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Research papers

Nutrient inputs through submarine groundwater discharge in an embayment: A radon investigation in Daya Bay, China

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ABSTRACT

Daya Bay, a semi-closed bay of the South China Sea, is famous for its aquaculture, agriculture and tourism. Although routine environmental investigations in the bay have been conducted since the early 1980s, evaluations of submarine groundwater discharge (SGD), an important process in exchange between groundwater and coastal seawater, and its environmental impacts have never been reported. In this study, naturally occurring radon isotope (^{222}Rn) was measured continuously at two sites (north-west and middle-east sites) and used as a tracer to estimate SGD and associated nutrient inputs into the bay. The SGD rates estimated based on the ^{222}Rn mass balance model were, on average, 28.2 cm/d at north-west site and 30.9 cm/d at middle-east site. The large SGD rate at middle-east site may be due to the large tidal amplitude and the sandy component with high permeability in sediments. The SGD-driven nutrient fluxes, which were calculated as the product of SGD flux and the difference of nutrient concentrations between coastal groundwater and seawater, were 3.28×10^5 mol/d for dissolved nitrates (NO_3–N), 5.84×10^3 mol/d for dissolved inorganic phosphorous (DIP), and 8.97×10^5 mol/d for reactive silicate (Si). These nutrient inputs are comparable to or even higher than those supplied by local rivers. In addition, these SGD-driven nutrients have a nitrogen-phosphorous ratio as high as ~43, which may significantly affect the ecology of coastal waters and lead to frequent occurrence of harmful algal blooms.

1. Introduction

Submarine groundwater discharge (SGD), which includes both fresh groundwater and infiltrated seawater with enrichment of nutrients, plays an important role in transport of water and dissolved materials such as nutrients, metals, and carbon from land to the coastal ocean (Charette, 2007; Lee et al., 2009; Liu et al., 2012; Luo et al., 2014; Wang et al., 2014; Lecher et al., 2015; Rodellas et al., 2015). More importantly, fluxes of nutrients from SGD are comparable to or even higher than those supplied by riverine and atmospheric sources in some areas (Kim et al., 2005; Hwang et al., 2005; Swarzenski et al., 2007; Rodellas et al., 2015). Such nutrient inputs may lead to various environmental problems such as harmful algal blooms and red tides which can deteriorate coastal ecosystems including corals, mangroves in coastal zones (Hu et al., 2006; Blanco et al., 2011; Su et al., 2013; Luo and Jiao, 2016).

SGD has been estimated widely using natural geochemical tracers such as radium isotopes (Moore, 1996; Kim et al., 2005; Moore et al., 2008; Peterson et al., 2008; Wang et al., 2015; Kim et al., 2015) and radon (Burnett and Dulaiova, 2003; Tse and Jiao, 2008; Gattacceca et al., 2011; Gleeson et al., 2013; Schubert et al., 2014; Sadat-Noori et al., 2015; Schubert et al., 2015). Natural radon (^{222}Rn) has a half life of 3.8 days, and is a non-reactive noble gas widely enriched in coastal groundwater. In addition, ^{222}Rn is easy to be measured and not likely to be influenced by the salinity, which make this tracer very useful for quantifying groundwater discharge into lakes, rivers and the coastal ocean (Cable et al., 1996; Burnett and Dulaiova, 2003; Smith et al., 2008; Schmidt et al., 2010; Santos et al., 2011).

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In the past decades, nutrient inputs from aquaculture, urbanization and anthropogenic discharge are increasing in Daya Bay, a semi-closed bay located in the northwestern part of the South China Sea (Wang et al., 2008). As a consequence, Daya Bay has become seriously eutrophic with the frequent (almost every year) occurrence of harmful algal blooms (Song et al., 2004, 2009). Although routine environmental investigations have been conducted in Daya Bay since the early 1980s (Zhou et al., 1998; Wang et al., 2008), the estimations of SGD and associated nutrient flux are never reported. Here, focusing on SGD and its influence on marine environments, we use natural radon isotope as tracer to estimate the fluxes of SGD and the associated nutrient inputs into Daya Bay and to evaluate their possible impact on the coastal ecosystem.

2. Materials and methods

2.1. Study area

Daya Bay, a semi-enclosed subtropical shallow embayment of northern South China Sea, is located at 22.45°-22.83°N, 114.50°-114.89°E, in the eastern coast of Guangdong Province, China (Fig. 1). It is one of a series of large bays along the southern coast of China and covers an area of ~550 km^2 in the waters, with a width of about 20 km and a north–south length of about 30 km. Water depth in Daya Bay ranges from 6 to 16 m with an average of 10 m, and is less than 10 m deep in approximately 60% of the area of the bay (Xu, 1989). Tidal current in the region is dominated by a semidiurnal irregular tide with a mean and maximum tidal range of 1.03 m and 2.60 m, respectively. The average annual temperature and precipitation controlled by subtropical and monsoonal climate are 22 °C and 1700 mm, respectively. About 80 percent of precipitation occurs from April to September. The strong northeast monsoon prevails from October to April; and the southwest monsoon predominates from May to September. The mean resident time of surface seawater is 3.2 days (Wang et al., 1996).

There is no large river discharging into the bay but several seasonal rivers (Han, 1995). DanAo River, with a mean flux of 3.14 × 10^5 m^3/d, is the largest one running into the bay in short distances. Since the early 1980s, there has been a rapid economic development in the region and it has now become an important aquacultural area in Guangdong Province with abundant fishery resources. In addition, it is a diverse area rife with agricultural, seaport transportation, industrial and tourist activities.

2.2. Methods

2.2.1. ^{222}Rn mass balance model

Burnett and Dulaiova (2003) derived a model to quantify SGD based on continuous measurements of ^{222}Rn. This model is further extended and used in many researches (e.g., Wu et al., 2013; Tse and Jiao, 2008; Zhang et al., 2016). In general, the variations of ^{222}Rn in the system are influenced by several important processes, such as ingrowth from the dissolved ^{226}Ra, SGD, diffusion from sediments, radioactive decay, tidal transportation, atmospheric evasion and mixing loss to the lower concentration waters offshore. Thus, the ^{222}Rn mass balance equation in a water body can be written as follows,

$$\frac{dI}{dt} = F_{SGD} + F_{tide} + F_{sed} - F_{atm} - F_{mix} - F_{dec} \quad (1)$$

where I is the excess ^{222}Rn inventory, t is the measurement time, F_{SGD} is the ^{222}Rn flux attributed to SGD, F_{tide} is the flux induced by

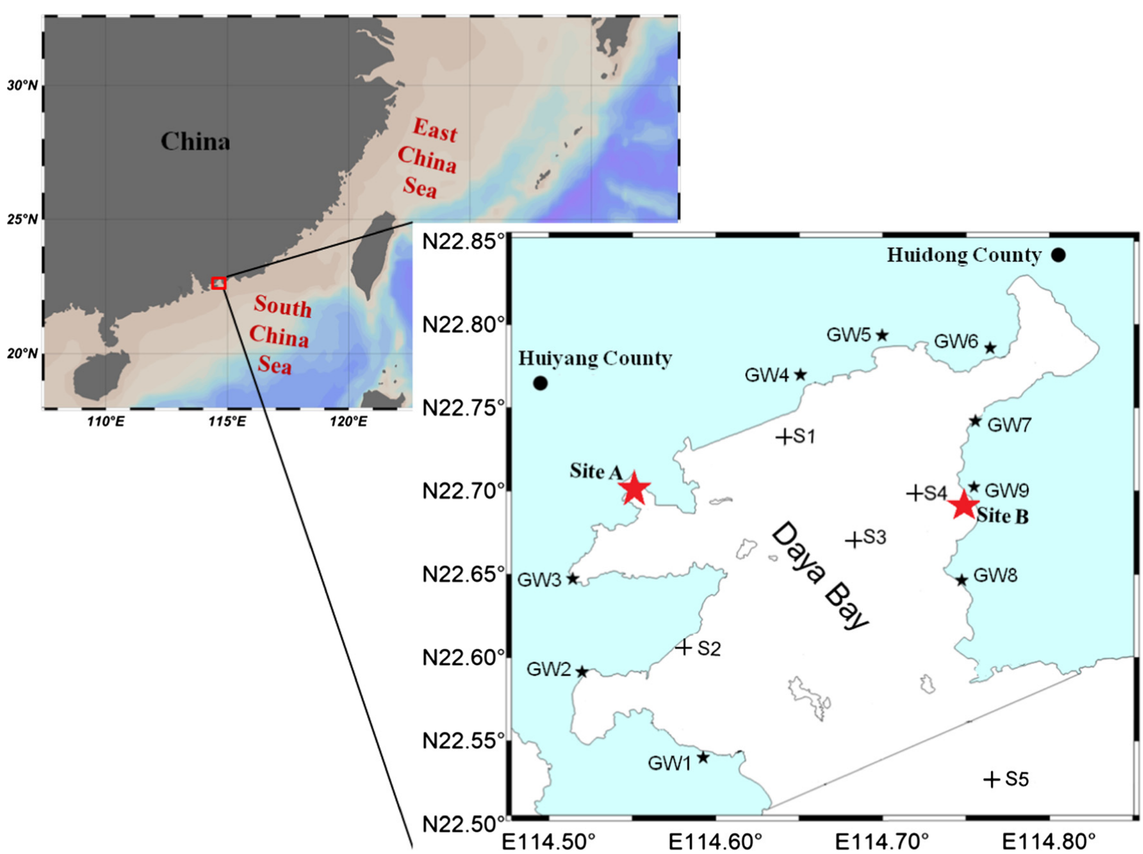

Fig. 1. Location maps of the Daya Bay. The black stars and crossed denote sampling stations for groundwater (GW) and sediments (S), respectively. Site A and B are the continuous ^{222}Rn monitoring stations.