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Research Paper

ESTUARY, RIVER AND SURROUNDING GROUNDWATER QUALITY DETERIORATION ASSOCIATED WITH TIDAL INTRUSION

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Abstract: Salinity intrusion is a problem in many coastal estuarine and waterways in various parts of the world. Brisbane is a river city close to the coast and as such the condition of the river influences the surrounding groundwater quality. The data gathered by various agencies relating to the river system are used in this paper to develop and calibrate a 3D model of tidal intrusion into the river and surrounding groundwater. The FEMWATER finite element package is used to solve the model equations. Model simulations showed that salinity as far as15-25km from the coast. The model simulations show tidal effects on Brisbane River and surrounding groundwater and water quality deterioration appear to be related to coastal seawater intrusion over time.

Keywords: Seawater intrusion, FEMWATER, coastal aquifer, freshwater, saltwater

INTRODUCTION

Damage to Australian land caused by salinity has been evident in the central parts of Australia where as the low lying coastal lands has been less affected at this time. The danger of sea water polluting river and aquifers is a longer term concern and is often ignored by agencies until disaster strikes. However, as climate changes, rainfall levels decrease and potable water shortages are recognized in Australia and in particular, Queensland, more attention has been paid to maintaining the quality of the underground water for an alternative source.

River cities close to coasts tend to be influenced by coastal waterways and the tidal influence may extend for many kilometres upland. For example, Gambia River in West Africa has a tidal excursion of 526 km and the Amazon River in Brazil 735 km. The distance tidal salinity penetrates inland depends on the balance between fresh water flow and the tidal influence [1-2]. Whenever the fresh water flow component is reduced by upstream extractions or by low flow conditions, saltwater front migrates upland potentially damaging useable land and polluting [1,3]. Figure 1 and Figure 2 show the results of analysis of recent data collected from the Brisbane river automated water quality monitoring project initiated in 2004. Although given for only two days in here, the data with comparable rainfall levels show that salinity level in the Brisbane river appears to have been increasing over time. The cause of the increase in the salinity may be attributed to a number of factors such as lack of rainfall, low flow conditions, or tidal influence but presently no models exist to investigate the significance of each.

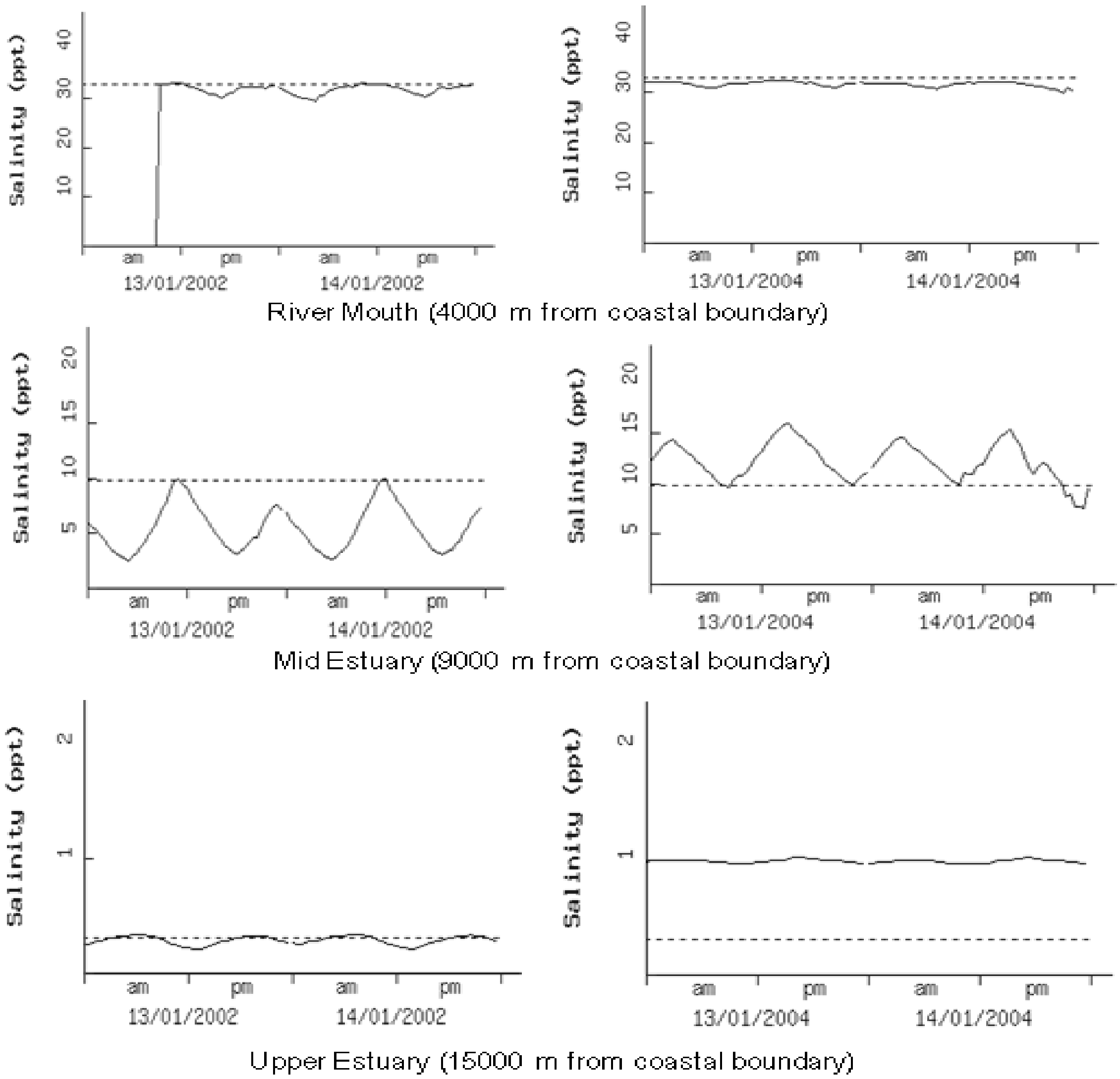

Fig. 1: Salinity levels at different points along the Brisbane River over time

As noted earlier, in a tidal system there is complex water flow dynamics that cause salt to move inland over time. The tidal river allow salt to move back and forth in the coastal waterways and mix with the fresher water flowing from upland out to sea [3]. Depending on levels of flow and recharge, this ongoing intrusion process together with other factors such as irrigation pumping can cause the Brisbane river to retain higher salt loads. This study develops a preliminary 3D finite element computer model using existing datasets to simulate tidal intrusion into the river allowing for groundwater interaction. The model will be used to develop longer term salinity profiles along the river.

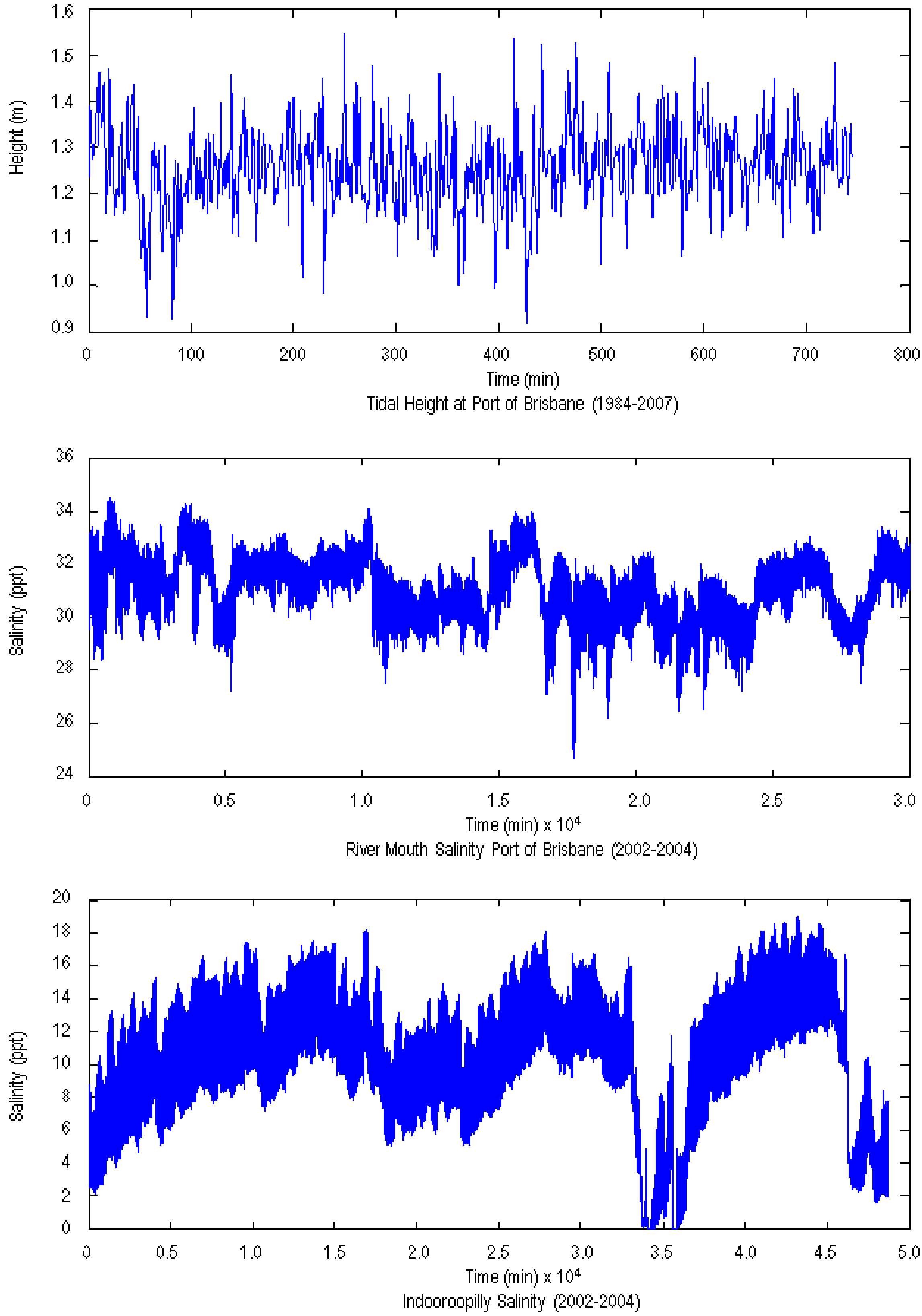

Fig. 2: Tidal Height and Salinity at River Mouth and Indooroopilly (every 15 min)

MATERIALS AND METHODS

Mathematical modelling

A coupled set of mathematical models can be used to represent the transport and flow of fluid and solute in material domains. To model the groundwater, river, creeks and drains all within the same domain, the Richard's equation was used with following definitions: ρ as fluid density (M/L^3), *k* as intrinsic permeability tensor of the media (L^2), μ as dynamic viscosity of the fluid (M/L/T), *p* as fluid pressure ($ML/T^2/L^2$), *g* as acceleration of gravity (L/T^2), *z* as potential head (L), *n* as porosity (L^3/L^3), *S* as degree of saturation (no dimension), V_s as velocity of the deformable material due to consolidation (L/T), ρ^* as density of the injected fluid, *q* as internal source sink ($L^3/T/L^3$) as *t* as time. The flow equation is derived taking into account the continuity of fluid, continuity of solid, consolidation of media, and the equation of state [4]. A 3D model for flow allowing for various aspects is initiated in the following manner:

$$\nabla \cdot [\frac{\rho kg}{\mu} \cdot (\nabla h + \frac{\rho}{\rho_0} \nabla z)] + \frac{\rho^*}{\rho_0} q = \frac{\partial (nS\rho)}{\partial t} = \frac{\rho}{\rho_0}(\beta'\theta + \frac{\theta}{n}\alpha' + n\frac{\partial S}{\partial p})\frac{\partial h}{\partial t} + \frac{\theta}{\rho_0}\frac{\partial \rho}{\partial c}\frac{\partial c}{\partial t} \quad (1)$$

If the apparent storage-coefficient, $F = \beta'\theta + \frac{\theta}{n}\alpha' + n\frac{\partial S}{\partial p}$ is substituted into Equation 1 and if the second term on the right is neglected (see Frind, 1982), the equation simplifies to

$$\frac{\rho}{\rho_0} F \frac{\partial h}{\partial t} = \nabla \cdot [\frac{\rho kg}{\mu} \cdot (\nabla h + \frac{\rho}{\rho_0} \nabla z)] + \frac{\rho^*}{\rho_0} q \; ; \quad (2)$$

and further if $K = \frac{\rho kg}{\mu}$ then the density-dependent flow-equation may be written as

$$\frac{\rho}{\rho_0} F \frac{\partial h}{\partial t} = \nabla \cdot [K \cdot (\nabla h + \frac{\rho}{\rho_0} \nabla z)] + \frac{\rho^*}{\rho_0} q \quad (3)$$

Using the laws of continuity mass material transport equations through groundwater may be determined. Applying the principle of mass balance with *c* and *s* being dissolved and adsorbed concentrations respectively, the following integral form is obtained:

$$\frac{\partial}{\partial t}[\int_v (\theta c + \rho s) dv] = -\int_\tau n.(\theta c V_{fs}) d\tau - \int_\tau n \cdot J d\tau - \int_v \theta K_w c + \rho K_s s) dv + \int_v m dv \quad (4)$$

Ignoring first order decays, the source/sink term, deriving and simplifying gives:

$$\frac{\partial (\theta c + \rho_b s)}{\partial t} = -\nabla \cdot (Vc) + \nabla \cdot (\theta D \cdot \nabla c) \quad (5)$$

In Equations 4 and 5, v is material volume containing constant amount of media (L^3), c is the dissolved concentration (M/L^3), S is the adsorbed concentration (M/M), ρ is the bulk density (M/L^3), τ is the surface enclosing the material volume (L^2), n is the outward unit vector normal to the surface G, V_{fs} is the fluid velocity relative to the solid (L/T), J is the surface flux with respect to fluid velocity, Vfs ($M/T/L^2$), K_w is the first-order biodegradation rate constant through dissolved phase (1/T), K_s is the first-order biodegradation rate constant through adsorbed phase (1/T), and m is the external source/sink per medium volume ($M/L^3/T$), and D is the dispersion coefficient tensor.

The above coupled flow and solute transport equations can be solved using the finite element Femwater code, which can simulate density dependent flow and transport in variably saturated media [4]. The finite element mesh can be constructed using the code allowing for the model domain and boundary conditions. The model domain is relatively simply as it is of coastal lowland geology. The sides of the domain are considered no flow boundary cases where the flow is taken to be parallel the outward coastal flow. The sea coastal boundary is fixed head with concentration of salinity kept at seawater concentration; while the upland fresher water boundary is also a fixed head boundary with no solute flows. Time dependent head can be used at the upland boundary. A river runs through the domain and it can be created using the Femwater code within the domain by choosing the stage of the river and providing various river nodes with appropriate field data gained from various agencies such as the Brisbane City Council (BCC) and Department of Natural Resources (DNRM). Figure 3 shows the initial heads and salinity levels in the river used in developing the model.

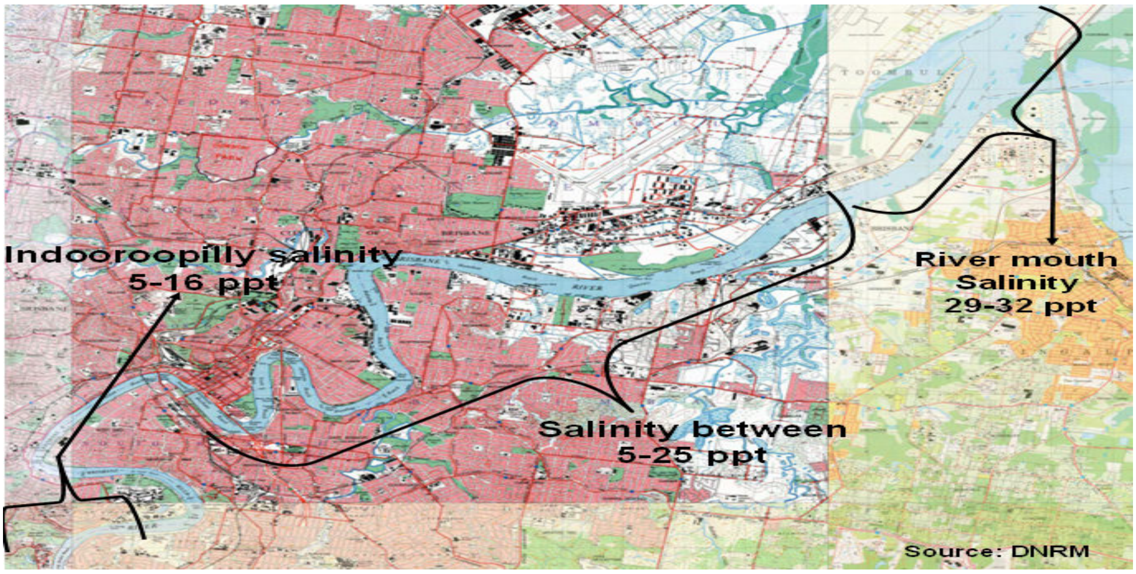

Fig. 3: Initial Brisbane River salinity levels

Using the field data from various boreholes, stratigraphy layer data and water table elevations were imported using the Femwater code to develop firstly, a 2D finite element mesh that is later up-scaled to construct a 3D mesh (see Figure 4). The data sets were provided by the Department of Natural Resources (Department of Natural Resources - Coastal Estuary Management, 2005)[5]. Figure 2 shows the seaward and freshwater boundaries including other hydraulic features such as the positions of river bed and sea coast and so on. The stratigraphy and layers elevation data was also supplied by DNRM [5] and coded in the model. Various regions were identified within the boreholes that are codes within the 3D domain and then each is joined to extrude the 2D projection mesh into 3D mesh (see Figure 4 and 5). The up-scaling within Femwater also allows for adaptive discretisation and significant increasing of the number of finite elements (reducing the aspect ratio) of which Figure 5 is one example.

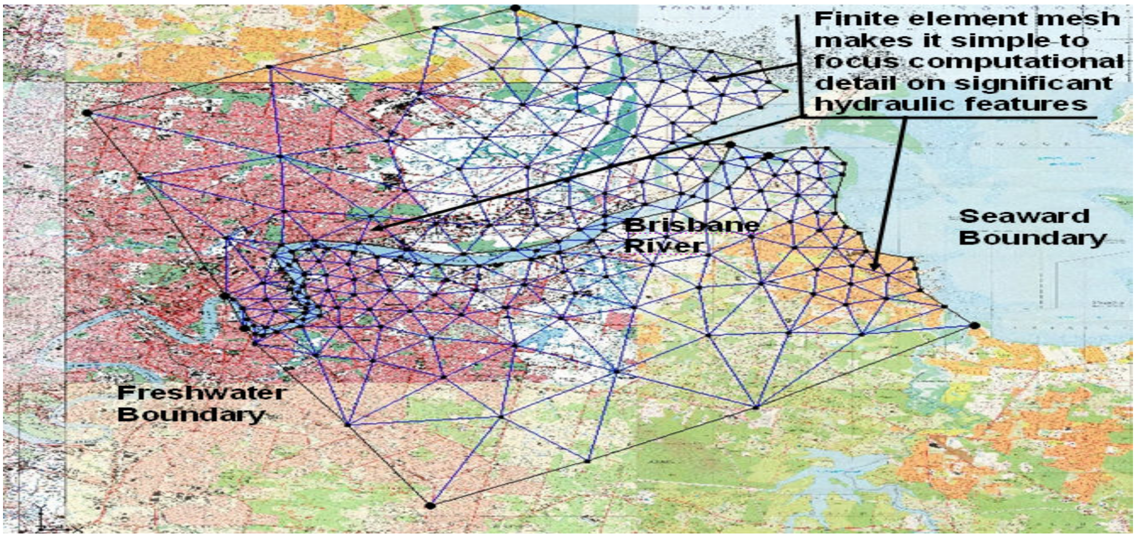

Fig. 4: Two dimensional projection mesh and hydraulic features

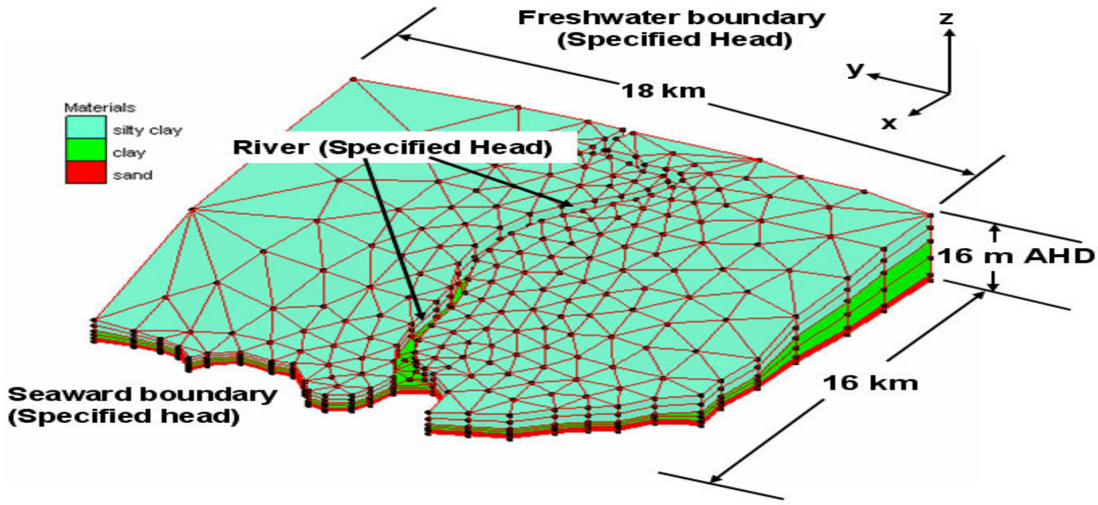

Fig. 5: Three dimensional mesh and model boundaries

Material properties

The parameters used in this study are summarized in the Table 1 [6-7]. The Femwater code requires the input of relationships between concentration with density and viscosity respectively. The relationship used is shown in Equation 6:

$$\frac{\rho}{\rho\circ} = a_1 + a_2C + a_3C^2 + a_4C^3 \text{ and } \frac{\mu}{\mu\circ} = a_5 + a_6C + a_7C^2 + a_8C^3, \quad (6)$$

where, ρ_0, and μ_0 are density and viscosity of freshwater respectively (see Table 1) and C is contaminant concentration. The concentration dependent coefficients from a_1 to a_8 are parameters used to define the dependence of water, density and viscosity. In this study, $a_1 = 1$, $a_2 = 0.001$, $a_5 = 1$ while all other parameters were kept at zero.

Each element in the 3D mesh is assigned a material corresponding to the zone or aquifer in which the element is located. The material soil properties were then identified and coded in the model; such properties included hydraulic conductivity, compressibility, longitudinal and transverse dispersivity, molecular diffusion coefficient, bulk density of the soil, tortuosity, and water retention curves describing how moisture content, relative conductivity, and water capacity vary with pressure head in the unsaturated zone [4]. The density of the soil is specified as a bulk density in units of M/L^3. The bulk density of a soil corresponds to its oven-dried mass divided by its in situ volume. The relationship between dispersion and diffusion coefficients is given in Equation 7:

$$\theta D = a_T |V| \delta + (a_L - a_T)\frac{VV}{|V|} + a_m \theta \tau \delta \quad (7)$$

where a_T is the transverse diffusivity (L), δ is the Kronecker delta tensor, |V| is the magnitude of Darcy velocity V (L/T), a_L is the longitudinal diffusivity (L), a_m is the molecular diffusion coefficient (L^2/T), τ is the tortuosity, θ is the moisture content, and D is the dispersion coefficient tensor. The parameters, $a_{L,}$, a_L, and a_m, are presented in Table 1.

Table 1: Parameters used [6-7]

Parameter	Value
Seawater Concentration, *Cs*	35.7 ppt
Groundwater Concentration, *Co*	0.5 ppt
Freshwater Density, ρ_f	1000 kg m^{-3}
Seawater Density, ρ_s	1020 kg m^{-3}
Hydraulic Conductivity, for Sand Layer, K_s	Variable according to layer, 5, 30, 100 m day^{-1}
Hydraulic Conductivity for Clay Layer, K_c	5-10 m day^{-1}
Hydraulic Conductivity for Silty Clay Layer, K_{sc}	5 m day^{-1}
Longitudinal Dispersivity, a_L	2.5 m
Transverse Dispersivity, a_T	0.5 m
Molecular Diffusivity of Solute, a_m	8.64e-5 m^2 day^{-1}
Viscosity of Water, μ	86.4 kg.m.day^{-1}
Effective Porosity (For Transport Calculations) , ε	
For flow, see next section	0.1-0.4
Tortuosity, τ	0.64
Compressibility of Water, β_w	4.47e^{-10} ms^2kg^{-1}

This 3D finite element model together with the initial and boundary conditions shown in the figures presented were used to simulate various river flow and seawater intrusion scenarios. The model was calibrated using existing field data supplied by DNRM and Brisbane City Council. The existing water table data were used to define the specified head boundary conditions for the river mouth and 25km upland. The solving of the partial differential (Equations 1 and 2) generated the velocity patterns before the transport equation iteratively predicted the movement of salt within the domain allowing for the given conditions. The model was run for a maximum of 50 years for constant time steps of 10 days.

RESULTS AND DISCUSSION

The results show that over a period of some time salinity levels could increase in the river by approximately 2 points and this effect may flow onto the groundwater depending on recharge levels, which are extremely low. Given that the rainfall pattern and recharge level during the period of study was virtually insignificant the results may change if rainfall patterns change. The model shows that if the present level of upland flow continues the results found seem likely in 50 year time frame. Figure 5 and Figure 7 show linear and colour concentration contours produced using the 3D model respectively. The figures show seawater intrusion into model domain via the Brisbane River over time.

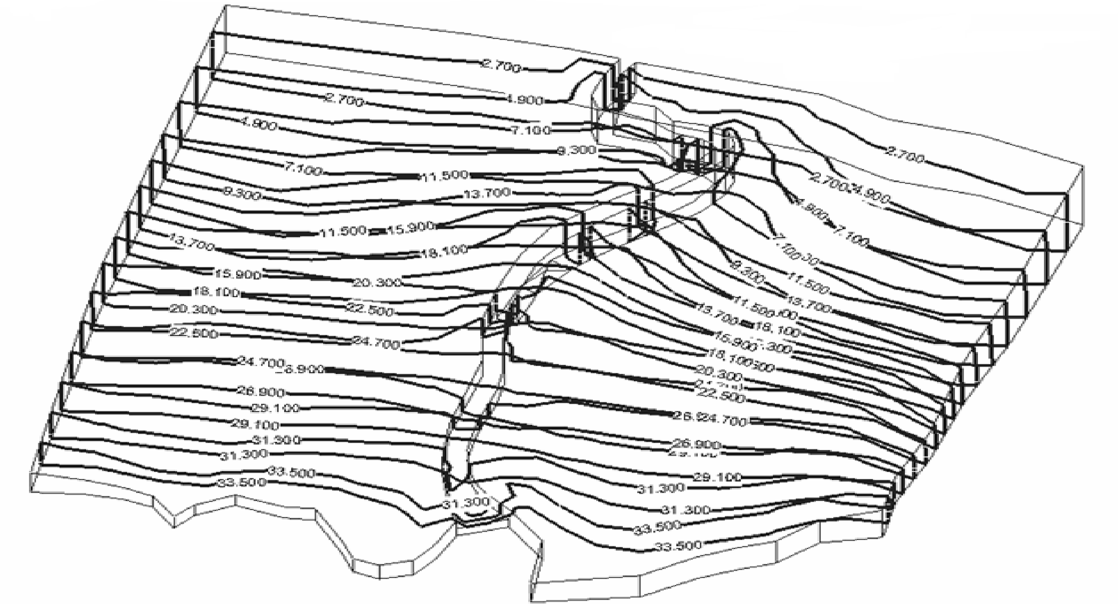

Fig. 6: Concentration contours (ppt) of the Brisbane River area

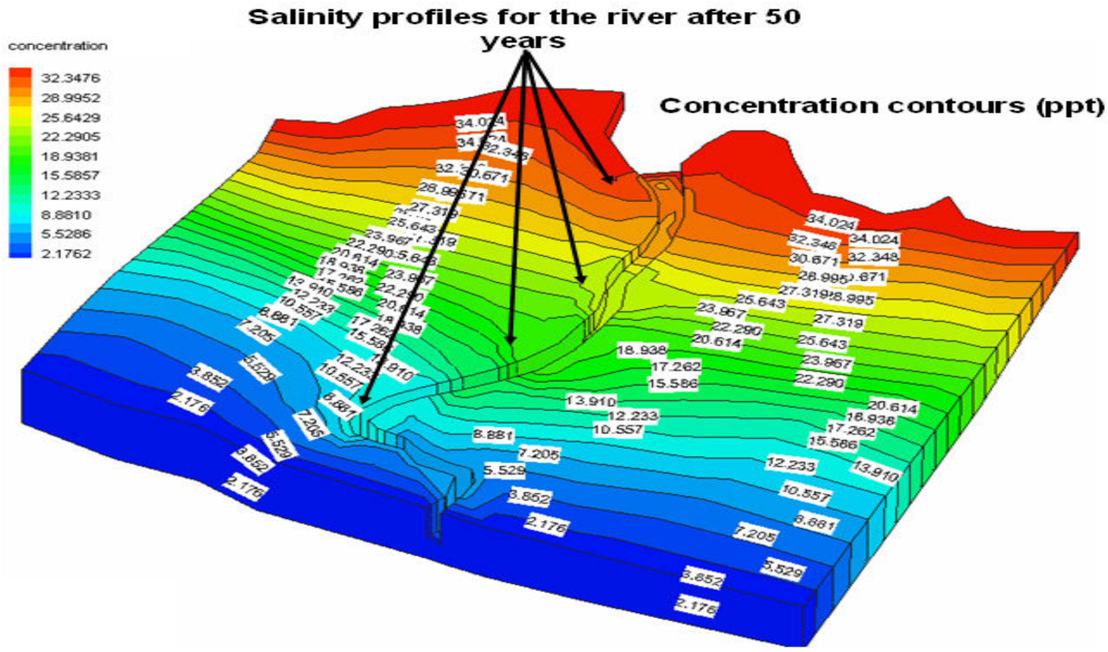

Fig. 7: Salinity concentrations (ppt) after 50 years

Seawater intrusion appears to influence the overall flow dynamics. The subsurface groundwater quality is being influenced in that both figures show curved contours along the river boundary. This effect is noted along the river but the contours straighten moving away from the river boundary. Moreover, salinity levels as high as 17ppt are observed up to 7 kms away from the seawater boundary assuming very low rainfall levels.

Figure 8 shows the concentration contours on a vertical cross section along the Brisbane river boundary. Seawater intrusion is noted more along the river boundary than away from the boundary as expected. Figure 9 shows the seawater intrusion process over time at different nodes away from the coast. Figure 9 shows high seawater intrusion rate during the first 500 to 1000 days and then gradually levelling to a constant value, suggesting a balance between the flow conditions. The rates of intrusion during the first 50 years vary depending upon the position of the nodes. The nodes closer to the seawater boundary exhibit a higher levels of salinity than the nodes situated away from the seawater boundary as expected.

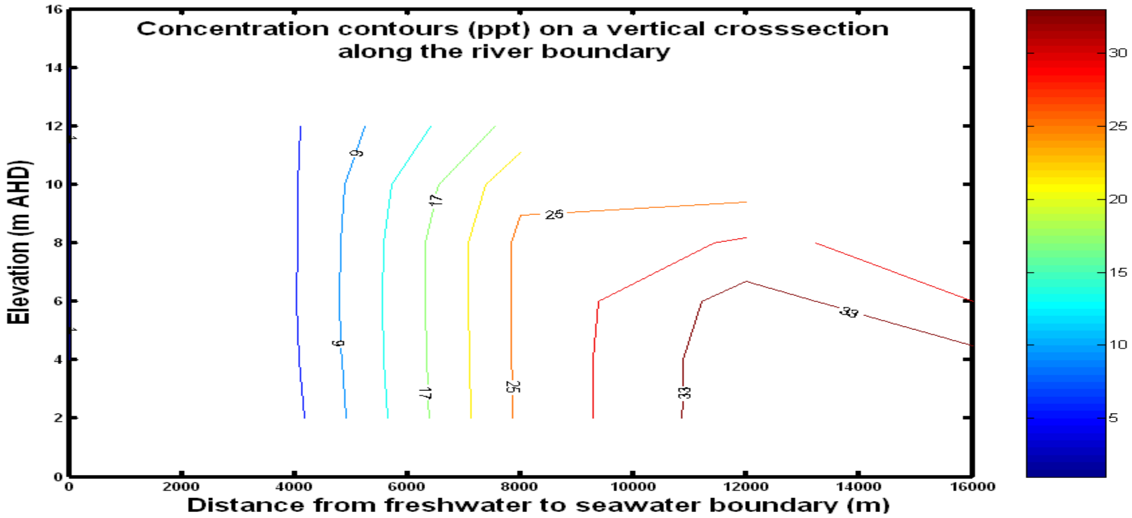

Fig. 8: Salinity (ppt) in a vertical cross-section along the river boundary.

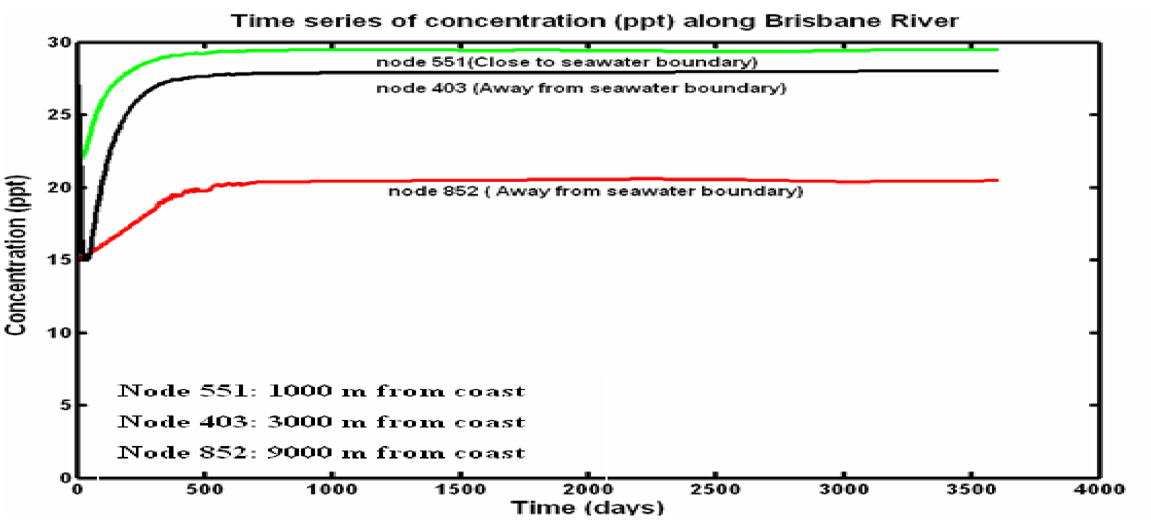

Fig. 9: Time series of concentration (ppt) at different nodes along the river

CONCLUSIONS

An analysis of the current situation of Brisbane River salinity was done using a new 3D model developed and calibrated using data from various agencies. The model of appears to be an accurate description of the dynamics in the domain in that it was able to capture the various factors including the effect of tidal intrusion process. The model simulations and predictions compared well with field data available although validation of the 3D model remains for future work. The river salinity has compounded the seawater intrusion problem close to the river boundary. High salinity levels were noted in groundwater close to the river boundary than the regions away from the river. This study is an important initial contribution on coastal river system dynamics for the new model may be used to study the effects of salt intrusion on river systems and the surrounding groundwater quality in Brisbane. The model may be improved and used to study possible management strategies and the influence of other nutrient loads from the city and agricultural activities.

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