Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Hydrology 302 (2005) 255–269
Journal of Hydrology
www.elsevier.com/locate/jhydrol

Interaction between shallow groundwater, saline surface water and contaminant discharge at a seasonally and tidally forced estuarine boundary

S.J. Westbrook[a,b], J.L. Rayner[b], G.B. Davis[b,*], T.P. Clement[a,c], P.L. Bjerg[d], S.J. Fisher[b]

[a]*Department of Environmental Engineering, University of Western Australia, Nedlands, WA 6907, Australia*
[b]*Perth Laboratory, Division of Water Resources, CSIRO Land and Water, Private Bag No. 5, Wembley, WA 6913, Australia*
[c]*Department of Civil Engineering, Auburn University, Auburn, AL, USA*
[d]*Environment and Resources DTU, Technical University of Denmark, Kongens Lyngby, Denmark*

Received 22 August 2003; revised 16 July 2004; accepted 30 July 2004

Abstract

This paper presents findings from a 2-year field investigation of a dissolved hydrocarbon groundwater plume flowing towards a tidally and seasonally forced estuarine river system in Perth, Western Australia. Samples collected from transects of multiport wells along the riverbank and into the river, enabled mapping of the fine scale (0.5 m) vertical definition of the hydrocarbon plume and its longitudinal extent. Spear probing beneath the river sediments and water table, and transient monitoring of multiport wells (electrical conductivity) was also carried out to define the zone of mixing between river water and groundwater (the hyporheic zone) and its variability. The results showed that groundwater seepage into the estuarine surface sediments occurred in a zone less than 10 m from the high tide mark, and that this distance and the hyporheic transition zone were influenced by tidal fluctuations and infiltration of river water into the sediments. The dissolved BTEXN (benzene, toluene, ethylbenzene, the xylene isomers and naphthalene) distributions indicated the behaviour of the hydrocarbon plume at the groundwater/surface water transition zone to be strongly influenced by edge-focussed discharge. Monitoring programs and risk assessment studies at similar contaminated sites should therefore focus efforts within the intertidal zone where contaminants are likely to impact the surface water and shallow sediment environments.

Keywords: Ground water; Surface water; Hydrocarbons; Discharge; Tides; Seasonal variations

1. Introduction

As urban and industrial development continues to expand around the world's rivers and coastlines, so does the rate of unintentional release of contaminants to subsurface and surface waters and the need for

* Corresponding author. Tel.: +61 89333 6386; fax: +61 89333 6211.
E-mail address: greg.davis@csiro.au (G.B. Davis).

0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2004.07.007

effective assessment of such environments (Winter, 2000). Hydrologists have long known that surface waters and groundwater are intrinsically linked systems (e.g. Glover, 1959; Cooper, 1959; Clement et al., 1996; Simpson et al., 2003). Areas around streams, rivers, lakes and coastal environments represent zones of interaction and transition between the two systems where dissolved constituents such as pollutants can be diluted, exchanged, transformed or destroyed. Identifying predominant processes affecting solute exchange across transition zones is therefore, critical in assessing contaminant fluxes to the sediment/water interface, and ultimately in estimating contaminant exposures for the receiving ecosystems.

Groundwater/surface water interactions in estuarine environments are influenced by a number of processes forming complex spatially and temporally variable systems. Density contrasts between the typically fresh groundwater and saline to brackish marine and estuarine surface waters leads to mixing and convective circulation at the groundwater discharge boundary so that the system is characterised by the intrusion of saltwater into the adjacent coastal aquifer (Glover, 1959; Cooper, 1959; Reilly and Goodman, 1985; Ataie-Ashtiani et al., 1999; Simpson and Clement, 2004). Tidal activity can often induce a fluctuating water table as well as infiltration of surface water into sediments, forming a surficial mixing zone with groundwater discharging from the adjacent aquifer (Robinson et al., 1998; Ataie-Ashtiani et al., 1999; Boudreau and Jorgensen, 2001; Acworth and Dasey, 2003). Although there is still no single conceptual definition for such a surficial mixing zone, the terms 'hyporheic zone', 'subsurface estuary' and 'groundwater/surface water interface' or 'GSI' are gaining common usage in the scientific literature. White (1993) conceptually defined the hyporheic zone as 'the saturated interstitial area beneath the stream bed and into the stream banks that contain some proportion of channel water or that have been altered by channel water infiltration'. This definition may be broadened to include rivers, lakes, estuaries and coastal environments where surface water infiltrates into the underlying sediments and interacts with groundwater.

Although numerous studies have addressed groundwater and solute inputs to surface water bodies (e.g. Harvey et al., 1987, Gallagher et al., 1996, Portney et al., 1998, Krabbenhoft et al., 1990, Lorah and Olsen, 1999, Winter, 2000; Tobias et al., 2001), few studies to date have examined near-shore groundwater discharge in detail. Studies of note however, include those by Robinson et al. (1998); Robinson and Gallagher (1999); Smith and Turner (2001); Linderfelt and Turner (2001); Simpson et al. (2003) and the initial study by Westbrook et al. (2000) related to the current work.

Robinson et al. (1998) presented results from a field investigation on unconfined groundwater discharge to estuarine waters at Chesapeake Bay, Virginia, showing strong tidal and seasonal controls on fresh groundwater discharge associated with infiltration of surface water into tidally exposed sediments. Robinson and Gallagher (1999) further developed a two-dimensional, field scale, finite-element model based on density dependent fluid flow with water table and dynamic tidal boundary conditions. The model was able to reproduce the Chesapeake Bay field data on the movement of the near-shore water table, groundwater salt concentrations and groundwater discharge rates and patterns but was unable to replicate short-term salt fluctuations in the hyporheic zone due to the wave action of tides within the intertidal zone (Robinson and Gallagher, 1999). Simpson et al. (2003) performed transport experiments in a sand tank to study the characteristics of the seepage-face zone that exists near a groundwater/surface water interface. Their study concluded that seepage-face zones, which are dominated by strong hydraulic gradients, play an important role in influencing the localized flow and solute transport processes in shallow unconfined aquifers.

Field observations and mathematical modelling of density dependent groundwater/surface water interaction in the Swan-Canning estuary by Smith and Turner (2001) showed that density contrasts between the estuary and adjacent fresh groundwater system are sufficient to drive mixed-convection cells that give rise to circulation of river water in the aquifer, providing a mechanism to transport nutrients between the nutrient-rich pore fluids in the riverbed sediments and groundwater. Further, results indicated unconfined groundwater preferentially discharges into the Swan River along the outside of river meanders, with very low discharges or at times saline river water recharge along the inside of meanders (Smith and Turner, 2001;