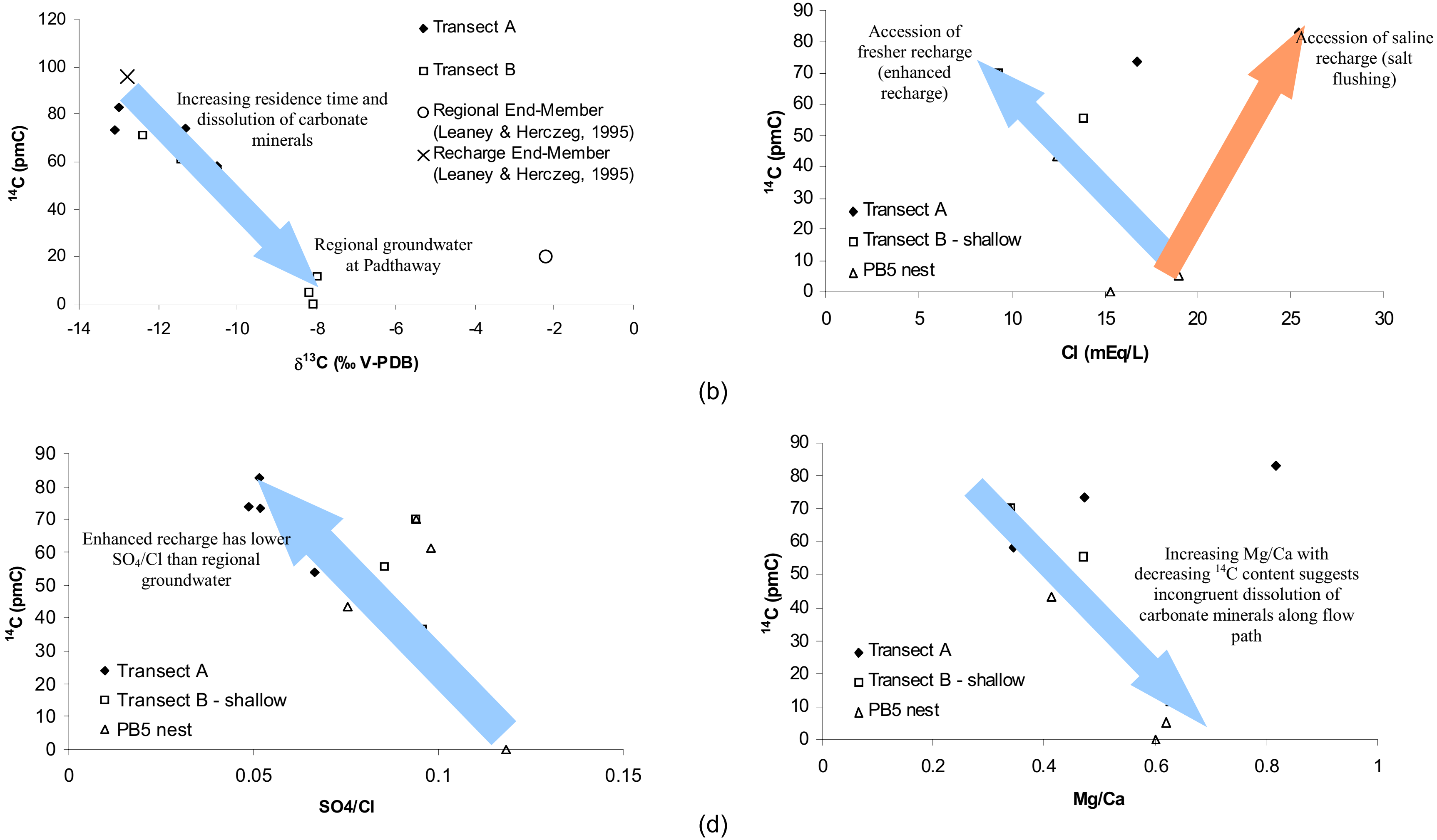


Figure 3.12 (a) ^{14}C vs $\delta^{13}C$, (b) ^{14}C vs Cl, (c) ^{14}C vs Mg/Ca and (d) ^{14}C vs SO_4/Cl for groundwaters from the Naracoorte Ranges.

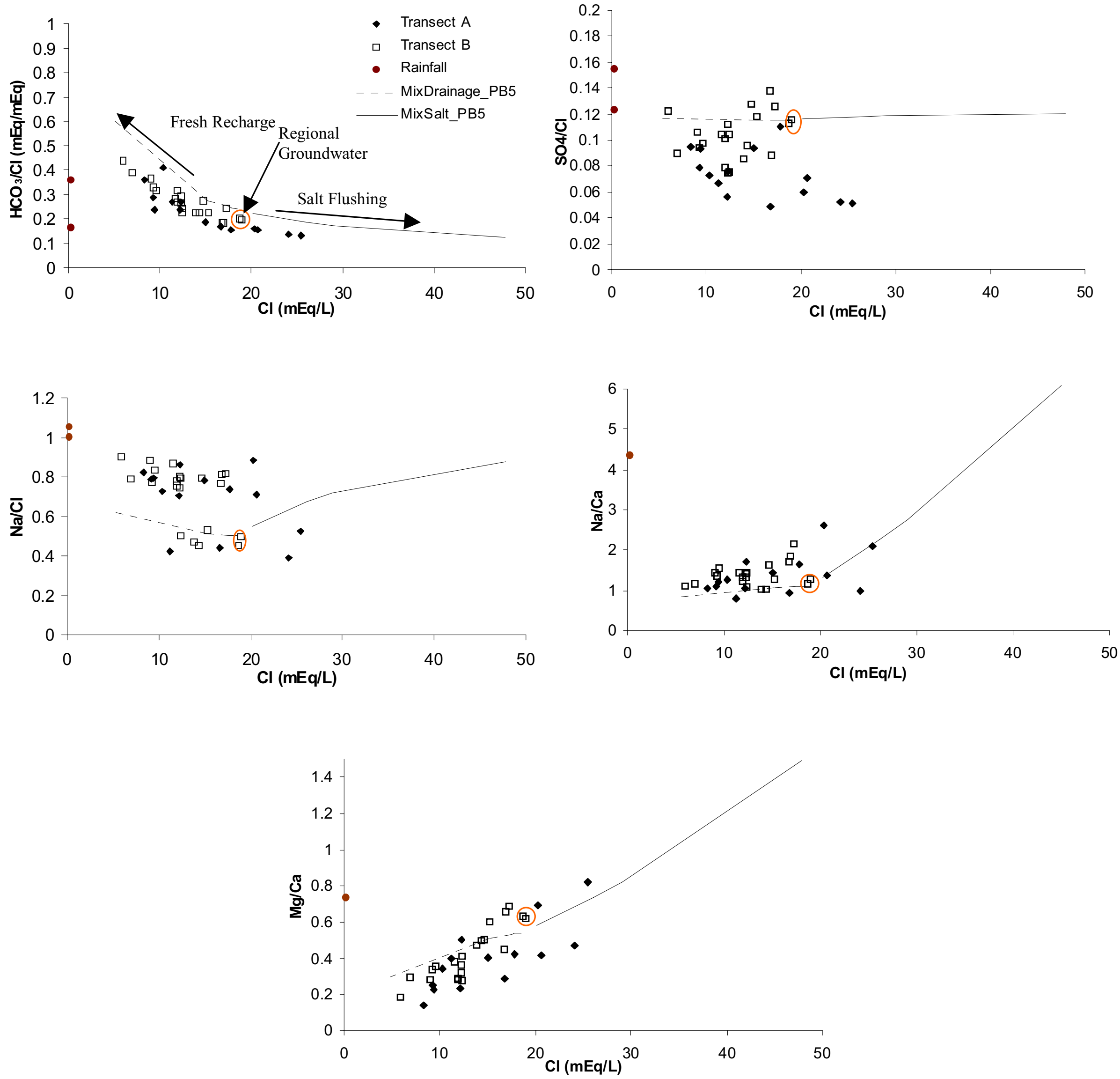


Figure 3.13 Groundwater chemistry graphs for the Naracoorte Ranges, showing the results of geochemical modelling of processes believed to be occurring in the Naracoorte Ranges.

MixDrainage_PB5 refers to the simulation of mixing of fresher recharge with regional groundwater and MixSalt_PB5 refers to mixing of saline recharge water with regional groundwater.

geochemical signatures in the Naracoorte Ranges quite well. Hence, the results also support the hypothesis that mixing between saline regional groundwater and fresher recharge is a significant process affecting groundwater salinities in the Ranges. As described above, the model does not account for the large observed range in SO_4/Cl ratios, and enhanced recharge apparently has a lower SO_4/Cl ratio than both rainfall and regional groundwater. Despite a lack of understanding of the process causing this, there is a clear trend in the SO_4/Cl data, indicating that the process is consistent throughout the system and may still be useful in determining the relationships between Naracoorte Ranges groundwaters and those on the Padthaway Flats. The presence of some groundwater compositions with higher Na/Cl than those predicted by the chemical model also suggest that there may be a regional end-member with a higher Na/Cl ratio than groundwater from piezometer PB5. However, similarly to SO_4/Cl, the clear trends in this data may also be used to interpret the Padthaway Flats data.

3.4 CONCLUSIONS ON SALT ACCESSION PROCESSES IN THE NARACOORTE RANGES

The conclusions from this study on salt accession processes in the Naracoorte Ranges portion of the Padthaway PWA can be summarised as follows:

- Clearing of native vegetation in the Naracoorte Ranges in ~1960, and replacement of this with shallow rooted perennial crops has caused increased drainage through the unsaturated zone and flushing of pre-existing saline soil water into the groundwater system.
- Large amounts of the historical unsaturated salt store have already been flushed and it is possible that this contributed to rising groundwater salinities that have been observed on the Padthaway Flats.
- Flushing of saline soil water is still occurring in parts of the Naracoorte Ranges and is likely to continue to occur in significant quantities over approximately the next 5–10 yrs depending on the exact time that land clearance occurred. This time scale is a rough estimate only as the modelling that was carried out to reach these conclusions carries with it some limitations in its accuracy.
- Similarly, flushing is expected to occur in very small parts of the Naracoorte Ranges over the next 100 yrs, although this time scale is considered to be indicative only due to the empirical nature of the model.
- The effects of mixing with saline soil water can be seen in the chemistry of groundwater in some parts of the Naracoorte Ranges.
- Where the unsaturated zone salt store has already been flushed, fresher enhanced recharge is now predicted by the one-dimensional model to be occurring at rates of up to 110 mm/y in parts of the Naracoorte Ranges.
- The effects of this fresher recharge are now being observed in the chemistry (and salinity) of the groundwater in some parts of the Naracoorte Ranges.
- The movement of this fresher groundwater from the Naracoorte Ranges into the Padthaway Flats irrigation area is likely to have a positive effect on the groundwater resource there or at least mitigate any salinity increases that are caused by the continued flushing of saline water in the Ranges or irrigation impacts on the Flats.

4. ONE-DIMENSIONAL CONCEPTUAL MODELS OF SALT ACCESSION UNDER THE DRIP IRRIGATED VINEYARDS

4.1 SITE NAP1

Figure 4.1 shows the physical and conceptual models of the water and salt balances at the vineyard site NAP1. This site is located on a duplex clay soil (Map 2), underlain by a hard calcrete-topped limestone layer to ~1.3 m. Between 1.3–4 m, the limestone forms layers of moderately cemented to extremely hard material and below 4 m this becomes a soft marly limestone. The groundwater salinity in the area is ~1760 mg/L and the water table depth is ~3.8 m. The patch of vines at NAP1 is irrigated with water from well GLE273, which has a salinity of ~900 mg/L, lower than that of the underlying groundwater due to location of the well at the base of the Naracoorte Ranges (Map 1).

4.1.1 SUCTION LYSIMETER AND GROUNDWATER SALINITY DATA

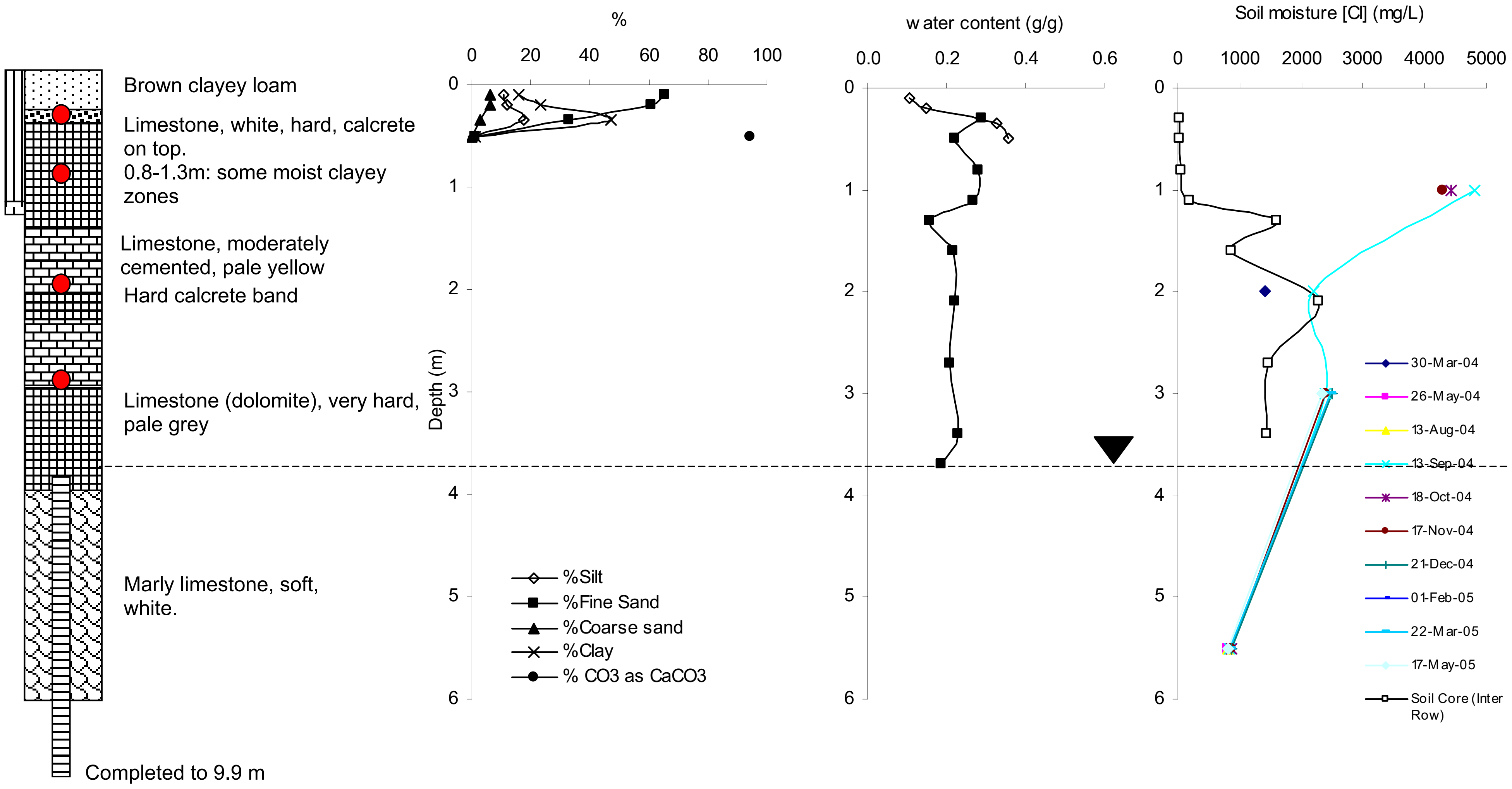
Soil water chloride concentrations from the suction lysimeters, which are located in the vine row, are shown on Figure 4.1 for comparison with the pore water chloride profile collected from the inter-row. The suction lysimeter data shows higher chloride concentrations at 1 m depth than the profile collected from the inter-row, indicating a greater influence of evapotranspiration by the vines in the vine row. Suction lysimeter salinity (TDS) data are shown in Figure 4.2. This figure shows some fluctuations in the salinity of the soil water at the 0.45 m and 1 m lysimeters, but that salinity at the 2 m and 3 m lysimeters remains constant at ~4000 mg/L TDS (Fig. 4.2). In general, the fluctuation in soil water salinity over the time scale of a year is negligible. This suggests that there is no long-term change in storage of salt (i.e. no salt accumulation or leaching) occurring at this site, although the data is limited and continued sampling is required to confirm this. The groundwater salinity in the piezometer at site NAP1 has remained fairly constant over the sampling period, varying by less than 200 mg/L, also suggesting that seasonal flushing of accumulated salt is not occurring. However, it must be noted that the screen of this piezometer is 6 m long and leaching of small amounts of salt may not be obvious in samples collected from it due to the effects of mixing over this depth interval.

4.1.2 WATER BALANCE

The water balance for site NAP1 was calculated using (a) the standard water balance (fortnightly to monthly calculations based on NMM sampling times) and (b) the Penman-Grindley methods (daily calculations) described in Section 2. Figure 4.3 shows drainage calculated over the entire study period using both methods, along with changes in soil water storage (ΔS) measured using a neutron moisture meter. Drainage over the nominal 12 month period from March 2004 to March 2005 was calculated to be 154 mm/y by the standard water balance and 116 mm/y by the Penman-Grindley method. The annual components of the water balance are shown on Figure 4.1.

NAP 1

Physical Model



Conceptual Model

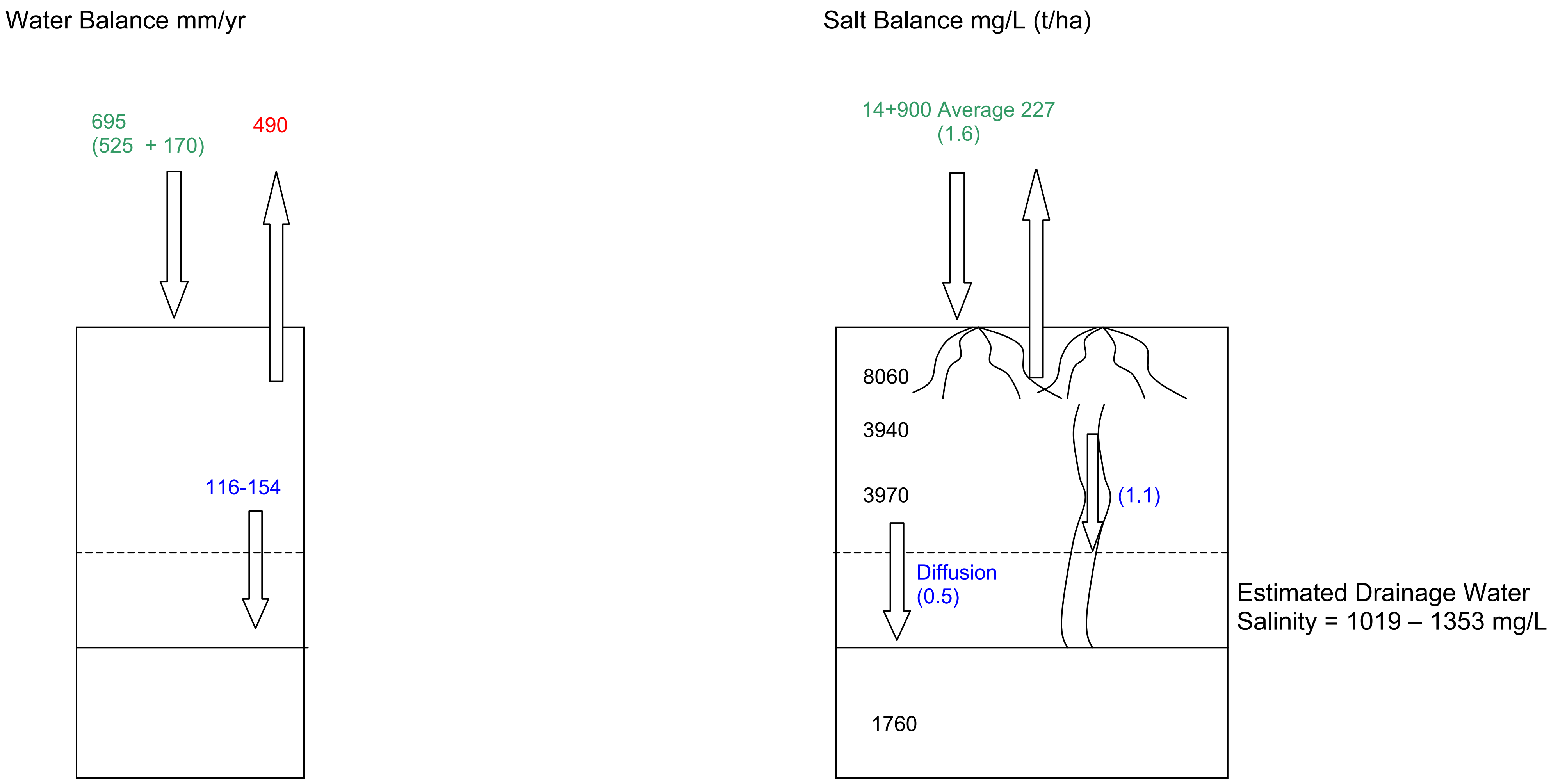


Figure 4.1 Conceptual model of NAP1.

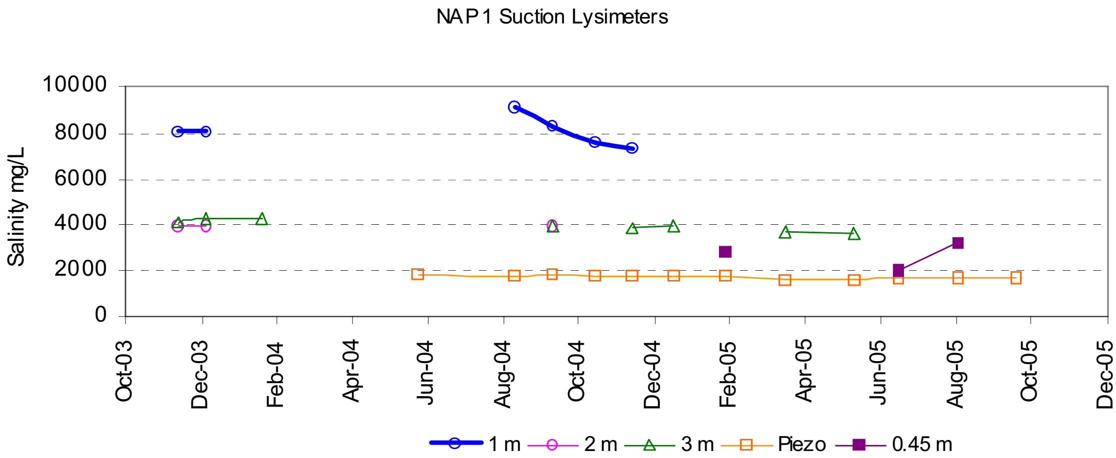


Figure 4.2 Suction lysimeter (TDS) data from vineyard site NAP1

Figure 4.3 shows that the main difference between the results of the standard water balance and the Penman-Grindley water balance is that drainage calculated by the standard water balance between March 2004 and April 2004 and November 2004 and February 2005 is not accounted for by the Penman-Grindley water balance. The first of these drainage events occurs when the soil column is at a moisture deficit, and is calculated as a series of drainage events because the input of water at that time is not observed by the neutron moisture measurements to be taken up as storage. The second event occurs when the input of water is accompanied by an observed decrease in the soil moisture store. As the only difference between the two methods is in the way they treat the soil moisture store, there are three possible explanations for these discrepancies:

1. Due to heterogeneities in the soil, the neutron moisture meter did not pick up the changes in soil moisture that occurred as a result of the input of water. It is important to note that all parameters in the standard water balance are averaged over the vineyard with the exception of ΔS, which is a point measurement (although the value used is an average over six locations in the vineyard).

2. The drainage water in the vicinity of the neutron moisture meter access tubes did not interact with the soil matrix at all, but moved past the root zone quickly via a preferential flow path.

3. There is a large time delay (days to weeks) between the application of water to the surface of the soil and its infiltration into the zone of influence of the neutron moisture meter measurements (approximately below a depth of 25 cm).

Additionally, Figure 4.3 shows that some negative drainage values are estimated for site NAP1 by the standard water balance. The only real explanation for this is groundwater use by the grapevines, which is not likely to be the case at all of the times indicated. Hence these negative values may be an indication of some inaccuracies in the estimation of the water balance by this method. The extrapolation of CSIROs evapotranspiration measurements from site NAP6 to this site may be one source of error and this will be investigated further at the completion of the CSIRO investigation (June 2006). Due to the limitations and uncertainties inherent in both water balance approaches, the estimates of drainage have been adopted as upper and lower limits for salinity impact calculations at this time.

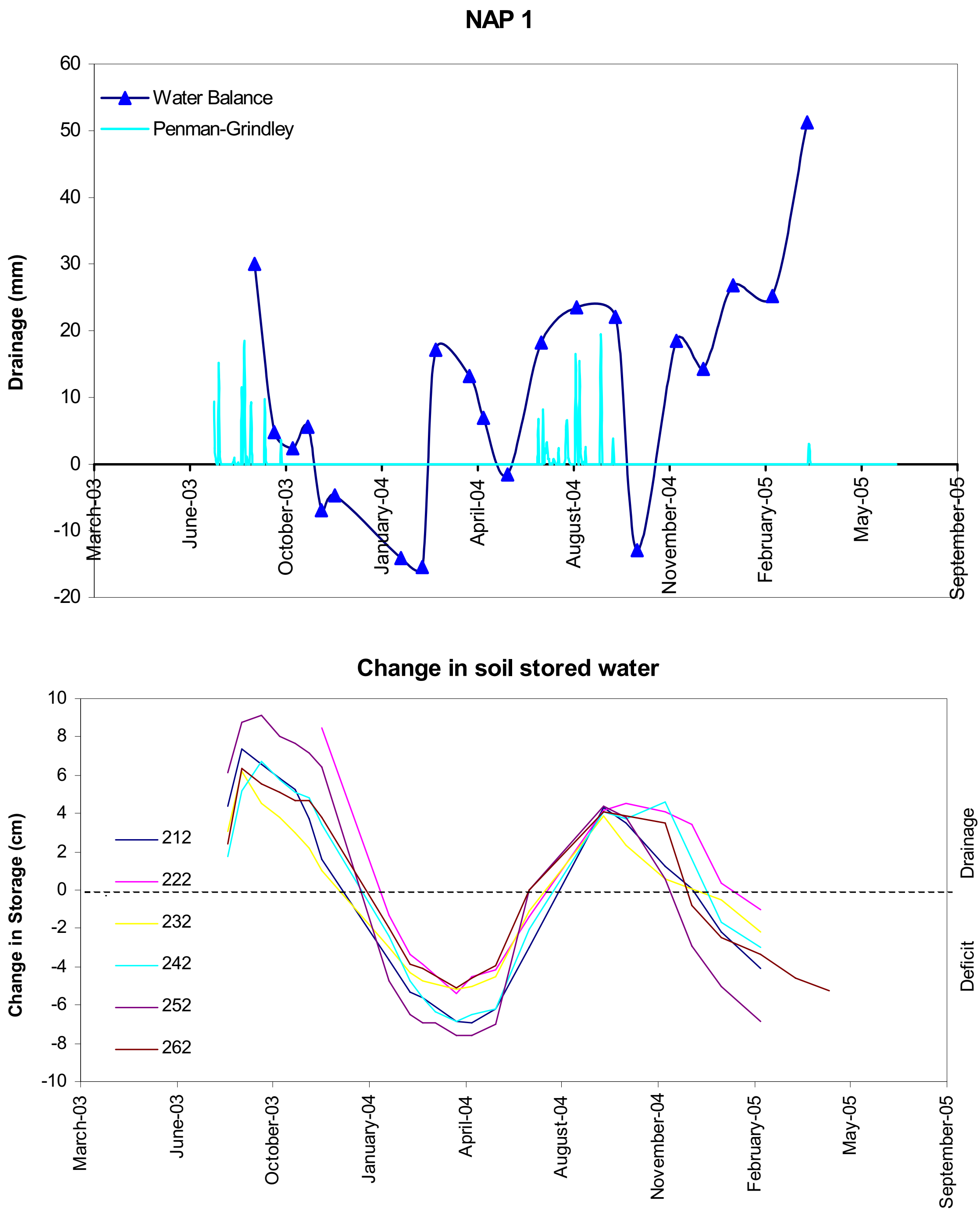


Figure 4.3 Estimated drainage and measured changes in soil moisture storage for site NAP1.

4.1.3 SALT BALANCE

The total application of salt via rainfall and irrigation was 1.6 t/ha/y from March 2004 to March 2005 (Fig. 4.1). As the suction lysimeter data has not identified any net changes in the soil profile salt store, it is reasonable to assume that the same mass of salt leaves the profile along with deep drainage (116–154 mm/y) as enters with rainfall and irrigation. This equates to a drainage water salinity of 1019–1353 mg/L. The salinity of the soil water below the root zone, measured in the 3 m lysimeter, is much higher than this, so it appears that uniform leaching of salt through the soil profile is not occurring at this site. How this salt leaves the profile is uncertain and any combination of (a) diffusion, (b) slow mass flow through the soil matrix and (c) mass flow via preferential pathways is possible.

Because of the large concentration gradient between the soil water at 1 m depth, diffusion is a plausible mechanism for the movement of salt. However, as described in Section 2.4, diffusion can be a very slow and ineffective transport mechanism in unsaturated soils. The maximum possible diffusive flux has been calculated using equation 2.5 to account for up to ~0.5 t/ha/y of the output (Fig. 4.1). In addition, it is proposed that some water, particularly winter rainfall, may travel through the profile via preferential flow in the sediment-filled cracks and root channels that have been observed in the soil profiles at various Padthaway vineyard sites (Fig. 4.4). This would not disturb the main solute profile, which remains in balance between accumulation through evapotranspiration and loss through diffusion or slow mass flow, but may wash through some salt that has accumulated seasonally within the root channel itself (Fig. 4.1). The irregular shapes of the pore water chloride versus depth profiles are also consistent with the hypothesis that non-uniform flow is occurring at this site (Fig. 4.1).

As the drainage water has an effective salinity that is between 119–453 mg/L greater than the irrigation water applied, a net salinity impact on the aquifer of 0.18–0.52 t/ha/y has been estimated for this site based on available data (see Section 2.3).

Figure 4.4 Sediment-filled cracks and root channels observed at various vineyard sites in the Padthaway Flats irrigation area.

4.1.4 INFORMATION FROM GROUNDWATER CHEMISTRY

The key groundwater chemistry graphs for site NAP1 are shown in Figure 4.5. The irrigation well GLE273 is located adjacent the main Keith – Naracoorte highway, near the boundary between the Naracoorte Ranges and Padthaway Flats irrigation area and hence intercepts fresher water than the groundwater sampled from below the site itself. The chemical signature of the irrigation water is similar to that of some Naracoorte Ranges groundwaters that have received some fresher recharge following flushing of the saline soil water (Fig. 4.5). This indicates that groundwater that has received some fresher recharge is moving through the vicinity of well GLE273.

Groundwater sampled from the piezometer below NAP1 plots close to the main chemical trends in Figure 4.5, suggesting little influence from evapotranspiration and that the salinity of the groundwater at that site can be predominantly explained by salt accession from the Naracoorte Ranges. However, a slight displacement to the right suggests a minor influence of evapo-concentrated irrigation water as a source of some salinity in this piezometer.

Full chemistry data from the suction lysimeters at site NAP1 was not available due to difficulties in extracting samples. However, the suction lysimeter chloride data shows concentrations ranging between 2400–4700 mg/L in the 1 m lysimeter (67.7–132.6 mEq/L), which is much higher than the groundwater in the piezometer and many of the other suction lysimeter samples. This is consistent with the presence of a large store of salt in the unsaturated zone that is currently having little interaction with the underlying groundwater.

4.1.5 CONCLUSIONS ON SALT ACCESSION AT THE NAP1 DRIP IRRIGATION SITE

- A net salinity impact to the aquifer of 0.18–0.52 t/ha/yr is estimated to be occurring due to irrigation at site NAP1.
- This salinity impact is calculated due to the extraction of comparatively low salinity water from up-gradient of the irrigation district and evapo-concentration of that with drainage back to the aquifer. This reduces the volume of fresher water moving through the irrigation district and transforms it into more saline water.
- However, the infiltration of saline drainage water at site NAP1 is not the direct cause of the elevated groundwater salinity at that site, as the equivalent salinity of the irrigation drainage water is less than that of the underlying groundwater itself.
- It should be noted that, as the screen of the piezometer directly below site NAP1 is 6 m long, it is possible that small changes in groundwater chemistry (and salinity) near the water table due to infiltration of small amounts of irrigation drainage water are not observed in groundwater samples from this piezometer.
- Interpretation of the groundwater chemistry data suggests that most of the salinity in the groundwater below site NAP1 can be explained by the salt accession processes occurring in the Naracoorte Ranges, although mixing with small amounts of saline irrigation drainage water along the flow path cannot be ruled out.

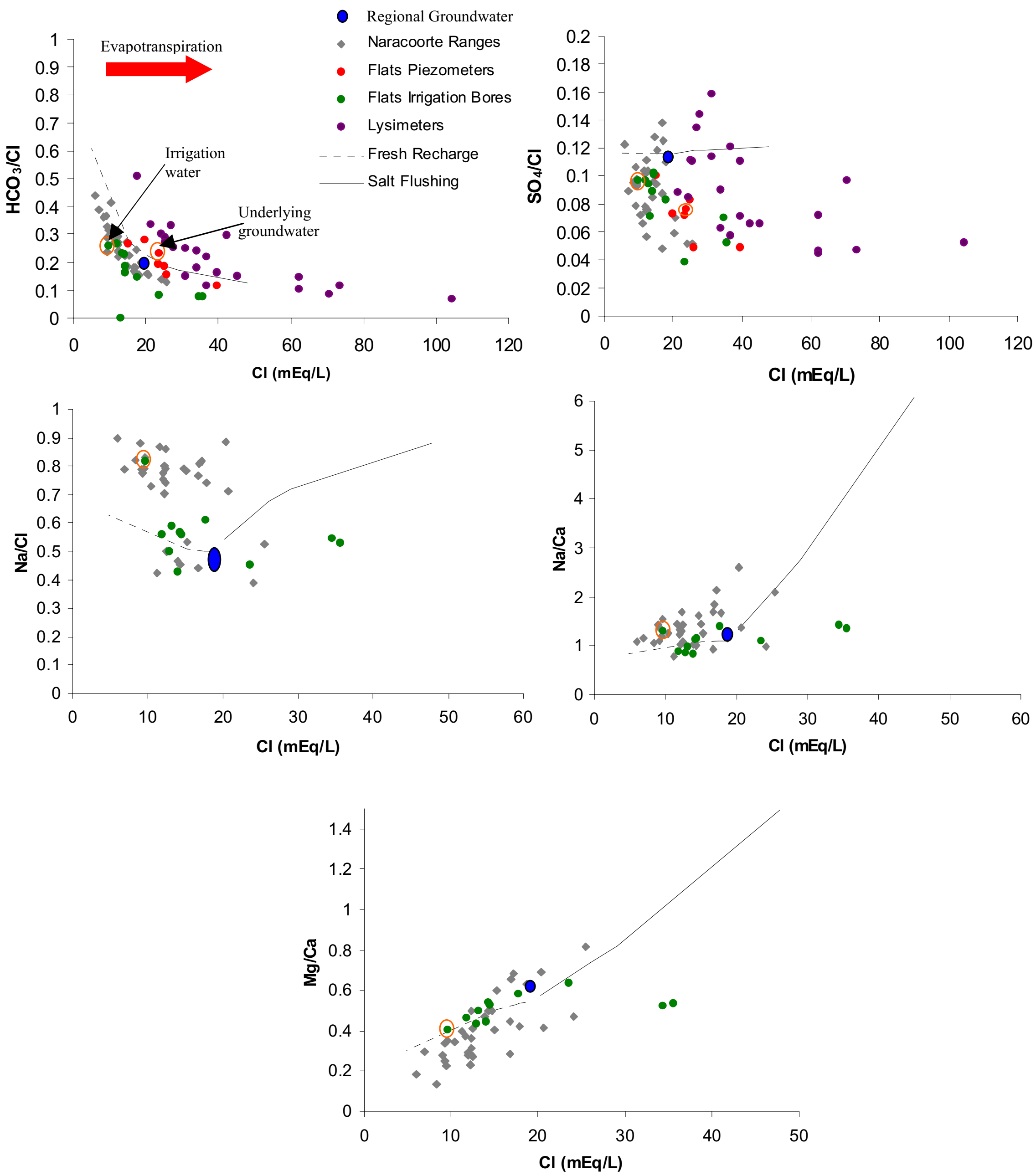


Figure 4.5 Groundwater chemistry graphs for drip irrigation site NAP1 (orange circled points).

Also shown are groundwater compositions predicted to result from salt flushing (solid line) and freshwater drainage (dashed line) in the Naracoorte Ranges, Naracoorte Ranges groundwater data (grey symbols) and other data from the Padthaway Flats.

4.2 SITE NAP2

Figure 4.6 shows the physical and conceptual models of the water and salt balances at the vineyard site NAP2. This site is located on a sandy loam soil underlain by a 30 cm thick clay layer (Map 2, Fig. 4.6). Below this is a hard limestone layer followed by a soft marly limestone interlayered with hard limestone layers (Fig. 4.6). The groundwater salinity in the area is ~1630 mg/L and the water table depth is ~3.2 m. The patch of vines at NAP2 is irrigated with water from wells PAR213 and PAR219, which have an average salinity of ~1050 mg/L.

4.2.1 SUCTION LYSIMETER AND GROUNDWATER SALINITY DATA

Similarly to site NAP1, the suction lysimeter chloride and salinity data from site NAP2 show negligible change in the salt storage over the time scale of a year (Figs 4.6–4.7). High salinities in the 1 m lysimeter suggest that there has been some salt accumulation in the root zone, although the exact depth and concentration of the salinity peak is not known. A slight shift in chloride concentrations in the lysimeters over the sampling period suggests that there may be a small amount of seasonal build-up and leaching of salt during the year, but the net effect on salt storage over time scales of a year or greater is again zero.

4.2.2 WATER BALANCE

The water balance for site NAP2 was calculated using (a) the standard water balance and (b) the Penman-Grindley methods described in Section 2. Figure 4.8 shows drainage calculated over the entire study period using both methods, along with changes in soil water storage measured using the neutron moisture meter and soil capacitance measured using the c-probe. Drainage over the nominal 12 month period from March 2004 to March 2005 was calculated to be 100 mm/y by the standard water balance and 91 mm/y by the Penman-Grindley method. The annual components of the water balance are shown on Figure 4.6.

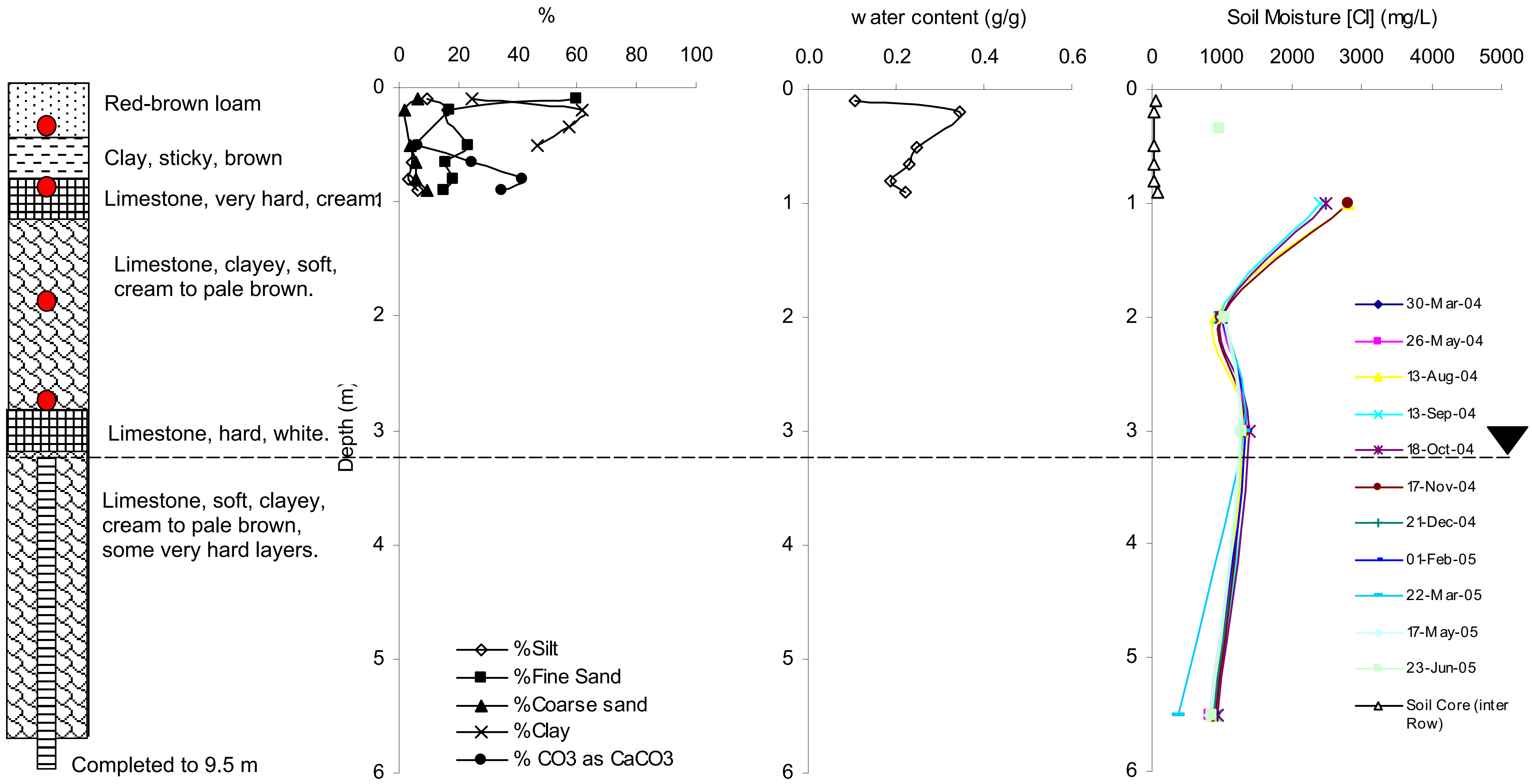
There is good agreement between the drainage estimates from the two water balance methods at this site. Figure 4.8 shows that the small difference is again due to some drainage estimates in March to May 2004 and February to March 2005 made by the standard water balance method that are not identified by the Penman-Grindley method. These differences, as well as some negative drainage values estimated by the standard water balance, can be discussed similarly to those for NAP1 above and a range of drainage values will therefore be used in calculations of salinity impact.

4.2.3 SALT BALANCE

The total application of salt via rainfall and irrigation to site NAP2 is 1.8 t/ha/y (Fig. 4.6). As the suction lysimeter data does not indicate any net accumulation or loss of salt in the soil profile, it is reasonable to assume that the same mass of salt leaves the profile along with deep drainage (91–100 mm/y). This equates to a drainage water salinity of 1780–1980 mg/L. Similarly to site NAP1, as the salinity of the soil water below the root zone measured in the 3 m lysimeter is much higher than this, it appears that uniform leaching of salt through the

NAP 2

Physical Model



Conceptual Model

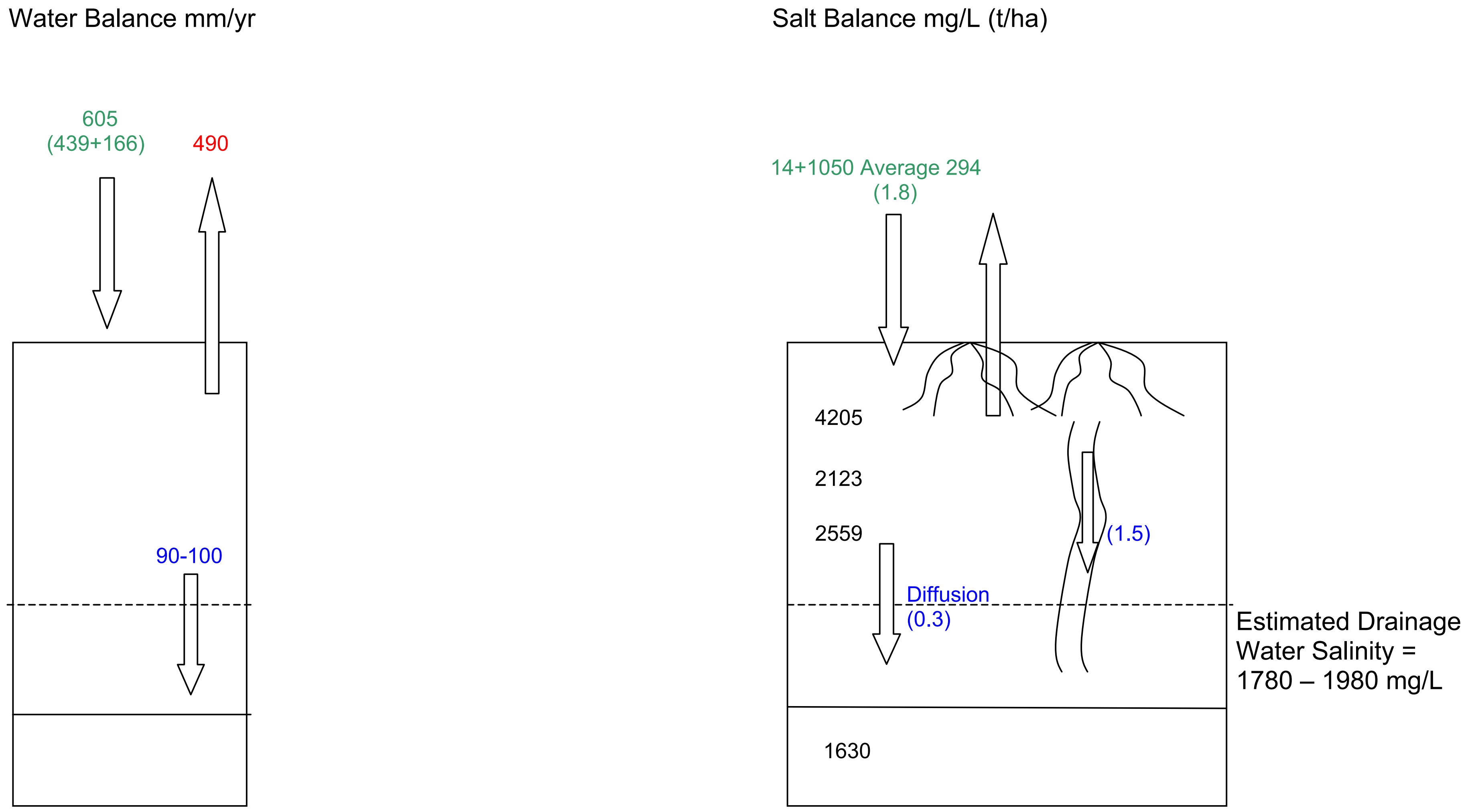


Figure 4.6 Conceptual model of NAP2.

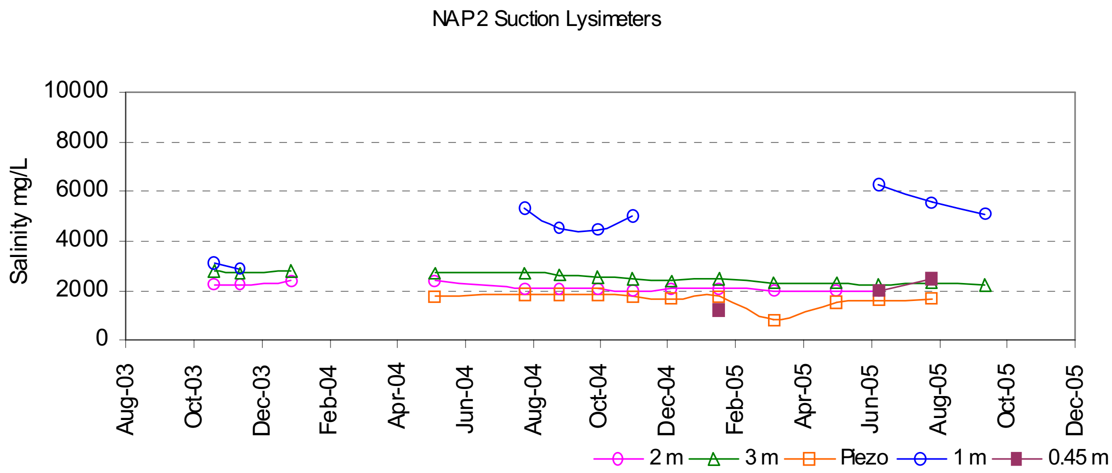


Figure 4.7 Suction lysimeter salinity (TDS) data from NAP2.

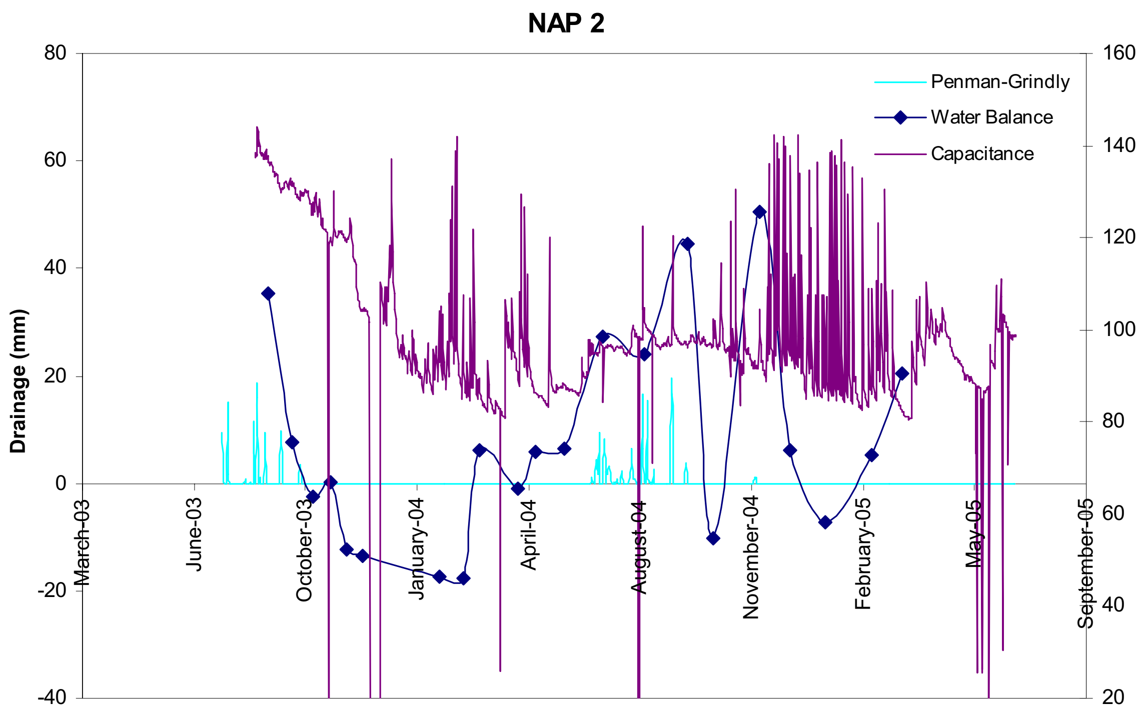


Figure 4.8 Estimated drainage and measured changes in soil moisture storage for site NAP2.

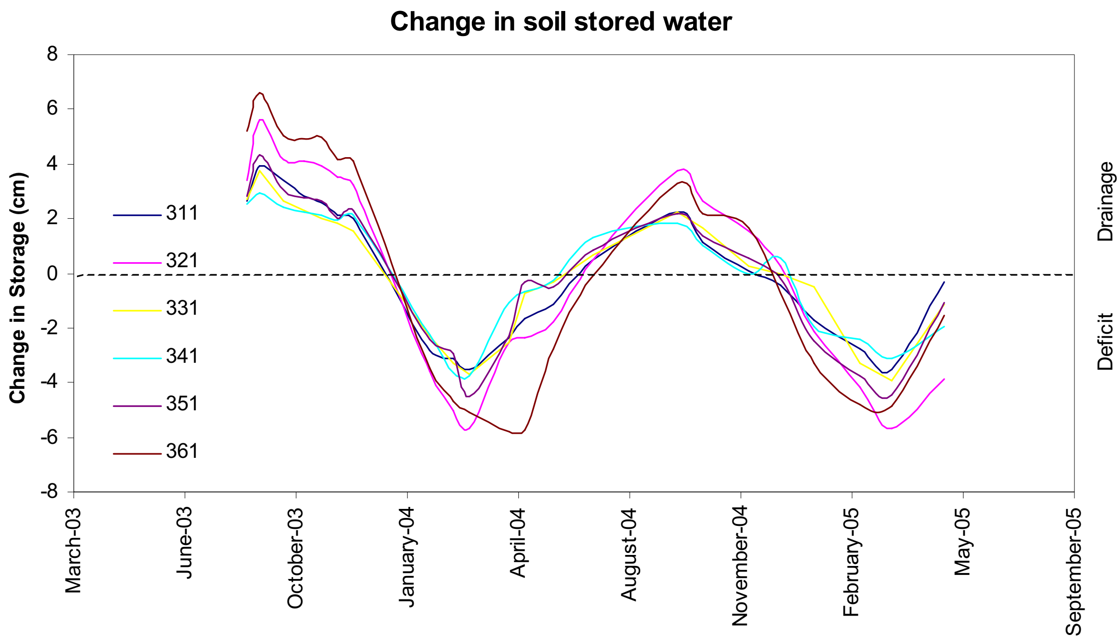


Figure 4.8 continued.

soil profile is not occurring at this site. Therefore, how this salt leaves the profile is uncertain. Because of the large concentration gradient between the soil water at 1 m depth, diffusion may be occurring and has been calculated using equation 2.5 to account for up to ~0.3 t/ha/y of the output (Fig. 4.1). As for site NAP1, it is proposed that some water, particularly winter rainfall, may travel through the profile via preferential flow in the sediment-filled cracks and root channels. This would not disturb the main solute profile, which remains in balance between accumulation through evapotranspiration and loss through diffusion or slow mass flow, but may flush through some salt that has accumulated seasonally within the root channel itself (Fig. 4.6). Similarly to site NAP1, a decrease in pore water chloride concentrations below the main peak (below the base of the root zone), rather than a constant value with depth suggests that non-uniform flow is occurring at this site (Fig. 4.6).

As the effective salinity of the drainage water is between 730–930 mg/L greater than that of the irrigation water applied, the net salinity impact of irrigation on the aquifer is calculated to be 0.73–0.84 t/ha/y for site NAP2.

4.2.4 INFORMATION FROM CHEMISTRY

The key groundwater chemistry graphs for NAP2 are shown in Figure 4.9. Irrigation water for the vineyards at site NAP2 is sourced from bores PAR213 and PAR219, which are close to the main Keith – Naracoorte highway and the boundary between the Padthaway Flats and Naracoorte Ranges. Hence the irrigation water is comparatively fresh compared with the groundwater underlying the study site. Samples for full chemical analysis were collected from bores PAR213 and PAR219. The chemical signatures of these samples are consistent with groundwater from the Naracoorte Ranges that has received some fresher drainage input following flushing of the unsaturated zone salt store. The chemical signatures of these groundwater samples are similar to that sampled from Transect B piezometer PB3, which is screened 12 m below the water table.

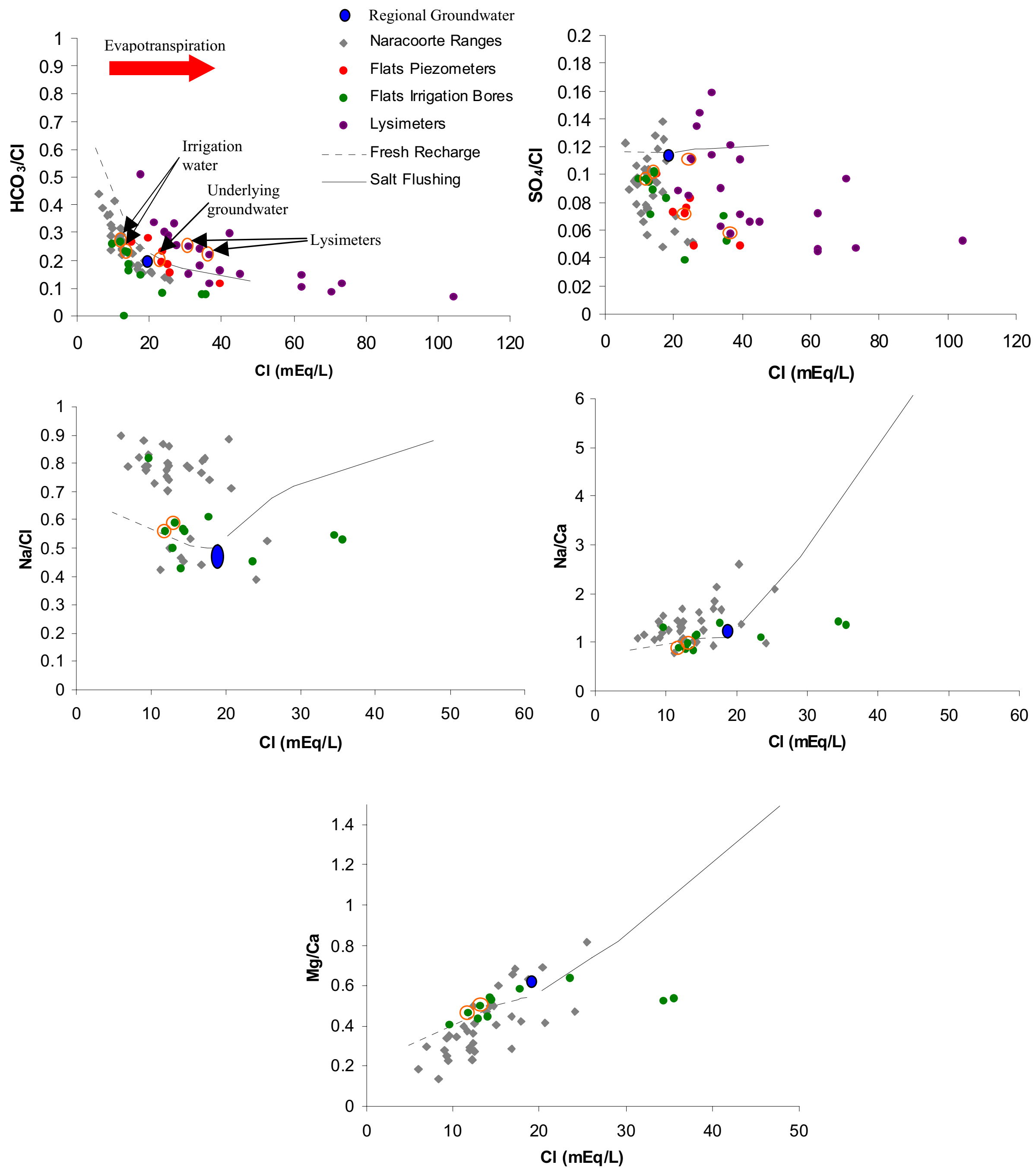


Figure 4.9 Groundwater and soil water (lysimeter) chemistry graphs for site NAP2 (orange circled points).

Also shown are groundwater compositions predicted to result from salt flushing (solid line) and freshwater drainage (dashed line) in the Naracoorte Ranges, Naracoorte Ranges groundwater data (grey symbols) and other data from the Padthaway Flats.

Groundwater below the study site has a higher TDS and lower HCO_3/Cl and SO_4/Cl ratio than the irrigation water, suggesting that it has a different chemical history from the irrigation water sourced from PAR213 and PAR219. The composition of the groundwater below site NAP2 is consistent with Naracoorte Ranges groundwater that has received some salt, flushed from the unsaturated zone salt store in the ranges. Its composition is similar to that of PA2 in the Naracoorte Ranges. Mixing with a small amount of evapo-concentrated drainage water may also be implied although the scatter in the data makes interpretation of this ambiguous. As the screen of the piezometer directly below site NAP2 is 6 m long, it is also possible that small changes in groundwater chemistry near the water table due to infiltration of irrigation drainage water may not be observed in groundwater samples from this piezometer.

The soil water sampled from the NAP2 suction lysimeters at 2 m and 3 m has a higher TDS (Cl) than both the irrigation water and the groundwater below the site, but a similar HCO_3/Cl ratio (Fig. 4.9). It is possible that some mixing with this saline soil water may be responsible for the small deviation to the right of the groundwater below the site from the HCO_3/Cl vs Cl diagram. As stated above, interpretation of this is ambiguous however.

4.2.5 CONCLUSIONS ON SALT ACCESSION AT THE NAP2 DRIP IRRIGATION SITE

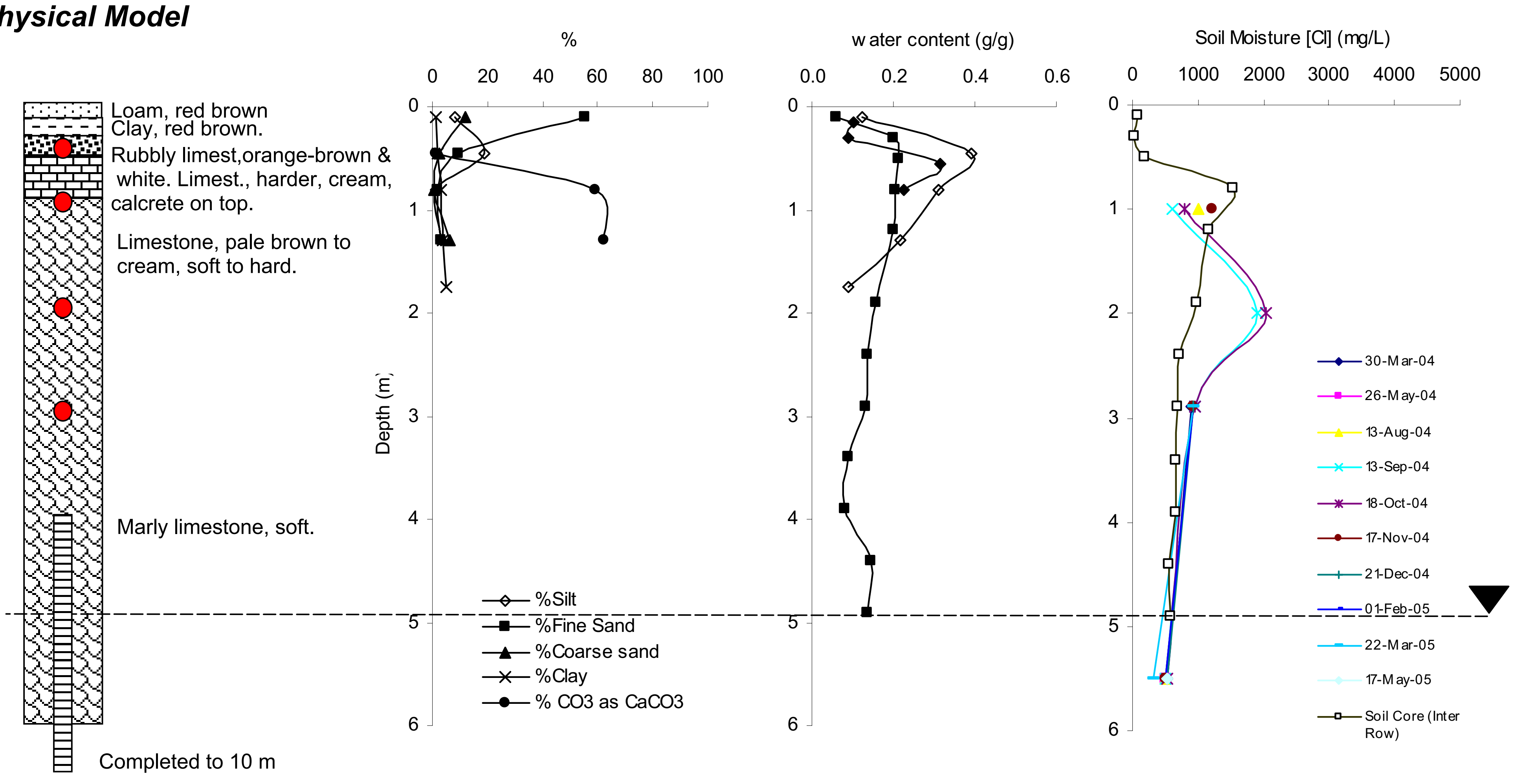
- A net aquifer impact of 0.73–0.84 t/ha/yr is estimated to be occurring due to irrigation at site NAP2.
- This salinity impact is calculated due to the extraction of comparatively low salinity water from up-gradient of the irrigation district and evapo-concentration of that. This reduces the volume of fresher water moving through the irrigation district and transforms it into saltier irrigation drainage water.
- Leakage of saline drainage water has probably had a slight effect on groundwater salinity directly below the vineyard at site NAP2, as the equivalent salinity of the irrigation drainage water is greater than that of the underlying groundwater itself. A slight deviation in the groundwater chemistry towards the composition of saline drainage water supports this.
- Interpretation of the groundwater chemistry data suggests, however, that most of the salinity in the groundwater below site NAP2 can be explained by the salt accession processes occurring in the Naracoorte Ranges, although mixing with small amounts of saline irrigation drainage water along the flow path is possible.

4.3 SITE NAP6

Figure 4.10 shows the physical and conceptual models of the water and salt balances at the vineyard site NAP6. This site is located on a terra rossa soil (Map 2), underlain by a thin rubbly limestone layer and a calcrete-topped limestone that grades downward to a soft marly limestone (Fig. 4.10). The groundwater salinity in the area is ~1200 mg/L and the water table depth is ~4.8 m. The patch of vines at NAP6 is irrigated with water from well GLE279, which has a salinity of ~1130 mg/L.

NAP6

Physical Model



Conceptual Model

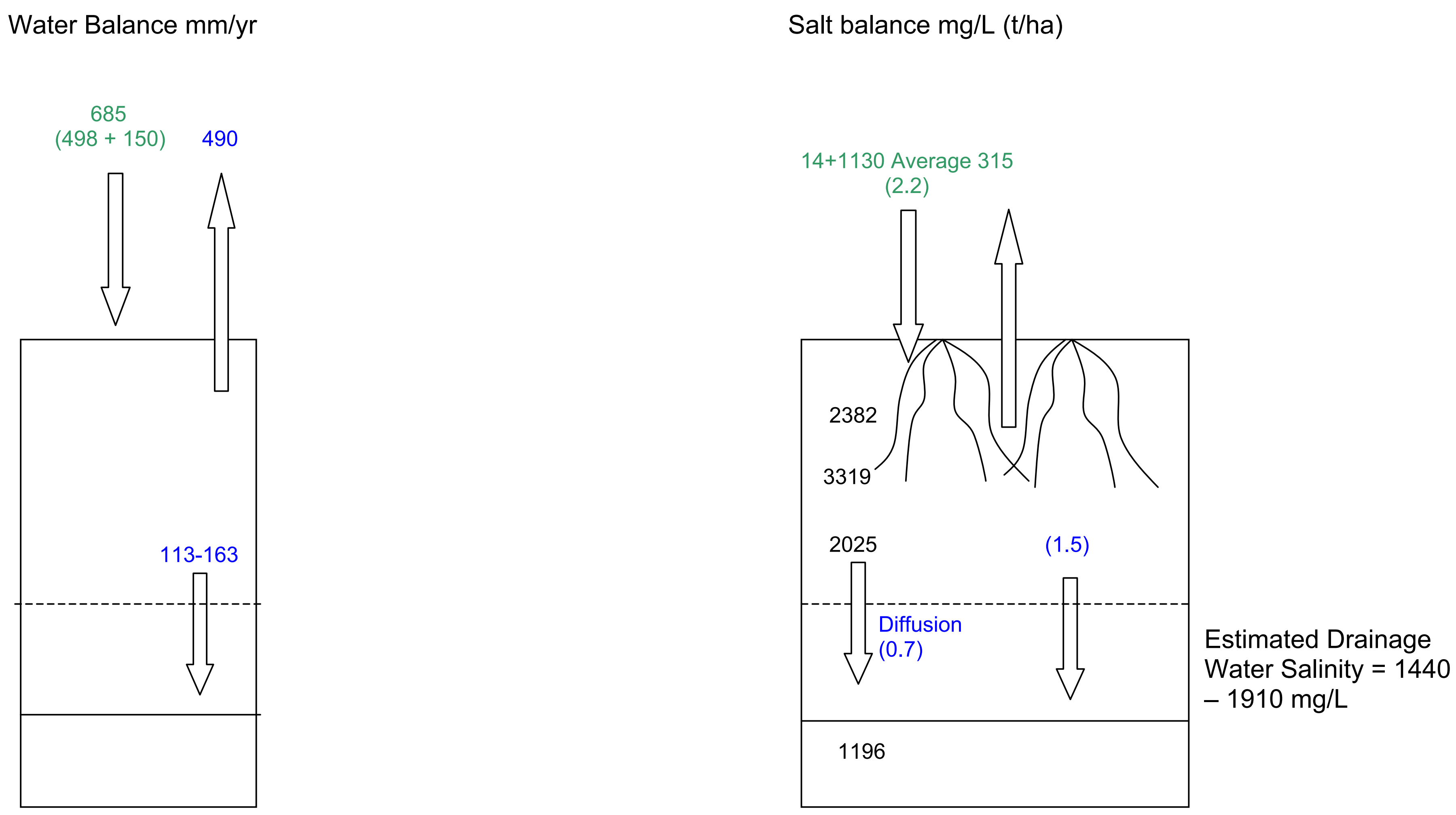


Figure 4.10 Conceptual model of NAP6.

4.3.1 SUCTION LYSIMETER AND GROUNDWATER SALINITY

Soil water chloride concentrations from the suction lysimeters, which are located in the vine row, are shown on Figure 4.10 for comparison with the pore water chloride profile collected from the inter-row and salinity (TDS) data from the suction lysimeters is shown in Figure 4.11. The suction lysimeter data shows a salinity maximum at 2 m, but the exact depth and magnitude of this salinity maximum is unknown. The soil water salinity at the 1 m, 2 m and 3 m lysimeters has fluctuated by up to 750 mg/L, 290 mg/L and 440 mg/L respectively over the sampling period, although there does not appear to be a net build-up or loss of salt over this period. Continued sampling is required to determine whether this is consistent over longer time periods. Groundwater salinity below the site has fluctuated by less than 100 mg/L, which is consistent with negligible seasonal flushing of salt from the unsaturated zone. Again, it must be noted that the screen of this piezometer is 6 m long and leaching of small amounts of salt may not be obvious in samples collected from it due to the effects of mixing over this depth interval.

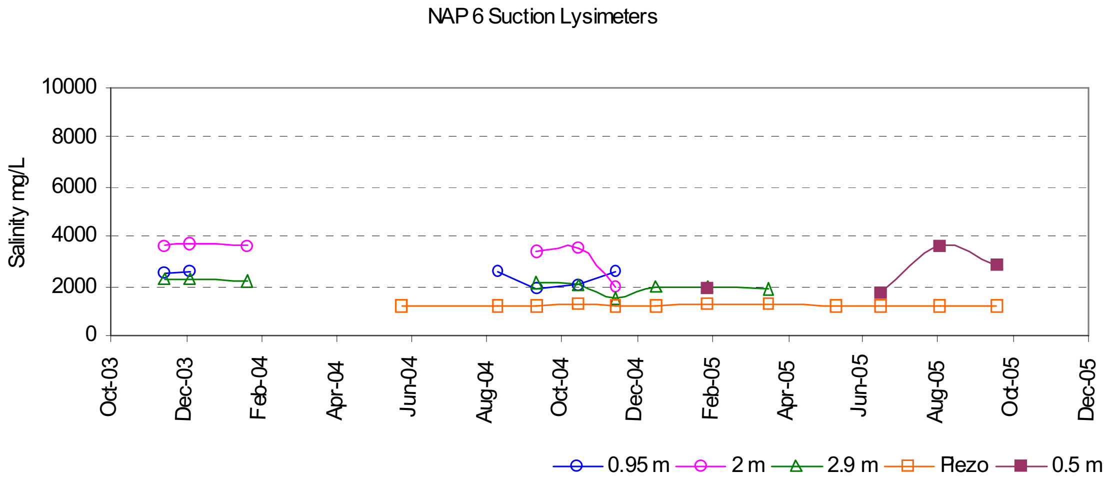


Figure 4.11 Suction lysimeter salinity (TDS) data from NAP6.

4.3.2 WATER BALANCE

The water balance for site NAP6 was calculated using (a) the standard water balance and (b) the Penman-Grindley methods described in Section 2. Figure 4.12 shows drainage calculated over the entire study period using both methods, along with measured changes in soil water storage. Drainage over the nominal 12 month period from March 2004 to March 2005 was calculated to be 113 mm/y by the standard water balance and 150 mm/y by the Penman-Grindley method. The annual components of the water balance are shown on Figure 4.10. Additional drainage estimates were obtained for this site using the chloride mass balance method described in Section 2.2.2, and by creating a one-dimensional model using the LEACHM model (Hutson, 2003), described in Section 2.2.3. The drainage estimates obtained from these two methods were 163 mm/y and 116 mm/y respectively.

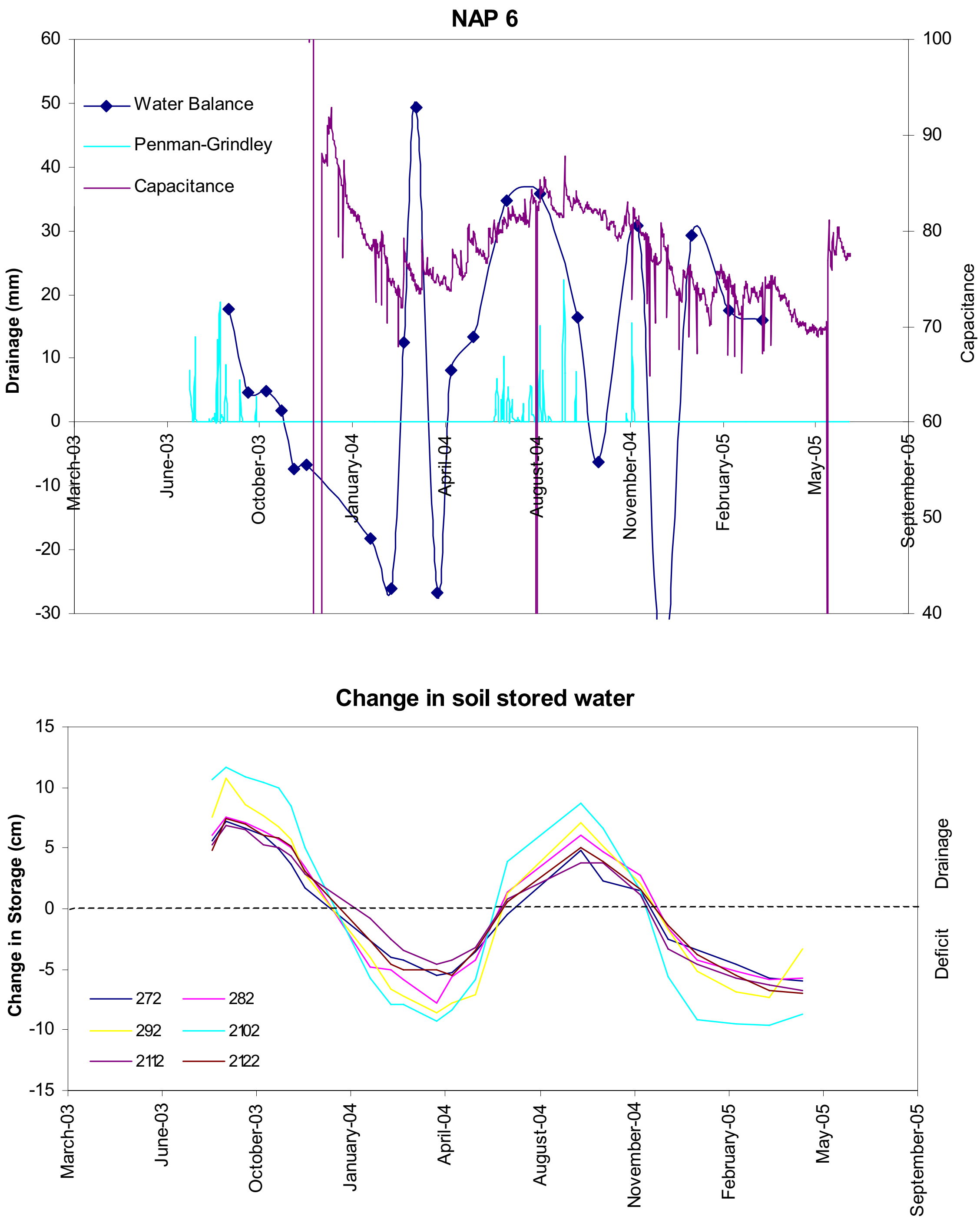


Figure 4.12 Estimated drainage and measured changes in soil moisture storage for site NAP6.

There is reasonable agreement in the drainage estimates between the four methods. The two water balance methods and the LEACM model use the same irrigation, rainfall and evapotranspiration data from 2004–05, but treat the estimation of soil storage differently. Soil moisture storage calculated by LEACHM is based on real soil particle size data collected from the field site. In this case, the standard water balance method estimates a lower drainage than the Penman-Grindley method. For the standard water balance method, drainage was calculated between soil moisture storage measurement events (neutron moisture meter), which were typically two to four weeks apart. For the Penman-Grindley method, drainage is calculated daily, albeit based on a theoretical soil moisture storage. Calculating drainage over time scales greater than daily has the potential to miss drainage events and hence severely under-estimate the annual drainage rate (Rushton & Ward, 1979). For this reason, the higher estimate, based on the Penman-Grindley method may be more accurate. The chloride mass balance is an independent method and integrates over longer time scales, but assumes that the salt flux is at steady state. Hence, application of this method at this site should be approached with caution. Although each of these methods has a different set of limitations, the agreement between the drainage estimates is quite good. Therefore, calculations of salinity impacts to the aquifer are made using the range of drainage values provided by these methods.

4.3.3 SALT BALANCE

The total application of salt via rainfall and irrigation to site NAP6 is 2.2 t/ha/y (Fig. 4.10). As the suction lysimeter data shows no net accumulation or loss of salt in the profile, it is reasonable to assume that the same mass of salt leaves the profile along with deep drainage (113–163 mm/y). This equates to a drainage water salinity of 1440–1910 mg/L. The latter value is similar to the average salinity of the soil water sampled by the 3 m lysimeter at this site, suggesting that the saline drainage water may move more uniformly through the soil profile at this site than at sites NAP1 and NAP2. However, similarly to sites NAP1 and NAP2, the decrease in pore water chloride concentrations below the main peak suggests the occurrence of some non-uniform flow. Because of the large concentration gradient between the soil water at 1 m depth, diffusion has been calculated using equation 2.5 to account for up to ~0.7 t/ha/y of the salt output (Fig. 4.1).

The final result of the salt balance is that the effective salinity of the drainage water is between 310–780 mg/L greater than the irrigation water applied, which equates to a net salinity impact on the aquifer of 0.46–0.88 t/ha/y.

4.3.4 INFORMATION FROM CHEMISTRY

The key groundwater chemistry graphs for NAP6 are shown in Figure 4.13. In contrast to sites NAP1, NAP2 and NAP7 (Section 4.4), irrigation water for site NAP6, extracted from well GLE279, is obtained from directly below the vines. Both the irrigation bore and the piezometer under the field site have chemical compositions that plot closely with groundwater from the Naracoorte Ranges, suggesting that this is the major source of salinity in these groundwaters. Their chemical signature is consistent with Naracoorte Ranges groundwater that has received some fresher water as a result of increased recharge. Its signature is similar to that of Transect B piezometers PB2, PB7 and PB8.

Full chemical analyses could only be carried out on soil water samples from the 3 m suction lysimeter due to low sample volumes obtained from the other two. Soil water from the 3 m lysimeter had a higher TDS (Cl) than both groundwater samples, but a similar HCO_3/Cl to the piezometer, suggesting that mixing with this irrigation drainage water may have slightly influenced the chemical composition of the piezometer. Again, the length of the screen on the piezometer at this site may mean that small amounts of irrigation drainage water leakage are not observed in groundwater samples from it.

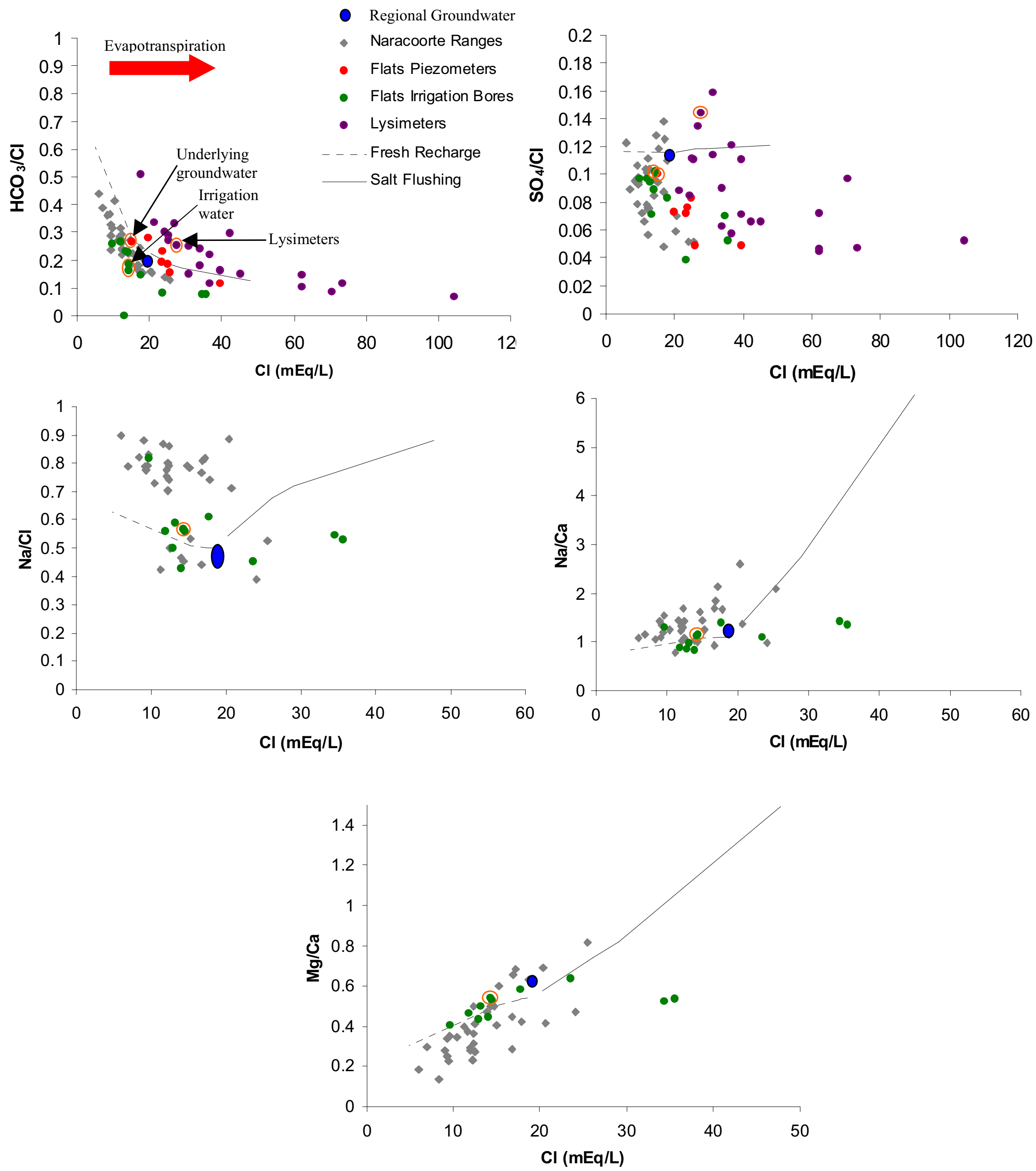


Figure 4.13 Groundwater and soil water (lysimeter) chemistry graphs for drip irrigation site NAP6 (orange circled points).

Also shown are groundwater compositions predicted to result from salt flushing (solid line) and freshwater drainage (dashed line) in the Naracoorte Ranges, Naracoorte Ranges groundwater data (grey symbols) and other data from the Padthaway Flats.

4.3.5 CONCLUSIONS ON SALT ACCESSION AT THE NAP6 DRIP IRRIGATION SITE

- A net aquifer impact of 0.46–0.88 t/ha/yr is estimated to be occurring due to irrigation at site NAP6.
- This salinity impact is calculated due to the extraction of comparatively low salinity water from up-gradient of the irrigation district and evapo-concentration of that. This reduces the volume of fresher water moving through the irrigation district and transforms it into saltier water.
- The equivalent salinity of the irrigation drainage water at NAP6 is greater than that of the underlying groundwater, meaning that this could have a negative impact on the quality of the underlying groundwater. The groundwater chemistry data suggests the possibility of a small impact from irrigation drainage water.
- However, interpretation of the groundwater chemistry data suggests that most of the groundwater salinity below site NAP6 can be explained by the salt accession processes occurring in the Naracoorte Ranges.

4.4 SITE NAP7

Figure 4.14 shows the physical and conceptual models of the water and salt balances at the vineyard site NAP7. This site is theoretically located on a terra rossa soil (Map 2), although field observations suggest that the soil contains more heavy clay than would be expected with this soil classification. It is believed that the boundary of the Baker Sand unit, which contains a mottled clay horizon, should be extended further south to incorporate site NAP7 (Map 2). The soil layer is underlain by a thick hard limestone layer to ~3.2 m, which then becomes soft and more clayey with only some clay layers, extending to the water table (Fig. 4.10). The groundwater salinity in the area is 1470 mg/L and the water table depth is ~4.9 m. The patch of vines at NAP7 is irrigated with water from well GLE287, which has a salinity of ~1090 mg/L.

4.4.1 SUCTION LYSIMETER AND GROUNDWATER SALINITY

Soil water chloride concentrations from the suction lysimeters, which are located in the vine row, are shown on Figure 4.14 for comparison with the pore water chloride profile collected from the inter-row and salinity (TDS) data from the suction lysimeters is shown in Figure 4.15. A peak in soil water salinity can be identified around the 2 m lysimeter, however the exact depth and salinity of this peak cannot be determined from three lysimeters alone. Soil water salinity in the 1 m, 2 m and 3 m suction lysimeters fluctuated by ~1610 mg/L, 630 mg/L and 770 mg/L respectively over the sampling period. Once again, despite this fluctuation, there is no apparent net build-up or loss of salt from the profile over the time scale of a year. Longer-term sampling is required to confirm this.

4.4.2 WATER BALANCE

The water balance for site NAP7 was calculated using (a) the standard water balance and (b) the Penman-Grindley methods described in Section 2. Figure 4.16 shows drainage calculated over the entire study period using both methods, along with measured changes in soil water storage. Drainage over the nominal 12 month period from March 2004 to March 2005 was calculated to be 115 mm/y by the standard water balance and 174 mm/y by the Penman-Grindley method. The annual components of the water balance are shown on Figure 4.14.

There is poor agreement between the drainage estimates calculated using the two methods at site NAP7. The discrepancy possibly relates to the difference in the time interval over which the two methods calculate drainage. For the standard water balance method, drainage was calculated between soil moisture storage measurement events (neutron moisture meter), which were typically two to four weeks apart. For the Penman-Grindley method, drainage is calculated daily, albeit based on a theoretical soil moisture storage. Calculating drainage over time scales greater than daily has the potential to miss drainage events and hence severely under-estimate the annual drainage rate (Rushton & Ward, 1979). For this reason, the higher estimate, based on the Penman-Grindley method may be more accurate.

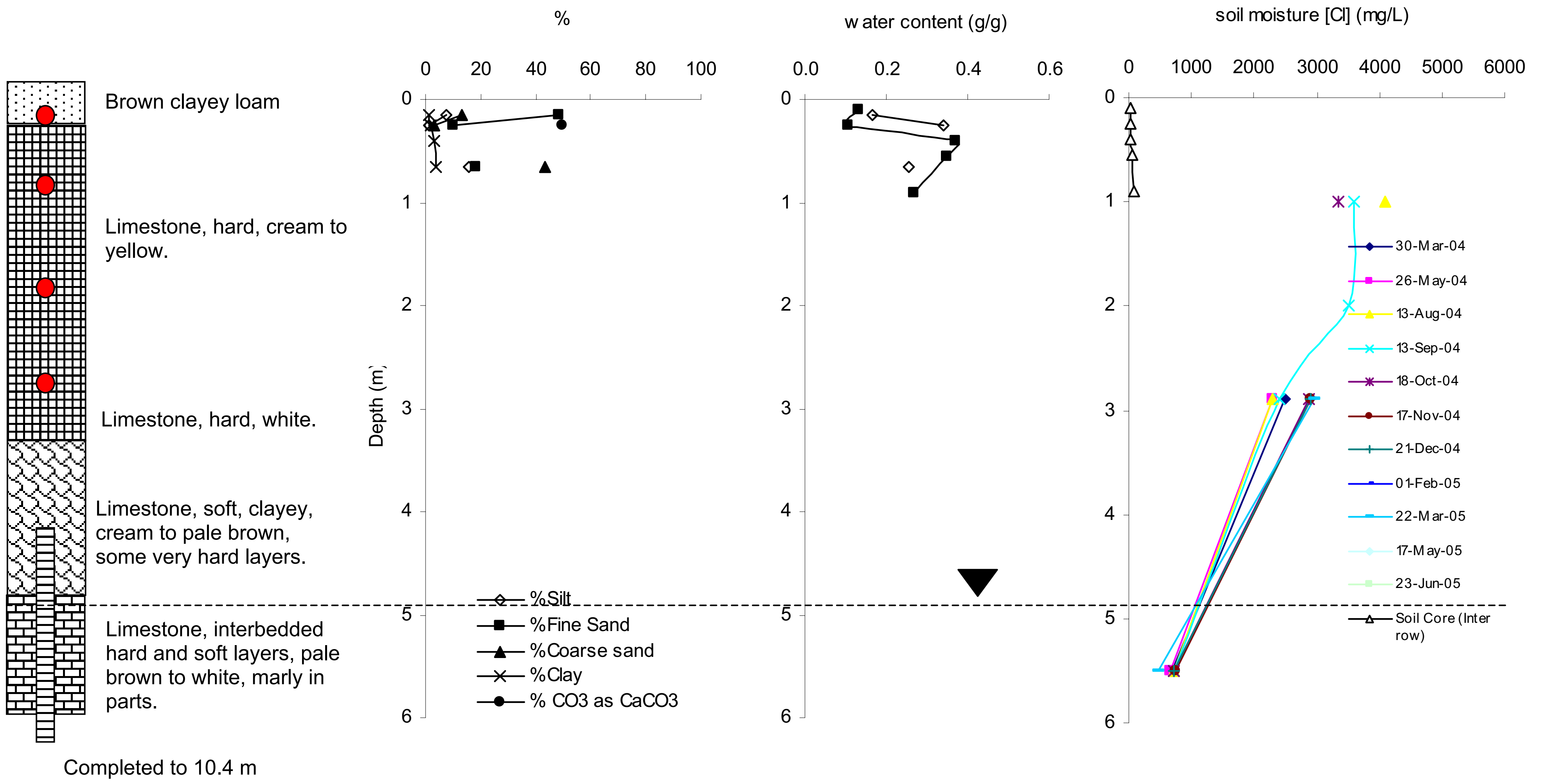
4.4.3 SALT BALANCE

The total application of salt via rainfall and irrigation is 1.7 t/ha/y (Fig. 4.14). As there appears to be no net accumulation or loss of salt in the profile, it is reasonable to assume that the same mass of salt leaves the profile along with deep drainage (115–174 mm/y). This equates to a drainage water salinity of 1018–1540 mg/L. Similarly to sites NAP1 and NAP2, as the salinity of the soil water below the root zone measured in the 3 m lysimeter is much higher than this, it appears that uniform leaching of salt through the soil profile may not be occurring at this site. Therefore, how this salt leaves the profile is uncertain. Because of the large concentration gradient between the soil water at 1 m depth, diffusion has been calculated to account for up to ~0.3 t/ha/y of the output (Fig. 4.14). As for sites NAP1 and NAP2, it is proposed that some water, particularly winter rainfall, may travel through the profile via preferential flow in the sediment-filled cracks and root channels. This would not disturb the main solute profile, which remains in balance between accumulation through evapotranspiration and loss through diffusion or slow mass flow, but may wash through some salt that has accumulated seasonally within the root channel itself.

The effective salinity of the drainage water from this site is between 0–450 mg/L greater than the irrigation water applied, which equates to a net salinity impact on the aquifer of 0–0.52 t/ha/y.

NAP 7

Physical Model



Conceptual Model

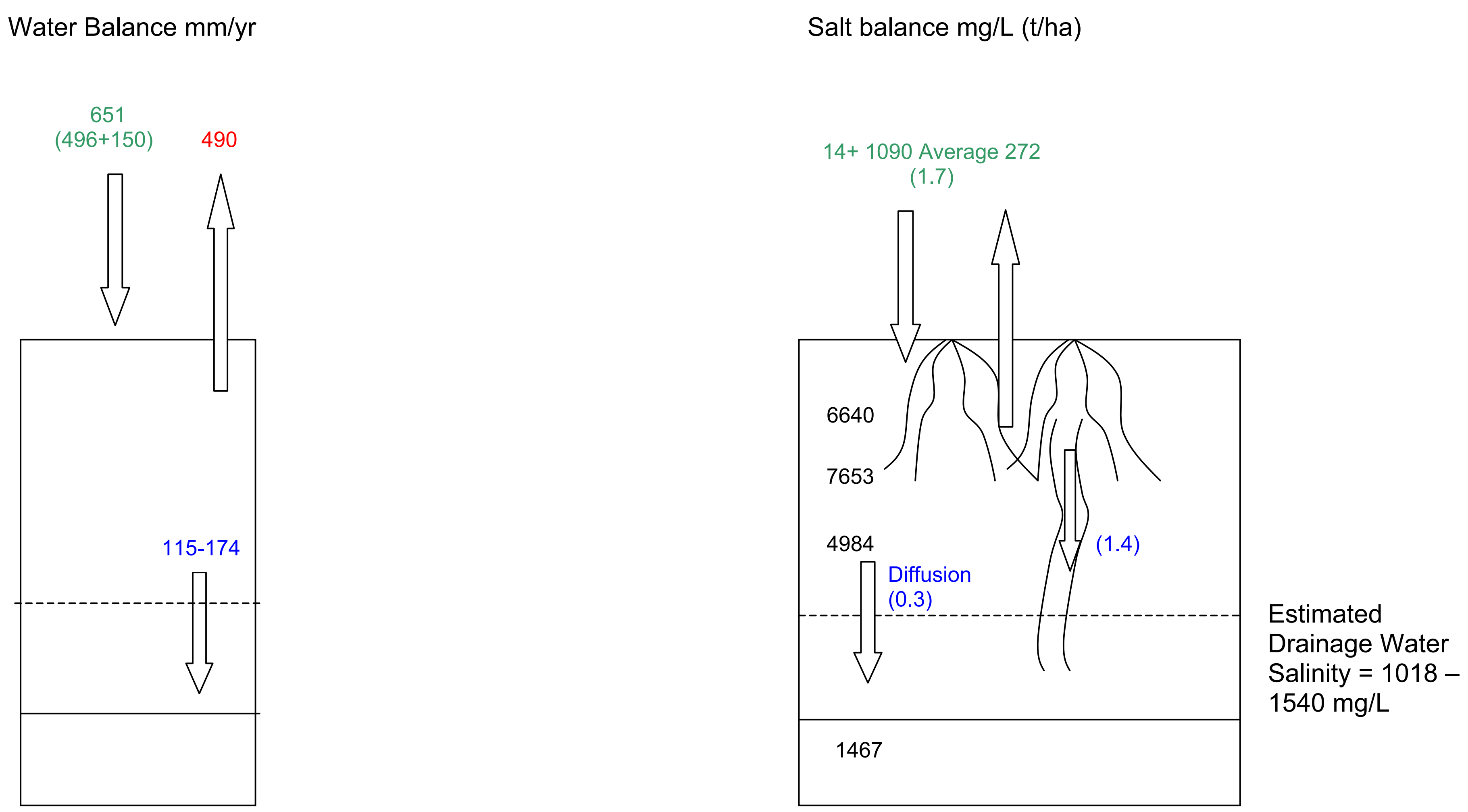


Figure 4.14 Conceptual model of NAP7.

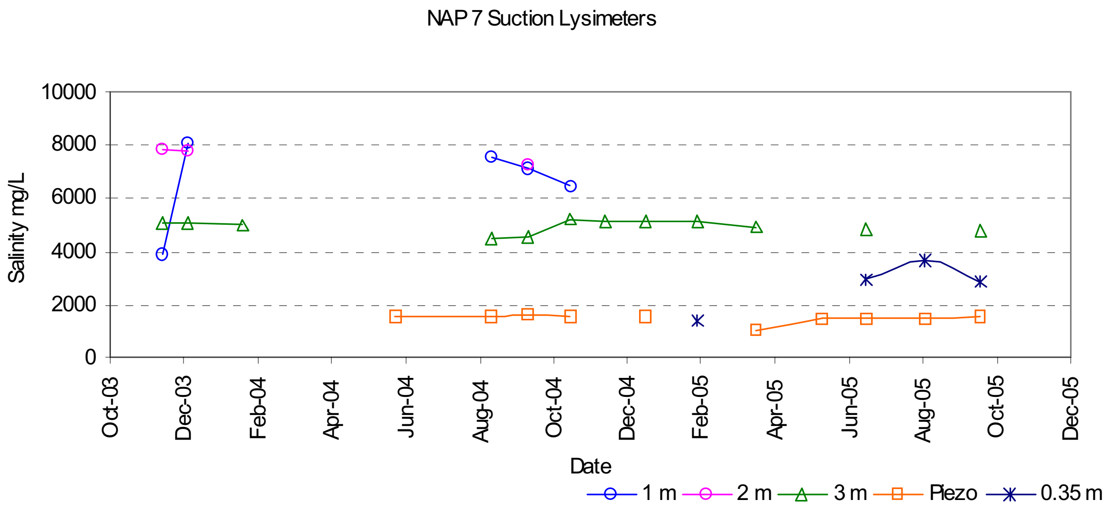


Figure 4.15 Suction lysimeter salinity (TDS) data from vineyard site NAP7.

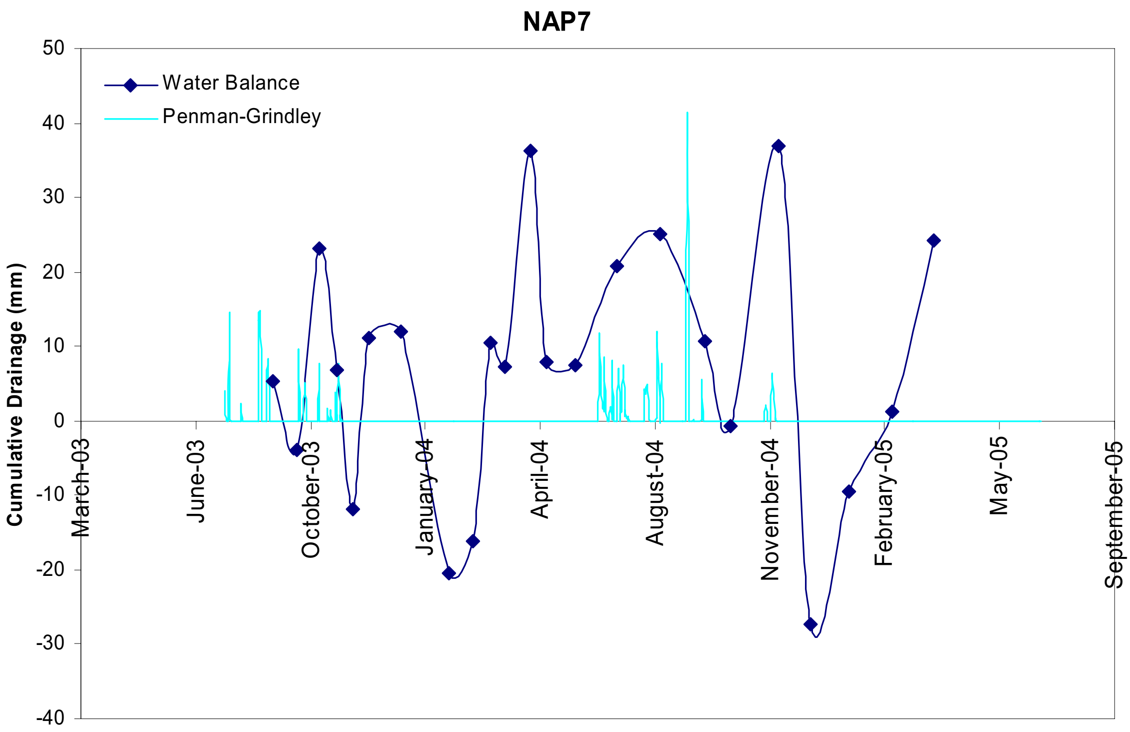


Figure 4.16 Estimated drainage and measured changes in soil moisture storage for site NAP7.

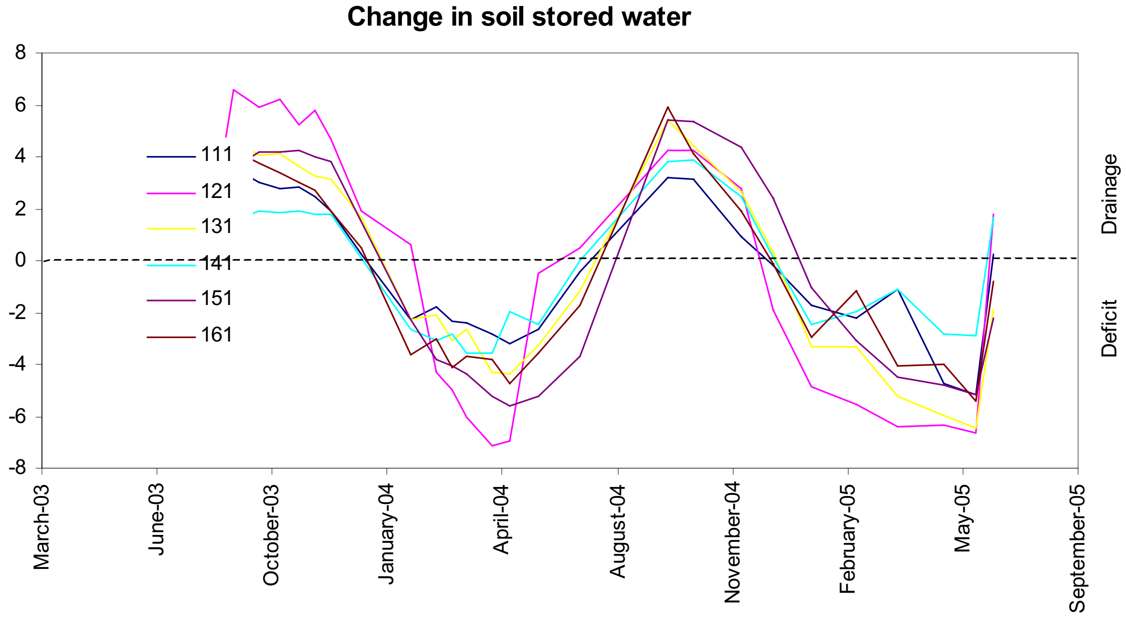


Figure 4.16 continued.

4.4.4 INFORMATION FROM CHEMISTRY

Irrigation water for site NAP7 was sampled from well GLE 287, which is close to the main highway (Map 1). The chemical signature of this groundwater is consistent with groundwater from the Naracoorte Ranges that has received a small amount of fresher recharge as a result of increased recharge in the Ranges, and is similar to that of Transect B piezometers PB2, PB7 and PB8 (Fig. 4.17). Groundwater in the piezometer below the study site has higher TDS (Cl), higher HCO_3/Cl, and a lower SO_4/Cl than the irrigation water. However, the groundwater plots close to the trend for the Naracoorte Ranges, which suggests little impact of irrigation drainage water.

Due to low sample volumes from the other two lysimeters, only the 3 m lysimeter sample could be analysed for full chemistry. This soil water sample had a much higher TDS (Cl) than either of the groundwater samples and a similar SO_4/Cl ratio to the irrigation water. The lower HCO_3/Cl ratio of the soil water sample suggests removal of HCO_3, possibly via precipitation of $CaCO_3$. Saturation index calculations using the geochemical model PHREEQC (Parkhurst & Appelo, 1999) indicate that the soil water sample is at equilibrium with respect to calcite ($CaCO_3$) and aragonite ($CaCO_3$), which supports this theory.

4.4.5 CONCLUSIONS ON SALT ACCESSION AT THE NAP7 DRIP IRRIGATION SITE

- A net salinity impact to the aquifer of 0–0.52 t/ha/yr is estimated to be occurring due to irrigation at site NAP7.
- This salinity impact is calculated due to the extraction of comparatively low salinity water from up-gradient of the irrigation district and evapo-concentration of that. This reduces the volume of fresher water moving through the irrigation district and transforms it into saltier water.

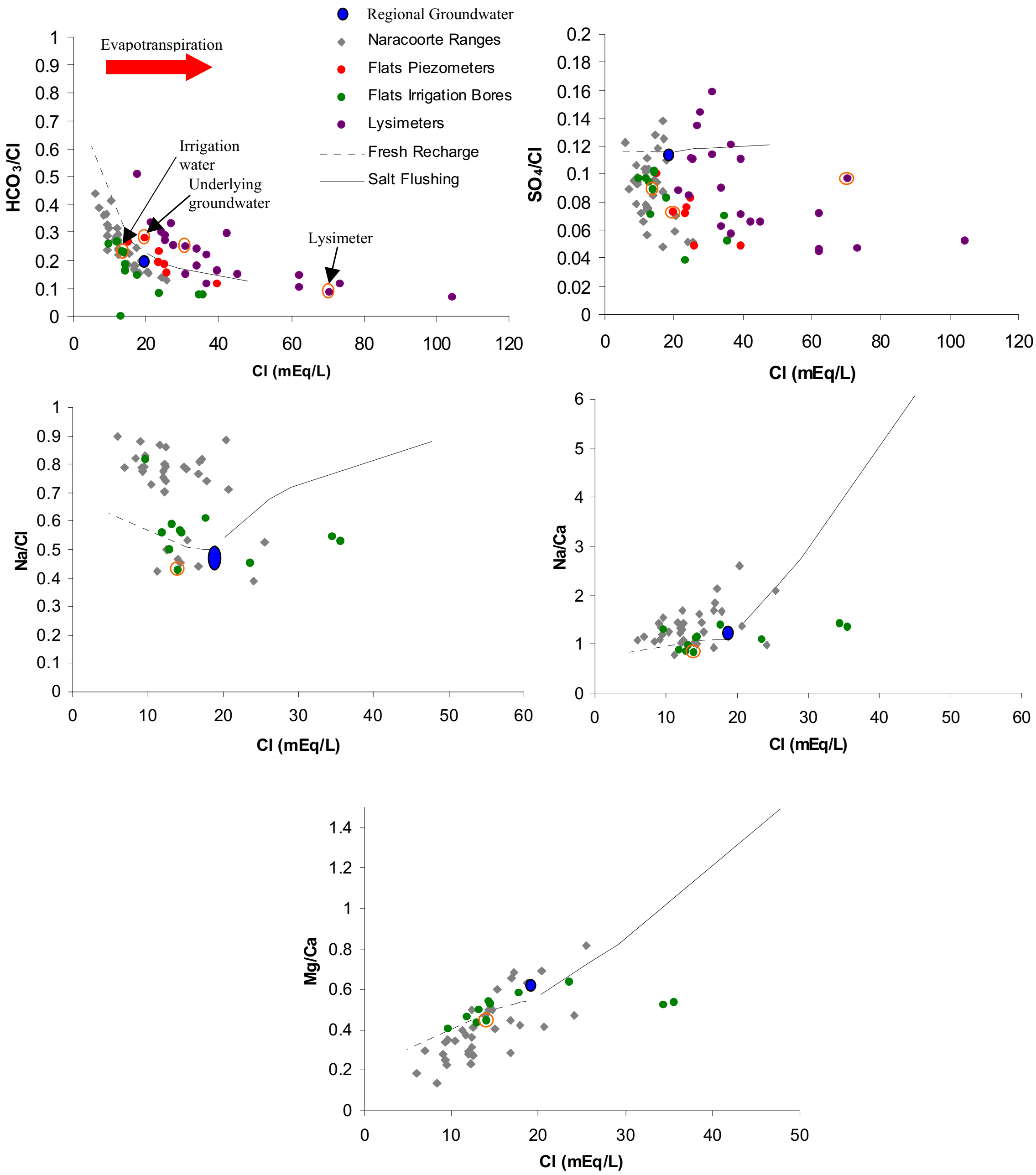


Figure 4.17 Groundwater and soil water (lysimeter) chemistry graphs for drip irrigation site NAP7 (orange circled points).

Also shown are groundwater compositions predicted to result from salt flushing (solid line) and freshwater drainage (dashed line) in the Naracoorte Ranges, Naracoorte Ranges groundwater data (grey symbols) and other data from the Padthaway Flats.

- The estimated equivalent salinity of the irrigation drainage water at NAP7 ranges from being lower to approximately equivalent to that of the underlying groundwater. This suggests that it is unlikely that irrigation drainage from this site would currently have a negative impact on groundwater quality below the vineyard.
- The groundwater chemistry data shows no indication of an impact from irrigation drainage water on groundwater underlying site NAP7, but that the salt load at this location is derived predominantly from salt accessions in the Naracoorte Ranges.
- It should be noted that, as the screen of the piezometer directly below site NAP1 is 6 m long, it is possible that small changes in groundwater chemistry near the water table due to infiltration of small amounts of irrigation drainage water are not observed in groundwater samples from this piezometer.

4.5 CONCLUSIONS ON SALT ACCESSIONS FROM THE DRIP IRRIGATED VINEYARDS

- Salinity impacts on the aquifer from drip irrigation range from 0–0.88 t/ha/y.
- This salinity impact is calculated due to the extraction of comparatively low salinity water from up-gradient of the irrigation district and evapo-concentration of that. This reduces the quality of fresher water moving through the irrigation district and transforms it into more saline water.
- Groundwater chemistry data suggests that the majority of the groundwater salinity currently observed in the Padthaway Flats irrigation area can be explained by salt accession processes occurring in the Naracoorte Ranges.
- Site NAP6, which is located on a Terra Rossa soil, is the only site where the estimated effective salinity of the irrigation drainage water is greater than the salinity of the underlying groundwater. This is due to irrigation with groundwater from directly below the site rather than from near the Ranges. Hence irrigation drainage from this site may be having a direct impact on the quality of the underlying groundwater.
- Drainage from the other vineyard sites has a lower effective salinity than the underlying groundwater, suggesting that this is not currently having a direct impact on the underlying groundwater quality.
- However, if groundwater of lower salinity moves through the area from the Naracoorte Ranges, the influence of drainage from these sites may begin to be evident.
- A mechanism of preferential flow of water down sediment-filled cracks and root channels appears to be occurring at the vineyard sites, perhaps with the exception of site NAP6. Beyond this, the mechanism of salt movement through the soil profile below the drip irrigated vineyards is unknown and probably involves a combination of diffusion and slow mass flow through the soil matrix and mass flow down preferential flow paths.
- There was reasonably good agreement between different methods of calculating drainage for the vineyard sites. A limitation of the water balance methods is that these are based on a blanket application of CSIRO's evaportanspiration measurements. These measurements may vary significantly between sites and hence these water balance calculations should be revised at completion of the CSIRO study.
- Due to the low water and salt fluxes involved, the direct identification of groundwater salinity impacts under drip irrigation may require piezometers with narrow screen intervals positioned just below the water table. It is possible that piezometers/ observation wells that are screened at deeper intervals in the aquifer, or with long screen

intervals, may not detect small changes in groundwater salinity and composition at the water table that have occurred as a result of accessions of irrigation drainage water under this irrigation type.

- Despite the low salinity impacts estimated for this irrigation type, large quantities of salt are observed to occur around the root zone under the irrigated vineyards at Padthaway. Over the time scale of the present study, this salt store appears to be in a steady state, with no net accumulation or leaching observed. However, due to a lack of understanding of the mechanisms of salt transport through the profile at these sites, the long-term fate of this salt store is unknown. Hence the salinity impacts under drip irrigated vineyards would be much greater than estimated here if conditions arose under which it was released into the underlying aquifer.

5. SALT AND WATER BALANCE UNDER THE CENTRE PIVOT SITE (NAP3)

Figure 5.1 shows the physical and conceptual model of the water and salt balance at the centre pivot site NAP 3. This site is located on a dark clayey sand (Map 2) underlain by a hard limestone interlayered with sand at depth. The groundwater salinity in the area is 1720 mg/L and the water table depth is ~3.95 m. The pivot is supplied with water from well MAR209, which has an average salinity of ~1765 mg/L.

5.1 SUCTION LYSIMETER AND GROUNDWATER SALINITY DATA

The average soil water salinity is two to three times greater than the concentration of irrigation water. Soil water salinity ranges from 3000 mg/L at a depth of 0.5 m to a maximum of 6000 mg/L at 2 m (Fig. 5.1). Monthly measurements taken at depths of 0.5 m, 1 m and 2 m show seasonal fluctuations, with an overall increase in salt storage over the sampling period (Fig. 5.2). Additional sampling is required to determine whether this increase in salt storage continues over time or whether the salt will eventually be leached out of the profile. The greatest increase in soil water salinity was observed in the top 0.5 m (root zone), where it increased from 2300 mg/L in August 2004 to 3600 mg/L in June 2005. At the same time, groundwater salinity decreased suggesting that either (i) the salinity of the drainage water was lower than that of the underlying groundwater, having a freshening effect, or (ii) that the salinity of groundwater flowing in from up-gradient had decreased and there was little contribution at all from irrigation drainage at the site. Small spikes in groundwater salinity in June of each year may be due to the rise in water table and dissolution of accumulated salt from the soil profile or via the leaching of salt during periods of deep drainage. The overall increase in salt concentration may be explained by an accumulation of salt through irrigation, followed by partial leaching during the period of deep drainage.

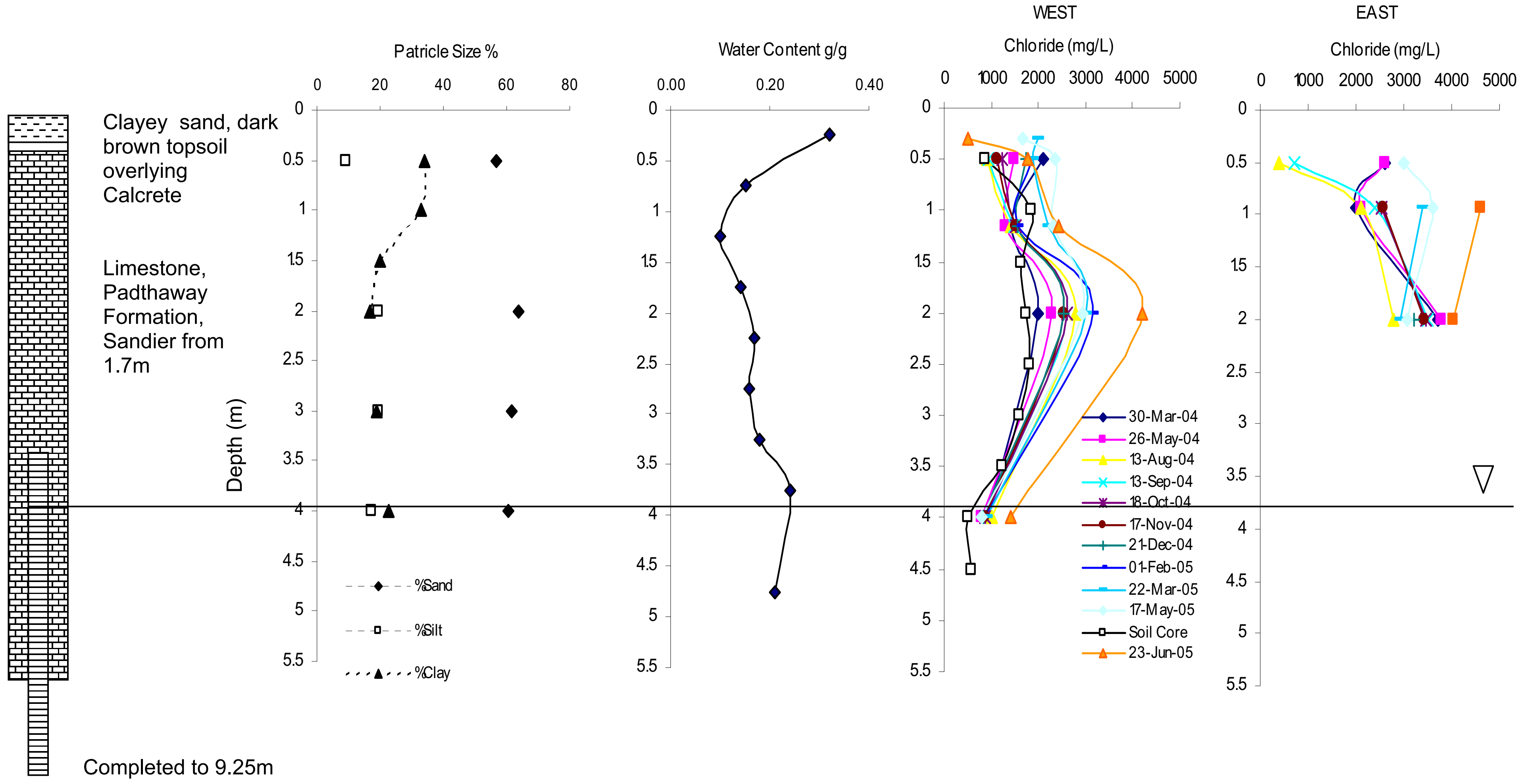
5.2 WATER BALANCE

The water balance for site NAP3 was calculated on a daily basis for both the eastern and western sites. Annual volumes for each component of the water balance are presented in Figure 5.1. The rain gauge at the eastern site recorded 559–450 mm of irrigation over 2003–04 and 2004–05 respectively. The rain gauge at the western site recorded 1104 mm of irrigation over the 2003–04 irrigation season and failed to operate over the 2004–05 irrigation season. Both rain gauges recorded similar rainfall leading up to the irrigation period.

According to Desmier (1992), the average crop irrigation requirement of lucerne seed and lucerne hay for the Padthaway PWA is 479 mm and 549 mm respectively. The volume of irrigation measured via the rain gauge at the eastern site, is in close agreement with the crop irrigation requirement and is therefore considered to be more representative of irrigation application. The following drainage calculations were hence based on measurements made at the eastern site.

NAP 3

Physical Model



Conceptual Model

Water Balance: mm (May 03 to Apr 04 and May 04 to Apr 05)

Salt Balance: Total Dissolved Salts mg/l (t/ha)

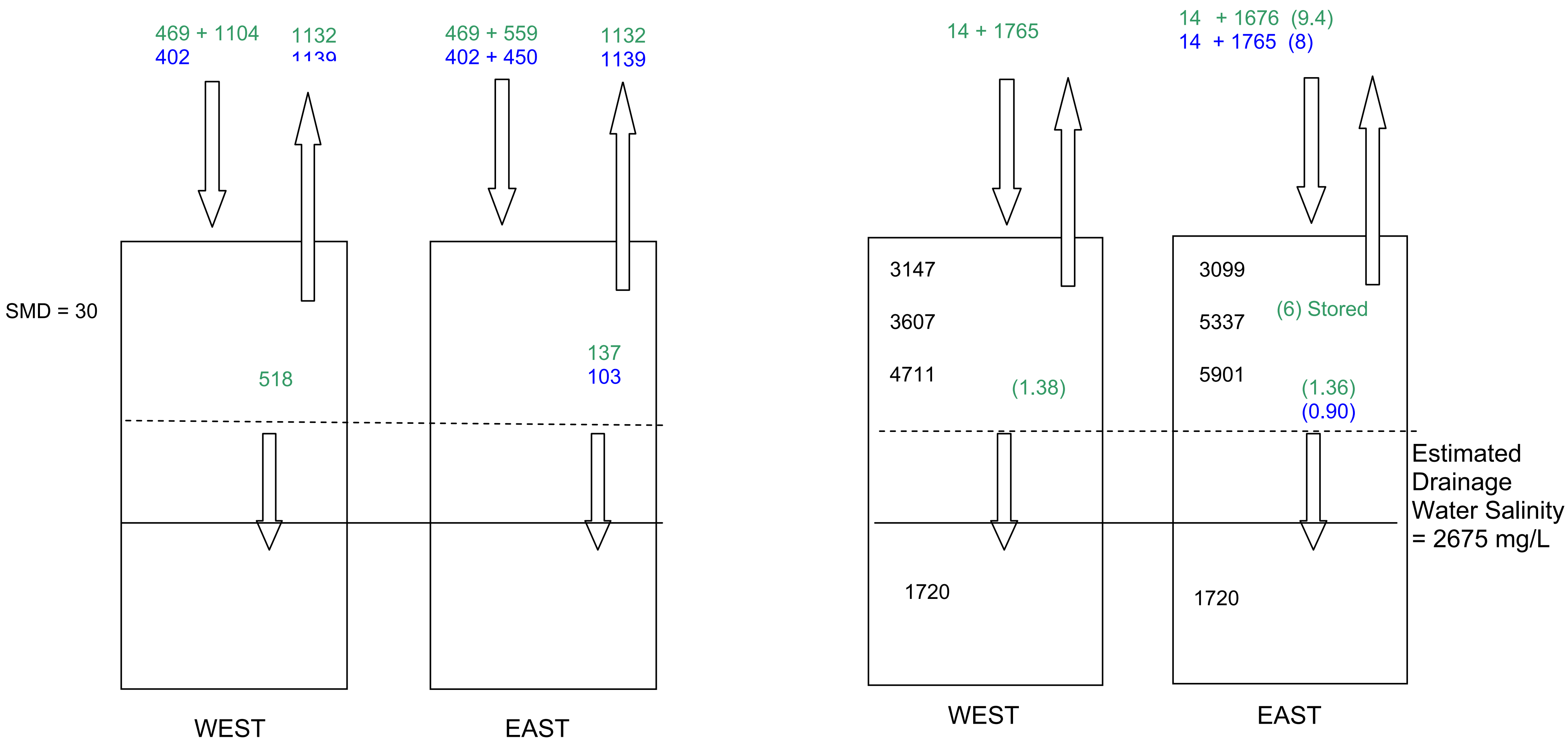


Figure 5.1 Conceptual model of NAP3.

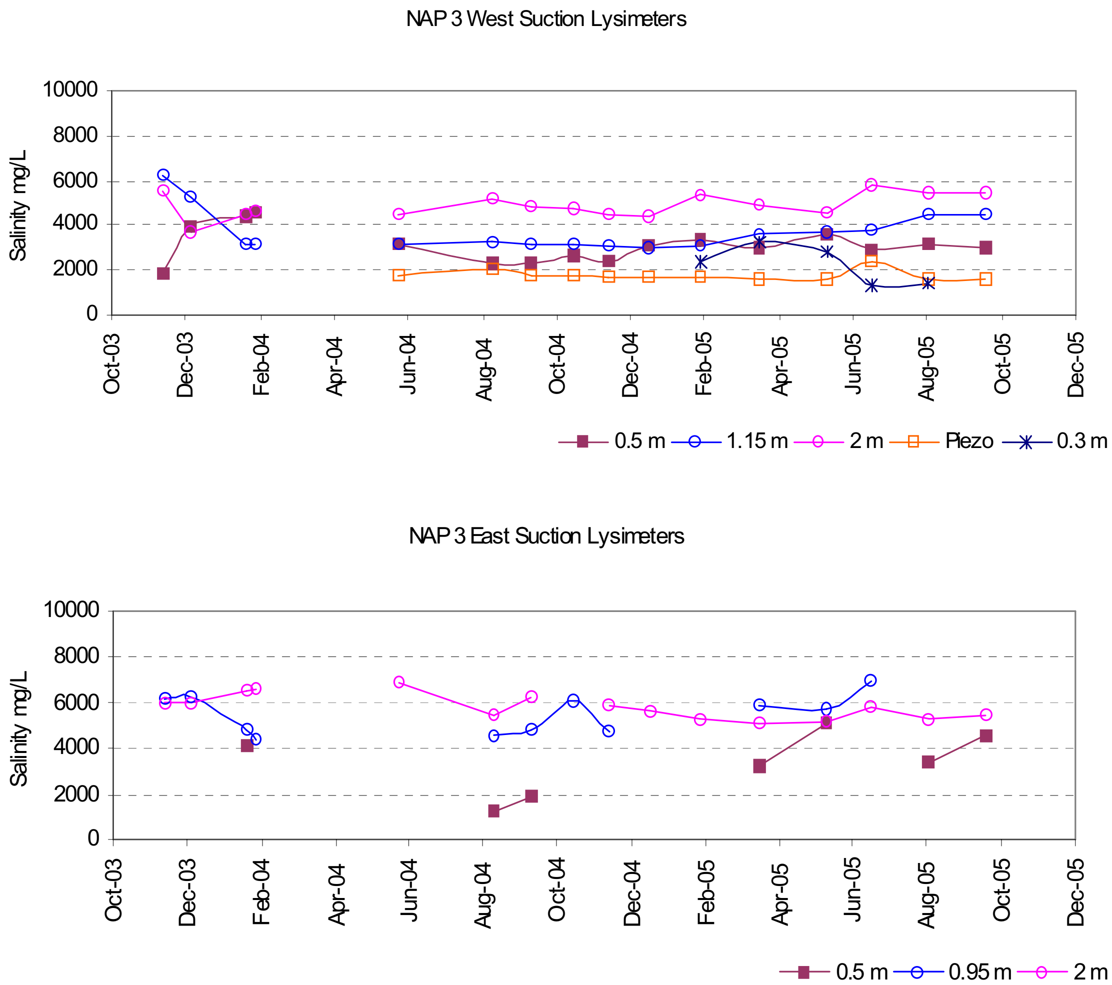
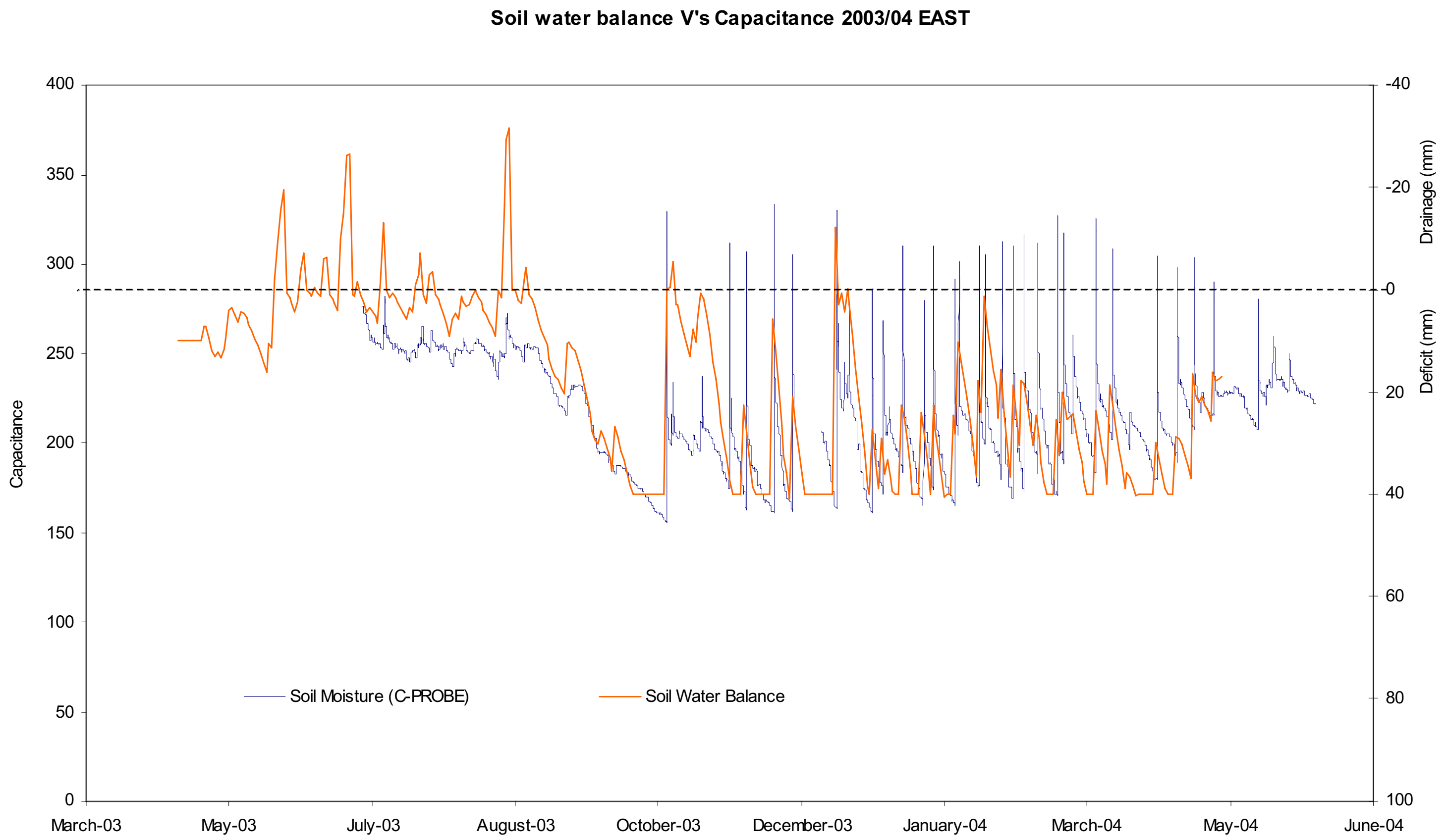


Figure 5.2 Suction lysimeter salinity (TDS) data from site NAP3 (both east and west sites).

A daily soil water balance was calculated via the method of Penman and Grindley (1948) described in Section 2 and is presented in Figures 5.3 and 5.4 for both the 2003–04 and 2004–05 seasons. Calculations began in May, a time when the soil profile was at a maximum soil moisture deficit (SMD) of 30 mm. The daily soil water balance was repeated for several crop coefficients (Kc) for lucerne seed and hay, ranging from 0.6–1.1 (Kc sourced from Desmier (1992)). Different Kc values did not influence the overall drainage term as Kc only influenced the soil moisture balance throughout the growing season, a time when a SMD existed and no drainage occurred.

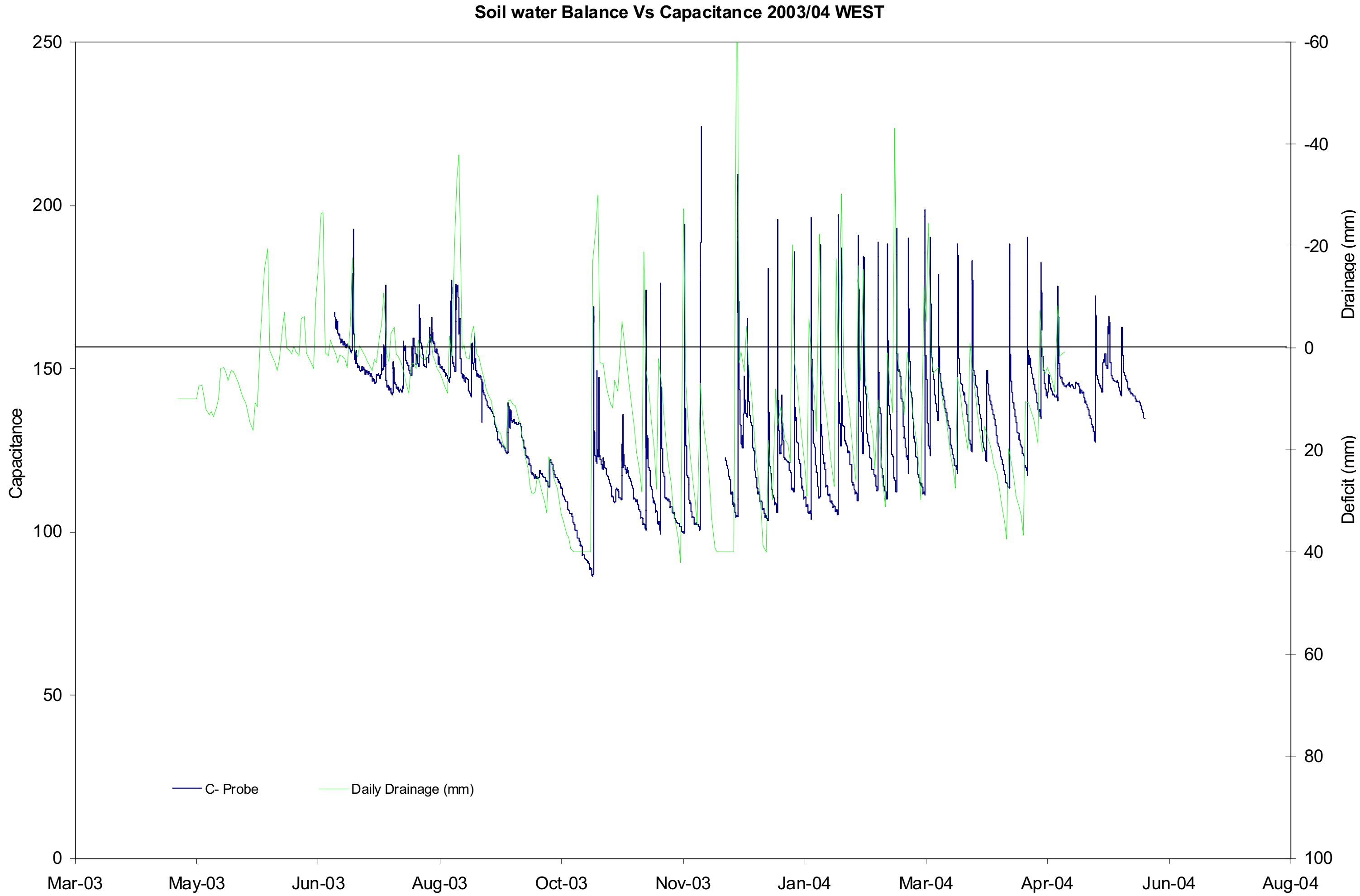
Capacitance probes proved useful in determining the period when the soil profile was at its maximum SMD, and enabled the initial theoretical SMD value to be adjusted correspondingly. Following this adjustment, Figures 5.3 and 5.4 show a strong correlation between the changes in soil moisture for both the c-probes and the daily water balance. The c-probes were able to support and verify periods of deep drainage.

At the eastern site, drainage did not occur as a result of irrigation, as potential crop water use exceeded irrigation and precipitation during the irrigation season. The eastern site experienced higher rainfall during the winter of 2003 than 2004, leading to greater drainage.



(a)

Figure 5.3 Estimated drainage and measured changes in soil moisture storage for site NAP3 2003–04, a) East, b) West.



(b)

Figure 5.3 continued.

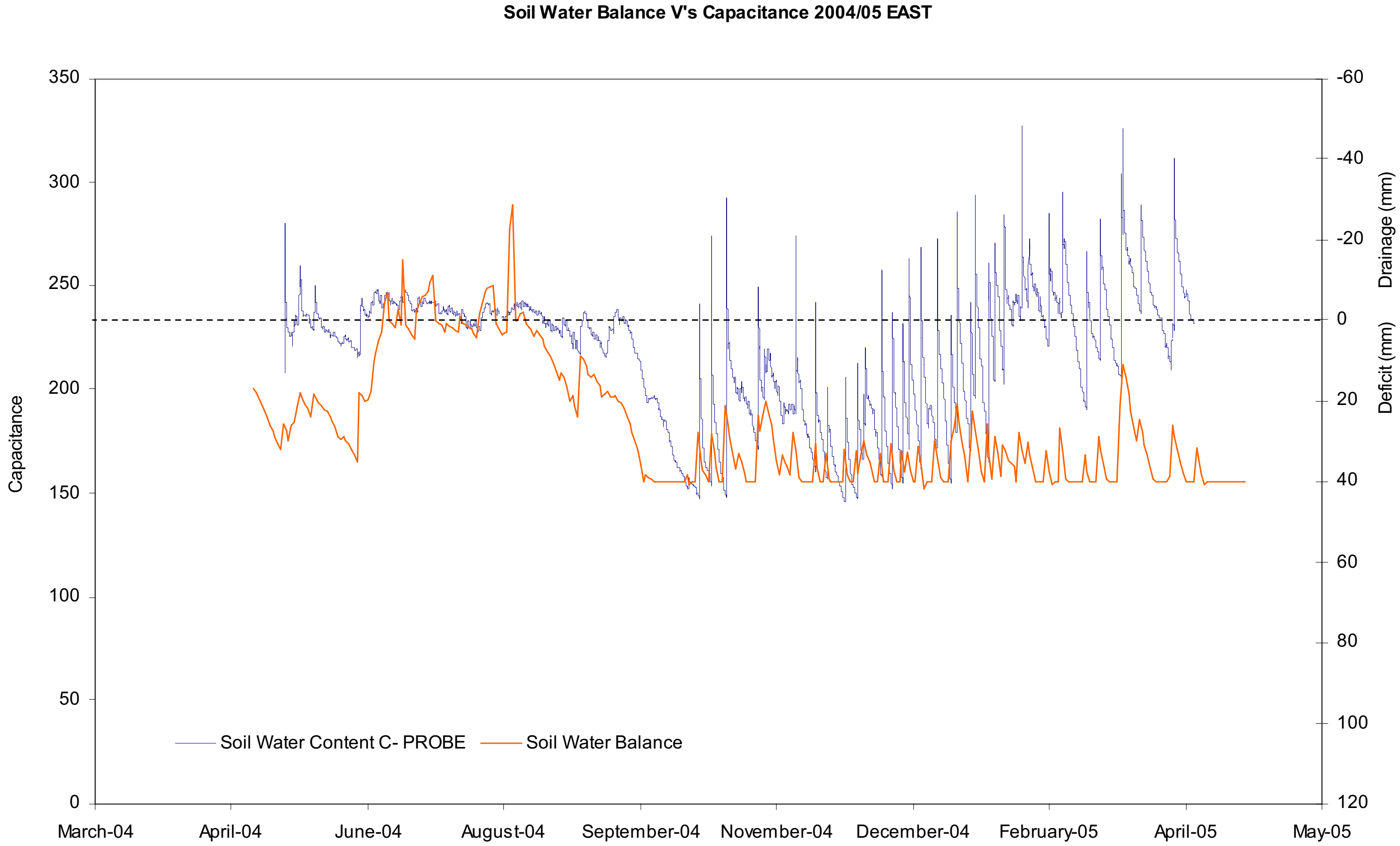


Figure 5.4 Estimated drainage and measured changes in soil moisture storage for site NAP3 2004–05.

137 mm of drainage occurred from May to August 2003, and 103 mm of drainage occurred from June to August 2004 (Fig. 5.1). At the western site, a higher recorded irrigation input has resulted in a drainage estimate of 518 mm, which occurred predominantly during irrigation. As described above, there is some uncertainty in this irrigation input value.

The chloride mass balance (CMB) method estimated drainage to be 139 mm during 2003 and 109 mm during 2004. Although the CMB method produced a similar drainage term to the Penman-Grindley method over both years, care must be taken when relying on this approach in environments such as this, which may not have reached steady state.

5.3 SALT BALANCE

As there is some uncertainty in the volume of irrigation and therefore drainage at the western site, calculations of salinity impact were based on measurements made at the eastern site. The amount of salt applied from precipitation and irrigation at the eastern site was 9.4 and 8 t/ha/y over 2003–04 and 2004–05 respectively. Short term soil water salinity data from the suction lysimeters suggests an accumulation of salt around the root zone. It is uncertain whether this represents a long term accumulation of salt or whether this would be periodically flushed out of the soil profile. The total input of salt to the aquifer (drainage multiplied by the salinity of drainage water of 2675 mg/L) was calculated to be 2.8–3.7 t/ha/y, which is less than the amount of salt added through irrigation. In this case, the net salinity impact on the aquifer is 0.9–1.4 t/ha/y. In the case that salt accumulation is not occurring, the equivalent salinity of drainage water is 6900–7800 mg/L. This gives a much larger net impact to the aquifer of 6.2–7.1 t/ha/y. Further data is required to verify the processes occurring under centre pivot irrigation. Until then, the upper and lower estimates of net salinity impact to the aquifer, based on the data available, are considered to be 0.9–1.4 t/ha/y. However, as it is unlikely that large amounts of salt are being accumulated in the profile over large time scales (i.e. this salt is probably being periodically flushed back into the groundwater system), the salinity impacts of this irrigation type are likely to be much larger than this.

The measured increase in soil water salinity at 0.5 m and 2 m multiplied by an estimate of water content at each depth was used to infer salt accumulation over one season at each depth. The total estimated salt accumulation in the profile was ~6 t/ha, which is in agreement with the above calculations.

5.3.1 INFORMATION FROM CHEMISTRY

The key chemistry graphs for the centre pivot site NAP3 are shown in Figure 5.5. Groundwater from both the irrigation bore and the piezometer plot approximately with the data from the Naracoorte Ranges, with signatures that support a model of groundwater salinity derived predominantly from flushing of saline soil water from the Ranges. The groundwaters have similar chemistry in all respects to Ranges groundwater sampled from piezometer PA2, which is currently receiving salt flushed from the unsaturated zone. A slight displacement of the NAP3 groundwater data to the right by small amounts of mixing with saline irrigation drainage water could be interpreted from some of the diagrams, but this interpretation is ambiguous and additional evidence is required. In general, the observed signatures are consistent with the model of salt being accumulated in the soil zone below the

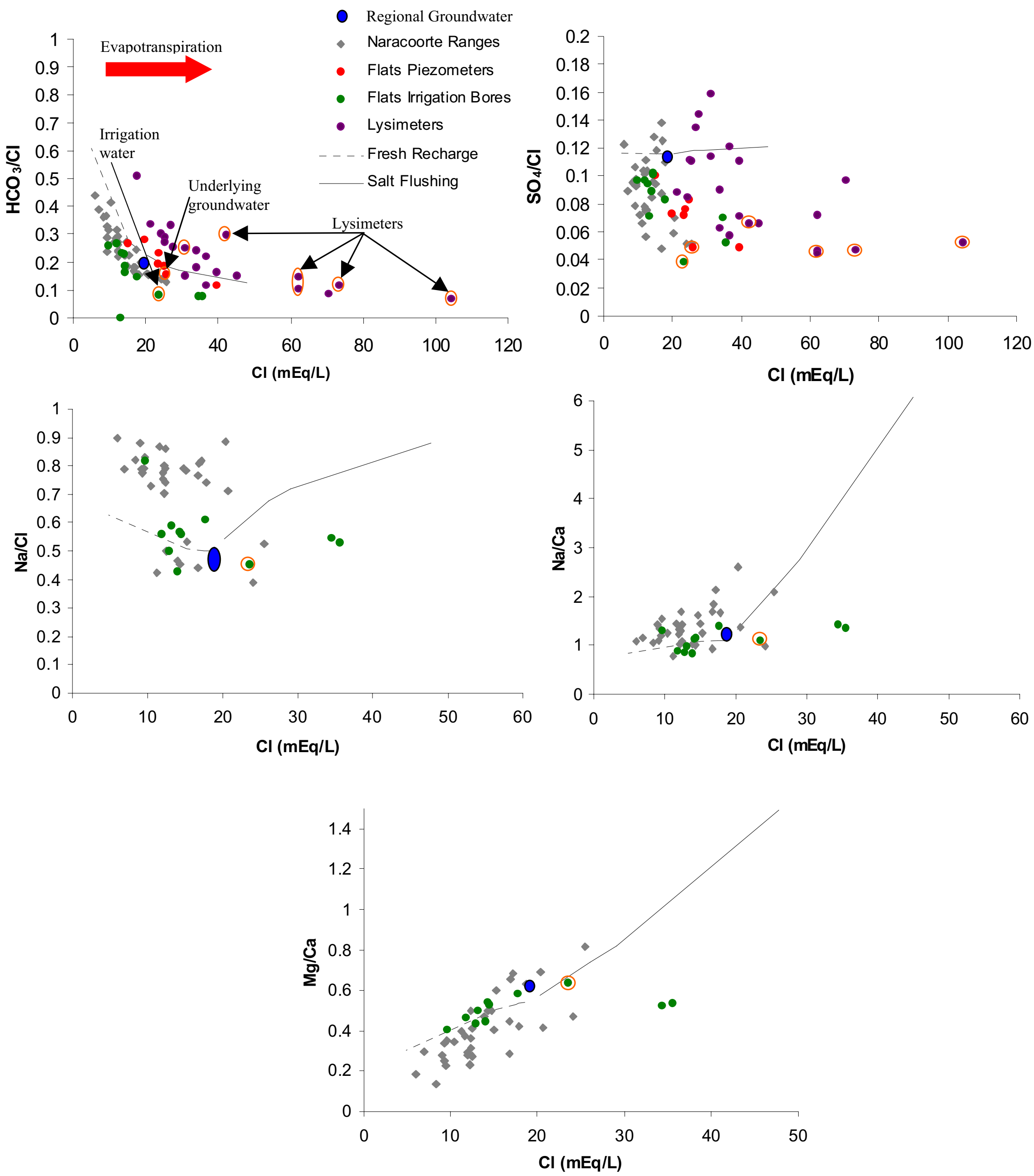


Figure 5.5 Groundwater and soil water (lysimeter) chemistry graphs for centre pivot irrigation site NAP3 (orange circled points).

Also shown are groundwater compositions predicted to result from salt flushing (solid line) and freshwater drainage (dashed line) in the Naracoorte Ranges, Naracoorte Ranges groundwater data (grey symbols) and other data from the Padthaway Flats.

pivot, rather than flushed into the groundwater system. Continued data collection would be required to determine whether flushing occurs periodically as a result of large rainfall events. The salinity difference between the soil water samples collected from the suction lysimeters and the groundwater samples is very large, also supporting the conclusion that little of this salt reaches the water table (Fig. 5.5).

5.3.2 CONCLUSIONS ON SALT ACCESSION BELOW THE CENTRE PIVOT SITE

The following conclusions on salt accession below the centre pivot site NAP3 have been derived from this study:

- Salt accumulation in the root zone has occurred over the study period. The total salt accumulation in the top 2 m of the soil profile was 6 t/ha/y.
- If this storage of salt from irrigation continues, the net impact of centre pivot irrigation on the salinity of the aquifer is estimated to be ~0.9–1.4 t/ha/y.
- If this accumulation is followed by periods of flushing of salt back into the aquifer, the salinity impact on the aquifer would be much higher, up to 6.2–7.1 t/ha/y.
- Under both models, the equivalent salinity of the drainage water is higher than that of the underlying groundwater. This means that some direct salinity impact on the underlying groundwater from the irrigation drainage water is likely to be occurring.
- The chemical signature of the groundwater below the centre pivot suggests that the majority of the salt in this groundwater is currently derived from salt accession in the Naracoorte Ranges. However, the screen length of the piezometer sampled to determine this is 6 m, and small changes in groundwater chemistry near the water table as a result of mixing with irrigation drainage water would not be identified by this method. Installation of short-screened water table piezometers would be necessary to directly identify the salinity impact of irrigation drainage below a centre pivot irrigation site.
- It is most unlikely that the currently observed salt build-up can continue indefinitely, and flushing of this salt into the groundwater system via some mechanism should occur at some time, eventually resulting in a large salinity impact to the aquifer.
- The results of this study indicate that longer term monitoring of soil and groundwater salinity below the centre pivot is required for an accurate quantification of the salinity impacts under this type of irrigation.

6. SALT AND WATER BALANCES UNDER THE FLOOD SITES

6.1 SITE NAP 4

Figure 6.1 shows the physical and conceptual model of the water and salt balance at the flood irrigation site NAP 4. This site is located over a loamy sand topsoil up to 0.6 m thick (Map 2), underlain by a sandy limestone. The groundwater salinity in the area is 1720 mg/L and the water table depth is ~4.6 m. The flood bay on which the site is located is irrigated from well MAR208, which has an average salinity of ~1524 mg/L.

6.1.1 SUCTION LYSIMETERS AND GROUNDWATER SALINITY DATA

Figure 6.2 shows that the salinity of soil water across both the eastern and western sites is reasonably constant at depth. The average soil water salinity at the eastern site is 1730–1790 mg/L (200 mg/L higher than irrigation water). The average concentration of soil water at the western site is 2130–2500 mg/L (up to 600 mg/L higher than irrigation water). As the irrigation water flows across the bay towards the west it become concentrated via evapotranspiration, which is reflected in the higher soil water salinity.

The soil water salinity at 1 m, 2 m and 3 m depths remained reasonably constant over the sampling period. Slight shifts in chloride concentrations in the 1 m lysimeter can be explained by seasonal influences, however the variation over one year is negligible. This indicates that there is no accumulation or release of salt over time scales longer than 1 year. The groundwater below the site has a similar salinity to the soil water at the eastern site and follows the same trend over time.

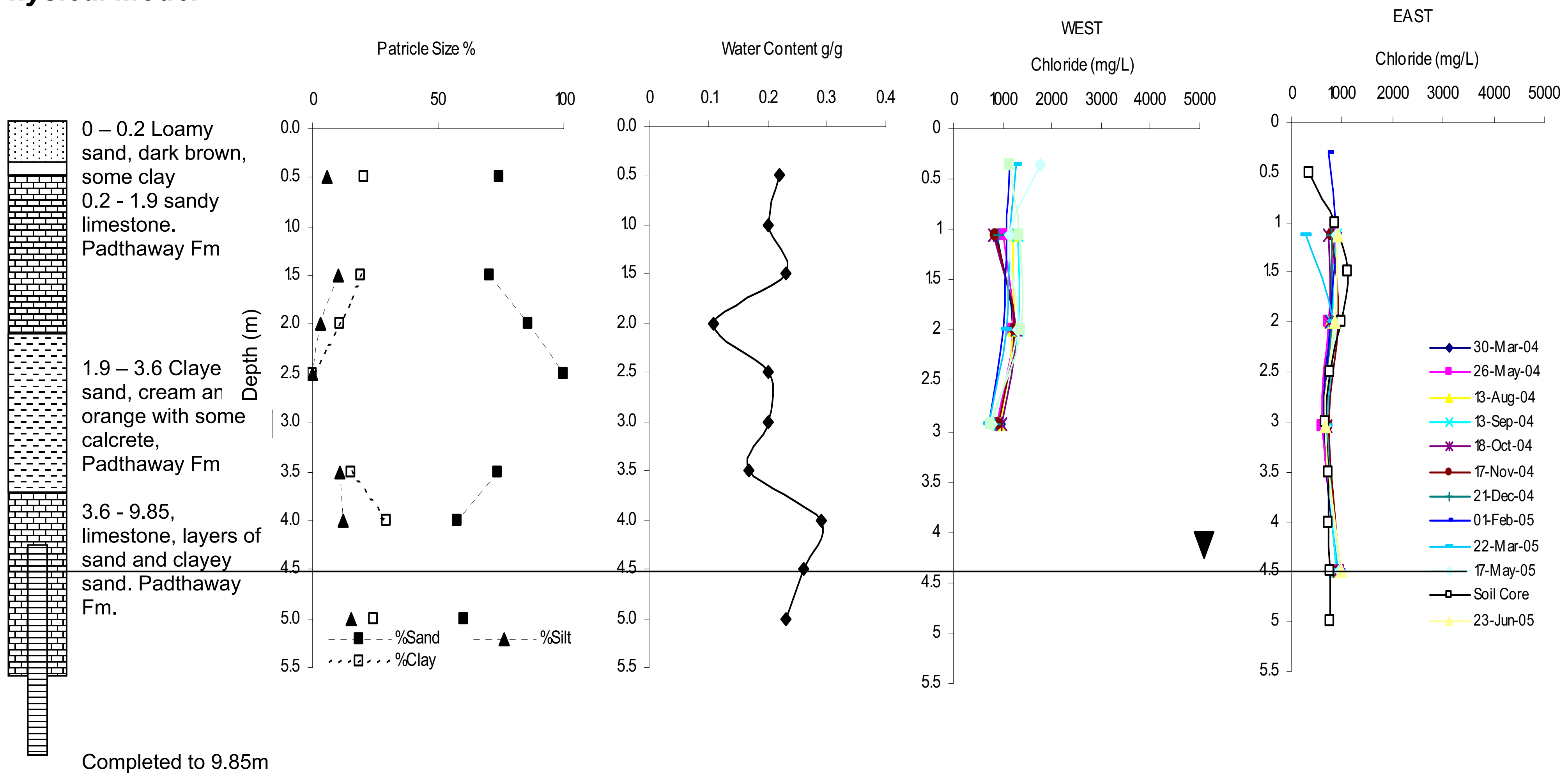
6.1.2 WATER BALANCE

The volume of irrigation water applied during the season of 2004–05 was measured via the shaft encoder, to be 131 ML. This volume was applied over two irrigation bays which are irrigated together. The average area of each bay is 3.25 ha. This equates to 20.31 ML/ha. This volume was confirmed by; a) The calculations supplied by the irrigator from his Annual Water Use Returns (AWURs) (20.25 ML) and b) The total volume of water pumped from irrigation bore MAR208 (364 ML) divided by the area (18 ha) of pasture irrigated (20.22 ML/ha). The shaft encoder did not capture the entire 2003–04 season, so therefore AWURs for the 2003–04 season were used.

Lower rainfall during 2004–05 was compensated for by higher irrigation and resulted in equal drainage occurring over both seasons, as estimated using the Penman-Grindley method described in Section 2. Large volumes of irrigation over light textured soil have resulted in large amounts of drainage. C-probes indicate rapid drainage to the water table after each irrigation event.

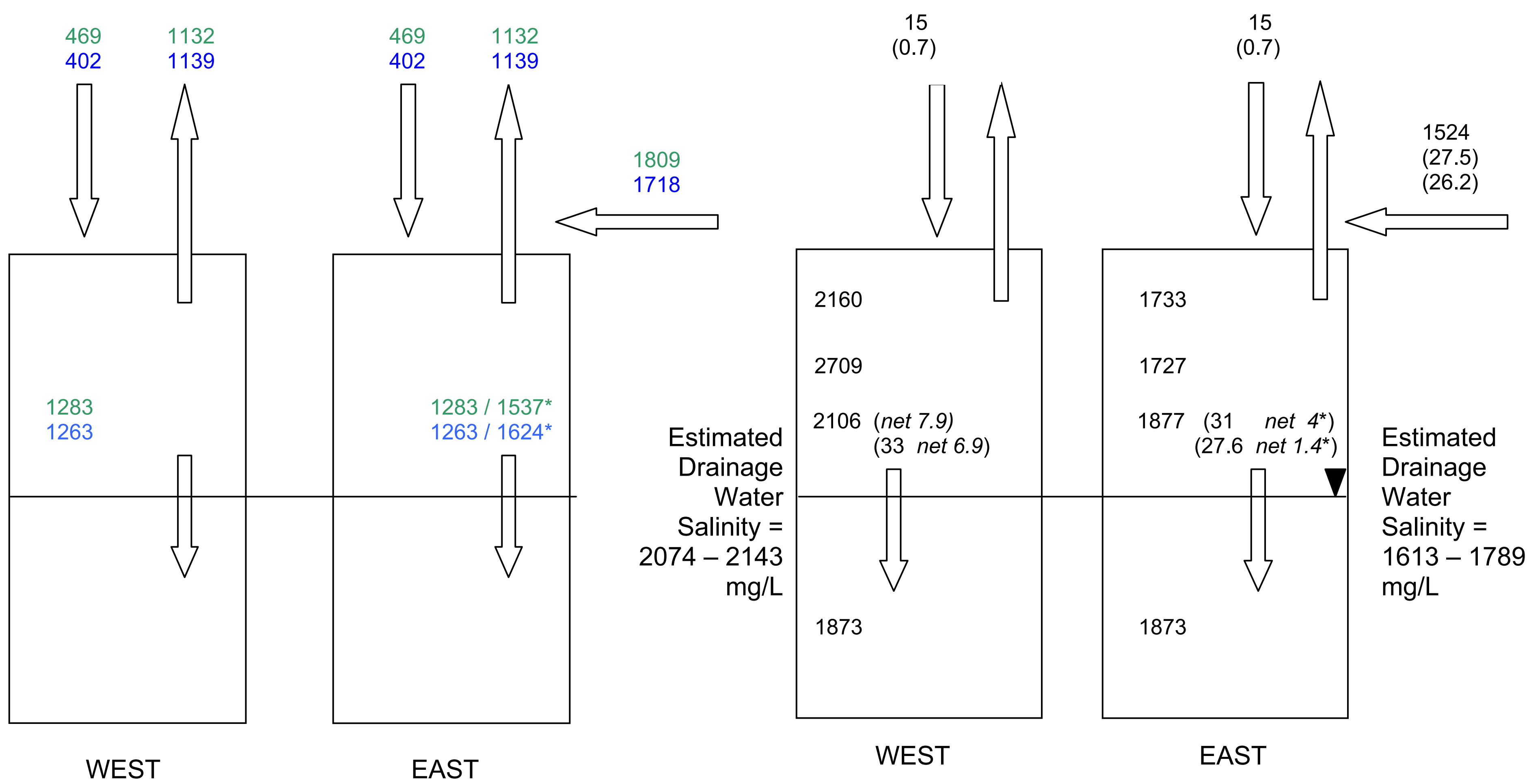
NAP 4

Physical Model



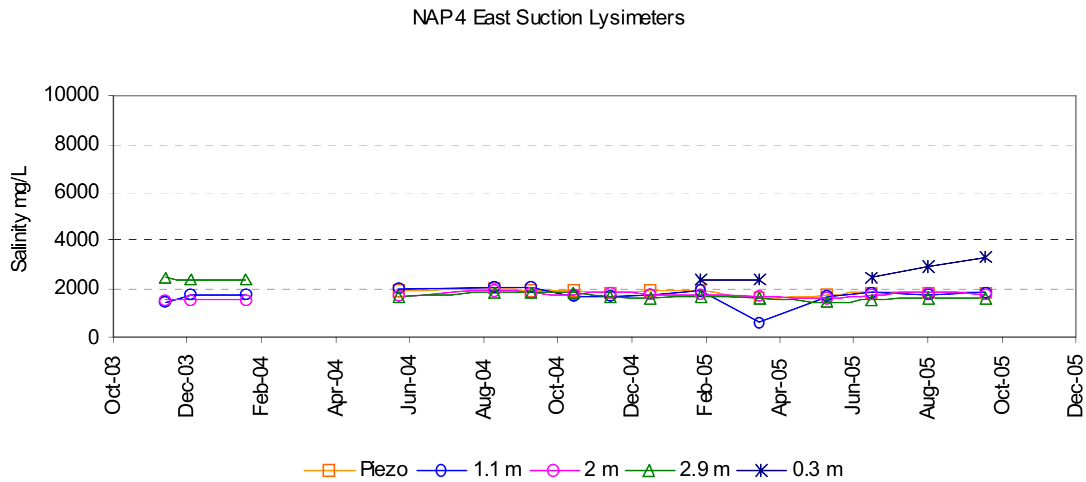
Conceptual Model

Water Balance: mm/yr (May 03 to Apr 04 and May 04 to Apr 05) *Salt Balance: Total Dissolved Salts mg/l and annual salt flux (t/ha)*



*Drainage and salt flux via chloride mass balance

Figure 6.1 Conceptual model of NAP4.



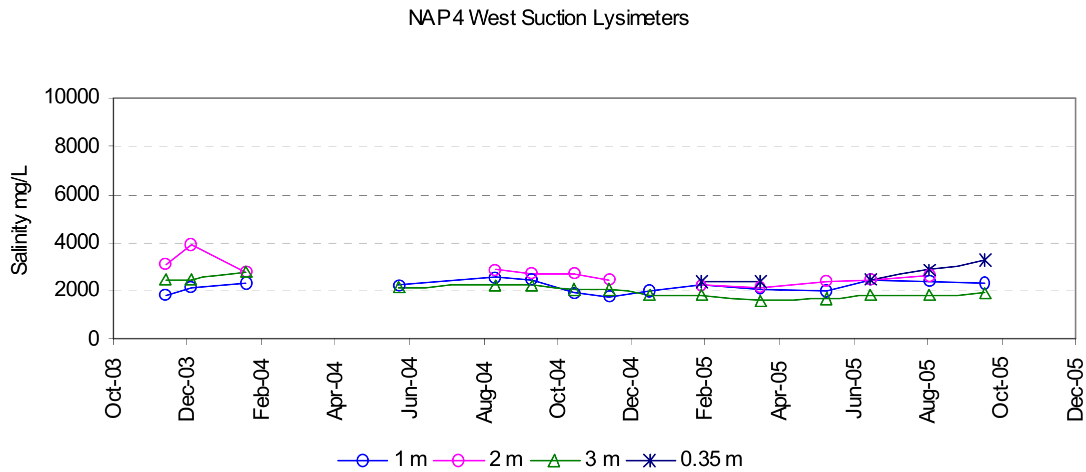


Figure 6.2 Suction lysimeter salinity (TDS) data from flood site NAP4 (east and west).

There is a strong correlation between the changes in soil water storage shown by the c-probes and drainage estimated by the Penman-Grindley soil water balance. Figure 6.3 shows that the c-probes were able to support and verify periods of deep drainage during winter and during irrigation. Over the 2004–05 season, 84 mm of drainage is estimated to have occurred as a result of winter rainfall (based on an initial SMD of 30 mm) followed by 1194 mm of drainage as a result of irrigation.

Drainage estimates using the chloride mass balance method were made for the eastern site (site closet to the sluice gate) only and ranged between 1527–1624 mm for 2003–05 and 2004–05 respectively. As the system is believed to be in steady state (no long term change in salt storage in the profile), higher confidence can be given to this method in the estimates of drainage than was allowed for the centre pivot site NAP3. It must be noted that this is a point scale measurement and represents the amount of drainage at the eastern site, near the sluice gate only. This is likely to be the maximum value for drainage across the bay due to the higher head of water applied near the sluice gate. The chloride mass balance method could not be applied to the western site, as there was a large degree of uncertainty in the volume of irrigation water that reaches this part of the bay. With this in mind, the drainage

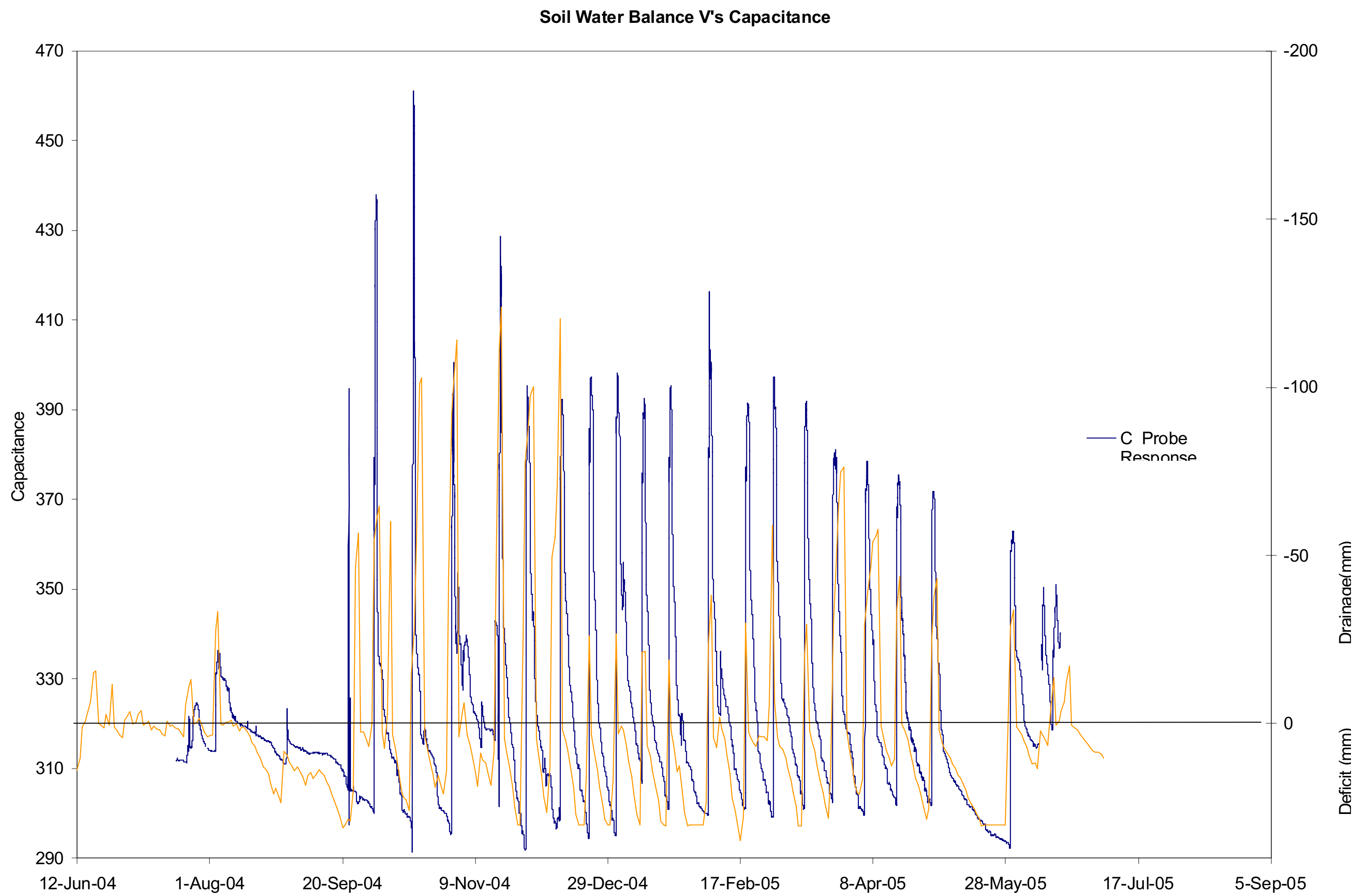


Figure 6.3 Estimated drainage and measured changes in soil moisture storage for site NAP3 2004–05.

estimate made using the chloride mass balance method is in good agreement with the results of the Penman-Grindley water balance.

6.1.3 SALT BALANCE

27.5 and 26.2 tonnes per hectare of salt were applied to the irrigation bay at site NAP4 over the 2003–04 and 2004–05 irrigation seasons respectively. Based on a lack of accumulation or leaching of salt observed in the suction lysimeters, it is reasonable to assume that input equals output, resulting in an equivalent drainage water salinity of:

- 2143 mg/L in 2003–04 and 2074 mg/L in 2004–05 at the western site, compared to an average measurement of 2106 mg/L from the lysimeter at 3 m
- 1789 mg/L in 2003–04 and 1613 mg/L in 2004–05 at the eastern site, compared to an average measurement of 1877 mg/L from the lysimeter at 3 m

Therefore the equivalent salinity of drainage water is 89 mg/L to 619 mg/L greater than that of the irrigation water, resulting in a net salinity impact of:

- 7.9 t/ha of salt in 2003–04 and 6.9 t/ha in 2004–05 at the western site.
- 4 t/ha of salt in 2003–04 and 1.4 t/ha in 2004–05 at the eastern site.

The lower salt flux measured at the eastern site is probably due to the lower amount of evapotranspiration affecting the irrigation water before drainage at the top of the bay near the sluice gate. Water that has flowed over the bay to the western site would have a naturally higher salinity due to greater evapotranspiration. At both sites, the net salt flux to the aquifer is lower over the second year, possibly due to less salt being applied through irrigation in that year. This trend is also illustrated by the soil water salinity, which decreased over the same period.

The average salinity impact to the aquifer as a result of evapotranspiration of irrigation water is estimated to be 6 t/ha during 2003–04 and 4.15 t/ha/y during 2004–05.

6.1.4 INFORMATION FROM CHEMISTRY

The key chemistry graphs for flood site NAP4 are shown in Figure 6.4. Both groundwater types have lower TDS (Cl^-) than the groundwaters from the other flood site, NAP5. The composition of the irrigation water plots very close to the trend for the Naracoorte Ranges groundwaters, especially the signature considered to represent that of native groundwater flowing from the Naracoorte Ranges pre-clearing. Groundwater sampled from the piezometer at NAP4 has a slightly higher TDS (Cl^-) than the irrigation bore. The signature of this groundwater is identical to soil water from the 1 m E suction lysimeter, and similar to that from the other suction lysimeters suggesting a significant influence of mixing with evapo-concentrated soil water (irrigation drainage water) on this groundwater.

6.1.5 CONCLUSIONS ON SALT ACCESSION PROCESSES OCCURRING BELOW THE FLOOD IRRIGATION SITE, NAP4

The following conclusions on salt accession processes occurring below flood irrigation site NAP4 can be derived from the results of this study:

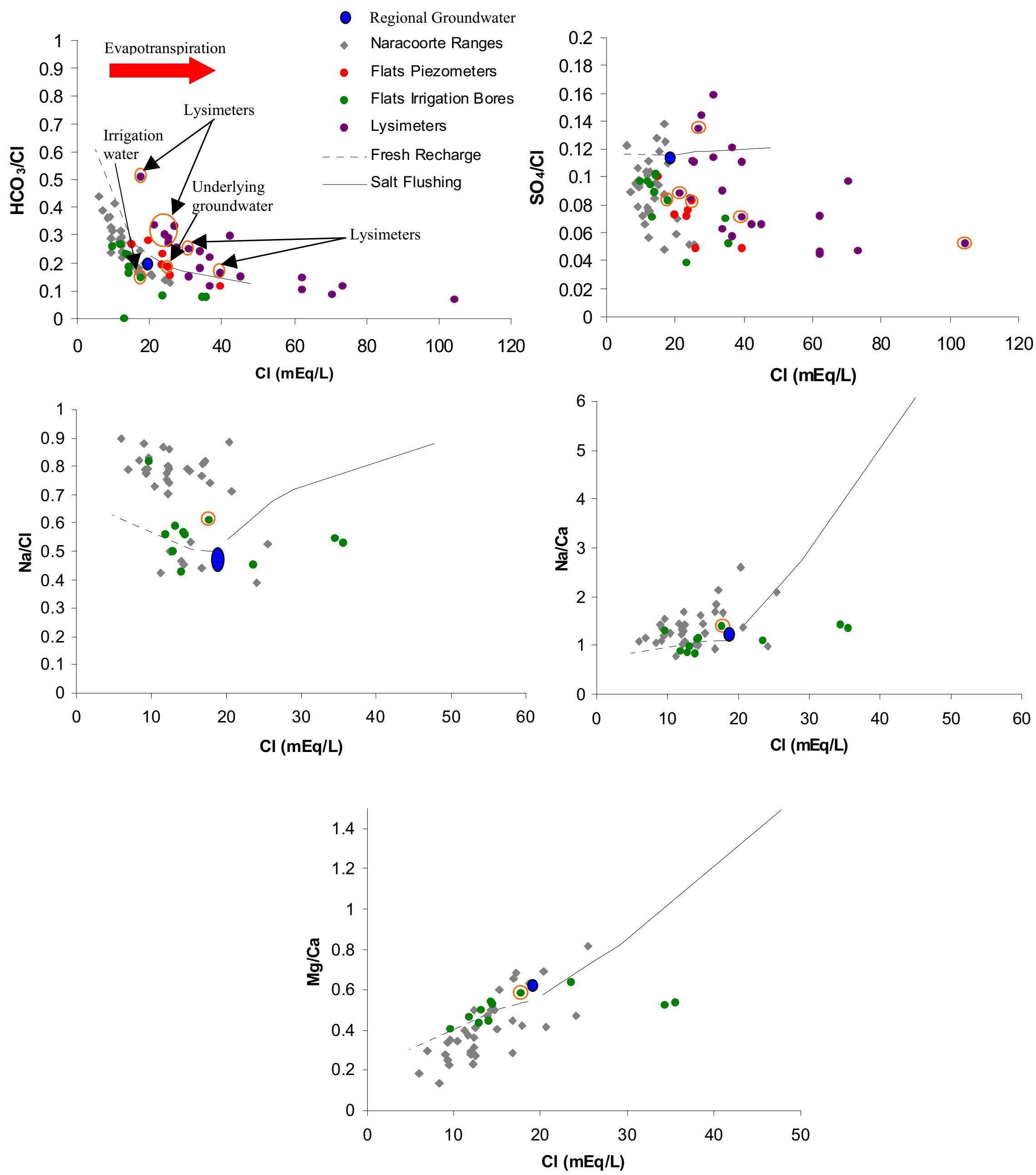


Figure 6.4 Groundwater and soil water (lysimeter) chemistry graphs for flood irrigation site NAP4 (orange circled points).

Also shown are groundwater compositions predicted to result from salt flushing (solid line) and freshwater drainage (dashed line) in the Naracoorte Ranges, Naracoorte Ranges groundwater data (grey symbols) and other data from the Padthaway Flats.

- The estimated effective salinity of drainage water at the eastern site, near the sluice gate, is similar to the salinity of the underlying groundwater, whereas the drainage water further down the bay has a higher salinity than the underlying groundwater.
- The average net salinity impact on the aquifer ranged between 4.15–6 t/ha/y over the two irrigation seasons studied.
- The groundwater chemistry data suggests that most of the groundwater salinity at the irrigation bore for site NAP4 can be explained entirely by salt accession processes occurring in the Naracoorte Ranges.
- However, the groundwater chemistry data indicates a significant impact from mixing with saline irrigation drainage water on the groundwater directly below the flood bay.
- As the groundwater salinity below the flood bay is similar to soil water salinity below the eastern site, it is believed that most drainage occurs at this end of the bay, near the sluice gate. Some impact from the more saline drainage water at the other end of the bay is also likely, however.

6.2 SITE NAP 5

Figure 6.5 shows the physical and conceptual models of the water and salt balances at the flood irrigation site NAP 5. This site is located on a brown clayey sand (0.1–0.3 m thick) (Map 2) underlain by a hard limestone that is interlayered with clayey sand. The groundwater salinity in the area is 2484 mg/L and the water table depth is ~4.3 m. The bay is irrigated from well MAR207, which has an average salinity of ~2415 mg/L.

6.2.1 SUCTION LYSIMETER AND GROUNDWATER SALINITY DATA

In contrast to site NAP4, soil water salinity remains uniform with depth (2390–2590 mg/L) across both the southern and northern sites, and is of a similar concentration to the irrigation water (2415 mg/L) and groundwater (2484 mg/L). The greatest changes in soil water salinity are observed at 1m and may be attributed to evapotranspiration and seasonal influences (Fig. 6.6). Suction lysimeters at all depths indicate negligible changes in soil water chloride concentrations (and salinity) over time scales longer than a year.

6.2.2 WATER BALANCE

Irrigation volumes for this site were determined from annual water use returns and via the amount of groundwater extracted divided by the area of pasture irrigated. Irrigation application was determined to be in the order of 20–24 ML/ha. A shaft encoder has accurately measured the head of water during the 2004–05 irrigation season, however a new set of discharge tests may need to be carried out to covert this to a volume.

Annual drainage was calculated via the water balance approach and estimated to be within the range of 1450–1750 mm during 2003–04 and 1350–1591 mm during 2004–05. Drainage estimates via the chloride mass balance were carried out using chloride data that was collected from the southern site (site closet to the sluice gate) only. Using this method, drainage was estimated to be in the order of 1750–1953 mm, which is considered to represent the maximum for the bay. The chloride profile suggests that the system is in steady state, and higher confidence can be given to this method in the estimates of drainage. This point-scale measurement represents the amount of drainage that occurred at the southern site. For the same reasons explained for site NAP4 above, this method could not be applied to the northern site.

6.2.3 SALT BALANCE

An estimated 50–58 t/ha of salt was applied to site NAP5 over the 2003–04 and 2004–05 irrigation seasons. Again, the suction lysimeter data have indicated a lack of salt accumulation or leaching from the soil profile, and it is reasonable to assume that the input of salt to the unsaturated zone equals output. An equivalent drainage water salinity of 2525 mg/L is estimated based on this assumption, which compares well with actual measurements of 2569 mg/L obtained from the 3 m lysimeter. Therefore, the equivalent salinity of drainage water is 110 mg/L greater than the irrigation water, which equates to a net salinity impact to the aquifer of 1.6–2.2 t/ha/y.

6.2.4 INFORMATION FROM CHEMISTRY

The key chemistry graphs for site NAP5 are shown in Figure 6.7. The chemical signatures of both groundwater types at NAP5 are consistent with mixing with evapo-concentrated irrigation drainage water, as the compositions of both groundwaters plot significantly to the right of the trend defined by the Naracoorte Ranges groundwaters. The salinity (Cl^-) of the piezometer is only slightly higher than that of the irrigation bore. This suggests that groundwater at NAP5 has been more affected by saline irrigation drainage occurring up-gradient of it than by mixing with irrigation water drainage from the immediate paddock. All suction lysimeter samples, except those from the 1 m N and 1 m S lysimeters have lower TDS (Cl) than the groundwater samples, further supporting this.

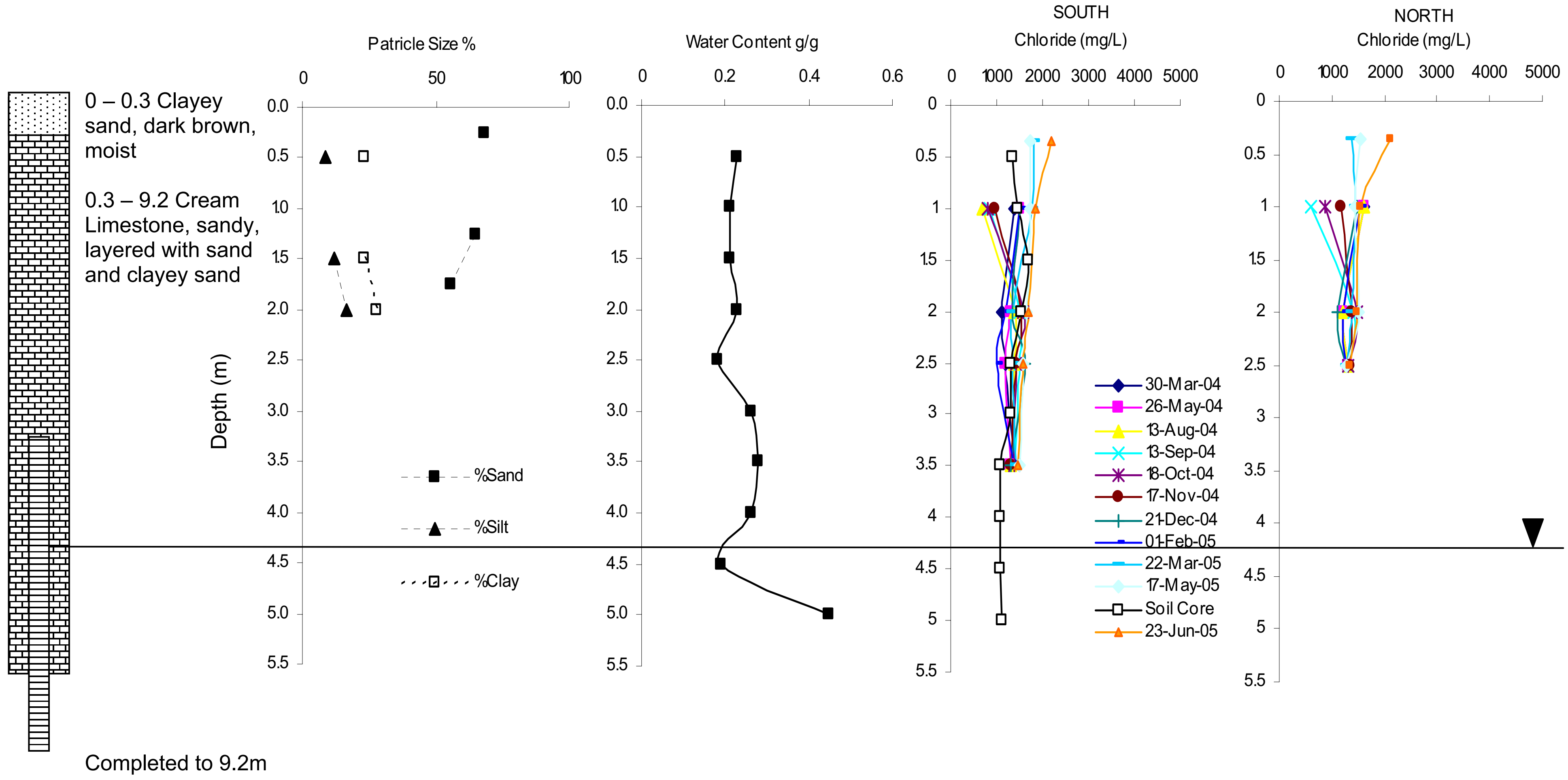
6.2.5 CONCLUSIONS ON SALT ACCESSION PROCESSES OCCURRING BELOW THE FLOOD IRRIGATION SITE, NAP5

The following conclusions on salt accession processes occurring below flood irrigation site NAP5 can be derived from the results of this study:

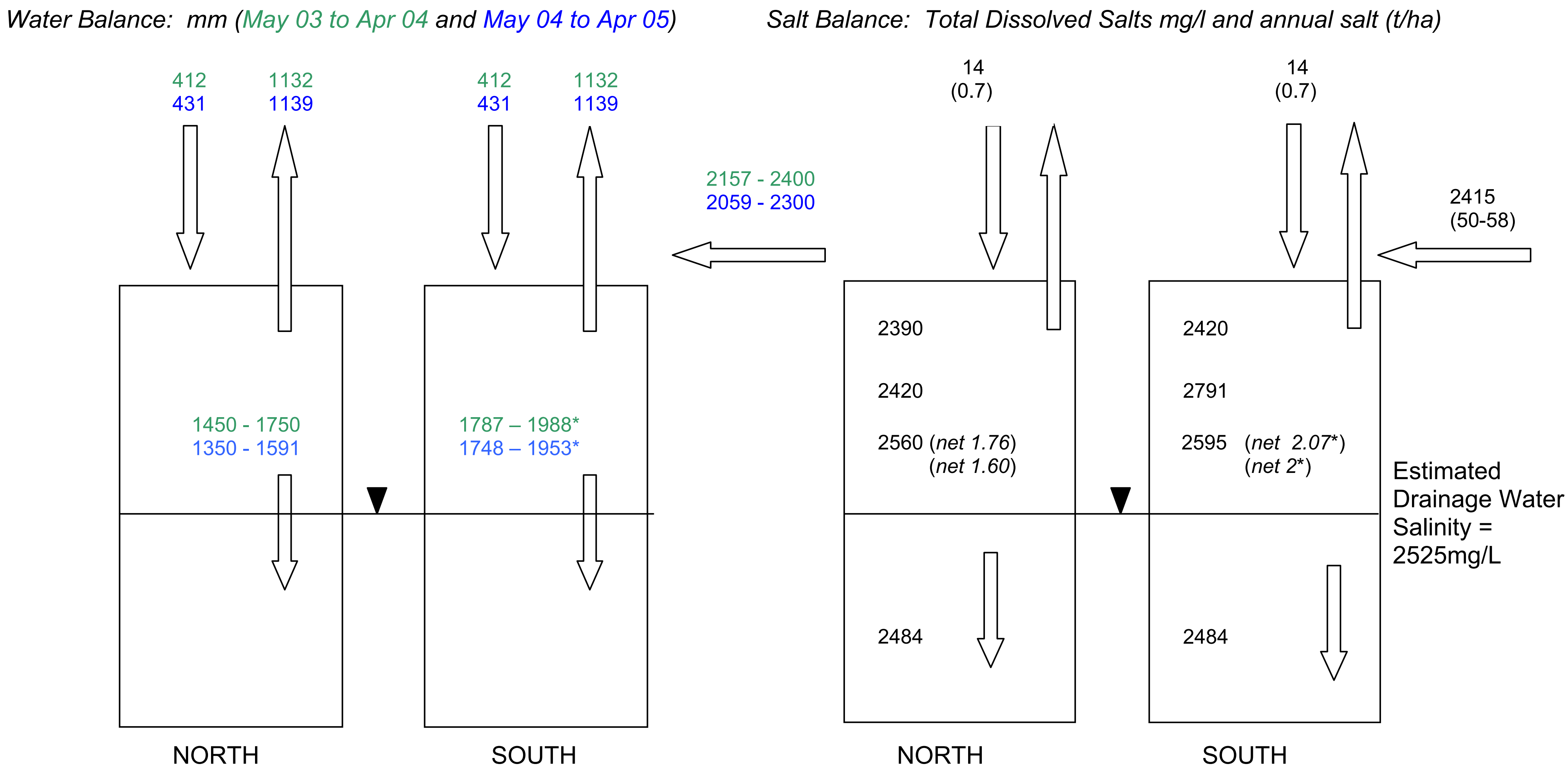
- The estimated effective salinity of drainage water is similar to that of the underlying groundwater, and the irrigation water, indicating a small salinity impact from this flood irrigation site compared with site NAP5.
- The average net salinity impact on the aquifer ranged between 1.6–2.2 t/ha/y over the two irrigation seasons studied.
- The salinity impact is so high, compared with that from the vineyard sites, due to the volumes of water that are used here, although the actual change in salinity due to evapotranspiration is quite low compared with the other irrigation types.
- The smaller salinity impact at site NAP5, compared with site NAP4, is currently believed to be related to a difference in the length of the irrigation channel between the two sites. Further work is being carried out to investigate this.

NAP 5

Physical Model



Conceptual Model



*Calculated via chloride mass balance

Figure 6.5 Conceptual model of NAP5.

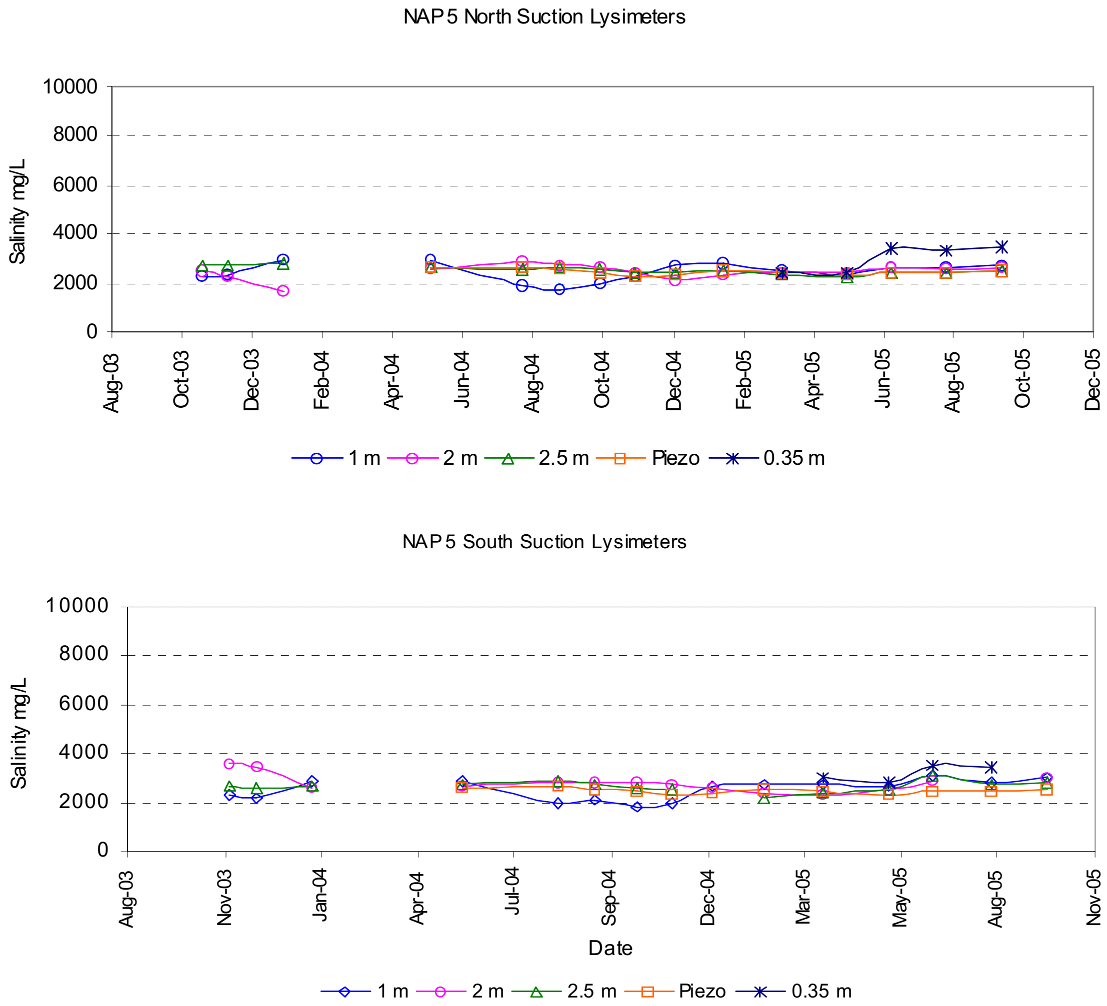


Figure 6.6 Suction lysimeter salinity (TDS) data from flood site NAP5.

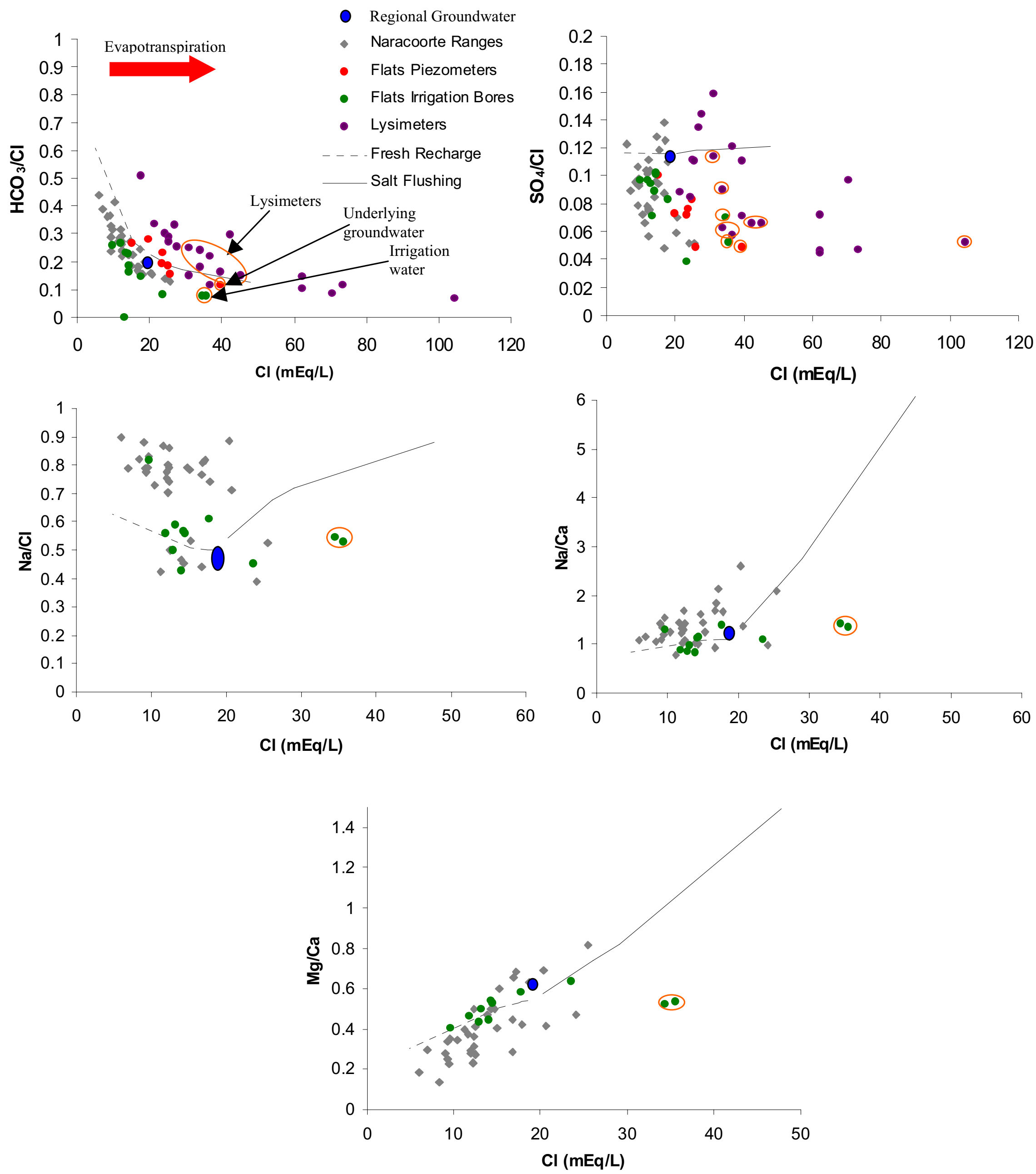


Figure 6.7 Groundwater and soil water (lysimeter) chemistry graphs for flood irrigation site NAP5 (orange circled points).

Also shown are groundwater compositions predicted to result from salt flushing (solid line) and freshwater drainage (dashed line) in the Naracoorte Ranges, Naracoorte Ranges groundwater data (grey symbols) and other data from the Padthaway Flats.

- The groundwater chemistry data suggests that, as well as effects from salt accession in the Naracoorte Ranges, the groundwater salinity at both the irrigation bore and below the flood bay at site NAP5 have been significantly affected by mixing with saline irrigation drainage water.
- Most of this mixing has occurred up-gradient of site NAP5 rather than at the site itself, suggesting that there are large salinity impacts from irrigation occurring in this northern part of the Padthaway PWA.

6.3 CONCLUSIONS ON SALT ACCESSION UNDER FLOOD IRRIGATION

The following conclusions can be made about salt accession processes under the flood irrigation sites at Padthaway:

- Evapotranspiration has not significantly concentrated the irrigation water as it moves across the bay at site NAP5, resulting in a minimal salinity impact to the aquifer at this site.
- In contrast to this, both the salinity of the soil water and the estimated salinity impact on the aquifer at NAP 4 is higher than at NAP5. The salinity of the drainage water is up to 300 mg/L greater at the eastern site and >600 mg/L greater at the western site than the irrigation water applied. This indicates that evaporation significantly concentrates the irrigation water as it moves from east to west across the bay, resulting in a higher salinity impact to the aquifer.
- Variations in the width of irrigation bays, pumping rates and thickness and type of topsoil will affect the rate of irrigation water movement across the bay and therefore the amount of surface water evaporation that occurs during irrigation. Site NAP 5 has narrower flood bays and shallower topsoil compared to NAP 4, which may contribute to quicker irrigation application and therefore a lesser salinity impact on the aquifer.
- A significant impact on groundwater salinity from evapoconcentrated irrigation drainage water is observed in the northern part of the Padthaway PWA.

7. SPATIAL EXTRAPOLATION OF ONE-DIMENSIONAL MODELS ACROSS THE PADTHAWAY FLATS IRRIGATION AREA

7.1 OVERVIEW OF RESULTS

Table 7.1 presents an overview of the key water and salt balance parameters, and drainage and salinity impact estimates for each of the irrigation field sites on the Padthaway Flat. Results of qualitative interpretation of the groundwater chemistry graphs in terms of salinity impacts from irrigation drainage water (evapotranspiration) are also given as an indicator only.

Table 7.1 shows that, for the vineyard sites, a lower drainage volume as a percentage of the total input generally results in a higher salinity impact to the aquifer. This is also the case for the centre pivot site, NAP3, which had a lower drainage as a percentage of input than the vineyard sites, and a correspondingly higher estimated salinity impact to the aquifer. The converse is true for the flood sites, where a higher salinity impact occurs at the site with the highest % drainage.

Qualitative interpretation of the groundwater chemistry data has suggested that the evapotranspiration of irrigation water has contributed less than 25% of the groundwater salinity under the main viticultural area and less than 35% under the predominantly flood irrigation district in the north of the PWA (Table 7.1).

7.2 SPATIAL EXTRAPOLATION OF SALINITY IMPACTS FROM DRIP IRRIGATED VINEYARDS

The four vineyard instrumentation sites cover four dominant soil types and represent 80% of the viticulture across the Padthaway Flat. A full description of soils in the Padthaway irrigation area can be found in Wetherby and Armstrong (1978). As the salt concentration of irrigation water for viticulture ranges from 900–1100 mg/L, the salt flux applied through irrigation was considered to be fairly consistent across the area. Therefore, zones of salinity impact were created on the basis of soil type and rainfall. Rain gauges at each of the irrigation sites indicate a small rainfall gradient (~5 mm/km) from north to south. Once the CSIRO flux tower has completed measurements across different grape varieties, soil type and vineyard architecture, the zones can be refined to account for variability in these parameters.

7.3 SPATIAL EXTRAPOLATION OF SALINITY IMPACTS FROM FLOOD AND CENTRE PIVOT IRRIGATION

Drainage under flood irrigation is highly dependent on the volume of irrigation water applied. Therefore, there is a large amount of uncertainty in extrapolating drainage and salinity impact estimates from our field sites across the Padthaway PWA. To partially account for this, minimum and maximum drainage terms derived from both flood investigation sites were

Table 7.1 Key water and salt balance parameters, and drainage estimates made using a range of methods for each of the irrigated field sites.

A drainage estimate was selected based on knowledge of the limitations of the methods at each of the sites and salinity impacts to the aquifer were calculated based on this drainage rate.

	NAP 1	NAP 2	NAP 3	NAP 4	NAP 5	NAP 6	NAP 7
	drip	drip	pivot	flood	flood	drip	drip
Water Balance							
Input (Rain+Irrigation) (mm)	695	605	1240	2200	2660	685	651
Drainage (mm)							
Standard Water Balance	154	100	80	1278	1450	113	115
Penman-Grindley	116	91	137	–	–	150	174
Chloride Mass Balance	na	na	139	1354	1750	163	na
LEACHM model						116	
Selected Drainage (mm/y)	135	95.5	137	1354	1450	136	145
Drainage as % Input	19	16	11	62	55	20	22
Salt Balance							
Salt Input (t/ha/y)	1.6	1.8	8–9.4	26.2–27.5	50–58	2.2	1.7
Irrigation Water Salinity (mg/L)	900	1050	1765	1520	2415	1130	1090
Maximum measured soil water salinity (mg/L)[1]	8060	4205	6000	1790–2500	2790	3320	7650
Minimum measured soil water salinity (mg/L)[1]	3970	2120	3000	1730–2130	2420	2025	4980
Drainage Water Salinity (mg/L)	1020–1350	1780–1980	2675	1880–2110	2525	1440–1910	1020–1540
Underlying groundwater salinity (mg/L)	1760	1630	1720	1720	2480	1200	1470
Salinity Impact to the Aquifer (t/ha/y)	0.18–0.52	0.73–0.84	0.9–1.4	4.0–6.0	1.6–2.2	0.46–0.88	0–0.52
From Groundwater Chemistry Interpretation							
Approx. % salinity from irrigation[2]	15–17	0	0	0–32	0–35	0	0–23

1 Observed maxima and minima soil water salinities are simply the highest and lowest values measured in a serries of four suction lysimeters at each site. Actual maxima and minima may be different and occur at slightly different depths from those sampled by the suction lysimeters.

2 Qualitative interpretation from chemistry graphs only. This interpretation is made based on the horizontal deviation of a groundwater sample to the right of the Naracoorte Ranges trend or the results of the geochemical model and is intended as an indicator only.

applied to other areas of flood irrigation. Due to the uncertainties in irrigation volumes across the PWA, the change in annual rainfall from north to south was not accounted for, as this small variability was considered to be insignificant to the overall water balance.

As discussed in Section 6, the soil thickness played an important role in the application rate and the net salinity impact to the water table. Therefore the soil type and thickness was also taken into consideration during the extrapolation of the results across the PWA.

Irrigation water salinity varies greatly across areas of flood irrigation. Fortunately, a large number of irrigation bores are designated observation monitoring bores and contain current groundwater salinity data. This information was also used in the spatial extrapolation of our site specific results across the PWA.

7.4 DISCUSSION

Figures 7.1–7.4 represent the best- and worst-case scenarios of drainage and salinity impacts under the three dominant types of irrigation practice in the Padthaway PWA. The results are based on data from the 2004–05 irrigation season.

These calculations indicate that, across the Padthaway flat:

- the greatest salinity impact to the aquifer was contributed by 2344 ha of flood irrigation, estimated at 4630–13 500 tonnes of salt.
- This is followed by 3214 ha of viticulture (under drip irrigation), which contributed between 1143–2347 tonnes of salt.
- 323 ha of centre pivot irrigation contributed between 290–445 tonnes of salt.

It must be noted that these figures are still preliminary and will be refined over the 2005–06 irrigation season, as additional data and interpretation comes to hand. Additionally, results of the CSIRO study into vineyard water and salt balances at Padthaway, due at the end of June 2006, will be used to update these maps.

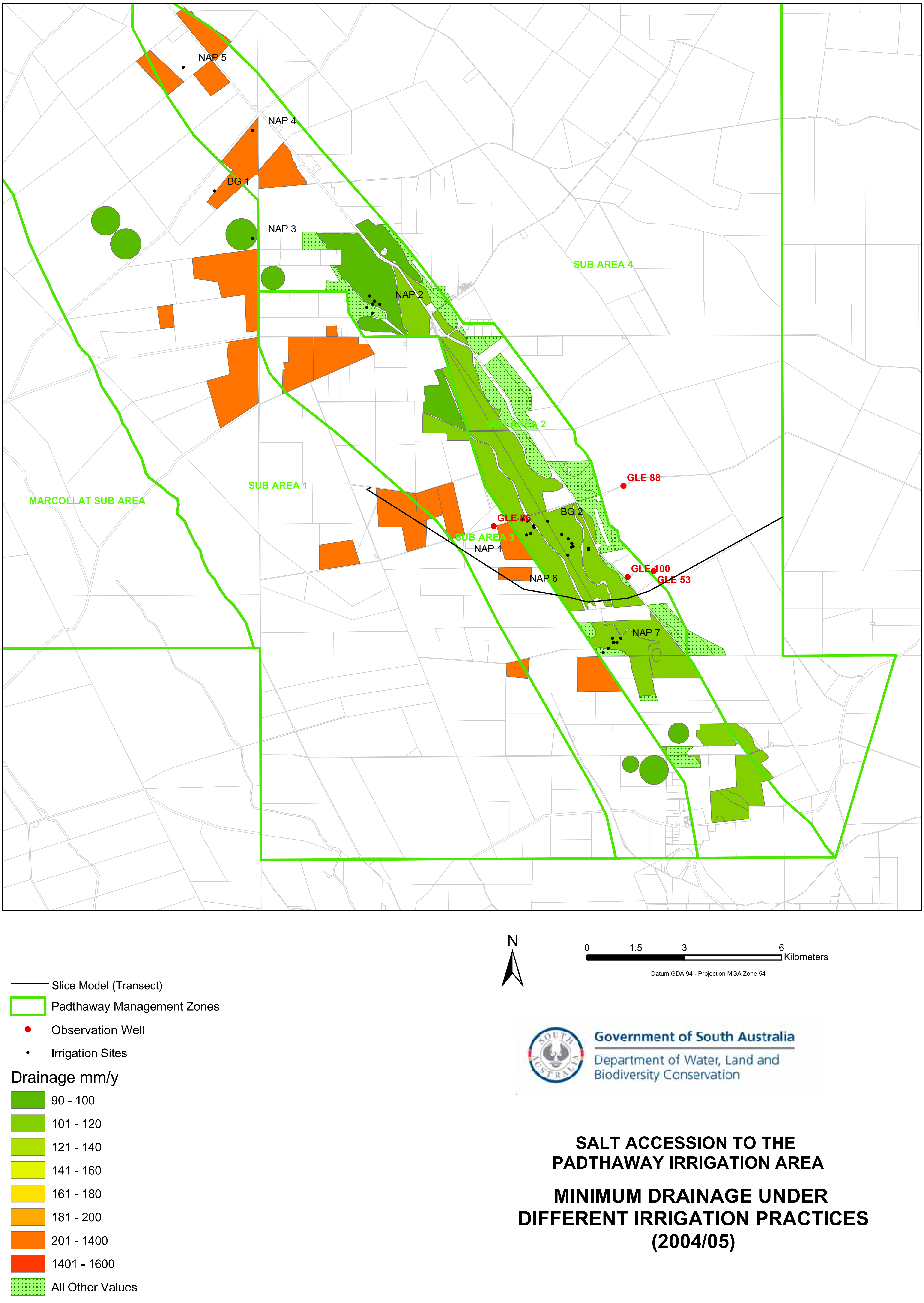
In some areas, the salt contribution under flood irrigation is likely to be less than the above estimates, as the calculation assumes that the same amount of flood irrigation was applied to all crops. The land use map fails to distinguish between pasture and other crops such as beans, coriander, wheat, and phalaris, which require less irrigation and may contribute a lower net accession of salt back to the aquifer. Preliminary results from both flood irrigation sites indicate that the degree of evapotranspiration and overall net salinity impact to the aquifer may not only depend on soil type, but also the thickness of the top soil, rate at which the water is applied and width/area of the flood bay. These additional variables make the extrapolation difficult and therefore, the estimates may not be representative of all flood irrigation in the area. In addition, flood irrigation in the southern portion of the PWA occurs over top soil which contains a much higher clay content than the top soil at sites NAP 4 and 5 in the north of the PWA. Based on this alone, it is assumed that drainage and net salinity impact in these areas would be considerably different than what was measured at our field sites. Despite these uncertainties, flood irrigation is likely to be the largest contributor of irrigation induced salinity impacts to the PWA.

The estimates of salt accession under centre pivot irrigation still require further interpretation. As discussed above, additional sampling is required to investigate whether salt is accumulating under the centre pivot, or if more salt is being leached over the longer-term than has been calculated for this type of irrigation. Drainage and salt flux terms will be refined over the next irrigation season.

The instrumented vineyard sites represent 2806 ha of viticulture across 4 different soil types. An additional three soil types, which cover a total of 408 ha of viticulture were not covered by our field sites. The one dimensional unsaturated zone model, LEACHM (Hutson, 2003) could be used to model salt and drainage fluxes under these soils. In the total flux estimates described above, average fluxes have been applied to these soil types.

Based on the above discussion, the following work is required to further refine the irrigation induced salt accessions to the unconfined aquifer on the Padthaway Flat:

- A better understanding of irrigation applications for all flood irrigation in the Padthaway PWA. This could be achieved through more thorough analysis of AWURs or through the collection of information from meters on irrigation bores.
- Estimation of salt accessions from dripper irrigation under some additional soil types using the LEACHM to model.
- Refinement of the vineyard salt and water balances based on soil type, vineyard architecture and grape variety. This will be done following completion of the CSIRO study.
- Updating of the 2002 land use map.



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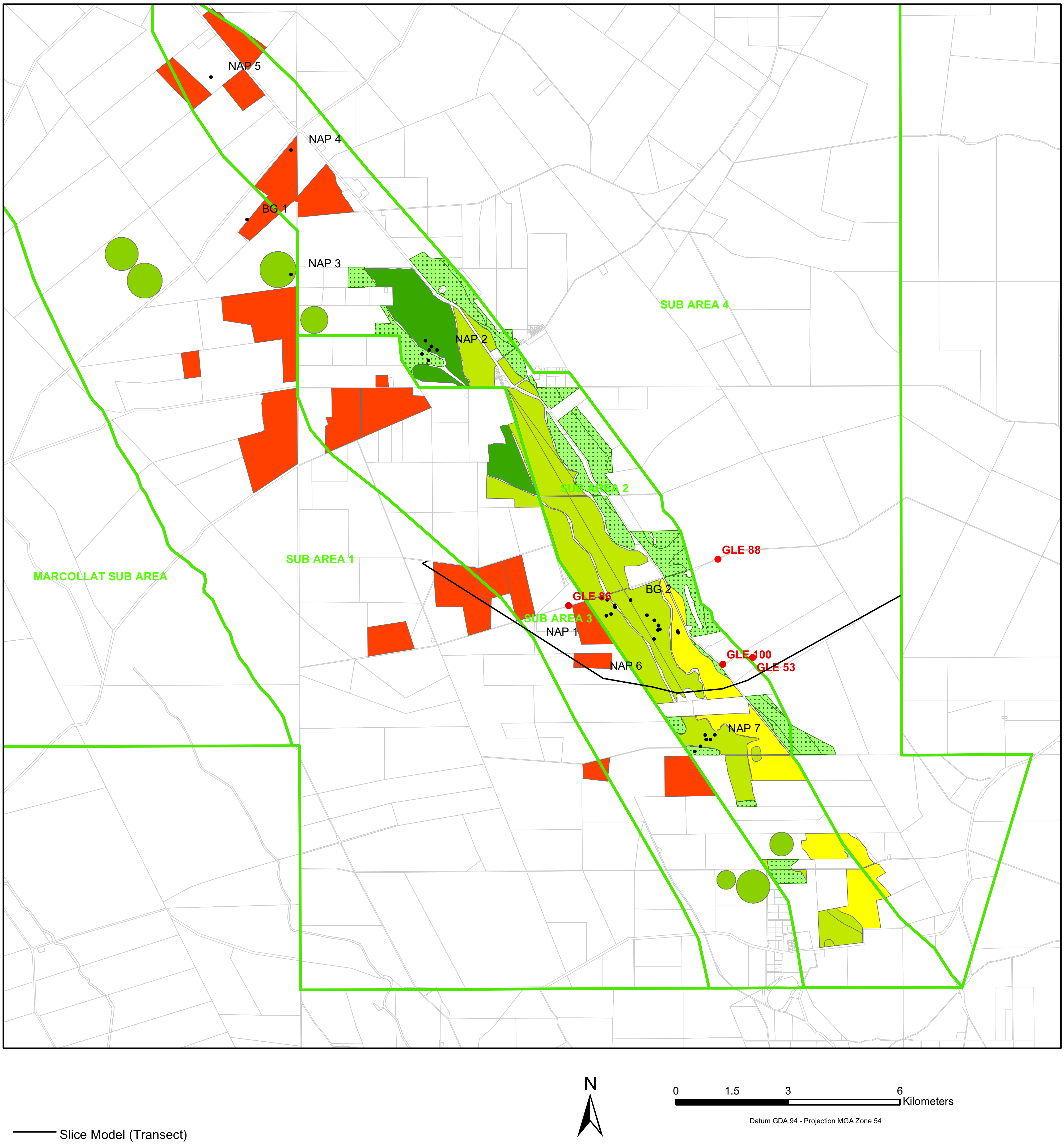
SALT ACCESSION TO THE PADTHAWAY IRRIGATION AREA

MINIMUM DRAINAGE UNDER DIFFERENT IRRIGATION PRACTICES (2004/05)

Figure 7.1



Slice Model (Transect)

Padthaway Management Zones

Observation Well

Irrigation Sites

Drainage mm/y

- 90 - 100
- 101 - 120
- 121 - 140
- 141 - 160
- 161 - 180
- 181 - 200
- 1200 - 1400
- 1401 - 1600
- All Other Values

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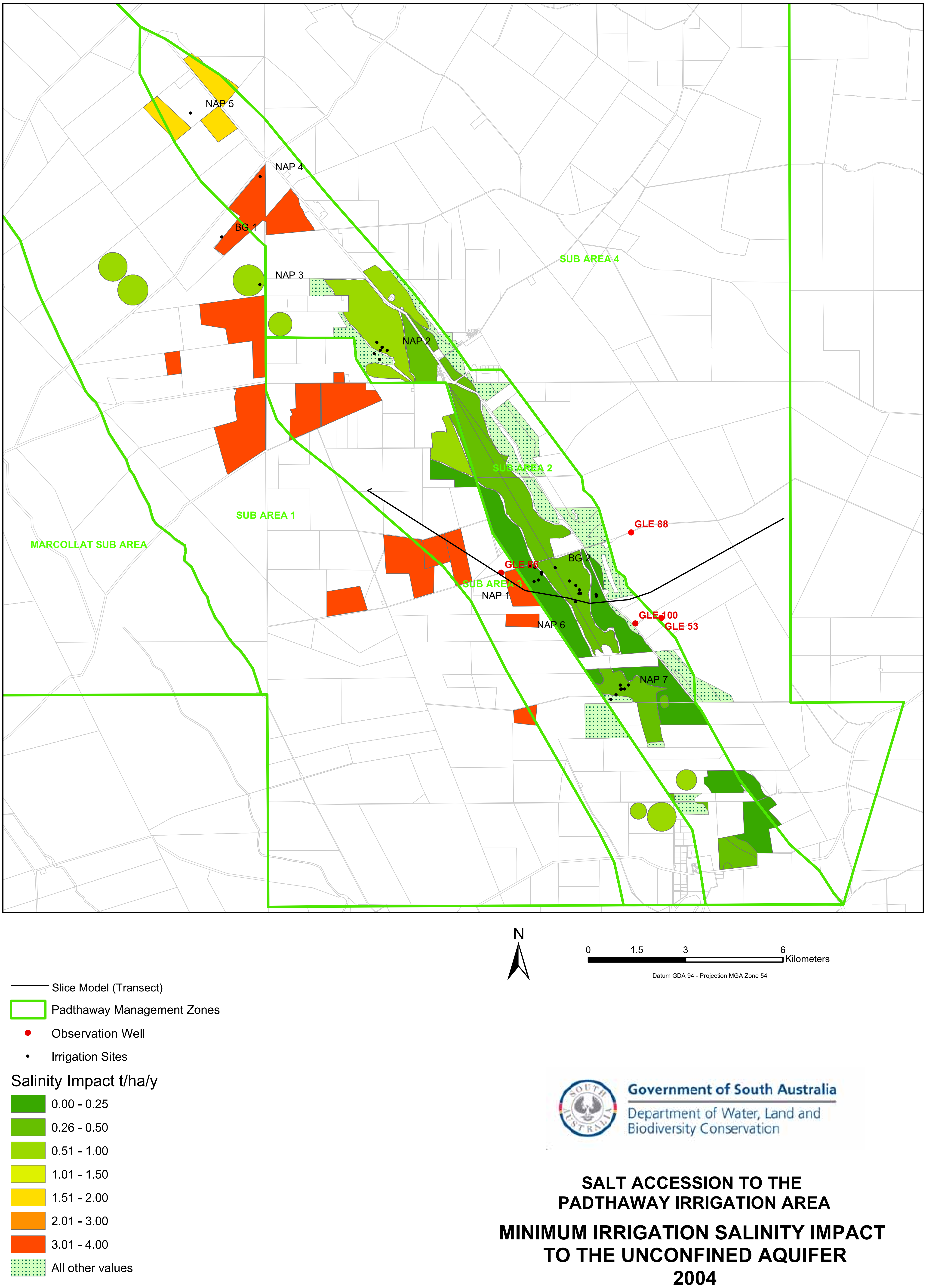
SALT ACCESSION TO THE PADTHAWAY IRRIGATION AREA

MAXIMUM DRAINAGE UNDER DIFFERENT IRRIGATION PRACTICES (2004/05)

Figure 7.2



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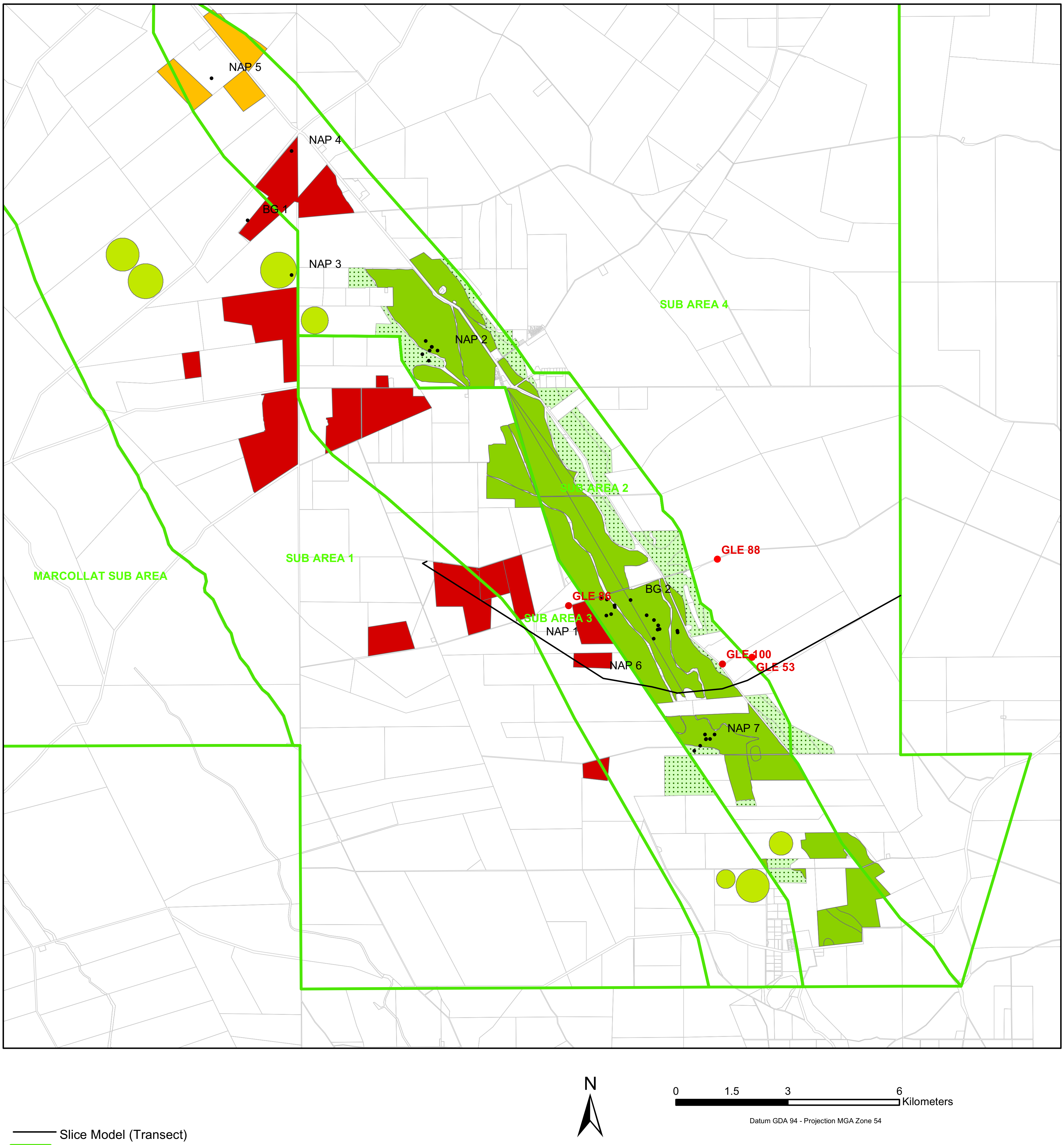
SALT ACCESSION TO THE PADTHAWAY IRRIGATION AREA

MINIMUM IRRIGATION SALINITY IMPACT TO THE UNCONFINED AQUIFER 2004

Figure 7.3



Slice Model (Transect)

Padthaway Management Zones

Observation Well

Irrigation Sites

Salinity Impact t/ha/y

- 0.00 - 0.25
- 0.26 - 0.50
- 0.51 - 1.00
- 1.01 - 1.50
- 1.51 - 2.00
- 2.01 - 3.00
- 3.01 - 4.00
- 4.01 - 6.00
- All other values

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SALT ACCESSION TO THE PADTHAWAY IRRIGATION AREA

MAXIMUM IRRIGATION SALINITY IMPACT TO THE UNCONFINED AQUIFER (2004/05)

Figure 7.4

8. TWO-DIMENSIONAL REGIONAL CONCEPTUAL AND NUMERICAL MODELS OF GROUNDWATER FLOW AND SALT FLUXES

8.1 FLOW MODEL

Details of the objectives, conceptual model, model design and construction for a two-dimensional numerical model running along the transect shown in Maps 1–4 are provided in Section 2.7. Figure 8.1 shows the simulated water table elevation and particle flow paths at 45 years post-clearing (2005). This diagram shows that a particle of water takes ~80 yrs to move the 9.5 km length of the model domain and ~40 years from the base of the Naracoorte Ranges to observation well GLE86 in the middle of the Padthaway Flat irrigation area (see Map 1).

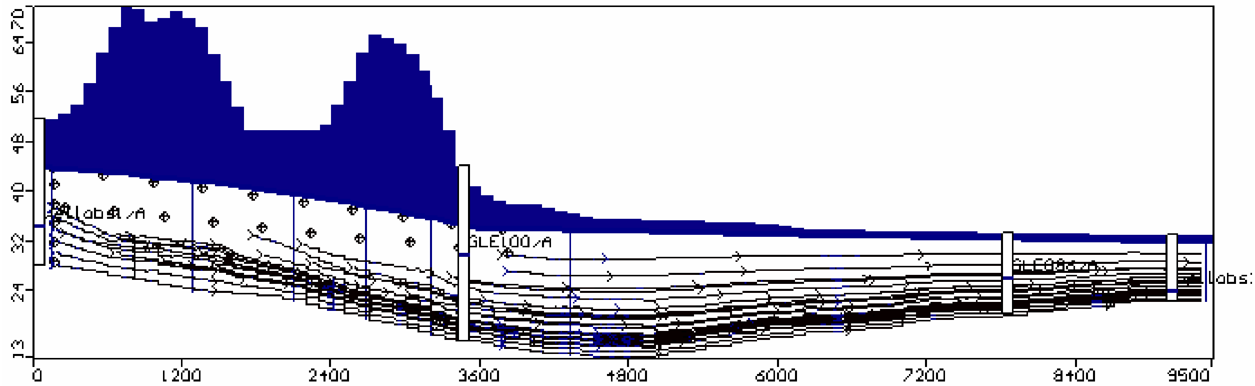


Figure 8.1 Equipotentials and particle flow paths simulated for 45 yrs post-clearing (2005). The distance between arrows on the particle flow paths represent a travel time of 10 yrs. Blue vertical lines are head equipotentials.

Figure 8.2 presents the observed and modelled hydraulic head distributions from observation wells GLE100 and GLE86 located along the model transect. The locations of the wells are shown on Figure 8.1 and Map1. The rise in the water level observed in a theoretical observation well, ObsWell1, placed at the eastern end of the transect is in good agreement with a general rise in the water table throughout the Ranges observed in Departmental observation wells over the past few decades (Fig. 8.2).

Hydraulic heads in unconfined aquifer observation wells in the Padthaway PWA are largely controlled by variations in rainfall, causing sinusoidal fluctuations such as those observed in observation wells GLE100 and GLE86 (Fig. 8.2). Due to the simplicity of the two-dimensional model and its objective of assisting with conceptualisation of the system, climatic variations in rainfall were not included. For this reason, the sinusoidal fluctuations in the observation well hydraulic heads could not be simulated (Fig. 8.2). Despite this, and considering the simplicity of the model, observed head data from GLE100 and GLE086 show a reasonable match with modelled heads. The discrepancy in the observed and modelled head differences between GLE100 and GLE86 may be explained by the fact that GLE100 is located immediately at the boundary of the Naracoorte Ranges and the Padthaway Flat, and that the

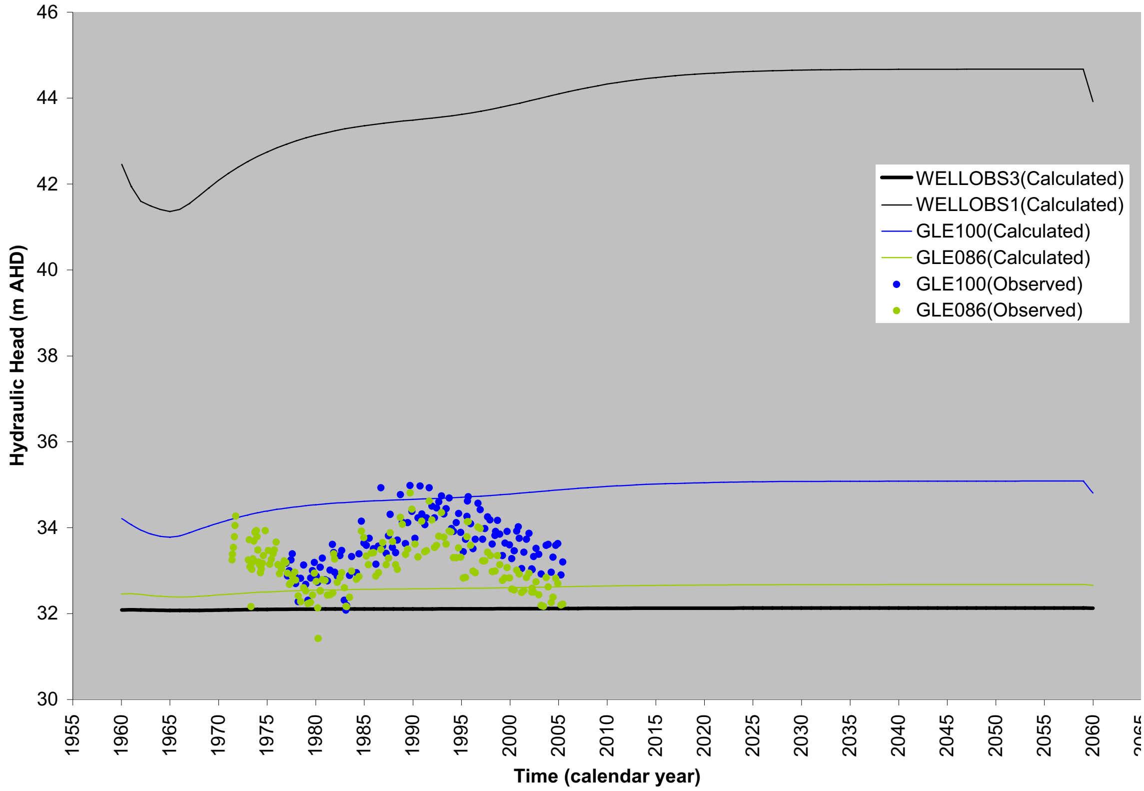


Figure 8.2 Observed and modelled hydraulic heads for observation wells GLE100 (base of Naracoorte Ranges) and GLE86 (Padthaway Flat). The black lines represent modelled heads in theoretical observation wells at each end of the model domain.

hydraulic conductivity of the aquifer in its vicinity is uncertain. It is possible that the higher conductivity zone that occurs on the Padthaway Flat extends further into the Naracoorte Ranges than was modelled. If this is the case, this would give rise to hydraulic heads similar to those in observation well GLE86 (as observed), rather than the higher values predicted by the model. Additionally, the effect of the Kanawinka Fault, which runs along the boundary between the Naracoorte Ranges and the Padthaway Flat, is unknown, but it is possible that it has given rise to higher hydraulic conductivities in that region. Despite this discrepancy, it is considered that the flow model represents the flow system adequately for the purpose of the modelling exercise.

The general rise in modelled heads is a result of increased recharge in the Naracoorte Ranges following land clearing. This head increase is less pronounced on the Padthaway Flat, where the aquifer is more transmissive than in the Ranges.

8.2 SOLUTE TRANSPORT MODELLING

Figure 8.3 shows the results of the solute transport modelling as cross-sectional diagrams of salt concentration in the aquifer at different times after clearing in the Naracoorte Ranges (assuming broad scale clearing occurred in 1960). These diagrams show:

- An initially uniform salinity (1961).
- By 1962, salt begins to flush into the aquifer from the lower-lying parts of the Naracoorte Ranges, mixing with the in-flowing groundwater (groundwater flow is left to right).

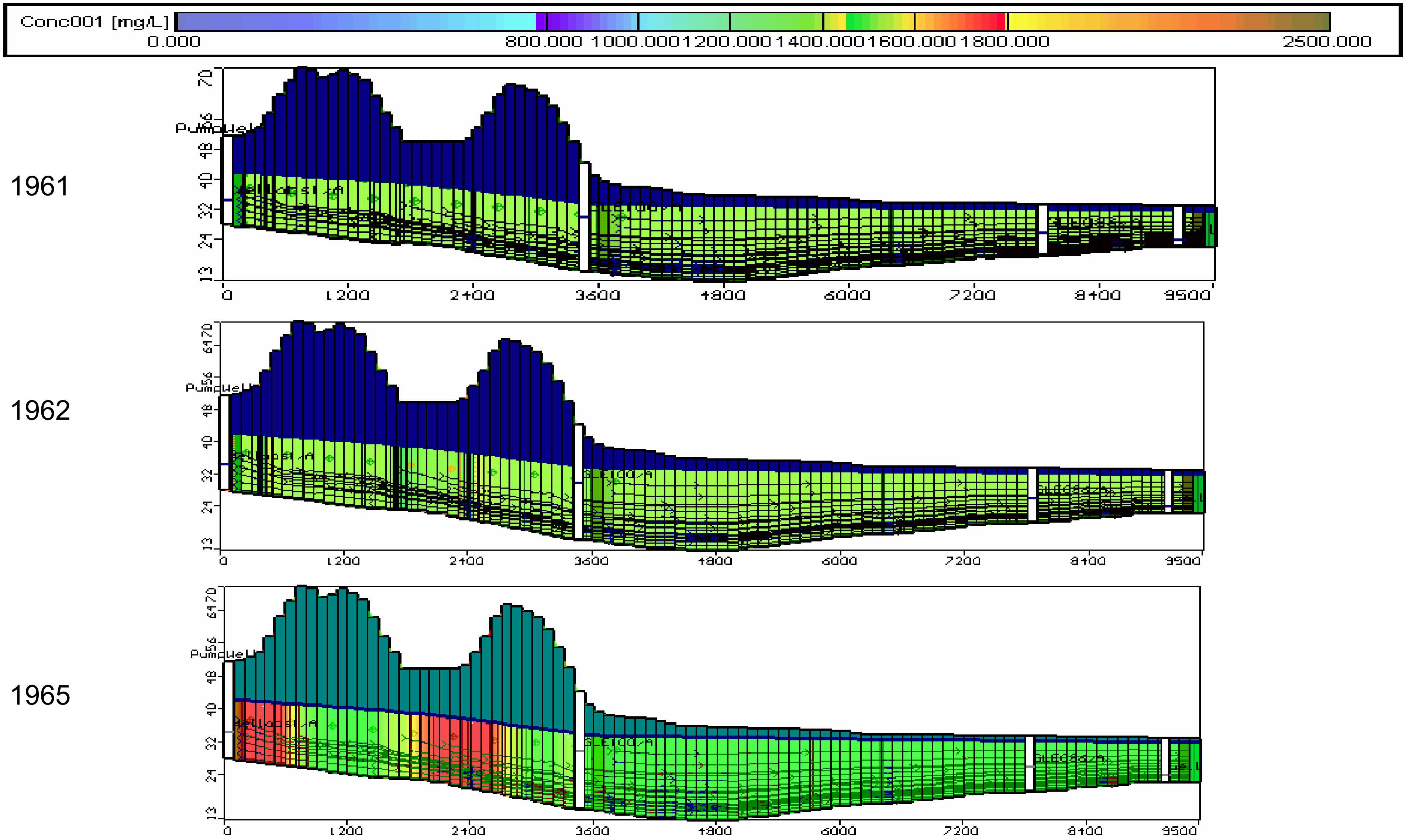
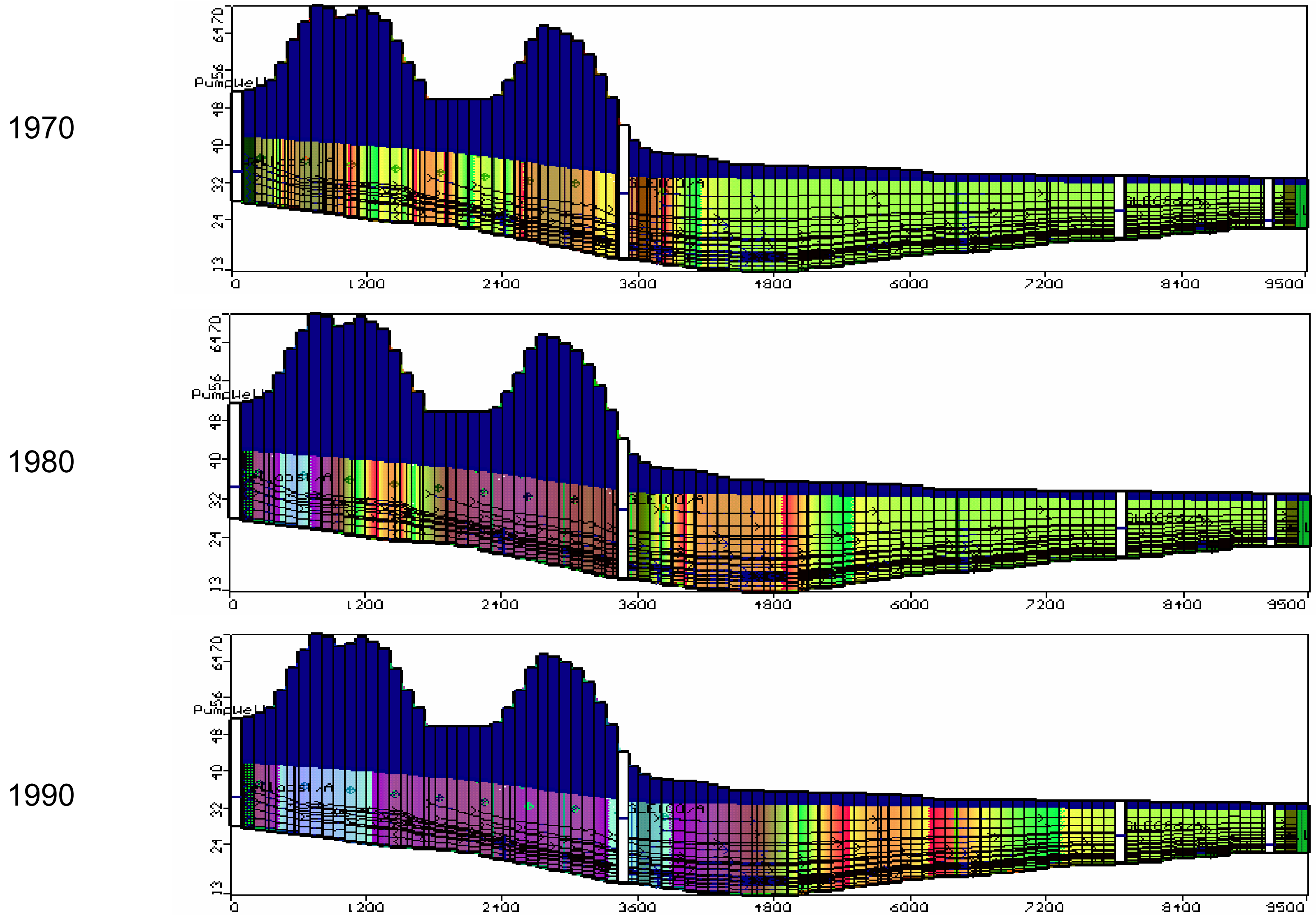


Figure 8.3 Modelled groundwater salinities at various times post-clearing in the Naracoorte Ranges (assumed to be 1960) in the unconfined aquifer along the modelled cross-section (see Map 1 for location of cross-section).



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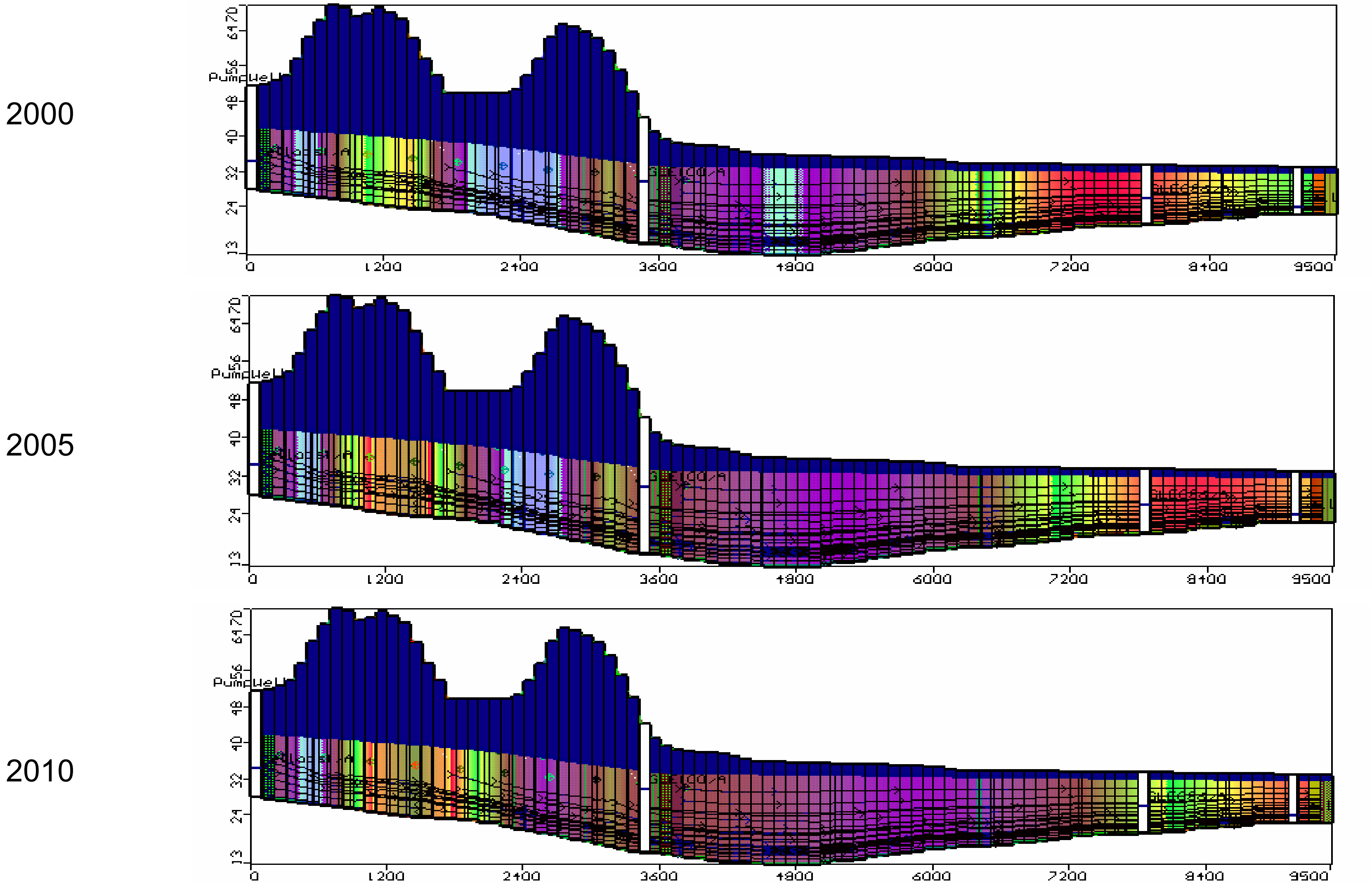
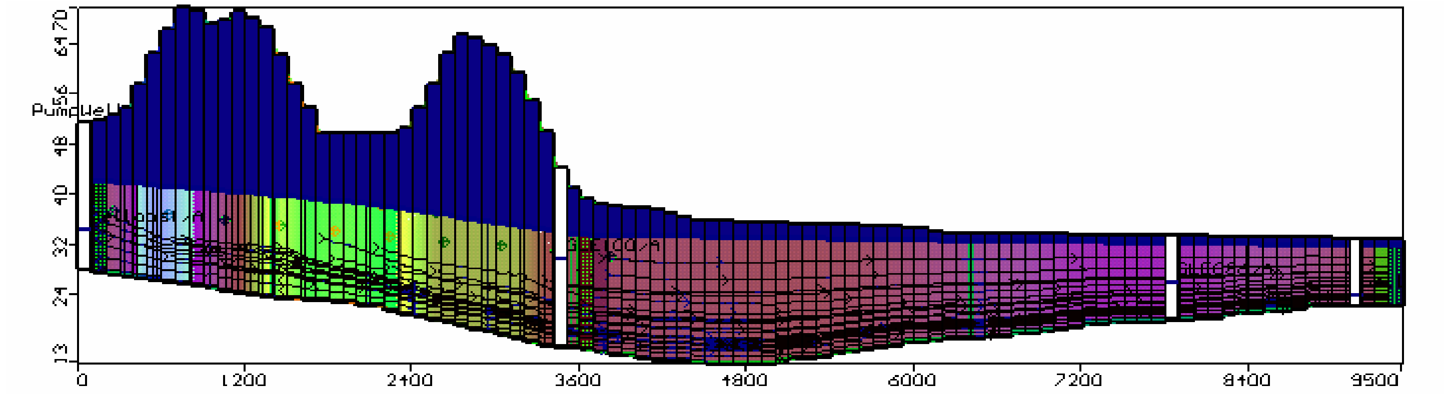


Figure 8.3 Modelled groundwater salinities at various times post-clearing in the Naracoorte Ranges (assumed to be 1960) in the unconfined aquifer along the modelled cross-section (see Map 1 for location of cross-section).

2020



2050

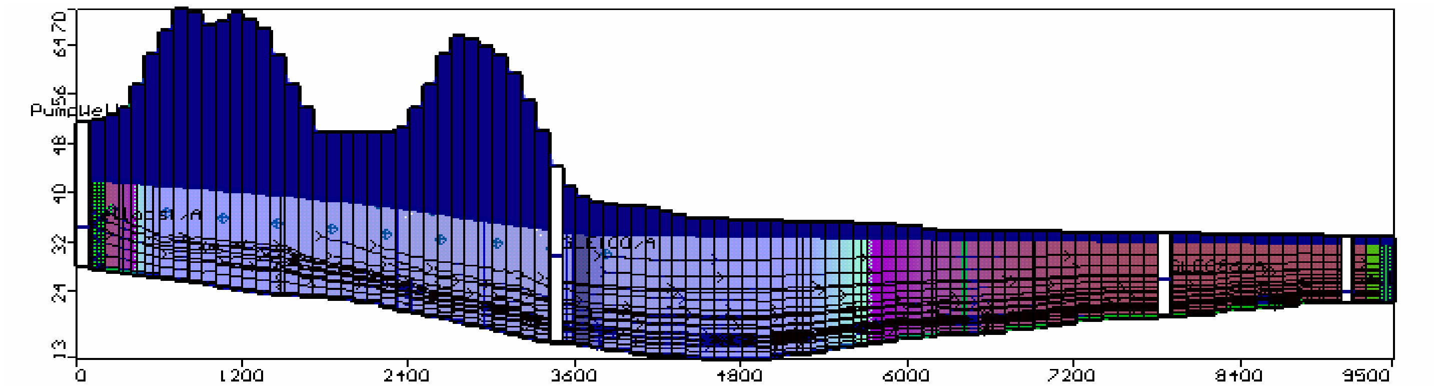


Figure 8.3 Modelled groundwater salinities at various times post-clearing in the Naracoorte Ranges (assumed to be 1960) in the unconfined aquifer along the modelled cross-section (see Map 1 for location of cross-section).

- By 1970, the groundwater system beneath the Naracoorte Ranges is quite saline and this saline plume begins to move out onto the Padthaway Flat in the direction of regional groundwater flow.
- Around 2000 and 2005, the groundwater in the vicinity of observation well GLE86 is saline, freshening slightly between 2010–20 before another plume of less saline water than the first moves through the region.
- By 2050, the groundwater system on the Padthaway Flats is beginning to freshen again.

The movement of the plumes of saline water from the Ranges onto the Flat can be seen in Figure 8.4, which also shows a good match between predicted and observed groundwater salinities in observation wells GLE100 (base of Naracoorte Ranges) and GLE86 (Padthaway Flat). For clarity, the two peaks in salinity are labelled as “Peak 1” and “Peak 2” for both the observed and modelled trends in Figure 8.4. Figure 8.4 shows:

- The first salinity peak of ~1800–1900 mg/L arriving at observation well GLE100 (base of Ranges) between 1965–78, before salinity monitoring data were available.
- This peak then commenced to be observed in well GLE86 in about 1994, as predicted by the model, and the peak has just passed that location now in the year 2005.
- The predicted sharp drop in groundwater salinity to 900 mg/L at GLE100 was not observed, probably due to the effects of salt arriving from further out in the Ranges (beyond the boundary of the model), which would have mixed with the fresher recharge now coming through from the nearer portion of the Ranges.
- A smaller and more gradual increase in salinity observed in GLE100 between about 1988 and 1996 may be the beginning of the second, lower and broader salinity peak coming through from the Naracoorte Ranges, however the observation data set is not sufficient yet to determine whether this is the case. If it is, the peak is being observed at GLE100 earlier than predicted.

The salt flux from the Naracoorte Ranges is estimated to be currently 35 tonnes per 100 m wide cross section, with the maximum salt flux of 45 tonnes per 100 m wide cross section occurring in 1976.

Although the model predictions appear to be supported by observation data, particularly in the prediction of the first and most significant salinity peak moving through the PWA, some of the drops in salinity subsequent to that have apparently been damped out by processes occurring in the Ranges beyond the extent of the model domain (i.e. salt moving through from flushing in that region). This is to be expected and assists greatly with our conceptualisation of salt movement through the system. The model only accounts for flushing in the nearest portion of the Naracoorte Ranges, hence its accurate prediction of the movement of the first and largest salinity peak. Based on our conceptual understanding of the system, it is considered likely that, rather than following the trend predicted by this model for observation well GLE86, groundwater salinities on the Flats will drop to approximately that currently observed in well GLE100 (1000–1300 mg/L), and fluctuate slightly around these values as salt flushed from the unsaturated zone in the Ranges mixes with fresher recharge and moves out onto the Padthaway Flat.

The model only includes the effect of salt accession processes occurring in the Naracoorte Ranges, and it can be seen that this alone can account for most of the increase in groundwater salinity observed on the Padthaway Flat. The slightly higher peak groundwater

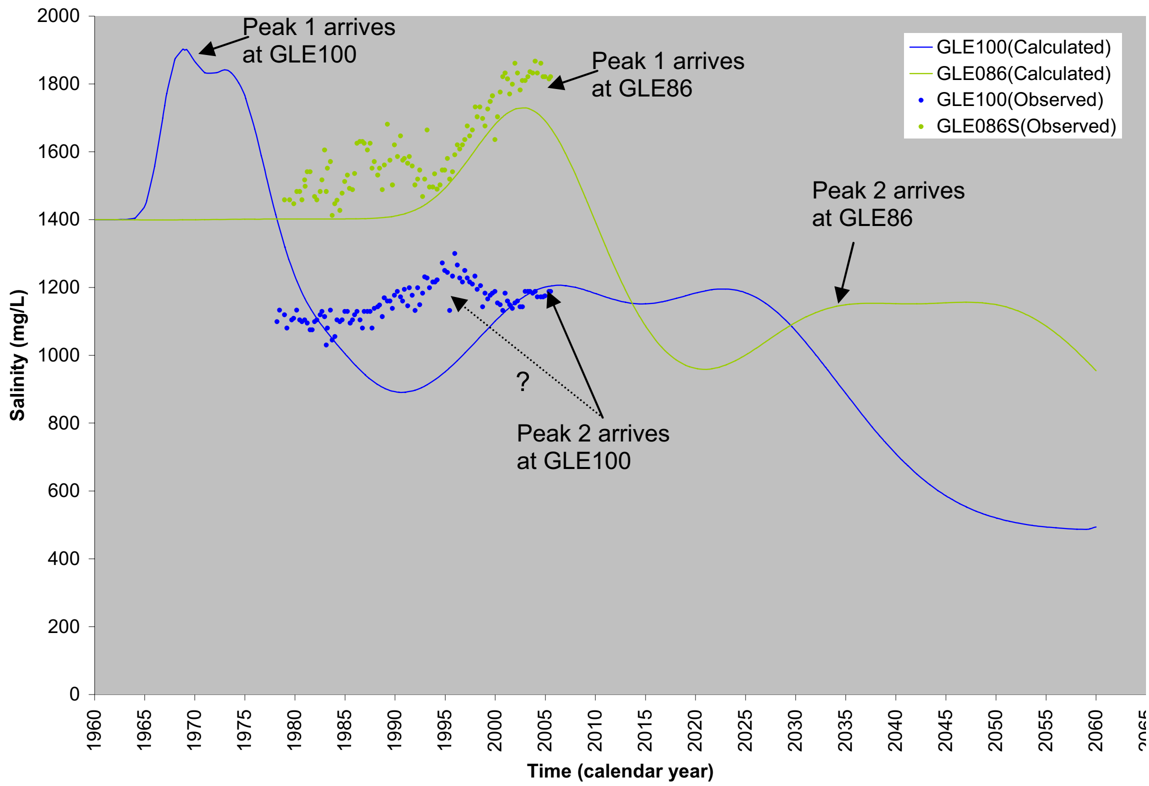


Figure 8.4 Observed and modelled groundwater salinities for observation wells GLE100 (base of Naracoorte Ranges) and GLE86 (Padthaway Flat).

salinity observed in GLE86 than that predicted by the model may be the result of salinity impacts from flood irrigation that occurred until the 1990s. Alternatively, it may be due to the model representing the aquifer as one layer. A one-layer model assumes mixing over the total thickness of aquifer whereas the observation well is screened in the upper, more concentrated part of the aquifer.

The model indicates that the Padthaway Flat is still in the process of flushing its original salt load. The effects of the current groundwater extraction regime on the movement of this saline groundwater through the irrigation district cannot be predicted with this simple model and a more comprehensive, three-dimensional model incorporating factors such as groundwater extraction rates is required for this.

8.3 LIMITATIONS OF THE MODEL

This relatively simple two-dimensional modelling exercise was carried out in order to improve our conceptual understanding of the solute system at Padthaway and, in particular, to test the hypothesis that the majority of the groundwater salinity increase observed on the Padthaway Flat has been predominantly controlled by salt accession processes in the Naracoorte Ranges. For this reason, the model was never intended to exactly represent groundwater flow and solute transport in the Padthaway PWA. Instead, comparison between the model predictions and observation well data, and assessment of discrepancies between these have greatly furthered our understanding of the system. In particular, the following assumptions made during the exercise and likely impacts on the model outcomes are important to consider when assessing the results:

- The initial start time for the model was 1960 and was selected as the most likely period that land clearance had occurred on the Range. This may be in error by +/- five years, and not all areas would have been cleared at the same time.
- Application of the correct groundwater inflow salinity affects the absolute concentrations of the model output. This has not been directly measured, and may have also varied over time due to a range of processes occurring up-gradient of the Padthaway PWA. However, the value of 1400 mg/L was based on measured salinity at depth in the Bridgewater Formation and Gambier formation aquifers and is considered to be representative of pre-land clearance aquifer salinity;
- Calibration of the model was limited to two observation wells. There are few long-term salinity observation wells located in the Naracoorte Ranges and the central part of the main irrigation area.
- Modflow and MT3DMS require that representative hydraulic parameters be assigned to each grid cell. In this model the grid cells are 100 by 100 metres and of variable thickness.
- Mechanical dispersion was not considered in the model. However it is generally considered that longitudinal dispersion is ~5% of the advection component, and would not have a significant impact on the model results.
- The use of one layer to represent the Bridgewater/Padthaway Formation aquifers does not allow for salinity stratification effects to be modelled.
- It is also important to consider that the non-uniqueness of the solution to groundwater flow means that a range of combinations of parameter values could produce similar results. In particular, it is important to have a good knowledge of the geological conditions. For example, the influence of the Kanawinka Fault on aquifer hydraulic properties and hence on groundwater movement is still uncertain. The effect of the fault, or a general uncertainty in aquifer properties, is most evident in the overestimation of hydraulic heads in observation well GLE100. However, a slight inaccuracy in the location of the boundary between the high and low conductivity zones of the aquifer does not appear to have affected the movement of the main salt plume, as seen in the good match for well GLE86.

8.4 CONCLUSIONS OF THE TWO-DIMENSIONAL MODEL

The two-dimensional numerical modelling supports the conceptual model that initially high salinity groundwater from the Naracoorte Ranges has had a significant impact on groundwater salinity beneath the Padthaway Flat, and that subsequent through-flow of lower-salinity recharge should have the effect of (i) offsetting further salinity increases caused by continued flushing in some areas, and (ii) flushing the poorer quality groundwater through the aquifer main irrigation area.

The model proved to be a reasonably quick and inexpensive method of assessing flow and salt accession from the Ranges onto the Flat. The solute transport code assisted in the calibration of the flow model, and was particularly useful in increasing our understanding of regional flow and mechanisms that control it. It also addressed some of the uncertainty associated with the calibration of the flow model, knowledge of which can be applied in the construction of the proposed three-dimensional flow and solute transport model.

9. SUMMARY AND CONCLUSIONS

This report collates and synthesises data obtained over the three year *Padthaway Salt Accession Investigations and Determination of Sustainable Limits (PAV)*. During this phase of the project, conceptual models were developed to describe hydraulic and hydrochemical observations made at field sites located on the Padthaway Flat and in the Naracoorte Ranges portion of the Padthaway PWA. These models were used as the basis to determine drainage and salt fluxes at each of the field sites that were subsequently up-scaled to determine total salt fluxes for the area. The following is a summary of and conclusions from this conceptual modelling exercise:

- Groundwater salinity beneath the Padthaway Flat is considered to be contributed from two main sources:
    - lateral inflow from the Naracoorte Ranges;
    - vertical recharge beneath irrigated and non-irrigated soils on the Padthaway Flat.
- The importance of the salt flux from the Ranges to the total salt load on the Flat is significant and hitherto unrecognised. Land clearance occurred in the Ranges ~45 years ago (~1960). Vertical recharge increased, over a relatively short period following land clearance, from nearly zero to more than 100 mm/yr. Increased recharge resulted in the mobilisation of significant quantities of salt (soil water >6000 mg/L) previously stored in the unsaturated zone that subsequently entered the unconfined aquifer. A plume of high salinity groundwater resulting from the addition of the salt load from the unsaturated zone has subsequently moved through the aquifer and onto the Flat. Flushing of the historical salt store in the unsaturated zone is near completion over large portions of the Ranges. The high vertical recharge to the aquifer now occurring in these parts of the Padthaway PWA is of a lower salinity and is in the process of flushing the groundwater system down gradient.
- Groundwater chemistry data suggests that most of the current groundwater salinity on the Padthaway Flat is derived from salt accessions in the Naracoorte Ranges (i.e. that there is comparatively little impact from evapotranspiration of irrigation water). The exception is under some flood irrigation in the north of the PWA.
- The salinity impact from drip irrigation of vineyards on the Padthaway Flat is currently estimated to range between 0–0.88 t/ha/y. This is to be revised on receipt of results from the CSIRO study of vineyard salt and water balances in June 2006. In most cases, as vineyards are being irrigated with comparatively fresh groundwater from adjacent the Naracoorte Ranges, this salinity impact is not observed as a groundwater salinity increase directly below the irrigated vineyard itself. The impact is in the salinisation of fresher water that would normally flow through the PWA and flush out the higher salinity water that is currently moving through the area.
- Despite the low salinity impacts estimated for this irrigation type, large quantities of salt are observed to occur around the root zone under the irrigated vineyards at Padthaway. Over the time scale of the present study, this salt store appears to be in a steady state, with no net accumulation or leaching observed. However, due to a lack of understanding of the mechanisms of salt transport through the profile at these sites, the long-term fate of this salt store is unknown. Hence the salinity impacts under drip irrigated vineyards could be much greater than estimated here if conditions arose under which it was released into the underlying aquifer.

- The average net salinity impact to the aquifer under flood irrigation ranged between 4.15–6 t/ha/y at site NAP 4 and between 1.6–2.2 t/ha/y at site NAP 5. The lower impact measured at NAP 5 may be attributed to the narrower flood bays and a shallower topsoil. These factors combined result in a quicker irrigation application, which leads to a reduction in the amount of irrigation water evaporated and therefore has reduced the salinity impact on the aquifer.
- Short-term soil water salinity data suggests an accumulation of salt under the centre pivot site. It is uncertain whether this represents a long-term accumulation of salt. The net salinity impact on the aquifer here ranges from 0.9–1.4 t/ha/y. Similarly to the drip irrigation sites, if periodic flushing of this salt store occurs, the impact of this irrigation practice is likely to be much greater, at ~6–7 t/ha/y. Further sampling over the 2005–06 irrigation season is expected to refine our understanding of the processes occurring under centre pivot irrigation, but sampling beyond that may also be required.
- To quantify the total salinity impact from irrigation drainage water on the Padthaway Flat, field site data was extrapolated across areas of similar crop type, soil type, irrigation practice and climate. Whilst it is recognised that a degree of uncertainty is introduced in any spatial extrapolation of site specific data it was estimated that, across the Padthaway Flat, 2344 ha of flood irrigation delivered the greatest salinity impact to the aquifer (~4600–13 000 tonnes annually). This was followed by 3214 ha of viticulture under drip irrigation, which contributed between 1143–2347 tonnes of salt, and 323 ha of centre pivot irrigation, which contributed between 290–445 tonnes of salt back to the aquifer annually.
- The benefit of changing from flood to drip irrigation on salt loads to the aquifer appears to be significant, especially given the estimates of the contribution of salt from under pivot and flood irrigation. However, the presence of large quantities of salt around the root zones of the irrigated vines is causing problems with wine quality and vine health. If this salt is re-mobilised, for example by periods of high rainfall, the salinity impact to the aquifer from this irrigation type would also be greater than estimated here.
- A two-dimensional numerical slice model was constructed to test the conceptual model that the majority of the groundwater salinity increase observed on the Padthaway Flat is caused predominantly by salt accession processes occurring in the Naracoorte Ranges. Groundwater flow and salt movement was simulated along a flow path from the Ranges onto the Flat. Results from the modelling show that the initial large salt plume sourced from the Ranges has moved into the main irrigation area and can explain the elevated groundwater salinities there.
- The salt flux from the Naracoorte Ranges is estimated from the modelling to be currently 35 tonnes per 100 m wide cross section, with the maximum salt flux of 45 tonnes occurring in 1976. Under a worst-case scenario, a 20 km stretch of drip-irrigated vineyards (100 m wide) would contribute a net salinity impact of 18 t/y, based on the current estimates of salinity impact.
- The modelling further predicts an overall decline in groundwater salinity over the hundred year modelling period. It is expected that further flushing of the historic salt in the Naracoorte Ranges, and inflow of that originating from areas beyond the PWA boundary, will be offset by mixing with fresher post-flushing recharge that is now occurring in significant areas of the Ranges.
- It should be noted that the time scales provided for solute transport processes are indicative only due to the limitations of the simple numerical model and the empirical model for salt flushing in the Naracoorte ranges upon which it is based.

APPENDIX

A. RECHARGE SALINITY VALUES DERIVED USING THE ONE-DIMENSIONAL MODEL FOR FIELD SITES PB1, PB5, PB7 AND PB8

These were applied to the model zones shown in Figure 2.6.

PB1			PB5			PB7			PB8		
Start Day	End Day	Recharge Salinity	Start Day	End Day	Recharge Salinity	Start Day	End Day	Recharge Salinity	Start Day	End Day	Recharge Salinity
0	365.3	11661	0	365.3	0	365.3	730.5	0	0	365.25	0
365.3	730.5	11355	365.3	730.5	0	730.5	1095.8	0	365.25	730.5	0
730.5	1095.8	8958	730.5	1095.8	8202	1095.8	1461	0	730.5	1095.75	0
1095.8	1461	3836	1095.8	1461	8182	1461	1826.3	0	1095.75	1461	0
1461	1826.3	815	1461	1826.3	8073	1826.3	2191.5	0	1461	1826.25	0
1826.3	2191.5	174	1826.3	2191.5	7659	2191.5	2556.8	0	1826.25	2191.5	0
2191.5	2556.8	105	2191.5	2556.8	6586	2556.8	2922	0	2191.5	2556.75	15732.70806
2556.8	2922	100	2556.8	2922	4758	2922	3287.3	0	2556.75	2922	15684.26959
2922	3287.3	100	2922	3287.3	2747	3287.3	3652.5	0	2922	3287.25	15548.27778
3287.3	3652.5	100	3287.3	3652.5	1282	3652.5	4017.8	0	3287.25	3652.5	15219.69297
3652.5	4017.8	100	3652.5	4017.8	526	4017.8	4383	0	3652.5	4017.75	14535.72573
4017.8	4383	100	4017.8	4383	228	4383	4748.3	0	4017.75	4383	13316.73605
4383	4748.3	100	4383	4748.3	134	4748.3	5113.5	0	4383	4748.25	11475.00049
4748.3	5113.5	100	4748.3	5113.5	108	5113.5	5478.8	0	4748.25	5113.5	9136.485508
5113.5	5478.8	100	5113.5	5478.8	102	5478.8	5844	0	5113.5	5478.75	6646.739259
5478.8	5844	100	5478.8	5844	102	5844	6209.3	0	5478.75	5844	4408.537025
5844	6209.3	100	5844	6209.3	102	6209.3	6574.5	0	5844	6209.25	2683.82019
6209.3	6574.5	100	6209.3	6574.5	102	6574.5	6939.8	0	6209.25	6574.5	1522.352215
6574.5	6939.8	100	6574.5	6939.8	102	6939.8	7305	0	6574.5	6939.75	825.2113067
6939.8	7305	100	6939.8	7305	102	7305	7670.3	0	6939.75	7305	445.5912964
7305	7670.3	100	7305	7670.3	102	7670.3	8035.5	0	7305	7670.25	255.21988
7670.3	8035.5	100	7670.3	8035.5	102	8035.5	8400.8	0	7670.25	8035.5	166.2042495
8035.5	8400.8	100	8035.5	8400.8	102	8400.8	8766	0	8035.5	8400.75	126.9939609
8400.8	8766	100	8400.8	8766	102	8766	9131.3	0	8400.75	8766	110.5834953
8766	9131.3	100	8766	9131.3	102	9131.3	9496.5	0	8766	9131.25	104.0105388
9131.3	9496.5	100	9131.3	9496.5	102	9496.5	9861.8	0	9131.25	9496.5	101.4755173
9496.5	9861.8	100	9496.5	9861.8	102	9861.8	10227	16959	9496.5	9861.75	100.5291423
9861.8	10227	100	9861.8	10227	102	10227	10592.3	16950	9861.75	10227	100.1856087
10227	10592.3	100	10227	10592.3	102	10592.3	10957.5	16938	10227	10592.25	100.1856087
10592.3	10957.5	100	10592.3	10957.5	102	10957.5	11322.8	16919	10592.25	10957.5	100.1856087
10957.5	11322.8	100	10957.5	11322.8	102	11322.8	11688	16894	10957.5	11322.75	100.1856087
11322.8	11688	100	11322.8	11688	102	11688	12053.3	16858	11322.75	11688	100.1856087
11688	12053.3	100	11688	12053.3	102	12053.3	12418.5	16810	11688	12053.25	100.1856087
12053.3	12418.5	100	12053.3	12418.5	102	12418.5	12783.8	16745	12053.25	12418.5	100.1856087
12418.5	12783.8	100	12418.5	12783.8	102	12783.8	13149	16659	12418.5	12783.75	100.1856087
12783.8	13149	100	12783.8	13149	102	13149	13514.3	16547	12783.75	13149	100.1856087
13149	13514.3	100	13149	13514.3	102	13514.3	13879.5	16404	13149	13514.25	100.1856087
13514.3	13879.5	100	13514.3	13879.5	102	13879.5	14244.8	16223	13514.25	13879.5	100.1856087
13879.5	14244.8	100	13879.5	14244.8	102	14244.8	14610	15997	13879.5	14244.75	100.1856087
14244.8	14610	100	14244.8	14610	102	14610	14975.3	15720	14244.75	14610	100.1856087
14610	14975.3	100	14610	14975.3	102	14975.3	15340.5	15387	14610	14975.25	100.1856087
14975.3	15340.5	100	14975.3	15340.5	102	15340.5	15705.8	14990	14975.25	15340.5	100.1856087
15340.5	15705.8	100	15340.5	15705.8	102	15705.8	16071	14527	15340.5	15705.75	100.1856087
15705.8	16071	100	15705.8	16071	102	16071	16436.3	13996	15705.75	16071	100.1856087
16071	16436.3	100	16071	16436.3	102	16436.3	16801.5	13396	16071	16436.25	100.1856087
16436.3	16801.5	100	16436.3	16801.5	102	16801.5	17166.8	12731	16436.25	16801.5	100.1856087
16801.5	17166.8	100	16801.5	17166.8	102	17166.8	17532	12007	16801.5	17166.75	100.1856087
17166.8	17532	100	17166.8	17532	102	17532	17897.3	11231	17166.75	17532	100.1856087
17532	17897.3	100	17532	17897.3	102	17897.3	18262.5	10416	17532	17897.25	100.1856087
17897.3	18262.5	100	17897.3	18262.5	102	18262.5	18627.8	9575	17897.25	18262.5	100.1856087
18262.5	18627.8	100	18262.5	18627.8	102	18627.8	18993	8721	18262.5	18627.75	100.1856087
18627.8	18993	100	18627.8	18993	102	18993	19358.3	7870	18627.75	18993	100.1856087
18993	19358.3	100	18993	19358.3	102	19358.3	19723.5	7036	18993	19358.25	100.1856087
19358.3	19723.5	100	19358.3	19723.5	102	19723.5	20088.8	6232	19358.25	19723.5	100.1856087
19723.5	20088.8	100	19723.5	20088.8	102	20088.8	20454	5470	19723.5	20088.75	100.1856087
20088.8	20454	100	20088.8	20454	102	20454	20819.3	4758	20088.75	20454	100.1856087
20454	20819.3	100	20454	20819.3	102	20819.3	21184.5	4103	20454	20819.25	100.1856087

PB1			PB5			PB7			PB8		
Start Day	End Day	Recharge Salinity	Start Day	End Day	Recharge Salinity	Start Day	End Day	Recharge Salinity	Start Day	End Day	Recharge Salinity
20819.3	21184.5	100	20819.3	21184.5	102	21184.5	21549.8	3509	20819.25	21184.5	100.1856087
21184.5	21549.8	100	21184.5	21549.8	102	21549.8	21915	2978	21184.5	21549.75	100.1856087
21549.8	21915	100	21549.8	21915	102	21915	22280.3	2509	21549.75	21915	100.1856087
21915	22280.3	100	21915	22280.3	102	22280.3	22645.5	2099	21915	22280.25	100.1856087
22280.3	22645.5	100	22280.3	22645.5	102	22645.5	23010.8	1746	22280.25	22645.5	100.1856087
22645.5	23010.8	100	22645.5	23010.8	102	23010.8	23376	1445	22645.5	23010.75	100.1856087
23010.8	23376	100	23010.8	23376	102	23376	23741.3	1190	23010.75	23376	100.1856087
23376	23741.3	100	23376	23741.3	102	23741.3	24106.5	978	23376	23741.25	100.1856087
23741.3	24106.5	100	23741.3	24106.5	102	24106.5	24471.8	802	23741.25	24106.5	100.1856087
24106.5	24471.8	100	24106.5	24471.8	102	24471.8	24837	658	24106.5	24471.75	100.1856087
24471.8	24837	100	24471.8	24837	102	24837	25202.3	540	24471.75	24837	100.1856087
24837	25202.3	100	24837	25202.3	102	25202.3	25567.5	445	24837	25202.25	100.1856087
25202.3	25567.5	100	25202.3	25567.5	102	25567.5	25932.8	369	25202.25	25567.5	100.1856087
25567.5	25932.8	100	25567.5	25932.8	102	25932.8	26298	309	25567.5	25932.75	100.1856087
25932.8	26298	100	25932.8	26298	102	26298	26663.3	261	25932.75	26298	100.1856087
26298	26663.3	100	26298	26663.3	102	26663.3	27028.5	224	26298	26663.25	100.1856087
26663.3	27028.5	100	26663.3	27028.5	102	27028.5	27393.8	195	26663.25	27028.5	100.1856087
27028.5	27393.8	100	27028.5	27393.8	102	27393.8	27759	172	27028.5	27393.75	100.1856087
27393.8	27759	100	27393.8	27759	102	27759	28124.3	154	27393.75	27759	100.1856087
27759	28124.3	100	27759	28124.3	102	28124.3	28489.5	141	27759	28124.25	100.1856087
28124.3	28489.5	100	28124.3	28489.5	102	28489.5	28854.8	131	28124.25	28489.5	100.1856087
28489.5	28854.8	100	28489.5	28854.8	102	28854.8	29220	123	28489.5	28854.75	100.1856087
28854.8	29220	100	28854.8	29220	102	29220	29585.3	117	28854.75	29220	100.1856087
29220	29585.3	100	29220	29585.3	102	29585.3	29950.5	113	29220	29585.25	100.1856087
29585.3	29950.5	100	29585.3	29950.5	102	29950.5	30315.8	109	29585.25	29950.5	100.1856087
29950.5	30315.8	100	29950.5	30315.8	102	30315.8	30681	107	29950.5	30315.75	100.1856087
30315.8	30681	100	30315.8	30681	102	30681	31046.3	105	30315.75	30681	100.1856087
30681	31046.3	100	30681	31046.3	102	31046.3	31411.5	105	30681	31046.25	100.1856087
31046.3	31411.5	100	31046.3	31411.5	102	31411.5	31776.8	105	31046.25	31411.5	100.1856087
31411.5	31776.8	100	31411.5	31776.8	102	31776.8	32142	105	31411.5	31776.75	100.1856087
31776.8	32142	100	31776.8	32142	102	32142	32507.3	105	31776.75	32142	100.1856087
32142	32507.3	100	32142	32507.3	102	32507.3	32872.5	101	32142	32507.25	100.1856087
32507.3	32872.5	100	32507.3	32872.5	102	32872.5	33237.8	101	32507.25	32872.5	100.1856087
32872.5	33237.8	100	32872.5	33237.8	102	33237.8	33603	101	32872.5	33237.75	100.1856087
33237.8	33603	100	33237.8	33603	102	33603	33968.3	101	33237.75	33603	100.1856087
33603	33968.3	100	33603	33968.3	102	33968.3	34333.5	101	33603	33968.25	100.1856087
33968.3	34333.5	100	33968.3	34333.5	102	34333.5	34698.8	100	33968.25	34333.5	100.1856087
34333.5	34698.8	100	34333.5	34698.8	102	34698.8	35064	100	34333.5	34698.75	100.1856087
34698.8	35064	100	34698.8	35064	102	35064	35429.3	100	34698.75	35064	100.1856087
35064	35429.3	100	35064	35429.3	102	35429.3	35794.5	100	35064	35429.25	100.1856087
35429.3	35794.5	100	35429.3	35794.5	102	35794.5	36159.8	100	35429.25	35794.5	100.1856087
35794.5	36159.8	100	35794.5	36159.8	102	36159.8	36525	100	35794.5	36159.75	100.1856087
36159.8	36525	100	36159.8	36525	102				36159.75	36525	100.1856087

PB5			PB7			PB8		
Start Day	End Day	Recharge Salinity	Start Day	End Day	Recharge Salinity	Start Day	End Day	Recharge Salinity
0	365.25	0	0	365.25	0	0	365.25	0
365.25	730.5	0	365.25	730.5	0	365.25	730.5	0
730.5	1095.75	0	730.5	1095.75	0	730.5	1095.75	0
1095.75	1461	0	1095.75	1461	0	1095.75	1461	0
1461	1826.25	0	1461	1826.25	0	1461	1826.25	0
1826.3	2191.5	0.1	1826.25	2191.5	0	1826.25	2191.5	0
2191.5	2556.8	2.8	2191.5	2556.75	0	2191.5	2556.75	0
2556.8	2922	25.5	2556.75	2922	0	2556.75	2922	0
2922	3287.2	78	2922	3287.25	0	2922	3287.25	0
3287.2	3652.5	127.9	3287.25	3652.5	0	3287.25	3652.5	0.2
3652.5	4017.8	153	3652.5	4017.75	0	3652.5	4017.75	1.2

	PB5			PB7			PB8	
Start Day	End Day	Recharge Salinity	Start Day	End Day	Recharge Salinity	Start Day	End Day	Recharge Salinity
4017.8	4383	161	4017.75	4383	0	4017.75	4383	4.6
4383	4748.3	162.8	4383	4748.25	0	4383	4748.25	11
4748.3	5113.5	163.1	4748.25	5113.5	0	4748.25	5113.5	19.1
5113.5	5478.8	163.1	5113.5	5478.75	0	5113.5	5478.75	26.4
5478.8	5844	163.1	5478.75	5844	0	5478.75	5844	31.5
5844	6209.3	163.1	5844	6209.25	0	5844	6209.25	34.4
6209.3	6574.5	163.1	6209.25	6574.5	0	6209.25	6574.5	35.8
6574.5	6939.8	163.1	6574.5	6939.75	0	6574.5	6939.75	36.4
6939.8	7305	163.1	6939.75	7305	0	6939.75	7305	36.6
7305	7670.3	163.1	7305	7670.25	0	7305	7670.25	36.7
7670.3	8035.5	163.1	7670.25	8035.5	0	7670.25	8035.5	36.7
8035.5	8400.8	163.1	8035.5	8400.75	0	8035.5	8400.75	36.7
8400.8	8766	163.1	8400.75	8766	0	8400.75	8766	36.7
8766	9131.3	163.1	8766	9131.25	0	8766	9131.25	36.7
9131.3	9496.5	163.1	9131.25	9496.5	0	9131.25	9496.5	36.7
9496.5	9861.8	163.1	9496.5	9861.75	0	9496.5	9861.75	36.7
9861.8	10227	163.1	9861.75	10227	0	9861.75	10227	36.7
10227	10592.3	163.1	10227	10592.25	0.1	10227	10592.25	36.7
10592.3	10957.5	163.1	10592.25	10957.5	0.2	10592.25	10957.5	36.7
10957.5	11322.8	163.1	10957.5	11322.75	0.4	10957.5	11322.75	36.7
11322.8	11688	163.1	11322.75	11688	0.7	11322.75	11688	36.7
11688	12053.3	163.1	11688	12053.25	1.1	11688	12053.25	36.7
12053.3	12418.5	163.1	12053.25	12418.5	1.8	12053.25	12418.5	36.7
12418.5	12783.8	163.1	12418.5	12783.75	2.7	12418.5	12783.75	36.7
12783.8	13149	163.1	12783.75	13149	3.8	12783.75	13149	36.7
13149	13514.3	163.1	13149	13514.25	5.2	13149	13514.25	36.7
13514.3	13879.5	163.1	13514.25	13879.5	6.8	13514.25	13879.5	36.7
13879.5	14244.8	163.1	13879.5	14244.75	8.6	13879.5	14244.75	36.7
14244.8	14610	163.1	14244.75	14610	10.6	14244.75	14610	36.7
14610	14975.3	163.1	14610	14975.25	12.6	14610	14975.25	36.7
14975.3	15340.5	163.1	14975.25	15340.5	14.6	14975.25	15340.5	36.7
15340.5	15705.8	163.1	15340.5	15705.75	16.6	15340.5	15705.75	36.7
15705.8	16071	163.1	15705.75	16071	18.4	15705.75	16071	36.7
16071	16436.3	163.1	16071	16436.25	20.2	16071	16436.25	36.7
16436.3	16801.5	163.1	16436.25	16801.5	21.7	16436.25	16801.5	36.7
16801.5	17166.8	163.1	16801.5	17166.75	23.1	16801.5	17166.75	36.7
17166.8	17532	163.1	17166.75	17532	24.2	17166.75	17532	36.7
17532	17897.3	163.1	17532	17897.25	25.2	17532	17897.25	36.7
17897.3	18262.5	163.1	17897.25	18262.5	26	17897.25	18262.5	36.7
18262.5	18627.8	163.1	18262.5	18627.75	26.7	18262.5	18627.75	36.7
18627.8	18993	163.1	18627.75	18993	27.2	18627.75	18993	36.7
18993	19358.3	163.1	18993	19358.25	27.6	18993	19358.25	36.7
19358.3	19723.5	163.1	19358.25	19723.5	27.9	19358.25	19723.5	36.7
19723.5	20088.8	163.1	19723.5	20088.75	28.2	19723.5	20088.75	36.7
20088.8	20454	163.1	20088.75	20454	28.3	20088.75	20454	36.7
20454	20819.3	163.1	20454	20819.25	28.5	20454	20819.25	36.7
20819.3	21184.5	163.1	20819.25	21184.5	28.6	20819.25	21184.5	36.7
21184.5	21549.8	163.1	21184.5	21549.75	28.7	21184.5	21549.75	36.7
21549.8	21915	163.1	21549.75	21915	28.7	21549.75	21915	36.7
21915	22280.3	163.1	21915	22280.25	28.8	21915	22280.25	36.7
22280.3	22645.5	163.1	22280.25	22645.5	28.8	22280.25	22645.5	36.7
22645.5	23010.8	163.1	22645.5	23010.75	28.8	22645.5	23010.75	36.7
23010.8	23376	163.1	23010.75	23376	28.8	23010.75	23376	36.7
23376	23741.3	163.1	23376	23741.25	28.8	23376	23741.25	36.7
23741.3	24106.5	163.1	23741.25	24106.5	28.8	23741.25	24106.5	36.7
24106.5	24471.8	163.1	24106.5	24471.75	28.8	24106.5	24471.75	36.7
24471.8	24837	163.1	24471.75	24837	28.8	24471.75	24837	36.7
24837	25202.3	163.1	24837	25202.25	28.8	24837	25202.25	36.7

PB5			PB7			PB8		
Start Day	End Day	Recharge Salinity	Start Day	End Day	Recharge Salinity	Start Day	End Day	Recharge Salinity
25202.3	25567.5	163.1	25202.25	25567.5	28.8	25202.25	25567.5	36.7
25567.5	25932.8	163.1	25567.5	25932.75	28.8	25567.5	25932.75	36.7
25932.8	26298	163.1	25932.75	26298	28.8	25932.75	26298	36.7
26298	26663.3	163.1	26298	26663.25	28.8	26298	26663.25	36.7
26663.3	27028.5	163.1	26663.25	27028.5	28.8	26663.25	27028.5	36.7
27028.5	27393.8	163.1	27028.5	27393.75	28.8	27028.5	27393.75	36.7
27393.8	27759	163.1	27393.75	27759	28.8	27393.75	27759	36.7
27759	28124.3	163.1	27759	28124.25	28.8	27759	28124.25	36.7
28124.3	28489.5	163.1	28124.25	28489.5	28.8	28124.25	28489.5	36.7
28489.5	28854.7	163.1	28489.5	28854.75	28.8	28489.5	28854.75	36.7
28854.7	29220	163.1	28854.75	29220	28.8	28854.75	29220	36.7
29220	29585.2	163.1	29220	29585.25	28.8	29220	29585.25	36.7
29585.2	29950.5	163.1	29585.25	29950.5	28.8	29585.25	29950.5	36.7
29950.5	30315.7	163.1	29950.5	30315.75	28.8	29950.5	30315.75	36.7
30315.7	30681	163.1	30315.75	30681	28.8	30315.75	30681	36.7
30681	31046.2	163.1	30681	31046.25	28.8	30681	31046.25	36.7
31046.2	32872.5	163.1	31046.25	31411.5	28.8	31046.25	31411.5	36.7
32872.5	34698.7	163.1	31411.5	31776.75	28.8	31411.5	31776.75	36.7
34698.7	36525	163.1	31776.75	32142	28.8	31776.75	32142	36.7
		163.1	32142	32507.25	28.8	32142	32507.25	36.7
		163.1	32507.25	32872.5	28.8	32507.25	32872.5	36.7
		163.1	32872.5	33237.75	28.8	32872.5	33237.75	36.7
		163.1	33237.75	33603	28.8	33237.75	33603	36.7
		163.1	33603	33968.25	28.8	33603	33968.25	36.7
		163.1	33968.25	34333.5	28.8	33968.25	34333.5	36.7
		163.1	34333.5	34698.75	28.8	34333.5	34698.75	36.7
		163.1	34698.75	35064	28.8	34698.75	35064	36.7
		163.1	35064	35429.25	28.8	35064	35429.25	36.7
		163.1	35429.25	35794.5	28.8	35429.25	35794.5	36.7
		163.1	35794.5	36159.75	28.8	35794.5	36159.75	36.7
		163.1	36159.75	36525	28.8	36159.75	36525	36.7
		163.1			28.8			36.7
		163.1			28.8			36.7
		163.1			28.8			36.7
		163.1						36.7

UNITS OF MEASUREMENT

Units of measurement commonly used (SI and non-SI Australian legal)

Name of unit	Symbol	Definition in terms of other metric units	Quantity
day	d	24 h	time interval
gigalitre	GL	$10^{6\ m3}$	volume
gram	g	10^{-3} kg	mass
hectare	ha	$10^{4\ m2}$	area
hour	h	60 min	time interval
kilogram	kg	base unit	mass
kilolitre	kL	1 m^3	volume
kilometre	km	$10^{3\ m}$	length
litre	L	$10^{-3\ m3}$	volume
megalitre	ML	$10^{3\ m3}$	volume
metre	m	base unit	length
microgram	µg	10^{-6} g	mass
microlitre	µL	$10^{-9\ m3}$	volume
milligram	mg	10^{-3} g	mass
millilitre	mL	$10^{-6\ m3}$	volume
millimetre	mm	$10^{-3\ m}$	length
minute	min	60 s	time interval
second	s	base unit	time interval
tonne	t	1000 kg	mass
year	y	356 or 366 days	time interval

^{14}C carbon-14 isotope (percent modern carbon)

TDS total dissolved solids (mg/L)

GLOSSARY

Ambient. The background level of an environmental parameter (e.g. a background water quality like salinity).

Aquifer. An underground layer of rock or sediment which holds water and allows water to percolate through.

Aquifer, confined. Aquifer in which the upper surface is impervious and the water is held at greater than atmospheric pressure. Water in a penetrating well will rise above the surface of the aquifer.

Aquifer test. A hydrological test performed on a well, aimed to increase the understanding of the aquifer properties, including any interference between wells, and to more accurately estimate the sustainable use of the water resource available for development from the well.

Aquifer, unconfined. Aquifer in which the upper surface has free connection to the ground surface and the water surface is at atmospheric pressure.

Aquitard. A layer in the geological profile that separates two aquifers and restricts the flow between them.

Bore. *See well.*

DWLBC. Department of Water, Land and Biodiversity Conservation. Government of South Australia.

Evapotranspiration. The total loss of water as a result of transpiration from plants and evaporation from land, and surface waterbodies.

Groundwater. *See underground water.*

Hydrogeology. The study of groundwater, which includes its occurrence, recharge and discharge processes and the properties of aquifers. *(See hydrology.)*

Irrigation. Watering land by any means for the purpose of growing plants.

Irrigation season. The period in which major irrigation diversions occur, usually starting in August–September and ending in April–May.

Leaching. Removal of material in solution such as minerals, nutrients and salts through soil.

Megalitre (ML). One million litres (1 000 000).

ML. *See megalitre.*

Model. A conceptual or mathematical means of understanding elements of the real world which allows for predictions of outcomes given certain conditions. Examples include estimating storm runoff, assessing the impacts of dams or predicting ecological response to environmental change.

Natural recharge. The infiltration of water into an aquifer from the surface (rainfall, streamflow, irrigation etc.) *(See recharge area, artificial recharge.)*

Pasture. Grassland used for the production of grazing animals such as sheep and cattle.

Permeability. A measure of the ease with which water flows through an aquifer or aquitard.

Potentiometric head. The potentiometric head or surface is the level to which water rises in a well due to water pressure in the aquifer.

Prescribed water resource. A water resource declared by the Governor to be prescribed under the Act, and includes underground water to which access is obtained by prescribed wells. Prescription of a water resource requires that future management of the resource be regulated via a licensing system.

PWA. Prescribed Wells Area.

Recharge area. The area of land from which water from the surface (rainfall, streamflow, irrigation, etc.) infiltrates into an aquifer. *(See artificial recharge, natural recharge.)*

Underground water (groundwater). Water occurring naturally below ground level or water pumped, diverted or released into a well for storage underground.

Well. (a) an opening in the ground excavated for the purpose of obtaining access to underground water; (b) an opening in the ground excavated for some other purpose but that gives access to underground water; (c) a natural opening in the ground that gives access to underground water.

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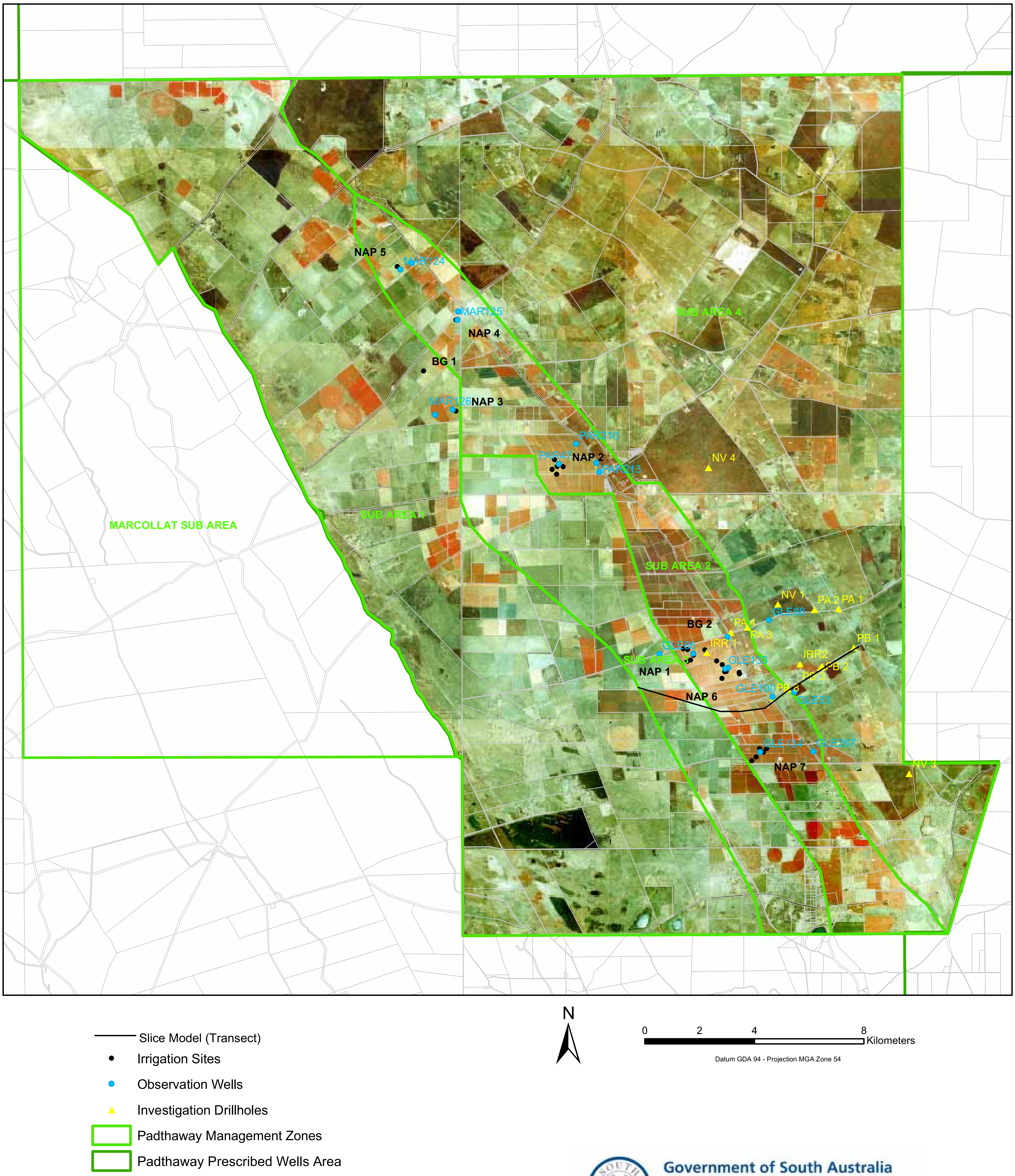
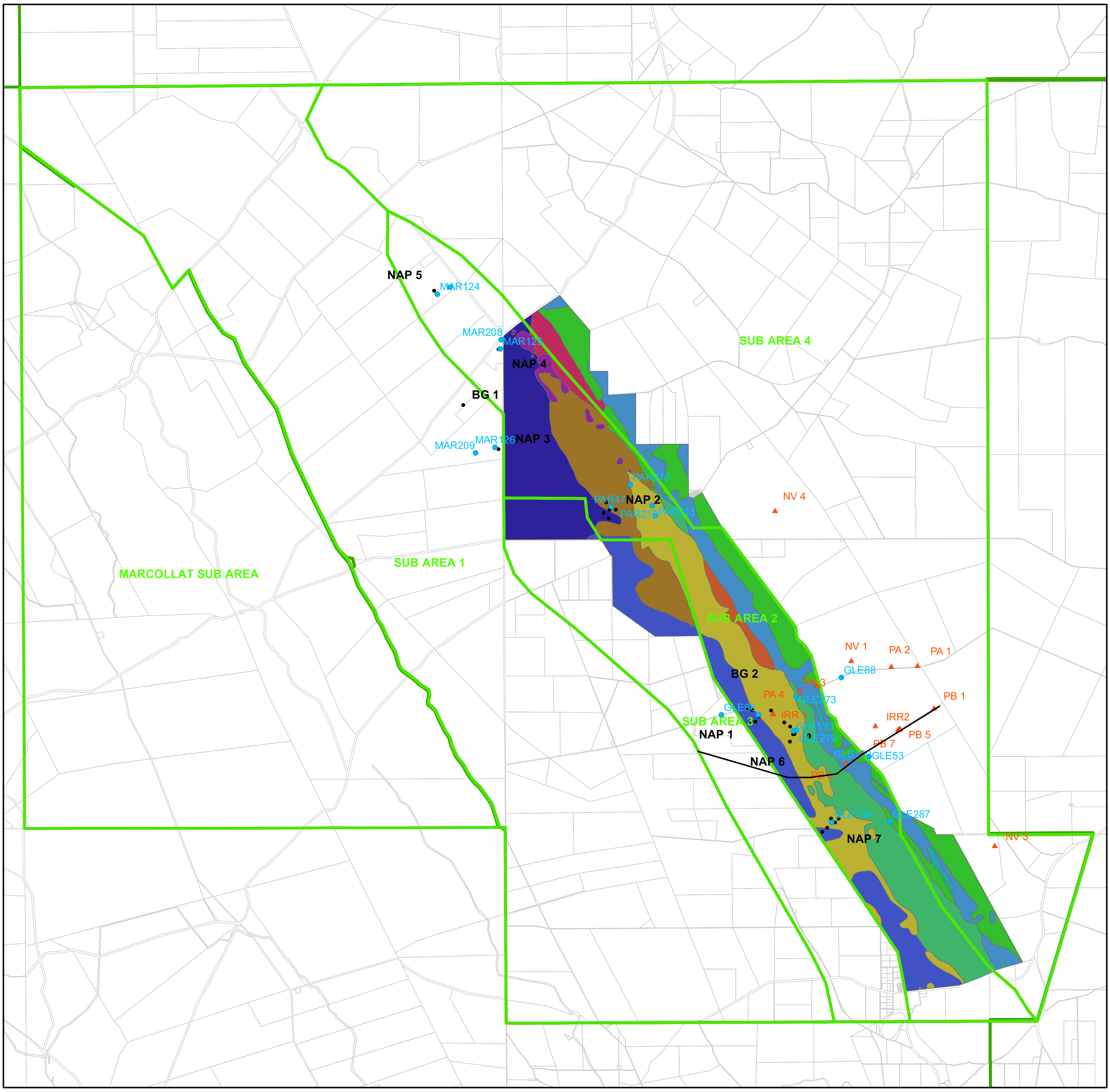


Government of South Australia
Department of Water, Land and Biodiversity Conservation

SALT ACCESSION TO THE PADTHAWAY IRRIGATION AREA

SITE PLAN

MAP 1



- Slice Model (Transect)
- Irrigation Sites
- Investigation Drillholes
- Observation Wells
- Padthaway Management Zones
- Padthaway Prescribed Wells Area

N

0 2 4 8 Kilometers

Datum GDA 94 - Projection MGA Zone 54

SYMBOL

- B
- C
- D
- G
- H
- L
- O
- P
- R
- S
- V

Refer to Wetherby and Armstron 1978
For a complete description of each soil unit

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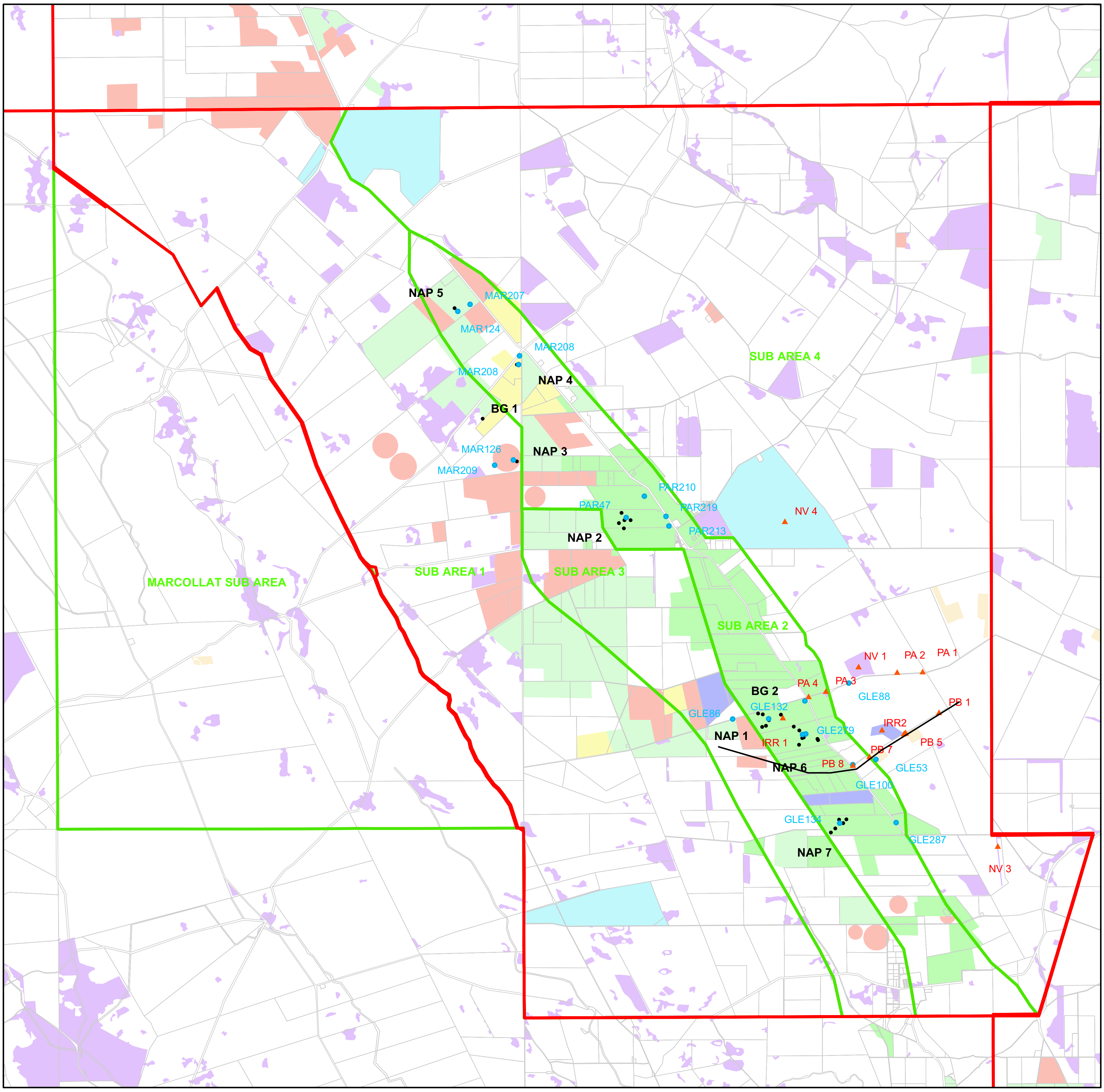
SALT ACCESSION TO THE PADTHAWAY IRRIGATION AREA

SOIL MAP OF THE PADTHAWAY IRRIGATION AREA

MAP 2



- Slice Model (Transect)
- Irrigation Sites
- Observation Wells
- Investigation Drillholes
- Padthaway Prescribed Wells Area
- Padthaway Management Zones
- Cereals
- Grazing modified pastures
- Irrigated cropping
- Irrigated hay & silage
- Irrigated modified pastures
- Irrigated pasture legumes
- Irrigated vegetables & herbs
- Irrigated vine fruits
- Natural feature protection
- Softwood plantation
- Woodland

N

0 2 4 8 Kilometers

Datum GDA 94 - Projection MGA Zone 54

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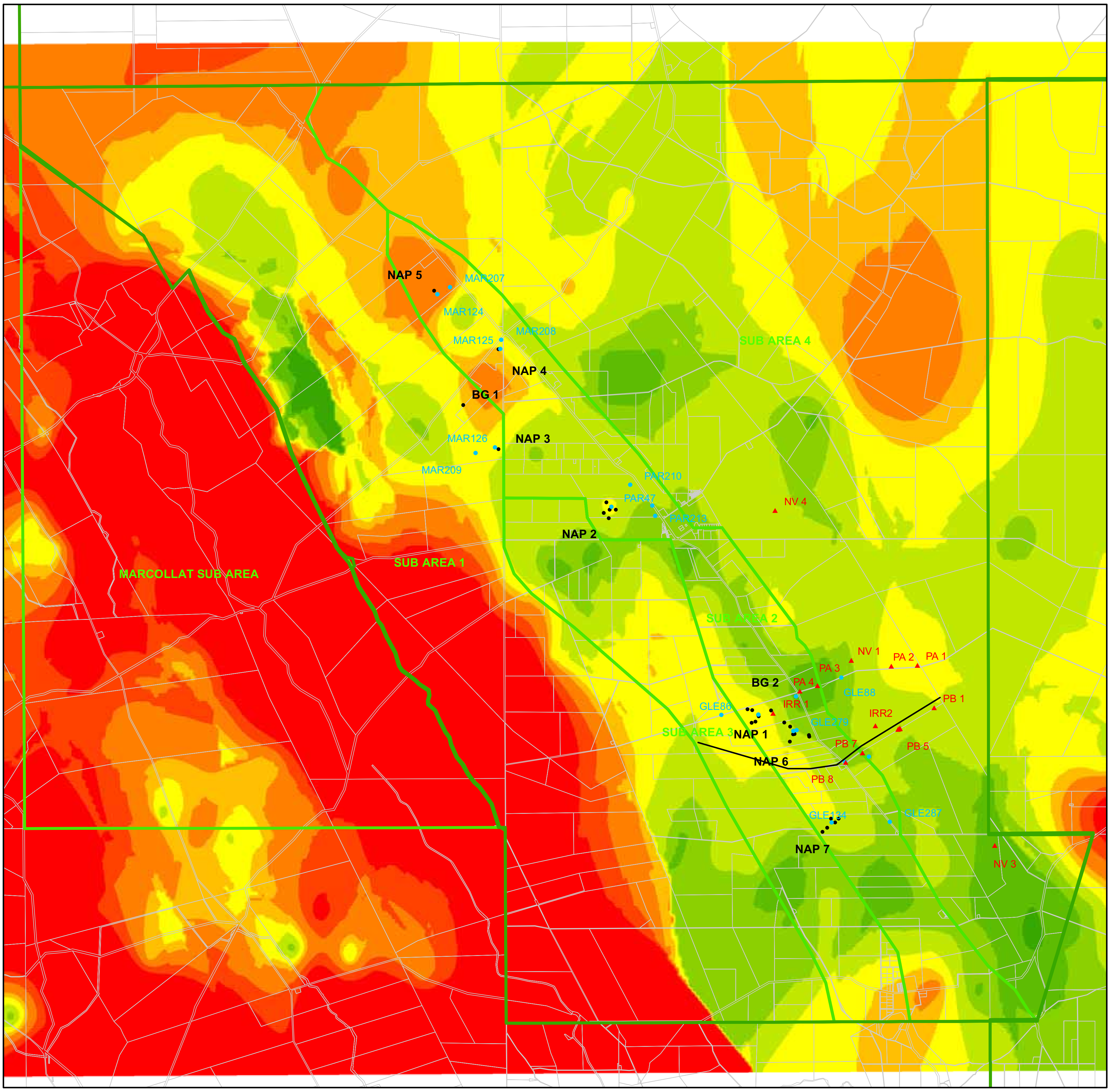
SALT ACCESSION TO THE PADTHAWAY IRRIGATION AREA

LAND USE IN THE PADTHAWAY PRESCRIBED WELLS AREA 2002

MAP 3



Slice Model (Transect)

Irrigation Sites

Observation Wells

Investigation Drillholes

Padthaway Prescribed Wells Area

Padthaway Management Zones

Groundwater Salinity (mg/l)

0 - 500

500.1 - 1,000

1,001 - 1,200

1,201 - 1,500

1,501 - 1,800

1,801 - 2,000

2,001 - 2,500

2,501 - 3,000

3,001 - 5,000

N

0 2 4 8 Kilometers

Datum GDA 94 - Projection MGA Zone 54

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SALT ACCESSION TO THE PADTHAWAY IRRIGATION AREA

CURRENT GROUNDWATER SALINITY OF THE UNCONFINED AQUIFER 2005

MAP 4