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Embayment scale assessment of submarine groundwater discharge nutrient loading and associated land use

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ABSTRACT

A shoreline survey of porewater nutrient concentrations and ^{222}Rn surface water activities was performed in Port Jefferson Harbor, NY, an embayment of Long Island Sound. Submarine groundwater discharge (SGD) was calculated for individual shoreline segments; shallow porewater nutrient concentrations were applied to calculated groundwater flux values in order to spatially depict the nutrient flux to overlying harbor water. Nitrate was the dominant form of inorganic nitrogen as porewater concentrations of ammonium were negligible. Land use analysis showed that nitrate to phosphate ratios (N:P) in SGD were positively correlated with medium to high development of inland aquifer watersheds. A multivariate regression model was developed which describes 79% of the variability in shoreline nitrate discharge. Three modes of nutrient transport were observed; 1) High SGD rates coupled with nutrient rich groundwater derived from high density development, 2) moderate SGD rates coupled with low nutrient groundwater from low density development/forested watersheds and 3) negligible SGD rates associated with recirculated seawater adjacent to low density development areas. Transport mode 1 dominated total SGD nitrate inputs primarily due to steep hydraulic gradient, a characteristic of tunnel valleys in glacial deposits, which highlights the critical role hydrogeology plays in groundwater nitrogen loading to surface water. Total nitrate inputs to the harbor from shoreline SGD alone are 980 mol d^{-1}, similar to average daily sewage treatment plant nitrogen inputs of 870 mol d^{-1}. The techniques used in this study represent an effective methodology for calculating SGD derived nutrient loads where a surface water nutrient source is present.

1. Introduction

Nitrogen flux to coastal waters is a known function of anthropogenic inputs (Howarth et al., 2002), with up to 45% of anthropogenic nitrogen inputs flowing towards the coast (Howarth, 2008). Groundwater is a primary sink of nitrogen entering the hydrosphere, with widely used numerical models assuming denitrification along groundwater flow paths to surface waters (Valiela et al., 2000; Van Breemen et al., 2002). Despite the presence of denitrification, which frequently occurs in 'hotspots' (Groffman et al., 2009), many studies have identified substantial nitrogen loading to surface waters *via* submarine groundwater discharge (SGD) along single study transects within individual embayments (Kroeger and Charette, 2008; Wang et al., 2011; Zhao et al., 2011). In sandy coastal aquifers, SGD is a diffuse, heterogeneous process that acts as a nutrient transport pathway along entire embayment shorelines (Burnett et al., 2006). In an embayment that receives diffuse SGD, a sampling strategy that focuses on one particular segment of shoreline may not provide sufficient information to accurately calculate total nitrogen loading to the entire embayment. In particular, this strategy does not account for heterogeneous flow and aquifer land use variations which alter nutrient composition of discharging water. Therefore, total diffuse SGD nutrient flux calculations which apply a single nutrient flux value to an entire embayment shoreline may over or underestimate the total load, and it is unclear if SGD derived nutrient fluxes can accurately be compared to point source inputs originating from springs, rivers and sewage discharge pipes (Tait et al., 2014).

Biogeochemical processing of nutrients occurs in the coastal aquifer over short spatial and temporal scales. At the shoreline fresh groundwater mixes with seawater, in a geochemically

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variable zone termed the subterranean estuary (STE) (Moore, 1999). Depending on local hydrogeology, these transformations can be either a source or a sink for nitrogen and phosphate (Kroeger and Charette, 2008; Charette et al., 2010; Santos et al., 2012). A study of nitrogen dynamics in a coastal plain STE of Waquoit Bay, MA, found removal of nitrate and ammonium with overall nitrogen loss due to the presence of different water masses with variable redox conditions, a result of local hydrogeology in the coastal aquifer (Kroeger and Charette, 2008). Desorption of phosphate from iron oxides during SGD can theoretically lower N:P ratios in systems with sufficient redoxcline between groundwater and the receiving coastal waters (Spiteri et al., 2008). Inland groundwater nutrient concentrations are not representative of nutrient concentrations in the STE just prior to discharge, and the use of inland concentrations as endmembers is likely to overestimate nutrient loads in well-oxygenated coastal plain aquifer systems. Nutrient concentrations in shallow porewater provide a better estimate of the total flux of nutrients from coastal aquifers to overlying surface waters (Santos et al., 2009), particularly in settings where land use is not uniform along the entire coastline. An individual embayment is typically comprised of multiple land use scenarios, due to high density coastal populations, which may lead to variation in SGD nutrient concentrations along the entire embayment coastline. Capturing land use variance is a key component to understanding the efficacy of remediation programs, such as municipal sewering, which aim to reduce coastal water eutrophication (Meeroff et al., 2008).

The heterogeneous nature of SGD makes direct measurements at the embayment scale difficult. Geochemical tracers have been used to provide integrated estimates of SGD over larger spatial scales. Radon (^{222}Rn), in particular, has been used as a geochemical tracer of total SGD in numerous settings (Povinec et al., 2008; Smith and Swarzenski, 2012; Wilson and Rocha, 2012; Wu et al., 2013). ^{222}Rn is highly enriched by three to four orders of magnitude in groundwater with respect to surface water; it has a short half-life of 3.8 days and is a non-reactive noble gas (Burnett and Dulaiova, 2003). Radon enters groundwater by alpha recoil from the solid aquifer material and as a result, it is present in both fresh groundwater and saline groundwater circulated through the coastal aquifer (Burnett and Dulaiova, 2003; Swarzenski, 2007; Dulaiova et al., 2008). In the absence of fluvial input and sediment diffusion, SGD is the dominant source of radon in surface waters.

Long Island Sound (LIS) is often referred to as an ‘Urban Sea’ whose history of industrialization and subsequent remediation efforts provides environmental lessons for the management of estuaries worldwide (Latimer et al., 2014). Eutrophication in the main body of LIS is well studied, although its nutrient budget is uncertain. Embayments comprise 30% of the total shoreline distance of LIS and are particularly vulnerable to nutrient loading because of concentrated human activity along their shorelines. Embayments may have long flushing times because of restricted tidal exchange with the main body of the Sound through narrow inlets (Rose, 2011). This extended residence time exacerbates the effects of nutrient loading by inhibiting nutrient dilution, leading to algal growth and depletion of surface water dissolved oxygen. Fresh surface water inputs are limited along LIS's south shore. Instead, freshwater into southern LIS is provided primarily by fresh groundwater flowing under the shoreline from thick, unconsolidated sand and gravel aquifers. Groundwater is thought to enter LIS embayments primarily *via* submarine groundwater discharge (SGD) (Scorca and Monti, 2001; Burnett et al., 2003).

In LIS embayments, nutrient loads to surface water *via* SGD have previously been calculated by multiplying average inland groundwater nutrient concentrations by freshwater underflow (Gross et al., 1972; Scorca and Monti, 2001). This procedure neglects biogeochemical processing of nutrients in the coastal aquifer and the variation in land use/land cover patterns in aquifer watersheds. Land use and land cover in the aquifer watershed of LIS's south shore has undergone substantial changes in the last 70 years, transitioning from agricultural and forested land to the current state of low to high housing density land use (Eckhardt and Stackelberg, 1995). Studies of Long Island's surficial Upper Glacial Aquifer have linked the transition from agriculture to suburban development with an increase in groundwater nutrient concentrations (Eckhardt and Stackelberg, 1995). As ~70% of homes in Long Island's Suffolk County are unsewered, low to medium housing density is approximately equal to on-site wastewater system density (Nelson, Pope, and Voorhis, 2007). Sewering in high development areas should lower groundwater nutrient concentrations, resulting in less nutrient loading to embayments *via* SGD. In this study we hypothesize that in LIS embayments, diffuse SGD is a major nutrient contributor to surface water. A linear fit model was used to investigate the impact of land use in the aquifer watershed on SGD nutrient flux to a LIS embayment.

2. Methods

2.1. Site description

Port Jefferson Harbor is located on the north shore of Long Island, NY, with direct connection to LIS through a 0.2 km wide inlet (Fig. 1). The harbor is 3.4 km long and 1.3 km wide. It is adjoined on its west shore to two small shallow bays; Setauket Harbor and Conscience Bay (Breslin and Sanudo-Wilhelmy, 1999). Port Jefferson Harbor has an average depth of 4.4 m but contains a 7–9 m deep dredged navigation channel oriented along the north-south harbor axis (Gross et al., 1972).

Port Jefferson Harbor rests on the Upper Glacial aquifer which is composed of glacially deposited, medium to coarse grained sand. Hydraulic conductivities in the Upper Glacial aquifer range from 27×10^{-3} to 84×10^{-3} cm s^{-1}, with a 10:1 horizontal to vertical anisotropy (Buxton and Modica, 1992). Surficial sediments in the northern half of the harbor are fine to coarse grained sand with an increasing proportion of fine grained sediments (<62 μm) in the southern portion of the harbor (Breslin and Sanudo-Wilhelmy, 1999), although the western edge of the harbor is characterized by coarse sand, pebbles and cobbles (Bittner, 1997). Tunnel valleys, formed by subglacial melt water during the last deglaciation, create steep topography in the watershed along the southeastern portion of Port Jefferson Harbor.

Primary nitrogen inputs to Port Jefferson Harbor occur from atmospheric deposition, the Port Jefferson sewage treatment plant and SGD. There is no existing data for direct deposition of nitrogen on water bodies on Long Island's north shore; however direct atmospheric deposition accounts for 26% of new nitrogen inputs to Great South Bay, located on Long Island's southern shore (Kinney and Valiela, 2011), based on data from eastern Massachusetts where nitrogen deposition averages 10 kg-N ha^{-1} y^{-1} (Bowen and Valiela, 2001). Applying the area of Port Jefferson Harbor to this figure, atmospheric nitrogen deposition is estimated to be 8.6 mol N d^{-1}. The Port Jefferson sewage treatment plant is a tertiary system which currently discharges an average of 870 mol N d^{-1}. Total maximum daily load regulations (TMDLs) seek to limit the amount of nutrients entering the harbor, but current TMDL regulations only address point source surface water input from the sewage treatment plant, neglecting nutrients delivered from SGD. Previous estimates of SGD derived nitrogen inputs to Port Jefferson Harbor are 2.63×10^4 mol N d^{-1} calculated using a hydrologic mass balance model (Gross et al., 1972).