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Tidal forcing groundwater dynamics in a restored coastal wetland: implications of saline intrusion

William Glamore
University of New South Wales

Buddhima Indraratna
University of Wollongong, indra@uow.edu.au

Tidal Forcing Groundwater Dynamics in a Restored Coastal Wetland: Implications of Saline Intrusion

W. C. **Glamore**[1], B Indraratna[2]

[1] Senior Project Engineer, Water Research Laboratory, School of Civil and Environmental Engineering, UNSW,
[2] Professor of Civil Engineering, University of Wollongong, NSW

110A King Street, Manly Vale NSW 2093
w.glamore@wrl.unsw.edu.au
P. 02 9949 4488 F. 9949 4188

Abstract: Tidal restoration projects are currently being undertaken throughout coastal Australia without a full understanding of the influence of tidal forcing on groundwater salinity. To determine the impact of restoring tidal flows on groundwater salinity levels, field investigations were undertaken at a study site near Berry, NSW. Fluctuations in groundwater and surface water chemistry (soluble chloride, pH, electrical conductivity) and hydrodynamics were measured over a 12-week period using multilevel peizometers and submersible data loggers spaced at discrete distances from a flood mitigation drain. Additional parameters, including saturated hydraulic conductivity (K_{sat}), were undertaken to determine baseline conditions and to provide initialisation data for a 3-dimensional finite element model. The finite element model was calibrated within $\pm 5\%$ of field data and developed to simulate saline intrusion during a 'worse-case' scenario. Results from the model simulations indicate that saline intrusion at the site is limited even under extreme conditions. To quantify the influence of $K_{sat(h)}$ levels on saline intrusion, material properties within the numerical model were altered to represent 1, 10 and 20 m/day. Model simulations showed that $K_{sat(h)}$ values >10m/day permitted saline intrusion in excess of ANZECC (1992) criteria. Based on the model findings a series of management criteria are proposed that detail acid sulfate soil remediation techniques, including tidal restoration, dependent on $K_{sat(h)}$ values. The proposed management criteria suggest that tidal restoration projects are most suited in sites where the $K_{sat(h)}$ values are <10m/day.

Keywords: Saline Intrusion, Hydraulic Conductivity, Acid Sulfate Soils, Numerical Model, Tidal Restoration.

1. INTRODUCTION

In efforts to remediate acid sulfate soil (ASS) leachate, restore fish passage and control exotic weed growth, one-way floodgates throughout coastal Australia are being modified to permit tidal flushing. As well as changing the hydrodynamic regime, the intruding tidal waters typically contain elevated concentrations of soluble chloride and bicarbonate. While these waters may be beneficial in buffering acidic products and controlling exotic freshwater weeds, elevated salinity concentrations can reduce agricultural production (Glamore, 2004).

In low-lying flood mitigation drains where tidal restoration works have been undertaken, saline waters can come into direct contact with important agricultural crops by overtopping the levee bank or through saline intrusion into the sub-soil matrix. To date, significant efforts have been undertaken to calculate the appropriate freeboard and develop modified floodgates which restrict overtopping of the levee bank (Glamore and Indraratna, 2004). However, saline intrusion into the subsoil matrix via tidal forcing in acid sulfate soil environments has only recently been highlighted as an important consequence of tidal restoration works (Johnston et al., 2003; Indraratna et al., 2002).

This paper details the mechanisms influencing tidal forcing on groundwater salinity levels and investigates the extent and distribution of saline intrusion following the restoration of tidal flows to a low-lying flood mitigation drain underlain with acid sulfate soils. Findings from previous field investigations are used to calibrate and verify a three-dimensional coupled flow and transport finite element (FE) model. The FE model is then used to quantify the extent and distribution of saline intrusion during a 'worse-case scenario'. Furthermore, to determine the influence of hydraulic soil conductivity on saline intrusion, the material properties within the model are varied and a series of model runs undertaken. While the FE model can be used to determine the extent of saline intrusion at any field site in coastal Australia, the outcomes of the model simulations have wider implications for acid sulfate soil management. Indeed, the results of the model simulations have been incorporated within a proposed acid sulfate soil

management strategy, which suggests different management techniques dependent on the saturated hydraulic conductivity of the soil. The model does not discuss biogeochemical reactions or long-term consequences of salination.
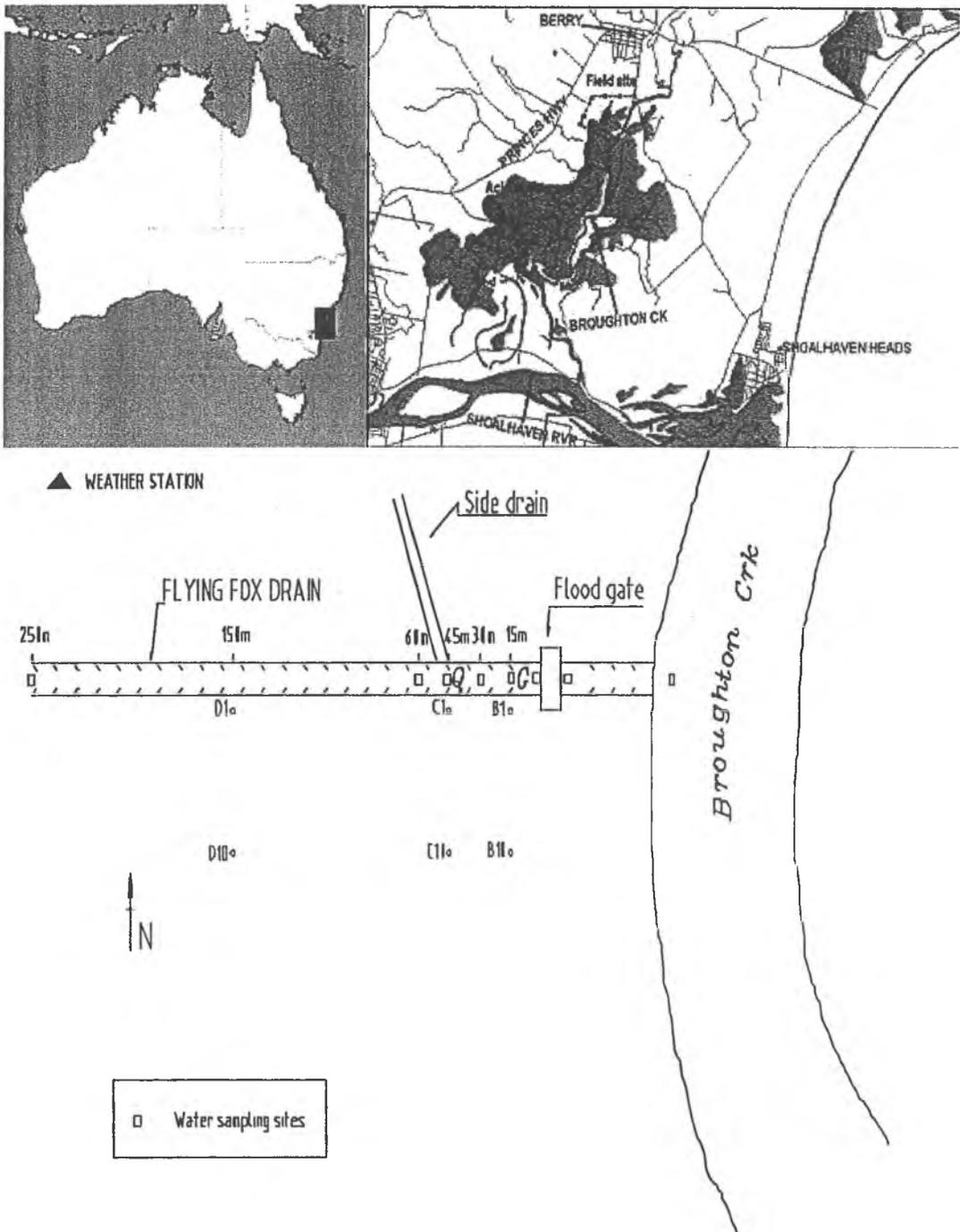

Figure 1 – Study Domain (note that the pyrite layer was located approximately 0.7 – 1.3 m below surface)

2. METHODS
2.1   Study Site

The study area is a low-lying coastal pasture located along Broughton Creek, 10.2 km upstream of the Shoalhaven River, near the township of Berry on the south coast of NSW (Figure 1). Elevation at the site ranges from 0.02m to 1.45m Australian Height Datum (AHD) with pyritic sediments -0.7m to -1.3m below the surface. The site is typical of ASS affected areas in that the drainage canal (8 - 10m wide by 3m deep) cuts through the pyritic layer and two top-hinged one-way floodgates maintain low drain water elevations and restrict saline intrusion.

Broughton Creek is in late stages of estuarine infilling (Roy, 1984), suggesting that in low flow conditions full tidal effects (1.4 - 2.1m fluctuations) are to be expected. The salinity regime of Broughton Creek is predominately Cl dominant brackish water (EC > 10000 μS/cm), but following large rainfalls (> 50mm) Na^+ dominated freshwater (EC < 5000 μS/cm) can persist for 7- 10 days. The Department of Natural Resources (DNR) listed Broughton Creek as one of the top seven 'hot spots' for acid sulfate soils in NSW.

2.2   Monitoring Regime

A detailed monitoring regime was undertaken over a 12 week period to determine temporal and spatial fluctuations in groundwater, surface water and soil chemistry/dynamics. Within the flood mitigation drain, surface water samples were taken weekly at 15m intervals upstream and downstream of the floodgate for the entire tidal reach. Collected samples were tested for pH, electrical conductivity (EC), dissolved oxygen (DO), temperature, and redox potential (Eh) using calibrated handheld probes. Additional samples were stored at 4° C and analysed in the laboratory for dissolved and total chloride, sulfate, aluminium, iron (II & III), magnesium, and potassium. Furthermore, four (4) submersible data loggers (SDL) were installed 1m and 45m upstream and downstream of the floodgate headwall. The SDLs (Greenspan CTDP 300 and CS 304) measured water elevation, temperature, pH, EC and DO at hourly intervals. Climatic information, including rainfall and evapotranspiration (calculated by the Penman-Monteith method), were measured using a Campbell Scientific WeatherWatch 2000 weatherstation located 500m from the floodgate.

Groundwater samples were obtained from bundled mini-piezometers installed at 1m, 2m, 4m, 8m, 16m and 32m perpendicular to the drain. The mini-piezometers were installed to 3m below the surface (approximately 0.5m below the potential ASS layer) and sampling ports were positioned at 0.25m intervals (9 samples per unit). Commencing on the mid-tide, weekly field groundwater measurements were taken for EC, pH, DO, Eh, temperature and water level using calibrated handheld probes. In addition to the above surface water species, groundwater samples were analysed for soluble nitrate and phosphate using appropriate methods given in APHA (1985). To obtain a spatial and temporal profile of the groundwater table, submersible water level sensors (Greenspan PS700) were installed and surveyed at each piezometer and logged at hourly intervals.

A range of physical and chemical soil investigations were undertaken throughout the study to determine the extent and distribution of pyritic oxidation products, saline intrusion levels and to provide initialisation data for the FE model. Soil samples were collected and chemically analysed for chromium reducible sulphur, pH, EC, POCAS, chloride, sulfate, NO_x, and phosphate concentrations at the beginning and end of the study. Furthermore, physical tests were undertaken on triplicate soil samples for lateral saturated hydraulic conductivity using the falling head method. The remaining material parameters given in Table 1 were determined by laboratory analysis of field samples or were obtained from previous soil analyses undertaken near the study site (Blunden and Indraratna, 2001).

2.3   Numerical Model

The flow and transport of saline contaminants into the soil matrix was simulated using a 3-dimensional (3D) commercially available FE model for variably saturated media, FEMWATER. The model requires a broad range of initialisation parameters including environmental, climatic and hydraulic information that was obtained from the above field sampling protocols. A complete description of FEMWATER is given by Lin et al (1997).

2.3.1   Mesh and Boundary Conditions

To simulate the flow and transport of contaminates over a realistic spatial scale, a 3D finite element mesh was constructed 150m long (the full tidal limit within the drain), 50m wide and 5m deep (Figure 2). To accurately simulate the surface contours, a high resolution digital elevation map (obtained using airborne laser scanning) was interpolated to the surface of the mesh. Fine mesh spacing was located nearest the drain boundary and element size progressively increased with distance from the drain. In total, there were 2400 elements and 1573 nodes within the mesh.
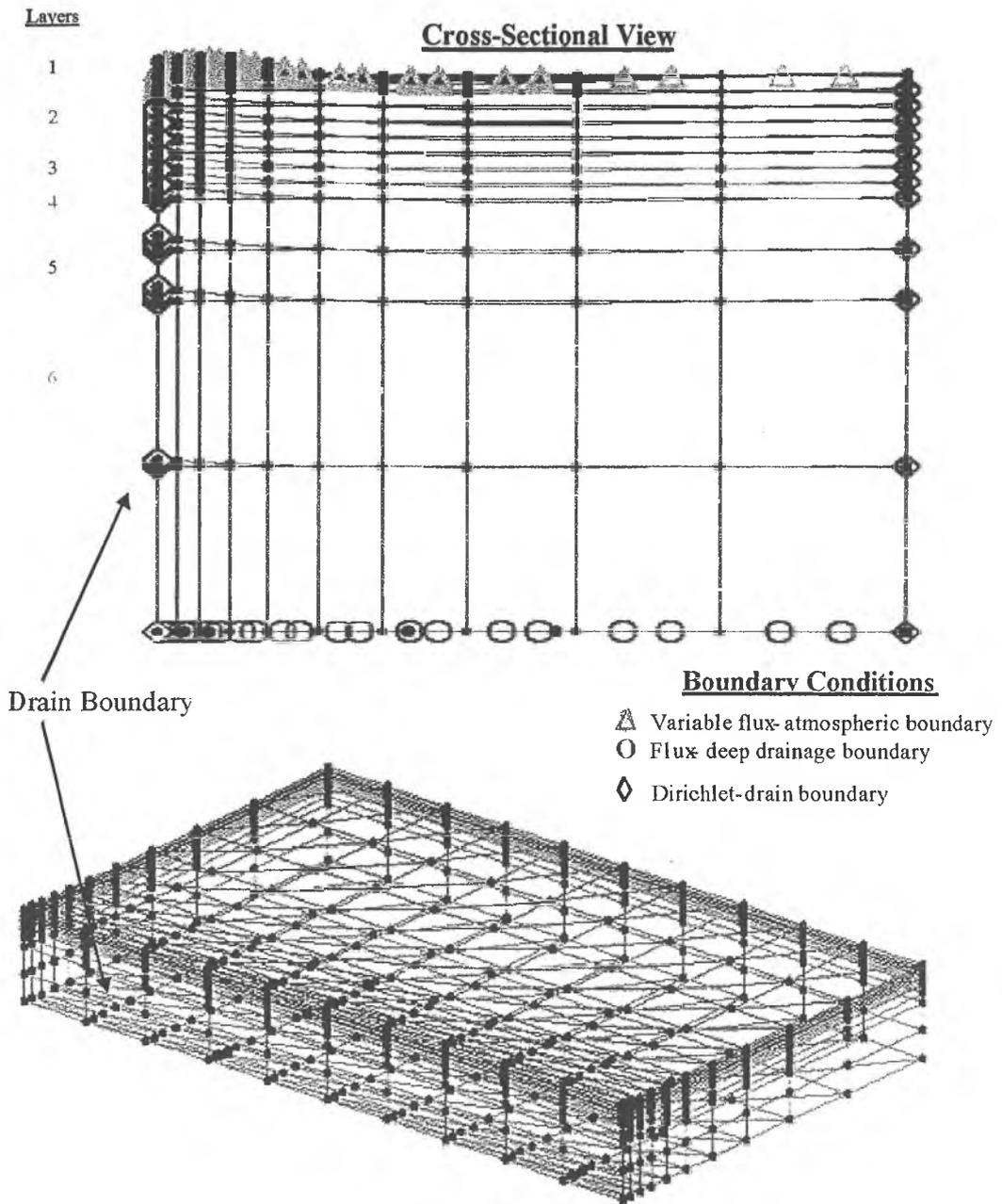
Figure 2. Finite Element Mesh and Boundary Conditions (Soil layers are further described in Table 1).

A range of boundary conditions were employed to cover the various environmental and data conditions necessary for coupled groundwater flow and transport simulations. Due to the large quantity of data obtained from the in-situ data loggers located in the surface drain, a Dirchlet boundary condition was employed on the nodes of the drain boundary. This boundary condition simulated fluctuating tidal and salinity levels over a 12-week period during the calibration phase, however, during subsequent model runs the salinity levels remained constant at 30.0 mS/cm. To simulate rainfall/evapotranspiration, a variable boundary condition derived from the weatherstation data was applied to the surface face elements. Finally, a specified flux boundary was employed along the base of the model as a calibrating tool to simulate the inflow/outflow of water through the semi-permeable base. The boundary conditions applied to the mesh are given in Figure 2.

2.3.2   Material Properties

Material properties include both fluid properties and soil characteristics. Standard International units were generally employed except for time, which was measured in hours rather than seconds. As such, mass concentration was calculated and is given in mg /L. Within the finite element mesh twelve elemental layers were created with 6 distinct material zones representing: (1) an organic surface layer; (2) a peaty-loam layer; (3) a jarositic layer; (4) an actual acid sulfate soil layer; (5) a potential acid sulfate soil layer; and (6) a Pleistocene semi-impermeable clay layer. A summary of the soil material parameters employed within the model is given in Table 1.

Table 1. Soil Physical Properties Used for Model Initialisation.

Layer	Depth (m AHD)	$?_r$ (m^3/m^3)	$?_s$ (m^3/m^3)	a (1/m)	n	k_v (m/hour)	k_h (m/hour)	$?_d$ (kg/m^3)
1	0.35	0.05	0.48	0.281	1.3	0.1653	0.1466	800
2	0.05	0.02	0.35	0.242	1.15	0.1578	0.1668	1110
3	-0.25	0.05	0.34	0.291	1.18	0.0651	0.0398	1050
4	-0.55	0.04	0.50	0.225	1.29	0.0899	0.0426	950
5	-0.85	0.06	0.49	0.474	1.09	0.0766	0.0099	1030
6	-1.85	0.06	0.49	0.474	1.09	0.0083	0.0065	1030

Note: $?_r$ and $?_s$ represent residual and saturated volumetric moisture contents, a and n are shape parameters based on the van Gneucthen (1980) equation, k is the hydraulic conductivity in the vertical (k_v) and lateral plane (k_h), and $?_d$ is the average dry bulk density. 1m/ hour = 2.77×10^4 m/sec.

2.3.3   Modelling Process

The model was calibrated over a 12-week (84 days) period that contained episodes of saline ingress from elevated drain water chloride concentrations and periods of saline flushing due to natural groundwater recharge following rainfall. To increase accuracy and model stability, a steady-state simulation was first performed with static boundary conditions and groundwater levels derived from field observations. The steady-state simulation output was then used as initial conditions for further coupled transient simulations. Once the model was calibrated to within ±5% of actual field measurements, additional simulations were undertaken to determine the maximum saline intrusion potential over a 12-week period (i.e. worse-case scenario) and the impact of increasing lateral hydraulic conductivity ($K_{sat(h)}$) on saline intrusion.

The worse-case scenario was simulated by (1) maintaining drain water salinity at 20 ppt on the surface drainage boundary; (2) removing any rainfall events; and (3) imposing a constant evapotranspiration rate of 2.21 mm day^{-1} (long-term average) on the surface boundary for the entire 12 week period. The influence of altered $K_{sat(h)}$ values on the saline intrusion front was examined by manipulating the material properties within the calibrated model to suite different flow and transport regimes. Three separate conditional states were simulated using $K_{sat(h)}$ values of 1 m/day, 10 m/day, and 20 m/day. Within the material properties, the highest $K_{sat(h)}$ values were assigned to the actual acid sulfate soil layer, and, to maintain model stability, the remaining layers $K_{sat(h)}$ were decreased by 25%. The model was run over a 1500-hour dry period (i.e. no rainfall and high saline concentrations on the drain boundary) to determine the extent and distribution of subsurface saline contaminates. At the 1500th hour, 100 mm of rainfall was applied to the surface boundary over two days. The model was then run for another 500 hours to ascertain the influence of natural recharge on the saline front. It was anticipated that higher $K_{sat(h)}$ values would be associated with a strong intrusion front and enhanced flushing. Each simulation exceeded its design criteria either when groundwater salinity was above 4.5 mS cm^{-1} at 10 m inland or if groundwater salinity concentrations were above 4.5 mS cm^{-1} within the root zone.

3. RESULTS AND DISCUSSION
3.1   Measured Versus Predicted Groundwater Profiles and Saline Intrusion

Numerical simulations indicated that the watertable fluctuated widely at 1m and 2m inland from the drain, and that tidal forcing dissipated with distance. Fluctuations in the saturated zone (not shown) were primarily associated with daily tidal changes, whereas groundwater recharge was controlled by rainfall. Moreover, the strong agreement between field and calculated results indicated that the constructed finite element model was adequate to simulate groundwater hydrodynamics through the soil matrix to an acceptable accuracy (Glamore, 2004).
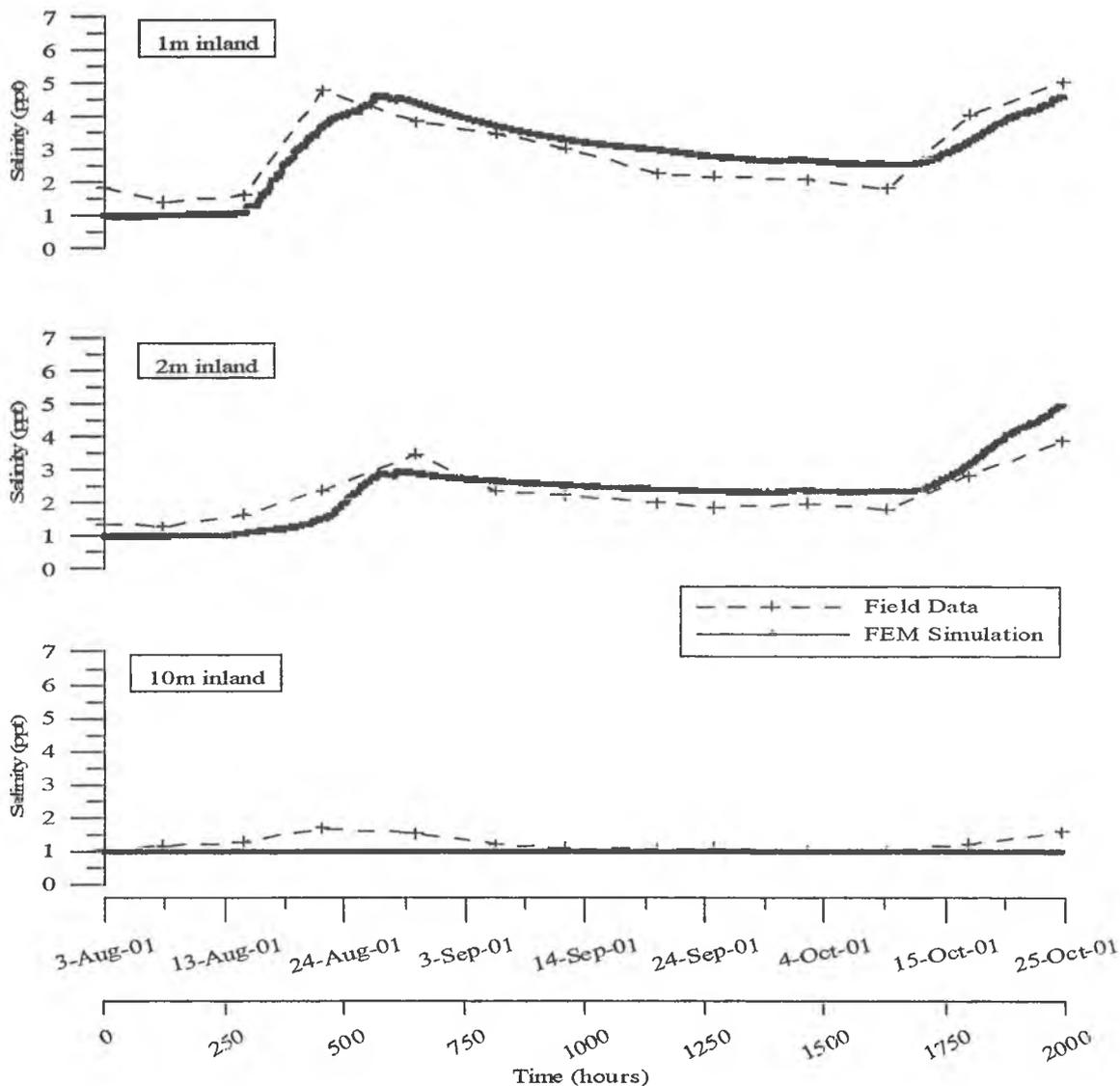

Figure 3 - Simulated Versus Field Results for Transport Simulation.

The contaminant transport simulations also agreed with field results. As shown in Figure 3, saturated groundwater salinity fluctuated greatest 1m inland and decreased with distance from the drain. In all cases, groundwater salinity levels were (i) within ANZECC (1992) criteria; (ii) did not negatively impact the shallow root zone and; (iii) were highest during dry periods when elevated salinity concentrations in the drain were drawn into the soil matrix through advection and dispersion. Strong rainfall also flushed saline contaminants from the soil zone and the dynamic intrusion-flushing cycle evident in the model is an important characteristic of the natural saline dynamics.

As well as depicting the removal of the saline contaminates in response to rainfall, the calibration simulations indicate that the salinity wedge is not a sharp interface, but, instead, a transitional zone between highly saline concentrations at the drain boundary and low ionic groundwater. The simulation also showed that while rainfall triggers groundwater flushing, it does not completely remove the contaminants. In fact, after rainfall an isolated saline 'pocket' develops within the soil matrix approximately 1-2m inland from the drain. Importantly, these results correlate well with field data and indicate that during this period (2000 hour timeframe) saline intrusion does not represent a significant threat to agricultural productivity.

3.2   Maximum Saline Intrusion

Using the above calibrated model, additional simulations were undertaken to determine the extent and magnitude of saline intrusion in response to extreme climatic factors. Due to the temperate rainfall patterns in south-eastern NSW, the dry conditions shown within this simulation represent well the influence of tidal forcing on the groundwater regime during a worse-case scenario (no rain, high salinity). The results from these simulations are best illustrated by a series of 3-D contour plots (Figure 4) where the vertical axis is magnified five times.

The findings from these model runs indicate that saline intrusion is not a significant concern even under extreme climatic conditions. As shown in Figure 4a, initially the groundwater salinity is low throughout the soil matrix, but under continued dry conditions saline seepage occurs in a subsurface wedge-shaped intrusion front. While the wedge continues to intrude into the soil matrix, after 2000 hours the majority of soil contaminants are restricted to less then 6m inland from the drain (Figure 4b). Salinity concentrations beyond 6m comply with ANZECC (1992) guidelines and do not pose a risk to agricultural productivity. Considering the temperate climate and year round rainfall pattern at the study site, these findings suggest that even under extreme conditions, saline intrusion should not be a concern in similar restored sites in south-eastern NSW.
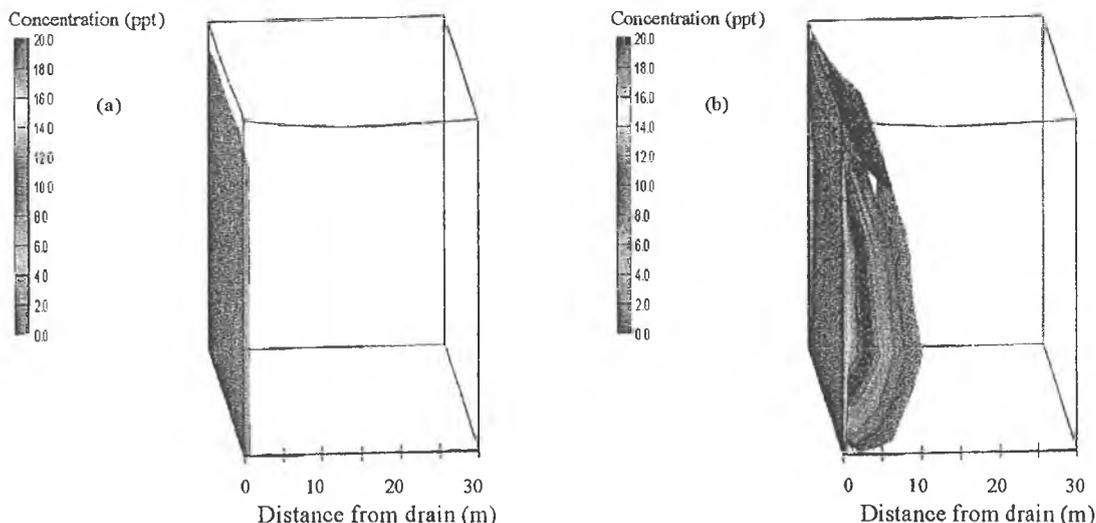

Figure 4 - Maximum Saline Intrusion Plots at 1 Hour (a) and 2000 Hour (b) Timestamps. Note Plot Height is 5m.

3.3   Influence of Altered Lateral Soil Hydraulic Conductivity on Saline Intrusion

As detailed below, the altered $K_{sat(h)}$ simulations indicated that saline intrusion is limited in regions with low $K_{sat(h)}$ values and more extensive in regions with high $K_{sat(h)}$ levels. In the low K_{sat} simulation (<10m day^{-1}), by the 1500th hour saline intrusion was limited to 4m inland and did not impact the root zone. In the 10m day^{-1} simulation, the saline front intruded beyond 15m inland but groundwater salinity concentrations were within the acceptable model criteria. However, in the 20m day^{-1} simulation, both the extent and distribution of the saline intrusion front exceeded the model criteria with salinity concentrations >4.5 ppt at 10m inland (> hour 509). Under these conditions, alternative methods, such as subsurface alkaline barriers, are required before tidal flushing can be restored.

Model simulations indicated that soils with high hydraulic conductivity levels allowed for effective contaminant flushing following rainfall (applied as 100mm over two days commencing at hour 1500). As shown in Figure 5, groundwater intrusion was greatest in the 20 m/day simulation. Within this simulation, groundwater salinity decreased at 10m inland from a peak of 5.26 ppm to 3.6 ppm by the 2000th hour. Note flushing from rainfall is not shown in Figure 5 below.
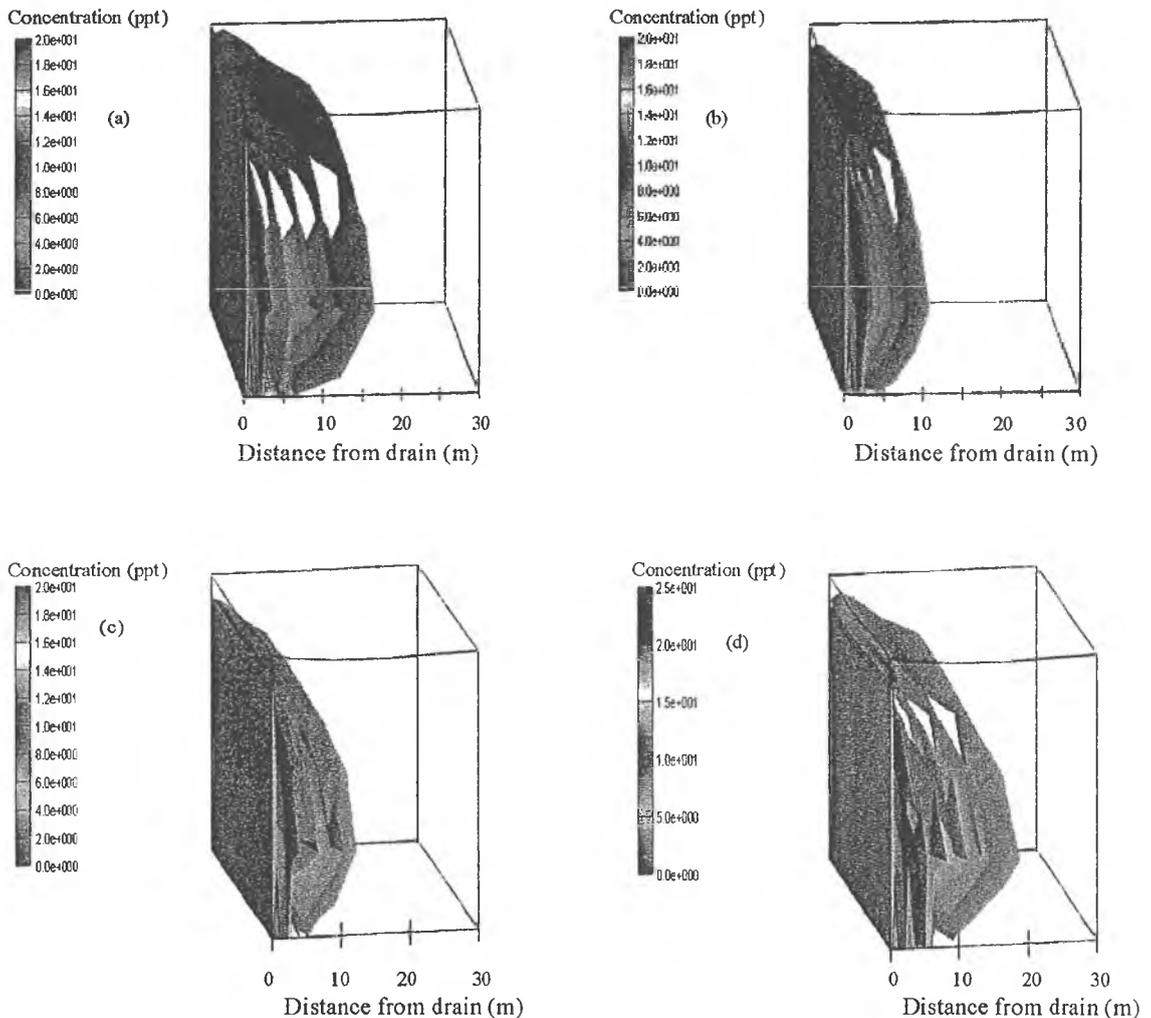

Figure 5 - Numerical simulations of saline ingress at 500 and 1500 hour timestamps with 10 m/day (a & b) and 20 m/day (c & d) lateral soil hydraulic conductivity values.

3.4   Implications for Floodplain Management

The flow and transport of saline contaminants into and out of the soil matrix is a major concern for any proposed tidal restoration (or floodgate manipulation) project. Findings from the above numerical model simulations indicate that even under extreme conditions saline intrusion into the soil matrix should not be a concern at the study site. These findings are further substantiated by long-term groundwater monitoring conducted at the site by Glamore (2004). Furthermore, the numerical model shows that the build-up of saline contaminates over time can be counteracted by flushing of the soil with freshwater after rainfall. These findings are applicable to additional sites throughout southeastern NSW where temperate rainfall patterns and similar K_{sat} values are present. Moreover, the 3-D numerical model provides a field-calibrated predictive tool that is useful in simulating the extent and distribution of saline intrusion in similar low-lying acid sulfate soil floodplains elsewhere in Australia.

Investigations into lateral soil hydraulic conductivity using the FE model indicate that different management strategies may be necessary depending on the in-situ $K_{sat(h)}$ measurements. Low $K_{sat(h)}$ values restrict tidal forcing and limit the extent of the saline front, whereas higher $K_{sat(h)}$ values which permit extensive saline intrusion may decrease agricultural productivity. As indicated by the model simulations, $K_{sat(h)}$ values >10 m/day exceeded the model criterion and, as such, tidal restoration would not be an appropriate management technique in these regions.

Based on the above findings, a series of management criteria were developed to assist in determining the appropriate ASS management strategy based on the lateral saturated hydraulic conductivity of the soil. These criteria, represented in Figure 6, show that different management strategies are necessary depending on the $K_{sat(h)}$ value of the soil and the distance from the surface water boundary (i.e. flood mitigation drain). The criteria are divided into two primary regions ('Region of Evapotranspiration Influence' and 'Region of Surface Boundary Influence') to represent the different management strategies required depending on the hydraulic influence of the surface water boundary. Furthermore, within the 'Regions of Surface Boundary Influence' three distinct management zones are denoted.

In Figure 6, the 'Region of Evapotranspiration Influence' includes all areas beyond which the surface water boundary has an influence. In areas with low hydraulic conductivity this region begins close to the surface boundary, while in sites with high hydraulic conductivity this region commences some distance from the drain/creek. In these regions, the primary management strategies are to maintain an elevated groundwater table, and/or treatment/containment of the acidic groundwater. In the 'Region of Surface Boundary Influence', Zone C is dominated by extremely low $K_{sat(h)}$ readings and hence, acid transport is primarily via surface transport following large rainfall events. In these areas, management should be focused on laser levelling, lime dosing and, to a lesser extent, tidal restoration works.

Throughout the majority of coastal Australia, $K_{sat(h)}$ measurements fluctuate between 0.1-10.0 m/day and consequently, fall within the 'Region of Surface Boundary Influence; Zone B' (Figure 6). Within this classification, acid sulfate soil transport is via subsurface drainage and management should be targeted on tidal restoration, drain reshaping, maintenance of elevated groundwater tables (i.e. weirs), and subsurface lime injections projects. Soils with $K_{sat(h)}$ measurements >12 m/day are classified in Zone C, because in these environments tidal restoration works are not recommended without extensive groundwater monitoring. In this zone, subsurface alkaline barriers and/or acid mine drainage techniques may be more appropriate to effectively manage the groundwater.

4.   CONCLUSIONS

Tidal restoration projects are currently underway throughout coastal Australia in efforts to remediate acid sulfate soil leachate. While bicarbonates within the tidal waters may buffer acidic constituents, the inherent salinity of the tidal water has the potential to severely impact agricultural production. This paper examined the likely extent and distribution of saline intrusion due to tidal forcing over a 12 week period on groundwater salinity levels at a study site located along Broughton Creek, in southeastern NSW, Australia.

A 3-D finite element model was developed using FEMWATER to simulate the coupled flow and transport of soluble chloride ions. The model was designed using soil, groundwater, environmental, topographic and surface water data from a field site underlain with acid sulfate soils. Appropriate boundary conditions were applied to mimic the real-time conditions. The FE model was then calibrated to within ±5% of obtained field data over a 12-week period. Once calibrated, the model was used to calculate the extent and distribution of soluble chloride ions during a worse-case scenario. Results from the model simulations indicated that even under likely maximum saline intrusion conditions, chloride concentrations in the groundwater would remain below ANZECC (1992) criteria. Importantly, these results do not take into account the influence of long-term biogeochemical reactions.
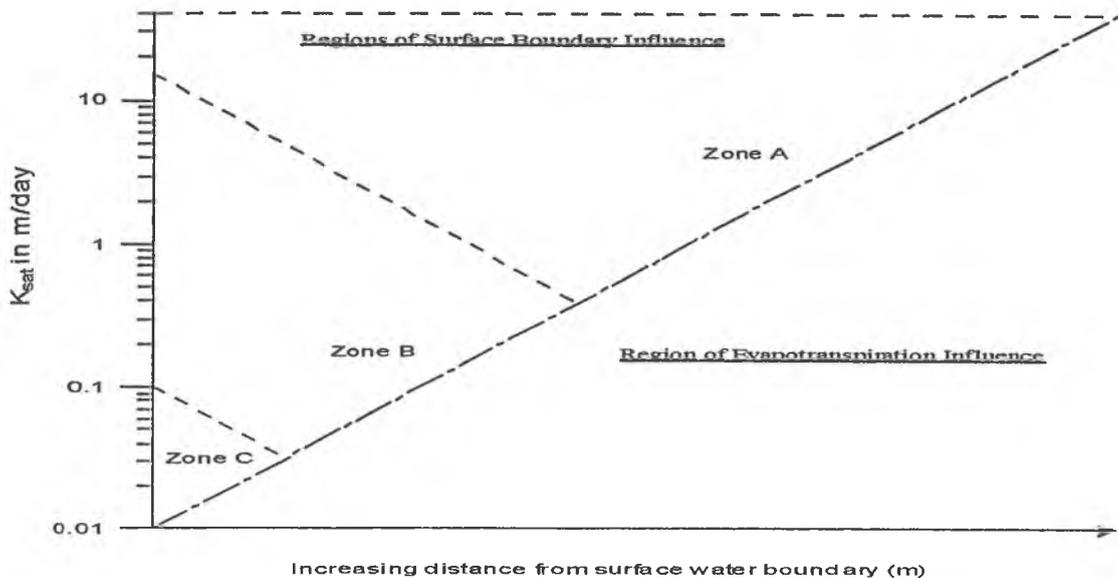
Figure 6 - Management Zones Based on Varying Saturated Hydraulic Conductivity of the Soil in the Lateral Plane.

Lateral soil hydraulic conductivity ($K_{sat(h)}$) plays an important role in controlling saline intrusion. To determine the influence of altered $K_{sat(h)}$ levels on soil salinity the FE model was rerun with different material properties ($K_{sat(h)}$ of 1, 10, and 20 m/day). Results from these simulations indicate that $K_{sat(h)}$ levels <10m/day are appropriate for tidal restoration projects. Based on the findings of the numerical simulations a series of acid sulfate soil management criteria were proposed. The criteria describe different management techniques dependent on the $K_{sat(h)}$ levels at a selected field site and highlight that tidal restoration projects are most effective in soils with $K_{sat(h)}$ measurements between 0.1 and 10.0m/day. The management criteria also suggest that different management techniques are required for regions not influenced by the surface water boundary. Further research is required to determine the influence of chloride salt accumulation over long periods.

5. ACKNOWLEDGEMENTS

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