Experimental and Numerical Studies to Quantify Groundwater Salinity Distribution within the Saturated Zone under Highly Saline Irrigation Systems

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Abstract: This study investigates the vertical distribution of groundwater salinity in the saturated soil profile for irrigation with saline waters for the Serial Biological Concentration of Salts (SBC) technique. The knowledge of salinity stratification could provide information for the crops to be managed more effectively on the SBC site. SBC experimental site in Griffith, NSW had been used for saline effluent irrigation since 1994. The area was sown with various crops of varying salinity tolerance such as oats, lucerne, rice and maize to determine the land productivity and plant tolerance to a range of salt concentrations in irrigation water. The salinity of irrigation water applied to the first stage of SBC varies between 0.6-1 dS/m and is enriched with nutrients. This water is drained and reused for the subsequent stages of SBC. While the volume of drainage water decreases the salinity of water available for subsequent stages of SBC increases. Experimental and numerical methods were used to quantify groundwater salinity distribution. Experimental method consisted of collection, collation, analysis and interpretation of field data. The data were collected from a series of nested piezometers and wells where piezometric levels and water quality were measured. In addition, pumping tests were conducted to establish the hydraulic properties of the aquifer. The study was undertaken before and immediately after the irrigation period to understand the mixing of waters. Numerical method involved a two-dimensional flow and solute transport model to evaluate the potential effect of changes in the quality and quantity of irrigation water being applied on the site. Salinity of shallow soil layers was low mainly due to constant drainage and circulation of water, but it was found to sharply increase with depth. The model has proven the effectiveness of the drains serving as the collector of salt leached from the soil profile and indicated that control of recharge and discharge from the system can be used to control salinity distribution in the shallow aquifer.

Keywords: *Salinity stratification, irrigation, numerical modeling, field experiments*

1. INTRODUCTION

The salinity of groundwater and soil has become an important issue in the Murrumbidgee Irrigation Area (MIA) due to loss of productive soil and lowered productivity due to rising water tables. The rising watertable brings salts to the surface causing the damage to the roots of the plants.

The Serial Biological Concentration of Salts (SBC) experimental site in Griffith has successfully managed to produce crops although with lower productivity by flood effluent irrigation with drainage waters. The site consists of bays, which are underlain by tile drains at one-meter depth below surface. Once the water is applied, the downward movement of water mobilises the salts from soil into the groundwater. Some of this water is intercepted by tile drains, which discharge into a sump. The drainage water is pumped out from sumps and reused in the subsequent stage of SBC. Each time the bay is irrigated the drained water quality deteriorates due to leaching of salts from soil profile and concentration of salts as most of the applied water is used through evapotranspiration.

The irrigation and precipitation cause the watertable to rise in the shallow aquifer beneath the SBC site. The stratification of groundwater salinity is an important issue for the selection of appropriate crops and for possible utilisation of shallow good quality water. Field experiments were conducted to aid in interpretations of salinity variations and to provide data for the development of a mathematical conceptual model. A two-dimensional flow and solute transport model was used to evaluate the potential effects of changes in the quantity and quality of irrigation water being applied to the SBC site on the depth to which the good quality groundwater can be found for crop growth.

2. METHODS

2.1. Experimental set up

The experiment is set up in a bay 250m long and 40 m wide, with banks built around. A network of piezometers and wells, total of 21, were installed (Figure 1). The observation network was placed approximately 200 m from the irrigation channel, which is at the higher end of the bay. The experiment consists of three 7 m deep piezometers, four 4 m deep piezometers, five 1.7 m and one 1.28 m piezometer all perforated at the bottom 30 cm, and 8 shallow test wells, five 1.7 m and three 1.2 m deep perforated throughout their length (Figure 1).

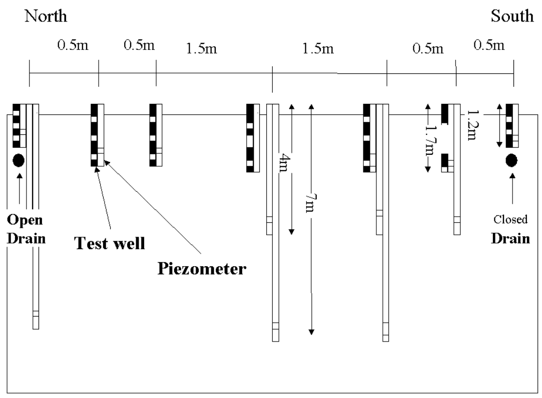

Figure 1 Vertical cross section of the experimental site; view perpendicular to drains

The observation system was placed between two drains running parallel to each other at 5 m distance in the direction east west. The diameter of both drains is 90 mm; they are soft plastic tubes with perforations along the whole length. The drain in operation is to the north of the piezometer network and the closed one is to the south (Figure 1). The water flowing in the open drain is collected in the sump. The sump pump has an automatic trigger, which gets activated as soon as certain water level is reached in the sump. Closed drain is not connected to a sump and the water is not pumped from it.

2.2 Field testing

The fieldwork included manual measurements of water levels and collection of water samples from all piezometers and wells, sump and from the irrigation channel using the bailer. Data was collected intermittently from June 2001 to August 2001 (28 June, 3 July, 6 July). A full set of data was collected prior to and following the irrigation from 6 August 2001 to 13 August 2001. Initially two sets of samples were collected at each location; one from the stagnant water in the piezometer and one following the removal of water after waiting for the recovery of "fresh" aquifer water. Electric conductivity was measured for all samples collected, while a full chemical analysis was conducted for a set of pre irrigation and post irrigation samples.

In order to determine the range of hydraulic conductivities and their small-scale variations in the study area, the aquifer slug test was conducted. Slug tests were completed for five piezometers and one well, including testing of deep layers corresponding to the screened section of deep piezometers. For piezometers the slug was added to 50% of depth to water, whereas for wells 50% of water column in the well was taken out. The recovery was observed for approximately three hours or until the water level had dropped by 70% in the case of deep piezometers. For the latter slug tests, the time involved in monitoring the recovery was significantly more, up to 28 hours (hydraulic conductivity as low as 0.0001m/day).

2.3. Numerical modelling

The collected field data, hydraulic conductivity determined from slug tests and chemical composition of groundwater including salinity provided the essential parameters for the development of a mathematical-conceptual model. A local scale groundwater model was developed to investigate the groundwater flow and the solute transport under the SBC Bay 2 using USGS MODFLOW/ MT3D model (MacDonald and Harbaugh, 1988) under the PMWIN environment (Chiang and Kinzelbach, 1998).

3. DATA ANALYSIS

3.1. Groundwater level monitoring

The irrigation water was applied on the bay on the 6 August 2001. Within one day after irrigation and the sump pumps operating, the piezometers above the open drain became dry. The strong decline in the watertable is a consequence of the drain operating. The flow is mainly concentrated towards the open drain while some flow occurs towards the closed drain, although not to the same extent as the open one. Hence, the closed drain also acts as a sink. This is possibly due to the increased storage pore space caused by the presence of the non-operational drain and the gravel envelope pack around it, as confirmed by piezometric data in the vicinity of the drain. Half way through the irrigation period the piezometric pressures stabilize. Subsequently, the flow is directed towards the deep drainage, which is indicated by decreasing hydraulic head. Water level monitoring in the deep layer indicates high vertical head gradient. Head stabilisation in deep piezometers was extremely slow following the bailing out of water. Therefore, it seems reasonable to assume very low hydraulic conductivity for this layer.

3.2 Salinity monitoring

The results of the salinity analysis indicate variations in the vertical salinity profile. Prior to irrigation, relatively low salinity zone of up to 10 dS/m can be found in the top 1.5 m below surface (Figure 2). The salinity increases with depth and the highest value of 35.4 dS/m is recorded at 7 m deep piezometer placed between the open and the closed drain (6 August 2001).

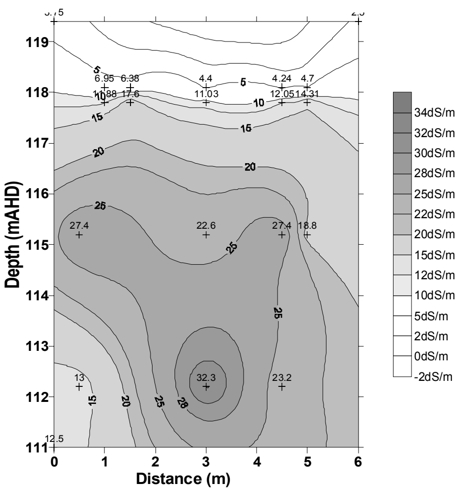

Figure 2 Plotted contour map of salinity concentration patterns with measurements taken at points of various depths before the irrigation

After irrigation water has been applied (irrigation water salinity is 1.28 dS/m) the lower salinity interface moves to the deeper zones, with the salinity below 10 dS/m now in the top 2 m (previously 1.5m) within surface (Figure 3). Both drains were closed at the time due to irrigation requirements and technical obstacles, however the effects of salinity dispersion were observed as seen on Figure 3.

Piezometers at 7m depth placed on the northern side and in the centre of the experiment area exhibit big variation in salinity. The one on the northern side has six times lower salinity, probably due to differences in lithology. This finding indicates that small-scale lithology variations can have great effect on salinity with the scale of influence increasing with increased salinity difference. Water samples collected from a well screened throughout its length have two to three fold lower salinity than the samples taken from piezometers of the same depth but screened only at the bottom 30 cm.

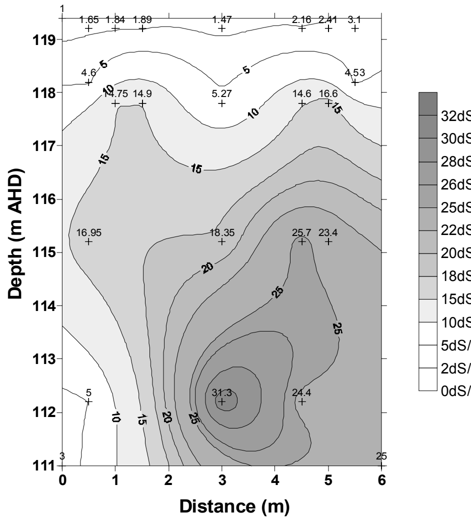

Figure 3 Contours of observed equal salinity concentrations one day after applied irrigation

Soluble salt concentration is therefore significantly affected by the method of sample collection. As confirmed by the literature, the accurate results can be obtained not from an integrated depth along the whole length of well screen but from a narrow screen of the relevant depth.

3.3. Aquifer hydraulic testing

Hydraulic conductivity value was measured by slug test at discrete vertical intervals from piezometers and averaged hydraulic conductivity value from the test well. Bouwer and Rice method (Bouwer and Rice, 1976) was used for data analysis. However, slug test should be regarded as point measurements that have limited representation of the soil layer as a whole, therefore this limitation has bearing on field applications (Gafni, *et al.*, 1992).

The analysis of the results indicated very quick response from the wells and shallow piezometers and very slow response from the 4.2 m and 7 m deep piezometers. Computing the ratio Ht/Ho (Ht is the drawdown for time at t=t (m) and Ho is the drawdown for time at t=0 after the slug has been introduced (m)) and plotting it versus time on semi-log scale yielded the curve with several straight-line segments. In terms of Bower and

Rice (1976) method, first straight line segment is the result of the gravel envelope around the well while the second segment represents the conductivity of the aquifer. The second segment was used to calculate the variable hydraulic conductivity in the range from 0.0001 m/day to 0.04 m/day (Table 1). Hydraulic conductivity values are two orders of magnitude higher for the shallow layers comparing to the 4 m deep layer.

Bore number	Depth (m)	Hydraulic conductivity (m/day)
39064TW	1.14	0.046
40205TW	1.7	0.039
43117P	1.28	0.0003
39238P	1.7	0.002
43351P	4.2	0.0001
43350P	7.25	0.0005

Table 1 Hydraulic conductivity obtained from hydraulic slug tests

This pattern is further observable in the 7 m deep layer where again K is two orders of magnitude lower than in the shallow zone. The point value for hydraulic conductivity in this study is obtained from the piezometers but in general the data obtained from the wells give better indication of the hydraulic conductivity of the aquifer. The data analysed allow rough division of study site into two major zones; the shallow layer within the top 2 m from the surface with conductivity of about 0.04 m/day, and deeper strata with conductivity of around 0.002 m/day.

3.4. Geochemical analyses

Initially two sets of data were collected; one from stagnant water in piezometers and one after purging the water and collecting the sample following the recovery. This was undertaken to investigate the discrepancy in the salinity and to avoid the bias in sampling. The results indicated significant difference in the results (Figure 4).

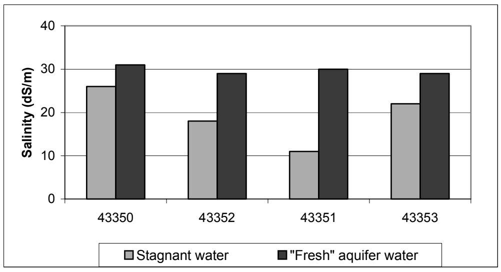

Figure 4 Salinity of stagnant versus purged water for four piezometers

However, chemical analysis of these samples indicated that there was no significant change in the ion concentrations between two types of water samples. In stagnant water there was an increase in Na^+ and HCO_3^- and at the same time decrease in Mg^{2+} and SO_4^{2-}. This suggests a shift from NaCl to $NaHCO_3$, and as expected the salinity has dropped.

Overall, the hydrochemistry is dominated by four ions Na^+, Mg^{2+} , Cl^- and SO_4^{2-}, but the dominant salt is sodium chloride followed by magnesium sulphate. There is a trend for the increase in sodium and decrease in calcium, magnesium and bicarbonate ions with the increasing depth along the groundwater path.

This may suggest possible exchange of calcium and magnesium ions for sodium. The ratio of Na/Cl expressed in meq/L is more or less constant in all layers.

4. NUMERICAL MODELLING

The aquifer system below the piezometer array was modelled as a 2-dimensional vertical profile model with 8 layers and vertical hydraulic connection between them. The model covers the area of 35 m^2. The finite difference grid for the model consists of 12 columns and 1 row; it is 8 m deep and 5 m long.

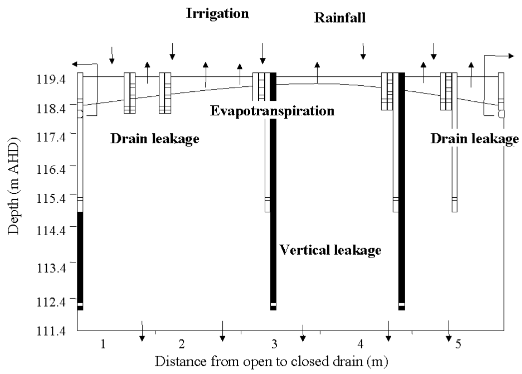

Figure 5 Conceptual 2-D model

Irrigation and rainfall represent the inflow into the groundwater system while the outflow is comprised of evapotranspiration, vertical leakage through the bottom of the model and drain leakage mainly through the open drain (Figure 5). Vertical leakage is the result of differences in hydraulic head. The boundary conditions attributed to the model domain are no flow boundaries to the left and the right side, top boundary is transient watertable boundary and bottom boundary is the specified leakage boundary. The model domain is discretised with an irregular grid consisting of 12 mesh intervals (varying from 0.045 m to 1.08 m) in x direction and 8 mesh intervals with uniform spacing of 1m in z- direction (Figure 6). This was designed in order to use small grid spacings in the area near drains where steep hydraulic gradients were expected and where narrow area needs to be defined. The grid was expanded in the x direction by increasing the nodal spacings by 2 times the previous nodal spacing starting from the right and left model boundary and progressing to the centre of the model domain.

Hydraulic conductivity values were calculated from the slug test, while specific storage and specific yield estimates were obtained from field studies and Anderson and Woessner, (1992). The latter represents general value specific for certain lithology.

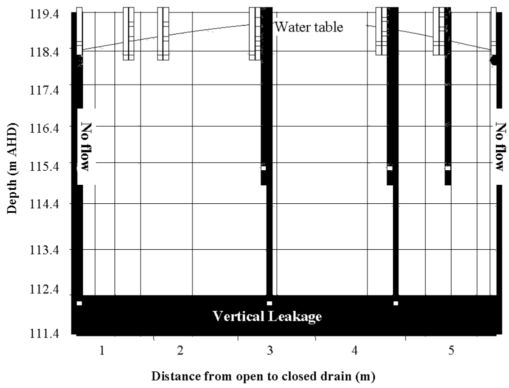

Figure 6 Grid model design

Vertical conductivity was assumed to be of the same order as horizontal. . The simulation is transient, the stress period is half day and the total simulation time is 7 days. The initial pressure heads were approximated on cell by cell basis by contouring the piezometric data measured before the irrigation was applied. The recharge from irrigation water applied amounts to 0.091m/event. The recharge values were assigned to top most active cells for the first stress period only (half day). This WELL package was used to simulate the vertical leakage through the bottom of the model domain. The discharge was calculated by assigning a discharge value for a particular cell obtained by multiplying estimated hydraulic gradient with vertical hydraulic conductance and the area of flow.

The evapotranspiration (ET) values used to simulate losses from the water table due to ET were obtained from Bureau of Meteorology, Griffith. The average for the two weeks period of monitoring was used for the model.

Drain package was used to simulate open and closed drain (90 mm slotted pipe). Two cells were assigned values in layer 2, one representing open and other closed drain. The closed drain was assumed partially active due to the increased pore space as a consequence of the presence of the gravel envelope. Water is discharged from the open drain at the rate calculated using Darcy's law:

$$Q_D = \frac{K_V ir\pi L}{M} \qquad (1)$$

Where,

K is vertical conductivity (m/day); i is hydraulic gradient between the head in the cell and head in the drain; 2rπL/2 is area of the drain divided by 2 to account for the half of the influence of the drain on the model (m^2); M is thickness of the drain sediments (m). The conductance for the closed drain was estimated at an order of magnitude less than the open drain as it was non-operational.

The model was calibrated through a series of model simulations by trial and error method. This consisted of variation of the model parameters within the realistic limits until a degree of correspondence was achieved between the computed and field measured values. The parameters that were changed to optimize the calibration include drain conductance, hydraulic conductivity, vertical conductivity, specific yield and vertical leakage. Pressure heads were initially too high when compared with the field measured values. The drain conductance (usually adjusted during calibration) and the hydraulic conductivities were changed in a series of model runs and simulations. Figure 7 shows good agreement between the modelled and observed hydrograph for piezometer located 0.5 m from the open drain at depth of 1.7 m (P43123).

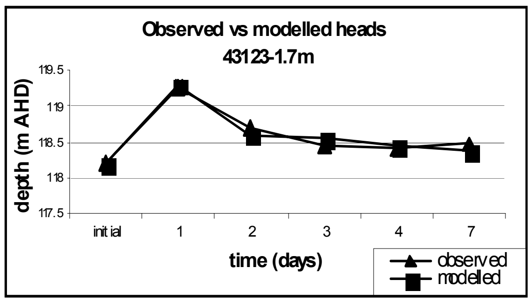

Figure 7 Calibration results for shallow piezometer 43123

The average error between simulated and field measured water levels for the shallow piezometers and test wells following the calibration was 0.03 m. Horizontal conductivity increase, for the layers 1 to 6, has greatly impacted the simulation results, but the groundwater model seemed to be insensitive to changes in vertical conductivity and specific yield.

MT3D solute transport model was run following the calibration of the flow model. It is assumed that advection and hydrodynamic dispersion govern the physical processes that contribute to the transport of dissolved salts. The longitudinal and transverse dispersivity values used in the model are 0.1 m and 0.01m, respectively. The computed salinity results were compared to the observed results, and the calibration was mainly focused on the shallow zone. Model results show that the shallow groundwater is gradually displaced by irrigation water of lower salinity and the dilution produces weak vertical gradients, which further results in the upward diffusion of salt. The authors interpret upward diffusion from the deeper layers outside the model boundary as the major process controlling the salinity of the deep layers causing salinity to return to its pre irrigation state. The control of salinity might also be to some extent influenced by the lateral flow (Figure 9).

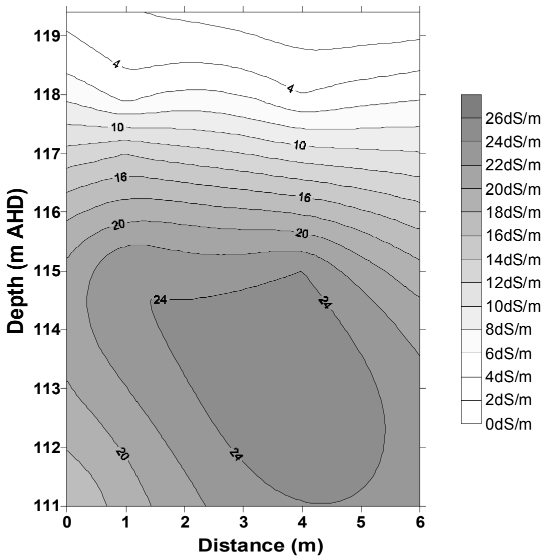

Figure 8 Simulated contours of equal salinity concentrations one day after irrigation

During the calibration process the effect of increased recharge rates and consequently increased discharge rates on the salinity concentration distributions as well as various initial salinity concentration rates for recharge were examined. The best agreement was achieved with the increased recharge rates causing the salinity to decrease to the level of the observed. The model did not seem to be sensitive to decreases in salinity of recharge water but was very sensitive to the changes in the increased recharge.

5. CONCLUSIONS

- Hydraulic conductivity is up to five orders of magnitude higher for layers above the tile drain compared to the 7 m deep layers
- Shallow layers above the tile drains are characteristic of low salinity due to constant drainage and circulation of water;
- Modelling of flow was successful for the shallow zone only, as the deeper layers did not recover due to low permeability;
- Solute transport modelling suggests that the modification of recharge and discharge rates from the groundwater system can be used to control salt distribution in the shallow layers.

The study suggests that the drains effectively lower the salinity of groundwater in the shallow zone but the deeper aquifer remains highly saline. Fairly good correlation was achieved between observed and simulated data for both flow model and solute transport model for the shallow groundwater, rendering numerical solutions applicable for the prediction of the salinity changes with depth and consequently for the selection of the crop with appropriate salinity tolerance level.

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