Effects Of Groundwater Pumping On Saltwater Intrusion In The Lower Burdekin Delta, North Queensland

K. A. Narayan[a], C. Schleeberger[b], P. B. Charlesworth[a] and K. L. Bristow[a]

[a] CSIRO Land and Water, Davies Laboratory, Townsville, Australia

[b] University of Applied Sciences, Höxter, Germany

Abstract: The Burdekin Delta is situated in the dry tropics of North Queensland and provides a major water resource for the irrigation of sugarcane. The Delta is unique in that it overlies a shallow groundwater system and is close to the Great Barrier Reef. Aquifer management practices include large recharge pits to assist with artificial replenishment of groundwater. Artificial recharge can be used to maintain groundwater levels and subsequently control seawater intrusion. This technique, however, is often costly and ineffective in areas where excessive groundwater pumping occurs. In the lower Burdekin Delta more than 1800 groundwater pumps are used for irrigation purposes and excessive pumping has resulted in seawater intrusion near the coastline. In this paper we describe the use of a variable density flow and solute transport model, SUTRA, to define the current and potential extent of saltwater intrusion in the Burdekin Delta aquifer under various pumping and recharge conditions. A 2-D vertical cross-section model has been developed for the area, which accounts for groundwater pumping and various artificial recharge sites currently being used in the delta. The Burdekin Delta aquifer consists mainly of sand and clay with granitic bedrock. The model domain uses vertical cross sections along the direction of groundwater flow. The initial conditions were based on the land use prior to agricultural development in the area when the seawater interface was in its assumed natural state. The results address the effects of variations in pumping and artificial and natural recharge rates on the dynamics of saltwater intrusion. The simulation has been carried out for a range of recharge, pumping rates and hydraulic conductivity values. The results show that the saltwater intrusion is far more sensitive to pumping rates and recharge than aquifer properties such as hydraulic conductivity. The impacts of possible management scenarios on groundwater quality have also been investigated.

Keywords: *Groundwater pumping, saltwater intrusion, SUTRA model, artificial recharge, Burdekin Delta*

1. INTRODUCTION

The coastal areas of the world accommodate high population with about 50% of the world population lives within 60 km of the shoreline. Overexploitation of the groundwater has become a common issue along the coast where good quality groundwater is available. Consequently, many coastal regions in the world experience extensive saltwater intrusion in aquifers resulting in severe deterioration of the quality of groundwater resources.

In Australia, coastal Queensland is fortunate to have extensive groundwater resources. Many rivers have well-developed alluvial tracts and deltas with extensive sand and gravel aquifers. The river delta systems usually contain rich soil and were an obvious target for the development of sugarcane plantations in the late 19th century. Groundwater use for irrigation commenced shortly after settlement, but it was not until the expansion of the sugar industry in the mid-20th century that irrigation was practiced extensively. Serious problems of saltwater intrusion exist in many coastal areas of Queensland (Volker and Rushton, 1982; Hillier, 1993; Murphy and Sorensen, 2001) and the first step in dealing with these problems is to evaluate the size and extent of the intrusion. The extent of this intrusion depends on climatic conditions, the characteristics of the groundwater flow within these aquifers, and the manner of groundwater usage.

Saltwater intrusion problems in coastal aquifers are not new. The initial model was developed independently by Ghyben in 1888, and by Herzberg in 1901. This simple model is known as the Ghyben-Herzberg model and is based on the hydrostatic balance between fresh and saline water in a U-shaped tube. They showed that the saltwater occurs at a depth h below sea level represented by:

$$h = [\rho_s / (\rho_s - \rho_f)]\, h_f \qquad (1)$$

where, ρ_f and ρ_s are respectively the density of fresh and saline water, and h_f is the elevation of fresh water level above mean sea level. Equation 1 is referred to as Ghyben-Herzberg relationship. Substitution of ρ_f (1000 kg m^{-3}) and ρ_s (1025 kg m^{-3}) in eqn. (1) shows that h = 40 h_f. In other words, the depth to the fresh-saline interface below mean sea level (h) is 40 times the elevation of the water table above sea level (h_f) (Freeze and Cherry, 1979).

This simplistic model ignores convection, dispersion and diffusion phenomena responsible for the distribution of salinity in coastal aquifers. In coastal aquifers, freshwater usually overlies the seawater separated by a transition zone. Management of limited groundwater resources in such situations is a delicate task and requires special attention to minimise the movement of the saltwater wedge into aquifers and upconing of saltwater near pumping stations. The extent of intrusion depends on a number of factors such as aquifer geometry and properties (hydraulic conductivity, anisotropy, porosity and dispersivity), abstraction rates, and depth, recharge rate, and distance of pumping wells from the coastline (Ghassemi et al, 1993). Complex models are required to quantify these factors.

Over the years, several mathematical and numerical models have been developed, which serve to predict the interface or transition zone between fresh groundwater of meteoric origin and seawater in the subsurface of coastal areas (Reilly and Goodman, 1985). The development of these models was largely motivated by groundwater issues; that is, assessment of fresh groundwater reserves, and prediction of saltwater intrusion (onshore salinity distribution) – the landward or upward movement of the interface in response to groundwater exploitation practices (e.g. Volker and Rushton, 1982; Custodio et al., 1987; Ghassemi et al., 1990; Ghassemi et al., 1993; Gotovac et al., 2001).

In this paper we describe the use of a variable density flow and solute transport model, SUTRA (Voss, 1984), to define the current and potential extent of saltwater intrusion in the Burdekin Delta aquifer under various pumping and recharge conditions. A 2-D vertical cross-section model has been developed for the area, which accounts for groundwater pumping and various artificial recharge schemes currently being used in the delta. Model results are compared with limited available data in the area. The impacts of possible management scenarios on groundwater quality have also been investigated.

2. SITE DESCRIPTION AND GENERAL HYDRGEOLOGY

The Burdekin Delta is a major irrigation area in the dry tropics of North Queensland, with about 40,000 ha of irrigated crops. The environmental and climatic conditions are ideal for the production of sugarcane and the region has a reputation of being one of the highest yielding sugarcane areas in Australia. The topography is essentially flat to slightly undulating, however, outcrops of basement rock occur in the south and southwest of the delta. Annual rainfall for the region averages 1032 mm with most falling in the December – March 'wet' season. Mean annual evaporation is 2062 mm. The delta is situated in close proximity to environmentally sensitive wetlands, waterways, estuaries, and the Great Barrier Reef. The location of the delta with regard to its regional setting is shown in Figure 1.

The history of groundwater irrigation, aquifer overdraft and consequent formation of the Burdekin Delta recharge scheme is summarised by Charlesworth et al. (2002). One of the main purposes of the lower Burdekin artificial recharge scheme is to maintain high water table levels to keep the saltwater wedge from moving inland and displacing the freshwater. Currently there are more than 1800 groundwater pumps used for irrigation water supply in the delta area. It is critical to understand the effectiveness of the artificial recharge scheme to withstand the movement of saltwater wedge under various irrigation and pumping regimes.

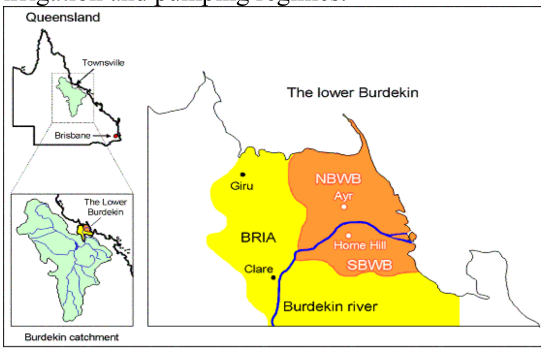

Figure 1. Location of the Lower Burdekin Delta (BRIA - Burdekin River Irrigation Area, NBWB – North Burdekin Water Board and SBWB – South Burdekin Water Board)

A single-layer approach to modelling the Burdekin Delta aquifers allows all minor variations to be incorporated into a single hydrostratigraphic unit (Arunakumaren et al., 2000). Groundwater within the delta is constrained by the unconsolidated alluvial and deltaic sediments, which were deposited by the Burdekin River and its distributaries. Typical cross-sections of the delta sediments show that strata layers usually are laterally discontinuous, making cross-bore correlations difficult to identify. Nonetheless, it is apparent from bore hydrographs that there is a significant amount of vertical hydraulic connection between sandy units.

In this work the delta is being simulated as a single-layer unconfined aquifer, with a bottom slope defined by the position of the granitic bedrock. The hydraulic conductivities of the aquifer have been estimated based on aquifer materials (Freeze and Cherry, 1979). Ongoing improvements in hydraulic characterization will be made as more data becomes available. A typical cross section of the delta aquifer is shown in Figure 2.

3. NUMERICAL MODELLING OF SALTWATER INTRUSION

3.1 Recharge and groundwater extraction

Recharge to the groundwater system is by a number of different processes. These include infiltration of rainfall, artificial recharge through pits and channels, river recharge, flooding, and irrigation return flows. From an assessment of these mechanisms, simulated annual groundwater recharge between 1981 and 1997 varied between 330,000 and 650,000 ML per year (Arunakumaren et al., 2000). For analyses in this study, total maximum recharge rate was set at 1,250 mm/yr (490,000 ML/yr.

Simulation of the saltwater intrusion requires a series of assumptions and estimations to be made about the various parameters involved. There are no volumetric metered records for groundwater pumping rates in the Burdekin Delta. The most recent estimate indicates a volume of 210,000-530,000 ML/yr is being extracted (Arunakumaren et al., 2000; SKM, 1996).

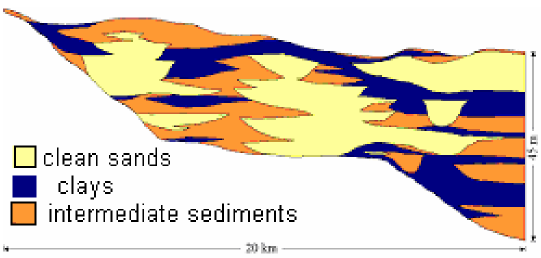

Figure 2. A cross-section of the Burdekin Delta in groundwater flow direction showing sediment distribution (after Arunakumaren et al. 2000)

The physical problem along the coast in the Delta is one of density-dependent groundwater flow and saltwater intrusion (Voss, 1984; Narayan and Armstrong, 1995). Prediction of the saltwater wedge can be obtained by the solution of two spatial differential equations describing the 'conservation of mass of fluid' and 'conservation of mass of salt' in a porous medium. Numerical procedures for solving the governing equations require adequate discretisation in space and time and appropriate initial and boundary conditions.

3.2 SUTRA model

SUTRA (Voss, 1984), in conjunction with the Argus-One Graphic User Interface, was chosen as the basis for numerical modelling because of its ability to solve density dependent groundwater flow and variably saturated flow, and also because it is readily available in source code form. This model implements a hybridisation of finite element and integrated finite difference methods employed in the framework of a method of weighted residuals. The hybrid method is the simplest and most economical approach, which preserves the mathematical elegance and geometric flexibility of finite element simulation, while taking advantage of finite difference efficiency.

3.3 Discretisation, Boundary Conditions and Model Parameters

To simulate saltwater intrusion in the Burdekin Delta aquifer, a cross-sectional vertical slice with a length of 5000 m, a depth of 30 m on the left boundary, 45 m on the right boundary (facing saltwater), and a thickness of 1 m was taken. The model area was discretised to 7500 (500 x 15) quadrilateral elements and 8016 (501 x 16) nodes. The details of the model domain with boundary conditions are shown in Figure 3.

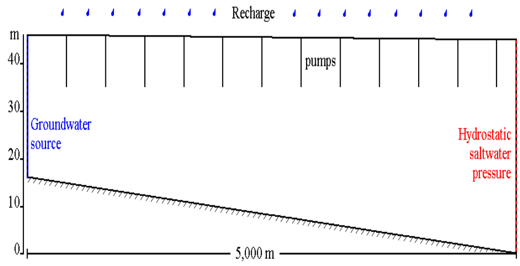

Figure 3. Model domain and boundary conditions

A steady state simulation with 200 mm natural recharge per year was used to generate the situation prior to agricultural development. The result is a saltwater wedge that extends about 50 m inland. Concentration and pressure outputs from steady state SUTRA runs were used as an initial condition to simulate realistic short-time effects of agricultural land use (groundwater discharge and recharge) on the groundwater system.

The boundary conditions for the transport simulation are dependent on its flow boundary conditions. On the right hand model boundary a hydrostatic pressure was imposed where pressure is zero at the sea surface, and increases linearly with depth. Based on field observations, a groundwater head of 2 m was chosen at a distance of 5km from the right hand model boundary. The concentration (TDS) of the recharge water is assumed to be 300 mg/L owing to irrigation with river- and groundwater.

The hydraulic conductivity varies across the delta from 10 to >300 m/d at the northern coast. In the area chosen for the SUTRA model (see Figure 2) K is estimated to be 10 to 100 m/d (Freeze and Cherry, 1979), salinity of groundwater in the cross-section as 500 mg/L (entire Burdekin Delta aquifer ranges: 300 to 2000 mg/L). Transverse dispersivity is even less well quantified than longitudinal dispersivity from field observations. The dispersivity values listed in Table 1 are an estimate only, governed to some extent by the practical limitations imposed by mesh size.

A total of 2187 pump locations were surveyed across the delta by GPS, including 367 open water pumps and 1811 groundwater pumps by NR&M (Arunakumaren et al., 2000). In this model, 12 perforated wells, with discharge rates of 5, 10, 15, 20, 25 or 50 L/s and a depth of about 10 m have been used along the transect. Nodes with negative fluid source describe these wells. Average calculated distance between pumps L_p [m] in the delta is about 470 m; for modelling purposes we used L_p = 400 m. The groundwater pumping rates vary across the delta because of different irrigation practices, field size, and precipitation as well as surface water availability. To obtain the linear discharge values for a one-meter thick vertical slice, the pumping rates were divided by L_p. For example, 10 L/s pumping rate can be converted to a line sink (Q_p') by 10/400 (kg/m·s) = 0.025 kg/(m·s). Model input parameters are given in Table 1.

Table 1. Input parameters.

Parameter	Value
Seawater concentration, C_S	35,700 mg/L
Groundwater concentration, C_G	500 mg/L
Recharge water concentration, C_R	300 mg/L
Freshwater density, ρ_F	1,000 kg/m³
Density change, $\partial\rho/\partial C$	700 kg²/(kg$_{TDS}$·m³)
Hydraulic conductivity, K	10, 50, and 100 m/day
Longitudinal dispersivity	2.5 m
Transverse dispersivity	0.5 m
Molecular diffusivity of solute in water, D_m	10^{-9} m²/s
Porosity, ε	0.3
Viscosity of water, μ	0.001 kg·m/s
Groundwater head (left of model boundary)	2 m
Recharge range	500 – 1250 mm/yr
Distance between wells, L_p	400 m
Pumping rate, Q_p	5 – 50 L/s

4. RESULTS AND DISCUSSION

One of the main purposes of the lower Burdekin artificial recharge scheme is to maintain high water table levels to keep the saltwater wedge from moving inland and displacing the freshwater. It is important to understand the effects of varying recharge and groundwater pumping on the movement of the saltwater wedge. Based on the work of Arunakumaren et al. (2000), simulation runs were conducted with recharge values of 600, 900 and 1250 mm/yr. The actual recharge differs seasonally during a year. SUTRA cannot simulate the seasonal variations properly, so the constant source value for recharge is spread over one year (e.g. 1250 mm/yr ≈ 0.0000396 kg/(m²·s)).

The pumping rates used in the model are 5, 10, 15, 20, 25 and 50 L/s. This corresponds to 0.432-4.32 ML/day. The first four values are more realistic for the Burdekin Delta. A series of salt concentration contours for various recharge rates (600-1250 mm/yr), hydraulic conductivities (10 - 100 m/d) and pumping rates (5–50 L/s) were obtained. Saltwater concentration profiles for 1250 mm/yr recharge rate and a typical pumping rate of 10 L/s are shown in Figure 4 after 10 years. Concentration profiles are influenced by the left hand boundary for longer pumping durations.

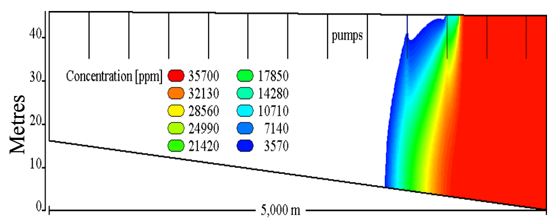

Figure 4. Saltwater concentration profile in a vertical cross-section after 10 years (R=1250 mm/yr, K=50 m/d, and Qp = 10 l/s)

Figure 5 shows the relation between pumping rate and saltwater intrusion length after 10 years with constant recharge rate of 1250 mm/yr and hydraulic conductivities of 10, 50 and 100 m/d. The results show that lower pumping and higher recharge can reduce saltwater intrusion effectively.

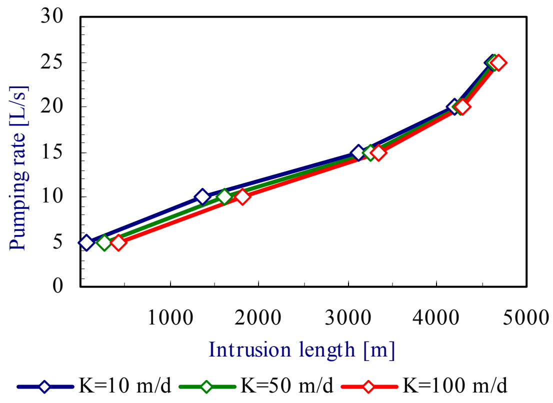

Figure 5. Pumping rate vs. saltwater intrusion length after 10 years *(R=1250 mm/yr)*

For a non-homogeneous aquifer such as the Burdekin Delta aquifer, the hydraulic conductivity changes with the medium. Several model runs were also carried out to study the effects of varying hydraulic conductivity on salt concentration profiles and intrusion lengths. Preliminary simulations show that the system is far more sensitive to recharge and pumping rates than aquifer properties such as hydraulic conductivity. Our simplified model developed in this work has assumed homogeneous aquifer properties. The effect of recharge on saltwater intrusion length for a pumping rate of 10 L/s is depicted in Figure 6. Higher hydraulic conductivities cause broader dispersion zones (not shown here) enhancing the total intrusion length. Intrusion length is inversely proportional to recharge rates.

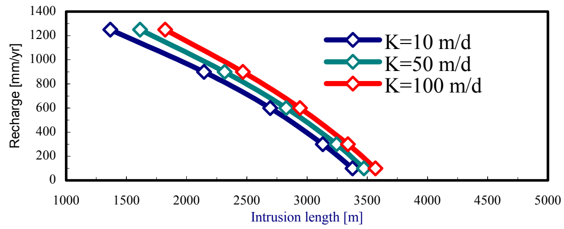

Figure 6. Effect of recharge on saltwater intrusion length after 10 years (Qp = 10 L/s)

Salinity in pumped waters along the model transect were also analysed. Figure 7 illustrates the change in pumping water salt concentration with time for the well located at 3000m from the seawater boundary. The results show that a higher pumping rate of 20 L/s near the coast causes saltwater intrusion and contamination of wells much quicker compared to a pumping rate of 10 L/s. As expected, no pumping near the coast resulted in slow movement of saltwater wedge in the aquifer as shown in Figure 8. This indicates a future direction for saltwater wedge management in the lower Burdekin.

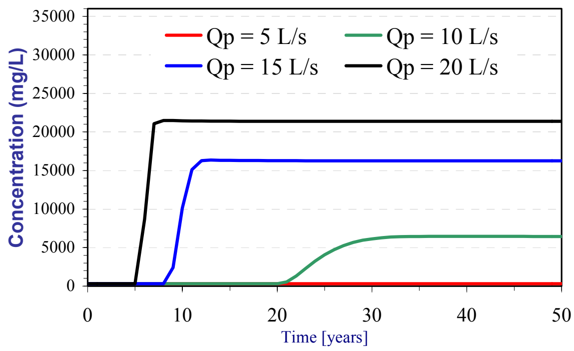

Figure 7. Evolution of salinity in the pumped water from the well located 3000m from the original saltwater boundary *(1250 mm recharge, K = 50 m/d)*

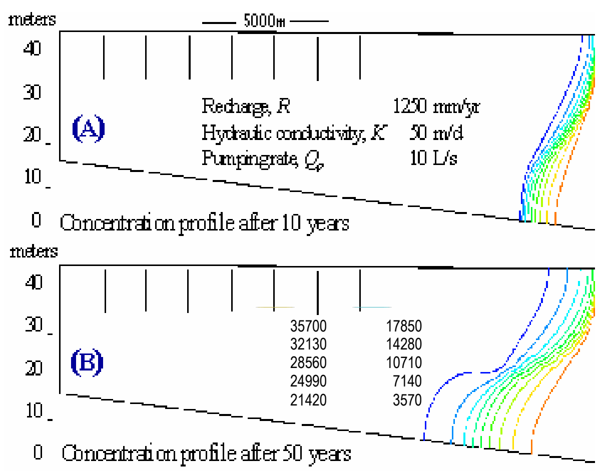

Figure 8. Salt concentration profiles (ppm) without pumping near the coast after (A) *10 years*, and (B) *50 years* of simulation

Currently no bores are monitored along the model transect, and in the area affected by saltwater intrusion in the Burdekin Delta. A direct comparison of the model results with the field data is therefore not possible. For a typical run with average aquifer parameters, the groundwater salinity (≥10 % of seawater salinity) moves about 3 km in the aquifer in 30 years. Comparison of the modelling results has been made with limited interpreted data of Arunakumaren et al. (2000) and are found to be in reasonable agreement.

5. CONCLUSION

A 2-D variable-density groundwater flow and solute transport model SUTRA has been used in cross-section to simulate saltwater intrusion in the Lower Burdekin Delta aquifer. The model accounts for groundwater pumping, recharge rates and hydrogeology of the aquifer system. The results of this study highlight the effects of pumping on saltwater intrusion. Less pumping and high recharge rate in the aquifer can reduce seawater intrusion effectively. Groundwater pumping near the coast should be avoided to help control the saltwater wedge. It is believed that some of the results from this preliminary study will be useful for water resources management in the Lower Burdekin Delta.

Acknowledgements: This work is funded by CSIRO Land and Water and Queensland Department of Natural Resources and Mines. We would like to thank Peter Gilbey, Sean Murphy and Pushpa Onta for useful discussion.

6. REFERENCES

Arunakumaren, N. J., G. A. McMahon, and K. Bajracharya, Water management in the lower Burdekin: Groundwater model conceptualization, Dept. of Natural Resources, Brisbane, 2000.

Charlesworth, P. B., K. A. Narayan, K. L. Bristow, B. Lowis, G. Laidlow, and R. McGowan, The Burdekin Delta – Australia's oldest recharge scheme, Proc. ISAR-4, 22-26 Sept., Adelaide, 2002.

Custodio, E., G. A. Bruggemen, and V. Cotecchia, Groundwater problems in coastal areas, Studies and Reports in Hydrology, vol. 35 , UNESCO, Paris 1987.

Freeze, R. A., and J. A. Cherry, *Groundwater*, Prentice Hall, New York, 1979.

Ghassemi F., A. J. Jakeman, and G. Jacobson, Mathematical modelling of seawater intrusion, Nauru Island, *Hydrological Processes,* 4, 269-281, 1990.

Ghassemi, F., T. H. Chen, A. J. Jakeman, and G. Jacobson, Two and three - dimensional simulation of seawater intrusion: performances of the "SUTRA" and "HST3D" models, *AGSO J. Australian. Geology. & Geophysics,* 14(2/3), 219-226, 1993.

Gotovac, H., R. Andrecevic, and M. Vranjes, Effects of aquifer heterogeneity on the intrusion of seawater, Proceeding: First International Conference on Saltwater Intrusion and Coastal Aquifers – Monitoring, Modelling and Management, Essaouira, Morocco, April 23-25 2001.

Hillier, J. R. (1993) Management of saltwater intrusion in coastal aquifers in Queensland, Australia. AGSO Journal of Australian Geology & Geophysics, 14 (2/3), 213-217.

Murphy, S. F., and R. C. Sorensen, Saltwater intrusion in the Mackay coastal plains aquifer. Proc. Aust. Sugar Cane Technol., 23, 70-76, 2002.

Narayan, K. A. and D. Armstrong, Simulation of groundwater interception at Lake Ranfurly, Victoria, incorporating variable density flow and solute transport, *J. Hydrology,* 165, 161-184, 1995.

Reilly, T. E., and A. S. Goodman, Quantitative analysis of saltwater freshwater relationships in groundwater systems – a historical perspective, *J. Hydrol*ogy, 80, 125-160, 1985.

Sinclair Knight Merz (1996) North and South Burdekin Water Boards – Burdekin River Issues. Sinclair Knight Merz.

Volker, R. E. and Rushton, K. R. (1982) An assessment of the importance of some parameters for seawater intrusion in aquifers and a comparison of dispersive and sharp-interphase modelling approaches. J. Hydrol. 56, 239-250.

Voss, C.I. (1984) SUTRA: a finite element simulation model for saturated-unsaturated, fluid-density dependent groundwater flow with energy transport or chemically reactive single-species solute transport, US Geological Survey, Water Resources Investigations, Report 84-4369, pp 409.