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The influence of groundwater inputs and age on nutrient dynamics in a coral reef lagoon

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ABSTRACT

Tritium dating of groundwater and a radon mass balance was used to assess the contribution of submarine groundwater discharge (SGD) to a nutrient budget in a tropical reef lagoon (Rarotonga, Cook Islands). Open ocean exchange accounted for the largest percentage of potential lagoon exports (nitrogen (N) = 61%, phosphorous (P) = 22%) with N export mostly in the form of dissolved organic nitrogen (DON) (93% of total N). SGD accounted for 29% and 11% of exported N and P respectively. Overall we could account for 92% of dissolved N but only 36% of dissolved P leaving the lagoon. However, if DON is assumed to be recalcitrant, SGD would be the major driver of lagoon N and would account for 81% of dissolved inorganic N (DIN) inputs and 47% of DIN exported form the lagoon. A small scale (~50 m), high definition survey indicated areas of higher NH_4^+ towards the middle of the lagoon. This is indicative of SGD input away from the seepage face and may mean that SGD measurements made at the beach face underestimate the broader contribution of SGD to nutrient fluxes. Time series observations during a 100 mm rain event indicated that these episodes can deliver high nutrient loads to the lagoon and may contribute to closing the phosphorous budget. Analysis of tritium concentrations in groundwater, surface waters and springs showed that old, deep groundwater (10–93 years old) was the main source of SGD derived nutrients to the lagoon. This study demonstrates that there may be a long time lag between nutrient infiltration into aquifers and the discharge of nutrient loaded groundwater into the lagoon. As such, potential mitigation measures which decrease terrestrial nutrient loads may not result in decreased SGD nutrient fluxes for decades to come.

1. Introduction

The flow of excess nutrients into marine waters is a major concern worldwide (Vitousek et al., 1997) and can lead to a range of impacts including adverse human health conditions (Townsend et al., 2003), eutrophication (Rabalais, 2002), and impacts on global nutrient cycling (Galloway et al., 2008; Slomp and Van Cappellen, 2004). A mass balance is an effective way to quantify and compare the various nutrient pathways into natural systems. While many studies have attempted to define and incorporate some portion of nutrient sources and sinks into mass balance budgets, detailing the extensive range of these variables can be difficult and many components of these mass balances remain poorly constrained (Eyre et al., 2011). While sources such as precipitation, river and creek discharge, seawater exchange and nitrogen fixation have all been shown to be important sources of nutrients to receiving waters, determining the contribution of nutrient delivered through submarine groundwater discharge (SGD) may also be essential (Gleeson et al., 2013; Howarth et al., 1996; Seitzinger et al., 2010).

Several studies have quantified SGD nitrogen (N) and phosphorous (P) in coastal lagoon and coral reef systems. Johnson et al. (2008) using thermal infrared imagery showed both diffuse flows and >30 large point source nutrient plumes along a large volcanic island of Hawaii. The SGD nutrient in the study was reported to be the sole source of new nutrient delivery to coastal waters. Kim et al. (2011) reported that >90% of the total dissolved nitrogen inputs to the bays surrounding Jeju Island, Korea can be attributed to SGD. However, other studies have found the contribution of SGD to be less significant. Umezawa et al. (2002), in two Japanese coral reef systems, estimated the contribution of SGD to the total nitrogen budget to be between 6% and 36%, while Liu et al. (2011) report that SGD was responsible for 28% of total dissolved nitrogen inputs in a lagoon on Hainan Island, China. However, there is the potential for studies quantifying SGD to either over or underestimate the contribution of SGD based on the mass balance assumptions and the hydrologic and geologic setting of the study site (Tait et al., 2013b).

In order to determine the flux of nutrients from groundwater into receiving waters, concentrations of nutrient end members must be

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known along with the amount of SGD entering the system. Natural tracers such as radon (^{222}Rn) have increasingly been used to estimate SGD advection rates. Determining SGD fluxes using ^{222}Rn relies on the presence of higher concentrations of ^{222}Rn in sediment porewater than in receiving waters. As groundwater percolates through the sediment profile, ^{222}Rn is discharged from the sediment into the water column. Measurement of ^{222}Rn concentrations in terrestrial end member bores and the water column can then be used to calculate advective rates of SGD. This allows for an integrated approach which incorporates a range of SGD drivers and allows for temporal and spatial variability in SGD fluxes to be smoothed out over time (Burnett et al., 2001; Dimova et al., 2011). However, using radon alone to quantify SGD may not account for large spatial scale or temporal variation.

To characterise the temporal and spatial contribution of groundwater nutrients, determining the age of groundwater may be useful. Groundwater ageing has been used in heterogeneous sub-surface environments where it can be difficult to determine the recent human impact and source of groundwater nutrients (Broers, 2004). A study by Morgenstern et al. (2014) involved age dating springs, bores, and groundwater-fed streams to assess how long it took nutrient-enriched groundwater to travel from pastoral land to lakes on the North Island of New Zealand. The study found that significant fractions of discharged groundwater were recharged before land-use intensification, and that these water discharges did not yet reflect the full effect of current land use practices on groundwater quality. Groundwater dating has also proved useful in determining the source of groundwater. For instance, Bratton et al. (2004) used groundwater dating to show that plumes of freshwater beneath the estuaries of coastal bays on the east coast of the United States were extensions of the surficial aquifer which carried nitrate from recharge on land. The study also found that the brackish groundwater surrounding the fresh water plumes was recharged beneath the estuary and contained high concentrations of ammonium and phosphate.

Natural radioisotopic tracers such as tritium have been proven effective at quantifying the age of nutrient laden groundwater (Morgenstern and Daughney, 2012; Reilly et al., 1994; Scanlon et al., 2002). The tracer tritium is particularly useful as it is not altered by chemical reactions or exchange processes in the unsaturated zone and near the water table (Morgenstern and Daughney, 2012). Tritium is a radioactive isotope of hydrogen (half-life 12.32 years) and can be used to date groundwater from 0 to 100 years of age (Lucas and Unterweger, 2000). It is produced naturally in small amounts in the atmosphere when cosmic rays enter the earth's atmosphere and was produced in larger amounts during the atmospheric H-bomb test in the 1950s and 1960s (Broecker et al., 1985). This has proven problematic for dating groundwater in the past as higher concentrations of tritium introduce a high degree of variability in age estimates. However, in the last decade, southern hemisphere atmospheric tritium concentrations have declined to almost natural cosmogenic concentrations (Morgenstern and Daughney, 2012). Thus it can be assumed that once tritium infused precipitation falls to the earth and infiltrates surface sediments, no further atmospheric tritium can be added and concentrations only decrease though radioactive decay (Morgenstern and Taylor, 2009). To date, no study has attempted to use groundwater ageing in the context of an overall nutrient budget in tropical coral reef lagoons vulnerable to eutrophication.

In this study, we compiled a nutrient budget for a tropical island lagoon that integrates multiple import/export pathways. Moreover, we assess the age of SGD derived nutrients reaching the lagoon in an attempt to characterise the current and future potential contribution of SGD to the lagoon nutrient budget. We build on the existing literature by using tritium to add a temporal quality to the SGD component of the nutrient mass balance and focus on a poorly known aspect of the nitrogen cycle in coral reefs. We then characterise groundwater nutrient dynamics via surveys, time series measurements and groundwater dating to explain the difference in the nutrient inputs and exports in the budget.

2. Methods

2.1. Site description

This study was undertaken in Muri Lagoon (21°14′S 159°47′W) on the main island of Rarotonga in the Cook Islands in the central South Pacific (Fig. 1). Rarotonga is a volcanic and karstic island with an area of 67 km^2. The island is surrounded by a fringing reef between 0.5 km and 1.5 km from shore that averages approximately 2 m deep. The lagoon is 1.75 km^2 in area and has an average residence time of 6.9 days (Tait et al., 2013b). The rugged interior of the island consists of volcanic basaltic and phonolitic soils. The coastal plain which runs from the base of the interior uplands to the shoreline consists of poorly drained inland depressions (taro swamps) and a raised ridge of free draining carbonate sand and gravel (Leslie, 1980). The streams draining into the lagoon are characterised by small drainage catchments and low flows which are punctuated by high discharge/rapid flooding events (Richmond, 1990).

The coastal plain is home to the majority of the commercial, residential and agricultural development on the island. Rarotonga has a resident population of approximately 12,500 and receives approximately 121,000 tourist visitors a year (Cook Islands Government, Accessed, 14 February, 2014). Septic tanks are common on Rarotonga with the septic effluent mostly flowing into traditional soak pits or small drainage fields (Dakers and Evans, 2007). Low density animal husbandry exists throughout the island with animal wastes mostly allowed to accumulate or flow into taro swamp drains. Rarotonga is located south of the South Subtropical Current which imparts a predominantly south westerly current on Rarotonga (Thompson, 1986). It has a semi-diurnal lunar tide with a range of approximately 1 m and the circulation and flushing of the lagoon is primarily driven by wave setup over the reef crest (Holden, 1992).

2.1.1. Nutrient mass balance

A nutrient mass balance for the lagoon was constructed by considering the input/export pathways outlined in Fig. 2. The lagoon area was delineated using the drogue deployments of Holden (1992) and aerial photographs. For calculating nutrient inputs, precipitation, surface waters, seawater exchange and SGD were measured in February 2011 and all rates normalized over a 24 hr period. For exports, the lagoon acts much like a one directional river. Breaking waves over the reef crest fill the lagoon at high tide and cause a predominantly outgoing current at the lagoon mouth (Holden, 1992; Tait et al., 2013b). Therefore we were simply able to measure the flow rate and nutrient concentrations at the lagoon mouth over a 24 hour period.

2.2. N and P inputs

To determine groundwater end member nutrient concentrations, a series of inland bores were sampled in February 2011 (Fig. 1). The bores ranged in depth from 2 m to 20 m and ranged from 10 m to 250 m inland from the shoreline. To determine SGD nutrient fluxes, the average nutrient concentration in the groundwater bores was multiplied by the average SGD estimate determined via the average of three SGD flux models generated for Muri Lagoon [31,454 ± 10,394 m^3 day^{-1}; Tait et al., 2013b]. Beach groundwater springs were limited, with the only identifiable spring (Titi Spring, Fig. 1) sampled for nutrient and groundwater ages. The spring flowed from under consolidated beach rock just below the high tide mark. The spring was not included in the nutrient mass balance calculations due to its limited flow and lack of similar springs along the coastline. Stream flows and nutrient concentration samples were taken from the six surface flow streams entering Muri Lagoon at the nearest point to the coast that was not tidally affected. Due to the shallow depth of the streams (1–5 cm), a floating object over a set distance was used to determine flow rates, with rates averaged over five trials. Stream nutrient inputs were calculated by multiplying the