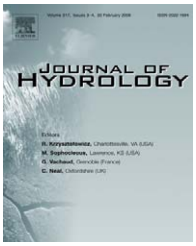
Journal of Hydrology (2006) **328**, 511–522

available at www.sciencedirect.com

journal homepage: www.elsevier.com/locate/jhydrol



Tidal impacts on riparian salinities near estuaries

Adrian D. Werner [a,*], **David A. Lockington** [b]

[a] *Queensland Government, Department of Natural Resources and Mines, 120 Meiers Road, Indooroopilly, Brisbane, Qld 4068, Australia*
[b] *Centre for Water Studies, School of Engineering, University of Queensland, Brisbane 4072, Australia*

Received 2 September 2005; received in revised form 9 December 2005; accepted 27 December 2005

KEYWORDS
Coastal processes;
Density-dependent flow;
Groundwater-dependent ecosystems;
Salinization

Summary Groundwater-dependent riparian biota is known to be sensitive to changes in soil and groundwater salinity in estuarine systems. The groundwater flow and salinity behaviour in a phreatic aquifer adjoining a partially penetrating, tidal estuary is investigated through two-dimensional numerical experiments for a lateral cross-section, which explore the influence of factors, such as aquifer and soil materials, tidal amplitudes, and regional groundwater hydraulic gradients. The density contrast between estuarine water and the fresh groundwater drives saltwater penetration of the aquifer even in the case of a marked groundwater hydraulic gradient towards the estuary. We show that tidal fluctuations in estuaries can significantly affect the groundwater salinity distribution in adjacent density-stratified phreatic aquifers. This has consequences for the expected distribution of salinity-sensitive biota in the hyporheic zone as well as vegetation and fauna dependent on water in the riparian soil and aquifer. The shape of the dense saltwater wedge propagating into the adjacent groundwater system is also modified by the estuarine tidal signal, although this effect appears to have only minor influence on the maximum distance penetrated into the aquifer (i.e., location of the 'toe' of the wedge). Tide-induced changes to riparian groundwater salinity are advection-driven, as evidenced by the modified time-averaged groundwater flow dynamics.

Introduction

The riparian ecotone and associated microbial, plant and fauna processes have important functions in maintaining stream health, including the control of water, nutrient, sediment and species movement (e.g., Hayashi and Rosenberry, 2002; Naiman and Decamps, 1997; Ostrom et al., 2002; Williams, 2003). The biodiversity and health of riparian ecosystems have been shown to be sensitive not only to estuarine salinity changes (Lymberey et al., 2003; Salinas et al., 2000), but also to changes in the salinity and available water in both the riparian soil (Ball, 1998; Glenn et al., 1998; Vandersande et al., 2001) and riparian phreatic aquifers (An et al., 2002; Gillikin et al., 2004; Ridd and Sam, 1996). While of obvious importance to estuarine riparian ecosystems, associated groundwater flow patterns and salt exchange

---

[*] Corresponding author. Tel.: +61 7 38969144; fax: +61 7 38969149.
E-mail address: adrian.werner@nrm.qld.gov.au (A.D. Werner).

doi:10.1016/j.jhydrol.2005.12.011

processes are not well understood, particularly where estuarine tidal loading causes cyclic hydrologic stresses on the system (e.g., Kitheka, 1998).

In shallow groundwater conditions, increasing the watertable salinity may produce soil salination through capillary rise (Prathapar et al., 1992; Werner and Lockington, 2004). Where the watertable is sufficiently high, evaporative concentration of groundwater salts may also occur at the ground surface. The mechanisms for soil and ground surface salination are similar to those producing *irrigation* or *dryland salination* (e.g., Connell and Haverkamp, 1996; Elrick et al., 1994; Cook et al., 2001; Cramer and Hobbs, 2002), except the watertable may be fluctuating under tidal forcing from the estuary.

The effect of estuarine tides on the riparian hydrology and hydro-salinity needs to be assessed before the ecological impacts of anthropogenic or climatic stresses on these systems can be predicted. In addition, any fluxes/variation in groundwater flow induced by estuarine tides will have implications for studies of nutrient reduction from estuarine riparian microbial processes (e.g., Tappin, 2002). Tidal fluctuations may also influence saltwater intrusion propagating from estuaries, although management models of estuarine saltwater intrusion typically ignore tidal fluctuations and focus on the density differences between surface water and groundwater at most (e.g., Neilson-Welch and Smith, 2001; Smith and Turner, 2001). The implications of neglecting estuarine tides in studies of riparian hydrology and hydro-salinity have not been examined previously.

Previous studies of density-dependent surface water-groundwater interaction under tidal forcing have focused on the ocean—aquifer interface. The study by Ataie-Ashtiani et al. (1999b) considers the influence of one tidal cycle on the salinity distribution in a shallow unconfined aquifer near a mildly sloping beach, and provides insight into the effects of modifying beach slope, tidal amplitude and groundwater hydraulic gradient on tidal impacts. The present system differs from that adopted by Ataie-Ashtiani et al. (1999b) because of the partial penetration of the estuary into the aquifer. Further, we explore salinisation processes occurring over multiple tidal cycles (up to 5 years of semi-diurnal tides) to assess long-term tidal impacts. The current study also examines the influence of including tidal fluctuations in simulations of riparian and aquifer salinity changes resulting from aquifer pumping effects (i.e., hydraulic gradient changes).

The present study adopts some of the system characteristics of Sandy Creek, an estuary in the Pioneer Valley, north-eastern Australia (Longitude 149.11°, Latitude −21.27°), in numerical simulations of an otherwise hypothetical estuary—aquifer system. Sandy Creek is a macro-tidal, partially penetrating watercourse deeply incised into a shallow coastal alluvial aquifer, which provides irrigation supplies to the local sugar cane monoculture. Rising salinity has been observed in observation and pumping bores adjacent to the Sandy Creek estuary, which extends some 11 km inland (Bedford, 1978; Murphy and Sorensen, 2000). Further, riparian habitats along the Sandy Creek estuary are of ecological significance (Cook et al., 2004; Brodie, 2004), and preserving their biodiversity despite considerable anthropogenic and climatic stresses on the groundwater system is a priority for natural resource managers.

The improved understanding of riparian groundwater and salt transport processes gained from this study will benefit predictive studies of changes to riparian ecosystem health caused by anthropogenic and climatic stresses, particularly where species' responses to salt stress are known (e.g., An et al., 2002). In addition, the assumption that non-tidal boundary conditions are an adequate representation of tidal estuaries in simulations of estuarine saltwater intrusion (e.g., Neilson-Welch and Smith, 2001) will be tested.

Methodology

Numerical experiments provide the basis for the present investigation. We use the finite-element code SUTRA (Voss, 1984) to predict density-dependent variably saturated groundwater flow and salt transport in a two-dimensional representation of an estuary—aquifer system. The SUTRA code has been adopted in previous studies of fluctuating watertable systems (Ataie-Ashtiani, 1997; Li et al., 2000), and SUTRA predictions agreed well with analytical and experimental solutions to groundwater wave propagation in shallow aquifers.

The basic system geometry and groundwater hydraulic gradients are based on Sandy Creek in the Pioneer Valley and the adjacent alluvial aquifer system. The model assumes symmetry about the estuary centreline, although only the northern riparian zone is represented. Given that the system geometry varies between the northern and southern riverbanks, it is possible that asymmetrical influences (e.g., Smith and Turner, 2001) are occurring in the Sandy Creek system; however, such effects are neglected for simplicity in this study. The conceptual model for exploring riparian zone salt movements is illustrated in Fig. 1.

The ground surface is represented in the model by a 'no flow' boundary condition. We model the vadose zone explicitly, so drivers of water and salt into this zone include flux from the estuary, capillary rise (i.e., capillary fringe dynamics) and dispersion. However, the vadose zone is not the primary region of interest, and therefore transport caused by surface evaporation or evapotranspiration is neglected, although such processes are likely to impact on vadose zone salinity distributions (e.g., Werner and Lockington, 2004; Morris and Collopy, 1999). Also, it is conceded in the SUTRA User Manual (Voss, 1984) that SUTRA is not specialized for the non-linearities of unsaturated flow and hence accurate predictions of vadose zone salinity distributions would require application of an alternative code (e.g., Ataie-Ashtiani et al., 1999a) and possibly a finer spatial discretisation.

The horizontal length of the model of (180 m) was selected to avoid the dampening influence of the inland fixed head boundary on tidal propagation, while maintaining the smallest possible domain size for computational efficiency. The model domain also needed to be sufficient to capture the entire salt plume (for the simulation periods considered), particularly in *active* saltwater intrusion (i.e., ambient groundwater flow away from the estuary) predictions, to avoid boundary influences on salt distribution computations. Consequently, the amplitude decay of a propagating groundwater wave (from an estuary source) was determined using a longer (1500 m) SUTRA model for a range of aquifer