# On Boundary Conditions for Seawater Intrusion Modelling at Gooburrum, Bundaberg, Queensland

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**Abstract** Extensive groundwater withdrawal has resulted in a severe seawater intrusion problem in the Gooburrum aquifers at Bundaberg. Numerical models are being used to predict the salt front movement for management purposes. As a basis for this study it is necessary to identify the most likely freshwater-saltwater interface situations that existed prior to the commencement of groundwater extraction in the Gooburrum area. This requires a determination of the appropriate boundary conditions and the predevelopment position of saltwater diffusion zone. A two-dimensional (2D) variable density numerical model (2DFEMFAT) was used as the first step of numerical simulations. The model was tested against the Elder free convection problem and against an experimental result for a steady state freshwater-saltwater interface before applying it to the field case. Numerical simulations show that seawater intrusion in the lower Gooburrum aquifer is sensitive to the seaward boundary conditions applied. The imposition of equivalent hydrostatic freshwater heads at the vertical seaward boundary may not reflect the real predevelopment situation in the Gooburrum aquifer system, where a tight aquitard is present. Seawater intrusion is overestimated using this boundary condition, while an impermeable seaward boundary produces reasonable agreement with limited field data.

## 1. INTRODUCTION

Bundaberg is located on the coast of Queensland, Australia. Groundwater is the major source of water used for urban water supply, irrigation and industrial purposes. Extensive groundwater withdrawal for agricultural purposes has resulted in a severe seawater intrusion problem in the Gooburrum area north of Bundaberg shown as the shaded area in Figure 1. In 1994 it was estimated that this intrusion had affected some 11,600 hectares of agricultural land [Dempster, 1998] and it has since been assessed that the interface is still moving at about 100 m per year in some permeable channels with 450 hectares of land lost in 1995 [Bajracharya et al., 1998]. Numerical models are employed to simulate the Gooburrum groundwater system to assist in developing management strategies.

The objective of this study is to identify the most likely seaward boundary conditions for numerical modelling and the freshwater-saltwater situation that existed prior to the commencement of groundwater extraction in the Gooburrum area. A fully three-dimensional (3D) model can not be justified at least initially because of lack of detail on aquifer parameters and uncertainties in boundary conditions. A two-dimensional (2D) variable density numerical model was used in this study. By using a relatively inexpensive 2D model, the influences of different potential boundary conditions can be assessed. A better understanding of the response of the groundwater system to different boundary conditions will help to construct a realistic 3D conceptual model if sufficient data become available.

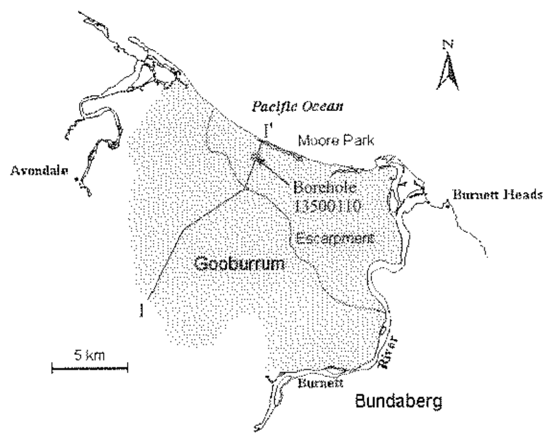



Figure 1. Plan view of Gooburrum area.

## 2. NUMERICAL MODEL AND VERIFICATION

The computer model 2DFEMFAT [Yeh et al., 1994] was chosen as a numerical simulator in this study. This is a saturated-unsaturated model. It employs the Galerkin finite element method to solve the equation for density-dependent groundwater flow, while for the transport equation, the hybrid Lagrangian-Eulerian approach is used. Details of the model can be found in Yeh et al. [1994] and Cheng et al. [1998].

The computer model was tested using the Henry seawater intrusion problem [Cheng et al., 1998].

However, the Henry seawater intrusion problem is a verification only for simulation of highly dispersed transition zones due to the large dispersion coefficient defined [Voss and Souza, 1987]. It does not check whether a model accounts for the density-driven flow accurately and whether the velocity is consistent. The Elder free convection problem [Elder, 1967] was suggested by Voss and Souza [1987] as a further testing example. The Elder problem can effectively check the ability of a model in simulating water flow driven purely by density differences of up to 20%. A coarse mesh of 44 × 25 elements and a finer mesh of 60 × 32 were used for the Elder problem. Both meshes produced satisfactory results showing a central upwelling (results not shown), which matches Elder's experimental result [Elder, 1967]. This implies that the computer code is not mesh-resolution sensitive. It can simulate the density-dependent flow mechanism and can generate a consistent velocity solution.

Furthermore, the model was also verified against our experimental result. This is to test the ability of the model to produce a narrow diffusion zone. Figure 2 shows a steady state saltwater interface (CD) in a two-dimensional unconfined porous medium (glass beads) with a sloping seaward boundary of 1:6.12. The result is for a freshwater head of 463 mm and a seawater head of 439 mm. The longitudinal dispersivity and the saturated hydraulic conductivity of the porous medium are measured to be 0.65 mm and 4.0 mm/s. Figure 3(a) shows the result from 2DFEMFAT by imposing equivalent freshwater heads at the seaward boundary, which is calculated as

$$H_f = Z + (H_s - Z) \cdot \frac{\rho_s}{\rho_f} \qquad (1)$$

where, $H_f$ (L) is the equivalent freshwater head; $Z$ (L) is the Z-coordinate of a node; $H_s$ (L) is the seawater head (=439mm); $\rho_s$ ($ML^{-3}$) and $\rho_f$ ($ML^{-3}$) are seawater and freshwater density, respectively ($\rho_s$=1025 g/L, $\rho_f$=995.1 g/L).

The boundary BC is an outflow face, where a zero salt concentration gradient is specified to allow free convective transport. A comparison of the position of the 0.5 solute contour and the water table is shown in Figure 3(b). The results from 2DFEMFAT in terms of the width of the diffusion zone and the position of the 0.5 contour are in excellent agreement with the experimental ones. The satisfactory agreement for all the testing examples leads to confidence in applying the model to the Gooburrum groundwater system.

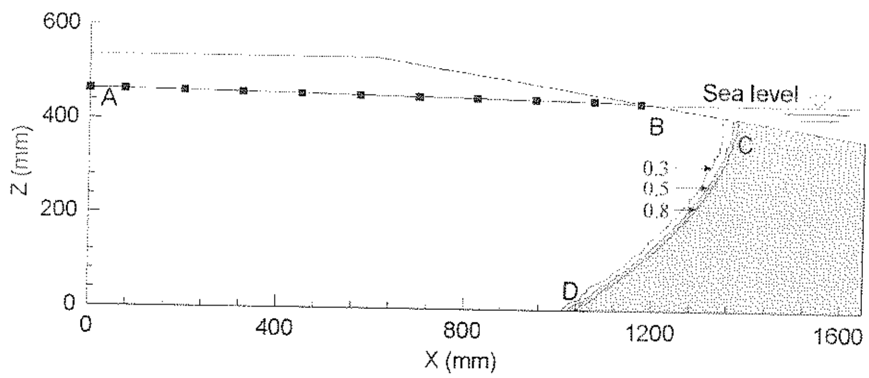
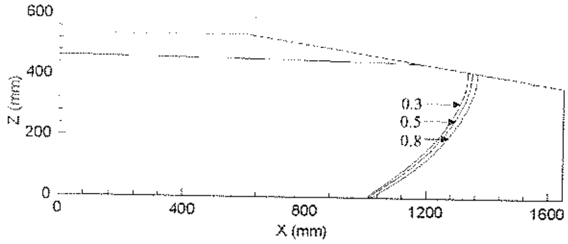
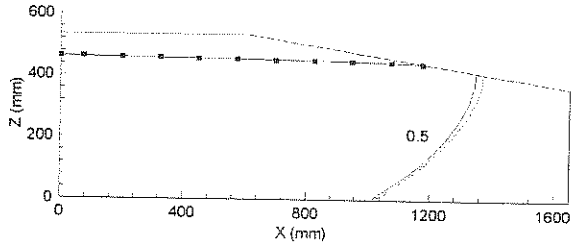



Figure 2. The freshwater-saltwater interface in an unconfined coastal aquifer (squares are the measured free surface; BC is the outflow face; CD is the diffusion zone shown by contours of relative salt concentration of 0.3, 0.5 and 0.8 obtained through an image processing approach; the shaded area is the seawater zone).




(a) steady state solution from 2DFEMFAT




(b) comparison of 0.5 contours

Figure 3. The steady state solution from 2DFEMFAT (the dotted line is the experimental result).

## 3. SIMULATION OF SEAWATER INTRUSION IN THE GOOBURRUM AQUIFER

In this part, numerical simulations using different boundary conditions are performed for a 2D vertical cross-section located at I-I′ (Figure 1). The section begins at Moore Park on the Pacific Ocean and ends about 14 km landward. The orientation of the vertical section is formulated parallel to the major groundwater flow direction to minimise the effects of water flow coming from the direction perpendicular to the section.

Figure 4 shows the geological units in the vertical section interpreted using the available data from observation bores in the area. This is a heterogeneous and anisotropic aquifer system. Numbers 1 to 8 indicate zones of different permeabilities. The upper aquifer consists of sand and gravel with minor clay. The top surface is the ground surface and receives spatially variable rainfall recharge. Rainfall recharge infiltrates through the unsaturated portion of the upper aquifer and then reaches the water table. Thus, the upper aquifer is treated as unconfined. The lower aquifer (zone 7 and 8) consists of sand, gravel and clays. The leaky aquitard (zone 6) is mainly silty or sandy clays and clays. The permeability of the aquitard is estimated to be approximately 5 orders of magnitude less than that of zone 8. The exact location and extent of the connections between the aquifers and the ocean are unknown. However, based on the National Bathymetric map series of Bundaberg, the aquifers are extended 1800 m from the coastline (C) to the ocean at the actual seabed slope ratio of 1250:1 and ended with a vertical boundary AB. The inland boundary (FG) and the bottom boundary (GHIJKA) of the domain are formed by relatively impermeable sediment.

A quadrilateral element mesh is constructed for the vertical section. The mesh consists of a total number of 3945 nodes and 3736 elements. The average horizontal and vertical dimensions of elements are 150 m and 1.2 m respectively.

The parameters shown in Table 1 are the same as those used in [Bajracharya et al., 1998], where a detailed description of the parameter estimation was also presented. The horizontal permeability is shown in Table 1, while the vertical one is one-thousandth of the horizontal one. The van Genuchten model [van Genuchten, 1980] is employed for the unsaturated soil parameters in the upper aquifer.

### 3.1 Equivalent Freshwater Heads and Constant Salt Concentration

One possible seaward boundary condition is to apply equivalent freshwater hydrostatic heads and a constant salt concentration on segment ABC in Figure 4. This set of seaward boundary conditions is often used in seawater intrusion modelling. In implementing it, the sea level is maintained at a static level at the coastline (C in Figure 4). The equivalent freshwater heads on ABC are calculated from equation (1) using a seawater density of 1025 kg/m$^3$. A relative salt concentration of 1.0 is assigned along boundary AB for the transport boundary condition.

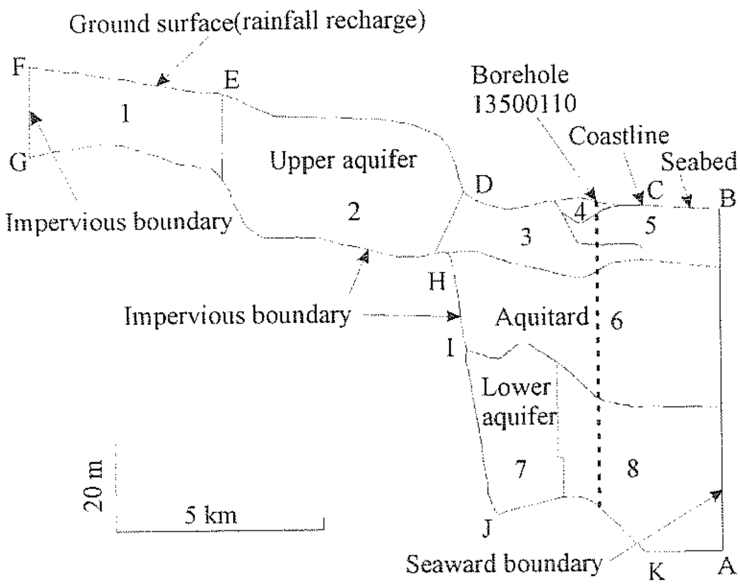



Figure 4. 2D vertical section (I-I′ in Figure 1).

Table 1. Basic parameters used for Gooburrum aquifer system.

| Parameter | Value | Unit |
|---|---|---|
| porosity | 0.34 | - |
| viscosity | 1.0e-3 | kg $m^{-1}$ $s^{-1}$ |
| gravity | 9.8 | m $s^{-2}$ |
| transverse dispersivity | 20 | m |
| longitudinal dispersivity | 100 | m |
| molecular diffusivity | 3.0e-9 | $m^2$ $s^{-1}$ |
| tortuosity | 1 | - |
| density of fresh water | 1000 | kg $m^{-3}$ |
| density of seawater | 1025 | kg $m^{-3}$ |
| constant of van Genuchten model | 3.34e-4 | - |
| constant of van Genuchten model | 1.78 | - |
| constant of van Genuchten model | 7.98e-2 | - |
| permeability | 1.2e-11 (zone 1) | $m^2$ |
| permeability | 4.0e-11 (zone 2) | $m^2$ |
| permeability | 1.0e-10 (zone 3) | $m^2$ |
| permeability | 4.0e-10 (zone 4) | $m^2$ |
| permeability | 5.0e-10 (zone 5) | $m^2$ |
| permeability | 2.0e-15 (zone 6) | $m^2$ |
| permeability | 3.5e-11 (zone 7) | $m^2$ |
| permeability | 3.5e-10 (zone 8) | $m^2$ |
| compressibility of water | 4.47e-10 | m $s^2$ $kg^{-1}$ |
| compressibility of soil matrix | 1.0e-8 | m $s^2$ $kg^{-1}$ |

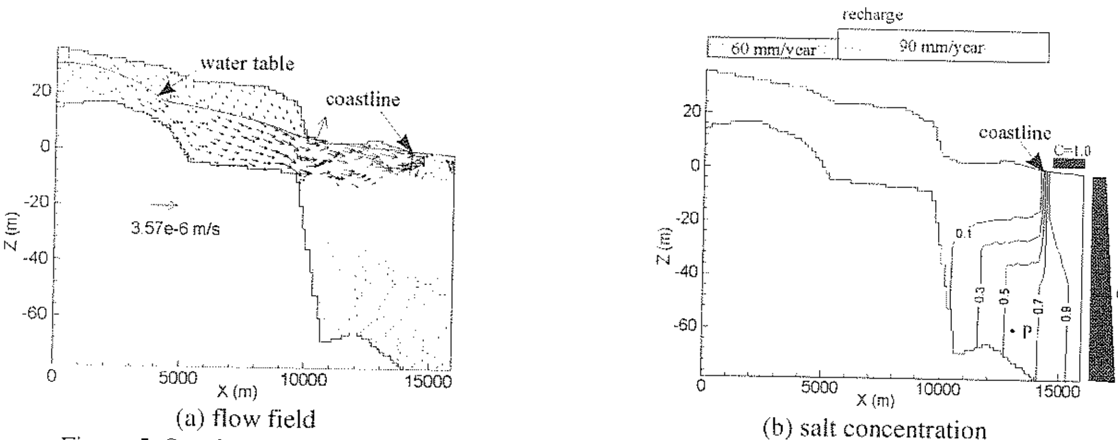



Figure 5. Steady state solution from 2DFEMFAT using equivalent freshwater heads and constant concentration conditions at the seaward boundary.

The ground surface (segment CDEF in Figure 4) is assigned a time-independent spatially variable rainfall recharge. The recharge intensities are 60 mm/year for segment FE (about 4.5 km) and 90 mm/year for segment CDE (about 9.6 km). These values were estimated from rainfall data [Bajracharya et al., 1998]. The inland and bottom boundaries (FG and GHIJKA in Figure 4) are assumed to be bounded by relatively impermeable material, thus a no-flow condition is used. To allow convective transport of salt across the boundary, a boundary condition of zero concentration gradient is used from coastline C to a distance of 1200 m seaward. On the other part of segment CB (600 m) a salt concentration of 1.0 is applied to represent the seawater. The initial condition is that the aquifer is free of salt. The initial flow condition is assumed to be hydrostatic with zero rainfall recharge.

The steady state solution for these boundary conditions is shown in Figure 5. It can be seen that the dominant flow occurs in the upper aquifer. Most of the groundwater exits at the coastline, not further seaward from under the seabed. Some outflows are present at the escarpment (D in Figure 4). A sharp interface occurs in the upper aquifer. The interface does not extend landward from the coastline due to the large flow velocity near the coastline exit point. The lower aquifer is almost completely separated by the aquitard with very minor quantities of freshwater entering into it (the groundwater velocity in the aquitard is in the order of $10^{-11}$ m/s to $10^{-12}$ m/s). A flow circulation occurs in the lower aquifer, where a wide diffusion zone is developed.

When measured field data from 1989 to 1997 are considered, however, it is noted that a salt concentration of less than 0.2 was observed at borehole 13500110 at a depth of 60 m from the ground surface as shown in Figure 6. The observation in Figure 6 was made after-development of the aquifer system when pumping had started. The observation location is indicated as point P in Figure 5 (b). Even though only one data point is shown, salt concentrations have remained relatively constant at that point over eight years. We assume that the salt concentration at observation point P was not much greater than, and probably less than or around 0.2 before pumping started. Therefore, the calculated salt concentration in Figure 5 (b) would not represent the predevelopment condition.

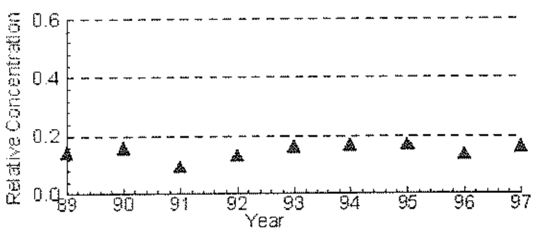



Figure 6. Relative salt concentration observed from borehole 13500110 at a depth of 60 m from the ground surface.

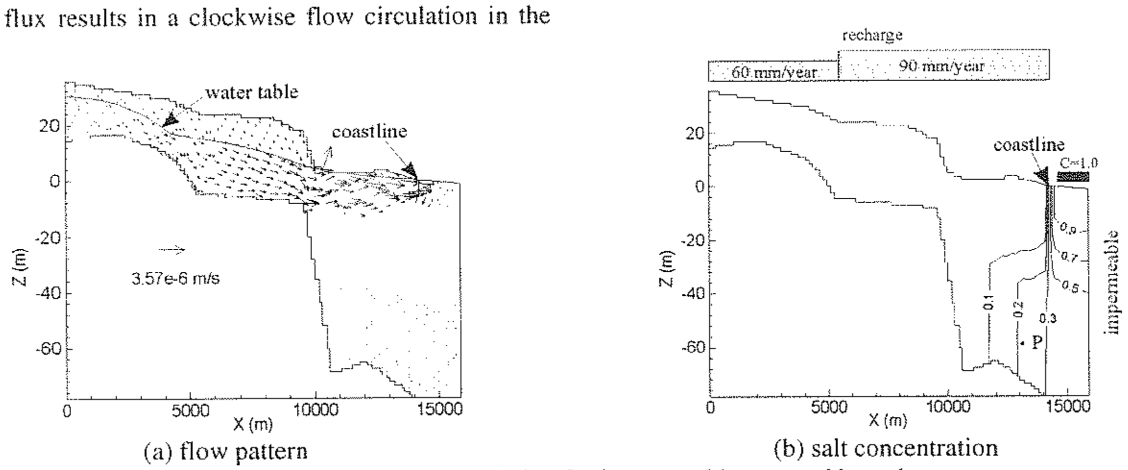
Further analysis indicates that the wide transition zone in the lower aquifer may result from an inappropriate imposition of the seaward boundary condition. Because it is almost isolated by the aquitard, the water in the lower aquifer is almost stagnant. However, by applying equivalent freshwater heads and constant salt concentration along the vertical seaward boundary, a horizontal flow flux occurs across the boundary. The flow flux results in a clockwise flow circulation in the lower aquifer. This circulation becomes dominant in the almost isolated lower aquifer and takes salt into the aquifer by advection from the lower portion of the boundary, where a concentration of 1.0 is applied. Because very minor freshwater enters into the lower aquifer, a wide transition zone results. Therefore, the imposition of equivalent freshwater heads generates an unrealistic flow circulation in the lower aquifer, which introduces a wide diffusion zone.

### 3.2 Impermeable Seaward Boundary Condition

From the above analysis, the imposition of equivalent freshwater heads and a constant salt concentration along the vertical seaward boundary may not be appropriate for the Gooburrum aquifer. To avoid this, the seaward boundary (AB in Figure 4) is treated as impermeable with no flow across it. The salt concentration along the vertical boundary is determined by the model rather than pre-specified. Salt enters into the aquifer system from the seabed only (segment BC in Figure 4). Figure 7 shows the steady state solution for this boundary condition.

Although the calculated concentration at point P is slightly larger than 0.2 and the predevelopment concentration at that point is likely to be less than or around 0.2, this result is in close agreement with the field evidence. The impermeable boundary condition, therefore, produces better agreement with the field data than the freshwater heads one.

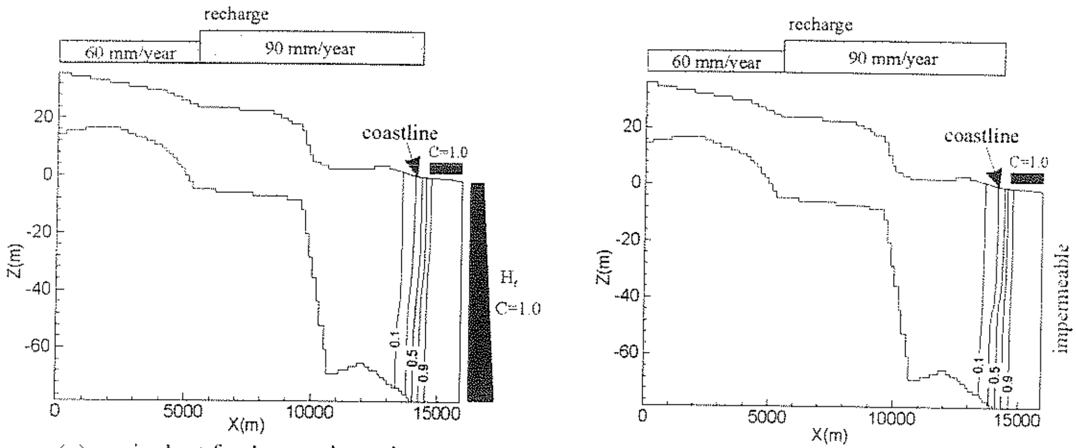
The impact of the aquitard can be demonstrated by a simple exercise. Assuming the aquitard does not exist, then the water in the lower aquifer becomes no longer stagnant. In this case, the imposition of equivalent freshwater heads at the vertical boundary or the treatment of an impermeable boundary should produce almost identical result for the steady state solution. Figure 8 shows the results for both boundary conditions. As expected, both results are identical.




(a) flow pattern

(b) salt concentration

Figure 7. Steady state solution for impermeable seaward boundary.




(a) equivalent freshwater boundary (b) impermeable boundary

Figure 8. Steady state solution by assuming aquitard does not exist.

## 4. CONCLUSIONS

The combination of equivalent freshwater heads and salt concentration is commonly used to represent a seaward boundary in seawater intrusion modelling. In most cases, the application of this seaward boundary condition is satisfactory. Because the imposition of this boundary condition allows flow across the boundary, which subsequently takes solute into the aquifer from the boundary where a concentration is specified, a careful check is essential to estimate whether too much mass of the solute is introduced. The inappropriateness of this boundary condition was demonstrated in the Gooburrum aquifer system. The assumption of an impermeable seaward boundary may be appropriate as long as the boundary is sufficiently far away from the area of interest.

A two-dimensional model is economical in terms of computing times and is appropriate if field data are limited. Results from two-dimensional simulations are valuable and also can assist in constructing an appropriate three-dimensional model if warranted.

### Acknowledgments

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