Sustainability Of Groundwater Extraction For The Pimpama Coastal-Plain, Queensland, Australia

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EXTENDED ABSTRACT

This paper presents results for field scale seawater intrusion simulations along the Pimpama coastal-plain using SALTFLOW. The simulations incorporated groundwater extraction and sea-level-rise, along with a sensitivity analysis for three physical forcings. The three physical forcings studied in the sensitivity analysis included variations in; freshwater inflow, sea-level-rise and groundwater extraction.

The field site selected to perform the field scale seawater intrusion simulations was the Pimpama coastal-plain, which is located between Brisbane and the Gold Coast in South-East Queensland (see Figure 1). The region is undergoing significant population growth and is an area of hydrological interest, since groundwater extraction is relied upon to provide water for domestic and agricultural supply. In addition to land use change, further stresses will be placed upon the Pimpama aquifer due to a predicted sea-level rise, whilst population growth should lead to a concomitant rise in groundwater extraction. Whether the extraction of groundwater from the Pimpama aquifer is sustainable for meeting future water use needs is a significant resource supply problem and as yet no attempt has been made to assess the sustainability of groundwater extraction in this area. Thus, the simulations performed in this study represent the first attempt to assess the sustainability of groundwater extraction for the Pimpama coastal-plain, in light of the stresses of sea-level-rise, and a potential seawater intrusion.

The SALTFLOW package was selected for the simulation of seawater intrusion for the Pimpama coastal-plain. Preliminary work tested the computational, physical and other modeling attributes for a suite of packages, as well as the performance of each package against benchmark problems from the literature. Ultimately, the SALTFLOW package was selected over PDE2D and SUTRA due to the ease with which time varying boundary conditions for groundwater flow could be incorporated into the model.

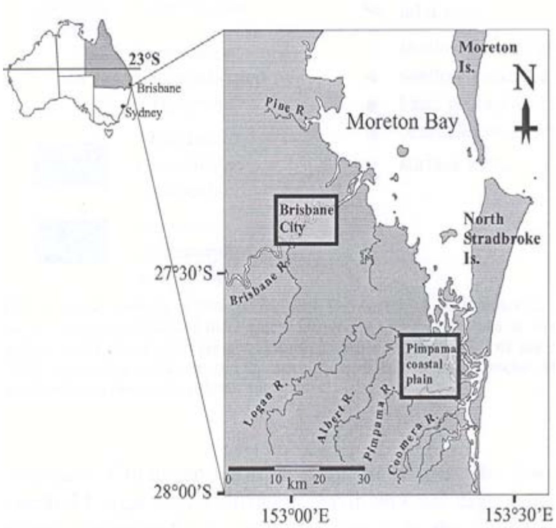

Figure 1. An illustration of the field site considered in this study.

Use of time varying boundary conditions for groundwater flow enabled the effect of sea-level-rise to be incorporated into the model. The model also considered the effect of groundwater extraction on future groundwater Chloride concentrations for the Pimpama coastal-plain. The field scale simulations suggest that a serious seawater intrusion is predicted to occur near the coastal boundary of the Pimpama coastal-plain over the next twenty years.

1. INTRODUCTION

Seawater intrusion is a naturally occurring phenomenon that involves the influx of seawater from the ocean into the fresher water of an aquifer (Oude Essink, 2001a). Globally, the problem of seawater intrusion is extensive and has been documented in many countries around the world (Ghassemi *et al.*, 1990). The influx of saline water from the ocean into aquifers is known to be exacerbated by groundwater extraction and sea-level-rise due to global warming, with both of these processes being caused by human activities (Oude Essink, 2001b). Seawater intrusion thus represents a significant threat to fresh groundwater resources.

Simulation is a useful tool in the management of groundwater resources since it can predict a future seawater intrusion (based on current hydrological practices) and can also enable the effect of remedial and preventative measures to be assessed (Ghassemi *et al*., 1997). Simulation of groundwater systems is of environmental importance since it ultimately plays a part in the development of sound water use policy that seeks a compromise between the preservation of water resources and also their utilisation (Frind, 1982).

As part of this research, it is hypothesised that due to the mechanism of seawater intrusion, groundwater Chloride concentrations will increase throughout the Pimpama coastal-plain over the coming decades. It is also hypothesised that the intrusion of seawater will be further exacerbated by groundwater extraction and sea-level-rise. Through the simulations performed in this paper, the aim was to explicitly test the above-mentioned hypotheses related to groundwater Chloride dynamics for the Pimpama coastal-plain.

2. METHODOLOGY

2.1. The studied transect

A one-dimensional 9.84 *km* transect spanning from Gilberton at the left-hand boundary to Cabbage Tree Point at the seawater boundary was investigated. The approximate location of the studied transect was from the South-West to the North-East of the Pimpama coastal-plain as illustrated in Figure 1.

A problem arose due to the lack of data near the coastal boundary of the above mentioned transect. Data sufficient for a seawater intrusion simulation was available up to the last borehole which was located approximately 1.3 *km* South-Westward of the coastal boundary. As a result, information from the borehole closest to the coastal boundary had to be extrapolated out to the coast so that the simulations could be performed. Moreover, performing this extrapolation simplifies the development of seawater boundary conditions, since a seawater concentration can be applied for Chloride.

At the borehole closest to the seawater boundary, the depth from the soil surface to the underlying and impermeable Neranleigh-Fernvale bed was approximately 22.9 *m* (Harbison and Cox, 2002a). The aquifer depth at this borehole has consequently been used to formulate the seawater boundary condition for groundwater flow in the absence of stratigraphical data at the seawater boundary.

2.2. Model parameterisation

Table 1 provides the hydrological and geological parameter values used in SALTFLOW (Molson and Frind, 2002) to perform a basic seawater intrusion simulation (for the transport of Chloride ions) along the Pimpama coastal-plain.

Table 1. Hydrological and geological parameter values used in SALTFLOW for a basic seawater intrusion simulation for the Pimpama coastal-plain.

Parameter	*Value*
Hydraulic conductivity	5.32×10^{-6} ms^{-1} (Harbison and Cox, 2002b)
Molecular diffusion co-efficient	10^{-9} m^2s^{-1} (Oude Essink, 2001b)
Porosity	0.54 (Rassam and Cook, 2002)
Fluid density change co-efficient	0.0245 (Molson and Frind, 2002)
Longitudinal dispersivity	0.1 *m* (Rassam and Cook, 2002)
Specific storage	10^{-4} m^{-1} (Harbison and Cox, 2002b)

Table 1 shows that a homogeneous parameterisation was assumed for hydraulic conductivity and porosity along the transect. This assumption was made despite data that suggested that three hydraulic conductivities and two porosities had been measured (and consequently could have been used) along the transect (Harbison and Cox, 2002b).

It should be noted that the SALTFLOW model requires the hydraulic conductivity to be kept constant along the top layer of the finite element mesh, to ensure that a convergent flow solution is obtained (Molson and Frind, 2002). Since a one-dimensional seawater intrusion model was developed, hydraulic conductivity must be held constant along this layer. For this reason, a heterogeneous parameterisation for hydraulic conductivity could not be explored.

At the time of performing the simulations, a version of SALTFLOW that permitted a heterogeneous parameterisation for porosity was not available. At the time of writing, it should be mentioned that a version of SALTFLOW exists that permits a heterogeneous parameterisation for porosity.

Once the assumption of parametric homogeneity was invoked, the median hydraulic conductivity and higher porosity value were selected so that model parameterisation was consistent with other physical parameters (like specific storage) measured near the left-hand boundary of the transect.

The spatial discretisation along the transect for all simulations contained 10 000 hexahedral finite elements, whilst a time step of 2.5 days was employed. The length of each simulation was 7300 days, consisting of 2920 numerical time steps.

2.3. Model boundary and initial conditions

The SALTFLOW numerical model involves a coupled system of partial differential equations. One equation describes the dynamics of groundwater flow, whilst the other equation describes the dynamics of solute transport. Consequently, a pair of boundary and initial conditions were required, one for fluid, and the other for solute. Figure 2 displays a schematic representation of the initial and boundary conditions employed by the SALTFLOW model for the simulation of seawater intrusion along the Pimpama coastal-plain.

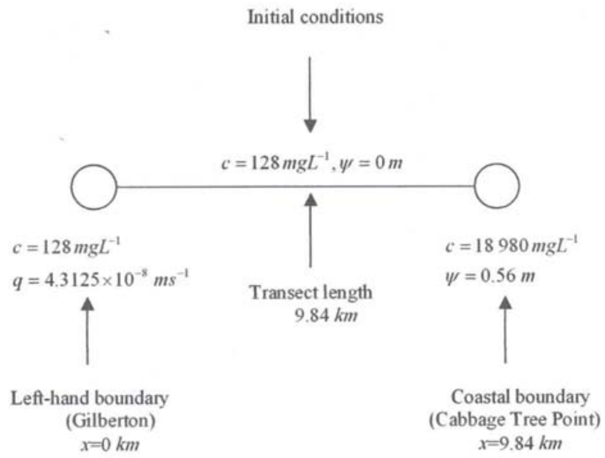

Figure 2. A schematic representation of the boundary and initial conditions employed.

A Dirichlet solute boundary condition was employed at both the left-hand and coastal boundaries. . The model seawater boundary employs the Chloride concentration specified by Reilly and Goodman (1985) of c=18 980 mgL^{-1}.

Field measurements were made on the 17th February 1998 at a borehole located approximately 400 *m* eastward of the model left-hand boundary. These measurements estimated the Chloride concentration to be 128 mgL^{-1} at a depth between 50 *cm* and 60 *cm* in the soil horizon (Manders *et al.*, 2002). In addition, the soil Chloride concentration measured by Manders *et al.* (2002) lies approximately at the level of the Australian Height Datum (*i.e.* AHD), which is the assumed level of the water-table for the one-dimensional seawater intrusion model. This soil Chloride concentration measurement has been used to represent the groundwater Chloride concentration for the model left-hand boundary at Gilberton. Whilst the location of this borehole does not agree completely with the left-hand boundary of the model, this is the best available information for establishing the solute boundary condition at Gilberton.

Manders *et al.* (2002) measured several Chloride concentrations along the transect considered in this study, however, the measured Chloride concentrations were not made on the same day. Thus it would not be logical to use an initial condition for Chloride that was measured after the model left-hand boundary Chloride concentration. For this reason, the initial condition for solute has also been set to 128 mgL^{-1} along the transect.

For groundwater flow, a Dirichlet boundary condition (*i.e.* describing a stationary body of seawater) was employed at the seawater boundary, whilst a Neumann boundary condition was employed at the left-hand boundary. In the absence of more complete information, the stratigraphy of the nearest borehole to the seawater boundary was used to estimate the seawater boundary head. The fixed saltwater head ψ used for simulations (not incorporating sea-level-rise) was 0.56 *m*. This value was obtained by multiplying the aquifer depth at the nearest borehole to the seawater boundary (*i.e.* 22.9 *m*) by the fluid density change co-efficient (*i.e.* γ=0.0245). This calculation was based on Molson and Frind's (2002) implementation of Dirichlet boundary conditions for describing a stationary body of seawater. For simulations incorporating sea-level-rise, the saltwater head ψ was incremented linearly by 9.8 *cm* over the twenty year simulation period.

A Neumann boundary condition for groundwater flow was employed at the model left-hand boundary, and this was in the form of a fixed freshwater inflow due to rainfall. Average annual rainfall at the Oxenford meteorological station (the closest such station) is 1360 $mmyear^{-1}$ (Rassam *et al.*, 2002), which leads to a freshwater inflow of $q=4.3125\times10^{-8}$ ms^{-1}.

A hydrostatic initial condition was employed for groundwater flow, meaning that the initial freshwater head was ψ=0 metres throughout the transect. This value was selected for the initial freshwater head, since freshwater heads measured by Harbison and Cox (2002b) were close to zero metres.

It must be emphasised that the basic seawater intrusion model for the Pimpama coastal floodplain incorporated sea-level-rise, along with groundwater extraction (*i.e.* 0.05 Ls^{-1} over nineteen extraction wells).

It should be noted all simulations started on the 17th February 1998 and ended on the 12th February 2018 (*i.e.* taking leap years into consideration). The start date for all simulations corresponds to the date for which the Chloride concentration at the model left-hand boundary was measured.

2.4. Model forcings

In addition to the basic simulation for seawater intrusion for the Pimpama coastal floodplain, a sensitivity analysis was performed in this study. The sensitivity measure employed was the concentration solution at the last time step (*i.e.* t=7300 days) at an observation well 49.2 *m* landward of the seawater boundary. The physical forcings explored in the sensitivity analysis were variations in; groundwater extraction rates, sea-level-rise, and freshwater inflow.

A high (*i.e.* 0.5 Ls^{-1}) and low rate (*i.e.* 0.05 Ls^{-1}) of groundwater extraction was investigated. A total of nineteen equally spaced (*i.e.* 492 *m* apart) pumping wells were distributed throughout the transect. The number of pumping wells distributed throughout the aquifer was an estimate of current use. Since groundwater extraction is known to occur for agricultural and domestic supply throughout the transect (Harbison and Cox, 2002a), this makes the assumed number of pumping wells slightly more informed.

According to Oude Essink (2001b), the sea-level-rise estimate for the coming century is 0.49 *m*, with an uncertainty in the range of 0.20 to 0.86 *m*. Two sea-level-rise scenarios were investigated in the sensitivity analysis. One scenario involved a sea-level-rise of 9.8 *cm* over the twenty years after the simulation start, whilst the other scenario did not incorporate sea-level-rise into the SALTFLOW model.

Three freshwater inflow rates (Q) were explored in total. The default rate of freshwater inflow used was $q=4.3125\times10^{-8}$ ms^{-1} (MEDIUM Q), whilst values of 50% (LOW Q) and 200% (HIGH Q) of the default freshwater inflow value were explored.

For a given rate of freshwater inflow, four sensitivity runs were performed. The four runs considered were:

> 1,2: simulations incorporating sea-level-rise (SLR) and high (H PUMP) (and low) (L PUMP) groundwater extraction,
>
> 3,4: simulations not incorporating sea-level-rise (NO SLR) with high (and low) groundwater extraction,

In total, twelve sensitivity runs were performed, since four groundwater extraction and sea-level-rise scenarios were investigated for each of the three freshwater inflows.

3. RESULTS

Figure 3 displays a breakthrough curve for an observation well located 49.2 metres landward of the seawater boundary. A monotonic increase in the groundwater Chloride concentration at the observation well can be observed. Over the simulation period (*i.e.* twenty years), the groundwater Chloride concentration increased from 128 mgL^{-1} to approximately 16 000 mgL^{-1}.

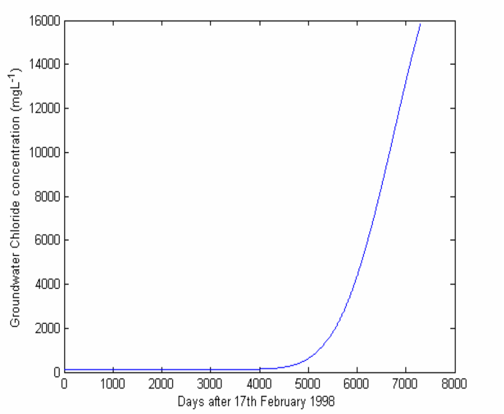

Figure 3. Breakthrough curve for an observation well 49.2 metres landward of the seawater boundary.

The approximate time at which seawater migrates through to the observation well can also be established from Figure 3. After approximately 4500 days, Chloride emanating from the ocean reaches the observation well near the seawater boundary.

Despite the short simulation time, a significant increase in groundwater Chloride concentration can be observed at the observation well near the seawater boundary. If the groundwater extracted from this well were to be used for domestic supply, the groundwater would no longer be potable by the end of the simulation period (*i.e.* twenty years).

According to the National Health and Medical Research Council (NHMRC, 1996), potable water for human consumption must contain a maximum Chloride ion concentration of 250 mgL^{-1}. As can be seen from Figure 3, the concentration threshold specified by the NHMRC (1996) was exceeded by a factor of over sixty.

The sensitivity of the model output at an observation well located 49.2 metres landward of the seawater boundary was explored for various physical forcings after 7300 days (see Figure 4).

From Figure 4 it can be observed that the four breakthrough curves display a monotonic increase in groundwater Chloride concentration. Additionally, the four breakthrough curves depicted in Figure 4 are not near steady-state, since the groundwater Chloride concentrations are still rising rapidly.

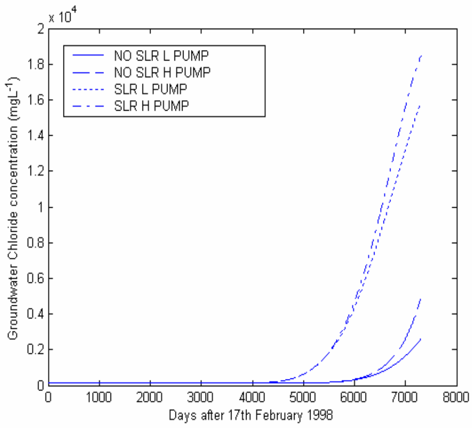

Figure 4. Breakthrough curves for an observation well 49.2 metres landward of the seawater boundary for various physical forcings.

It can be observed from Figure 4 that a combination of sea-level rise (SLR) and high groundwater extraction (H PUMP) leads to the highest groundwater Chloride concentration (*i.e.* just over 18 000 mgL^{-1}) at the observation well after 7300 days. Alternatively, the forcing combination of no sea-level-rise (NO SLR) and low groundwater extraction (L PUMP) results in the lowest groundwater Chloride concentration at the observation well after 7300 days (*i.e.* just over 2 000 mgL^{-1}).

The largest change in groundwater Chloride concentration at the observation well was due to perturbations in sea-level-rise, followed by groundwater extraction, whilst perturbations of freshwater inflow did not change the groundwater Chloride concentration. For this reason, only four of the twelve sensitivity runs have been displayed in Figure 4, since perturbations in freshwater inflow did not change the groundwater Chloride concentration for fixed sea-level-rise and groundwater extraction.

4. DISCUSSION AND CONCLUSIONS

The sensitivity results showed that the groundwater Chloride concentration measured at the observation well after 7300 days was insensitive to freshwater inflow. It is proposed that the insensitivity of the model output to the rate of freshwater inflow for the Pimpama coastal floodplain was due to the rate of freshwater inflow not being high enough for water to migrate from the model left-hand boundary to the observation well located near the seawater boundary over the twenty-year simulation period.

The results show that sea-level-rise has a significant impact on the intrusion of seawater into an aquifer. Oude Essink (2001a) discussed the impact of sea-level-rise on the intrusion of seawater, and concluded that the mechanism of sea-level-rise would be overshadowed by groundwater extraction in terms of its ability to increase groundwater solute concentrations. Oude Essink (2001a) neglected to mention that for aquifers with a relatively small groundwater yield (like the Pimpama coastal-plain), sea-level-rise is more important in governing the intrusion of seawater than groundwater extraction.

The model output was shown to be moderately sensitive to groundwater extraction. This was not an expected result, since groundwater extraction is limited throughout the Pimpama coastal floodplain (Harbison and Cox, 2002a). According to Harbison and Cox (2002a) the maximum rate at which groundwater can be pumped from estuarine deposits (like those found in the Pimpama coastal-plain) is 1 Ls^{-1} per pumping well. This result is suggestive of the sensitivity of an aquifer to even small rates of groundwater extraction.

Each of the breakthrough curves for the different sensitivity runs were not near steady-state. It is proposed that the absence of a steady-state solution for the breakthrough curves was due to the imposition of stresses on the aquifer. For the sea-level-rise sensitivity runs, the seawater boundary condition for groundwater flow is time varying, which would make obtaining a steady-state solution impossible. Similarly, each sensitivity run incorporates groundwater extraction, for which a steady-state solution is not possible if a critical rate of groundwater extraction is exceeded (Dagan and Bear, 1968). It is likely that the critical groundwater extraction rate has been exceeded for the Pimpama coastal-plain.

A very fine spatial and temporal discretisation was required to overcome the problem of the preconditioned conjugate gradient method incorporated into SALTFLOW breaking down. The pre-conditioned conjugate gradient method is an iterative technique for solving algebraic systems that requires the corresponding matrix to be positive definite. For some model parameterisations, diagonal elements of the matrix system become negative and the method breaks down. A big disadvantage of the SALTFLOW package is that it only contains one algebraic system solver, namely, the pre-conditioned conjugate gradient method. The absence of an alternative algebraic system solver means that a solution can not be found for problems where matrix symmetry is violated during iterative solution of the transport and flow matrices. This problem could be rectified by supplying the SALTFLOW user with an iterative matrix solver that provides solutions for both symmetric and non-symmetric matrices. Thus when the pre-conditioned conjugate gradient method breaks down, the matrix solver could then switch to a Jacobi or Gauss-Seidel iterative scheme for example.

From the graphical sensitivity results presented in Figure 4 we can conclude that the model output was very sensitive to sea-level-rise, moderately sensitive to groundwater extraction and insensitive to freshwater inflow. The sensitivity analysis only investigated perturbations of three parameters. Future research could focus on assessing the sensitivity of all model parameters with the use of a formal sensitivity analysis method. Performing this further research would help to better establish the dynamics of seawater intrusion as encapsulated by the SALTFLOW model.

The results of this study suggest that a serious seawater intrusion is predicted to occur near the seawater boundary of the Pimpama aquifer over the next twenty years. The extraction of groundwater from this aquifer at the current rate is not sustainable and action should be taken to ameliorate the seawater intrusion so that a fresh supply of groundwater is available for future domestic and agricultural supply. Several options for the management of seawater intrusion are outlined in Oude Essink (2001a), such as freshwater injection and the construction of physical barriers. Based on the options available for seawater intrusion mitigation, and economic yet effective management plan needs to be established to ensure that a potable supply of groundwater is available in the Pimpama area well into the future.

Future research could however attempt to formulate a more plausible hydrogeological model for the Pimpama coastal plain. This issue could be addressed by constructing a model that takes in account parametric heterogeneity for hydraulic conductivity and porosity, as well as including more spatial dimensions to the model. Performing this further research would lead to simulations that better represent seawater intrusion dynamics along the Pimpama coastal-plain.

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