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Estimation of nearshore groundwater discharge and its potential effects on a fringing coral reef

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ABSTRACT

Radon (^{222}Rn) measurements were conducted in Shiraho Reef (Okinawa, Japan) to investigate nearshore submarine groundwater discharge ($SGD_{nearshore}$) dynamics. Estimated average groundwater flux was 2–3 cm/h (maximum 7–8 cm/h). End-member radon concentration and gas transfer coefficient were identified as major factors influencing flux estimation accuracy. For the 7-km long reef, $SGD_{nearshore}$ was 0.39–0.58 m^3/s, less than 30% of Todoroki River's baseflow discharge. $SGD_{nearshore}$ was spatially and temporally variable, reflecting the strong influence of subsurface geology, tidal pumping, groundwater recharge, and hydraulic gradient. $SGD_{nearshore}$ elevated nearshore nitrate concentrations (0.8–2.2 mg/l) to half of Todoroki River's baseflow NO_3^-–N (2–4 mg/L). This increased nearshore Chl-*a* from 0.5–2 μg/l compared to the typically low Chl-*a* (<0.1–0.4 μg/l) in the moat. Diatoms and cyanobacteria concentrations exhibited an increasing trend. However, the percentage contributions of diatoms and cyanobacteria significantly decreased and increased, respectively. SGD may significantly induce the proliferation of cyanobacteria in nearshore reef areas.

1. Introduction

Submarine groundwater discharge (SGD) may account for a significant fraction of the freshwater inflow in areas where river input is not significant (Valiela and D'Elia, 1990). SGD is ecologically significant as it is an important pathway for nutrients and other dissolved species (Simmons, 1992; Slomp and Van Cappellen, 2004). Groundwater discharge conditions at the coastal boundary are both intriguing and complex, as they are strongly influenced by the tides, modifying the location of the discharge zone, quantity and quality of discharge, and direction of flow (Urish and McKenna, 2004). Furthermore, the discharge from a sandy beach is typically composed of both a freshwater component from landward-based recharge and a salt water component from flood tide infiltration in the intertidal zone (Urish and McKenna, 2004).

Many studies have been conducted to estimate submarine groundwater discharge using various methods. In particular, natural tracers, such as radium and radon isotopes, have been utilized extensively to describe SGD and quantify its rates. Radon-222 (^{222}Rn) is a naturally occurring inert gas produced by the decay of radium-226 (^{226}Ra) within the decay chain of uranium-238. ^{222}Rn ($t_{1/2}$ = 3.8 days) emanates from the surface of mineral grains by recoil and enters the water-filled pore space of sediments and aquifers. The use of radon as an SGD tracer is largely due to the fact that radon activity in groundwater is much higher by 2–4 orders of magnitude than in surface water. In addition, being a noble gas, radon is not likely to be influenced by salinity, redox, and diagenetic conditions present in aquatic environments (Dulaiova et al., 2008). However, porewater ^{222}Rn activities may considerably be affected by the presence of ^{226}Ra which accumulates with manganese hydroxides in a thin layer (i.e., the salinity transition zone) in the subterranean estuary (Dulaiova et al., 2008). Where the discharge is fresh or a mixture of fresh and recirculated seawater, radon has a greater utility than radium as an SGD tracer since any groundwater in the aquifer that is in contact with sediments and rocks is enriched in radon (Dulaiova et al., 2008). Radon monitoring has been successfully employed in a number of studies either singly (e.g. Burnett and Dulaiova, 2003; Lambert and Burnett, 2003; Tse and Jiao, 2008) or in combination with other natural or artificial geochemical tracers (e.g. Cable et al., 1996; Crusius et al., 2005a,b; Dulaiova et al., 2006; Cable and Martin, 2008). While a considerable number of radon-SGD studies were conducted in open beaches and coastal ocean shores, very few attempts have been made in reef environ-

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ments. Radon measurements were conducted in the Great Barrier Reef but only to identify zones affected by groundwater discharge (see Stieglitz, 2005). Considering that most coral reefs are less influenced by direct freshwater discharge, groundwater discharge can be considerable and exerts a significant effect on reef ecosystem. Conventional approaches (e.g. seepage meters) and innovative methods (e.g. weir method, see Hays and Ullman, 2007) have been employed in coral reefs. The weir method basically involves forming a tidal pond by trapping discharged water from the shoreline and then measuring discharge from this pond using a weir (Hays and Ullman, 2007). However, these methods are tedious and time-consuming. Furthermore, seepage meters are difficult to use in coral reefs where groundwater discharge occurs above sea level during low tides (Umezawa et al., 2002a). On the other hand, the weir approach can only be used over a very limited time (i.e., few hours during low tide). With the reported relative ease in measurement (due to the development of portable radon-in-air monitors) and reasonably accurate results, the radon approach is promising for groundwater discharge estimation in reef areas.

Shiraho Reef, located on the east coast of Ishigaki Island in the southwest portion of Japan (Fig. 1), has been subjected to various environmental stresses such as sedimentation (Omija et al., 1998; Mitsumoto et al., 2000) and nutrient discharge (Umezawa et al., 2002a; Nakasone et al., 2001; Blanco et al., 2008). Together with other stresses such as high temperatures and grazing by crown-of-thorns starfishes (COTS), these have resulted in the degradation of the reef. Only one river, the Todoroki River, discharges into the reef. This river transports sediment and nutrient loads from the Todoroki watershed, mostly during typhoons and strong rainfall events. Under normal conditions, the river plume affects reef areas around the river mouth and its immediate north (Tamura et al., 2007). During typhoons, the plume travels farther northwards or southwards depending on wind direction. Thus, south Shiraho Reef, in particular, is not so much influenced by river discharge. However, groundwater discharge from land areas adjacent to the coral reef can be significant and is an important source of nutrients (Umezawa et al., 2002a) owing to the fact that the adjacent lands are overlaid with permeable bedrock (e.g. limestone). For Shiraho Reef, studies on groundwater discharge and associated nutrient loading were so far limited to annual groundwater discharge estimated based on monthly precipitation and evaporation data and land use information (see Umezawa et al., 2002a). Based on these methods, groundwater discharge was found to be contributing significantly to the nitrogen budget (i.e., 36% of the total N input) of southern Shiraho Reef. Considering the time scale and inherent uncertainties in these estimation approaches, more detailed investigation on groundwater discharge dynamics and associated nutrient loadings are warranted. However, groundwater discharge measurements, which are needed to accurately determine discharge rates, are lacking and thus, more accurate quantitative methods (e.g. radon approach) must be evaluated.

Some studies have investigated the effect of groundwater discharge and associated nutrient loads on the biota of Shiraho fringing reef. Using stable nitrogen isotope ratio (δ^{15}N) as a tracer of terrestrial N input, Umezawa et al. (2002b) found that terrestrial N was primarily used by nearshore macroalgae based on the decreasing value of the isotope as distance from the shoreline increases. Higher concentration of benthic microalgae were found in nearshore areas where salinity was low and nutrient concentrations were high, jointly indicative of groundwater effect (Blanco et al., 2008). However, both studies have focused on the spatial variation of groundwater influence. Though the δ^{15}N study involves a temporal component in that δ^{15}N indicates integrated N utilization over a certain period of time, information on the response of primary producers over shorter time scales is desirable.

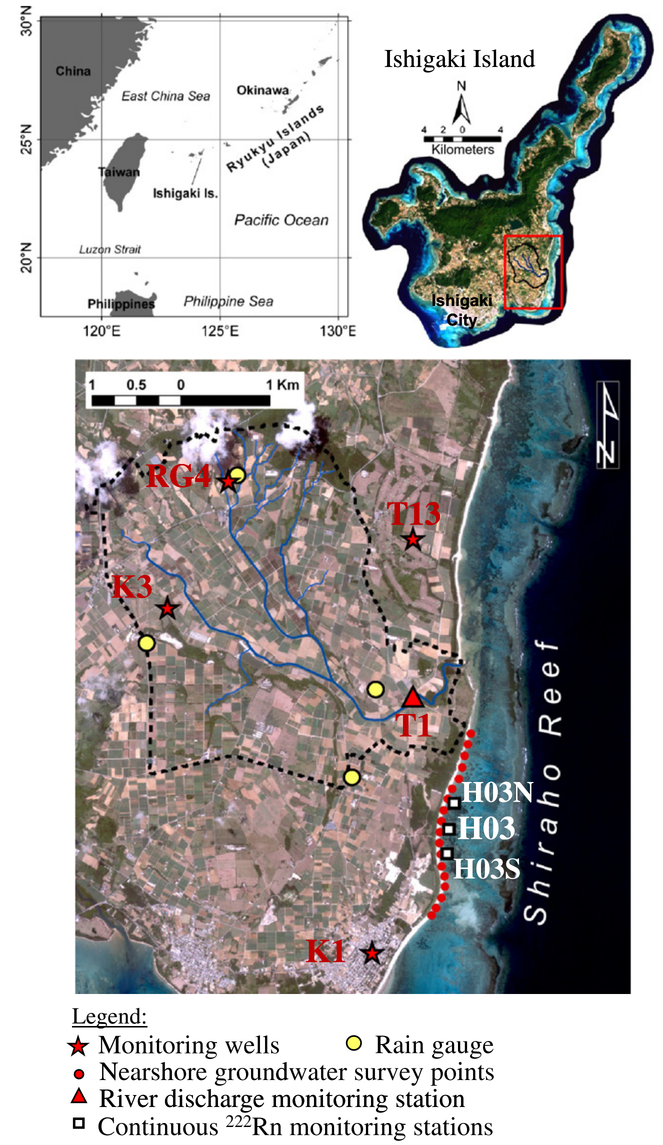

Fig. 1. The study site: Shiraho Reef in Ishigaki Island (Okinawa, Japan). Water quality measurements and water sampling were made at several points (●) along the shoreline during low tide (23 July 2008; 30 January 2009). Radon monitoring was conducted at stations H03, H03N, and H03S. Water level is monitored at wells RG4, T13, K3 and K1.

In Shiraho Reef, phytoplankton response to groundwater discharge has not been investigated.

In this study, foreshore groundwater discharge dynamics were investigated by monitoring radon concentration and salinity. To address associated uncertainties (e.g. atmospheric evasion) in the estimation of SGD rates, a sensitivity analysis was performed. Groundwater discharge was also estimated using a salinity model based on mass balance approach. The influence of groundwater seepage on the nutrient concentration, Chl-*a* level and phytoplankton community composition in the nearshore reef area was also examined.

2. Materials and methods

2.1. Study site

Shiraho Reef is a well-developed fringing reef with typical topographic features such as reef pavement, reef crest, moat (i.e., the