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Defining the hyporheic zone in a large tidally influenced river

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SUMMARY

An investigation was conducted to characterize the spatial and temporal distribution of the hyporheic zone of a large tidally influenced river. The field site is located on the Fraser River in British Columbia, Canada, approximately 30 km from its outlet to the ocean. The physical attributes of the riverbed were mapped using geophysical techniques coupled with sediment sampling. The spatial and temporal distribution of groundwater composition beneath the riverbed was determined through detailed profiling. Contaminated (fresh) groundwater discharges through a narrow band of the riverbed at a distance approximately 88–105 m from the shoreline coinciding with the termination of a massive silty unit. Saline groundwater, as part of a regional flow system, dominates the riverbed sediments from 105 m beyond the shoreline towards the centre of channel. Three water types occur within the upper 2 m of the riverbed sediments; a result of both mixing of river water, contaminated (fresh) groundwater, and saline groundwater and modification by cation exchange reactions. The interaction of these waters produced distinct zones of Ca–HCO_3^-, Na–Cl, and Ca–Cl type waters. The distribution of groundwater solutes indicates that during a single tidal cycle, river water penetrates the riverbed to a depth of approximately 15 cm but the long term effects of tidal pumping of river water into the riverbed is observed to a depth of approximately 1 m below the river bed.

1. Introduction

Surface water bodies such as lakes and rivers can be an integral component of a groundwater flow system. Linkages between the two are controlled by the physiography of the landscape, defined by geologic framework and topology, and climate. These links can be part of a regional, intermediate or local scale groundwater flow system. A critically important interaction between groundwater and surface water is hyporheic flow, where water flows to and fro between near-river channel sediments and the active channel. It is at this scale that hyporheic flow paths, which return to the stream in distances less than tens of meters, are distinguished from the regional-scale paths that support base flow. Hyporheic processes are viewed as smaller scale interactions between channel water and groundwater occurring within larger-scale patterns of loss and gain of channel water in drainage basins (Harvey and Wagner, 2000).

Several definitions have been proposed for hyporheic zones (HZ). For example, Hynes (1974) defined the HZ based on observations of stream organisms and dissolved oxygen, while Triska et al. (1989) defined the HZ as the region where subsurface water contains at least 10% surface water. In this paper the definition proposed by White (1993) is adopted: the saturated interstitial areas beneath the stream bed and into the stream banks that contain some proportion of channel water as a result of hyporheic flow. In a tidally-influenced river, hyporheic flow is dominated by tidal forcing: flow paths are oscillatory (recharging and discharging) under high- and low-tide river stages, respectively (Bianchin et al., 2010).

The characteristics of groundwater–surface water interactions (GWSi) on smaller order streams (Anderson et al., 2002; Harvey and Bencala, 1993; Harvey et al., 1996; Kasahara and Wondzell, 2003; Landmeyer et al., 2010; Wroblicky et al., 1998), and on ephemeral streams (Boulton and Stanley, 1995; Stanley and Boulton, 1995; Valett et al., 1994) are comparatively better understood than GWSi of larger, tidally-influenced rivers. Only a few studies such as that of Hinkle et al. (2001) on the Willamette River in Oregon have been conducted on larger order streams. Most studies on smaller systems have focused on the influence of riverbed geomorphology on GSWi. Bed-induced perturbations to stream flow result in pressure variations that drive the exchange of surface water and groundwater at the stream bed (Anderson et al., 2002; Cardenas et al., 2004; Harvey and Bencala, 1993; Kasahara and Wondzell, 2003; Marion et al., 2002; Packman and Brooks, 2001; Storey et al., 2003). The composition of the river bed sediments also influences the degree to which bed-form induced hyporheic exchange occurs (Cardenas et al., 2004; Salehin et al., 2004; Storey et al., 2003; Vinson et al., 2001).

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Tidal pumping is also a mechanism for GSWi in rivers adjacent to the coastal zone (Land and Paull, 2001; Trefry et al., 2007; Westbrook et al., 2005). Westbrook et al. (2005) and Trefry et al. (2007) investigated the hypoaigic zone [otherwise known as the subterranean estuary (Moore, 1999)] beneath the Canning River, near Perth, Australia. They showed the effect of a seasonally stratified river on groundwater discharge patterns and discussed implications for contaminant transport through this mixing zone. However, the frequency of their data collection was too low to observe the effect of the tides on groundwater – surface water exchange. The effect of tidal pumping on contaminant transport has been the focus of several model studies (e.g. (Neeper, 2001; Yim and Mohsen, 1992). Neeper (2001) found that oscillatory flow in the presence of a sorbed phase contaminant increases the time-average flux of contaminants through increased dispersal, beyond that which would be found in steady flow without sorption processes. Yim and Mohsen (1992) showed that tides could result in the mixing of surface water with groundwater, diluting contaminants up to a distance of 12 m inland from the surface water–aquifer interface. This large mixing zone reflects the relatively large dispersivity value (~3 m) used in their simulations. They noted that tidal pumping hastened the migration of contaminants to the estuary in comparison to a non-tidal simulation. These results were not verified by field data.

The effects of tidal pumping on submarine groundwater discharge (SGD) have also been investigated (Burnett et al., 2003; Land and Paull, 2001; Preito and Destouni, 2005; Robinson et al., 2007; Taniguchi, 2002). Preito and Destouni (2005) and Robinson et al. (2007) have shown that the discharge characteristics of SGD, that is, size of discharge zone and degree of surface water [ocean water] and groundwater mixing are controlled by the magnitude of groundwater flux and amplitude of tidal oscillation. Maji and Smith (2009) emphasize the importance of mixed-water discharge occurring within the intertidal zone.

Little is known of the hyporheic zone of large rivers and, to the knowledge of the authors no such work has been conducted on large tidally-influenced rivers in that part of the estuary beyond the landward ingress of saline (ocean) water. Further, one cannot extrapolate the effect of tidal pumping from SGD studies because density dependent flow, wave fetch and slope break modify the groundwater flow patterns and are not active on a tidally-influenced river.

The transport of groundwater contaminants through the riverbed sediments of a tidally influenced river is complex. Considering the many processes on a tidally-influenced river that could drive exchange, the nature and spatial extent of hyporheic flow can also be expected to be complex; leading to the following key questions: Where does river water recharge the aquifer or near channel sediments? To what depth does river water penetrate the riverbed? Does the depth of penetration vary across the riverbed and if so, why? Based on the observed GWSi patterns on the riverbed, is it possible to develop a qualitative statement of the process or processes likely responsible for driving this exchange? The motivation for this study is to gain an understanding of how tidal forcing on a large river influences GWSi and ultimately the physical and chemical characteristics of the hyporheic zone, both spatially and temporally. The objectives include: (1) determining the extent to which river water penetrates the river bed and the resulting influence on groundwater chemistry, thus delineating the hyporheic zone; and (2) determining the controls on how and where groundwater discharge occurs.

1.1. Site description

The location of the field site is on the north bank of the Fraser River, near Vancouver, Canada (Fig. 1). Historic wood treatment practices dating back over 70 years have led to a zone of non-aqueous-phase creosote that penetrates 27 m beneath the ground surface. Groundwater flow south across the site towards the Fraser

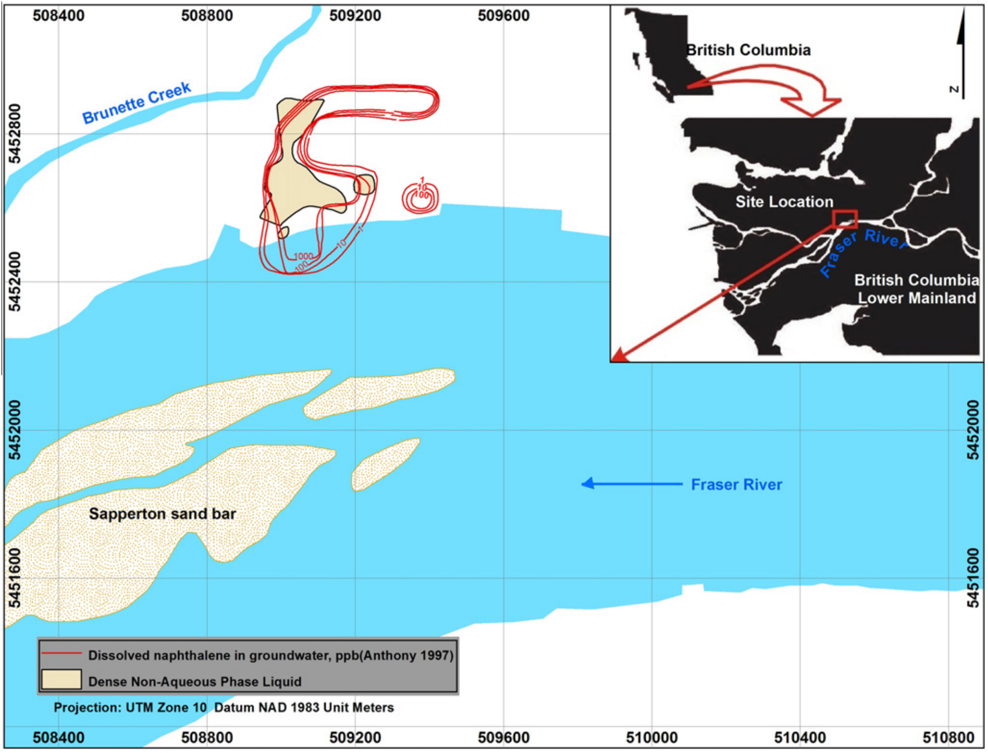

Fig. 1. The field site is located offshore of a wood preservation facility on the north bank of the Fraser River in the Lower Mainland Area of British Columbia, CANADA. On shore contamination with wood preservatives has led to the development of a dissolved phase PAH plume that extends approximately 100 m south of the riverbank to where it eventually discharges to the river.