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Modelling seawater intrusion in the Burdekin Delta Irrigation Area, North Queensland, Australia

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ABSTRACT

The Burdekin Delta is a major irrigation area situated in the dry tropics of North Queensland. It is unique in that (i) it overlies shallow groundwater systems that serve as a major water supply for the irrigation of sugarcane, and (ii) it is adjacent to the world heritage listed Great Barrier Reef. Water management practices include large recharge pits and surface spreading of water to assist with replenishment of the groundwater. This has been useful in maintaining groundwater levels to help control seawater intrusion. This technique, however, can be costly and ineffective in unconfined aquifer systems, which are subjected to large amounts of groundwater pumping for irrigation. There are more than 1800 production bores currently used for irrigation in the Burdekin Delta and the large volumes of water extracted have at times lowered the regional water tables and made it difficult to control seawater intrusion.

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 seawater intrusion in the Burdekin Delta under various pumping and recharge conditions. A 2D vertical cross-section model, which accounts for groundwater pumping and recharge, was developed for the area. The Burdekin Delta aquifer consists mainly of sand and clay lenses with granitic bedrock. The model domain uses vertical cross-sections along the direction of groundwater flow. The initial conditions used in the model are based on land use prior to agricultural development when the seawater wedge was in its assumed natural state. Results of this study demonstrate the effects of variations in pumping and net recharge rates on the dynamics of seawater intrusion. Simulations have been carried out for a range of recharge, pumping rates and hydraulic conductivity values. Modelling results show that seawater intrusion is far more sensitive to pumping rates and recharge than to aquifer properties such as hydraulic conductivity. Analysis also shows that the effect of tidal fluctuations on groundwater levels is limited to areas very close to the coast. Tidal influences on saltwater intrusion therefore can be neglected when compared with the effects due to groundwater pumping. The impacts of various management options on groundwater quality are also discussed.

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1. Introduction

Surface water has been the traditional primary water source for agricultural use in tropical environments. The main reason for intensive use of surface water is its easy access and associated low cost. However, increasing pressure on surface water resources generated by economic and population growth has lead to diversification of the water supply sources.

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Thus, during the second half of the 20th century, groundwater withdrawals have increased and currently groundwater accounts for about one-third of the world's freshwater consumption (Essink, 2001). This increase in groundwater extraction rates, often higher than natural recharge thresholds, has resulted in substantial falls in aquifer levels in many areas (Hiroshiro et al., 2006; Sethi et al., 2006; Zhang et al., 2004; Sadeg and Karahanoglu, 2001; Zhou et al., 2000). In coastal aquifers freshwater is hydraulically connected to seawater. Under most natural conditions the hydraulic gradient ensures the net water flow is towards the sea, which protects the freshwater. However, the gradient is usually relatively small and any excessive net withdrawal can alter the hydrostatic balance. In this situation seawater can enter the aquifer and replace the freshwater. This phenomenon, known as seawater or salt water intrusion (SWI), can have adverse and long term impacts on coastal groundwater systems and limit their use as a supply of good quality water for human and agricultural uses.

The coastal areas of the world are characterised by high populations with about 50% of the world's population living within 60 km of the shoreline (Essink, 2001). Overexploitation of the groundwater has become a common issue with many coastal regions in the world now experiencing extensive seawater intrusion in aquifers resulting in severe deterioration in groundwater quality, and hence from a use point of view, quantity as well (Paniconi et al., 2001; Ma et al., 2005; Karahanoglu and Doyuran, 2003).

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 agricultural development, particularly plantations of sugarcane 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 we saw a rapid increase in irrigation from groundwaters and the emergence of serious problems of seawater intrusion in many coastal areas of Queensland (Volker and Rushton, 1982; Hillier, 1993; Arunakumaren et al., 2000; Murphy and Sorensen, 2001; Zhang et al., 2004). The extent of this intrusion depends on climatic conditions, the characteristics of the groundwater flow within the aquifers, and the manner of groundwater usage and irrigation practices in the area.

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

$$h = \left[\frac{\rho_f}{\rho_s - \rho_f}\right] h_f \qquad (1)$$

where ρ_f and ρ_s are, respectively, the density of fresh and sea water, and h_f is the elevation of fresh water level above mean sea level. Substitution of ρ_f (1000 kg m^{-3}) and ρ_s (1025 kg m^{-3}) in Eq. (1) shows that $h = 40h_f$. 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 seawater wedge into aquifers and up-coning of seawater near pumping stations (Reilly and Goodman, 1987; Bower et al., 1999). The extent of intrusion depends on a number of factors such as aquifer geometry and properties (hydraulic conductivity, anisotropy, porosity and dispersivity), abstraction rates, depth, recharge rate, and distance of pumping wells from the coastline (Ghassemi et al., 1993). Complex models are required to quantify these factors.

During the last three decades, numerous papers have been published dealing with various aspects of solute movement in aquifers. Modelling of seawater intrusion into groundwater systems has also received much attention and several mathematical and numerical models have been developed. These models predict the interface or transition zone between fresh groundwater of meteoric origin and seawater in the subsurface of coastal areas. Reilly and Goodman (1985) provide a historical perspective of quantitative analyses of seawater–freshwater in groundwater systems. Bear (1979) provides an excellent mathematical description of the problems related to seawater intrusion in coastal aquifers.

The development of these models was largely motivated by groundwater issues; that is, assessment of fresh groundwater reserves, and prediction of seawater intrusion—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, 1993; Bear et al., 1999; Zhou et al., 2000; Sadeg and Karahanoglu, 2001; Gotovac et al., 2001; Paniconi et al., 2001). The problem of pumping optimisation using aquifer simulation has also been extensively investigated in the literature (Gorelick et al., 1984; Ahlfeld and Heidari, 1994; Gordon et al., 2000; Mayer et al., 2002; Cheng et al., 2000; Mantoglou, 2003; Mantoglou et al., 2004). Optimum pumping rates of coastal unconfined aquifers based on linear and non-linear optimisation techniques and the concepts of a sharp interface and the Ghyben–Herzberg approximations were utilised in most of these studies.

A US Geological Survey model SUTRA is available for simulation of variable density flow and solute transport (Voss, 1984). The SUTRA model has been successfully applied to solve seawater intrusion problems (e.g. Voss and Souza, 1987; Souza and Voss, 1987; Bush, 1988; Ghassemi et al., 1990). In this paper we describe application of the variable density flow and solute transport model, SUTRA (Voss, 1984), to define the current and potential extent of seawater intrusion in the Burdekin Delta agricultural area under various pumping and recharge conditions. A 2D vertical cross-section model has been developed for the area, which accounts for groundwater pumping and net recharge occurring in the delta. This is a first attempt to develop a seawater intrusion model for the Burdekin Delta groundwater system. Model results are compared with the

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