RICE CRC

FINAL RESEARCH REPORT

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Integration of 1401 Graduate Studies (Groundwater Management for Sustainable Farming Systems)

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SUMMARY

This report presents the integration of research studies carried out by the graduate students at UTS and UNSW as part of the CRC for Sustainable Rice Production Graduate Studies Program. It evaluates the methodologies and modelling scenarios in rice-based irrigation areas. Moreover, the report collates the research findings and conclusions to establish the benefits to rice industry. The main objective of the graduate studies was to develop strategies for managing groundwater for salinity mitigation at farm and regional scale. Through field experimentation and modelling approaches, the studies examined the impacts of land use on the environment and the effect of irrigation water with different quality levels on the rising watertable and the subsequent salinisation. These studies developed hydrogeological information base for rice growing areas mainly MIA (Murrumbidgee Irrigation Area) and WID (Wakool Irrigation District) has been developed that includes monitoring groundwater levels, groundwater quality, soil analysis and geophysical surveys.

The modelling exercises show strong interaction between shallow and deep aquifer. The simulations show significant rise in groundwater levels during the rice crop season and fall during the fallow season. Subsurface lateral groundwater flows are dominant from east to west; from Narrandera to Hay. Groundwater monitoring indicated a rapid response to rainfall as well as irrigation events with a recharge estimation of about 80% for the shallow aquifer and 50% for the deep aquifer. The shallow aquifer (2 m) responds slightly faster than the deep aquifer (7 m) to irrigation events. Groundwater quality at Whitton (M.I.A) is classified as brine and therefore not suitable for irrigation. However, the irrigation water was classified as fresh. Sodium, Sulfate and Chloride were the most abundant elements found in the four water samples.

The piezometers in irrigated paddocks showed substantially lower salinity indicating that irrigation water was recharging the aquifer. The deep aquifer piezometers monitoring displayed conductivity values of about 5 to 6 ms/cm. The geophysical resistivity imaging has shown a great promise for developing understanding about surface-ground water interactions and salinization. Large spatial variations in apparent resistivity were observed in irrigated and non-irrigated areas. Resistivity decreases with depth in a linear fashion. Variations in resistivity have been noticed in the upper 10 metre layer of soil indicating recharge zone. Increase of resistivity closer to rice paddocks during irrigation is due to the fresh water infiltrating to the aquifer. Irrigation events resulted in decreased resistivity at most depths, particularly at 15 m that reflecting rising water table or input of fresh water from the irrigated paddocks. These studies have shown a strong correlation between resistivity and electromagnetic responses from EM31 and EM34.

The MODFLOW model developed by the UTS graduates with a 10 m minimum discretisation and a refined time scale (2 days stress period) simulated the groundwater dynamics with 80% accuracy. Six key parameters are identified influencing the system. They include rice ponding, precipitation, drainage, evapotranspiration deep leakage and lateral groundwater flow. The solute transport model revealed that the groundwater salinity is controlled by rising groundwater levels due to rice ponding. Salinity concentration is higher in top 2 metres below

ground surface. The solute transport model has successfully simulated salinity trends. The irrigated areas are affected by irrigation water salinity. The salinity of top 3 m profile is higher and decreases with depth. Groundwater salinity ranges from 1500 mg/l directly below and is approximately 2500 – 3000 mg/l in the fallow paddocks adjacent to the rice pond.

According to the optimization results, an extensive bore network of several hundred pumping bores at shallow depths would be necessary to lower water levels around the irrigated area. However, it impossible to pump out the necessary groundwater volumes in order to lower water table to the targeted levels in low permeability areas as vertical hydraulic conductivity is one order of magnitude lower than horizontal hydraulic conductivity.

The UNSW PhD (Xu, 2003) study in Wakool region predicted that about 2 kg/m2 salt will be added to root zone per one rice crop per season. This prediction quantifies to 20 t/ha per crop season each year. Moreover, if repeated irrigation with saline water is practiced, the salt concentration in root zone will continue to increase with time, which is alarming for future of rice industry. Therefore, careful decisions need to be done while working out the soil suitability for rice growers regarding existing soil salinity and the EC levels in irrigation water.

The ponded rice irrigation is a major contributing factor to groundwater accessions resulting in rising watertables and subsequent salinity problem. The alternative use of fresh and low salinity water could be practiced on short-term basis for ponded irrigation as long as it does not affect rice growth or rice yield. This will help remove accumulated salts in the root zone by fresh water irrigation after the irrigation with water containing salts.

The six graduate modelling studies described in this report are site specific. Efforts to apply these methods to other farms or regions will need to incorporate site specific information on cropping, topography and groundwater systems to describe and calibrate the salinisation processes.

1. Background

The CRC for Sustainable Rice production funded graduate research projects at University of Technology, Sydney and University of New South Wales, Sydney for gaining in-depth knowledge of the waterlogging and salinity impacts on rice based farming system in the riverine plains. This research work was carried out by one Ph.D. and five M.Sc. students. The main objective of the research was the estimation of salt transport and salinisation in rice based irrigation areas and to develop management strategies for reducing further risks to land salinisation. The overall study was carried out in four stages that included one Ph.D. thesis by UNSW (Xu, 2003) and five MSc theses by UTS students (McLachlan, 2000, Hudson, 2000, Hautefeuille, 2001, Lloyd, 2002 and Mahamud, 2002). The four stages of this study are listed below:

Stage 1: To monitor and examine the dynamics of groundwater and salinity adjacent to a rice paddock during a growing season. The heterogeneity of the project site was examined using 3 dimensional resistivity imaging. This stage was completed by Megan McLachlan (MSc Student at UTS)

Stage 2: To develop a MODFLOW/MTD3D model of groundwater flow and solute transport at paddock scale and at short time scale (1 to 7 days stress period). This stage was completed by Anita Hudson (MSc Student at UTS)

Stage 3: To develop a management model at the farm scale and to address options for reducing salt discharge to groundwater. This was resolved by the application of two modelling approaches, i.e. a numerical model and an analytical approach through the application of the HOTSPOTS software developed by Dr Noel Merrick.

Stage 4: To examine the impacts of land use on the environment and the effect of irrigation water with different quality levels on the rising watertable and the subsequent salinity problem in Wakool/Tullakool Irrigation Area. A computational model is developed consisting of ALSIS (Atmosphere Land Surface Interaction Scheme), MODFLOW (Modular Finite-Difference Groundwater Flow Model), MOC3D (A Three Dimensional Method of Characteristics Solute Transport Model), DAFLOW (Diffusion Analogy Surface-Water Flow Model) and two new modules for simulating solute transport in unsaturated zone and for calculating the spatial and temporal distributions of overland flow during wet season. This work is completed by Peng Xu (PhD student at UNSW)

1.1 Project Sites

1.1.1 Location 1

The project area is located near Whitton, approximately 30 km southeast of Griffith in the Riverina area of NSW. The CRC trial site is located 10 km east of Whitton, NSW (Paddock) (Figure 1). The field layout as described by Figure 2 consists of three laser graded paddocks at slope of 1:4000 in westerly direction. The observation paddocks remain fallow till October when rice growing commences in the area. The rice paddocks are supplied by gravity fed water at the south-eastern corner of each paddock. The main drain, located on the northern boundary of the study area, is a mixture of irrigation supply fresh water and bore water. The drain located to the west of the fallow paddocks is the overflow from the flooded rice paddock and drains into the main drain at the southwest corner of the trial site.

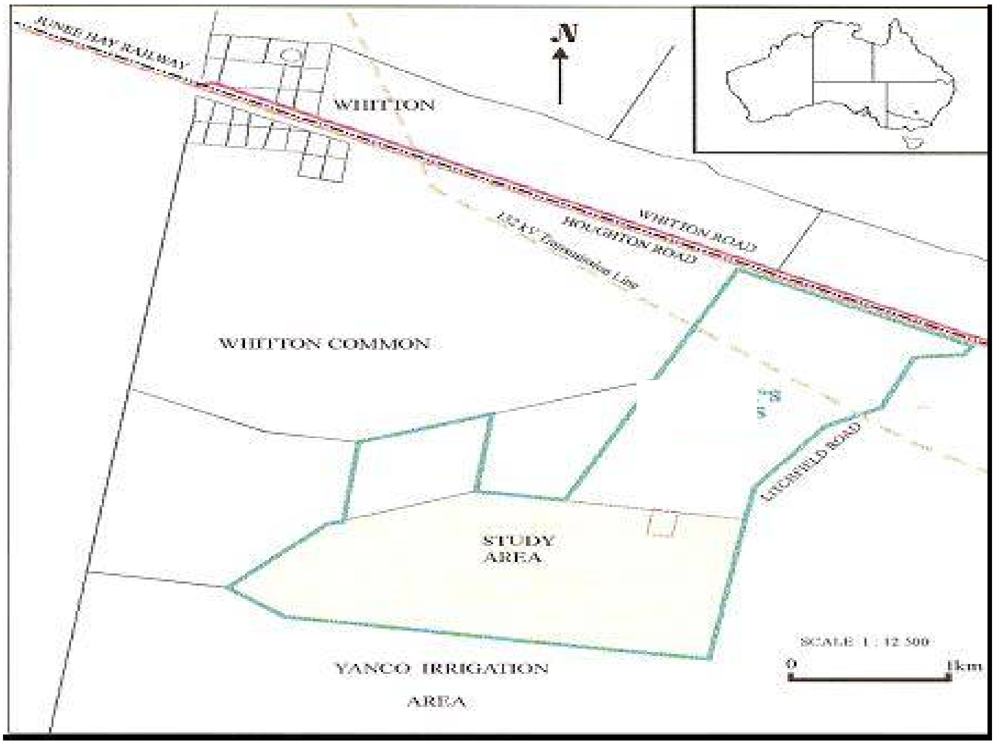


Figure 1: Study area location

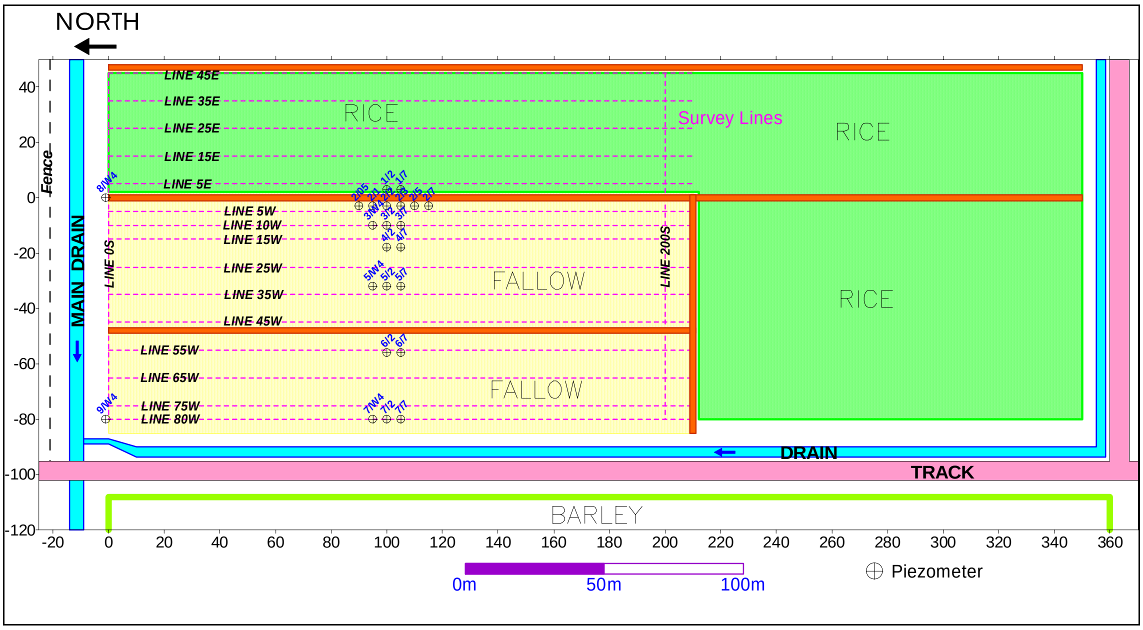


Figure 2: Whitton CRC Rice Trial Site (Paddock 39)

1.1.2 Climate

The study area receives an average annual rainfall of 356 mm. It is characterized by hot summers with high evapotranspiration rate and cold winters. Figure 3 shows rainfall-evapotranspiration variations as recorded at Yanco Agricultural College for the period October 1998 – October 2000 (Period of survey).

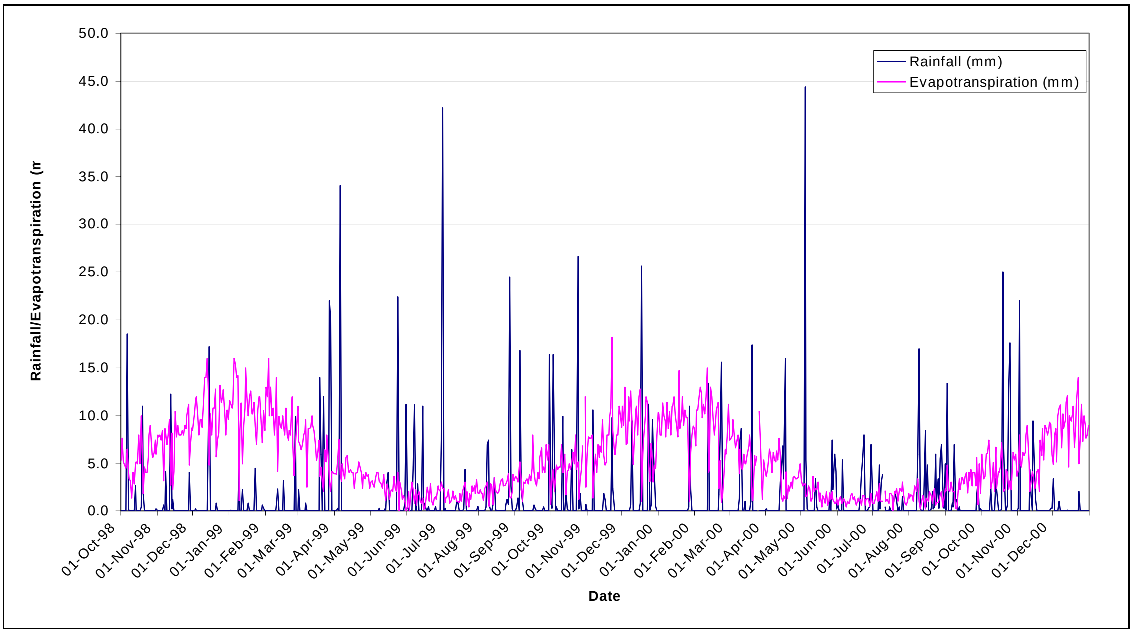


Figure 3: Evapotranspiration / Rainfall variation at Yanco

1.1.3 Geology

The trial site located in the eastern part of the Murray basin is marked by the outcropping of the bedrock constituting the foothills of the highland areas to the east and southeast which are the sources of the Murray, Murrumbidgee and Lachlan rivers as well as their tributaries. Brown and Stephenson (1991) categorized the sediments based on age and type of deposition into 3 units, The Renmark group which consists of unconsolidated to poorly consolidated fluvio-lacustrine sand silt and clay deposited between the middle Eocene and early Oligocene, its horizontal conductivity averages between 10-30 m/day (Evan and Kellet, 1989); The Calivil formation which consists of sand and gravels with lenses of kaolin and carbonaceous clay deposited by the ancient Murray river system during the middle Miocene, it is considered to be quite transmissive with an average hydraulic conductivity of 130 m/day (Prathapar et al. 1997); And the Shepparton formation which consists of fluvio-lacustrine clay, silt and sand deposited between the Pliocene and the Quarternay age (Brown, 1989), it is considered as a poor producer of groundwater due to the discontinuous nature of its sands, its hydraulic conductivity is estimated at 2-3 m/day (Evans and Kellet, 1989). (Figure 4).

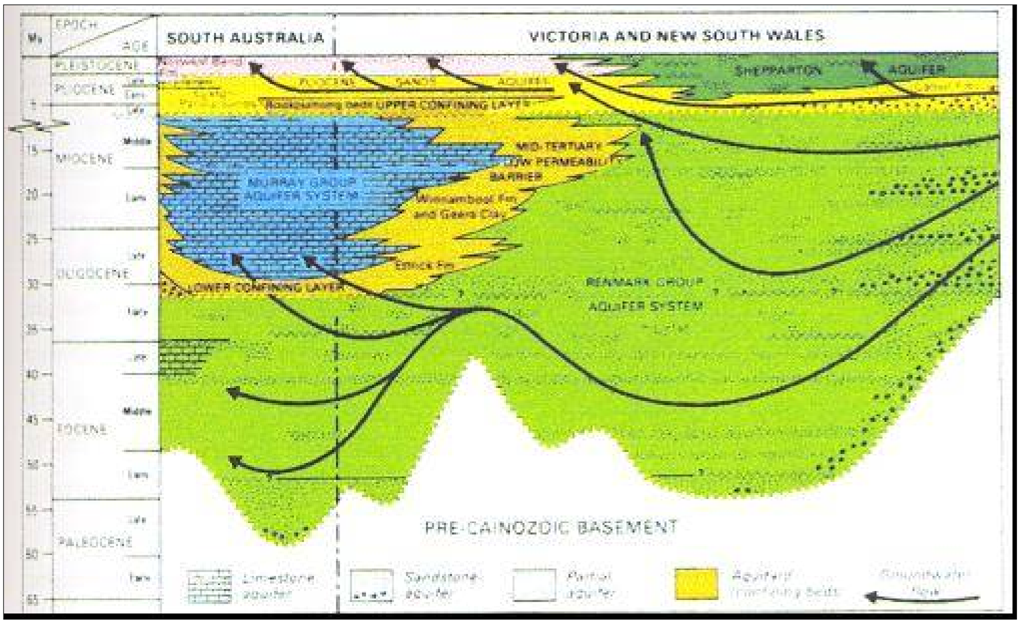


Figure 4: Regional Geology

1.1.4 Soil Characteristics

A soil survey was conducted at two sites in the study area (Eastern side and Western and central side) to identify soil characteristics such as colour, texture, pH, moisture, conductivity and salinity. Soil samples were collected at 0.25 m intervals down to a depth of one metre. Two different soil types at the two sites in the field, the western and central sections are found to be Gogeldrie Clay, and the Eastern section is found to be Mundiwa clay loam. The normalization used in this analysis was as follows (Table 1):

TABLE 1
PARTICLE SIZE RANGES FOR VARIOUS SOIL TYPES

Soil type	Particles size
Coarse Sand	> 0.2 mm
Fine sand	0.02 – 0.2 mm
Silt	0.002 – 0.02
Clay	< 0.002

The visual variations in soil colour across the study site are marked by the Mundiwa series to the east and the Gogeldrie series to the west. The location and soil profile of the study site are shown in Figures 1, 2 and 4. Colour classification in the Munsell soil colour chart was used. Soil colour and PH results are shown in Table 2.

TABLE 2
SOIL COLOUR AND PH IN MIA

	Depth(m)	Hue[1]	Value[2]	Chroma[3]	Colour Name	pH & Description
LOCATION 1	0.25	5YR	4	4	Reddish brown	8.5 Strongly Alkaline
	0.50	5YR	4	4	Reddish brown	8.5 Strongly Alkaline
	Mottles	7.5YR	7	0	Light Grey	
	0.75	5YR	3	4	Reddish brown	9.0 Strongly Alkaline
	1.00	7.5YR	5	4	Brown	9.0 Strongly Alkaline
LOCATION 2	0.25	5YR	4	6	Yellowish Red	9.0 Strongly Alkaline
	0.50	5YR	4	6	Yellowish Red	9.0 Strongly Alkaline
	0.75	2.5YR	4	4	Reddish brown	9.0 Strongly Alkaline
	1.00	5YR	4	6	Yellowish Red	9.0 Strongly Alkaline

(Munsell colour company, Inc 1954)

Soil Texture:
Soil from survey 1 and 2 were classified respectively as clay and clay loam.

Soil Moisture:
The soil moisture estimated at site 1 and 2 is given in Table 3.

Soil Salinity:
The soil salinity at site 1 and 2 is reported in Table 4.

[1] Represent the dominant spectral colour (range 1 to 9)
YR: Represent the zone the colour fall into on the chart
[2] Measurement of the lightness of the colour (range 0 to 9)
[3] Represent the relative purity or strength of the colour (range 0 to 9)

TABLE 3
SOIL MOISTURE (YEAR 1999)

	Depth(m)	*Wet Weight (g)*	*Dry Weight (g)*	*Moisture(g)*	*% Moisture*
LOCATION 1	0.25	554.2	434	120.2	21.7
	0.50	738.7	578.9	159.8	21.6
	0.75	791.1	621.9	169.2	21.4
	1.00	670.6	529.8	140.8	21.0
LOCATION 2	0.25	501.5	381.6	119.9	23.9
	0.50	562.7	431.0	131.7	23.4
	0.75	563.5	433.1	130.4	23.1
	1.00	544.4	417.9	126.5	23.2

TABLE 4
SOIL SALINITY (YEAR 1999)

Site	*Depth (m)*	*Conductivity $EC_{1:5}$ (mS/cm)*	*Conductivity Ece (mS/cm)*	*Salinity (mg/L)*
LOCATION 1	0.25	956	8221	463
	0.50	1125	9675	546
	0.75	945	8127	455
	1.00	736	6329	352
Average		940	8088	454
LOCATION 2	0.25	1391	11962	682
	0.50	2258	19418	1130
	0.75	1176	10113	577
	1.00	1986	17079	989
Average		1702	14643	844

1.1.5 Location 2

The Wakool Irrigation District (WID) and the Tullakool Irrigation Area (TIA) are located on the riverine plain of southern NSW. The WID was proclaimed an irrigation district in 1939 following the completion of the Stevens Weir on the Edward River. The Wakool Irrigation District, southwest NSW, extends in the central part of the Murray-Darling Basin. It is bounded by the Wakool River in the south and the Edward River in the north (Figure 5).

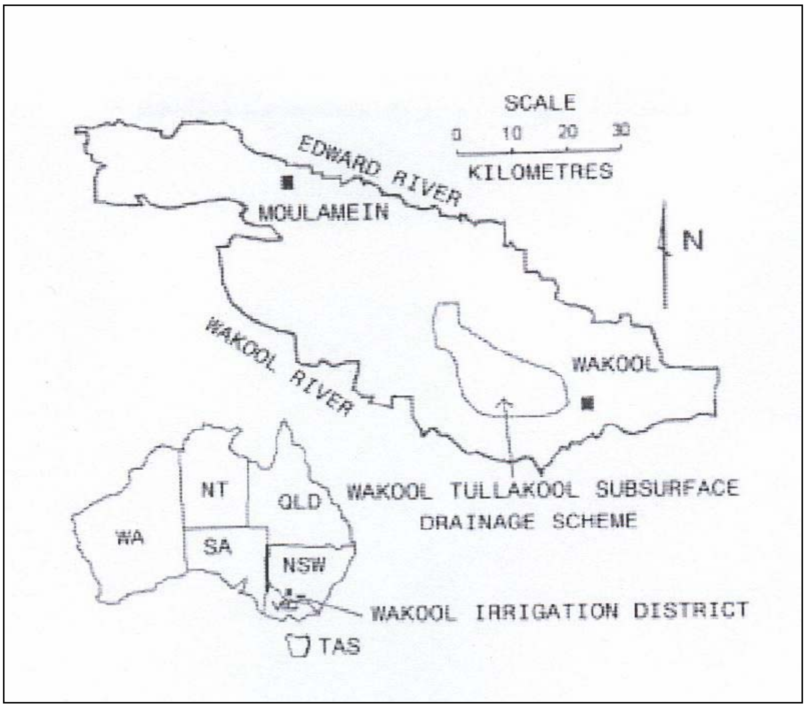


Figure 5: Location of Wakool Irrigation District

The Wakool Catchment (35.5º S, 144.0º E) is a major source of agricultural production. Total catchment area is approximately 3,200 km2. The topography is slightly sloped from southeast to northwest direction. The climate is semi-arid with average annual rainfall of 360 mm of which heavy rains occur during June to August.

The major hydrological formations are the Shepparton, Calivil and Renmark. The Shepparton constitutes the upper aquifer while Calivil and Renmark make the deep aquifer system. The soil types in Wakool region are: 1 - grey soil subject to inundation, 2 - grey brown earth soil, 3 - red brown earth and 4 - sandhills as presented in Figure 6. The soil properties are explained in Table 19.

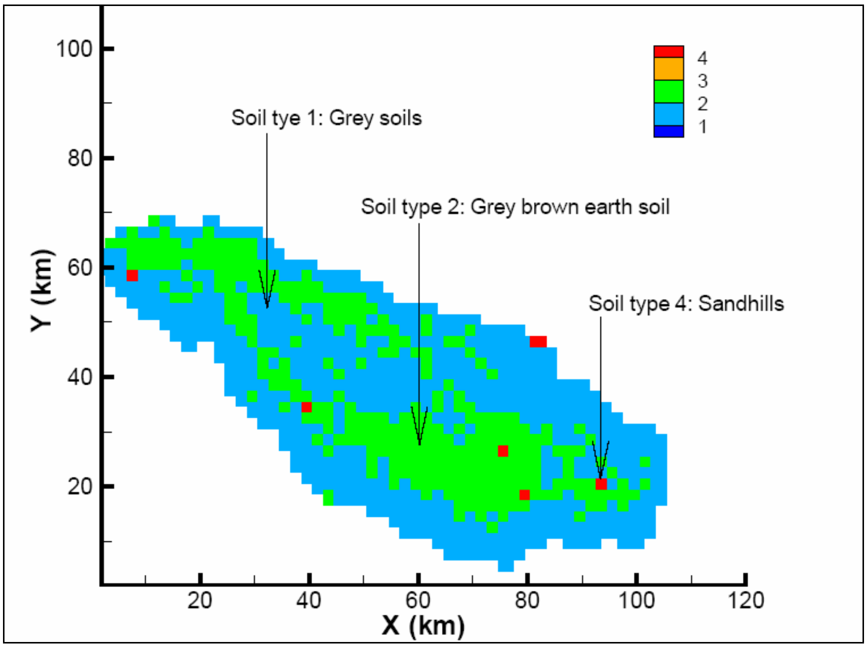


Figure 6: Spatial variation of soil types in Wakool region

The current extent of irrigated agriculture is expanded to 220,000 ha. Crops growing in this region include rice, summer crops (perennial), autumn crops and natural pasture as shown in Figure 7.

The recharge through rainfall and repeated irrigations has caused a rise in the watertable (<2m) from 7,200 ha to 47,500 ha during 1960-75. The Wakool Tullakool Sub-Surface Drainage Scheme has partially reduced the problem but an area of 26,000 ha is still affected by shallow watertable and under continuous threat of salinisation due to saline groundwater and present irrigation practices. Given the unique hydrogeology of the area, the effects of irrigation on groundwater and resulting salinisation are of particular interests.

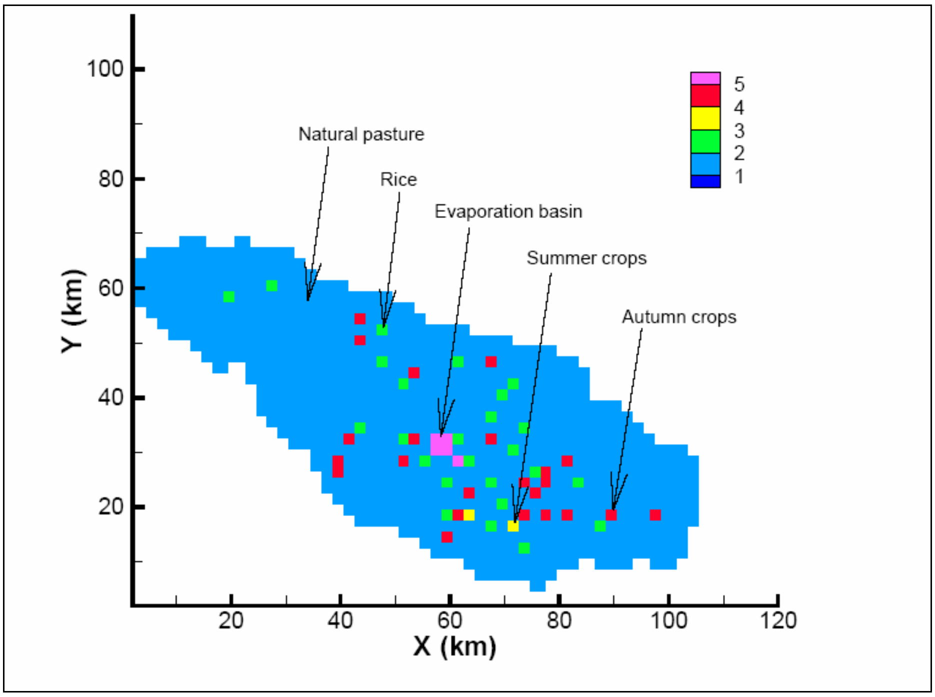


Figure 7: Spatial distribution of crops in Wakool Irrigation District

In 1944, the average depth to watertable was 8 m in the WID and TIA 8 years after the commencement of irrigation. The average annual increase in watertable was 8 cm during 1945-81. The watertable reached the stage that thousands of hectares had become unproductive through salinity by 1970's. In 1981, 32,300 ha. of land had watertable within 2 m of the soil surface. In 1992, shallow groundwater salinity in the area was commonly 30 dS/m, ranging from 1 dS/m to over 60 dS/m, with approximately 2 % of the district being less than 5 dS/m. By comparison, the salinity of seawater is approximately 50 dS/m (Willinck et al., 1992). During early 1990s, the land area influenced by rising watertable had 18 % low, 48 % moderate and 34 % high to extreme soil salinity compared to natural salinity accounted for the WID and TIA of 68 % low, 27 % moderate and 5 % high to extreme (Willinck et al., 1992). Most recent figures indicate that 13 % and 63.1 % of land affected by watertable is within 2 m and 4 m respectively (EPA, 2003).

Wakool is predicted to have 42200 ha of watertable within 2 meters of the surface by the year 2025. This will be more than 18000 ha increase over the high watertable area of 23600 ha during 1995 (Wakool LWMP Working Group, 2001). These concerns about expanding high watertable areas, land salinisation, the role of groundwater pumping and

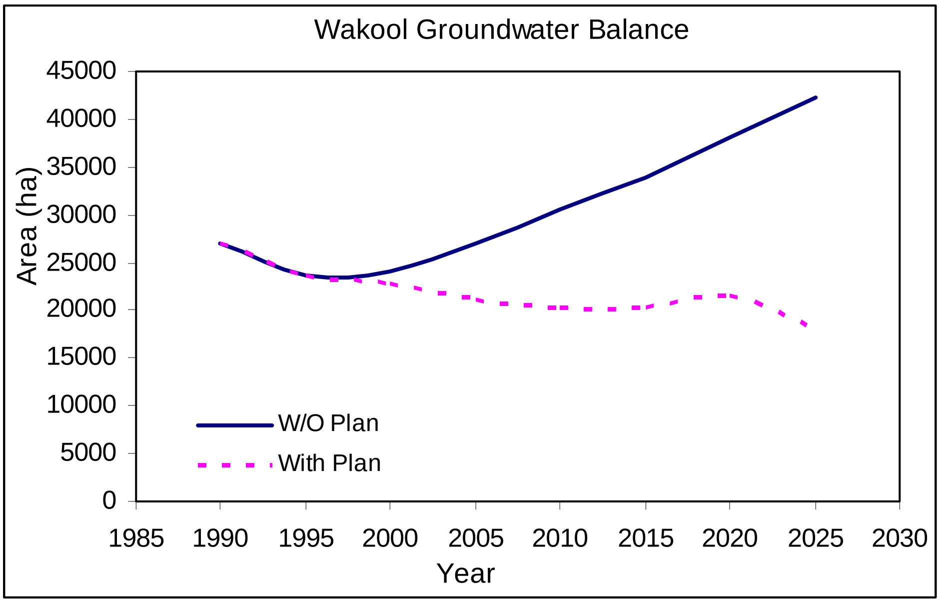


Figure 8: Wakool Groundwater Balance Predicting High Watertable Area "With" and "Without" LWM Plan

the region's sustainability led to developing intensive research tools that help policy making for framing and reviewing Wakool Land and Water Management Plans.

1.2 Limitations of Simulation Studies

1.2.1 One Dimensional Simulation at Local Scale

The area under consideration is specified for rice crop. No crop grows after harvest until the start of next rice season. The rice-growing season is of 6 months starting from early October to the end of March next year. The rice is grown under ponding irrigation. The water quality of irrigation is not known and four scenarios have been developed for testing the impact of water quality on soil salinity.

1.2.2 Three Dimensional Simulation at Regional Scale

The Wakool Irrigation District is selected to get insight about the impact of land use on salinity and effects of irrigation with different water qualities on salinisation process at regional scale. The whole area of WID is 320,000 ha and area under irrigation was 208,000 ha in 1993 (EPA) and 220,000 ha in 1999 (Demetriou, 1999). There is no such calculation from the GIS analysis in results that indicates the extent of area under simulation.

2. Objectives

2.1 The key objectives of the overall study are listed below:

- To evaluate the computational modelling system for groundwater management and prediction of salinisation in irrigated areas.
- To evaluate scenario options used in the simulations and investigate the impact of irrigation and land use on salinisation in root zone.
- To examine the connections between land use, ponding irrigations and irrigation water quality and groundwater accessions.
- To view the benefits to rice industry for sustainable rice production.

2.2 Modelling of Risk-based Irrigation Management

Many techniques for land salinity prediction have been developed. Among these methods, mathematical modelling using high-speed computers is fast, reliable and trustworthy technique but it depends upon the assumptions, scenarios, adequacy and precision of input data. Simulation models incorporate variety of input data that include satellite and digital elevation model data, establishing water balance budget and using climatic parameters. The mathematical models are of two types: analytical models and numerical models. The numerical modelling is both cost-effective and efficient in assessing the impacts of land use on the environment and for predicting the impact of land use management options. Numerical models, once calibrated with observed data, can be applied to studying regional scale problems and to generating continuous data under given land use practices and climatic conditions. This study is focused to developing a better understanding of how salt is transported and accumulated in the root zone using numerical models under rice based farming system.

3. Introductory technical information

3.1 Field Monitoring of Groundwater Levels and Water Quality at Farm Level

3.1.1 Groundwater Level using Data Loggers in MIA

A total of 16 data loggers were installed in October 1999 to take measurements every hour. The frequency of measurements changed to 6 hourly from July 2000. Data was not recorded between April 2000 and July 2000 due to a failure of equipment. (See Figure 2 for locations of piezometers).

Initially, the water table depth was 0.72 m below the surface with no water in the rice bays. After flooding occurred, the water table went up slowly over a few days which indicated low infiltration rate in the soils (heavy clay). During ponding, infiltration rate increased to a maximum sustained rate corresponding to the saturated hydraulic conductivity of the soil. Similarly, the water table decreased back to its initial measurement of 0.7 m below the surface at the end of the ponding.

Rainfall events over 10 mm/d were observed to affect groundwater levels in about 2 days after the event. There existed a strong interaction between groundwater and water in the rice bay. Figure 9 shows the response of groundwater to ponded water recorded at piezometer 1/2 (located directly in the rice bay). Further away from the rice bay groundwater levels response to irrigation became minimal as shown by the record at piezometers 6/7 and 7/7 (Figure 10).

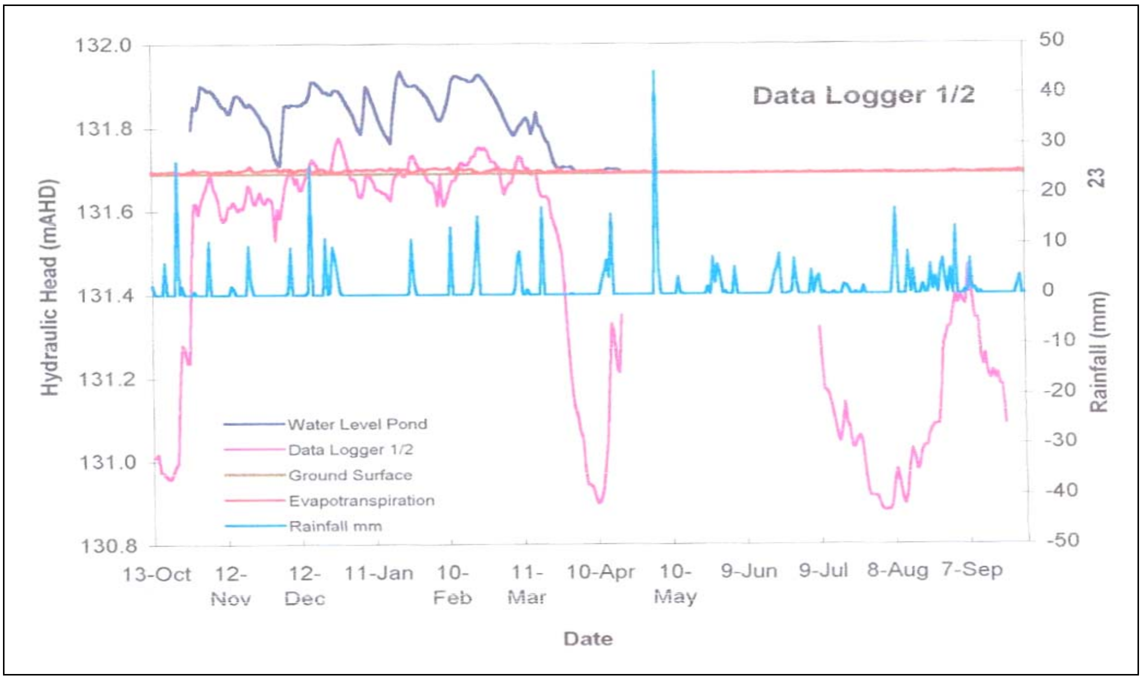


Figure 9: Daily Watertable Hydrograph for Piezometer 1/2

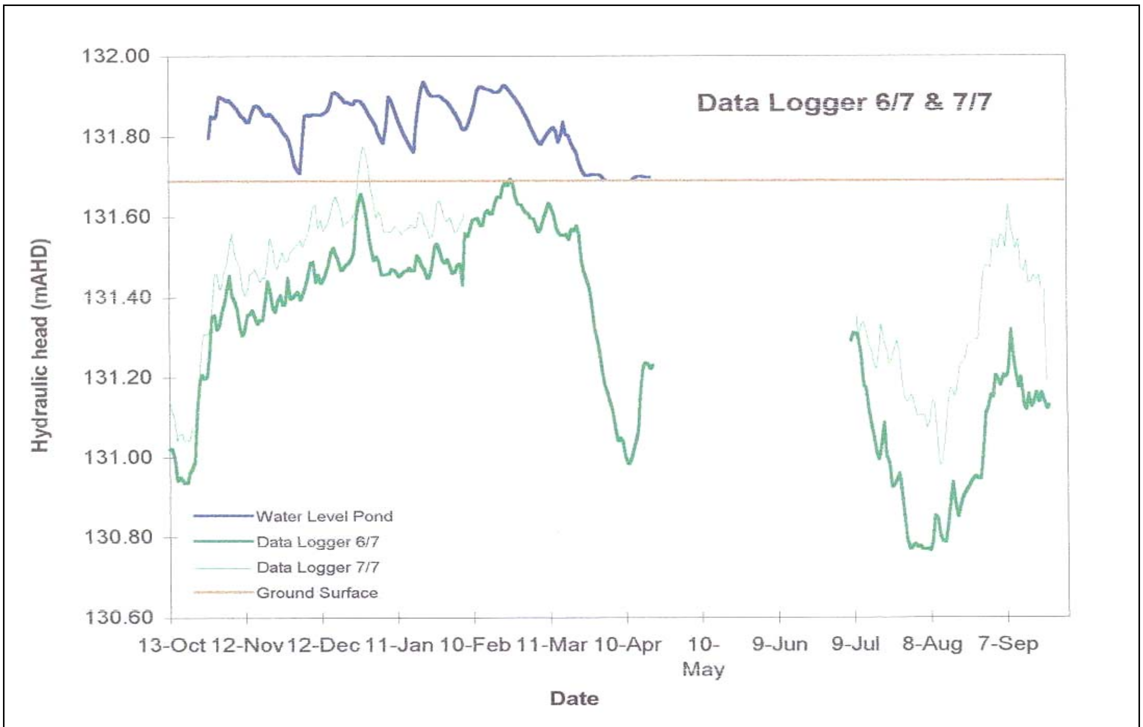


Figure 10: Daily Watertable Hydrographs for Piezometers 6/7 and 7/7

3.1.2 Topography and Groundwater Levels in WID

The topography and initial depth to groundwater in the upper Shepparton Formation (surface layer) for the Wakool area are shown in Figure 11. In the surface layer, groundwater flow direction is from the southeast to northwest. This feature can be easily seen to be reasonable because of the slope of topography and the initial piezometric head.

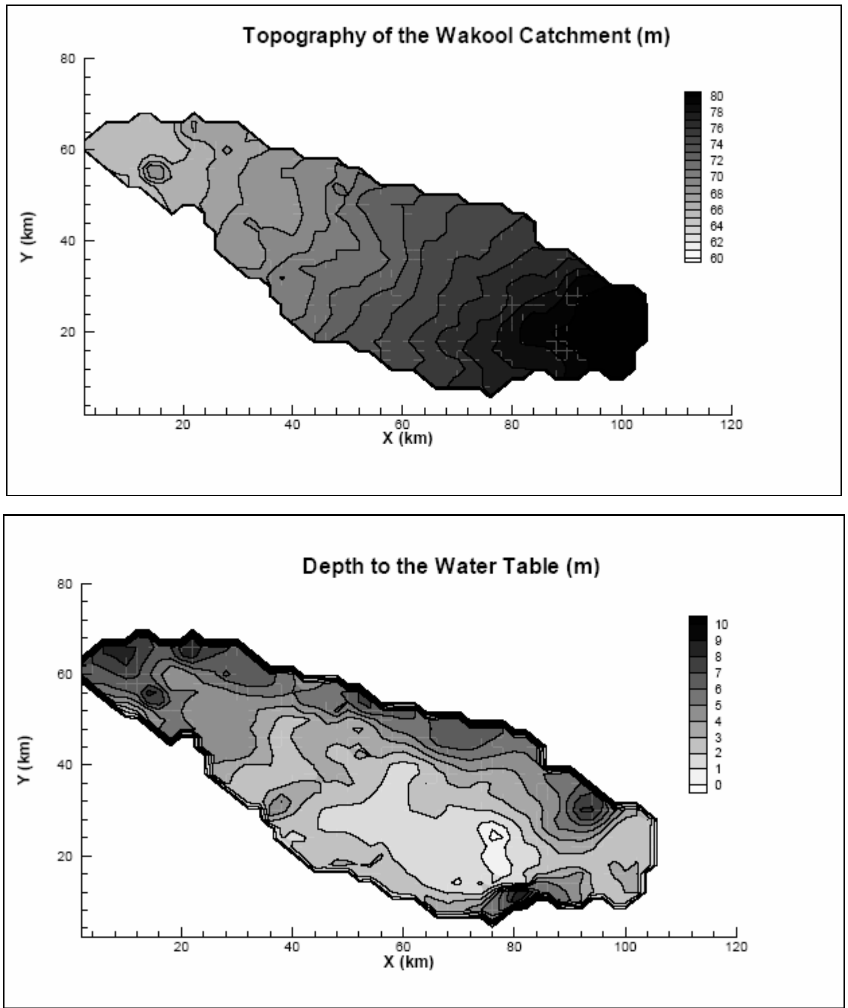


Figure 11: Topography and initial depth to watertable for the Wakool Catchment

In the Wakool irrigation area, there are more than a thousand groundwater level observation bores. Historical measurements of groundwater levels are screened in the sandy layers of the Shepparton Formation. Among these, 128 bore records of groundwater level time series in different locations distributed over the WID are selected. The data record interval is 6 to 8 months. The selected bore records are re-grouped into each grid square according to their locations (latitude, longitude). In the grid square where more than one observation bore exist, the average is taken and used as one measurement. Figure 12 shows the comparison of observed groundwater levels with model results.

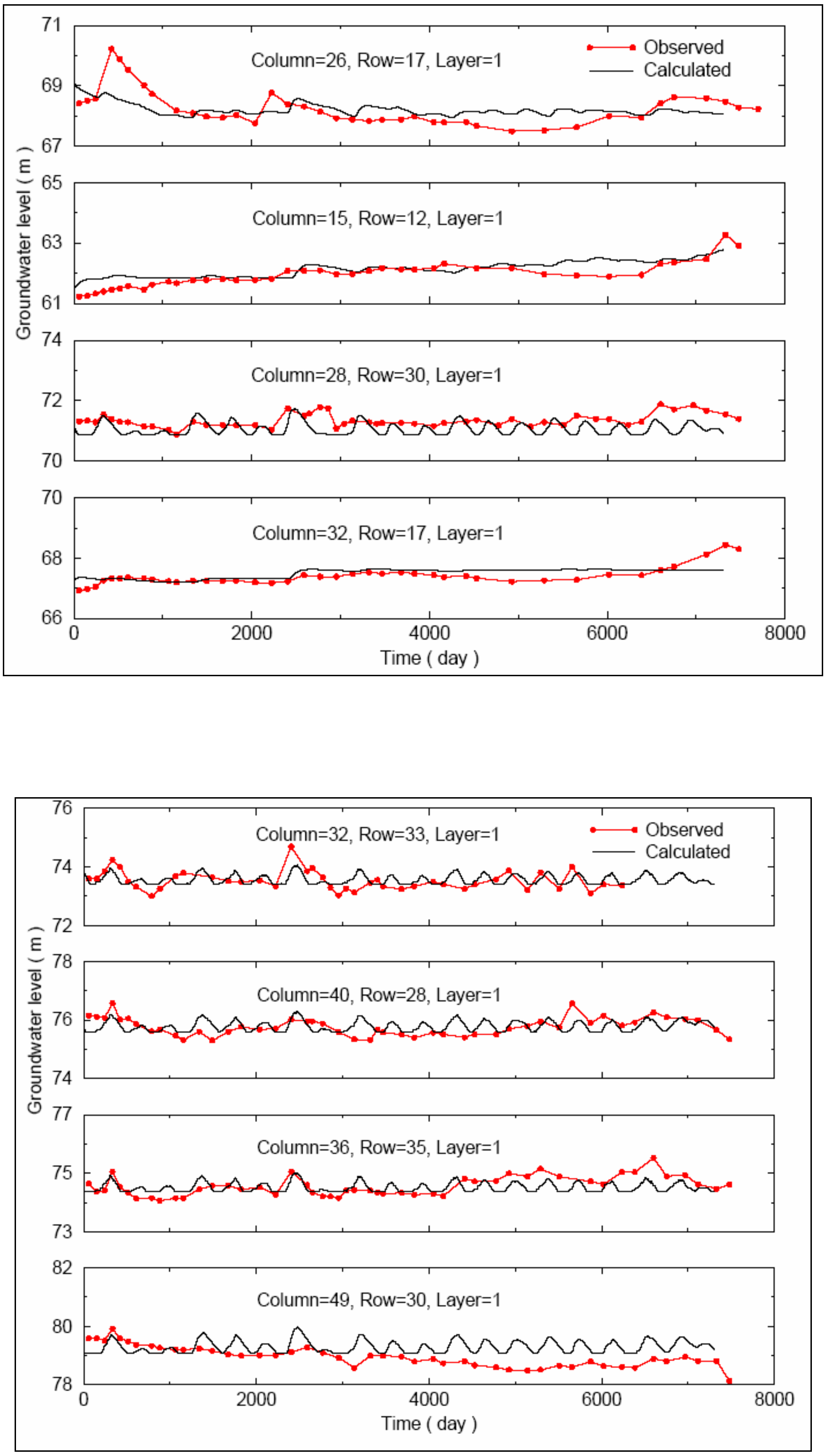


Figure 12: Comparison of observed and predicted groundwater levels for different locations in the Wakool Irrigation District

3.1.3 Groundwater Flow Directions

Groundwater flows are in the direction East to West. Water elevations recorded at piezometers 1/2, 1/7 and 2/2, 2/7 (directly under the rice bay) indicate downward vertical flow component during the first rice ponding. The piezometers adjacent to the rice bay show downward flow from layer 1 to 2 followed by vertical flows from layer 2 to 1.

During the fallow season, groundwater flows vertically from layer 1 to layer 2. This is in contrast to the irrigation season where groundwater flows upward from layer 2 to layer 1. Six months after ponding started, there is no significant vertical flow and the horizontal groundwater flow dominates. In the month following ponding, piezometer 7/7 which is located near the main drain, records a high hydraulic head. This indicates a drain recharging the aquifer instead of discharging it.

3.1.4 Groundwater Salinity Measurements

Figures 13 and 14 show the electrical conductivity of groundwater tested from a number of piezometers at various depths. The 2 m piezometers showed little variation in salinity between surveys except for piezometer 7/2 which displayed a gradual decrease in conductivity values over time due to fresh water infiltrating from nearby drain. Piezometers 1/2 and 2/2 displayed lower salinity readings possibly due to fresh irrigation water infiltration into the aquifer. Conductivity and salinity results for the 7 m piezometers of around 5 to 6 mS/cm do not show great variations over the irrigation season. In the paddock, there is decrease in salinity at wells 3/W4, 5/W4 and 7/W4 in December 2000 probably due to fresh water infiltration.

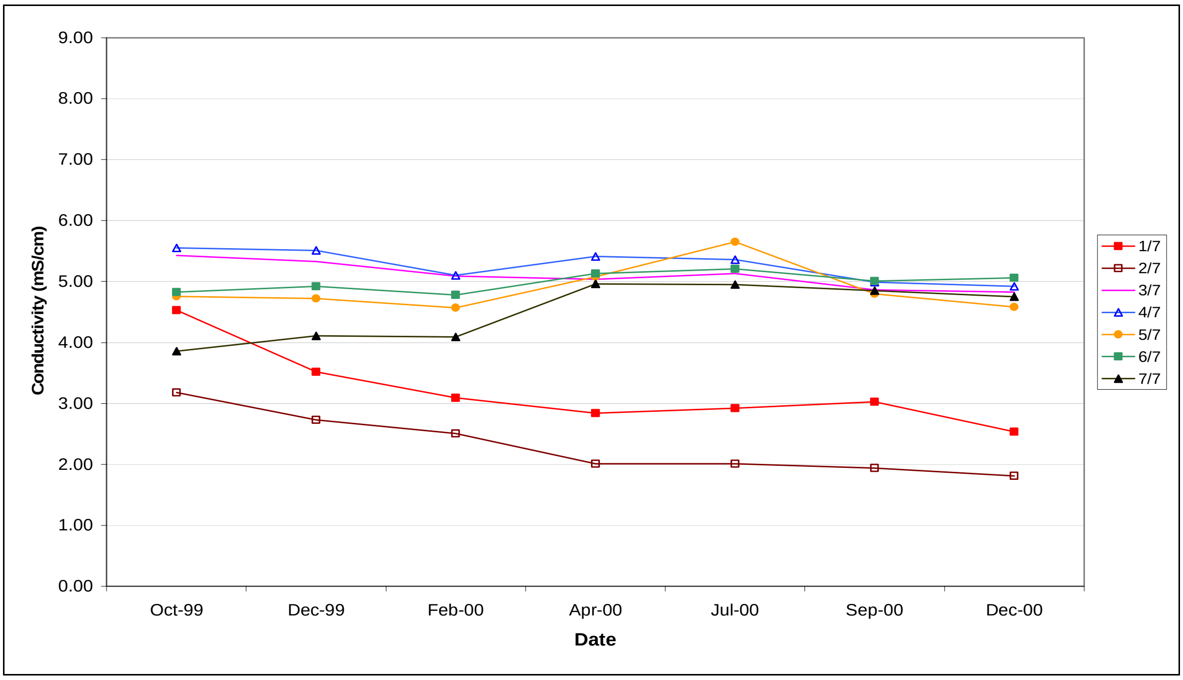


Figure 13: Electrical conductivity for 2 m deep piezometers - Oct 1999 to Dec 2000

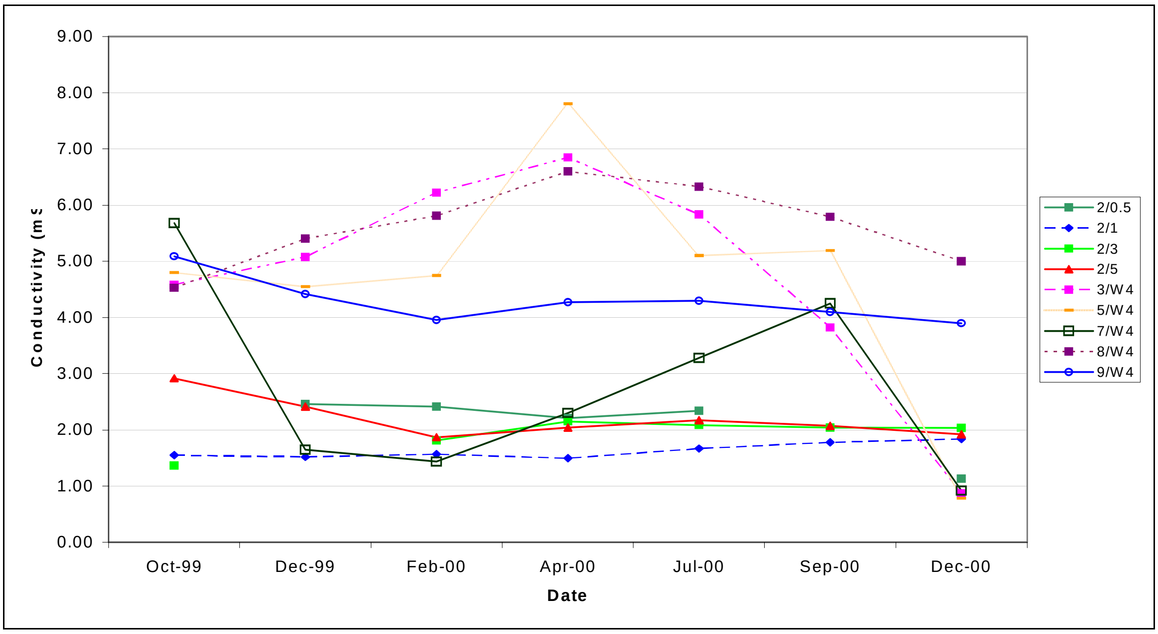


Figure 14: Electrical conductivity for wells and piezometers (≠ 2 m depth) – Oct 1999 to Dec 2000

3.1.5 Pumping Test

A pumping test has been conducted at the CRC trial site over a 48 hours period (7th to 10th July 2000) to estimate the hydraulic conductivity. The pumping test was conducted at four piezometers. The piezometers 1/2 and 7/2 were screened at 2 m. The piezometers 1/7 and 7/7 were screened at 7 m. (Figure 15). The analysis of the pumping test using Kirkham's approach (1945) was performed to determine hydraulic conductivity and the final results are given in Table 5. Figures 16 to 19 depict the groundwater levels responses.

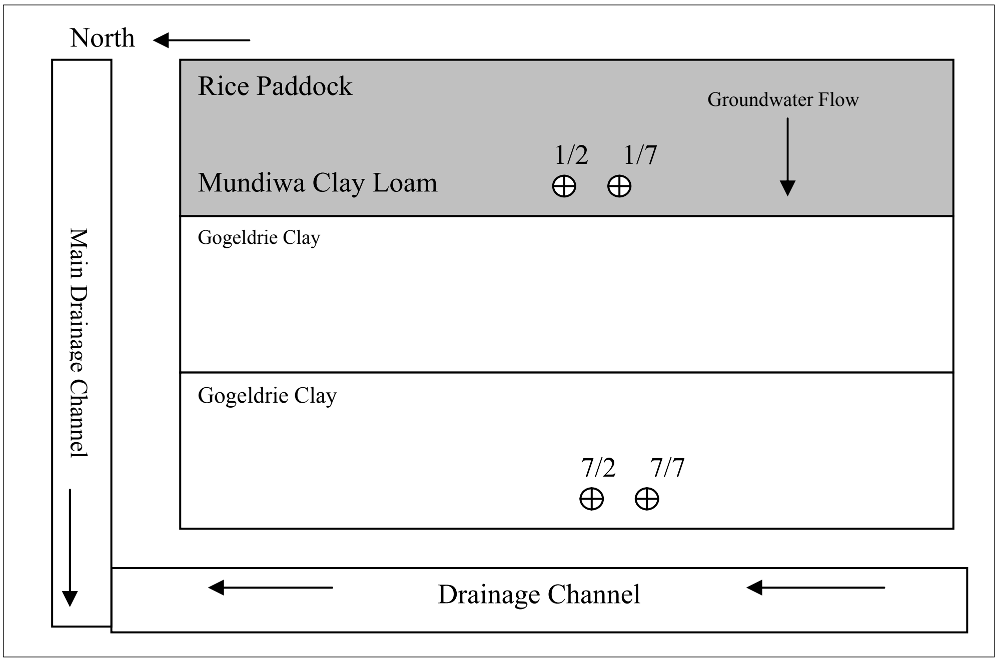


Figure 15: Location Map of Pumping Test Piezometers

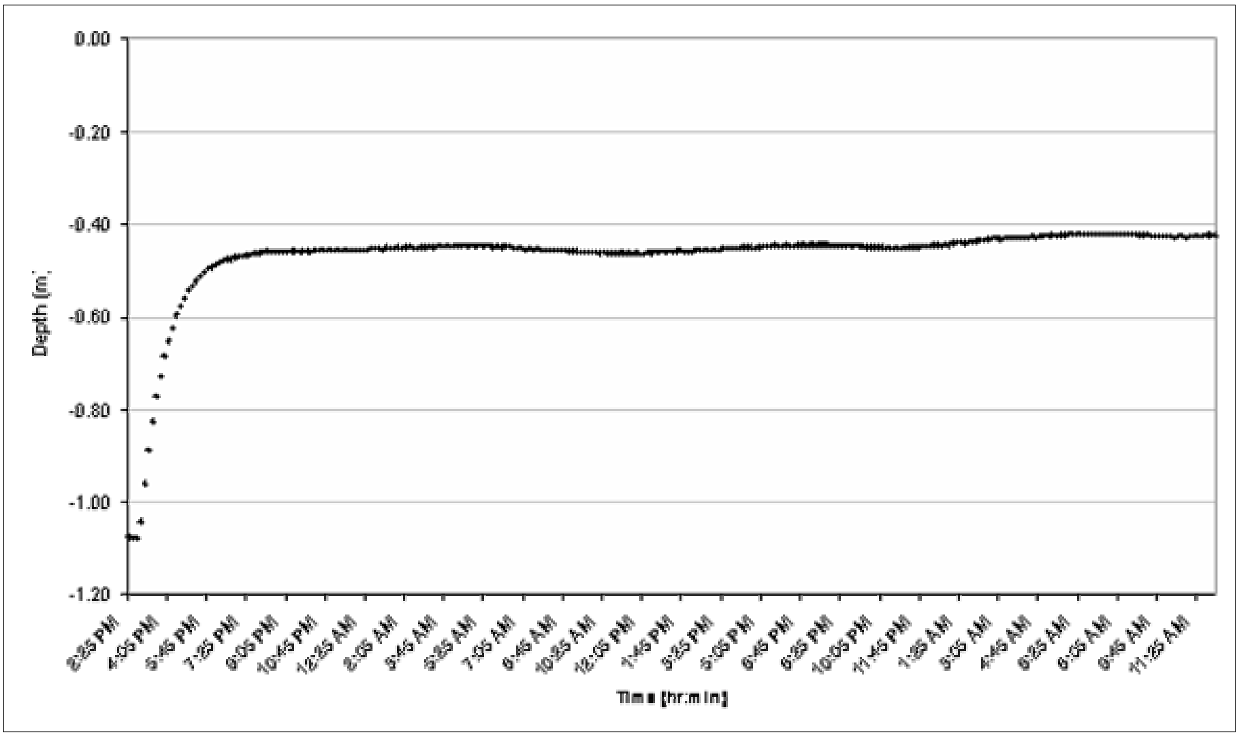


Figure 16: Results of Pumping Test for Piezometer 1/2

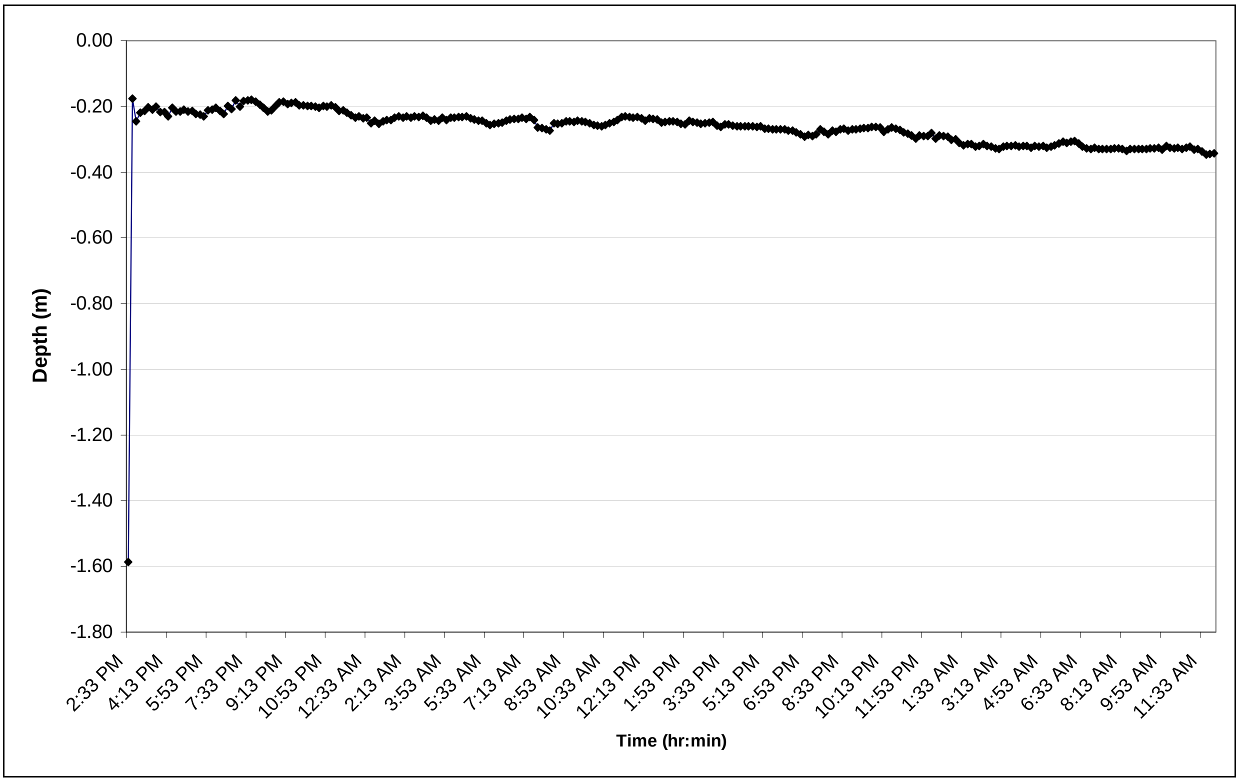


Figure 17: Results of Pumping Test for Piezometer 1/7

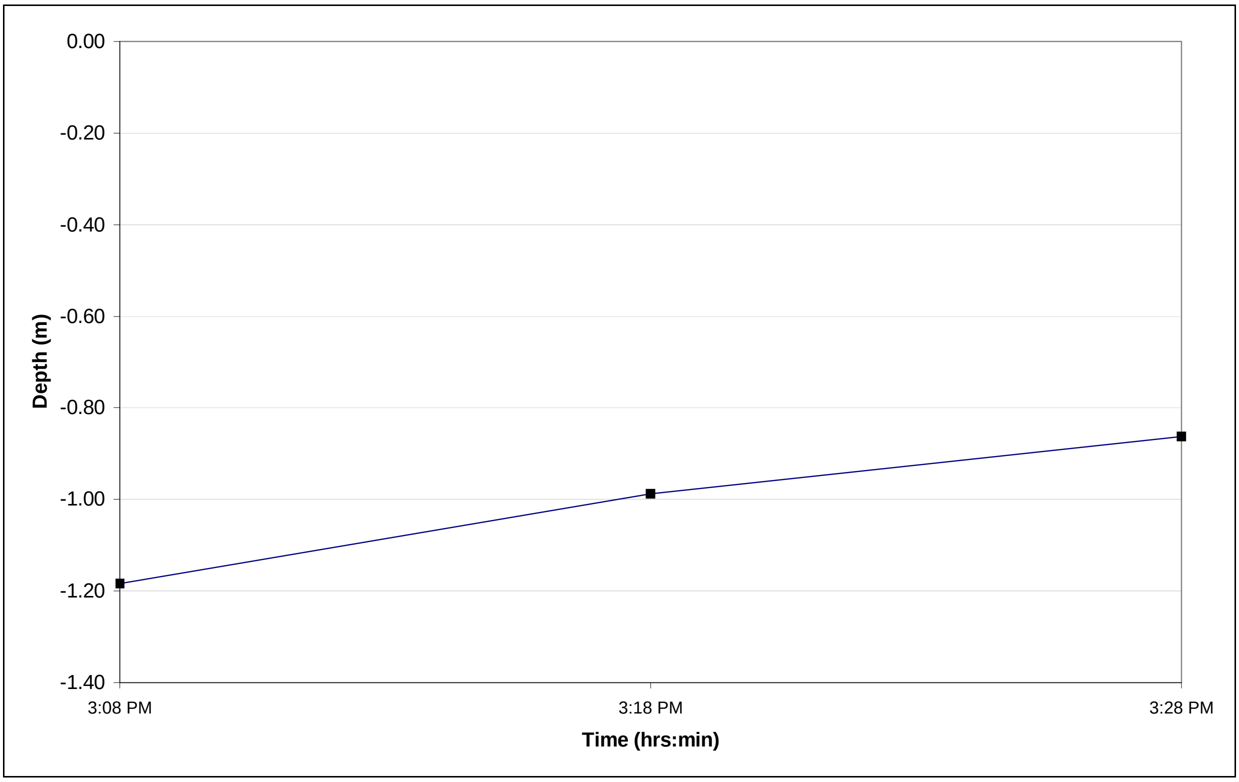


Figure 18: Results of Pumping Test for Piezometer 7/2

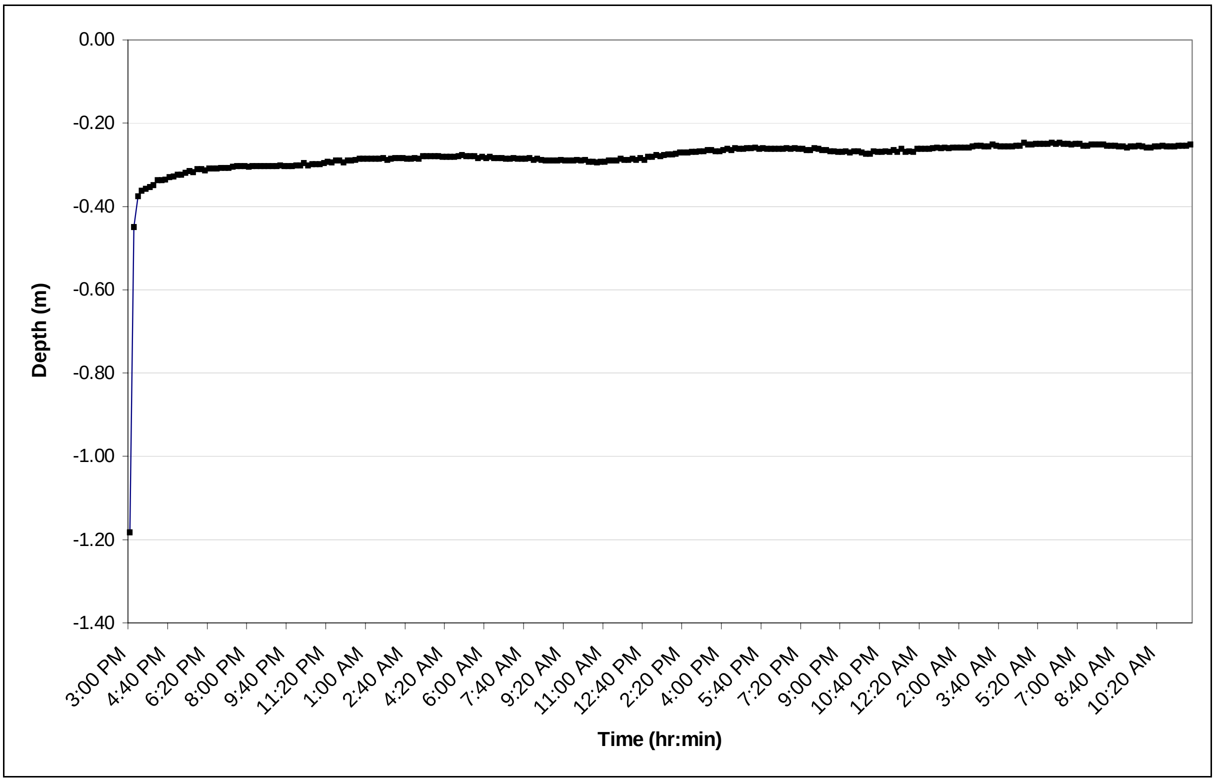


Figure 19: Results of Pumping Test for Piezometer 7/7

TABLE 5
HYDRAULIC CONDUCTIVITY - MEAN AND STANDARD DEVIATION

Piezometer	Hydraulic Conductivity Mean (m/day)	Standard Deviation (m/day)
1/2	0.08	0.023
1/7	0.99	1.36
7/2	1.26	0.089
7/7	0.82	0.67

3.1.6 Groundwater Quality

Water samples were collected from piezometers 1/2, 1/7, 5/2 and 5/7 in September 2000 using a hand bailer. Chemical analysis of these samples is presented in Table 6.

TABLE 6
CHEMICAL ANALYSIS RESULTS OF WATER SAMPLES FROM PIEZOMETERS

Ion	Sample 1/2		Sample 1/7		Sample 5/2		Sample 5/7	
	mg/L	meq/l	mg/L	meq/l	mg/L	meq/l	mg/L	meq/l
Na^+	205	8.917	560	24.360	900	39.150	525	22.838
K^+	2.6	0.067	2.9	0.074	4.5	0.115	1.3	0.033
$Ca+^2$	11	0.549	38	1.896	120	5.988	110	5.489
$Mg+^2$	11	0.905	44	3.621	100	8.230	60	4.938
Total Cations		**10.438**		**29.951**				**33.298**
Cl^-	45	1.269	260	7.332	790	22.278	510	14.382
HCO_3^-	500	8.200	550	9.020	300	4.920	240	3.936
SO_4^2	52	1.082	700	14.560	1300	27.040	760	15.808
NO_3^-	3.0	0.048	1.2	0.019	4.1	0.066	5.1	0.082
PO_4^{-3}	<0.1		<0.1		<0.1		<0.1	
F^-	0.74	0.039	0.64	0.034	1.0	0.053	0.48	0.025
Total Anions		**10.638**		**30.965**		**54.357**		**34.233**

The main chemical parameters considered in the water quality analysis were: total dissolved solids (TDS), sodium, sulphate, and chloride. The classification suggested by Gorrell (1958) as shown in Table 7 was used as a basis of classification for the trial site.

TABLE 7
CLASSIFICATION OF WATER BASED ON SALT CONCENTRATION –TDS

Water Quality	Concentration of Total Dissolved Solids in Parts per Million (ppM)
Fresh Water	0-1000
Brackish Water	1000-10,000
Salty Water	10,000-100,000
Brine	More than 100,000

Source: Gorrell, (1958)

CSIRO SWAGMAN Saltimetre was used to convert TDS obtained to conductivity values, which ranged from 1 to 7 mS/cm, with average values between 4 and 5 mS/cm. Water used for irrigation was tested in February 2000 and December 2000. River and bore water had a conductivity range of 0.112 to 0.315 mS/cm, and that qualifies it as fresh water suitable for agricultural uses.

Sodium adsorption ratio (SAR) was used to classify water samples taken on site. SAR is expressed by:

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$

Where; Ca, Mg and Na expressed in milliequivalents per litre.

Piezometer	SAR	Hazard ness
1/2	10.46	Low hazard
1/7	14.67	Medium hazard
5/2	14.68	Medium hazard
5/7	10	Medium hazard

Most sulphate compounds are readily soluble in water. The most effective natural process for removal from water is through reduction of sulphate by bacteria. The resulting reduction of sulphate ions produces hydrogen sulphide gas. The presence of hydrogen sulphide gas (“rotten egg” gas) was observed when pumping out the piezometers during each survey with “strength” varying greatly from no smell to quite strong.

Concentration of chloride in natural water varies from 1.0 ppm in rainfall to 150,000 ppm in brines. Shallow ground water in areas of low rainfall may have concentrations of 1000 ppm. The four samples ranged from 45 to 790 ppm.

3.2 Geophysical Surveys

3.2.1 Resistivity Imaging Survey

Nine surveys have been completed over the period October 1998 – September 2000. The objective was to map ground resistivity variations to a depth of 25 m. Dates and locations of survey lines are given in Figure 2 and Table 8.

TABLE 8
DATE AND LOCATIONS OF SURVEY SITES

Date of Survey	Number of Lines Surveyed	Survey Crew	Status of Irrigation (before, during, after)
Oct 98	15	Eric Gordon, Joshua Lloyd (DLWC), Noel Merrick (UTS)	Before Irrigation
Dec 98	10	Eric Gordon, Matt Baker (contract)	Approximately 1 week after irrigation start
Mar 99	10	Eric Gordon, Matt Baker (contract)	During Irrigation
Apr 99	15	Eric Gordon, Matt Baker (contract)	Approximately 1 week after irrigation finish
Oct 99	15	Eric Gordon, Matt Baker (contract)	Before Irrigation
Dec 99	10	Eric Gordon (contract), Megan McLachlan, Marija Jukic (UTS)	During Irrigation (Start date 29th October '99)
Feb 00	10	Megan McLachlan, Marija Jukic (UTS)	During Irrigation
Apr 00	15	Megan McLachlan (UTS), Tess Cassar (Friend)	After irrigation (Finish date 2nd April '99)
Sept 00	15	Megan McLachlan, Anita Hodson (UTS)	Before Irrigation

3.2.2 Conductivity Surveys

Because of the limitations in resistivity survey, nine EM34 and two EM31 surveys were completed in order to assist in the validation of the resistivity interpretations. The EM31 and EM34 surveys were conducted using the EM31-D system and EM34-3 system developed by Geonics, Inc. (Canada). Data were collected manually for the horizontal dipole configuration (20 and 40 m coil spacing).

EM 31 Survey

Data were collected using a quad bike for two fallow bays. The horizontal dipole configuration was used with a standard coil spacing of 3.66 m. For analysis purposes, the resistivity lines have been grouped into three sections, which are:

- Line 45E to 5E : Eastern Section
- Line 5W to 35W: Central Section
- Line 45W to 80W: Western Section

The surveys were conducted before, during and after irrigation. They show an overall decrease in conductivity (on the other hand: increased resistivity) at most depths with irrigation. Detailed results are summarized in Table 9.

TABLE 9
MINIMUM AND MAXIMUM RESISTIVITY VALUES FOR GEOPHYSICAL SURVEYS

1st IRRIGATION 2nd IRRIGATION

Line	Oct-98		Dec-98		Mar-99		Apr-99		Oct-99		Dec-99		Feb-00		Apr-00		Sep-00	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
45E	5.39	12.11					4.90	13.38	5.44	13.14					4.79	12.61	5.58	12.70
35E	5.15	12.97					4.63	13.00	4.99	12.75					4.55	12.93	5.16	13.11
25E	4.99	12.78					4.78	13.40	5.04	13.21					4.63	13.22	5.18	13.40
15E	5.13	12.63					4.61	12.93	5.03	13.29					4.63	12.91	4.91	13.13
5E	5.23	12.67					4.69	11.73	5.25	12.84					4.95	12.35	5.51	12.66
5W	4.89	12.79	3.57	14.96	4.31	13.17	4.46	12.95	4.83	12.84	4.90	12.91	4.31	12.68	4.87	12.35	5.12	12.85
10W	4.47	12.78	3.75	19.60	3.72	12.90	3.86	13.04	4.20	13.05	3.90	12.92	3.71	12.63	3.86	12.97	4.38	13.17
15W	4.36	12.57	3.75	15.24	3.64	12.80	3.83	12.80	4.12	12.84	3.90	12.69	3.62	12.55	3.82	12.64	4.23	12.66
25W	4.27	12.50	3.79	15.05	3.68	12.22	3.82	12.38	4.04	13.39	3.82	12.39	3.61	12.30	3.83	12.38	4.26	12.35
35W	4.25	12.60	3.87	14.81	3.64	12.54	3.82	12.78	4.04	13.04	3.85	12.52	3.62	13.47	3.74	12.44	4.27	12.72
45W	5.39	12.56	4.26	13.71	4.56	12.23	4.72	12.41	4.85	12.54	4.08	12.03	4.59	11.94	4.68	11.96	5.25	12.14
55W	5.29	12.06	4.90	12.26	4.70	12.44	4.91	12.20	5.34	12.02	5.04	11.88	4.66	11.68	4.82	11.72	5.09	11.81
65W	5.43	12.47	4.73	13.17	4.25	12.17	4.81	12.54	5.22	12.07	4.80	11.80	4.67	11.63	4.73	11.90	5.22	12.00
75W	5.07	12.32	4.75	12.48	4.28	11.69	4.50	11.90	4.88	11.87	4.64	11.96	4.31	11.75	4.48	11.82	5.05	11.92
80W	4.98	11.42	4.67	13.27	4.31	11.69	4.45	11.20	4.63	12.00	4.50	11.06	4.31	11.02	4.42	11.53	4.92	12.06

<u>Year 1: October 1998 – April 1999</u>

All lines are less resistive above 5 m below ground surface in the eastern side of the study area (45E to 5E). Some more resistive areas are apparent less resistant at shallow depths reflecting the intrusion of fresh water from the main drain and the flooded rice paddies located to the north and the east respectively. In the central part (5W to 35W) all surveyed lines showed a decrease in resistivity in the upper 5 m. The western area (45W to 80W) also displayed the same pattern with exception of line 65W which has a higher resistivity section between 80 and 100 m along the line. Southerly (67.5S and 137.5S), the resistivity values decreased at most depths, with the lowest values at 2.5 m depth at line 10W. The only two areas of slightly more resistivity were found below 20 m depth at lines 35E, 25E and 75W suggesting fresher water from depth ascending in response to rising water table.

Year 2: October 1999 – April 2000

The upper 5 m depth shows lower resistivity for all lines on the eastern section (45E to 5E). In the central section (5W to 35E) all lines shows less resistivity near the surface except for the 5W line which shows numerous anomalies with greater resistivity at all depths. Lines 25W and 35W show higher resistivity along the northern boundary. This could be due to fresh water intrusion from the main drain. Line 45W is predominately more resistive below 15 m depth. Scattered single point anomalies are found along lines 55W to 80W probably due to the effect of the flooded rice paddocks which would have a slower reaction time at this distance.

EM 34 Survey

Nine EM34 surveys were conducted using the EM34-3 system. Data were collected for the horizontal dipole (vertical coil) configuration for 20 and 40 m coil spacings that represent effective depths of 7.4 m and 14.8 m respectively. The following findings are the results of the EM34 surveys:

Period 1: October 1998 – April 1999

- Effective depth 7.4 m

An increase in resistivity values has been observed for up to 0.8 Ω.m along the northern boundary of line 45E to 35W and the eastern boundary along line 15E due to the intrusion of fresh water from the main drain. Minor increases in resistivity were observed along line 80W. While numerous areas of lower resistivity of up to 12 Ω.m were found along line 5W which was probably caused by the proximity to the rice paddock recently drained. The highest decrease in resistivity (up to 1.4 Ω.m) was found along the southern boundary (Line 45E – 15E).

- Effective depth 14.8 m

An increase of resistivity of up to 0.6 Ω.m was found in the eastern boundary along line 5E and a decrease of 0.6 – 1.2 Ω.m was found along lines 35E, 15W, 25W and 65W, and along the southern boundary of line 45E – 5E. In general, the eastern section was found to be more resistive than the central section due to the fresher water infiltrating through the rice paddocks.

Period 2: October 1999 – April 2000

- Effective depth 7.4 m

An increase in resistivity of up to 2.5 Ω.m was found at the southern end of line 45E – 15E. A decrease in resistivity (up to 3 Ω.m) was found in the northern boundary of line 45E – 35W and in the southern boundary of line 10W-80W due to fresher water driving saline water towards unloaded paddocks.

- Effective depth 14.8 m

The highest resistivity values (up to 1.6 Ω.m) are found in the southeast corner side of the field. Increased resistivity of up to 0.6 Ω.m is found along areas of line 5E – 55W. This is due to the deep aquifer still recovering from recent irrigation events. All other areas show less resistivity.

3.2.3 Three-Dimensional Resistivity Imaging

The report completed at stage 1 had described the resistivity imaging of the field site. Resistivity surveys were completed between October 1998 and September 2000. An additional survey was completed in June 2001. The objective of the filed survey was to visualize the ground resistivity variation using 3 dimensional animations. Slicer 3D (Fortner Research LLC) was used for visualisation purposes. Movies were generated for the period October 1998 – June 2001 to visualise the temporal variations of apparent resistivity along these surveyed lines. Figure 20, 21, 22 show extracts from the generated movies for line 10W for the period October 1998 to September 2000.

Slicer 3D principles

Slicer3D visualises data by using ray tracing to render them as volumes, slices or iso-surfaces. Full control of the "Alpha" values allows any object or data values transparent, translucent or opaque. And, it allows for creation of animations and views.

Software characteristics:

Version: 1.1 (May 1996) for Windows.

Minimum requirements:

- Intel 386 or better
- 3.5 Floppy disk drive
- MSDOS V5 or later
- Microsoft Windows 3.1
- 8 MB Ram and 10 MB disk space
- 8 bit, 256 colours, 640 x 480 or better

Limitations:

- Annotations cannot be animated
- No real value of coordinates can be shown on the axis
- Colour scale cannot be shown
- Colour table does not display any scale
- Animation script cannot be reused
- No possibility to overlay base maps over the horizontal view

Inputs and Outputs:

Inputs:

It consists of a three dimensional matrix of apparent resistivity ordered values. Figure 20 shows an example matrix of data for slicer (10 x 6 x 3). Slicer accepts binary and ASCII files in X, Y, Z, Resistivity format.

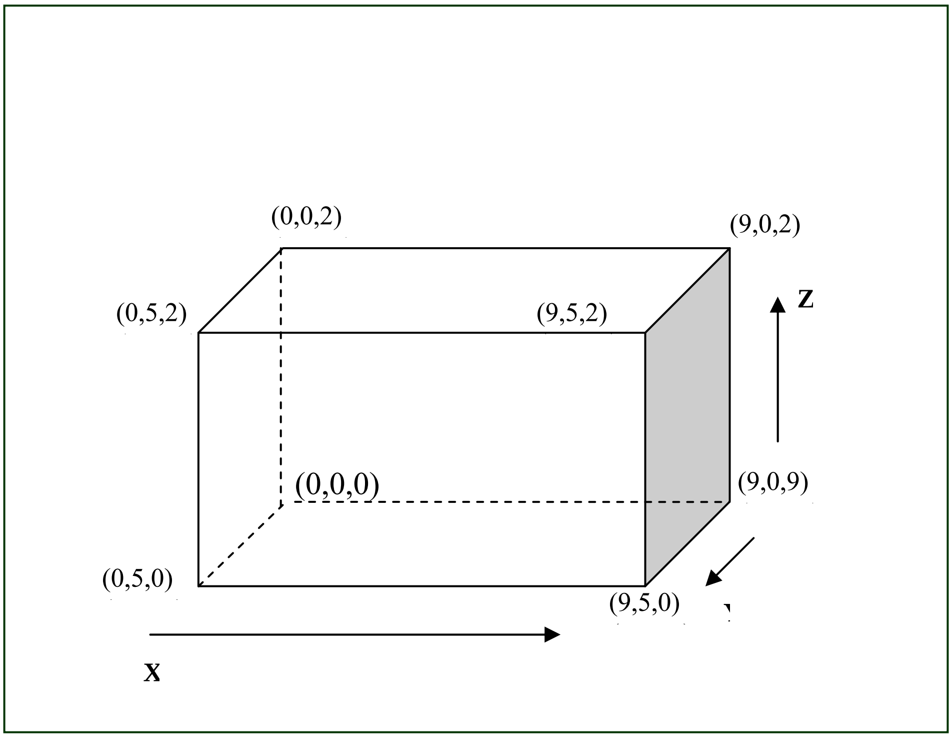


Figure 20: Example of Slicer Data Matrix (10 x 6 x 3)

Outputs:

An HDF (Hierarchical Data Format) file format is the primary data storage format for slicer outputs. Animations in slicer are created from a series of successive frames.

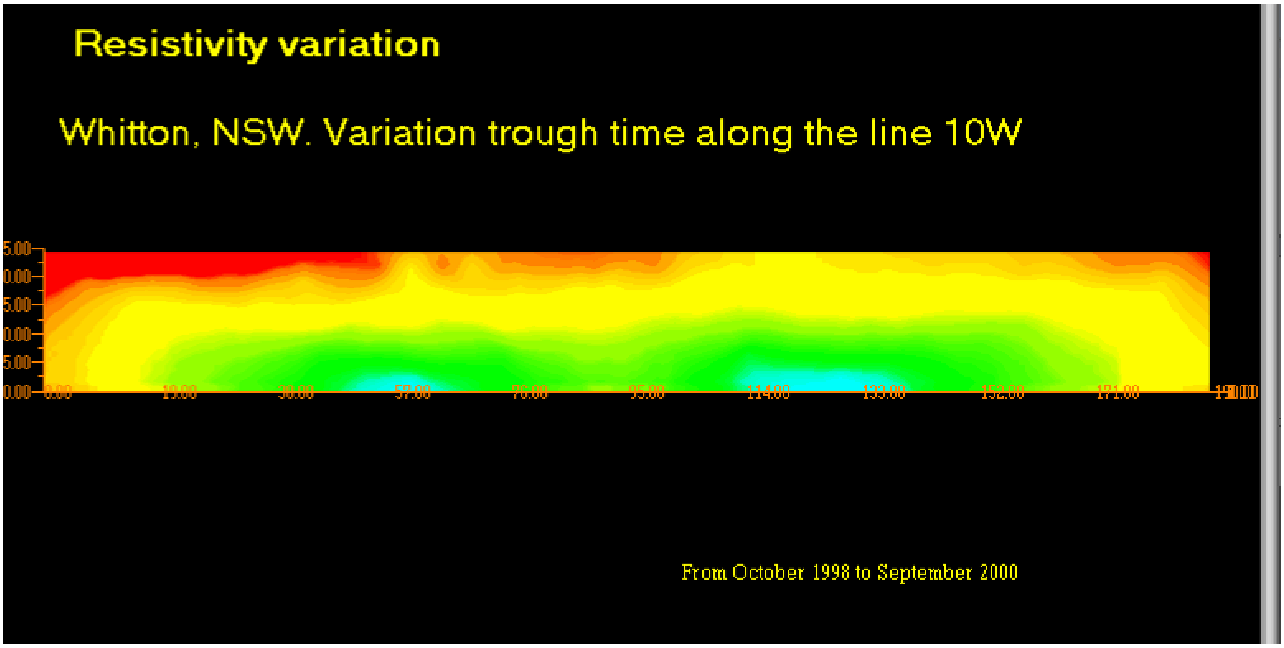


Figure 21: Resistivity distribution along line 10W - October 1998

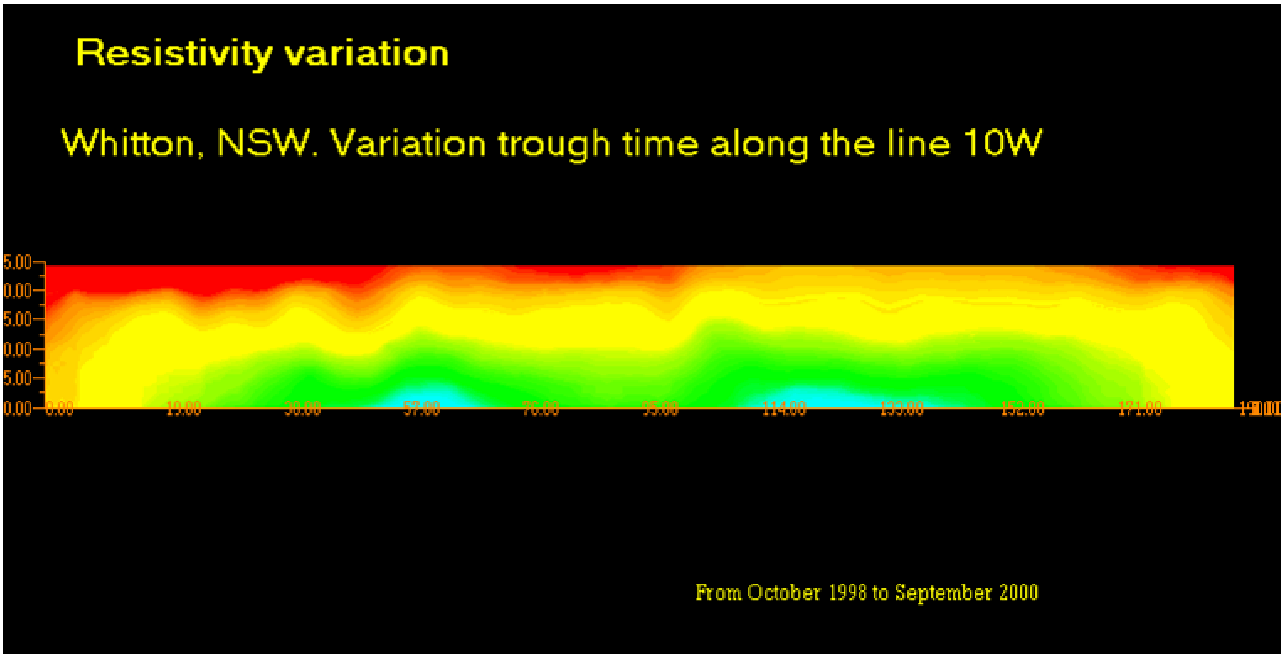


Figure 22: Resistivity distribution along line 10W – October 1999

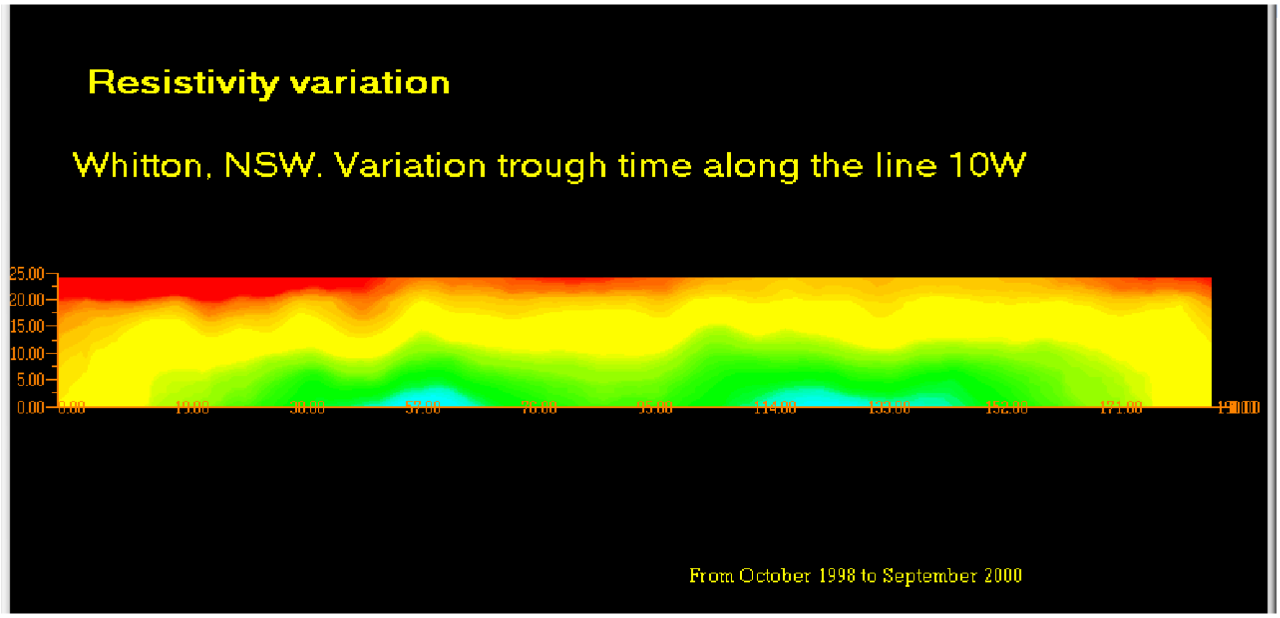


Figure 23: Resistivity distribution along line 10W – September 2000

3.2.4 Comparison of EM34 Vs Resistivity Surveys

A fairly good correlation at both depths exists for the October 1998 survey. Both EM34 and resistivity surveys are showing more resistive areas in the southeast corner of the surveyed area. No correlation exists when comparing results from EM34 and resistivity surveys in April 1999 survey. The later finds more resistive areas in the southeast corner as opposed to the northeast corner for the EM34 survey. Possible justification for that is the time delay between the two surveys. The EM34 surveying completed two weeks after the end of irrigation, as compared to the resistivity survey completed directly after the end of irrigation.

For the surveys completed in October 1999 and April 2000, very good correlation is achieved between both survey methodologies. Both approaches show higher resistivity in the south east areas of the site.

4. Methodology & Results

4.1 Simulations of Groundwater Flow and Solute Transport using MODFLOW at Whitton Farm (MIA)

A two layers model was developed with estimations of the initial key hydraulic parameters and stresses influencing the system. MODFLOW finite difference flow model was used. The approximate modelled area is 3 km2. The observation bores are located in the 3 paddocks outlined in red (Figure 2). The conceptual modelisation of the study area is shown in Figure 24.

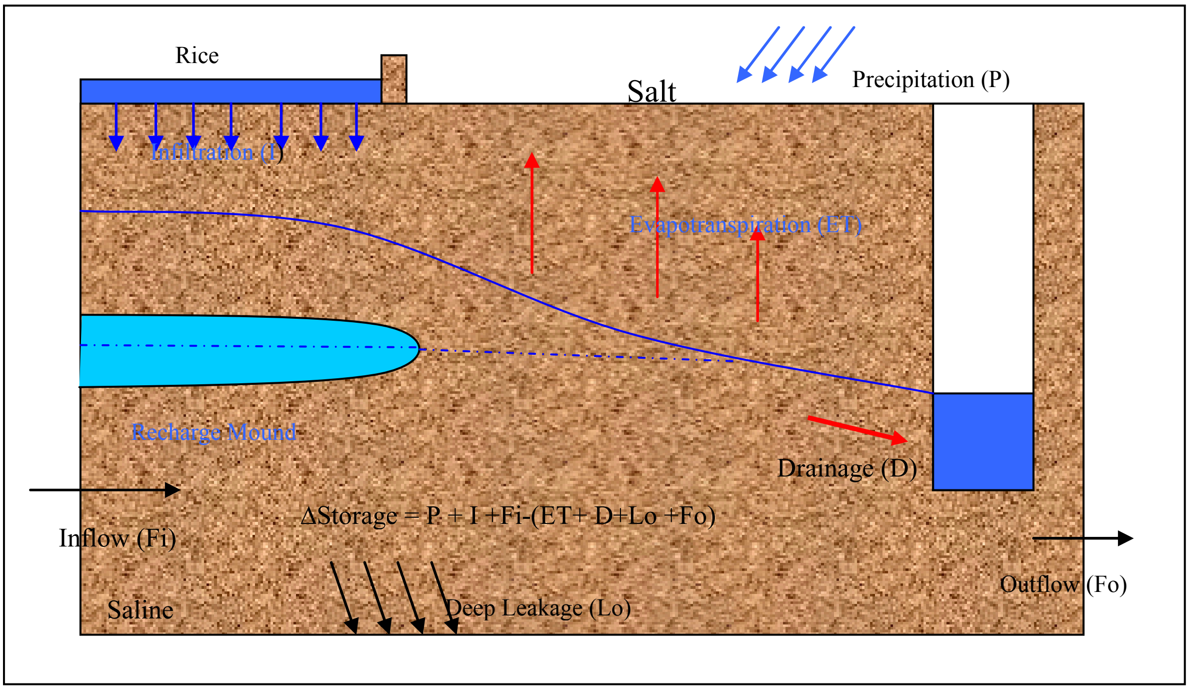


Figure 24: Conceptual Model

4.1.1 Model Parameters

4.1.1.1 Grid Parameters

The grid was designed with two layers: a top unconfined layer of 4 m depth, and second layer of 6 m thickness. The second layer is assumed semi-confined with variable transmissivity. The grid mesh was oriented eastwest to follow the principal groundwater flow direction to reduce numerical dispersion. The grid cell size was adjusted from a 10 x 10 m at the bores where higher accuracy is required to a maximum grid cell size of 200 m. The grid has 45 columns and 36 rows to cover the study area (Figure 25). Topographic surface was derived from available survey information and its contoured plot is shown in Figure 26.

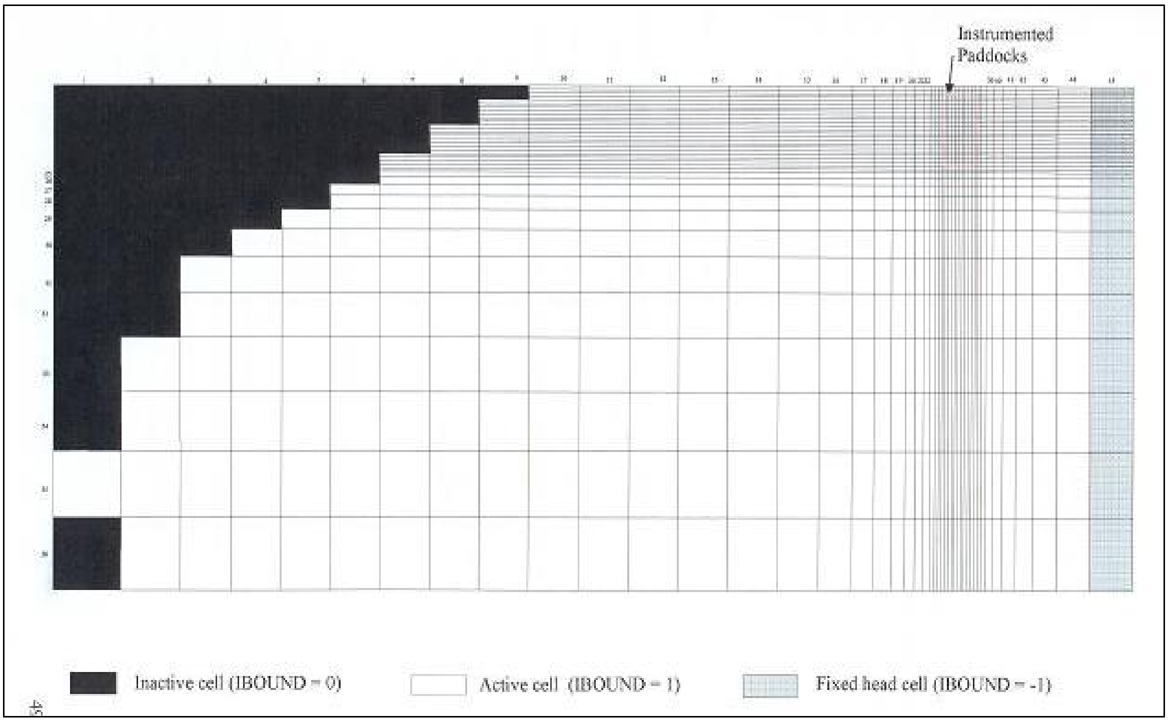


Figure 25: Grid Design

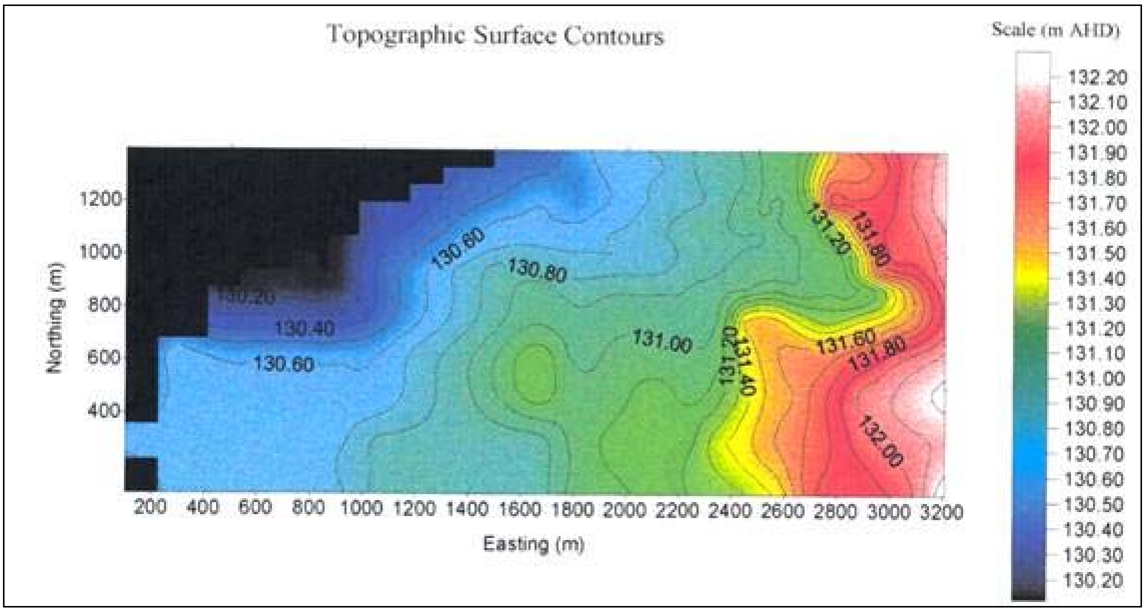


Figure 26: Topographic Surface Contours

4.1.1.2 Temporal Discretisation

Water levels were recorded at 6 hourly intervals for a period of 1 year. (from Oct. 14th 1999 to Sep. 22nd 2000). The simulation runs for a total 366 days, with 183 stress periods, with a time step of 2 days.

4.1.1.3 Initial Hydraulic Heads and Borehole Locations

24 boreholes are contained in the study area. 20 are piezometers and 4 water wells. Data loggers measuring water levels every 6 hours were installed in 12 of the piezometers at 2 and 7 m depth. The hydraulic head was successfully recorded at piezometer 1/2, 1/7, 2/2, 2/7, 4/7, 5/2, 6/7, 7/7 and 8w4. (Figures 27 and 28).

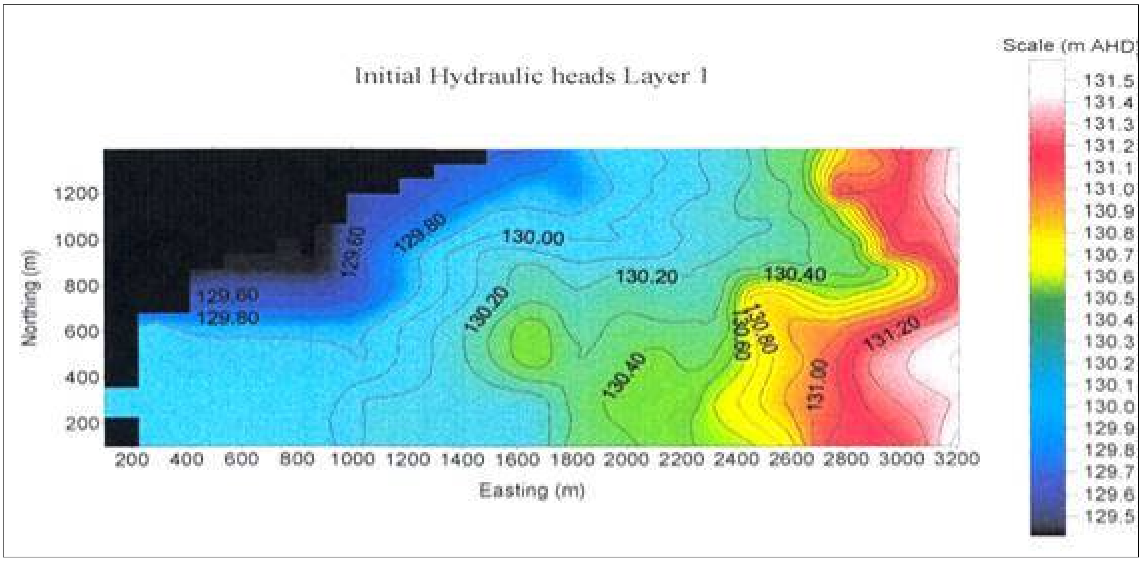


Figure 27: Initial hydraulic heads (Layer 1)

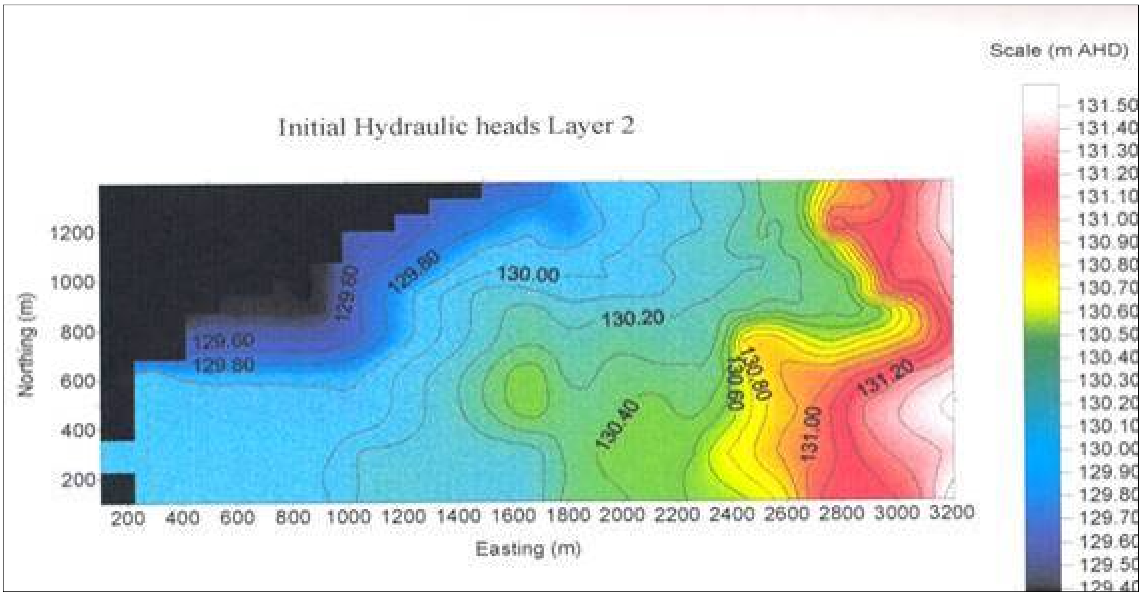


Figure 28: Initial hydraulic heads (Layer 2)

4.1.1.4 Hydraulic Conductivity

The hydraulic conductivity was estimated from a pump test at the study area in July 2000. The values used are given in Table 10.

4.1.1.5 Specific Yield

The value of specific yield in the study area ranges from 0.01 to 0.18 (Spitz & Moreno, 1996). The value used in the model was set to 0.05

4.1.1.6 Evapotranspiration

Evapotranspiration was set to 10 % of the maximum ET. The extinction depth was set to 1 m.

4.1.1.7 Recharge

Recharge into the model domain was considered to be mainly from rainfall, and was set to be 10 % of the rainfall as recorded at Yanco site.

4.1.1.8 Ponded Rice

MODFLOW River package was used to simulate ponded rice. The river bottom was set at ground elevation and the river stage values were derived from the height recorded at the water gauge within the pond.

4.1.1.9 Lateral Groundwater Outflow

Lateral groundwater flow is from east to west. Inflow to the eastern boundary is nominated as specified head boundary. The outflow along the western boundary is from specified flow into the drain in layer 1. Outflow from layer 2 was simulated using the well package as a negative pumping rate of -1 m3/day.

4.1.1.10 Deep Leakage

It was simulated using the General Head Boundary package.

4.1.1.11 Drain Package

Drains are surrounding the study area to the north, south and west. MODFLOW Drain package was used to simulate these drains. The drain elevation was set to be 0.98 below the ground surface. The hydraulic conductance was set to be 10 mm.day-1.

4.1.2 Model Calibration

After a process of trial end error, the model was calibrated against all parameters. The final calibrated model shows the following match between observed and simulated heads (Figure 29) and the final hydraulic parameters (Table 10).

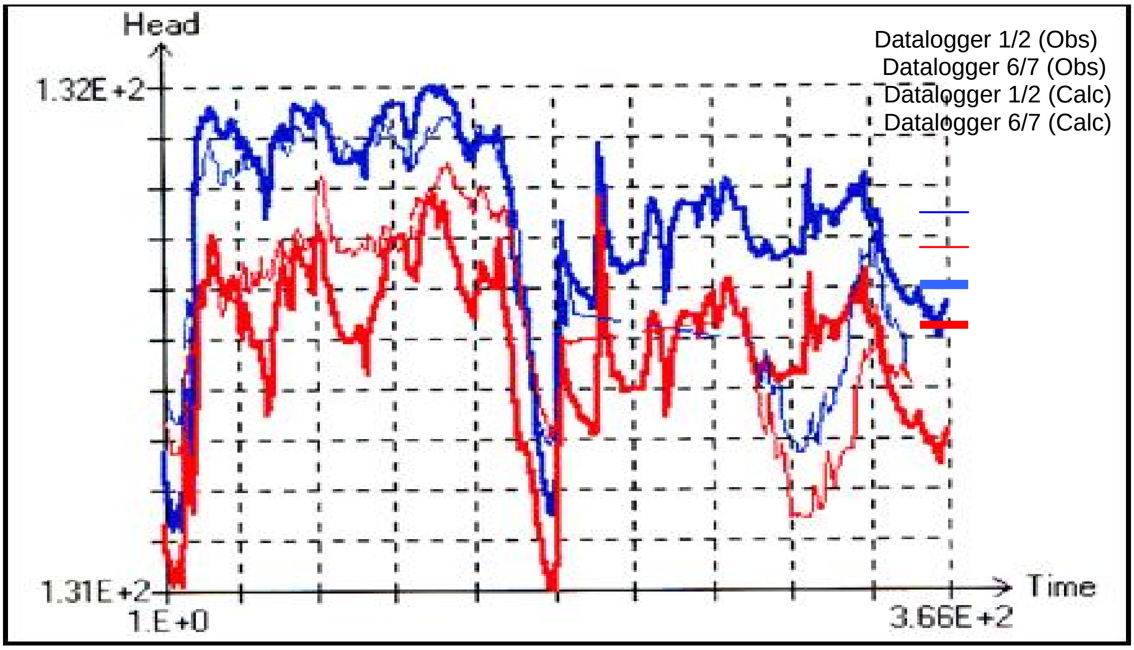


Figure 29: Observed vs simulated heads after calibration (piezometers 1/2 and 6/7)

TABLE 10
CALIBRATION PARAMETERS

Parameter	*K-Horizontal*	*K- Vertical*	*Specific Yield*	*Storage Coefficient*
Layer 1	*1.0*	*0.1*	*0.005*	*0.005*
Layer 2	*1.0*	*0.1*	*0.005*	*0.005*

The heads spatial distribution at the end of the simulation period is shown in Figure 30 below.

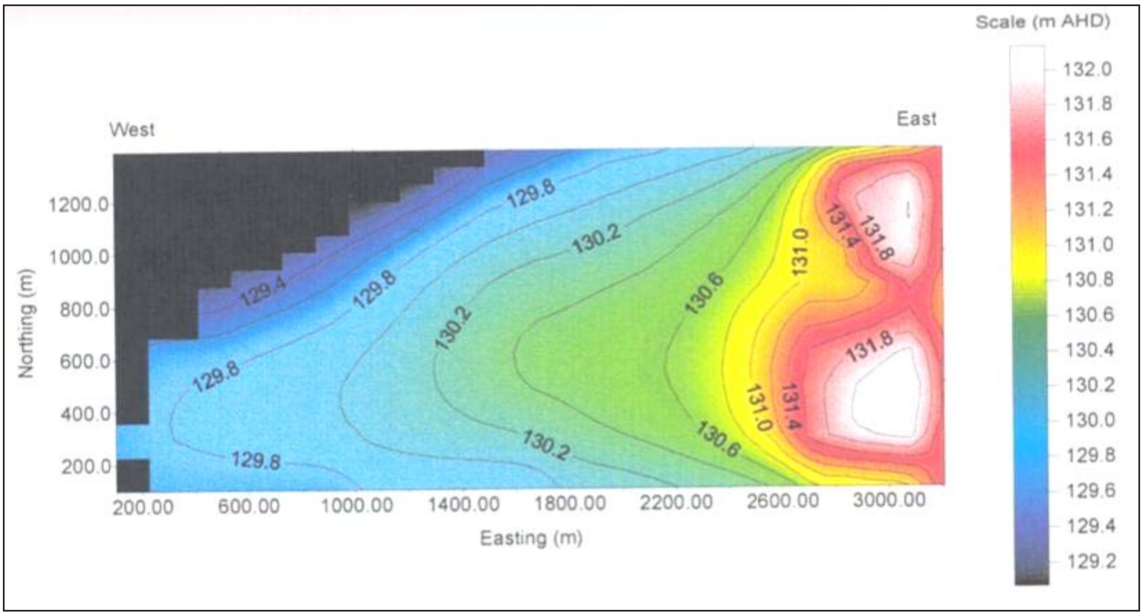


Figure 30: Spatial head distribution in layer 1 at 20th January 2000

4.1.3 Water Budget

The cumulative water budget at simulation period 183 is given in Table 11.

TABLE 11
CUMULATIVE WATER BUDGET

Parameter	*Inflow (ML/year)*	*Outflow (ML/year)*
Storage	***100.58***	***99.22***
Constant Head	***3.84***	***19.94***
Wells	***0.00***	***13.18***
Drain	***0.00***	***115.05***
River Leakage	***171.06***	***21.9***
Evapotranspiration	***0.00***	***270.22***
Head Dependant Boundaries	***0.00***	***19.19***
Recharge	***283.27***	***0.00***
Total	***458.17***	***459.48***

4.2 Simulations of Solute Transport using MT3DMS Model

The MT3DMS transport model was used to simulate changes in salt concentration in the groundwater and its path over time in the study area.

4.2.1 Initial data

- Salt concentration in each layer: 2000 mg/l
- Recharge concentration 20 mg/l
- River concentration: 400 mg/l

4.2.2 Mechanism of Salt Transport

Two processes were considered:

- Advection
- Dispersion

<u>Advection</u>
The contaminants are transported in the aquifer by the average linear groundwater velocity. The driving force is the hydraulic gradient, and the constraint effective porosity ne.

<u>Dispersion</u>
It is the spreading of contaminant caused by aquifer heterogeneity.

The model is initially run with the following salt concentration estimates:

- Recharge salt concentration: 20 mg/l
- River water salt concentration: 400 mg/l
- Soil layers concentration: 2000 mg/l

After an increase of the salinity of the recharge to 2000 mg/l, the results of the model simulation are much closer to the observed values. The temporal trends are similar to those measured in the field. Figure 31 shows the salt concentration variation compared to the measured salinities.

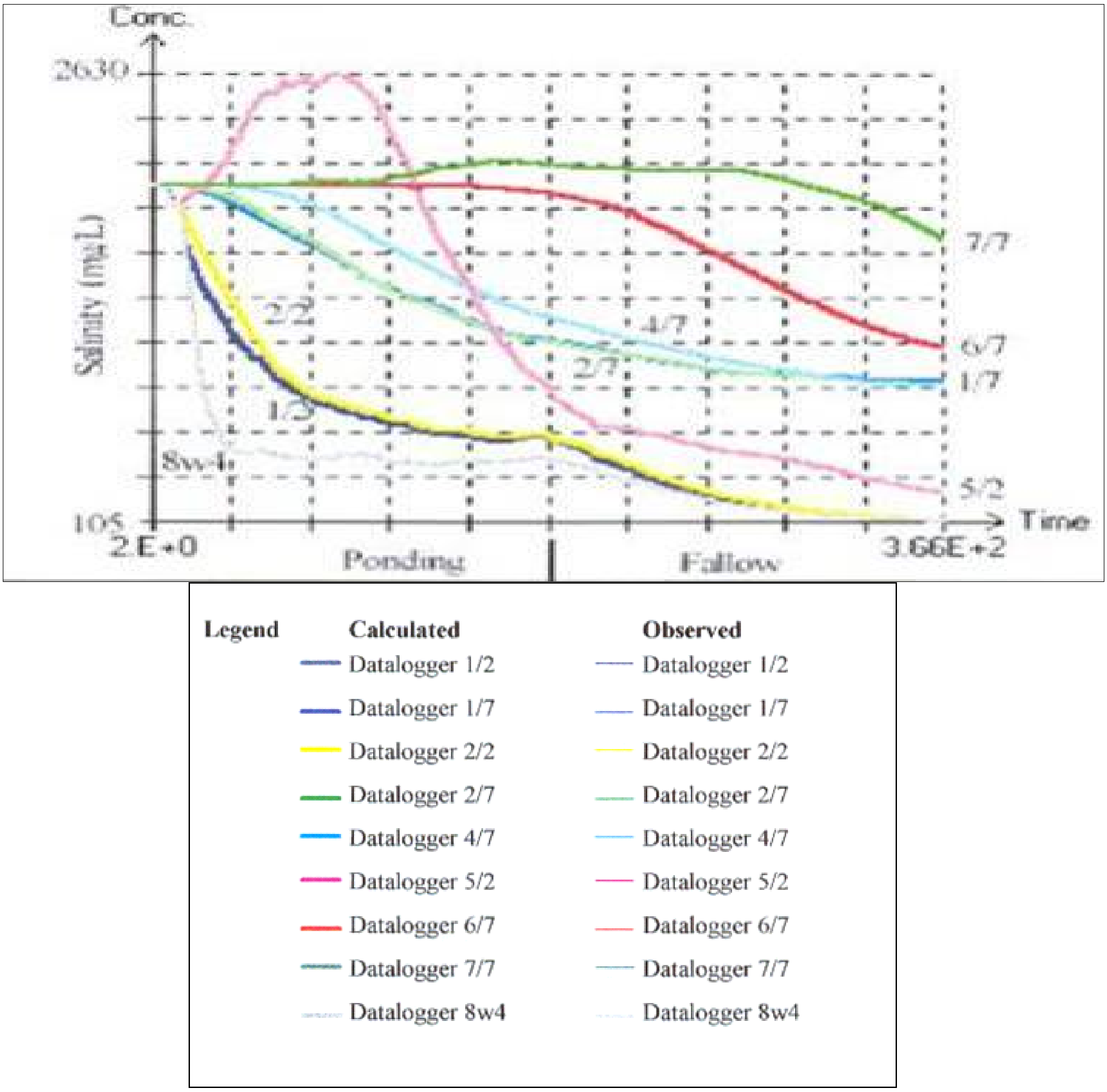


Figure 31: Initial Solute Transport Concentrations

After a process of trial and error, the final salt concentrations calculated by the model that match the observed ones are:

- Layers salt concentration: 2000 mg/l
- River/pond salt concentration: 400 mg/l
- Recharge salt concentration: 2000 mg/l

It is concluded that the model respond to both advection and advection processes. The spatial distribution of salts for the summer period and the winter period is shown in Figures 32, 33, 34 and 35 for layers 1 and 2.

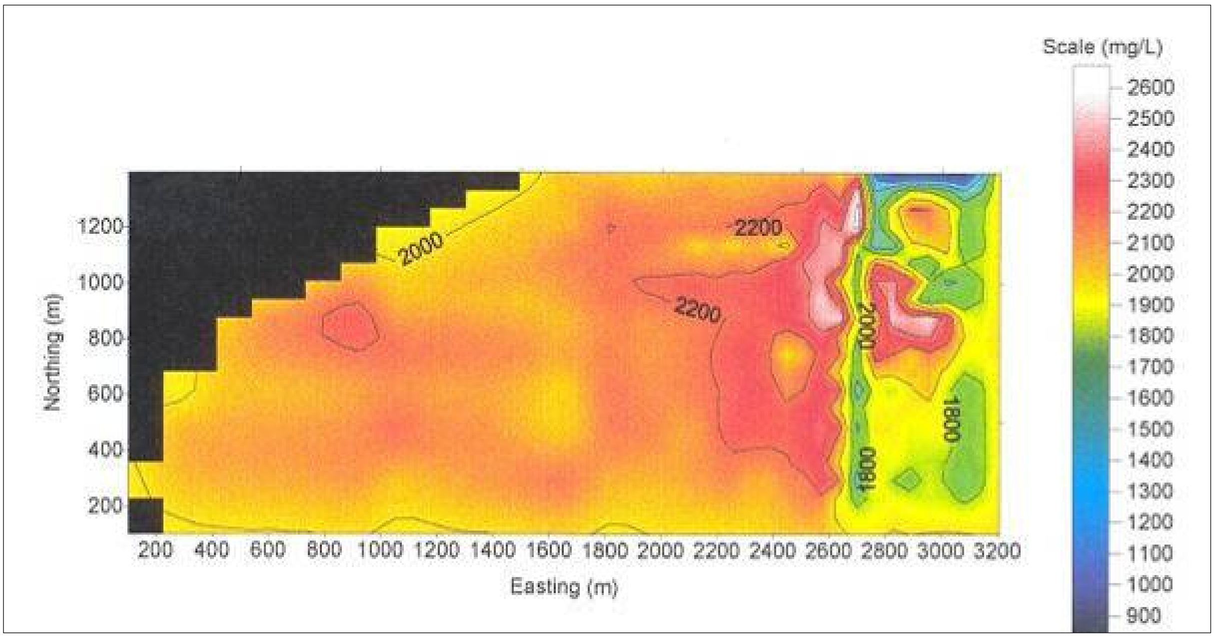


Figure 32: Salinity distribution in layer 1 during the ponding season

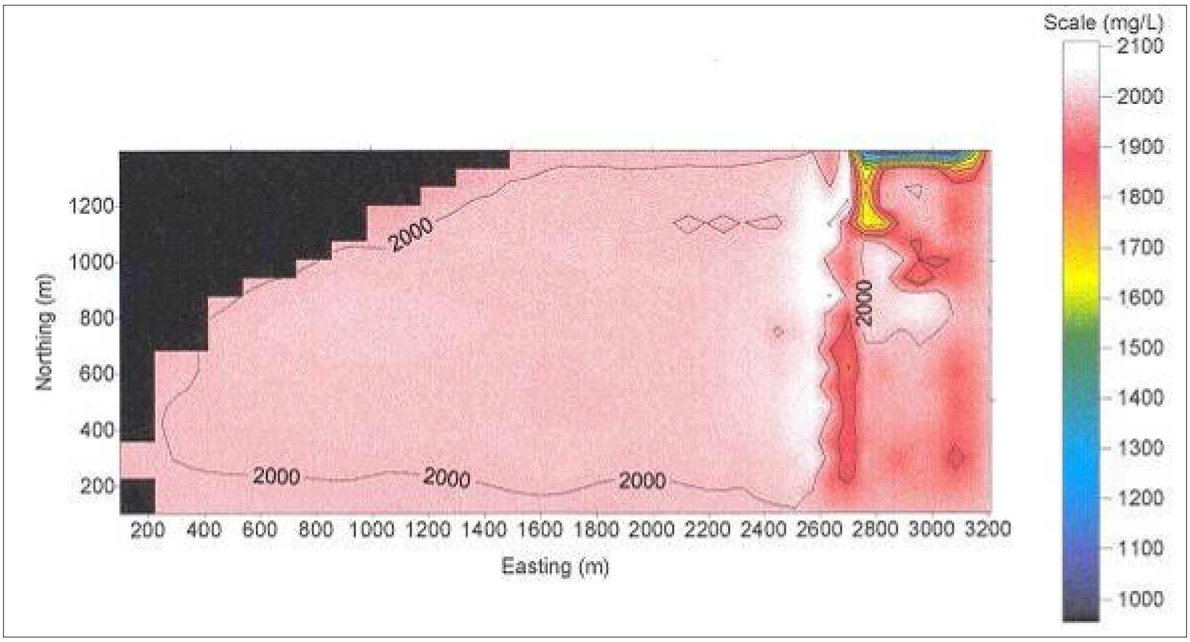


Figure 33: Salinity distribution in layer 2 during the ponding season

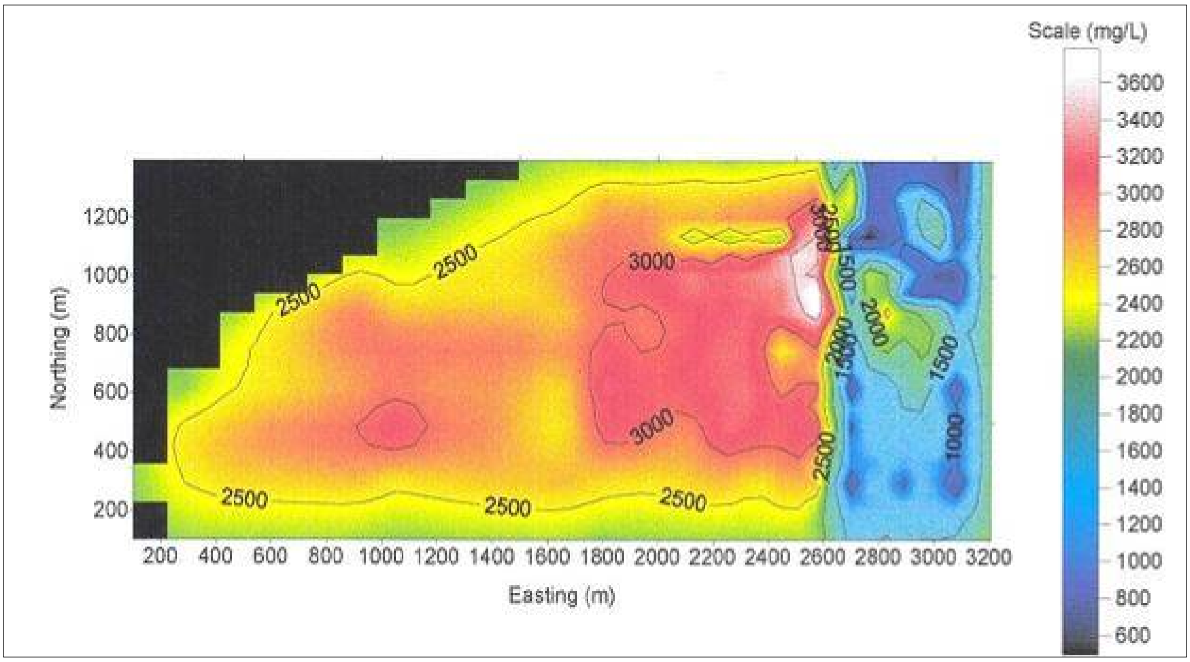


Figure 34: Salinity distribution in layer 1 during the fallow season

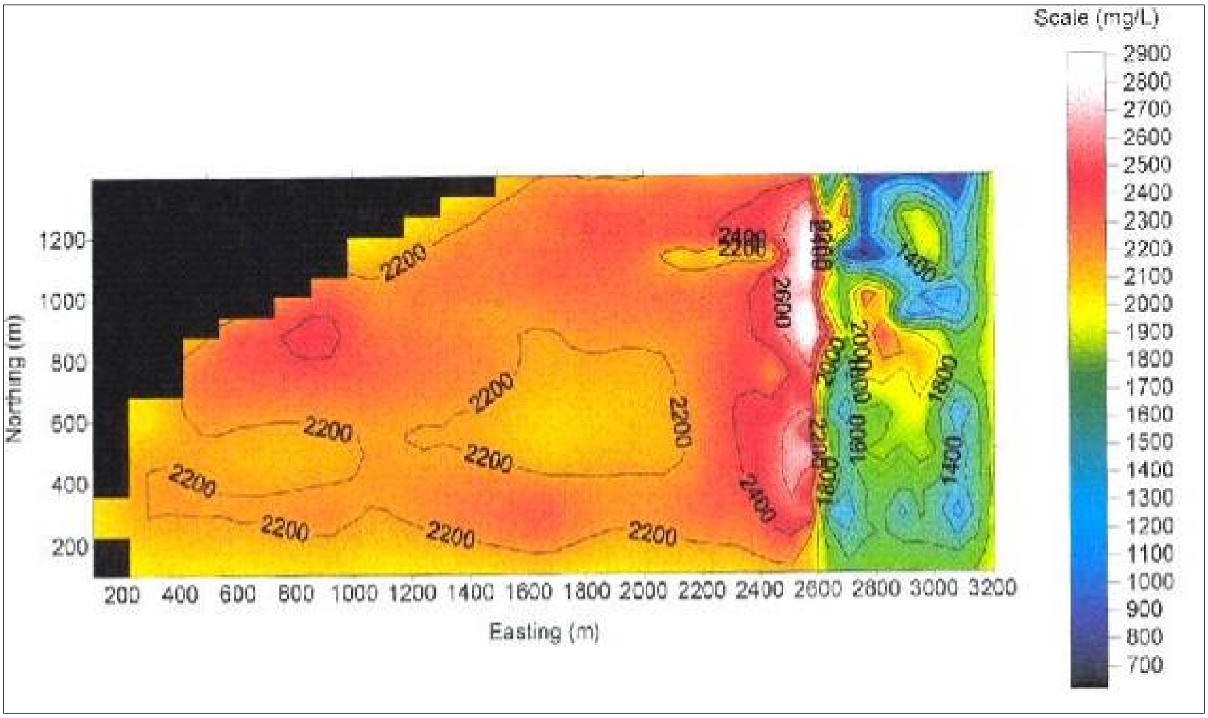


Figure 35: Salinity distribution in layer 2 during the fallow season

4.3 Numerical Groundwater Management Model for Salinity Mitigation at Farm Scale

A management model at farm scale was developed using the MODFLOW simulation model to address options for reducing salt discharge from irrigation into groundwater. Investigation of various interception schemes were evaluated in order to come up with an optimal solution by using an optimisation model coupled with the previously developed numerical model. The model was designed to represent the irrigation period only as it represents the majority of groundwater entering the drains. The model was modified to steady state conditions to minimize run times.

Long term averages used for the steady state simulation are as follow:

- Evapotranspiration: 0.0008 m/day
- Recharge : 0.0000136 m/day
- River : 0.175 mAHD

4.3.1 Optimisation Outline

The optimisation problem is defined in the following steps:

- Formulation
- Variables statement
- Decision variables definition
- Objective function
- Constraints
- Optimisation solution methodologies
- Simulation and optimisation coupling by:
    - a) Response matrix
    - b) Embedding
    - c) Linked simulation/optimisation.

4.3.2 Scenarios

- All 220 bores pumping
- Minimal bores pumping from both layers
- Pumping from layer 1 only (110 pumping bores)
- Pumping from layer 2 only (110 pumping bores)

The objective function for the optimisation is to minimise production whilst meeting the water level constraints imposed by the drains. The decision variables are the pumping rates at each active pumping bore. Targets and initial water levels used in the optimisation was the water level from the drain adjacent to the pumping cell. Constraints were imposed on the maximum drawdown (10 m on both layers). The initial maximum pumping rate for scenario 1 was set to 10 m3/day and was changed during the optimisation process.

4.3.2.1 Scenario 1

The optimisation model with scenario 1 (Figure 36 shows layer 1 and Figure 37 shows layer 2) yielded the following results:

- 142 Pumped bores
- 6 Bores pumped at maximum rate of 255 m3/day
- Total production over the planning period 1369.2 m3/day
- Average drawdown 0.23 m
- Standard deviation 49.97 m3/day

4.3.2.2 Scenario 2

It consisted of minimizing the number of pumping bores in both layers, using the GAMS input file. Results of this run (Figure 38 shows layer 1 and Figure 39 shows layer 2) are:

- 56 Pumped bores
- Pumping rate varying from 10 m3/day to 300 m3/day
- Total production during irrigation season 1564.87 m3
- Average drawdown 0.5 m
- Average production 17.1 m3/day
- Standard deviation 50.17 m3/day

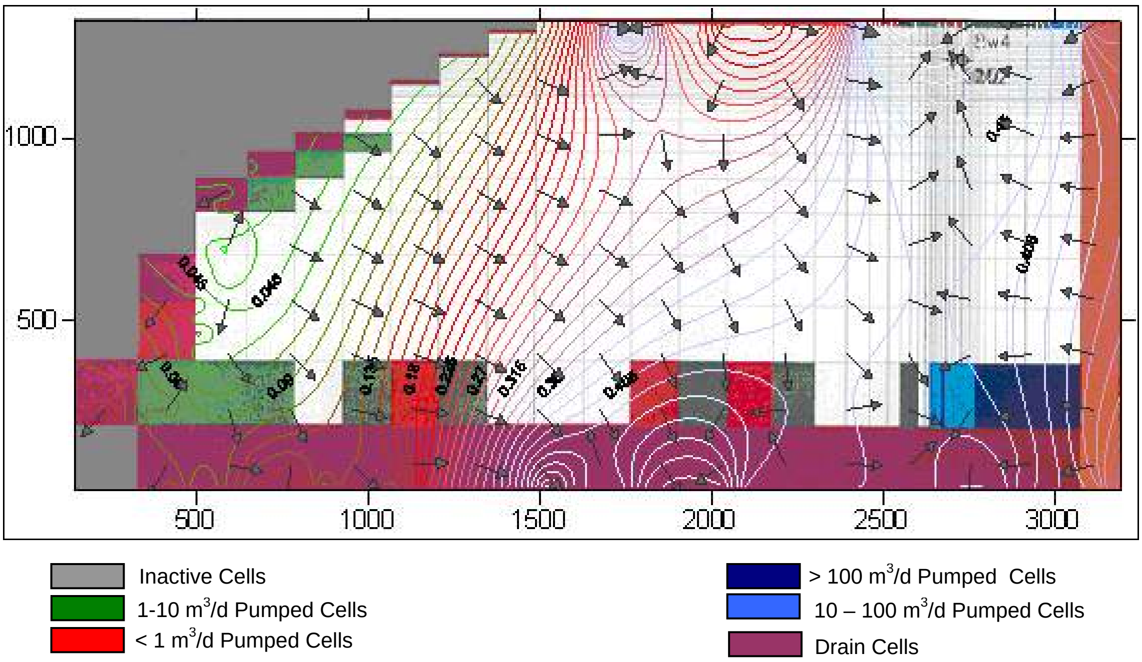


Figure 36: Drawdown curves and flow direction in layer 1 for scenario 1

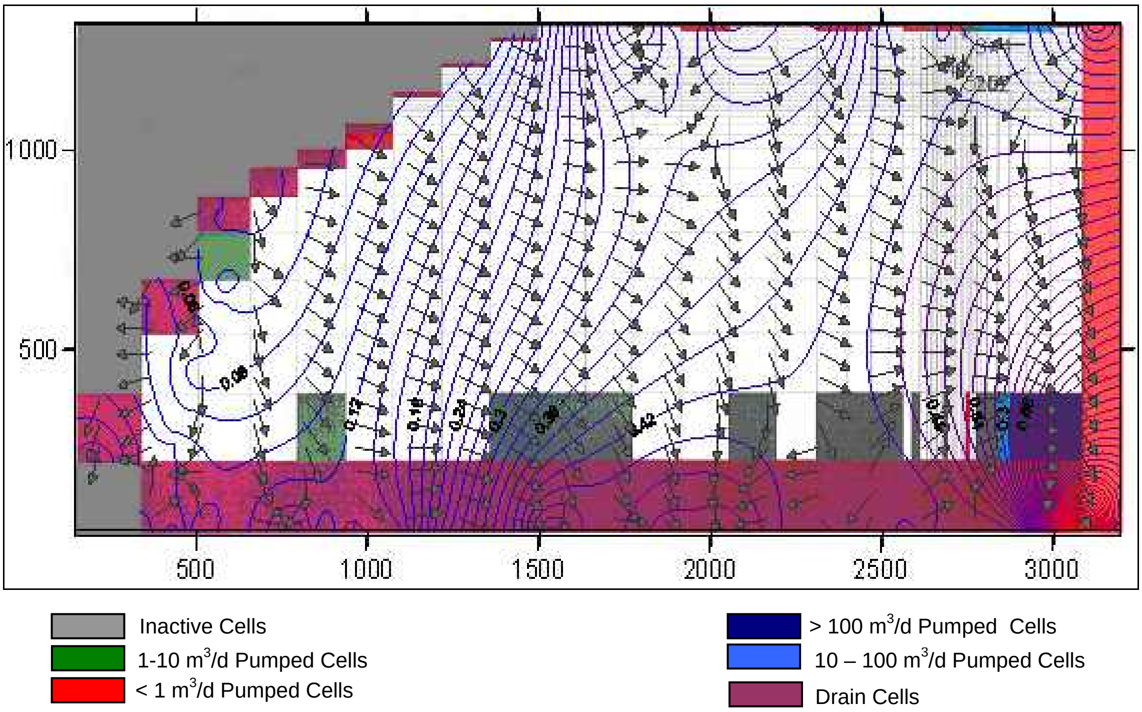


Figure 37: Drawdown curves and flow direction in layer 2 for scenario 1

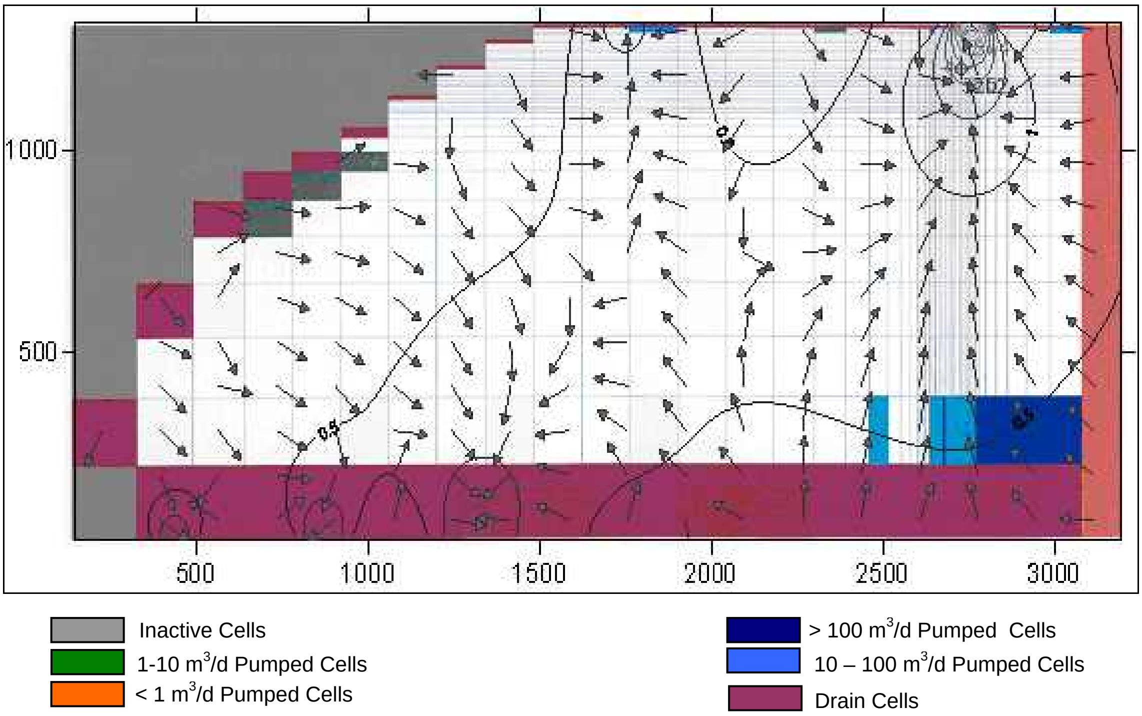


Figure 38: Drawdown curves and flow direction in layer 1 for scenario 2

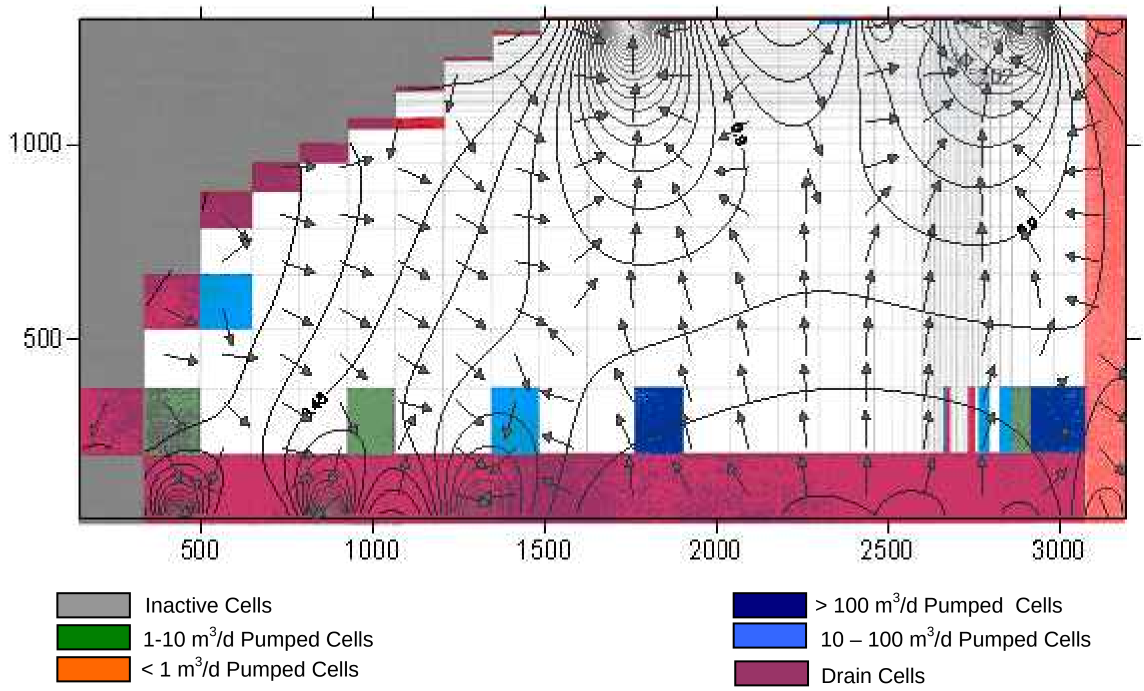


Figure 39: Drawdown curves and flow direction in layer 2 for scenario 2

4.3.2.3 Scenario 3

It involved pumping from layer 1 only. The optimisation yielded the following results (Figure 40 shows layer 1):

- 70 bores pumped
- Maximum pumping rate 514 m3/day
- Average pumping rate 19.17 m3/day
- Average drawdown 0.37 m
- Standard deviation 66.89 m3/day
- Total production 1540.3 m3

4.3.2.4 Scenario 4

It involved pumping from layer 2 only. The optimisation results (Figure 41 shows layer 2) are as follows:

- 68 bores pumped
- Maximum pumping rate 530 m3/day
- Average pumping rate 18.33 m3/day
- Total production of 1472.86 m3
- Average drawdown 0.37 m

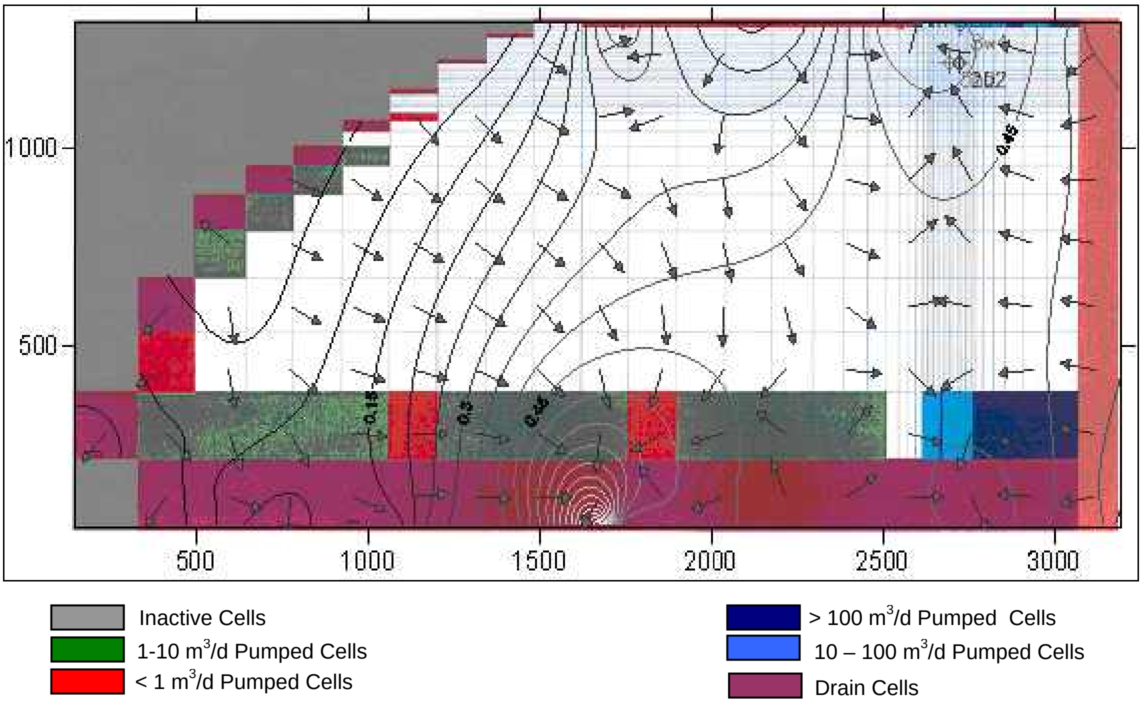


Figure 40: Drawdown curves and flow direction in layer 1 for scenario 3

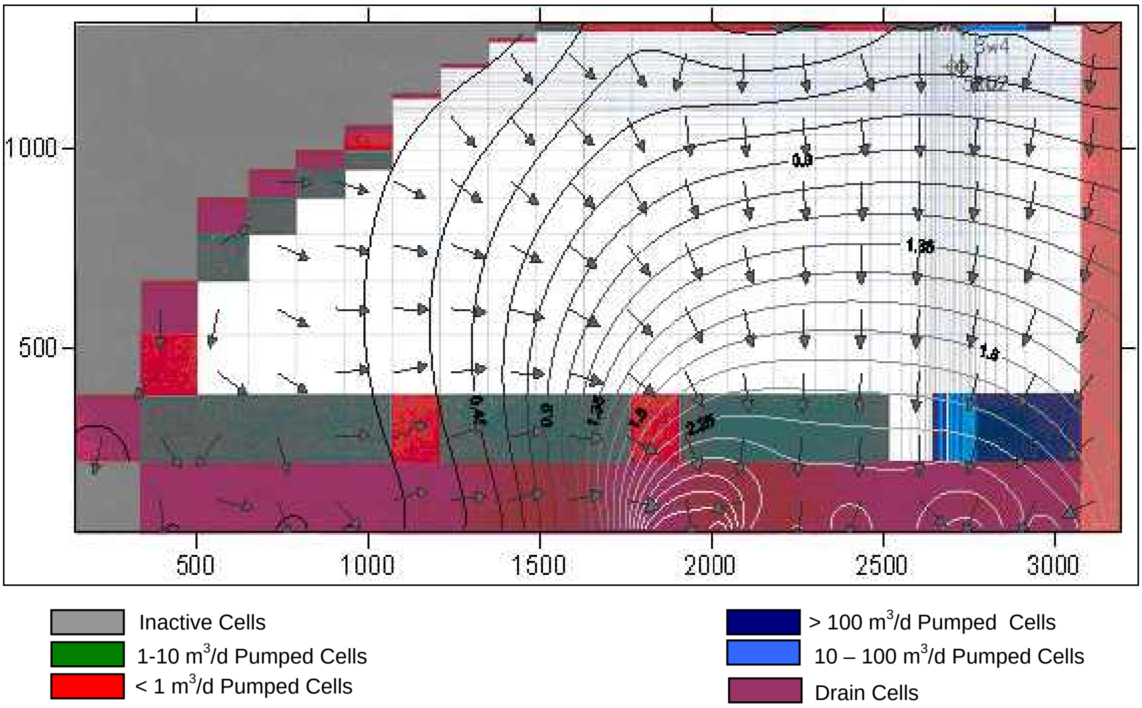


Figure 41: Drawdown curves and flow direction in layer 2 for scenario 4

4.4 Analytical Groundwater Management Model for Salinity Mitigation at Farm Scale

4.4.1 Objectives

The objectives of this part are to:

- Gain insight into the nature and impact of irrigated induced salinity from economical, environmental and social perspectives
- Develop a management model at farm scale to address options for reduction of salt discharge to water bodies and look at the option of planting trees along side the drainage channel in order to capture both surface runoff and base flow saline water before it reaches the channel

4.4.2 Conceptual Model

The modelled area is conceptualised as follow (Figure 42):

- Dual layers of 2m and 7m thickness for the upper and lower aquifers respectively with intervening aquitard. (depth extent limited to the Shepparton formation)
- Study area has horizontal dimensions of 220 m length by 130 m width
- The boundary conditions are assumed to be infinite for HOTSPOTS (analytical model)
- Rainfall recharge
- Rice pond recharge (simulated as a series of recharge point with HOTSPOTS River module – Figure 43)
- Initial hydraulic head
- One permeability region

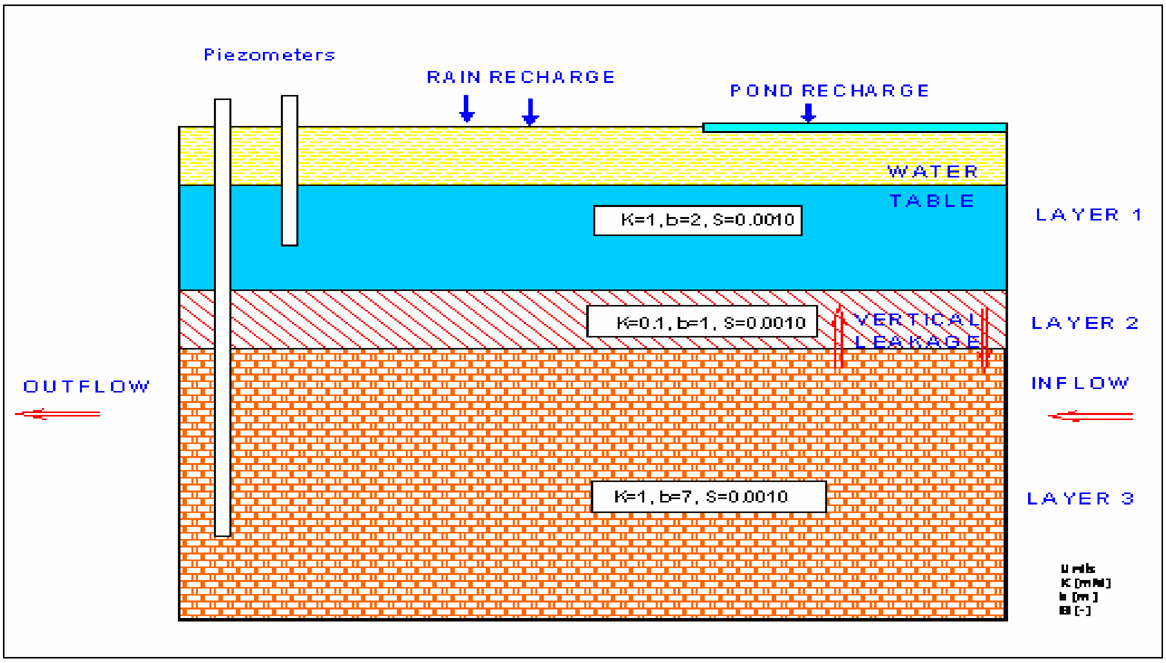


Figure 42: Conceptual model and parameterisation of the study area

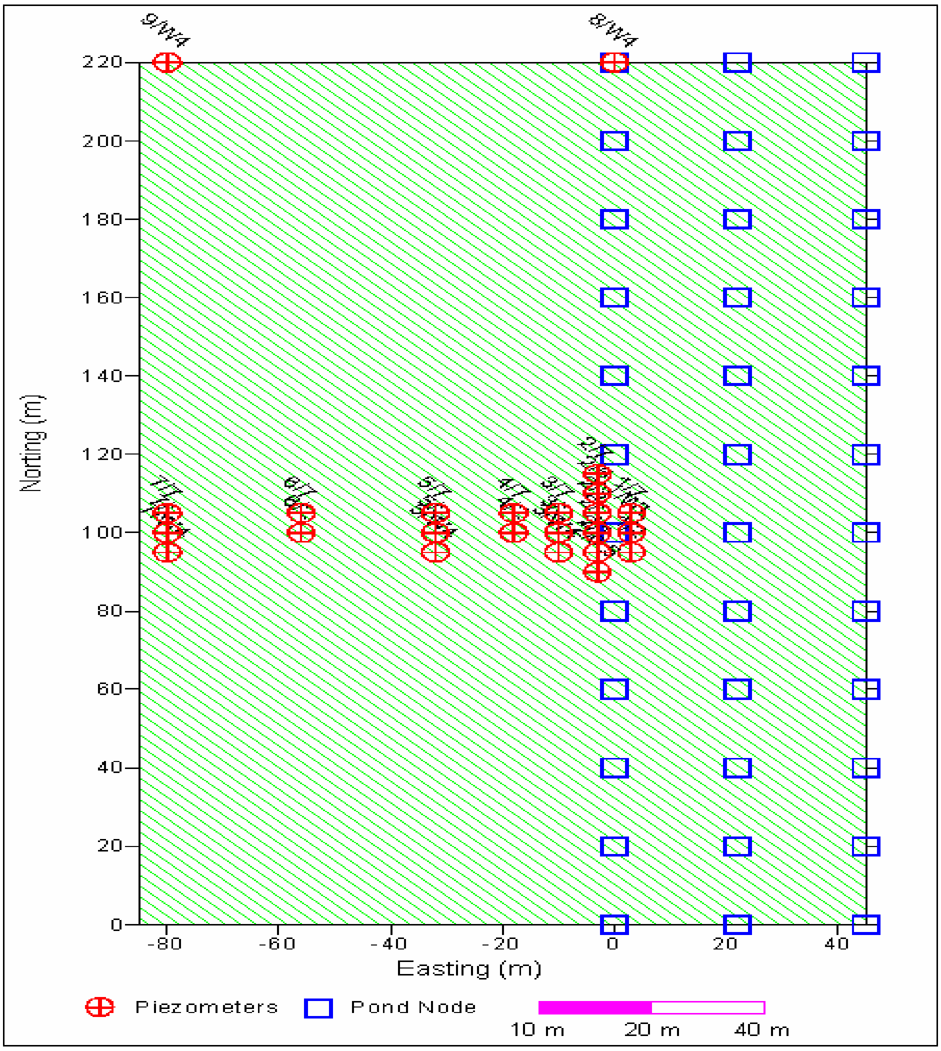


Figure 43: Base map for the study site suitable for the simulation package

4.4.3 Temporal Discretisation

The length of stress period is 7 days with the total number of stress periods set to 52. The number of time steps and the time step multiplier are set to 1.0 and 1.1 respectively. The initial time step is calculated using:

$$DELT(1) = \frac{PERLEN \times (1 - TSMULT)}{1 - TSMULT^{NSTP}}$$

Where;

DELT(1) : Initial time step
PERLEN : Length of stress period
TSMULT: Time step multiplier
NSTP : Number of time steps

4.4.4 Initial Conditions

They are summarized in Table 12:

Table 12
Initial Conditions

Reference piezometer	1/2
Flow direction (bearing)	340º
Hydraulic Gradient	1:4000
Groundwater Elevation (@ 9/07/2000)	130.9 mAHD
Natural Ground elevation	131.3 mAHD

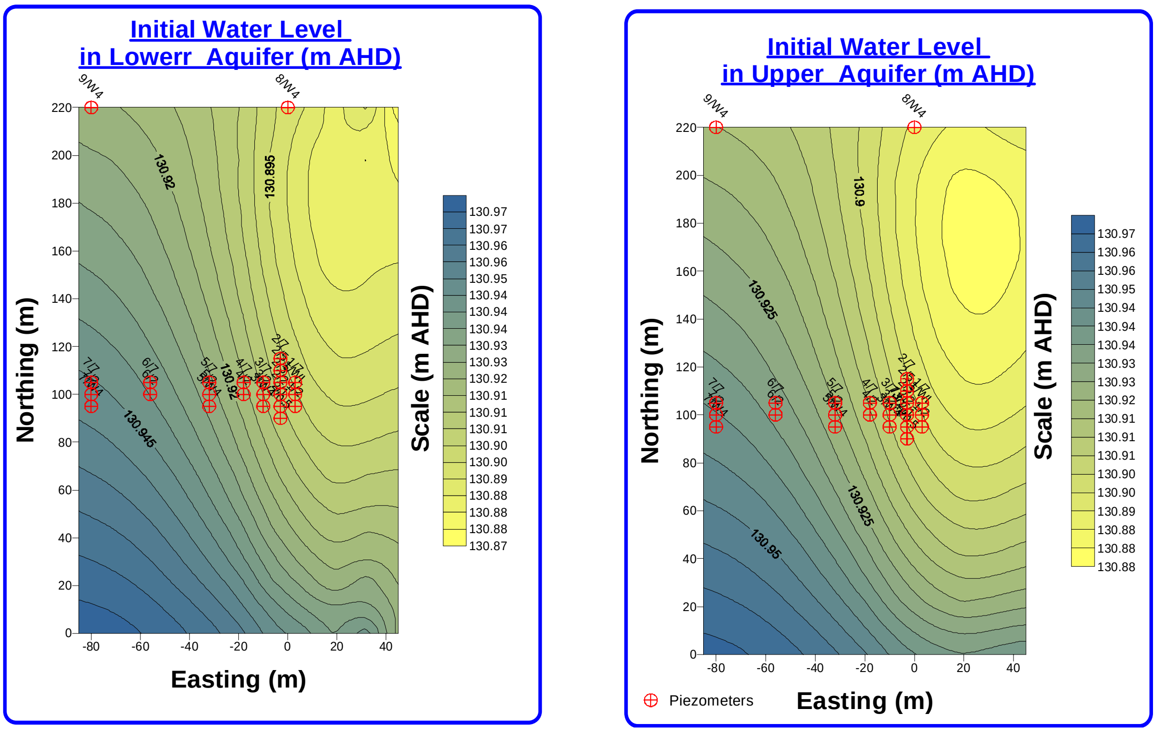


Figure 44: Initial head distribution in layer 1 (upper aquifer) and 2 (lower aquifer)

The hydraulic conductivity at the site was calculated by a pumping test in July 2000 and the data is presented in Table 12.

TABLE 12
HYDRAULIC CONDUCTIVITY (K) MEAN AND STANDARD DEVIATION OF RESULTS FOR ALL PIEZOMETERS

Piezometer	Mean K (m/day)	Std. Deviation (m/day)	Mean K (m/s)	Std. Deviation (m/s)
½	0.08	0.023	9.27 E-7	2.69 E-7
1/7	0.99	1.36	1.15 E-5	1.57 E-5
7/2	1.26	0.089	1.56 E-4	8.18 E-6
7/7	0.82	0.67	9.49 E-6	7.76 E-6

Source: McLachlan (2000)

4.4.5 Specific Yield and Storativity

The initial value of specific yield is set to 0.001. The initial storativity value for the model bottom layer is set to be equal to 0.001

4.4.6 Rain and Rice Ponding Recharge

The rainfall recharge has been set as 10 %. As for the rice ponding recharge, HOTSPOTS determines automatically the value at each node (rice pond simulated as a series of river nodes).

The reference node parameters are defined as follow:

Bed elevation : 131.32 mAHD

Width : 18 m

Hydraulic Gradient : 0.001

Leakage Coefficient : 0

4.4.7 Initial Model Run

The initial model simulation results are displayed in Figure 45 and summarised in Table 13.

TABLE 13
INITIAL MODEL PARAMETERS ESTIMATE

Parameter	K horizontal (m/day)	Leakage Coeff (d^{-1})	Specific Yield	Storage Coeff
Layer 1	1	0.001	0.001	
Layer 3	1	0.001		0.001

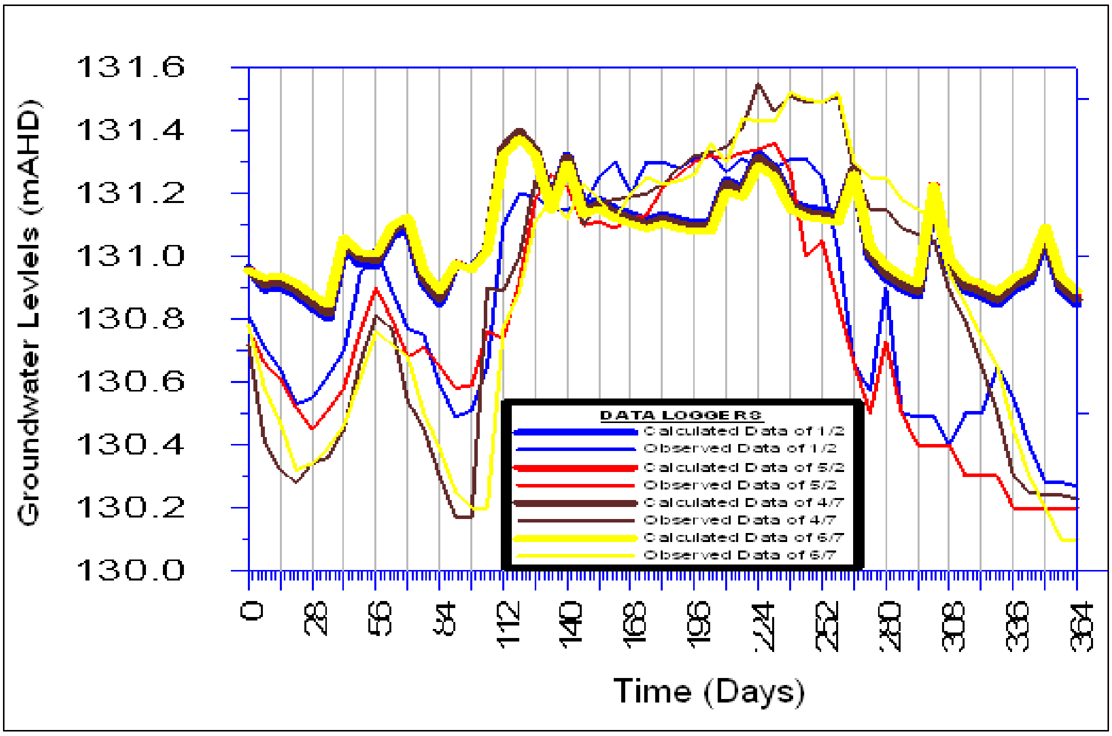


Figure 45: Initial results of model simulations

4.4.8 Model Calibration

The calibration of the model was achieved by varying hydraulic parameters till an acceptable match between the simulation outputs and the measured heads was achieved. The calibrated model hydraulic parameters are given in Table 14.

TABLE 14
CALIBRATED MODEL HYDRAULIC PARAMETERS

Parameter	Horizontal Hydraulic Conductivity (m/day)	Leakage Coefficient (d-1)	Specific Yield	Storage Coefficient
Layer 1	0.5	0.001	0.001	
Layer 3	0.5	0.001		0.001

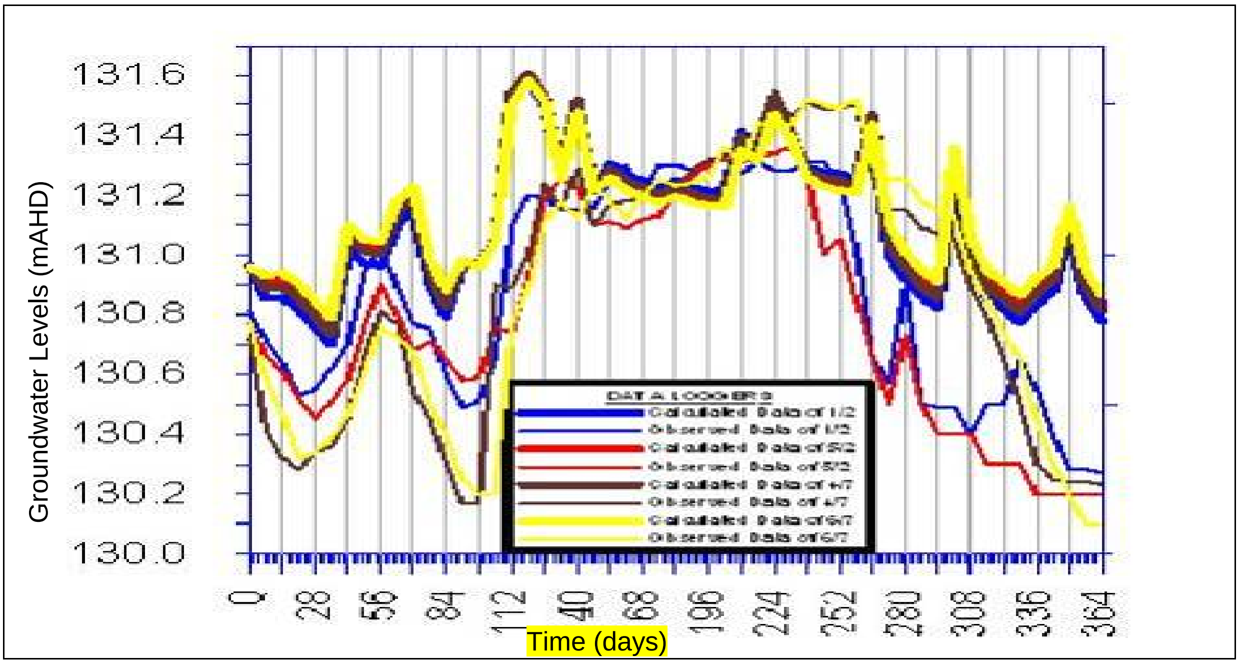


Figure 46: Comparison of calibrated vs modelled heads of groundwater

4.4.9 Water Balance

A simulation output for HOTSPOTS is summarized in Table 15.

TABLE 15
WATER FLUX (ML/DAY) AS SIMULATED BY HOTSPOTS

Water Balance	Simulation Flux (ML/day)
Rainfall recharge	0.00359
River Recharge	0.00198
Discharge to River	- 0.01323
Storage Change	- 0.00766

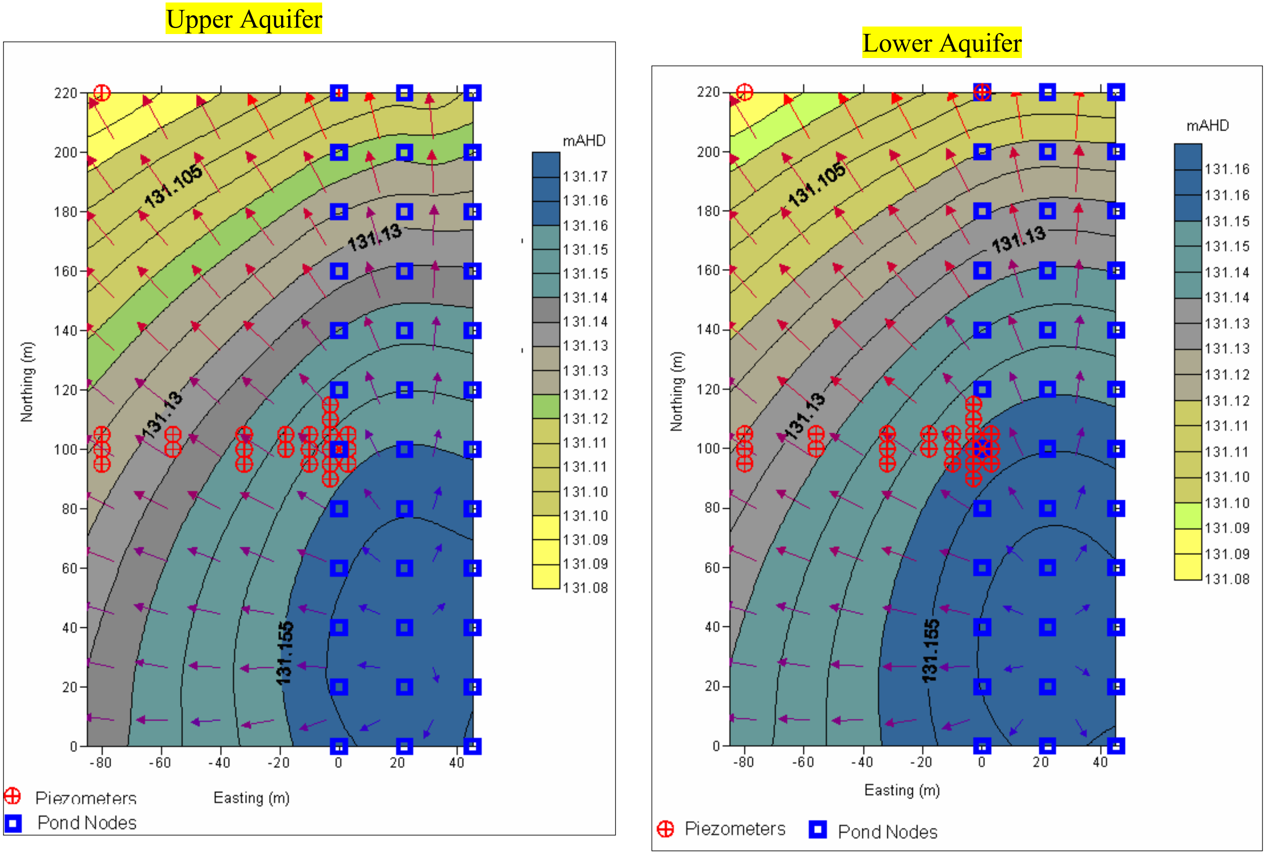


Figure 47: Upper and lower aquifer GW elevation (6 months)

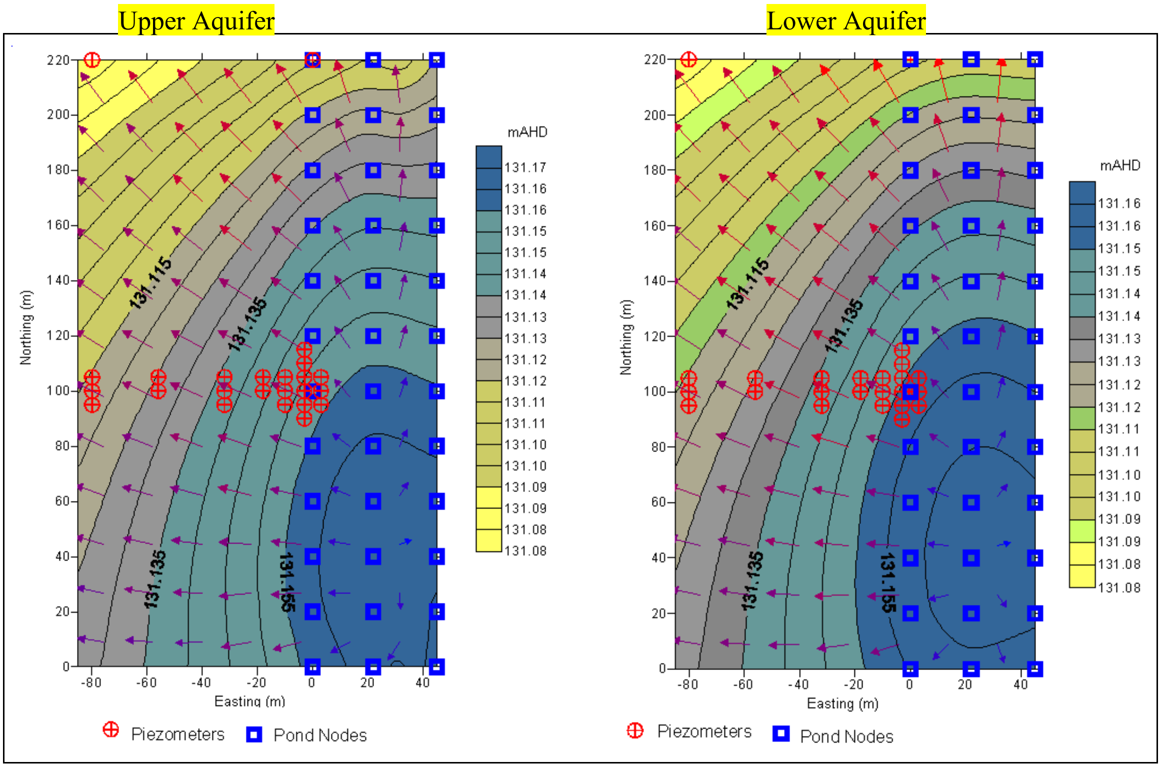


Figure 48: Upper and lower aquifer GW elevations (9 months)

4.4.10 Error Analysis

Validation of the HOTSPOTS simulation is accessed by comparing gauged and calculated heads at piezometers 1/2, 5/2, 4/7 and 6/7. The comparative analysis yielded acceptable results as shown in Table 16.

TABLE 16
COMPARATIVE ANALYSIS BETWEEN OBSERVED AND CALCULATED GW LEVELS

Piezometers	Gradient of best fit	Coeff of determination R2
1/2	0.9986	0.45
5/2	0.9979	0.37
4/7	0.9987	0.35
6/7	0.9987	0.26

4.4.11 Model Optimisation

The optimisation module incorporated in HOTSPOTS was used to investigate interception options such as pumping bores and high water intake of trees. The HOTSPOTS software is built to use the response matrix approach.

<u>Response Matrix Theory</u>

It can be summarised by the following equation:

$$s(i,T) = \sum_{j=1}^{n}\sum_{t=1}^{T}\left[a(i,j,T-t+1)Q(j,t)\right] = \sum a_{iTjt}Q_{jt}$$

Where:

i : location at which drawdown is observed
s : Drawdown
j : Location at which pumping, tree or recharge stress Q occurs
n : number of pumping bores, trees or recharge nodes
T : number of time periods t

- Number of planning periods : 2
- Planning period length : 182.625
- Time step : 1
- Tome step multiplier : 1.1
- Abstraction rate; 100 m3/day
- Median river stage at reference gauge: 131.04 m
- Long term median rainfall: 409 mm/year

Hydrological constraints include setting water level at a specified level (below or above a specified maximum and minimum elevation) in each aquifer and each observation site for each planning period. In this case the water level constraints were set at observation points between every two pumping bores (Figure 49).

Optimisation Strategies

HOTSPOTS operational limitations restrict the number of possible management solutions to be investigated. Any solution will have to fall in the following threshold:

- Maximum of 30 production bores
- Maximum of 40 observation bores
- Maximum of 10 planning periods
- Maximum of 25 properties
- Maximum of 10 production bores per property

The scenarios investigated consisted in simulations of a diverse combination of abstraction bores near the main drain and in installing rows of trees along the same location. The resulting drawdown and minimised productions are presented in Table 17.

TABLE 17
HOTSPOTS OPTIMISATION SCENARIOS

Scenarios	Number of Pumping and Observation bores						Trees	Total Minimised Drawdown (m)	Total Minimised Production (m3/day)
	100 (m3/day)		10 (m3/day)		1 (m3/day)		0.1 (m3/day)		
	Pump	Obs	Pump	Obs	Pump	Obs			
1	1	2	-		-		-	2.44	3.80
2	2	3	-		-		-	4.96	4.72
3	3	3	-		-		-	7.50	4.47
4	4	3	-		-		-	9.97	4.47
5	-		1	2	-		-	2.44	3.80
6	-		2	3	-		-	4.97	3.99
7	-		3	3	-		-	7.54	4.62
8	-		4	5	-		-	10.02	4.94
9	-		5	5	-		-	12.51	4.86
10	-		6	5	-		-	15.08	4.96
11	-		-		6	5	-	16.01	5.19
12	-		-		7	7	-	18.34	5.25
13	-		-		5	11	5	30.10	4.96

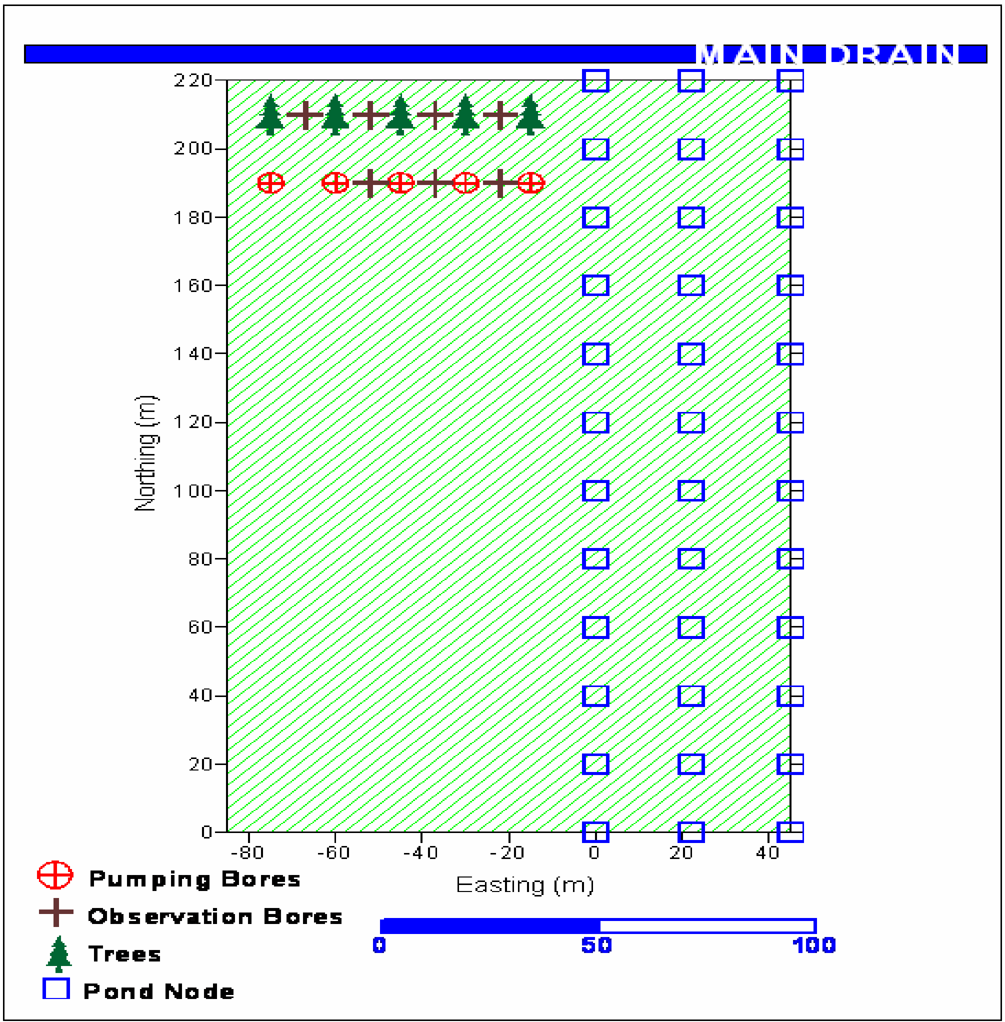


Figure 49: Location of trees and pumping bores

4.5 Salinity Mitigation in Wakool Irrigation District

The computational model developed by Xu (2003) is described in the Appendix A. The model is applied to Wakool Irrigation District for scenario development and impact analysis of land use management and irrigation water on land salinisation. In this section, we discuss the assumptions, scenarios and outcome of 1-dimensional and 3-dimensional simulations.

4.5.1 Scenarios

4.5.1.1 Impact of Irrigation on Root Zone Salinity

(1-D Simulation of Soil Moisture and Salt Transport)

Scenarios:

- No irrigation
- Irrigation with fresh water
- Irrigation with saline water
- Repeated irrigation with saline water

Assumptions:

Simulation period	=	6 years (1/1/1975 to 31/12/1980).
Crop	=	Rice (October to March).
Groundwater table	=	6-meter depth.
Soil column	=	8 model layers (0.05, 0.15, 0.3, 0.5, 0.75, 1.05, 1.4, 1.8 m).
Root zone	=	First four layers (1.0 m)
Climatic data	=	3-hourly data processed into hourly interval.

TABLE 18
MODEL PARAMETERS USED IN 1-D SIMULATIONS

Initial watertable depth	6 m
Simulation layers	8
Simulation period	6 years
Initial salt concentration	1 kg m-3
Lower boundary salt concentration	10 kg m-3
Upper boundary	with or without irrigation
Irrigation levels	fresh or saline (10 kg m-3)
Sorption coefficients	10-5 m3 kg -1
Decay rate	0.0 s-1
Soil bulk density	1500 kg m-3
Diffusivity for salt	computed
Longitudinal dispersivity	8 m
Irrigation infiltration	0.7 Ks to 0.33 Ks
Irrigation period	day 60 to 240 or 120 to 300

ALSIS has been already validated by Irannejad and Shao (1998) and is not included in model validation. The validation is focused on the Salt Transport Model. It is assumed that infiltration rate, drainage rate at upper and lower boundaries and the soil moisture remains constant for 6 years period.

4.5.1.2 Land Salinisation on Regional Scale

(3-D Simulation MODFLOW-ALSIS)

Scenarios:

1. Impact of land use on soil salinity irrigated area
    a. Precipitation to natural pastures
    b. Precipitation and irrigation to rice filed
2. Short term effects of irrigation
    a. Irrigation with Zero salinity
    b. Irrigation with water of 400 mg/l conc.
    c. Irrigation with 1000 mg/l conc.
    d. Irrigation with 2000 mg/l conc.

3. Long term effects of irrigation
    a) Irrigation with Zero salinity
    b) Irrigation with water of 400 mg/l conc.
    c) Irrigation with 1000 mg/l conc.
    d) Irrigation with 2000 mg/l conc.

Assumptions:

Simulation period = 20 years (1/1/1975 to 31/12/1994).

Model domain = 2 km x 2 km mesh of 810 soil columns.

Soil types = 3 (heterogeneous in vertical direction and two soil horizons)

Rainfall data = interpolated into hourly intervals by averaging over 24 hours.

Crops = a. No crop (natural pasture)
b. Rice
c. Autumn crops like wheat and grazing oats
d. Summer (perennial) crops like lucernes and phalaris

TABLE 19
SOIL PARAMETERS USED IN 3-D SIMULATIONS

Parameter	Soil 1		Soil 2		Soil 4
	Horizon A	Horizon B	Horizon A	Horizon B	Horizon A+B
Ks	1.8×10-9	5×10-8	1×10-7	8×10-7	1×10-5
θ s	0.43	0.43	0.43	0.43	0.43
θr	0.1604	0.1604	0.1007	0.1007	0.03
Pf-fc	2.477	2.477	2.477	2.477	2.477
Pf-w	4.0	3.0	4.0	3.5	3.0

Where:

Ks = Saturated hydraulic conductivity
θ s = Saturation water content
θr = Residual water content
Pf-fc = Capillary pressure
Pf-w = Capillary pressure

Assumptions:

1. Initial salt concentration is uniform in unsaturated zone
2. Solute concentration of groundwater is constant
3. Initial piezometric head is same for all three aquifers

4. Groundwater flow direction is from southeast to northwest
5. No flow across north and south boundaries (Edward and Wakool rivers)
6. Fixed head boundary condition along eastern and northwestern boundaries

TABLE 20
MODEL PARAMETERS USED IN 3-D SIMULATIONS

Initial watertable depth	varying
Simulation layers	varying
Simulation period	20 years
Initial salt concentration	1 kg m-3
Lower boundary salt concentration	10 kg m-3
Upper boundary	variable irrigation
Sorption coefficients	10-5 m3 kg -1
Decay rate	0.0 s-1
Soil bulk density	1500 kg m-3
Diffusivity for salt	computed
Longitudinal dispersivity	8 m

4.5.1.3 Overland Flow and Salinity

Scenarios:

1. No surface runoff
2. Surface runoff
3. Manning coefficient of 0.07, 0.05 and 0.04

Assumptions:

Topography	slightly sloped from southeast to northwest direction
Overland flow	sheet flow
Hydraulic radius	approximated to flow water depth
Surface conditions	Manning's roughness coefficient to range of 0.03 to 0.08
Simulation period	1/1/1975 to 31/12/1994

4.5.2 Scenario Analysis

The salt transport model is applied to simulate soil moisture and salt movement in the root zone. There are four scenarios of 'Irrigation' which are tested in the modelling system. However, there is no reference available in the thesis that supported the decision making about these scenarios.

No Irrigation:

1. 6-month fresh water irrigation in the first year
2. 6-month saline water irrigation in the first year
3. 6-moth saline water irrigation every year

The main focus of this section is to determine: 1) the impact of land use on soil salinity; 2) the short and long term effects of irrigation water with different qualities on soil salinity.

Regarding first task of finding impact of land use on spoil salinity, the assumption that the crop distribution of 1993/1994 is not the truly representative distribution for the period of 20 years time (from 1975 to 1995). There is no adequacy shown about this assumption and even not supported by any reference in the literature. The time-variant land use pattern and its areal extent are critical and decisive factors regarding their impact on salinisation. Further, the application of real land use by its very nature is somewhat considerable to know its actual contribution in salinisation process. There is abundance of satellite data available, which should be used for more accurate and reliable results. Therefore, quality assurance in land use data is needed to ensure relatively trustworthy results of the modelling system. Consequently if assumption of land use data as averaging of 20 years record is followed, proper interpretation supported by evidences stated in Land and Water Management Plans should be adequately taken up.

4.5.2.1 Impact of Irrigation on Root Zone Salinity

<u>A. Model Calibration and Validation:</u>

- One-dimensional modelling system consisting of ALSIS and the new developed solute transport model is applied to simulate soil moisture and salt movement ion root zone.
- ALSIS (water flow component) is not included in the verification as it has been already validated by Irannejad and Shao, 1998.
- The salt transport model is verified in terms of a salt budget for the mass conservation based on the following assumptions.

    - ➢ Groundwater table is fixed at 6 m depth.
    - ➢ The soil column of 6 meter is divided into 8 layers
    - ➢ A constant infiltration and a drainage rate are assumed at lower and upper boundaries
    - ➢ A soil moisture for whole soil column is maintained for 6 years
    - ➢ Initial solute conc of 1 kg/m3 (EC=1.56 dS/m) is assumed
    - ➢ Salt conc. at lower and upper boundaries is 10 kg/m3 (EC=15.63 dS/m)

- The model simulation is reliable as simulated change of total salt is consistent with net salt inflow of salt mass.

<u>B. Model Results:</u>

Model is tested for four-year period (1.1.1977 to 31.12.1980)

Fresh Water Irrigation

- The simulated infiltration, soil moisture in topsoil, average soil moisture in root zone are shown in Figure 50.
    - ➢ It is shown that infiltration pattern (Figure 50 (a)) is closely linked with rainfall and evaporation data. However, rainfall and evaporation are not drawn for comparison purpose. In particular, rainfall pattern for four-year period is very much important and must have been elaborated to get insight about the infiltration and modelling response after first fresh water irrigation.

The top-soil moisture and root zone soil moisture show annual variations in relation to seasonal change (Figure 50 (b and c). The summer and winter indication should have been given for reader reference.

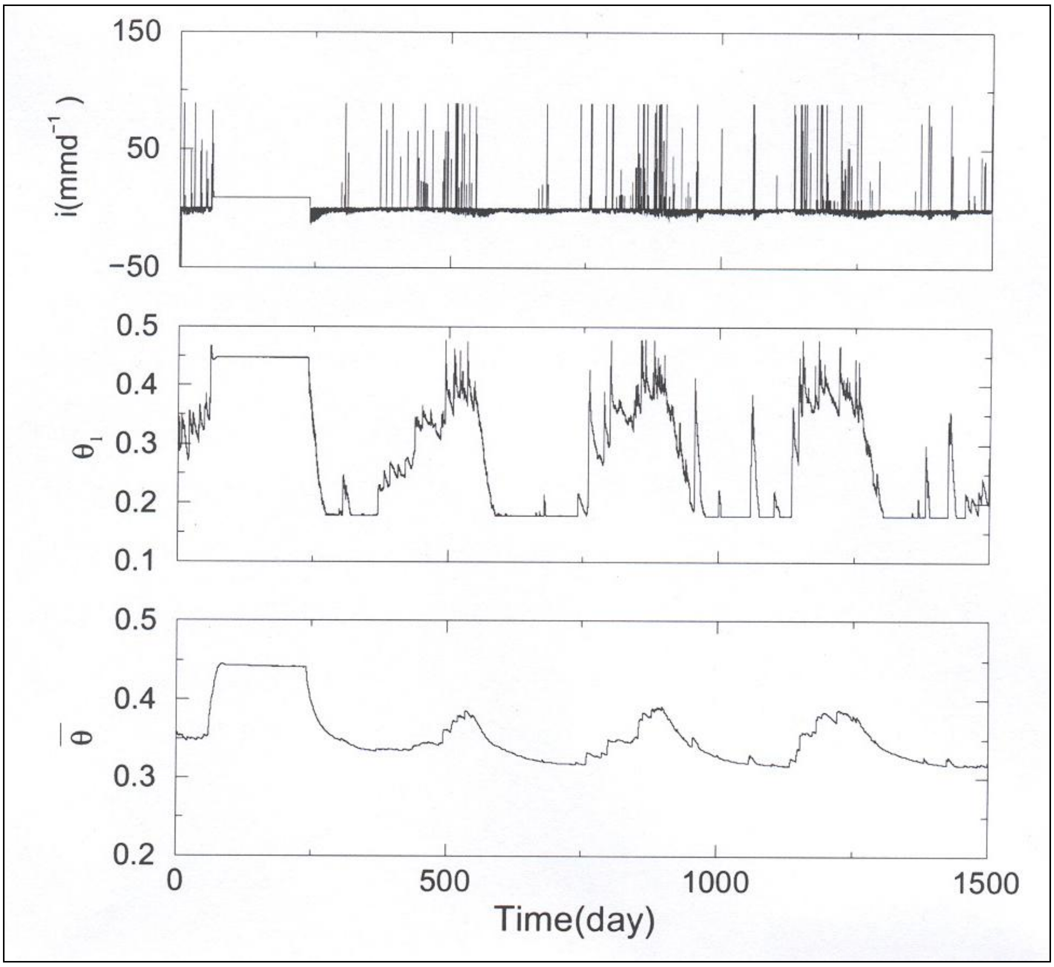


Figure 50: (a) Simulated infiltration, (b) soil moisture in the top soil layer and (c) averaged soil moisture in the root zone. Irrigation is applied during 60-240 days in WID

Comparison of Freshwater Irrigation and Non-Irrigation

The time series comparison is shown in Figure 51 and 52.

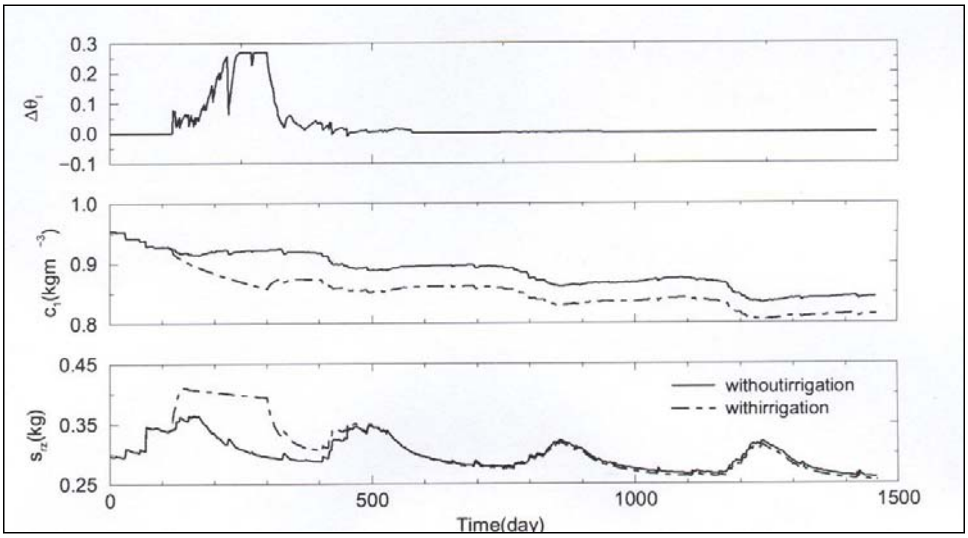


Figure 51: (a) Simulated time series of soil moisture difference between irrigated and unirrigated cases in the top soil layer, (b) solute concentration in top soil layer and (c) total mass of solute in the root zone in WID

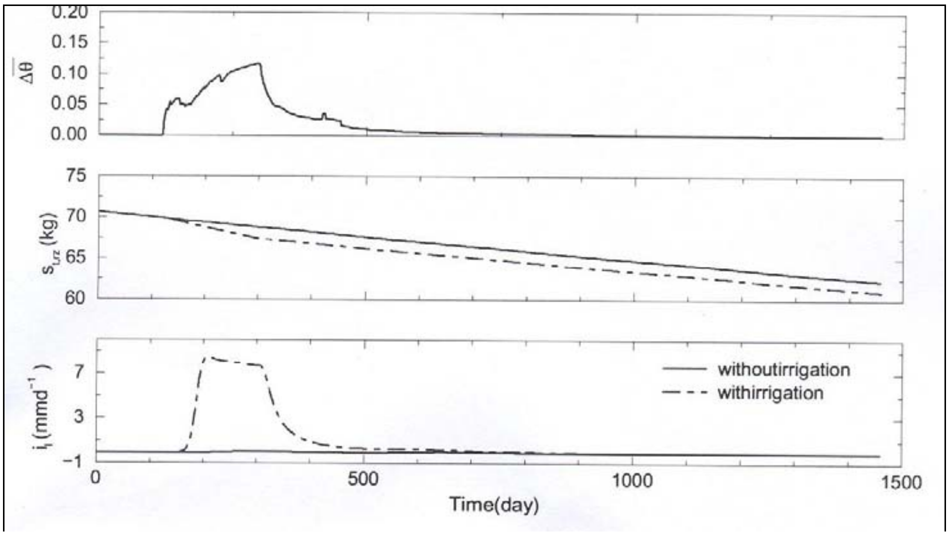


Figure 52: (a) Average soil moisture in the root zone, (b) total solute mass in the root zone, and (c) drainage to ground water system in WID

- Soil moisture difference in topsoil layer is plotted in Figure 51 (a) and is shown as large during irrigation time in first year. The topsoil holds similar moisture pattern for irrigation and non-irrigation scenarios and no difference is noticed. However, moisture pattern should be drawn separately for clear understanding. Average soil moisture in the root zone is drawn in Figure 52 (a) but it is not clearly indicated for irrigation or non-irrigation.

- The solute concentration in topsoil decreased significantly as irrigation reduces the salt concentration, Figure 51 (b).
- The pattern of model prediction for salt concentration in top soil (Figure 51 (c)) are quite similar and for total salt mass in the root zone (Figure 52 (b)) exhibits the same pattern in both scenarios of irrigation and non-irrigation.
- The total salt mass in the root zone is somewhat similar or lower for the irrigation case (Figure 52 (b)) for the period of 500 days to 1500 days except it is significantly higher during irrigation because the soil water dissolves the absorbed soil in the soil, Figure 51 (c).
- The effect on recharge to groundwater system is extremely high during irrigation period (Figure 52 (c)) touching to the rate of 7 mm/day for about 150 days. It is indicated that about 70 % of the infiltration at the land surface will percolate into the groundwater but it is not supported by any assessment of infiltration and recharge to groundwater.
- The total solute salt in the root zone is observed same for both scenarios from 500 days to 1500 days as shown in Figure 51 (c). Therefore, we disagree with the statement that irrigation with fresh water can reduce salinity at the cost of increased recharge into groundwater.
- Figures 54(a) and (b) show the time series impact of "No Irrigation" and "6-month fresh water irrigation" on salt accumulation in root zone. The initial assumed salt concentration is 1 kg/m3. Figure 54 (a) shows relative decrease in salt concentration but the pattern is same in all four layers. The fresh water irrigation has major impact in lowering topsoil salt concentration as they are dissolved in fresh water.

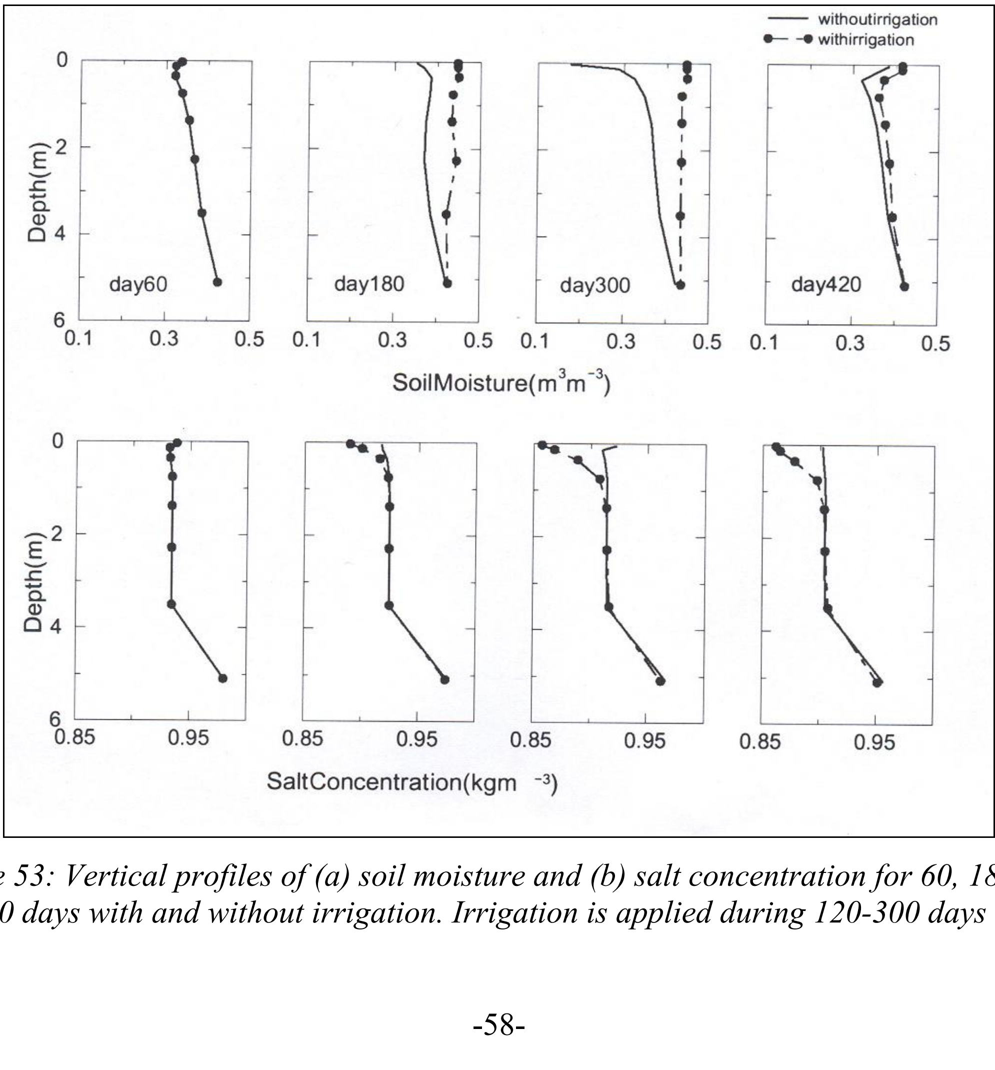


Figure 53: Vertical profiles of (a) soil moisture and (b) salt concentration for 60, 180, 300 and 420 days with and without irrigation. Irrigation is applied during 120-300 days in WID

- The profile soil moisture and salinity is given in Fig 53

  - Clearly soil moisture increases in the topsoil layers when irrigation is applied and if irrigation is continued for longer time (420 days), the whole soil column will be saturated (Fig. 53 (a)).
  - The solute concentration decreases as irrigation with fresh water is introduced especially in root zone of 1-m depth. However, there is no difference noticed for solute concentration beyond root zone and the same concentrations are noticed in bot scenarios (Figure 53 (b)).

Saline Water Irrigation

- The irrigation with saline water greatly increases the salinity in the root zone (Figure 54). Figure 55 shows an amount of 1 kg/m3 is added to layers 1 and 2 by single irrigation only. The salts are not leached down to further layers and the total salt mass in layers 4 and 6 remain as of assumed initial salt concentration of 1 kg/m3.
- The irrigation with saline water has a long-term impact on root zone salinity because it continuously adds salt to root zone.
- Model prediction shows clear difference in time series salt concentration in topsoil layer. Therefore, if saline water irrigation continued for indefinite time, there is high risk of salt accumulation shown in Figure 55 (b).
- The time series total mass of salt in root zone in shown in Figure 55 (b) and it is evident that repeated irrigation with saline water will add considerable salts in the root zone.

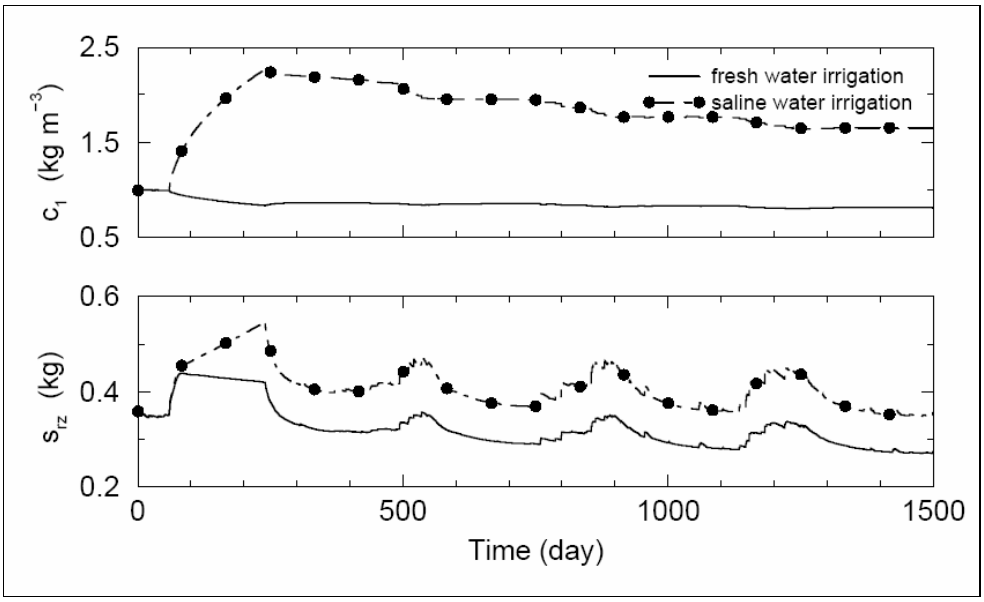


Figure 54: Time series of solute concentration in (a) top soil layer (b) total solute mass in the root zone for irrigation with fresh and saline water in WID

Repeated Saline Water Irrigation

- There is 6-month saline water repeated irrigation every year for four-year simulation period.
- There is gradual rise in salt concentration in layer 1 and layer 2 till simulation terminates during 4th year. The salts that added to layers 1 and 2 are more or less 2 kg/m3 in four-year period. This indicates that how much salt will be added if saline water irrigation of rice field continues for decades.
- The curves of increasing salt concentration become relatively flat during dry period of 6 month but start increasing during next phase of saline water irrigation.
- There is no significant effect of repeated saline water irrigation on layers 4 and 6. The layer 4 is somewhat affected after 1000 days. Therefore, the layer 4 is also susceptible to be saline with repeated saline water irrigation.

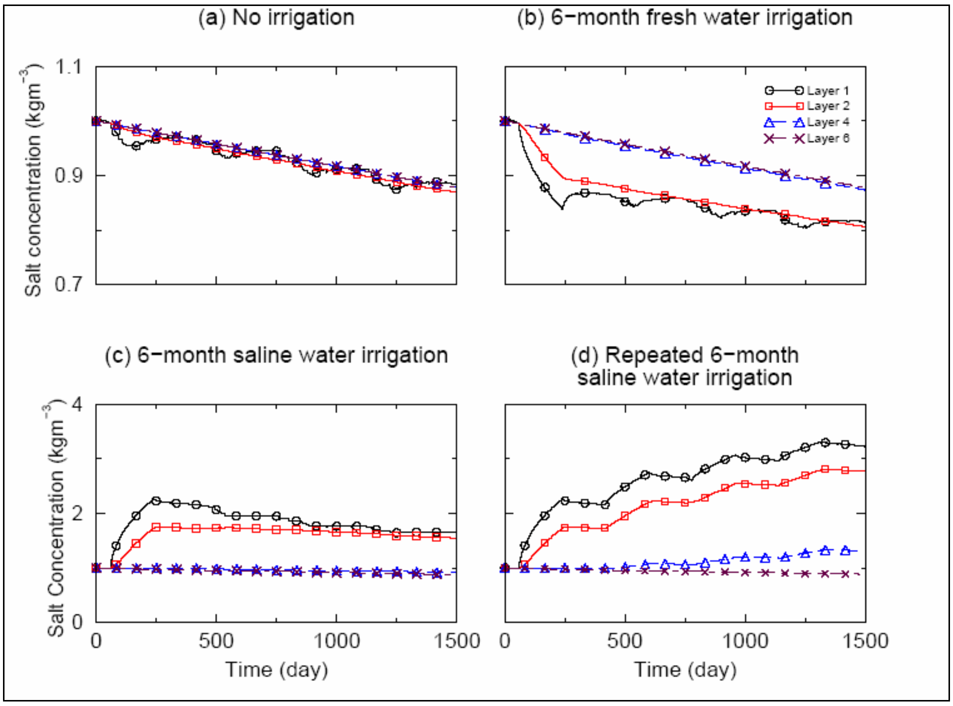


Figure 55: Salt concentration in soil layers 1, 5 and 7 for different irrigation practices; (a) no irrigation, (b) 6-month fresh water irrigation in the first year, (c) 6-month saline water irrigation in the first year, and (d) repeated 6-month saline water irrigation in WID

Four scenarios of irrigation are tested. Of course, there is no further risk of salinisation for the first two levels; 'No Irrigation' and 'Irrigation with Fresh Water'. The solute concentration in soil layer decreased significantly. Irrigation increased the moisture fluxes that carried salt into deeper soil layers and finally accession to groundwater system. It is found that about 70 % of the infiltration at the land surface will percolate into groundwater. Recognition of groundwater recharge is very well known fact and does not reveal any innovation and originality. Moreover, the conclusion "irrigation with fresh water reduce salinity at the cost of increased recharge into groundwater" is questionable. When compared with third scenario of 'Irrigation with Saline water', it is shown that the threshold salinity level of most agricultural plants is below 6 dS/m. As salinity levels increases, changes need to be made to agricultural practices to minimise yield loss and prevent further land degradation of salinisation. On land areas that have soil salinity levels above 6 dS/m, there is a high risk of further salinisation.

One question that is not adequately addressed is "how the existing agricultural practices will affect the area in accordance with the tested scenarios and research findings"?

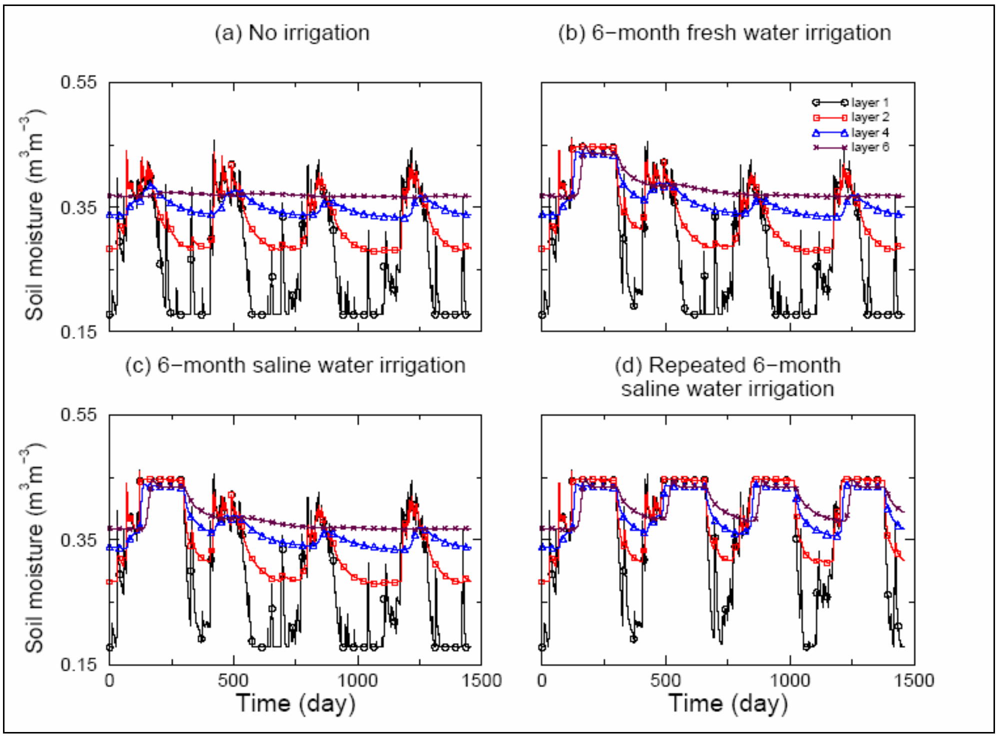


Figure 56: Volumetric moisture in soil layers 1, 5 and 7 for different irrigation practices; (a) no irrigation, (b) 6-month fresh water irrigation in the first year, (c) 6-month saline water irrigation in the first year, and (d) repeated 6-month saline water irrigation in WID

4.5.2.2 Modelling Land Salinisation at Regional Scale

<u>A. Model Calibration and Validation:</u>

- The modelling system consisting of 1-D ALSIS, 2-D Overland Flow Model and 3-D Groundwater Flow Model (MODFLOW) is applied to simulate soil moisture and salt movement in the root zone of entire Wakool region.
- Total area (3,240 km2) of Wakool is divided into 810 grids of 4 km2 each depending upon the soil texture distribution within the same grid. Figure 6 shows this distribution in three types of soil. Vertically, each soil grid consist of two horizons (0.5 m and 11.3 m)
- The crops used in the model are (1) no crop (natural pasture), (2) rice, (3) autumn crops (wheat, oats) and (4) summer perennial crops (lucernes, phalaris). There is assumption that crop distribution of 1993-94 is a representative distribution for the period between 1975 and 1995. We don't agree with this assumption because the land use change is function of time and there could have been big changes between 1975 and 1994. It is suggested that model calibration be done, at least, based on 4 groups consisting of 5-year land use pattern.
- The precipitation data for 1975-95 is taken from DLWC.
- The calibration is based on the following assumptions.
    - ➢ Groundwater flow direction is from southeast to northwest.
    - ➢ The initial piezometric head is same in the area.

- Initial salt concentration to be uniform and groundwater salt concentration is constant.
- Initial solute concentration of 1 kg/m3 (EC=1.56 dS/m) for the unsaturated zone to be uniformly distributed for the entire area.
- Salt concentration at lower boundary is 10 kg/m3 (EC=15.63 dS/m)
- Very short time steps varying from 24 hours to as low as 2 minutes (1 hour for ALSIS, 5 minutes for Overland flow model and 24 hours for MODFLOW) are applied.
- Calibration period is 20 years (1.1.1975 to 31.12.1994)

- Out of 1000 groundwater observation bores, representative 36 bores in different locations are selected for which the groundwater levels are compared with the model results.
- In general, 95 % of the modelled results fall within ±0.5 m difference from the bore reading and all modelled groundwater levels within ±0.1 m.

B. Model Results:

Model is tested for 20-year period (1.1.1975 to 31.12.1994)

Impact of Land Use on Soil Salinity

- Period of simulation is 20 years from 1.1.1975 to 31.12.1994
- The 1993-94 crop distribution is repeatedly used for 20 year period
- The irrigation data for each crop for 1993-94 is also repeatedly used for the simulation period.
- No information about the initial watertable in the region is stated?
- In Root Zone:

  - The south-eastern part of the Wakool district where rice is grown with ponding irrigation is mostly affected by irrigation water. Consequently, high salinity and shallow groundwater table are shown in simulation as in Figure 4.11.
  - During the overlay analysis, it is evident that total salt mass corresponds well with areas of high watertable. The saline groundwater is the major source of salinity. No comparison on temporal basis like 5 year or 10-year interval time is conducted. It is very important that pixel to pixel comparison must carried out in GIS environment to have insight of the salinity process. Temporal change is not considered. We suggest that areal distribution of total salt (kg) and depth to watertable (m) must be calculated.
  - The effect of Wakool Tullakool Subsurface Drainage Scheme is described but the extent of any improvement through figures and tables is not described.
  - Lateral movement of groundwater is eliminated as small change initial watertable is noticed in areas with small irrigations. The irrigation, rainfall and evapotranspiration are determining factors for any change in watertable levels.

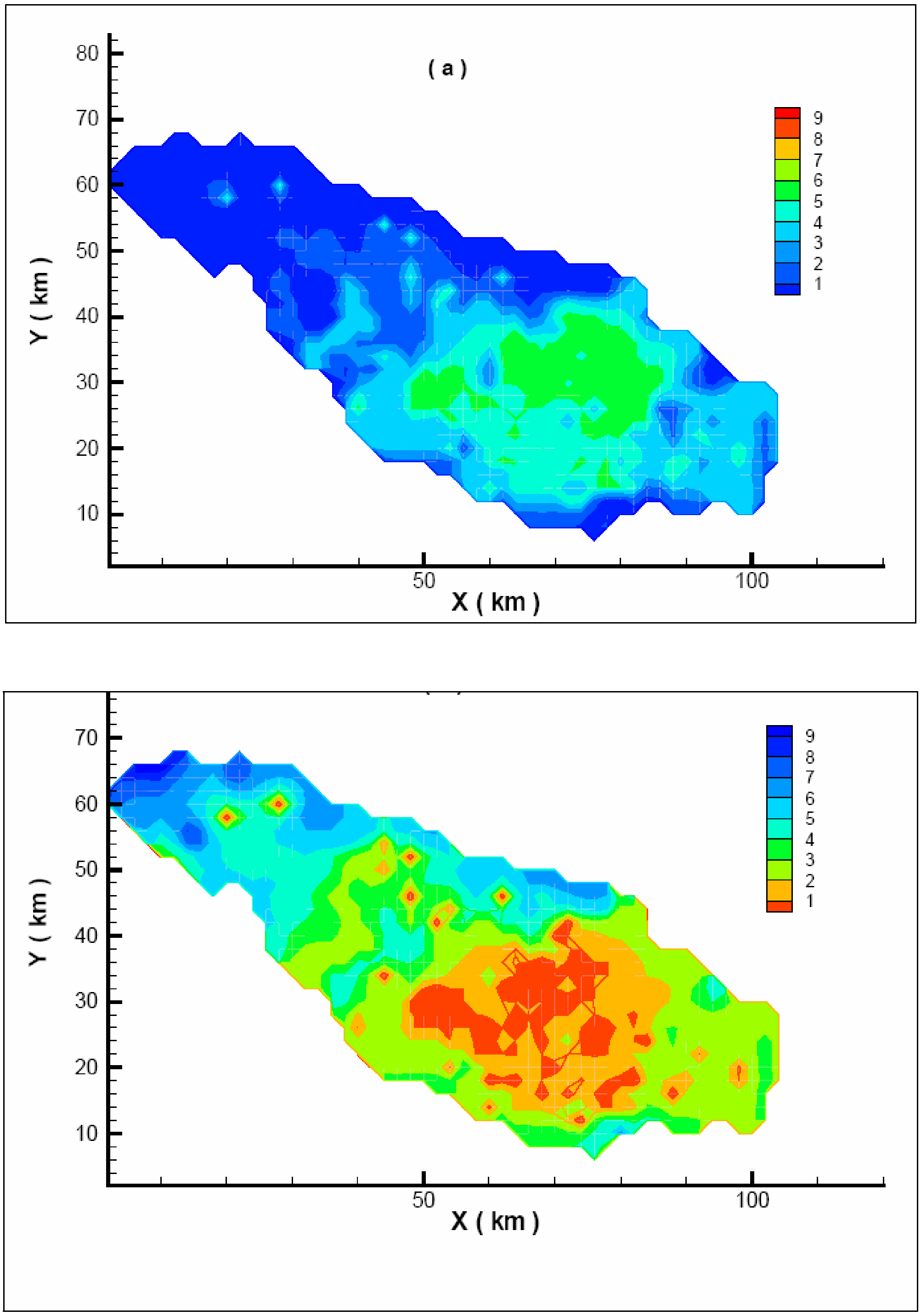
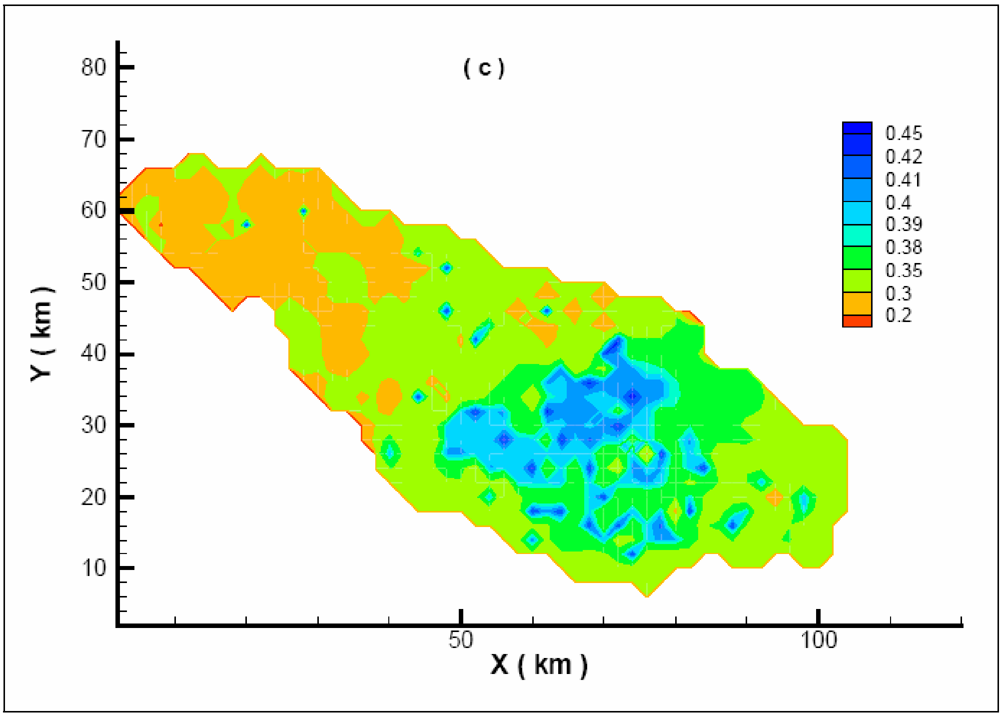


Figure 57: Total salt (kg) in the root zone (a) and depth (m) to watertable (b) in WID over 20 years (1975-1994) Root zone depth is assumed to be 1 m.



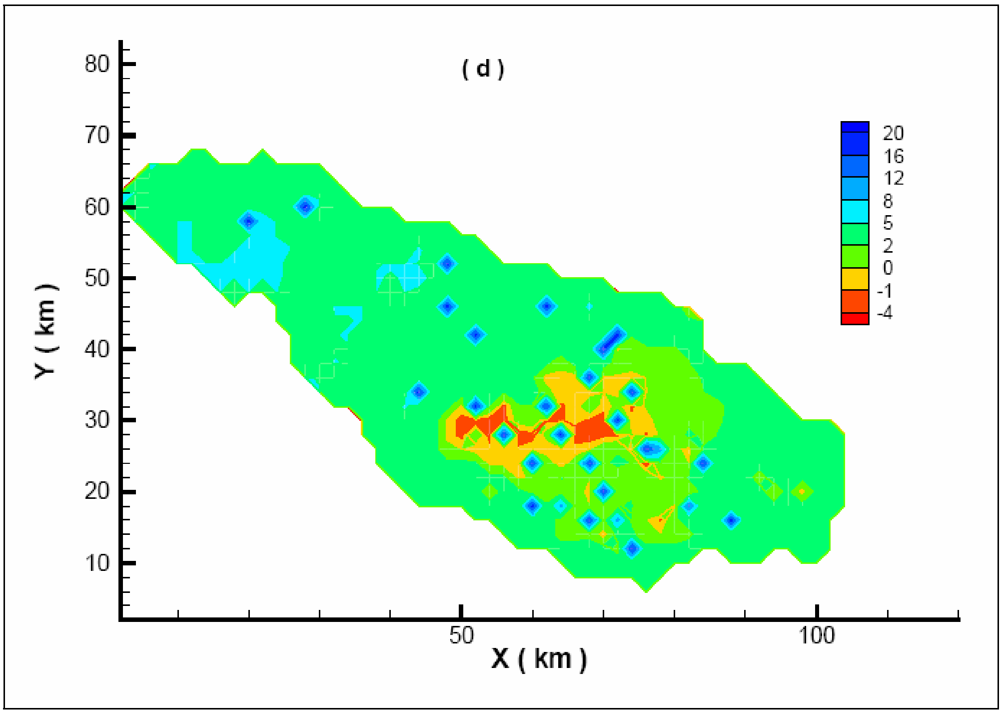


Figure 58: Total water (m3) in the root zone (c) and average infiltration (d) in WID over 20 years (1975-1994) Root zone depth is assumed to be 1 m.

- Soil Profile (Irrigated Rice Land Use):

    - Two rows (grids) of almost 50-km length in the area passing through rice paddocks are selected as shown in Figures 59 and 60. The soil moisture varies significantly in horizontal direction but increases with depth due to different permeability and infiltration rate.
    - Soil columns under rice paddocks were fully saturated because of continued infiltration with unlimited source of water from ponding irrigation (Figure 59 (a)). The rice paddock is at distance of 20-22 km showing more moisture percentage (Figure 59 (b)). In case of second row, the rice paddocks at distance of 50-52 km and 70-72 km (Figure 59) exhibit the same pattern of moisture distribution.
    - The added salts due to saline water irrigation in rice paddocks show sever concentration under the rice bay (Figures 59 (b) and Figure 60 (b)).
    - The effect of annual rainfall in irrigated rice filed is also significant. During dry period after the harvest, the soil moisture of the root zone is reduced. However, the salt concentration in root zone (up to 1-m depth) increased significantly when saline watertable approached the land surface. This situation lasted until the start of the next rain season when heavy rainfall again reduced the salt concentration.

- Soil Profile (Natural Pastures and Precipitation):

    - A location at distance of 40 km east, 36 km north (grid of col.=20, row=22) is selected. Soil moisture and salt concentration profiles are plotted for two-year data (1.1.1975 to 31.12.1976). The temporal variations in soil moisture are large near the land surface and decreases with depth.
    - The salt concentration varies with precipitation. It increased in the dry season and decreases in wet season.

- Spatial and Temporal Variations in Watertable at Regional Scale:

    - The spatial behaviour is plotted for four different years (1979, 1984, 1989, 1994) of the same date.

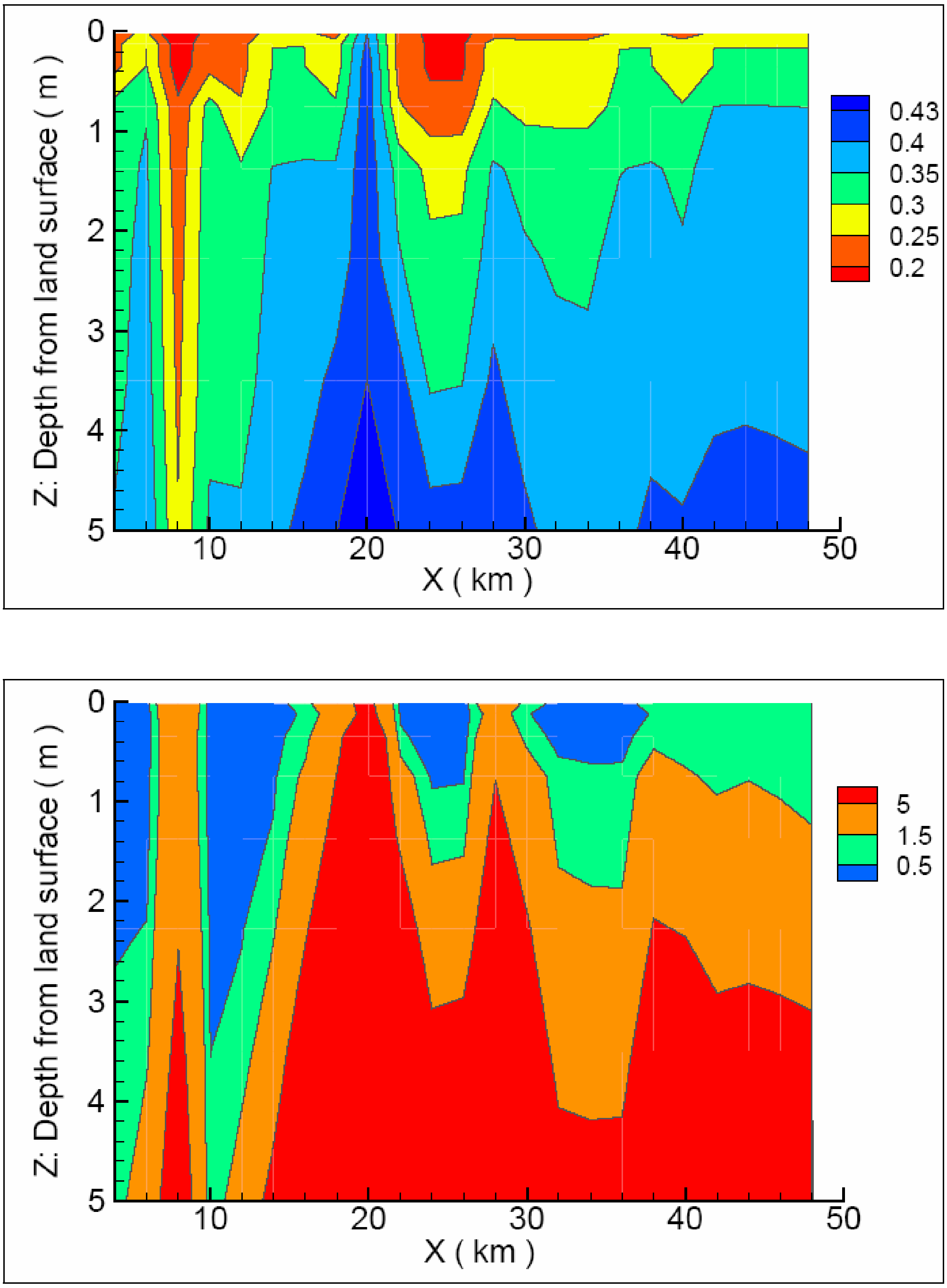


Figure 59 Cross sectional distribution at row:12 for (a) soil moisture, and (b) salt concentration (kg/m3) in December 1994. Rice bay is located at x=20 to 22 km in WID

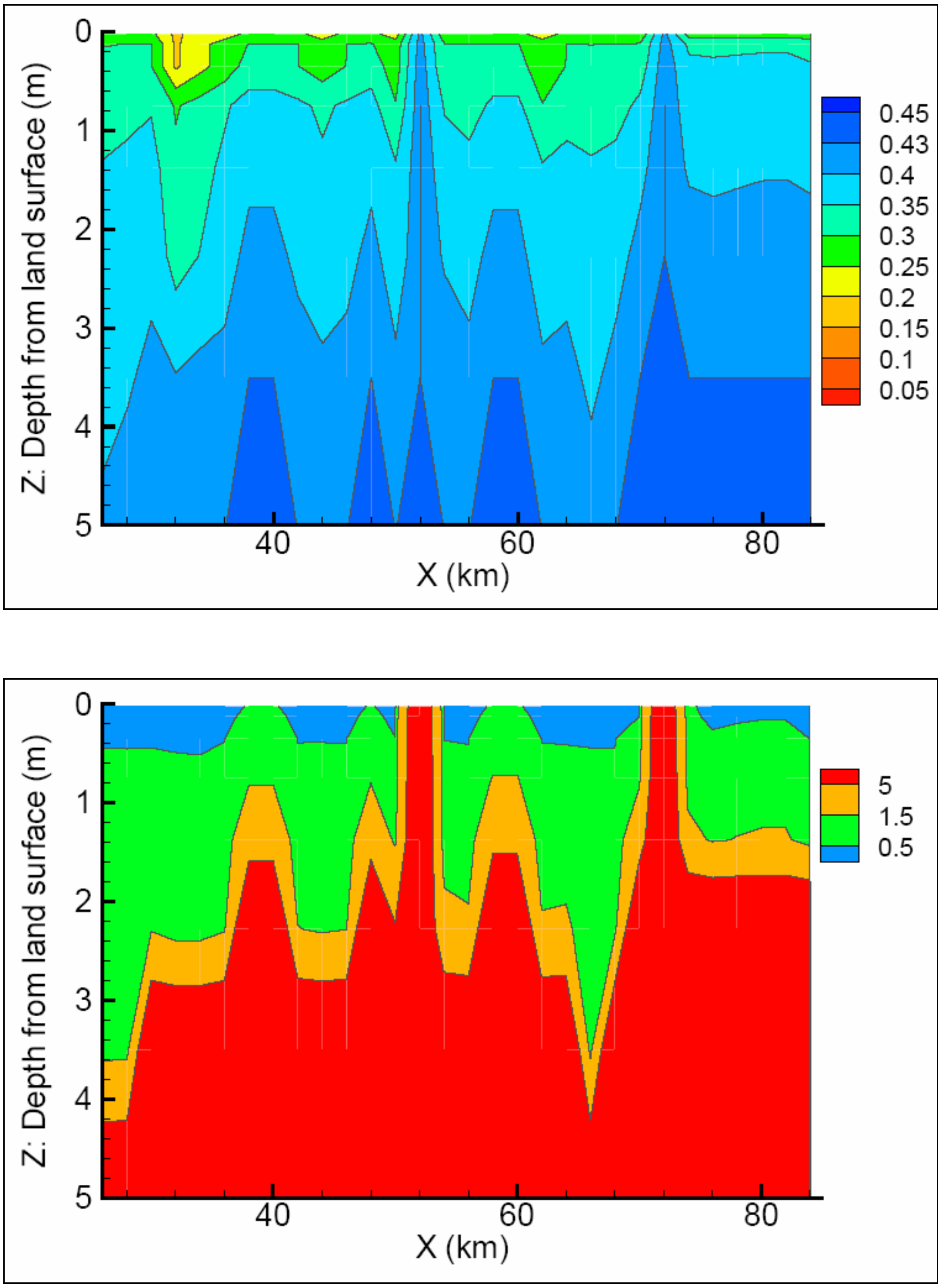


Figure 60: Cross sectional distribution at row:20 for (a) soil moisture, and (b) salt concentration (kg/m3) in December 1994. Rice bay is located at x=50 to 52 km and x=70 to 72 km in WID

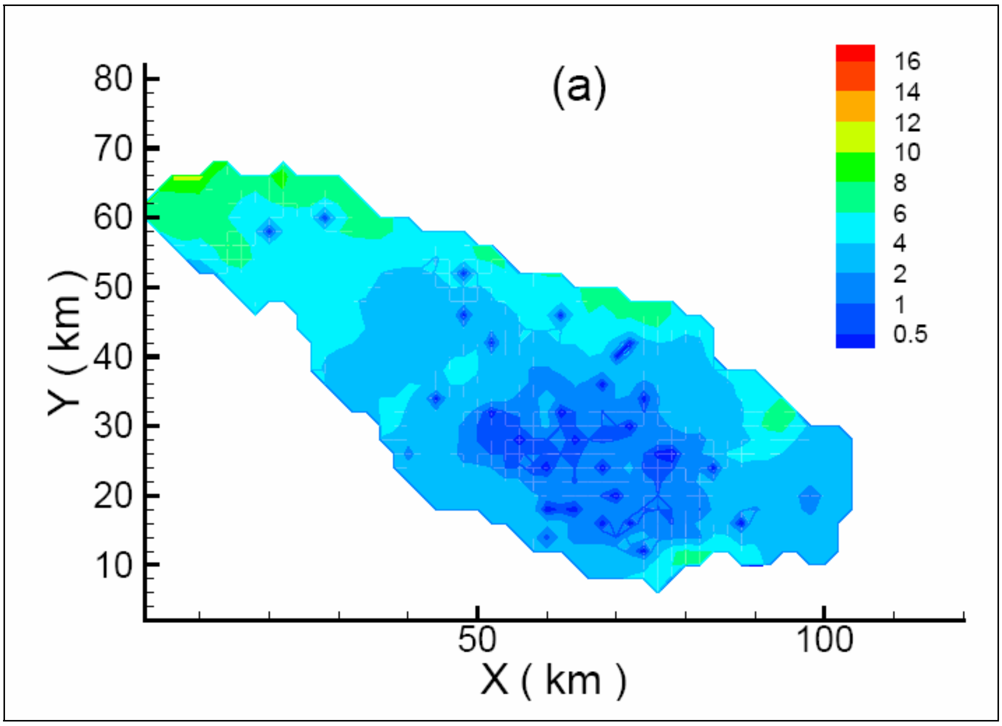
- How much area of Wakool Region is under risk of high watertables is not calculated.
- There is no calculation performed to exactly know about the temporal change after every 5-year period.
- Reports of EPA (1993) and DWR (1994) show that 13 % and 63 % of total area was within 2 m and 4 m respectively from the land surface. There is no such comparison?
- It is stated that the expansion of shallow watertable area stopped by 1980s. However, such conclusion is not supported by any calculation except for two figures.

- The impact of rising of watertable on the total salt mass accumulated in the root zone (1 m depth) is plotted for different years (1979, 1984, 1989, 1994). The spatial change is not calculated that we are not sure about the extent in percentage.
- The statement "high salinity area was not increasing by 1980 and remained unchanged until 1994" has not any calculations in numerical values.

Impact of Ponding Salty Water in Rice Field on Root Zone Salinity

Scenario:

- Irrigation with fresh water (zero salinity)
- Irrigation with water of 400 mg/l (EC=0.625 dS/m)
- Irrigation with water of marginal quality (1000 mg/l, EC=1.563 dS/m)
- Irrigation with water of brackish quality (2000 mg/l, EC=3.125 dS/m)



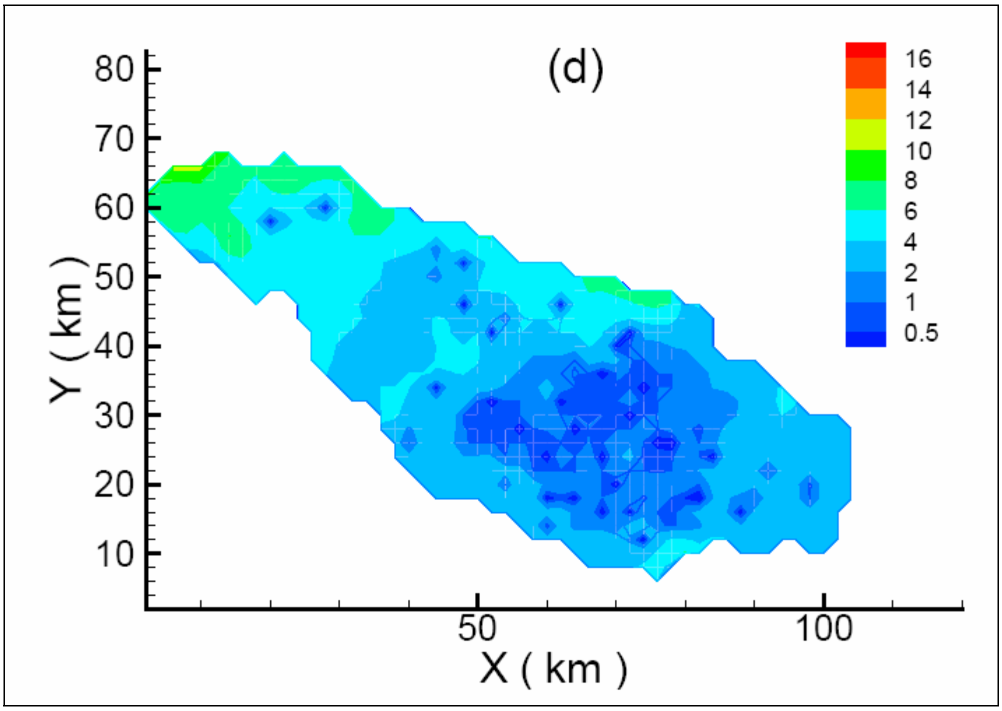


Figure 61: Spatial variations of water table depth (m) in the root zone (root zone depth = 1m) in WID for (a) 31 December 1979, (d) 31 December 1994

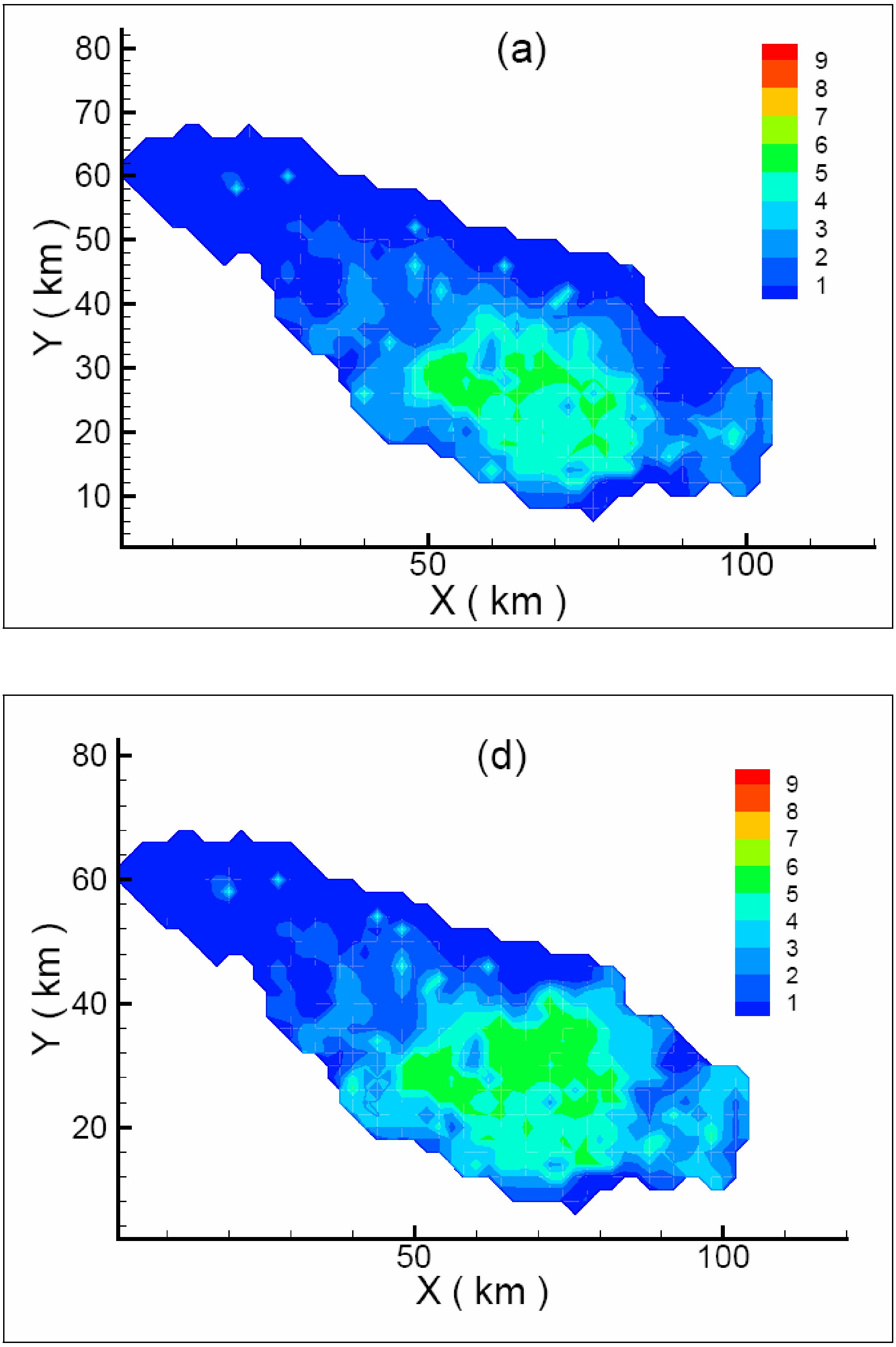


Figure 62: Spatial variations of total mass (kg) in the root zone (root zone depth = 1m) in WID for (a) 31 December 1979, (d) 31 December 1994

- Impact of Short Term Application (5 Consecutive Years)
    - The simulated results for tested four scenarios are presented for the starting year 1975. Maps of 1979 after five-year period are not given and no comparison is carried out.
    - It is stated that the short-term impact on the total salt in the root zone is small.

- Impact of Long Term Applications (20 Consecutive Years)
    - The simulated results of ponded irrigation no spatial comparison by pixel to pixel. There is no such conclusion that leads to decision-making policy.
    - For profile salinity, "no significant difference" for four scenarios is noticed. The results are not as of expectations and there is no such explanation.
    - The local effect of ponding irrigation in rice field is shown that soil salinity increases with brackish water application.

4.5.2.3 Modelling Overland Flow at Regional Scale

<u>A. Model Calibration and Validation:</u>

The 2-D model is essentially based on Manning Equation. It is assumed that no flow across the district border. The Manning roughness coefficient is set to range of 0.03-0.08. The sheet flow is assumed for which hydraulic radius is approximated to be flow depth. Three values of Manning roughness coefficient as 0.07, 0.05, 0.04 are tested.

<u>B. Model Results:</u>

- Model is tested for 20-year period (1.1.1975 to 31.12.1994). The time step is set to be 5 minutes.

Impact of Overland Flow on Surface Soil Moisture

- It is shown that evaporation and infiltration rate almost remain constant before and after the rainstorm

- The soil moisture in 5cm top layer with and without surface runoff predicted the same pattern. It increases after the rain and gradual decreasing till next rain occurs which increases the soil moisture again

- The soil moisture is not sensitive to the Manning roughness coefficient and very small difference is observed.

- The peak flow is routed in the downhill direction from southeast to northwest (Figure 63). The simulation for peak flow is performed for 12, 24, 36, 48 hours after the rainfall occurrence.

• Hydrograph of the rainfall event for three selected locations are plotted.

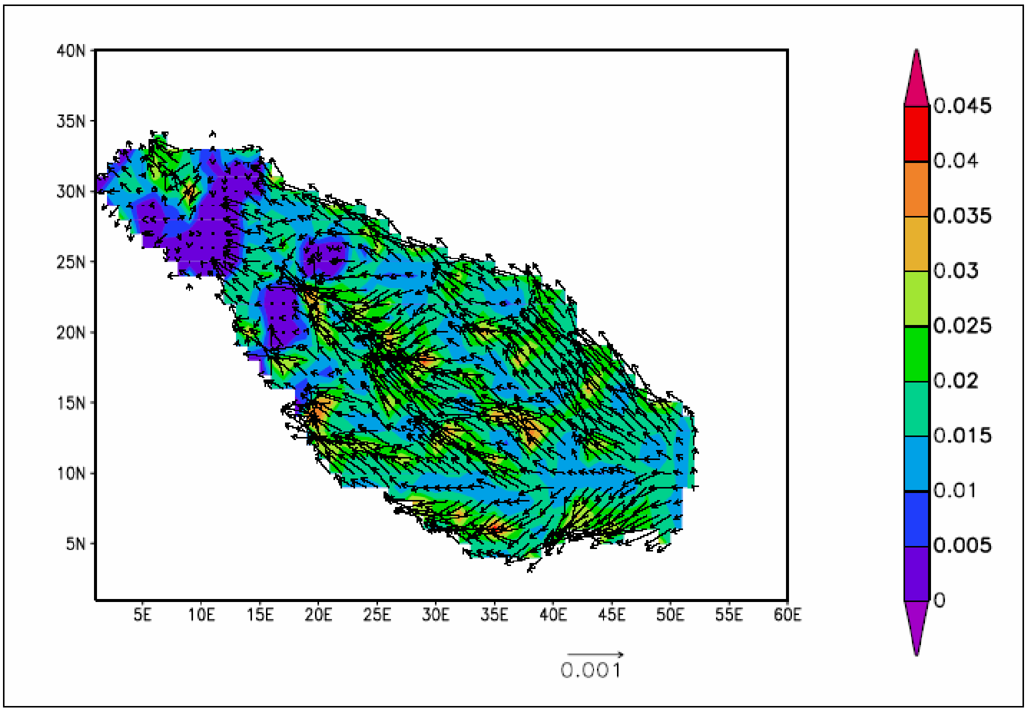


Figure 63: Surface runoff in WID during August 1975 immediately after the rainstorm.

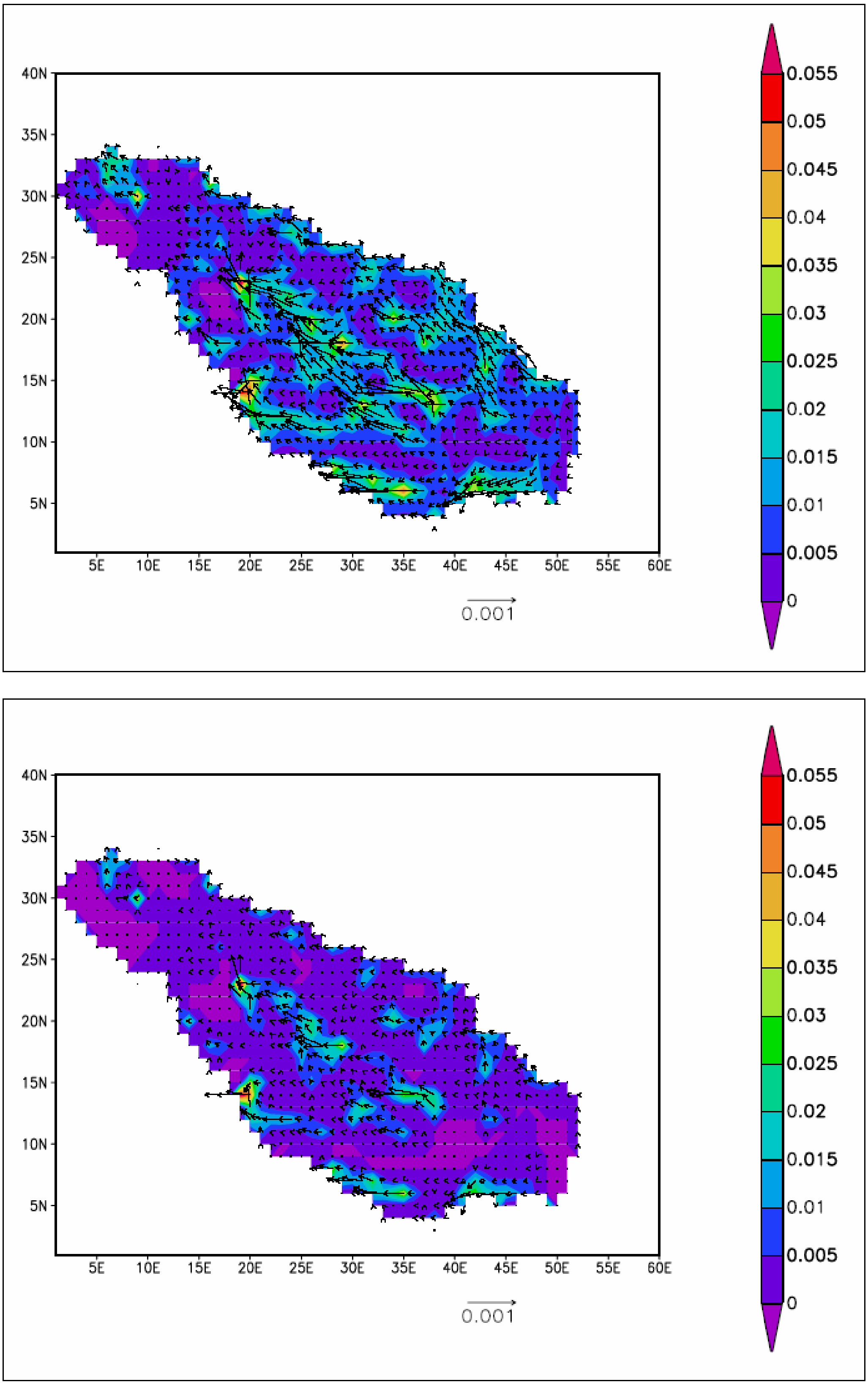


Figure 64: Surface runoff in WID during August 1975 (a) 12 hours after rainstorm (b) 24 hours after rainstorm

5. Discussion

5.1 Summary of Key Features of Graduate Studies

5.1.1 Adequacy of Literature Review

A number of studies groundwater management and salinity mitigation have been conducted in MIA. CSIRO Land and Water has played a major role in such studies that include local and regional context covering agronomic and modelling approaches. Some studies on the land degradation problem in Wakool have also been conducted. The modelling effort by Xu (2003) is quite innovative since it tried to address comprehensive water flow and solute transport cycle responsible for salinisation in Wakool District.

5.1.2 Hydrogeology of the Study Area

The project area in MIA is located near Whitton, 30 km southeast of Griffith in the Riverina area of NSW. The rice paddocks are laser graded and irrigations are given by gravity fed water as shown in the layout of the trial site farm at Whitton. The rainfall and evapotranspiration data is well presented for only four year period only. The data source is Yanco Agricultural College. The geology is well described and supported by a number of references (Brown, 1989; Evan and Kellet, 1989; Brown and Stephenson 1991; Prathapar et al. 1997).

To identify soil characteristics such as colour, texture, pH, moisture contents, conductivity and soil salinity, samples were collected at 25 cm intervals down to one meter. The laboratory analyses were carried out and the results were reported in the proper format.

To map ground resistance variations in 3D to a depth of 25 m, geophysical investigations including resistivity imaging survey and EM31, EM 34 were conducted. A total of 16 dataloggers were installed for groundwater level monitoring. The frequency o f measurement was 6 hourly. However, there is missing data due to failure of equipment. It is concluded that the data needed for modelling is adequately gathered and collated.

The hydrogeology of Wakool catchment has only two references: Bogoda et al., 1994; Demetriou et al., 1999. The rising and lowering of watertable and its corresponding areal extent is given in temporal variations. The Wakool Tullakool Sub-Surface Drainage (WTSSD) system is adequately discussed. Its role to lower the watertable and effectiveness to ameliorate the salinisation process is described. However, the figures and facts used by Xu (2003) are not supported by any reference and past research.

5.1.3 Surface-Groundwater Interactions

A Land and Water Management Plan (LWMP) was developed by the Wakool Landholders and the Wakool Landcare Group in June 1991 in recognition of the need to adopt an integrated approach to the management of salinity and waterlogging problems. The plan aimed at ensuring both long and short term economic sustainability of the area and the preservation of its natural resources in harmony with the environment. The plan has identified appropriate management practices to maintain and improve productivity in a sustainable and environmentally acceptable manner. Since then, many reports about the action plan, its benefits and outcomes have been published (Willinck et al., 1992; Beale, 1992; Moore, 1995a; Moore, 1995b; Gunaratne et al., 1995; WLWMP Working Group, 2001).

Watertable within Wakool area was at depths of 10 to 30 metres when irrigation commenced in 1939 (Marsden-Jacob Associates 1994). Rising watertable has already affected 23,600 ha of land till 1995. According to DIPNR model, further 18,600 ha land is expected to be affected by 2025 if there is no implementation of the proposed action plans (Moore, 1995). Figure 65 shows the extent of high watertable during 1994 projected by DIPNR model. It shows the area of 26400 ha under serious threat of within 2 m watertable depth and 101400 ha at risk of within 2-4 m depth. Now, if we analyse the scenarios of watertable that are tested in the Wakool study it is evident that spatial extent of watertable depths is produced as shown in Figure 66. However, there is no such information on how much area under different categories was present during 1995.

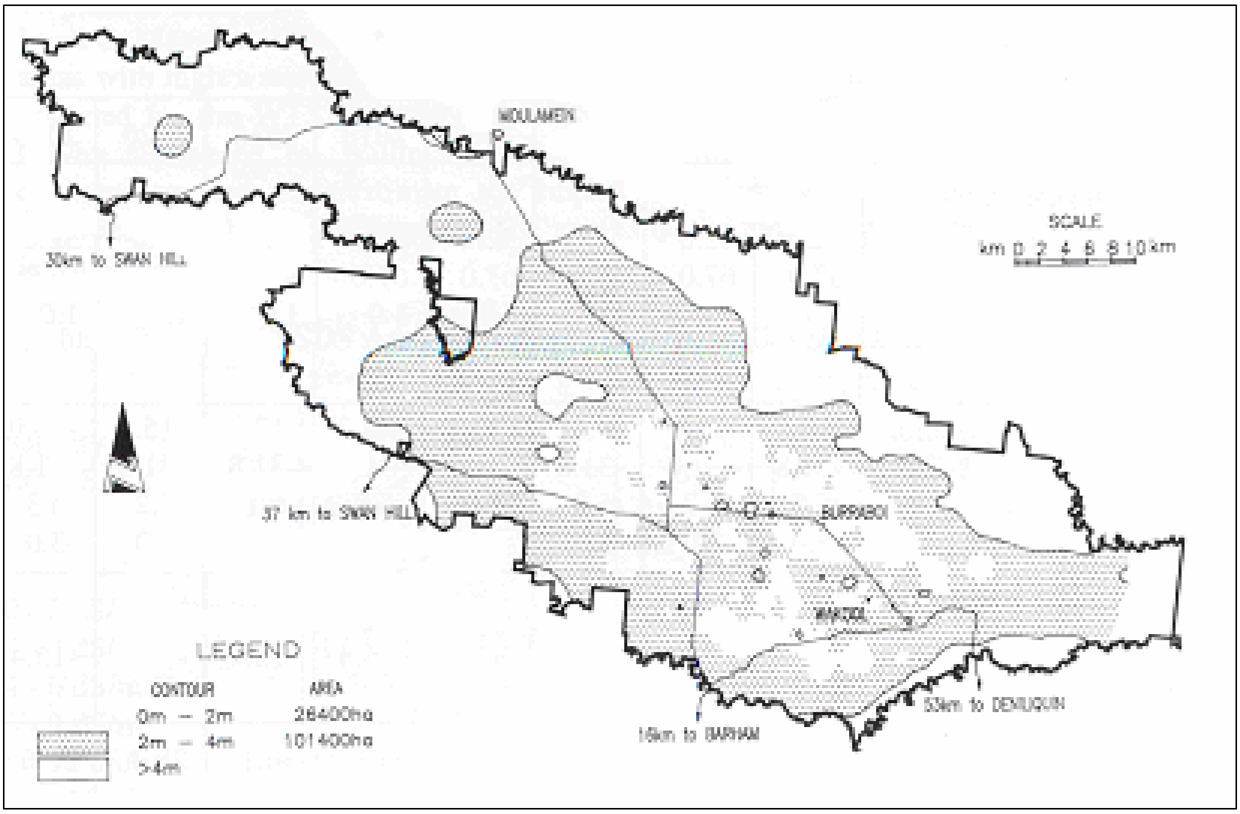


Figure 65: Projected High Watertable Area during 1994 (Source: Wakool LWMP 2001, Courtesy: DIPNR)

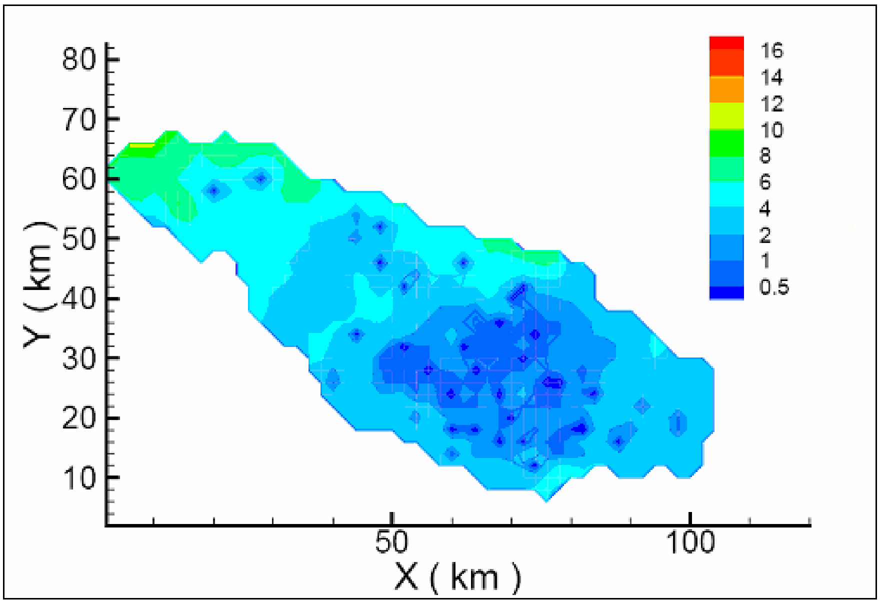


Figure 66: Spatial extent of water table in Wakool irrigation District for 31 December 1994

The watertable levels as plotted by Murray Irrigation Limited (MIL) during August 2000 are shown in Figure 67. It describes four categories of shallow water tables. In 1981, 30900 ha had shallow watertables within Wakool and it was reduced by 3089 ha in Aug 2000 as shown in Figure 67 due to favourable climatic conditions and the operation of subsurface drainage scheme. The watertable projection by DIPNR model for year 2000 is 24000 ha. If the action plans had gone well, there would be reduction of 1200 ha and high watertable extent may go to an area of 22800 ha. In contrast, the actual situation (27800 ha under shallow watertables) is even higher than the model projection. Such important scenarios were considered in Xu's thesis. It is a matter of concern that the study only covered temporal extent of shallow watertables till year 1995 and did not include the latest data in consultation with MIL.

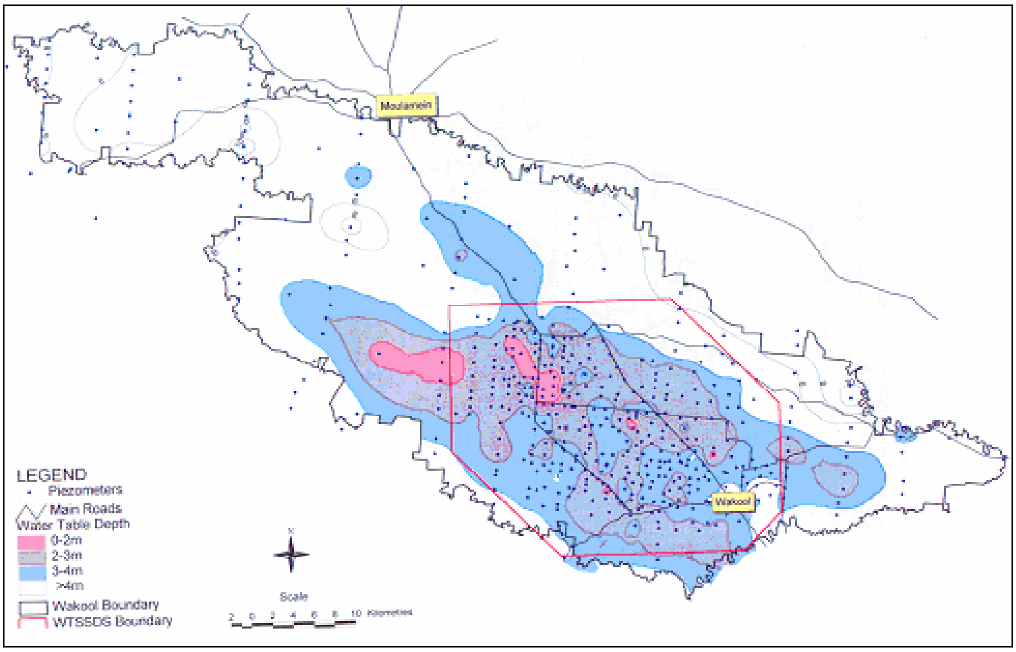


Figure 67: Wakool Watertable levels during Aug. 2000 (Source: Wakool LWMP 2001; Courtesy: Murray Irrigation Limited)

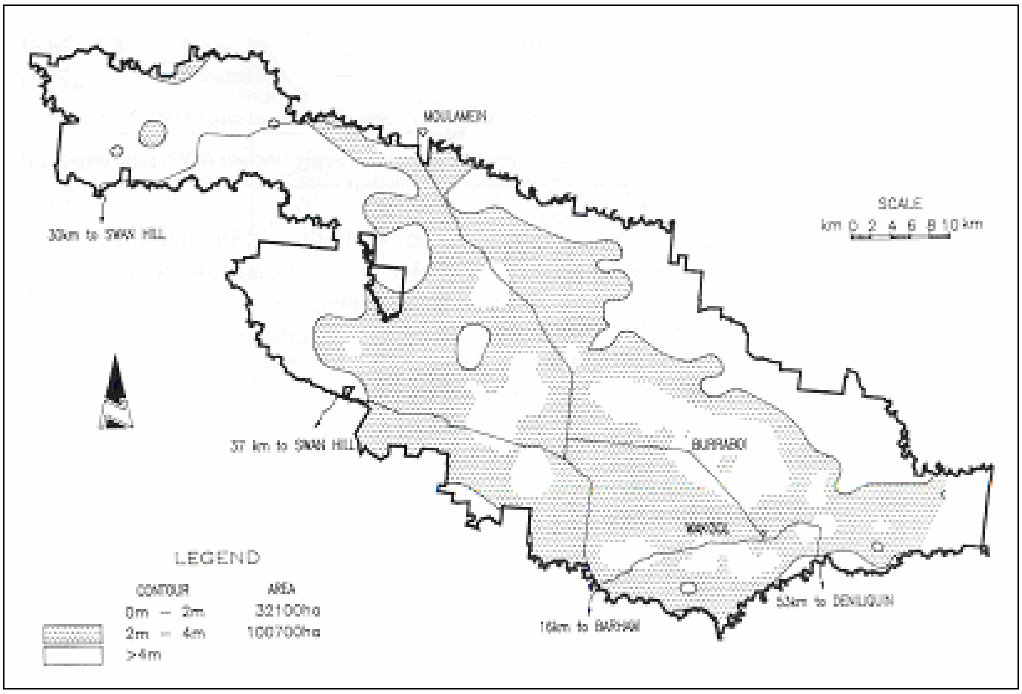


Figure 68: Projected High Watertable Area during 2020 (Source: Wakool LWMP 2001, Courtesy: DIPNR)

DIPNR model had projected estimate of 132800 ha under shallow watertables as shown in Figure 68. In Xu (2003), there is no such scenario development for future prediction of shallow watertables under given climatic conditions and the action plans of LWMP. Therefore, we are unable to cross validate the extent of shallow watertables and no further conclusion could be drawn about surface-groundwater interactions.

Hence, it is necessary to run more scenarios in GIS-based modelling system to confirm the data projections in earlier reports of DIPNR and LWMP. The initial water level used in the computational model is assumed to be 6 m. We believe that averaging watertable level to 6 m for the whole Wakool Irrigation District is not justified.

5.1.4 Salinisation

Salinisation is one of the land degradation processes as it reduces agricultural production, damages vegetation and increases the salinity of surface waters. Salinisation in Australia is the result of rising groundwater levels mobilising large quantities of salt previously stored deep within the soil. The source of this salt is ancient oceanic sediments, rock weathering and the deposition of sea spray. When irrigation water is surplus to plant needs, or there is leakage from supply canals and water storages, it percolates into the groundwater. These water losses from the irrigated region are significant enough to raise the watertable and with it the salt (Pengelly and Fishburn, 2002). Land salinisation inevitably leads to increasing river salinity. A large proportion of the salt brought to the land surface is exported into the waterways and river systems.

After a brief review of salinisation process in the graduate studies, only two references (Peck and Williamson 1987; Schofield et al., 1989) are cited to explain the land degradation of salinisation in Australia. There are plenty of publications on salinity issue by various organisations like Department of Infrastructure, Planning and Natural Resources (DIPNR), NSW Agriculture, and CSIRO. Recent literature should have been reviewed for the concise and comprehensive understanding of the reader. In the thesis, there has been more emphasis on the severity of the salinity problem, its origination and the areal extent but nothing is described about the LWMPs' effectiveness and efficacy. There would have been a complete comparison among the results of modelling system and any improvement noticed due to implementation of management plan. Such detailed literature review will help establish scenario levels depending upon time intervals. Such methodology will execute model with different scenarios depending upon the real conditions as function of time rather than run continuously for 20 years time. No literature review is concisely described in the thesis that discusses LWMPs, implementation schedule, improvement and effectiveness.

It is important to note that most of the shallow groundwater within Wakool area is saline. Once a saline watertable rises to a critical depth (< 2 m) from the soil surface, the upward movement of salt to the root zone occurs with consequent deleterious effects on agricultural and pastoral production. Regarding salinisation process in Wakool District, detailed information is lacking.

5.1.5 Modelling Approach

The central focus of the study is the development of a computational model and its application to focus prediction and assessment of salinisation in Wakool region. Because of the importance of prediction tool (modelling system), the past research review is of utmost importance. It is found that considerable literature on modelling techniques and their application has been examined (Bathurst, 1986; DeCoursey, 1991; Irannejad et al., 1999; Jobson and Harbaugh, 1999; Koivusalo et al., 1995; Konikow et al., 1996; McDonald and Harbaugh, 1988; Mualem, 1976; Rabbani et al., 1997; Scheidegger, 1961; Shao and Irannejad, 1999; Todini and Ventutelli, 1991; Vogel et al., 1996; Wallach et al., 1989; Wallach et al., 2001).

According to the results of the optimization, an extensive bore network of several hundred bores would be necessary to lower water levels around the irrigated area. The water levels targets are easily achievable outside the irrigated area but not possible inside the irrigated area where most of the saline water is entering the drain.

HOTSPOTS optimisation module limited the study of more realistic approaches as it only handles a maximum of 10 pumping bores. The limitations and assumptions for each model need to be well defined before the application of existing models to different conditions.

5.1.6 Appropriateness of Methodologies

The computational model developed for simulations of water flow and solute transport addresses three submodels: I. Surface II. Subsurface III. Groundwater. Methodologies for salinity assessment are worked out and the validation is not carried out through historical data of the area. Each of these sub-models is developed independently. However, the models were later coupled to make a modelling system.

The geophysical survey needed more interpretation for the geologic layers, extent of soil salinity and groundwater salinity.

The spatial and temporal analysis of rising water table and salinisation is not included to know about the temporal and spatial extent of the severity of the problem. The images are just produced in the GIS environment but they are not quantified and presented in tabulated forms.

5.2 Generic Findings

The generic findings of the six graduate studies are summarised below:

- The geophysical surveys of apparent resistivity for soil profiles to depth of 25 m reveal heterogeneity in rice bays before and after the irrigation period. The surveys were carried out during Oct. 1999 to Sep. 2000 at 9 sites in Riverina. A uniform pattern of resistivity variation is observed at about 10 m from the rice bay. Farther more from the rice bay (65 m), the resistivity increases uniformly with depth. The low resistivity values suggest rising watertables with high salinity.
- There is a need to install shallow pumping bores to lower the watertable for sustainable farming systems. However, the low hydraulic conductivity of geologic layers at few sites makes it impossible to pump out the necessary volumes of groundwater in order to keep water table to the targeted levels. According to the results of the optimization model, an extensive bore network of several hundred bores would be necessary to lower water levels around the irrigated area.
- The water level targets are easily achievable outside the irrigated area but not possible inside the irrigated area where most of the saline water is entering the system.
- Validation of the numerical model indicates that it has a good predictive capability of the hydraulic head for a time series following the calibration model to within 89% of the observed heads. The model is sensitive to changes in leakage from the ponded rice and to a lesser degree changes in rainfall infiltration. The numerical model is more reliable at predicting the head distribution under rice ponding conditions than during the fallow conditions. The model also simulates heads in Layer 1 with more accuracy than in Layer 2.
- The salinity concentration in the groundwater is controlled by rising groundwater levels from rice ponding. The concentration of groundwater salinity is highest in the top two metres below the surface. The rising groundwater mobilizes the high concentration of salts in the unsaturated zone.
- The groundwater salinity trends of high salinity near the surface and lower salinity under the ponded rice bays are observed.
- The drawdown predictions using analytical model show that one pumping bore of 100 m3/day capacity may result in a minimised average drawdown of 2.44 m. However, the increase of pumping capacity did not result in any further change. It is concluded that once the maximum water withdrawal is attained, no different outcome is achievable by increasing the number of bores.
- No ptimization strategy for bores and their capacity is feasible with less than 61 m3/day pumping bore. An additional approach of mixing high intake trees (0.1 m3/day) and pumping bores (5 x 1 m3/day) has shown to be the best option.
- The model prediction shows that irrigation with fresh water is effective in reducing existing salinity in the root zone. However, the irrigation method and irrigation frequency are the determining factors to groundwater recharge and not the water quality.

- The ponded rice irrigation is a major contributing factor to groundwater accessions resulting in rising watertables and subsequent salinity problem. However, lateral flows, seepage from irrigation supply system, irrigation of other land use practices and shallow rooted vegetation are not considered.
- The alternative use of fresh water and low salinity water could be practiced on short-term basis for ponded irrigation as long as it does not affect rice growth or rice yield. This will help remove accumulated salts in the root zone by fresh water irrigation after the irrigation with water containing salts.
- The soluble salt concentration in subsoil layer in rice field is lower than that of the adjacent areas. It means ponding irrigation flushes out salts from root zone and subsoil profile to groundwater reservoir.
- The salinity increases with depth during ponding or wet season and decreases during dry season. Initial salt concentration in soil, salt load in irrigation water and groundwater salinity jointly contribute to salinization of the aquifer.
- The Wakool Tullakool Subsurface Drainage Scheme has been successful in reducing watertable rising and subsequent salinity problem in the area.
- The simulation results show the areal extent of different categories of depth of watertable with respect to time. The watertable and total salt maps describe the areal extent of waterlogging and salinity.
- The module for overland flow is run and the data is presented in the form of maps for the recession time after occurrence of rainfall. However, no maps or data was provided that show dissolution of salts along overland flow path. The temporal and spatial distribution of soil salinity after the rainstorm or recession of overland flow in the region was not addressed in Xu (2003). Moreover, the effect of topography and land use was not included in overland flow simulations.

6. Knowledge from Graduate Studies to Better Manage the Rice Based Farming Systems

6.1 Major knowledge outputs from these studies are given below:

- The ponded rice irrigation is a major contributing factor to groundwater accessions resulting into rising watertable and subsequent salinity problems. Hence, the ponded irrigation is not only a cause of rising water table but reduced water productivity. There is a need to change agronomic practices or to adopt best water management options to enhance water productivity.
- The UTS groundwater modelling approaches could be successfully used in simulating groundwater salinity trends of high salinity near the surface and lower salinity under the ponded rice bays.
- The optimization results show that rice based systems needs an extensive network of shallow pumping bores to lower water levels in and around the irrigated area.
- The geophysical surveys can play a significant role in developing better understanding of geological layers, groundwater resources and their quality. This will help in deciding the locations and the extent of the radial influence of shallow bores.
- The Xu study overviews the extent of rising watertable and salinisation in rice-based irrigation areas. The several scenarios of irrigation water quality provides insights into the use of water with different EC levels. The tested water quality scenarios are selected in comparison with a base level (salt free irrigation water).

- Xu’s study show a quasi 3D-model implementation with a GIS system which can be used to draw maps of geo-referenced watertable and total salt data. This study reveals that fresh water irrigation is effective in reducing existing salinity but sufficient subsurface drainage system should be assured to reduce the groundwater recharge. Therefore, rice based systems need to include subsurface drainage systems in order to ameliorate existing salinity problem and lessen further risk of land degradation.
- Xu (2003) ran the model with four levels of irrigation water quality. The irrigation with saline groundwater predicted that about 2 kg/m2 salt will be added to root zone per one rice crop per season. This prediction quantifies to 20 t/ha per crop season each year. Moreover, if repeated irrigation with saline water is practiced, the salt concentration in root zone will continue to increase with time, which is a matter of concern for future sustainability of the region.
- The modelling studies by Xu included overland flow and solute transport module in modelling system provided a better awareness of salt transport in streams and rivers. It also gives an insights into the runoff pattern in the catchment just after the rain and salt dissolution in sheet flow and finally to creeks and rivers.

6.2 Future Directions

The following additional studies are necessary to convert the knowledge base developed by the graduate studies into management actions:

- The recent groundwater trends in the Wakool Irrigation District shows effect of Wakool Tullakool Subsurface Drainage Scheme (WTSDS) in lowering of watertables and slowing the salinisation process. Therefore, the simulation period in Xu (2003) should be changed to 1985 to present (after the WTSDS was functional) and all model scenarios need a rerun for much better understanding of salinisation processes in the region.

- The scenario of conjunctive use of water, groundwater use only having acceptable water quality to rice cropping and fresh water application is to be run over a longer period (1985 to present) to gain insights into the solute deposition in the soil profile.

- To incorporate the effect of land use, satellite imageries after their classification from groundtruth data would help understand role of agronomic options.

- A module for seepage losses from irrigation supply systems covering the whole channel network of the area needs to be included in the modelling system to determine the groundwater accessions in rising watertables and subsequent salinity.

- The use of spatial analysis with a GIS model needs to be developed for predicting the spatial suitability of groundwater systems for rice cropping. The data to be used in the spatial analysis would include irrigation water quality, soil salinity status (EC data), and soil characteristics like texture and leachability. Such exercise can lead to the development of a "Land Suitability Decision Support System for Rice Cropping"

- Temporal and spatial analysis in the GIS environment for various scenarios of irrigation water quality, irrigation depths and different land use is necessary to get insight about the water saving options, environmental benefits and enhancing water productivity.

- Integration of geophysical surveys of resistivity profiling and vertical sounding with hydraulic characteristics of aquifers are needed to help decide location of shallow pumps to lower shallow watertable in rice based farming systems.

- The six graduate modelling studies described in this report are site specific. Efforts to apply these methods to other farms or regions will need to incorporate site specific information on cropping, topography and groundwater systems to describe and calibrate the salinisation processes.

7. Relevant References

ABC (2003). Four Corners: Water Pressure. Australian Broadcasting Corporation (ABC). http://www.abc.net.au/4corners/water/map/nsw.htm

Beale, P. and Moore, S. (1993). District Summary, Wakool Land and Water Management Plan. NSW Agriculture, Deniliquin.

EPA (2003). Environmental Aspects of Irrigation Areas in Southern NSW, Agriculture - Environmental Conditions & Pressure. http://www.epa.nsw.gov.au/soe/95/23_2s3.htm

Gunaratne, N., Wall, L., Marshall, G. and Jones, R. (1995). Economics of On-Farm Proposals. Wakool Land and Water Management Plan. NSW Agriculture.

Hudson, A. (2000). Groundwater Flow and Solute Transport at Stott's Farm, Murrumbidgee Irrigation Area. MSc Thesis, National Centre for Groundwater Management, The University of Technology.

Hautefeuille, F. D. (2001). Heterogeneity of Field Site Using 3-Dimensional Resistivity Imaging. MSc Thesis, National Centre for Groundwater Management, The University of Technology.

Lloyd, J. C. (2002). A Numerical Groundwater Management Model for Salinity Mitigation at Irrigated Farm Scale. MSc Thesis, National Centre for Groundwater Management, The University of Technology.

Mahamud, G. (2002). An Analytical Groundwater Management Model for Salinity Mitigation at Irrigated Farm Scale. MSc Thesis, National Centre for Groundwater Management, The University of Technology.

Marsden-Jacob Associates (1994). Institutional Arrangements for Management Options: Priorities, Principles and Issues - Berriquin Land and Water Management Plan. Melbourne: Marsden-Jacob Associates.

McLaughlin, G. (2002). Data collection Report for Modelling Groundwater flow and Solute Transport at Stott's Farm, Murrumbidgee Irrigation Area. MSc Thesis, National Centre for Groundwater Management, The University of Technology.

Moore, S. (1995). On-Farm Options. Wakool Land and Water Management Plan. NSW Agriculture.

Moore, S. (1995). On-Farm Options: Discussion Papers and Recommendations. Wakool Land and Water Management Plan. NSW Agriculture.

Pengelly, S. and Fishburn, G. (2002). Land, Water and People. In Haygarth, P.M. and Jarvis S.C. (2002) Agriculture, Hydrology and Water Quality. CABI Publishing.

Wakool Land and Water Management Plan Working Group (2000). Wakool Land and Water Management Plan 2000-2005.

Willinck, E., Beale, P., McLeod, G. and Slavich P. (1992). Soil Salinity Survey of the Wakool Irrigation District and the Tullakool Irrigation Area. Land and Water Management Plan. NSW Agriculture, Deniliquin.

Xu, Peng (2003). A Computational Model for the Assessment and Prediction of Salinisation in Irrigated Areas. Ph.D. Thesis, The University of New South Wales, Sydney.

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APPENDIX A

The Computational Model for Water Flow and Salt Transport at Regional Scale Based on Xu (2003)

The Water Flow and Solute Transport Model consists of three components:

A. Moisture Flux and Solute Transport in Vadose Zone or Unsaturated Soil

B. Groundwater Flow and Solute Transport in Saturated Soil

C. Surface Runoff and Solute Transport

   i. Overland Flow and Solute Transport

   ii. River Flow and Solute Transport

The modelling system consists of following modules:

A. Moisture Flux and Solute Transport in Vadose Zone or Unsaturated Soil

   i. ALSIS: Land-surface scheme for unsaturated soil moisture and moisture flux.

   ii. MODULE: Solute transport in unsaturated zone

B. Groundwater Flow and Solute Transport in Saturated Soil

   i. MODFLOW: Model for spatial and temporal behaviour of groundwater

   ii. MOC3D: 3-Dimensional model for solute transport in groundwater

C. Surface Runoff and Solute Transport

   i. DAFLOW: Surface flow model for water flow in river networks

   ii. MODULE: Spatial and temporal distribution of overland flow during wet season.

The land surface scheme is coupled with groundwater flow model to account for the interactions between the saturated and the unsaturated zones. The modelling system uses a finite difference to form a quasi three-dimensional model. In the horizontal direction, the total area of 3,240 km^2 of the Wakool Irrigation District is divided into a 2 km x 2 km mesh of 810 soil columns. The soil distribution in the area is heterogeneous and two soil horizons (A & B) are assumed in the vertical direction. They are 0.5 m and 11.3 m deep respectively. The theoretical presentation of each component is given below.

A.1 Moisture Flux and Solute Transport in Unsaturated Soil

A.1.1 ALSIS

The Atmosphere and Landsurface Interaction Scheme (ALSIS) describes the soil hydrological and thermal processes in the unsaturated zone. Irannejad and Shao (1998) incorporated the calculation of drainage from the unsaturated medium to groundwater and its temporal and spatial variations. Using Darcy's law, the Richards equation presents 1-D moisture flux in a variably saturated medium:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial z}\left(K - K\frac{\partial \varphi}{\partial z} \right) + R_c - S \tag{1}$$

θ	=	soil water content
t	=	time (s)
q_z	=	soil moisture flux (m/s)
z	=	depth (m)
K	=	unsaturated hydraulic conductivity (m/s)
φ	=	soil water potential
R_c	=	source (1/s)
S	=	sink (1/s)

A.1.2 Solute Transport in Unsaturated Soil

Two basic processes, diffusion and advection, are responsible for the solute transport in unsaturated soil. The governing equation for 1-D solute transport during transient water flow in a variably saturated rigid porous medium is presented.

$$\theta R\frac{\partial c}{\partial t} - \frac{\partial}{\partial z}\left(\theta D_{zz}\frac{\partial c}{\partial z} \right) + q_z\frac{\partial c}{\partial z} + \left(\lambda\theta R + R_c - S \right)c = R_c C_r - SC_s \tag{2}$$

Where $R = \left(1 + \frac{\rho_b k_d}{\theta} \right)$, which is dimensionless

θ	=	soil water content
c	=	solute salt concentration (kg/m^3)
σ_s	=	absorbed salt concentration (kg/kg)
ρ_b	=	bulk density of the porous medium (kg/m^3)
k_d	=	solid-liquid phase partitioning coefficient
D_{zz}	=	dispersion coefficient in vertical direction (m^2/s)
λ	=	radioactive decay rate (1/s)
C_r	=	concentration of source solution
C_s	=	concentration of soil solution taken by plants roots, evaporation and drainage or seepage (kg/m^3)

q_z = soil moisture flux in vertical direction (m/s)

R_c = source (m^3/s)

S = sink (m^3/s)

Assumptions:

1. The solute travels at the same rate as the average velocity of the soil moisture flow.
2. There is linear between absorbed salt concentration and solute concentration - the linear Freundlich isotherm is adopted.
3. The solute concentration in soil moisture leaving the region is same as in the region.
4. A zero concentration is assumed extracted by plant roots and through evaporation process.
5. The decay process occurs at the same rate for both dissolving and absorbing phases.

A.2 Groundwater Flow and Solute Transport in Saturated Soil

A.2.1 MODFLOW

3-D water flow model in a saturated confined aquifer is written as:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)+W = S_s \frac{\partial h}{\partial t} \qquad (3)$$

Where K_x, K_y, K_z = hydraulic conductivity in x, y, z directions (LT^{-1})

h = hydraulic head (L)

S_s = specific storage coeff. for confined aquifer (L^{-1})

W = volumetric flow rate via sources or sinks (T^{-1})

2-D water flow in unconfined aquifer is known is the Boussinesq Equation and is:

$$\frac{\partial}{\partial x}\left(T_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_y \frac{\partial h}{\partial y}\right)+Q = S\frac{\partial h}{\partial t} \qquad (4)$$

Where S_y = specific yield for unconfined aquifer (dimensionless)

T_x, T_y = transmissivity of the aquifer in x, y direction (L^2T^{-1})

Q = volumetric flow rate per unit horizontal surface (LT^{-1})

A.2.2 MOC3D

The governing equation for 3-D solute transport is given as:

$$\frac{\partial c}{\partial t}+\frac{V_i}{R}\frac{\partial c}{\partial x_i}-\frac{1}{\nu R}\frac{\partial}{\partial x_j}\left(\nu D_{ij}\frac{\partial c}{\partial x_j}\right)-\frac{\sum\left[W\left(c'-c\right)\right]}{\nu R}+\lambda c=0 \qquad (5)$$

Where	ν	=	soil porosity
	V	=	vector of interstitial fluid velocity component (LT^{-1})
	D	=	dispersion coefficient (L^2T^{-1})
	W	=	volumetric fluid sink (W<0) or fluid source (W>) (T^{-1})
	c′	=	volumetric concentration in sink/source fluid (ML^{-3})

A.3 Surface Runoff and Solute Transport

A.3.1 Overland Flow and Solute Transport Model

A.3.1.1 Overland flow

When precipitation exceeds infiltration capacity of soil, depressions are filled and overland flow occurs. The exact route of overland flow and the quantity are determined by the topography, flow resistance and the losses due to evaporation and infiltration along the flow path. The equation governing 2-dimensional overland flow is mass conservation equation and is given by (derived from Navier-Stokes equations and the Manning formula):

$$u_{ro}h_{ro}=\frac{1}{n_x}\left(-\frac{\partial H}{\partial x}\right)^{1/2}h_{ro}^{5/3} \qquad (6)$$

$$u_{ro}h_{ro}=\frac{1}{n_y}\left(-\frac{\partial H}{\partial y}\right)^{1/2}h_{ro}^{5/3} \qquad (7)$$

Where $H=Z_g+h_{ro}$

	H	=	water surface level to datum
	h_{ro}	=	flow depth above the ground surface
	u_{ro}	=	flow velocity
	$u_{ro}h_{ro}$	=	discharge per unit area
	x, y	=	rectangular Cartesian coordinates in x- and y- directions

A.3.1.2 Solute transport

It focuses on the transfer of solute substances from spoil to surface runoff, solute transportation with surface flow during periods of heavy rainfall or surface irrigation. Under the assumptions that diffusion and dispersion are negligible, the mass balance equation defines the solute transport by overland flow:

$$\frac{\partial(c_{ro}h_{ro})}{\partial t}+\frac{\partial(c_{ro}u_{ro}h_{ro})}{\partial x}+\frac{\partial(c_{ro}v_{ro}h_{ro})}{\partial y}=k_r(c0-c_{ro})-i_s c_{ro} \quad (8)$$

Where c_{ro} = c_{ro}(x,y,t), dissolved solute concentration in overland flow

c = c(x,y,z,t), solute concentration in soil

c0 = c(x,y,0,t), solute concentration at the soil surface

k_r = empirical coefficient that limits the rate of substance dissolving into the surface runoff water

i_s = infiltration rate when soil surface is saturated

A.4.2 River Flow and Solute Transport Model

A.4.2.1 DAFLOW

Overland flow, subsurface interflow and groundwater seepage are routed downstream into river system. The governing equation for flow in rivers is essentially one-dimensional and similar to that of overland flow.

$$Au_{ri}=\frac{1}{n}\left(-\frac{\partial Z}{\partial x}\right)^{1/2}Ah_{ri}^{2/3} \quad (9)$$

Where $Z = Z_o + h_{ri}$

Au_{ri} = flow

A = cross-sectional area

h = depth of flow

A.4.2.2 Solute transport

Assuming diffusion and dispersion are small compared with advection, the governing equation is:

$$\frac{\partial(Ac)}{\partial t} + \frac{\partial(Au_{ri}c_{ri})}{\partial x} = q_L c_{ro} + wc' \qquad (10)$$

Where $c_{ri}(x)$ = solute concentration in river water

c_{ro} = solute concentration in overland flow water

w = seepage between river and the aquifer

c' = solute concentration in groundwater

A.5 Numerical Techniques

The entire system is divided into three regions which include the land-surface, the unsaturated soil and the saturated soil. Model for each region is established and coupled by the leakage flux terms between the regions. The finite difference method is employed to model water flow and solute transport in the unsaturated zone. The zone is discretized in finite number of points to form a regular mesh in which the approximate solutions are determined. The solute concentration, soil moisture and soil water potential are calculated at the centre of each layer while solute mass and water fluxes are calculated at the interface between layers. Transpiration is treated as sink and evaporation, precipitation are combined to estimate infiltration. For overland flow and solute transport, it is similar to that used for solving flow in unsaturated soils. A Weighted Implicit method is used as it allows relatively large time step and improves numerical stability.