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Flow and discharge of groundwater from a snowmelt-affected sandy beach

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ABSTRACT

The study is based on a complex and unique data set of water stable isotopes (i.e., δ^{18}O and δ^{2}H), radon-222 activities (i.e., ^{222}Rn) and groundwater levels to better understand the interaction of fresh groundwater and recirculated seawater in a snowmelt-affected subterranean estuary (STE) in a boreal region (Îles-de-la-Madeleine, Qc, Canada). By using a combination of hydrogeological and marine geochemical approaches, the objective was to analyze and quantify submarine groundwater discharge processes through a boreal beach after the snow melt period, in early June. The distribution of δ^{18}O and δ^{2}H in beach groundwater showed that inland fresh groundwater contributed between 97 and 30% of water masses presented within the STE. A time series of water table levels during the 16 days of the study indicated that tides propagated as a dynamic wave limiting the mass displacement of seawater within the STE. This up-and-down movement of the water table (~10–30 cm) induced the vertical infiltration of seawater at the falling tide. At the front of the beach, a radon-based mass balance calculated with high-resolution ^{222}Rn survey estimated total SGD of 3.1 m^3/m/d at the discharge zone and a mean flow to 1.5 m^3/m/d in the bay. The nearshore discharge agreed relatively well with Darcy fluxes calculated at the beach face. Fresh groundwater makes up more than 50% of the total discharge during the measuring campaign. These results indicate that beaches in boreal and cold regions could be important sources of freshwater originate and groundwater-borne solutes and contaminants to the marine environment after the snowmelt.

1. Introduction

Submarine groundwater discharge (SGD) is widely recognized as a significant transport pathway for chemicals entering the coastal ocean (Li et al., 1999; Moore, 2010; Robinson et al., 2007). This is particularly important where rapidly growing coastal populations induce complex changes in landscapes and ecosystems as well as increased pressure on coastal water resources. In locations around the world, deterioration in coastal water quality (e.g., bacterial proliferation, harmful algal blooms, hypoxia, acidification, fish and shellfish mortality) have been attributed to changes in the quality and volume of groundwater discharged to the ocean (Hwang et al., 2010; Valiela et al., 1990).

The intertidal and nearshore zones of sandy beaches play key roles in the connection across the coastal continuum, from watershed to coast (Heiss and Michael, 2014; Robinson et al., 2007). Moore (1999) coined the term "subterranean estuary (STE)" for the beach aquifer to emphasize the importance of freshwater and seawater mixing and water–rock interactions as fresh groundwater transits toward the sea. Similarly to surficial estuaries, solute concentrations change greatly in the dispersion zone of the subterranean estuary (Beck et al., 2015). Their chemical behaviors within the STE are complex and closely tied to the subsurface salinity distribution. Multiple physical forces drive subsurface flow and residence times, and thus control the reaction rates and transformations in this biogeochemically active zone (Cable and Martin, 2008; Michael et al., 2005; Robinson et al., 2007). Santos et al. (2012) identified at least 12 independent drivers that include both terrestrial (e.g., hydraulic gradient, seasonal oscillation of the water table) and marine (e.g., wave and tidal pumping, ripple and bed form migration, bioirrigation) processes that interact in complex ways. These processes force flow across the water–sediment interface, albeit under different spatial and temporal scales, and consequently influence the export of groundwater-borne,

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recirculated, and newly formed compounds to the sea. Thus, an in-depth understanding of the hydrological SGD processes is necessary to accurately predict chemical fluxes to coastal environments.

The nearshore area of the beach aquifer is a dynamic zone where fresh groundwater exits the subterranean system through a narrow discharge zone often bounded by two saline zones. At the seaward boundary below the discharge zone, the saltwater wedge is a fresh groundwater–seawater interface induced by a density gradient where dispersion dominates the exchanges. The nearshore location of this interface moves on a seasonal scale (Michael et al., 2005) in relation to the hydraulic pressure and density difference between fresh and seawater. At the landward boundary, above the discharge zone of fresh groundwater, tides and waves drive seawater into the beach aquifer, forming an upper surficial recirculation cell where advection is the primary process by which solutes move across the sediment–water interface. The resulting hydraulic gradient generates downward and seaward circulations of seawater to the nearshore aquifer, which forms a seawater–freshwater mixing zone where dispersion dominates the chemical processes (Abarca et al., 2013; Heiss and Michael, 2014; Ullman et al., 2003; Xin et al., 2010). Many recent studies on groundwater dynamics in beaches employed groundwater models based on salinity and sometimes on water level measurements (Abarca et al., 2013; Evans and Wilson, 2017; Heiss and Michael, 2014; Heiss et al., 2014; Robinson et al., 2007; Xin et al., 2010). These investigations have all highlighted the necessity to obtain integrated *in situ* measurements of SGD in specific-sites to characterize the nearshore groundwater dynamics.

In boreal and cold regions, the water table elevation is high after snow melt (i.e., in early June), inducing in the inland aquifer a strong horizontal head gradient perpendicular to the shore and high Darcy flows to the coastal embayment (Chaillou et al., 2016). However, these cold regions are still rarely considered as SGD sources. A more detailed knowledge of groundwater discharge, and particularly of fresh groundwater, is critical to the determination of regional and global mass fluxes to coastal zones. Such quantification is particularly crucial in the North where the hydrology is changing rapidly, and is expected to continuously change, in response to climate warming (Adam et al., 2009). The aim of this study was to combine hydrogeological and geochemical *in situ* measurements to analyze SGD processes in a snowmelt-affected STE settled in the Îles-de-la-Madeleine, an archipelago located in the southeastern of the Gulf of St. Lawrence. The study relied on a time series analysis of hydraulic heads measured along a shore-perpendicular transect of multilevel sampling wells to examine the effect of tidal oscillation on the mixing zone. The spatial and temporal distribution of radon-222 (^{222}Rn; an effective proxy of short-term processes ($t_{1/2}$ = 3.8 d) at the groundwater–surface water interface Burnett et al., 2001) and stable isotopes of water (δ^{18}O and δ^{2}H) were also examined to characterize the fresh groundwater dynamics and to estimate the magnitude of fresh groundwater discharge to the bay after the snowmelt in early June. According to our knowledge, this study presents the first in-depth analyses of nearshore groundwater dynamics influenced by the snowmelt in a boreal sandy beach.

2. Materials and methods

2.1. Hydrological context of the study area

This study was conducted in the subterranean estuary at Martinique Beach on Îles-de-la-Madeleine in the province of Québec (Canada) (Fig. 1). The hydrogeological context of the Îles-de-la-Madeleine has been presented by Comte and Banton (2007). The main aquifer of the Archipelago is composed of sandstones from the Permian Inferior period (the Cap-aux-Meules formation; Brisebois, 1981) with a mean transmissivity of ~1.5–4 × 10^{-3} m^2/s and a mean recharge of ~230 mm/y (i.e., ~25–30% of the annual precipitation; Madelin'Eau, 2004). Groundwater flows through the unconfined Permian sandstone aquifer and discharges to the sea, both directly and through the overlying Quaternary deposits. Martinique Beach originates from a recent transgression sequence. The rapid rates of sea-level rise along the Atlantic coasts of Canada over the middle to late Holocene buried the unconfined Permian sandstone aquifer that is now covered by tidal sediments. These buried environments are geological evidence of local and regional submergences over the last millennia (Scott et al., 1995). Sediment cores collected on Martinique Beach were analyzed using scanning electron microscopy (SEM) coupled to an energy dispersive X-ray spectrometer and revealed that the Quaternary sediment of the beach are ~300 μm and mainly composed of silicate mixed with small amount of silt (>5%). The underlying sandstone aquifer is composed of fine red-orange sands (~100 μm) composed of silicate and aluminosilicate (Chaillou et al., 2014). Its localization in the beach and its offshore extent is unknown. The site experiences little wave action except during storm events. Tides are semi-diurnal with a spring tide range ≤1 m.

Previous studies on groundwater discharge and biogeochemistry of the superficial STE have been conducted at this site (Chaillou et al., 2016; Chaillou et al., 2014; Couturier et al., 2016). The shallow superficial unconfined beach aquifer releases both fresh groundwater and recirculated seawater to the coastal embayment. Within the beach, fresh groundwater flows towards the seaward discharge region below a narrow intruding saline circulation cell located near the top of intertidal sediments. In spring 2013, Chaillou et al. (2016) used mean regional and local water table levels to estimate groundwater flows ranging from 0.02 m/d in the sandstone Permian aquifer to ~0.30 m/d at the beach face.

2.2. Field measurements

2.2.1. Water table levels and hydrogeological properties

Three piezometers equipped with pressure sensors were installed in a 45 m transect of the study site perpendicular to the beach front (Figs. 1c and 2). The first piezometer was located at the mean low tide mark (P_3); the second one was located in the intertidal area, 10 m further inland (P_{13}); and the third was located on the beach terrace, 43 m from P_3 (P_{44}; Fig. 2). The piezometers were made from 38 mm ID PVC pipes sealed at the base and equipped with 0.4 m long screens at the bottom end. At every location, piezometers extended ~1.50 m below the beach surface so that the bottom end would always be below the water table. Automated level loggers (Hobo U20-001) recorded groundwater levels every 10 mins from 20 May 2013 to 7 June 2013 (16 days). Time series were corrected for barometric pressure from a barologger located at the study site. A permanent Government of Canada sea-level station (Cap-aux-Meules CAM Station #1970; http://tides.gc.ca/) was used as a reference. The station is located at 5 km from the study site (Fig. 1b). This station recorded water levels every three minutes during the sampling period. Guelph permeameter measurements (N = 15) provided a mean hydraulic conductivity of 11.4 ± 4.4 m/d in the unsaturated surficial sands.

2.2.2. Stable isotopes of water and physicochemical parameters of groundwater

Groundwater was sampled for salinity, ^{222}Rn and stable isotopes of water at high (27–31 May 2013) and low (3 June 2013) tides. A ~20 m cross-shore transect of multi-level samplers (M_{1-7}; Fig. 2) was set up in the intertidal zone, where beach groundwater and recirculating seawater most likely discharge. The multi-level samplers consisted of 2.5 m PVC pipes with eight