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Submarine groundwater discharge estimation in an urbanized embayment in Hong Kong via short-lived radium isotopes and its implication of nutrient loadings and primary production

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ABSTRACT

^{224}Ra and ^{223}Ra are adopted as tracers to qualify submarine groundwater discharge (SGD) in Tolo Harbor, a highly urbanized embayment in Hong Kong. Based on the sampling data, a two-layered radium mass balance model is used to estimate lateral SGD and bottom SGD. Total SGD is estimated to be 1.2–3.0 cm d^{-1}, including lateral SGD of 5.7–7.9 cm d^{-1} and bottom SGD of 0.3–2.0 cm d^{-1}. Fresh SGD is estimated to be $(2.1–5.5) \times 10^5$ m^3 d^{-1}. Nutrient fluxes (mol d^{-1}) from SGD are estimated to be $(3–7.4) \times 10^4$ (dissolved inorganic nitrogen), $(2.4–6.2) \times 10^2$ (dissolved inorganic phosphate) and $(6.5–16) \times 10^4$ (dissolved silicate). Primary productivity is estimated to be $(1.5–15) \times 10^6$ gC d^{-1}, 2–53% of which is supported by SGD-induced phosphate fluxes. The study indicates that SGD is a significant source of nutrients to coastal waters and may cause an obvious increase of primary production. These findings must be considered in future coastal ecological management.

1. Introduction

Submarine groundwater discharge (SGD) has been widely studied for decades (Johannes and Hearn, 1985; Cable et al., 1996; Moore, 1996; Li et al., 1999; Burnett et al., 2001, 2003; Taniguchi et al., 2002; Moore et al., 2008). Burnett et al. (2003) defined SGD as any or all water on continental margins coming from the seabed to the coastal oceans regardless of fluid composition or driving forces. SGD is comprised of terrestrial freshwater and infiltrated seawater; these components react with sediments in coastal aquifers, releasing nutrients, carbon and metals (Moore et al., 2008). Because it supplies freshwater as well as important chemical constituents to coastal waters, SGD is a major component of the global hydrogeological cycle (Moore, 1996; Kim et al., 2005; Moore et al., 2008). The mixing zone between fresh groundwater and sea water in coastal aquifers has been called a subterranean estuary by Moore (1999). Subterranean estuary groundwater usually is concentrated in various chemicals, which makes SGD a significant material exchange process between marginal land and coastal waters (Li et al., 1999). Slomp and Van Cappellen (2004) and Hwang et al. (2005) indicated that SGD induces large nutrient input into coastal zones. Charette and Buesseler (2004) proved that SGD is a relatively small source of copper to the estuary compared to the main input contributed by boat paints. Windom et al. (2006) illustrated SGD can be an important pathway for dissolved iron flux into ocean. SGD can also lead to large rare earth element input (Johannesson et al., 2011; Kim and Kim, 2011) and can be a potential source of mercury and arsenic (Bone et al., 2006; Black et al., 2009; Lee, 2011). Moreover, it has been shown that SGD can cause large fluxes of DIC and DOC into coastal waters (Paytan et al. 2006; Liu, 2011; Moore, 2011; Santos et al., 2012). Large fluxes of nutrients, carbon and trace elements derived from SGD would greatly affect coastal ecosystems. Kim et al. (2011) showed that nutrients derived from SGD can enhance net primary productivity in the coastal zone. Hu et al. (2006) and Lee and Kim (2007) revealed a compelling relationship between SGD derived nutrient flux and red tide blooms. Boehm et al. (2004) showed that growth or increased persistence of fecal indicator bacterial (FIB) is associated with SGD. Radium isotopes (^{223}Ra, ^{224}Ra, ^{226}Ra, ^{228}Ra) are highly concentrated in coastal groundwater and show conservatively mixing (after decay is considered) during hydrogeological processes. This makes them ideal chemical tracers to qualify SGD and water mass ages in coastal zones (Moore, 2000; Hougham and Moran, 2007; Kim et al., 2008).

Tolo Harbor, locating at the north western of New Territories in Hong Kong, China, is a semi-closed embayment (Fig. 1A). It has been highly urbanized in the past 30 years as human population

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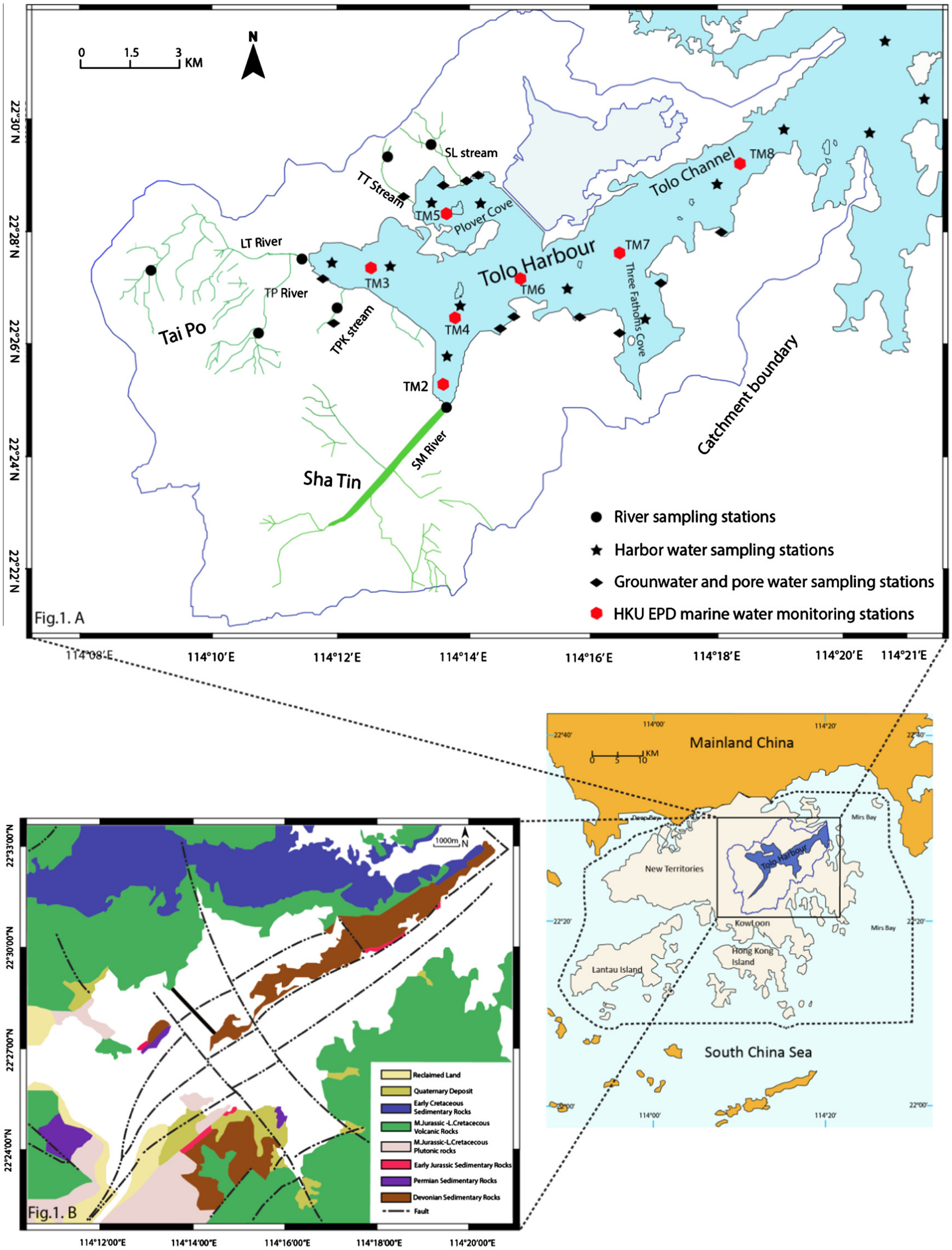

Fig. 1. River water, groundwater water and harbor seawater sampling stations distribution (A) Geological setting map of Tolo Harbor (B) (A) modified from Lee et al. (2012), (B) modified from Fyfe et al. (2000)).

expanded from 70,000 in 1973 to over 1 million after 2000 (Tse and Jiao, 2008). The weakly flushed harbor experienced frequent algal blooms due to eutrophication caused by high nutrient loadings from anthropogenic waste discharge (Lee and Arega, 1999), sediment release (Hu et al., 2001) as well as SGD. The land-locked topography, relatively long flushing time and prevailing easterly winds prevent the effective flushing of nutrients from the harbor (Tse and Jiao, 2008; Lee et al., 2012).

A previous SGD study conducted by Lee et al. (2012) in this area calculated a total SGD of $8.28 \times 10^6\ m^3\ d^{-1}$ based on ^{226}Ra mass balance model. A further catchment water mass budget indicated a fresh SGD of $2.31 \times 10^5\ m^3\ d^{-1}$. Our results indicate that total SGD in Lee et al. (2012) is overestimated due to underestimation of radium concentrations in groundwater. A repeated and modified measurement of the same ^{226}Ra samples of Lee et al. (2012) shows that ^{226}Ra activities in coastal groundwater should be much higher (around 2.5 times) than that in Lee et al. (2012) (unpublished data), which consequently produces a lower total SGD.

Tolo Harbor has an overall surface area of 52 km, an average depth of 12 m and a shoreline of 82 km (Fig. 1A). It extends about