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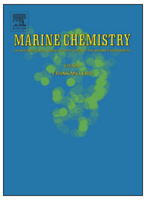

Influence of porewater exchange on nutrient dynamics in two New Zealand estuarine intertidal flats

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ABSTRACT

We use concomitant radon (^{222}Rn, a natural groundwater tracer) and nutrient time series observations upstream and downstream of two New Zealand estuarine intertidal flats to assess porewater exchange rates and/or submarine groundwater discharge (SGD) and their influence on surface water nutrient dynamics. A detailed radon mass balance model and an uncertainty analysis revealed porewater exchange rates of 27 ± 7 and 14 ± 6 cm d^{-1} (or $cm^3\ cm^{-2}\ d^{-1}$) in Waikareao and Te Puna, respectively. The upscaled porewater exchange rates were slightly higher than the creek input upstream of both intertidal flats. A water and salt balance compared to the radon balance indicated that about 16% (Waikareao) and 49% (Te Puna) of the total volume of porewater exchange consisted of fresh SGD and the remaining was related to seawater recirculation in intertidal sediments. Porewater exchange in Waikareao released about 1.9- and 1.6-fold more total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP) than creek inputs at the upstream end of the intertidal flat even though observations followed a 140 mm rain event. Dissolved organic nitrogen (DON) accounted for about 25% of TDN in shallow porewater. Nitrate dominated the nitrogen pool in Waikareao and ammonium was the main form of nitrogen in Te Puna porewaters. These dominant porewater N species were reflected in the surface waters that showed a relative enrichment of nitrate in Waikareao and ammonium in Te Puna as upstream waters travel to the downstream station and collect seeping porewater along the way. We suggest that porewater exchange may act as a buffered nutrient source to the estuary, continually releasing nutrients to surface waters and potentially sustaining primary production when other nutrient inputs cease. This study illustrates that combining bottom up (i.e., porewater exchange flux estimates) and top down (i.e., nutrient response and transformations in the water column) evidence may provide deeper insight when assessing the contribution of porewater to nutrient dynamics in estuaries.

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1. Introduction

Intertidal flats are highly productive, complex environments characterized by active exchange at the sediment–water interface. Sandy intertidal flats may not accumulate organic matter but rather release mineralization products such as nutrients and dissolved inorganic carbon (Billerbeck et al., 2006b) and methane (Røy et al., 2008) on tidal and seasonal time scales. Benthic fluxes in intertidal flats and coastal sediments have been typically estimated under diffusive conditions using benthic chambers (Viollier et al., 2003). In the last decade, there has been an emerging recognition that porewater advection and/or submarine groundwater discharge (SGD) may dramatically enhance benthic fluxes in intertidal flats. For example, in Wadden Sea intertidal flats, advective porewater exchange is a major factor regulating the dynamics of nutrients, alkalinity, dissolved organic carbon (DOC) and trace metals (Beck et al., 2008; Moore et al., 2011). In Korean intertidal flats, shallow porewater was highly enriched in DOC and nutrients relative to terrestrial fresh groundwater (Kim et al., 2012) and linked to high microphytobenthos productivity (Waska and Kim, 2010). In France, porewater seepage from intertidal flats was shown to be a major source of nutrients to Arcachon Bay (Deborde et al., 2008).

A number of recent investigations in oceanic islands such as Hawaii (Knee et al., 2010; Peterson et al., 2009b), Jeju Island (Hwang et al., 2005), Mauritius (Povinec et al., 2012), and Cook Islands (Cyronak et al., 2013; Tait et al., 2013) revealed relatively high and heterogeneous fresh SGD rates as a result of the high rainfall rates, steep relief and high soil permeability. Large volcanic islands such as New Zealand may contribute a disproportionate amount to fresh SGD into the ocean but current global fresh SGD estimates rely primarily on typological extrapolations (Zektser, 2000). These high fresh SGD fluxes from islands combined

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with high solute concentrations may represent a major source of nutrients, carbon and trace metals to the ocean. The immature, permeable soil of many oceanic islands makes their groundwater particularly prone to nitrogen contamination by fertilizers and sewage (Knee et al., 2010). Since oceanic islands are often surrounded by oligotrophic waters, even small inputs of SGD with high dissolved nitrogen concentrations may represent an important source to the nearby ocean (Kim et al., 2013).

While volcanic islands in general may be a hotspot for fresh SGD, a number of physical processes may drive seawater recirculation in sandy intertidal flat sediments. These processes include convection, tidal pumping, bioirrigation, gas bubble upwelling, flow- and topography pressure gradients, and several others (Santos et al., 2012b). The difficulty of modeling this complex combination of physical processes in heterogeneous sandy sediments (Sawyer et al., 2013) has led to the exploration of alternate ways of quantifying the effect of porewater exchange on surface water budgets. The increased use of natural geochemical tracers such as radon and radium isotopes in recent years has contributed to closing knowledge gaps on how porewater exchange contributes to marine biogeochemical cycles (Moore, 2010). These geochemical tracers integrate the signal associated with various groundwater and porewater pathways and may be a good approach to characterize spatially heterogeneous and temporally dynamic systems (Burnett et al., 2006; Stieglitz et al., 2010). Radon (^{222}Rn, half life = 3.84 days) is often highly enriched in groundwater (or porewater) relative to surface waters. In addition, advances in technology now allow continuous, automated radon-in-water measurements (Burnett and Dulaiova, 2003). Using high temporal resolution radon observations to assess SGD and porewater exchange is particularly useful in tidally dominated systems with surface water residence times comparable to the half life of radon.

Tracer investigations typically rely on spatial surveys or time series observations to resolve the contribution of groundwater or porewater to tracer budgets. One of the limitations of spatial surveys is that it may take several hours or days to survey an area of interest (e.g., Santos et al., 2010; Stieglitz et al., 2010). Because tracer concentrations in shallow tidal waters are often highly variable over hourly time scales (Atkins et al., 2013; Dulaiova et al., 2010; Garcia-Orellana et al., 2010; Moore et al., 2011; Peterson et al., 2009b; Stieglitz et al., 2013), it is difficult to determine whether chemical gradients encountered during a spatial survey represent a true snapshot or are a result of temporal variability. In contrast, time series observations alone may not provide insight into the location of groundwater inputs (Burnett et al., 2010; de Weys et al., 2011). This may represent a challenge to achieve an accurate mass balance because major loss terms in radon mass balances (i.e., decay, atmospheric evasion, and mixing) are a function of transport processes between the location where groundwater enters surface waters and the location where tracer observations are made. A number of studies have now combined temporal and spatial observations in estuaries and coastal waters, but the experiments were not necessarily conducted synchronously (Dulaiova et al., 2010; Peterson et al., 2010; Santos et al., 2011), making it difficult to separate spatial from temporal effects. Ideally, several long term time series stations along an estuary would be needed to decrease uncertainty when solving a mass balance, but this is logistically challenging.

In this paper, we use detailed temporal observations at the upper and lower boundaries of estuarine tidal flats in New Zealand to solve a radon mass balance and to assess whether SGD drives nutrient dynamics in surface waters on tidal time scales. We hypothesize that fresh SGD and/or porewater exchange are major sources of nutrients to surface estuarine waters. This paper builds on the literature by (1) investigating SGD for the first time in New Zealand, a major oceanic island; (2) relying on two concomitant time series stations to resolve the radon mass balance over a tidal cycle, and (3) combining bottom up (i.e., porewater-derived nutrient fluxes) and top down (i.e., nutrient responses in estuarine surface waters) approaches to assess the influence of porewater exchange on nutrient dynamics.

2. Methods

2.1. Study site

Field investigations were performed in Tauranga Harbor, a coastal lagoon on the north eastern coast of New Zealand (37°40′S, 176°03′ E; Fig. 1). The harbor has a northern and a southern basin that are poorly connected and separated by intertidal flats (Tay et al., 2013). This study focused on the southern basin which is more developed and receives larger amounts of freshwater input. The southern basin catchment has a total area of 1300 km^2 and a mean freshwater inflow of 30.5 m^3 s^{-1}, most of which is delivered by the Wairoa River (average flow of 17.6 m^3 s^{-1}) (Park, 2004). The average annual rainfall in the region is 1200 mm and daily temperatures range from 5 °C in the winter (June to August) to 25 °C in the summer (December to March) (Tay et al., 2012).

The harbor is a barrier-enclosed estuarine lagoon with many embayments along the landward side. Several of these embayments represent sub-estuaries with constricted mouths and extensive intertidal areas within. Sandy sediments cover most of the estuary (mean grain size of 0.156 mm in Waikareao and 0.281 in Te Puna; Hancock et al., 2009) bottom with an increasing proportion of mud in the upper reaches (Stokes et al., 2010 and references therein). Even though the harbor is microtidal (tidal range from 1.2 to 1.9 m), the system is tidally dominated. The freshwater input into the southern basin represents only 0.5% of the tidal prism volume and about 66% of the 201 km^2 harbor area is intertidal (Park, 2004).

The southern end of Tauranga Harbor is surrounded by the city of Tauranga with a population of about 100,000. The upstream catchment is well developed with extensive horticultural and agricultural use. Increased sediment fluxes in recent years has altered sedimentation patterns within the harbor and caused mangrove colonization of fringing saltmarshes (Stokes et al., 2010). Similar to several other estuaries in New Zealand, Tauranga Harbor is showing signs of nutrient over-enrichment and related algal blooms. Tauranga Estuary has had repeated Ulva. sp. blooms. Long term dissolved nutrient observations are available since 1991 (Tay et al., 2012), but the monitoring program has not focused on resolving the drivers of nutrient dynamics within the estuary.

2.2. Experimental approach

A series of experiments were conducted in Tauranga Harbor (Fig. 1) to provide insight into how porewater exchange may drive nutrient dynamics in the estuary. First, a spatial survey was performed on 7–8 June 2010 to map potential groundwater discharge hotspots and design more quantitative experiments. Second, 24 h time series observations were performed upstream and downstream of two selected sub-estuaries in both the winter (9 Jun 2010 Waikareao and 10 Jun 2010 Te Puna) and summer (24 Jan 2011 Waikareao and 25 Jan 2011 Te Puna). Third, shallow groundwater was sampled to define the endmember concentrations used in a radon mass balance. Fourth, sediment core incubations were performed to estimate diffusive radon inputs.

Radon measurements in surface waters were performed using a Rad7 radon-in-air monitor (Durridge) modified for radon-in-water (Burnett et al., 2001). In short, surface water was continuously pumped at about 3 L min^{-1} into a shower head gas equilibration device with a closed air loop established between the shower head exchanger and the radon-in-air monitor. Water temperature and salinity were used to quantify the solubility of radon and back calculate radon-in-water concentrations (Schubert et al., 2012). The radon analytical uncertainties are a function of the counting time and concentrations encountered. During the survey, readings were integrated over 10 min which yielded analytical uncertainties of 20 to 30% which allow a qualitative assessment only. During the time series, readings were integrated

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