Numerical simulation of groundwater flow and solute transport on a saline floodplain in South Australia using a density dependent model SUTRA


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Abstract

The density dependent groundwater flow and solute transport model SUTRA has been used to investigate stream-aquifer interaction and floodplain processes on a saline floodplain in South Australia. Evapotranspiration and recharge during a flood have been incorporated into the numerical model and a proposed salinity mitigation scheme has been modelled in cross section. Numerical simulations have shown that the creek near the River Murray is relatively fresh and carries substantially less salt compared to the creek in the middle of the floodplain and that salt load to the creeks are strongly dependent on the rising and falling heads in the river and creeks. The peak salt load to the creeks occurs immediately after the flood recession and subsequently declines within a six month period to baseline salt inflow. The effect of pumping on the floodplain has been simulated and sufficient drawdown and salt load reduction can be obtained by using the proposed interception scheme.

1 Introduction

Increases in River Murray salinity of more than 2% per annum have been measured since 1970 at two locations in South Australia. As 50% of South Australia's water supply comes from the River Murray, increases of this magnitude are of considerable public concern. Indeed, one of the largest sources of salt to the river in South Australia is the Chowilla anabranch system. This region is typical of floodplains in the lower reaches of the River Murray in that it is underlain by shallow saline groundwater (2-4 m depth) which can flow into the river. Significant portions of the Chowilla area are of considerable ecological value and the South Australian portion of the Chowilla floodplain has been classified under the UNESCO Ramsar Convention as Wetlands of International Importance, NEC [1].

In order to reduce salt accessions from this region, a salinity mitigation
scheme has been proposed for the Chowilla region by a multidisciplinary working group CWG [2] which takes into account the health of riparian vegetation, effect of pumping on water table to the floodplain and reduction in salt loads to the anabranch system.

Whilst a number of investigations have been carried out on the Chowilla floodplain to estimate discharge, understand recharge processes and water uptake by riparian vegetation, no detailed analysis on salt movement to the creeks has been performed. We have applied a variable density flow and solute transport model SUTRA to simulate stream-aquifer interaction to i) estimate salt loads to the floodplain ii) study the effects of the salinity mitigation scheme and iii) simulate rising and falling heads in the river and creeks.

2 Governing Theory and Equations

The SUTRA model employs a two-dimensional finite element approximation of the governing equations in space and an implicit finite difference approximation in time. For solute transport, two partial differential equations are solved simultaneously, the fluid mass-balance equation and the solute mass-balance equation. A brief description of the governing equations are given below.

2.1 Conservation of mass of fluid:
The fluid mass balance is expressed as:

$$\frac{\partial (\epsilon \rho)}{\partial t} = -\nabla \cdot (\epsilon \rho \mathbf{v}) + Q_p$$

(1)

where $\epsilon(x,y,t)$ is a dimensionless porosity, $\rho(x,y,t)$ is the fluid density, $\mathbf{v}(x,y,t)$ is the average fluid velocity, $Q_p(x,y,t)$ is a fluid mass source, $x$ and $y$ are coordinate variables, $t$ is the time and $\nabla$ the usual gradient operator.

Density is given as a linear function of concentration:

$$\rho = \rho_0 + \frac{\partial \rho}{\partial C} (C - C_0)$$

(2)

where $\rho_0$ is the fluid density at a base concentration $C_0$ and $\partial \rho/\partial C$ is a constant coefficient of density variability.

In quantitative terms the implied coupling between flow and salinity in some confined enclosure requires a form of Darcy’s law that includes both pressure and density forces. With variable fluid density, the fluid flow equation is expressed in terms of the pressure variable since the potential head function does not exist. The pressure gradient form of Darcy’s law gives the mass average fluid velocity at any point in a cross section as:
\[
V = -\left( \frac{k}{\varepsilon \mu} \right) \cdot (\nabla p - \rho g)
\]  

(3)

where \( \rho(x,y,t) \) is the fluid density, \( g \) is the gravity vector, \( \mu \) is fluid dynamic viscosity and \( k(x,y) \) is the intrinsic permeability tensor.

2.2 Conservation of mass of salt:

For a single species stored in solution, the solute mass balance equation may be expressed as:

\[
\frac{\partial (\varepsilon \rho C)}{\partial t} = -\nabla \cdot (\varepsilon \rho \nabla C) + \nabla \cdot [\varepsilon \rho (D_0 I + D) \cdot \nabla C] + Q_p C^* 
\]  

(4)

where \( D_0 \) is the apparent molecular diffusivity in a porous medium of solutes in solution, \( I \) is the dimensionless identity tensor, \( C^* \) is the concentration of the fluid sources expressed as a mass fraction. Bear [3] has formulated the components of the mechanical dispersion tensor \( D \) to account for both transverse and longitudinal dispersivities respectively.

3 Site Description

3.1 The Setting and General Hydrogeology

The Chowilla floodplain is a separate and distinct region of the River Murray system, situated near the junction of the South Australian, Victorian and New South Wales borders. It covers an area of 177 km² and is dissected by more than 100 km of anabranch creeks. Before the installation of lock 6 the floodplain streams were ephemeral and flowed only during times of flood. Since then the River Murray level and saline watertable has risen by approximately two metres and the anabranch creeks now carry a significant portion of the River Murray flow. As a result significant dieback of trees and degradation of the floodplain has occurred.

The relatively impermeable surface clay known as the Coonambidgal Formation is up to 3 m thick and overlies highly saline and unconsolidated alluvial sand deposits known as the Upper and Lower Monoman Formation which consist of fine to coarse grained sands with occasional thin clayey or silty lenses. Beneath the Monoman Formation is an extensive deposit known as the Loxton-Parilla Sands. The aquifer is a unconfined and varies in thickness between 20 m and 25 m. Underlying the entire region is the Murray group limestone aquifer, which is confined by the Bookpurnong Beds of consolidated shelly sand and clay formation [4].
4 Numerical Modelling

4.1 Spatial Discretisation and Boundary Conditions
A non-uniform finite-element mesh with 1705 nodes and 1620 quadrilateral elements was used to discretise a representative cross section of the Chowilla floodplain aquifer. The mesh extends 6300 m in the horizontal direction and 46 m in the vertical direction. The modelled cross section has an arbitrary thickness of 1 m.

The boundary conditions for the simulation are shown schematically in Fig. 1. The near surface Coonambidgal formation which confines the aquifer is not simulated. A no flow boundary condition is specified along the bottom of the mesh where the Bookpurnong Beds are considered impermeable. A constant head boundary of 19 m is imposed along the northern vertical boundary and on the southern boundary (river end) a constant head boundary of 19.25 m is imposed.

A time dependent boundary condition is employed to simulate the rising and falling heads during the flood by making minor modifications to SUTRA. Three sine functions as shown in Fig. 2 were used to represent the rising river levels of the River Murray, Slaney and Punkah Creek and each function was calibrated by trial and error to represent the 100,000 ML day⁻¹ 1990 flood level.

Evapotranspiration is evenly distributed along the top boundary and recharge due to rainfall is assumed to be negligible. Inflow occurring through the northern specified pressure boundary has the groundwater concentration of
45,000 mgL⁻¹ TDS (c=.045 kg TDS/kg fluid) and from the river end of 350 mgL⁻¹ TDS (C=.0035 kg TDS/kg fluid). Any flow out of the mesh at the specified pressure boundaries occurs at the ambient concentration of the aquifer fluid.

Figure 2 Sinusoidal function used to simulate the rise and fall of river and creek heads for the 1990 flood (peak flow of 100,000 ML day⁻¹)

4.2 Model Parameters
Given in Table 1 are the fixed values used for input into the SUTRA model. Measurements taken at Lake Littra South indicate the hydraulic conductivity of the Upper Monoman Sands to be 10-12 m day⁻¹, EWS [4]. The hydraulic conductivities for the Lower Monoman Sands and the Loxton Parilla Sands are 3-4 m day⁻¹ and 3-6 m day⁻¹ respectively. For simplicity both the Lower Monoman Sands and the Loxton Parilla sand were simulated at the approximate hydraulic conductivity value of 4 m day⁻¹. Based on field measurements the ratio of vertical hydraulic conductivity to horizontal conductivity was taken to be 1:10.

Field scale dispersion has not been measured for the Upper or Lower Monoman sands and thus longitudinal dispersivity has been primarily based on guidelines provided by Voss [5] for proper discretisation. In most cases, to guarantee spatial stability the condition Δₙ ≤ 4αₙ is, must be enforced where Δₙ is the local distance between element sides along a flow line and αₙ is the longitudinal dispersivity. Given the longest dimension in the finite element mesh is 300 m it was considered appropriate to simulate with αₙ=76 m. Transverse dispersivity (αₜ) is normally lower by a factor of 5-20 and so a value of αₜ=5m has been used in our modelling.
Table 1. Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freshwater density ((\rho))</td>
<td>1000 kg m(^{-3})</td>
</tr>
<tr>
<td>Groundwater density ((\rho_{gw}))</td>
<td>1030 kg m(^{-3})</td>
</tr>
<tr>
<td>Fluid viscosity ((\mu))</td>
<td>(10^{-3}) kg (ms)(^{-1})</td>
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<tr>
<td>Coefficient of fluid density change ((\partial \rho / \partial C))</td>
<td>700 kg m(^{-3})</td>
</tr>
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<td>Water compressibility ((\beta))</td>
<td>(4.5 \times 10^{-10}) Pa(^{-1})</td>
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<tr>
<td>Porosity ((\varepsilon))</td>
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<tr>
<td>Molecular diffusivity ((D_0))</td>
<td>(1.5 \times 10^{-9}) m(^2) s(^{-1})</td>
</tr>
<tr>
<td>Evapotranspiration rate ((E))</td>
<td>0.1 mm day(^{-1})</td>
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<tr>
<td>Upper Monoman Sands thickness</td>
<td>6 m</td>
</tr>
<tr>
<td>Lower Monoman Sands thickness</td>
<td>20 m</td>
</tr>
<tr>
<td>Loxton Parilla Sands thickness</td>
<td>20 m</td>
</tr>
<tr>
<td>River Murray depth</td>
<td>11 m</td>
</tr>
<tr>
<td>Slaney Creek depth</td>
<td>6 m</td>
</tr>
<tr>
<td>Punkah Creek depth</td>
<td>6 m</td>
</tr>
<tr>
<td>Distance between interception wells ((L_w))</td>
<td>2000 m</td>
</tr>
<tr>
<td>Pump discharge ((Q_w))</td>
<td>1 ML day(^{-1}) = 11.574 Ls(^{-1})</td>
</tr>
<tr>
<td>Line sink (= Q_0 = Q_w \rho_{gw} L_w^{-1} = 5.9 \times 10^{-3}) kgs(^{-1})</td>
<td></td>
</tr>
</tbody>
</table>

4.3 Evapotranspiration
Evapotranspiration for the area is a function of the depth to the watertable. Given the Coonambidgal Formation of approximate depth 2 m was not modelled, a fixed evaporation rate of 0.1 mm day\(^{-1}\) was chosen which corresponds to a watertable depth of approximately 2 m below the surface.

4.4 The Groundwater Interception Scheme
CWG [2] recommended the installation of 15 tubewells. Each tubewell is expected to pump at approximately 1 ML day\(^{-1}\), giving a total pumping rate of 15 ML day\(^{-1}\) for the Chowilla region. The Murray-Darling Basin Commission provide full details of the proposal. Simulation of the tubewells in the SUTRA model could only be achieved by replacing the wells with a line sink of equivalent magnitude to the well discharge divided by the longitudinal extent of the influence of the well. Two wells were simulated in the two dimensional cross sectional model to draw water over a 26 m length, starting 7 m below the surface.

4.5 Initial Conditions
In order to produce concentration and pressure gradients which preserve numerical stability for the transient runs, a steady state simulation was run to synthesise conditions before lock 6 was built. The boundary conditions for this simulation had the River Murray head at 17m and a concentration of 350 mgL\(^{-1}\) and a constant head boundary of 19.0 m at the northern end with a concentration of 45,000 mgL\(^{-1}\). Both Slaney and Punkah Creeks were not
simulated as the floodplain creeks flowed only during times of flood. Using the results of this simulation, the River Murray head was then raised to its present pool level of 19.25m, Slaney and Punkah at 17.5 m and 17.2 m respectively and simulated for the locks existence of 60 years to provide initial conditions for the proceeding simulated scenarios.

5 Modelling Results and Discussion

Two categories of simulations were conducted based on likely physical scenarios. The first category studied the stream-aquifer system over a 10 year period in which no flooding occurred. For these scenarios we simulated the system a) without a groundwater interception scheme and b) with the operation of the groundwater interception scheme. The second category of simulations incorporated a 150 day flooding scenario and studied the stream-aquifer interaction over a 2.5 year period. For these flooding scenarios the system was simulated a) without a groundwater interception scheme, b) with a groundwater interception scheme and various management options and c) to produce a sensitivity analysis of the flooding event. Peak salt loads occur under the flooding situation and as such only flooding scenarios are detailed here.

5.1 No Interception Scheme

This flooding scenario modelled the 1990 (100,000 ML day\(^{-1}\)) flood that extended for 150 days with a peak River Murray level of 20.4 m. The flooding simulation continued with initial conditions from simulations which employed no flooding and was modelled initially with no interception scheme in place to simulate the present day conditions. From the hydraulic head profile at the flood peak (Fig. 3), the increased head in the River Murray and creeks has forced the flow back towards the edge of the floodplain and towards the 2200m mark, where the freshwater front is located. From the concentration profile (Fig. 4) there has been no flushing beneath the surface of the floodplain and slightly further flushing around Punkah Creek in comparison with that of no flood modelling. From the hydraulic head profile (Fig. 5) immediately following the flood recession, most of the flow is towards Punkah Creek. This is complemented by the increase in salt load in Punkah Creek of approximately five times that of the computed base salt load (Fig. 6). The salt load also increases in Slaney Creek, but the effects are reduced with salt loads increasing by three fold (Fig. 6). From the graph it can be seen that following the flood, Punkah Creek and Slaney Creek (not shown) salt loads return to their base loads within six months and three months respectively which is in reasonable agreement with the available field data.
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Figure 3 Equivalent freshwater head profile at peak of flood

Figure 4 Concentration profile at the recession of flood

Figure 5 Equivalent freshwater head profile at the recession of flood

Figure 6 Effect of flooding on salt load to Punkah Creek

5.2 Interception Scheme
The next set of simulations model two options for the management of the
pumping scheme: i) pumping before the flood and ii) pumping before and after the flood recession.
(1) Pumping prior to the flood had no effect on the concentration profile and no flushing beneath the floodplain was predicted. The peak salt load is reduced by approximately 35% in Punkah Creek and no change was predicted in Slaney Creek. The salt load in Punkah Creek continues to decline after the flood to about half of the baseline salt load. Approximately 2.5 years after the flood recession, the salt load gradually starts to return slowly to the baseline salt load. Slaney Creeks salt load remains unaffected with the salt load constant at baseline.
(2) Pumping after the flood event produced results similar to the first scenario. Salt loads in Punkah Creek increased to 96 tons day$^{-1}$ and Slaney Creek to 1.5 tons day$^{-1}$. However pumping immediately after the flood event reduces the salt load by full interception of salt within one month as can be seen in Fig. 7.

![Comparison of pumping scenarios with that of no pumping for Punkah creek](image)

5.3 Sensitivity Analysis
A sensitivity analysis was performed on various model parameters including storativity, hydraulic conductivity and recharge during a flood. With increased storativity salt load was seen to rise substantially and the delivery time is prolonged before returning to baseline salt inflow. Changing the ratio between vertical and horizontal hydraulic conductivity had no effect on salt inflow, the concentration profiles or equivalent freshwater head profiles. An increase in recharge (diffuse and local) led to higher the salt loads to the creeks, the details of which are given in Charlesworth and Narayan [6].

6 Conclusions

Using SUTRA, a U.S. Geological Survey numerical model for density dependent groundwater flow, it has been shown that computed salt loads for non-flooding and flooding to creeks are in good agreement with available field data. The simulation of the groundwater interception scheme for non-flooding conditions predicted that nearly full interception of the salt load entering Punkah Creek can be achieved and that 80% interception can be achieved in
Slaney Creek. The predicted salt inflow during a flooding event can be significantly reduced by up to one third of the computed peak salt load provided pumping before the flood event occurs. Continued pumping after the flood recession reduces the salt load into the creeks within one month to maximum interception possible. Model simulations have shown that a drawdown of \(~1.5\) m may be obtained at well sites. As with all interception schemes however, the degree of drawdown and interception will vary along the line of the interception. The numerical model has indicated that there will be freshening around the creeks and some further flushing at the saline/freshwater interface. Freshening at the surface of the floodplain is not evident.

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**References**


