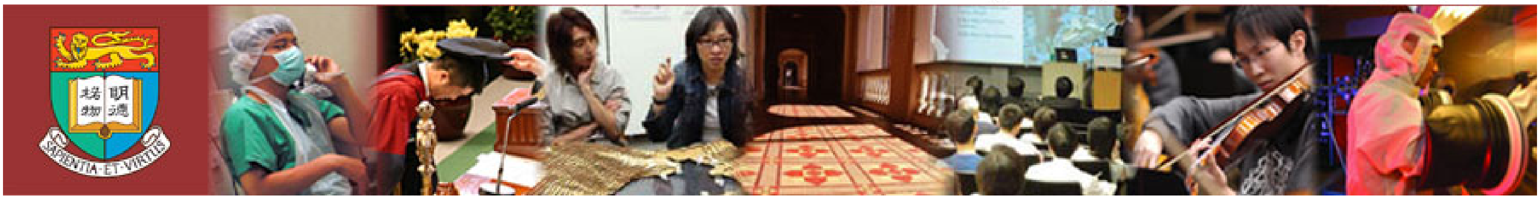

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Estimation of submarine groundwater discharge in Plover Cove, Tolo Harbour, Hong Kong by ^{222}Rn

Kiu Chung Tse, Jiu Jimmy Jiao*

Department of Earth Sciences, the University of Hong Kong,

Hong Kong Special Administrative Region, China

*Corresponding author

Abstract

Algal blooms in Tolo Harbour, Hong Kong have received much attention and submarine groundwater discharge is speculated to be a significant pathway carrying nutrients into the constricted estuary. Plover Cove, a small cove in the Harbour, was selected for SGD analysis using ^{222}Rn budget. The volumetric SGD rates are estimated to be about 8,000 m^3/day for neap tide and about 17,000 m^3/day for spring tide. Result of nutrient analysis of the porewater indicates that the nutrient loading through this pathway is speculated to be crucial for eutrophication in Tolo Harbour. Current practice for the management of algal blooms in Hong Kong, in which nutrient loading through SGD was ignored, has to be reviewed and the control measures of groundwater contamination are obviously required.

Index terms: Geochemical tracers; Groundwater hydrology; Groundwater transport; Hydrological cycles and budgets; Pollution: urban, regional and global.

Introduction

Tolo Harbour is located in the northeastern part of Hong Kong's New Territories (Figure 1). It is susceptible to pollution because of the bottlenecked coastline configuration as well as the prevailing northeasterly wind direction (Yin, 2003). Current is low for the harbour and the estimated water residence times in the inner harbour range from 16-42 days (Hodgkiss and Yim, 1995). All these factors result in preventing the pollutants to be removed effectively. While the harbour is already under stress due to natural factors, urban development since 1970s has further deteriorated the water quality. Dramatic expansion of human population, from 70 000 in 1973 to 1 000 000 in 1990, has degraded the environment.

As a consequence, algal bloom incidents increased from 1 per year in 1978 to over 40 in 1988 (Holmes, 1988; Environmental Protection Department (EPD), 2004). Holmes (1988) has attributed the environmental degradation to reduction of the mangrove coastline through the process of land reclamation. The mangrove coastline serves as an effective sink for nutrients, so the loss of this natural resource shifts the primary biological productivity to planktonic algae.

In order to alleviate the pollutant loading on Tolo Harbour, the government has enforced the Tolo Harbour Action Plan in 1988 which included livestock waste control, sewage treatment modification, effluent export scheme, legistration enforcement and landfill restoration. An ecosystem model, which was developed for the Hong Kong government, claimed that the concentrations of ammonia and nitrate could drop to zero after the Action Plan was implemented (Holmes, 1988). After the action plan has been implemented, the number of algal bloom incidents has been decreased to ~10 incidents per year. The total phytoplankton densities, however, were still 2-6 times higher at stations in Tolo Harbour and Channel than those in other water control zones over Hong Kong (EPD, 2004). Xu et al. (2004) showed that the loadings of total phosphorus and total nitrogen in Tolo Harbour even reached another peaks in 1996 and 1998 respectively. It is speculated that the phytoplankton may be sustained by nutrients from other sources.

Hodgkiss and Ho (1997) suggested that implementation of the Tolo Harbour Action Plan resulted in a lower N:P ratio which led to a shift in algal species compostion from diatoms to dinoflagellates and the dominance of dinoflagellates was the major cause of the dramatic increase in red tide occurrence. This replacement of algal species was neither found by Yung et al. (1997) nor supported by the long-term monitoring by EPD. Hu et al. (2001) conducted a sediment diffusion experiment by placing undisturbed sediment core into a settling column in laboratory and adding water sample collected from corresponding site. They demonstrated that sediments can release 0.5 mmol of orthophosphate phosphorus and 2.2 mmol of nitrate-nitrite nitrogen per square metre per day.

Recently research in other coastal areas indicates that the direct discharge of groundwater into the coastal zone may be a potentially significant pathway of dissolved nutrients into the coastal environment (Laroche et al., 1997; Griggs et al., 2003; Miller and Ullman, 2004). Terrestrial groundwater can discharge into the sea directly in response to the hydraulic gradient, with groundwater head higher than sea level (Johannes, 1980). Li and Jiao (2002) proposed a tide-induced seawater-groundwater circulation that SGD happens even in the absence of net inland recharge of groundwater.

It is speculated that eutrophication in Tolo Harbour may be attributed to the nutrient fluxes through the pathway of submarine groundwater discharge (SGD). Tolo Harbour is enclosed by such a large catchment that the amount of SGD is believed to be comparable to the river water flux. This study focused on Plover Cove that has no major river system.

Plover Cove is adjacent to a mountain range including Wong Leng (639 m) and Pat Sin Leng (500-600 m), with a surface area of around 4 km^2 (Figure 1). Radium study was conducted for Tolo Harbour (Tse, 2006) and based on this radium study, Plover Cove is identified as a key area in Tolo Harbour receiving potentially significant amount of SGD and details of the radium study can be found in Tse (2006). The current paper focuses on radon study and the SGD flux was estimated by ^{222}Rn following the approach described by Burnett and Dulaiova (2003).

Background of the Site

The overall surface area for Tolo Harbour is 52 km^2 including the part of Tolo Channel. In the inner harbour the water depth is less than 10m, while along the channel the average depth is about 12 m. The mean sea level is 1.15 m above Principal Datum (mPD), with average diurnal tidal range of 0.97 m (EPD, 1994). There are several rivers entering Tolo Harbour and according to the monitoring data between 1998 and 2004 from EPD, the total annual discharge rate is 3.61×10^{10} m^3/yr. The mean annual rainfall is 2214 mm.

Tolo Harbour is enclosed by a large catchment with an area of 50 km^2. The catchment is formed by three main mountainous blocks divided by the new towns Tai Po and Sha Tin. The geology was described in detail by Tam (1980), Addison (1986) and Lai et al. (1996). The district is formed mainly of Mesozoic stratified pyroclastic rocks sandwiched between the Mesozoic sedimentary rocks, with sandstone, siltstone and conglomerate above and marine mudstone and siltstone below.

The volcanic rocks are intruded by a complex granitic pluton at the age of Late Jurassic to Early Cretaceous, which crops out at the low-lying areas. A series of faults trending northeast and northwest was generated and one of the biggest faults is the Lai

Chi Kok – Tolo Channel Fault which belongs to a fault zone extending across Sha Tin Valley to Tolo Channel.

The superficial soils, including the mantle of weathered rock, colluvium, alluvium and beach sand are considered as shallow unconfined aquifer, which can be over 20 m thick (Ruxton and Berry, 1957). The sandy deposit is subsequently replaced by silt or marine mud in the estuary which serves as an extensive layer of aquitard. There are successive layers of marine and alluvial deposits underlain the Holocene marine mud, which indicates that channelized sand bodies can be found offshore as confined aquifers. These channels are potentially fresh if they are hydraulically connected with the recharge area onshore.

The bedrock, according to the degree of decomposition, varies from fresh rock to residual soil. Fracture zones exist along the rockhead below the decomposed rock which form a relatively deep confined aquifer (Jiao et al., 2005; Jiao et al., 2006).

Grant (1989) investigated the permeability in Lam Tsuen and Tolo Harbour Areas and in his study, the permeabilities of alluvial plain and terrace lands are 1.17×10^{-4} m/s and 2.17×10^{-4} m/s respectively.

Methodology

The SGD flux was estimated by ^{222}Rn following the approach described by Burnett and Dulaiova (2003). In general, ^{222}Rn concentration in the system is influenced by various sources and sinks, such as ingrowth from ^{226}Ra dissolved in the water, tidal effect, atmospheric loss, diffusion from sediments, mixing loss to the open sea and SGD (Figure 2). An increase or decrease of ^{222}Rn concentration over a time interval is referred to the net balance between these sources and sinks during that period. ^{222}Rn concentrations in coastal waters are measured continuously to determine the difference between two successive measurements. This is then corrected for all other sources and sinks to obtain the ^{222}Rn flux attributed to SGD. With this flux divided by ^{222}Rn concentration in fresh groundwater or porewater, the SGD flux is computed.

$$F_{SGD} = F_t - F_{sed} - F_o + F_{atm} + F_i + F_m \quad (1)$$

where F_{SGD} is the ^{222}Rn flux attributed to SGD

F_t is the difference in concentrations of excess ^{222}Rn between two successive hours

F_{sed} is the flux diffused from sediments

F_o is the flux leaving with the outgoing tide

F_{atm} is the flux into the atmosphere

F_i is the flux entering with the incoming tide

F_m is the flux out of the system by mixing

A site in Plover Cove was selected for ^{222}Rn analysis in July 2005. ^{222}Rn in coastal waters was monitored continuously by a commercially available radon-in-air monitoring system called RAD7 produced by Durridge Co., Inc. for four days, with 48 hours during the neap tide (14-16 July) and 48 hours during the spring tide (21-23 July). In the meantime, water depth was estimated from the iron framework where a height indicator was made. Water samples were collected bihourly for ^{226}Ra analysis. Sediments were collected from the sea bottom to estimate ^{222}Rn in porewater. Wind speed, salinity, air and water temperatures were measured manually every 10 minutes. At the same time, a continuous heat-type automated seepage meter (Taniguchi and Iwakawa, 2001) was also deployed for direct SGD measurement. It was pushed into the sea bottom and programmed to take readings every 6 s. During the sampling period, monitoring of ^{222}Rn in coastal waters was suspended twice: from 00:23, July 16 onwards to measure ^{222}Rn in ambient air, and from 05:00, July 22 onwards because of a storm. ^{222}Rn in groundwater from two private wells (Po Sum Pai and Chim Uk) was collected and measured in March 2006. Po Sum Pai private well is situated on Quaternary deposits of volcanic rocks with a depth of 2.7 m, while Chim Uk private well is situated on granitic rocks with a depth of 3.3 m.

Continuous Monitoring of ^{222}Rn

In order to monitor ^{222}Rn in coastal waters continuously, an iron framework was placed on the sea bottom on which the submersible pump was fastened so that it was fixed at 0.5 m above the sea bottom. Seawater was pumped out and filtered through a 1 μm cartridge filter to screen out the particulates. It was then sparged into an air-water exchanger where radon was distributed from the running flow of water to a closed air loop until the two phases reached equilibrium. The air stream was then fed to the RAD7 for measurement, which was converted to ^{222}Rn in the water by the following equation (Durridge Co., Inc., 2001),

$$\alpha = 0.105 + 0.405 e^{-0.0502T} \quad (2)$$

where α is the partition coefficient (concentration ratio of water to air)

T is the water temperature in °C, which was measured by a temperature probe inserted into the air-water exchanger

The RAD7 was programmed to integrate counts every hour.

^{226}Ra analysis

The water from the air-water exchanger was fed into a 50 L water tank for radium extraction. After 50 L of the water had been collected, it was forced to flow through 30 g of Mn-fiber described by Moore (1976) to extract the radionuclide. The flow rate was controlled below 1 L/min so that sufficient time was allowed for the adsorption. In the laboratory, ^{226}Ra was extracted from the Mn-fiber by refluxing with HCl, and the filtrate was co-precipitated with 10 mL of saturated $Ba(NO_3)_2$ and 25 mL of 7 M H_2SO_4. The precipitate [$Ba(Ra)SO_4$]] was then filtered out by 0.45 μm glass-fiber filter and washed with 3 M HCl and water to remove the Mn remains. Finally the precipitant was air-dried, stored in a small vial for 3-4 weeks for equilibrium, and measured by gamma ray spectrometer (Rutgers van der Loeff and Moore,1999).

Determination of ^{222}Rn in Groundwater

Groundwater samples were pumped out from two private wells (Figure 1) and collected in 250 mL collection vials. As radon in groundwater can be quickly distributed into air, narrow tubing was attached to the pump and inserted into the bottom of the collection vial which was placed inside a 1 L plastic beaker. The vial was filled from bottom with fresh sample until the water overflowed into the beaker and the water in the beaker rose well above the vial. In this way, the vial was flushed with fresh sample without exposure to air and it was capped while still under the water.

The samples were then measured by RAD7 with the RAD-H_2O accessory. RAD-H_2O aerates the sample for 5 minutes to deliver ^{222}Rn to the RAD7. The system will wait a further 5 minutes for the equilibrium between ^{222}Rn and ^{218}Po. The air stream is then measured by RAD7 in 4 runs of five-minute period and the result is given as the average of the 4 runs.

Determination of ^{222}Rn in Porewater

Concentration of ^{222}Rn in porewater was determined by sediment equilibration experiment which was described by Corbett et al. (1998). Sediments from the sea bottom and seawater were collected for the experiment. In the laboratory, 85 g sediments were mixed with 300 mL seawater in a 500-mL Erlenmeyer flask. The flask was sealed and agitated for 1 month until ^{222}Rn in head space, water and sediments reach equilibrium. The water was then pumped out and transferred into a 40 mL collection vial, with the special sampling technique employed to prevent air contact. The sample was then measured by RAD7 with the RAD-H_2O accessory.

Determination of Nutrients in Porewater

Wet sediment at a depth of 0.5 m was collected along the foreshore during lowest tide. It was immediately brought to the laboratory where the porewater was separated from the sediment by centrifuge. Nutrients in porewater (NO_2-N, NO_3-N, NH_3-N, PO_4-P and silica) were then analyzed by a spectrophotometer.

Result and Discussion

The results of the continuous ^{222}Rn measurements in the water column, together with the observed water depth, during the neap and spring tides are shown in Figures 3 and 4, respectively. The concentrations of ^{222}Rn were high during low tide, and low during high tide, which fluctuated between 110 and 688 Bq/m^3 with an average of 222 Bq/m^3. Tidal period cyclicity of the ^{222}Rn data was generally accepted to reflect dilution of offshore waters at flood tide, mixing offshore and most importantly, SGD variation (Kim and Hwang, 2002; Burnett and Dulaiova, 2003; Lambert and Burnett, 2003). At low tide, recirculated seawater drains out due to tidal pumping. Simultaneously the hydrostatic pressure is lowered and the hydraulic gradient between seawater and groundwater is increased, which contributes to a larger SGD flux. At high tide, recirculated seawater seeps into the seabed sediments due to tidal pumping. Simultaneously the hydrostatic pressure is increased and the hydraulic gradient between seawater and groundwater is decreased, which contributes to a smaller SGD flux.

Tidal Effects

In order to account for the dilution effect during flood tide, Lambert and Burnett (2003) introduced the concept of excess ^{222}Rn inventory to eliminate the effect. Excess

^{222}Rn inventory is defined as the product of excess ^{222}Rn in water (Concentration of ^{222}Rn – Concentration of ^{226}Ra) and the water depth (*h*). During flood tide, a larger *h* is multiplied so that the dilution effect can be compensated. Apart from that, ^{226}Ra which is about 6 Bq/m^3 was also subtracted from ^{222}Rn in excess ^{222}Rn inventory so that the radon supported by ^{226}Ra was also corrected.

Excess ^{222}Rn inventory can actually be interpreted as the excess ^{222}Rn in a water column within an area of 1 m^2. From this definition, it is deduced that inventory is still subject to changes in tidal height: ^{222}Rn is removed from the water column with the outgoing waters on the ebb tide (F_o) while extra ^{222}Rn is added to the water column with the incoming waters on the flood tide (F_i). Correction is required to remove this tidal effect. The excess ^{222}Rn inventory is corrected by an addition of the removed ^{222}Rn inventory (Δh x concentration of ^{222}Rn in the study domain) at low tide or a subtraction of the extra ^{222}Rn inventory (Δh x concentration of ^{222}Rn in offshore waters) at high tide, where Δh is the difference between the two successive tidal heights.

Atmospheric Loss

^{222}Rn is slightly soluble gas in water, exchange across the air-water interface is possible if ^{222}Rn in the two phases are in disequilibrium. At equilibrium,

$$C_w = \alpha C_a \tag{3}$$

where C_w is the concentration of ^{222}Rn in water

C_a is the concentration of ^{222}Rn in air

α is the partition coefficient

When $C_w > \alpha C_a$, ^{222}Rn will diffuse across the air-water interface and according to MacIntyre et al. (1995), the diffusive flux is,

$$F_{atm} = k(C_w - \alpha C_a) \quad (4)$$

where F_{atm} is the diffusive flux across the air-water interface

k is the gas transfer velocity

Considerable effort has gone into determining empirical relationship between the gas transfer velocity and wind speed, which was based on five experiments on lakes with deliberate tracers SF_6 (MacIntyre et al., 1995; Lambert and Burnett, 2003),

$$k_{600} = \begin{cases} 0.45\mu^{1.6}\left(\frac{Sc}{600}\right)^{-0.5} & \text{for } \mu > 3.6\ m/s \\ 0.45\mu^{1.6}\left(\frac{Sc}{600}\right)^{-0.6667} & \text{for } \mu \le 3.6\ m/s \end{cases} \quad (5)$$

where μ is the measured wind speed (m/s)

Sc is the Schimidt number

k_{600} is the gas transfer velocity normalized to the Schimidt number of CO_2 at 20 °C in freshwater (cm/hr)

At wind speeds of less than 1.5 m/s, the value for k is assumed to be 0.91 cm/hr (Lambert and Burnett, 2003). This value is calculated based on the k value for CH_4 (0.75 ± 0.54 cm/hr) measured by Happell et al. (1995) at zero wind speed.

The Schmidt number for ^{222}Rn in seawater is given by Pilson (1998) as a function of the water temperature.

Five measurements were made from 23:40, July 15 to the end of neap tide period for ^{222}Rn in air and the average (30 Bq/m^3) is used for calculation (Table 1). Figures 5 and 6 show the temporal variations of wind speed and the diffusive flux of ^{222}Rn across the air-water interface during the two sampling periods.

Diffusive Flux from Seabed Sediments

Similar to the air-water interface, exchange across the sediment-water interface is possible if concentration of ^{222}Rn in porewater is greater than that in the overlying water. The diffusive flux across the sediment-water interface is given by Martens et al. (1980),

$$F_{sed} = (\lambda D_s)^{0.5}(C_{eq} - C_o) \tag{6}$$

where F_{sed} is the diffusive flux across the sediment-water interface

λ is the decay constant of ^{222}Rn, which is 0.181 day^{-1}

D_s is the effective wet bulk sediment diffusion coefficient

C_{eq} is the concentration of ^{222}Rn in porewater

C_o is the concentration of ^{222}Rn in the overlying water

Ullman and Aller (1981) pointed out that the effective wet bulk sediment diffusion coefficient is approximately equal to the product of porosity and the molecular diffusivity coefficient of ^{222}Rn. Molecular diffusivity coefficient was described by Peng et al. (1974) as a function of temperature,

$$D_o = 10^{-\left[\left(\frac{980}{T+273}\right)+1.59\right]} \tag{7}$$

where D_o is the molecular diffusivity coefficient

T is the temperature in °C

Particle size analysis classified the seabed sediments as loose uniform sand. The porosity estimated from soil analysis is around 0.41.

Concentration of ^{222}Rn in porewater was determined by sediment equilibration experiment. From the experiment, the activity of ^{222}Rn released from the wet sediments is 0.6 Bq/kg. Concentration of ^{222}Rn in porewater is calculated by,

$$C_{eq} = \frac{^{222}\text{Rn released from the wet sediment} \times \rho_{wet}}{n} \quad (8)$$

where n is the porosity (0.41)

ρ_{wet} is the wet bulk density, which is measured as 2086 kg/m^3, which is based on excavation method and sand displacement test.

From the sediment equilibration experiment, concentration of ^{222}Rn in porewater is estimated to be 3052 Bq/m^3. Concentration of ^{222}Rn in overlying water was monitored continuously during the two sampling periods. The diffusive flux of ^{222}Rn across the sediment-water interface is calculated to be 0.4 Bq/m^2·hr, which is insignificant in comparison to the total flux.

Mixing Loss

Figures 7 and 8 show the net ^{222}Rn flux after correcting for atmospheric loss and sediment diffusion, which should be a balance between supply from SGD and mixing loss to the open sea. Burnett and Dulaiova (2003) and Lambert and Burnett (2003) chose the negative net ^{222}Rn fluxes as conservative estimates of the mixing loss. Indeed a larger mixing loss is possible to be balanced by a larger supply from SGD, but the conservative estimates of the mixing loss provide a good guess for the minimum SGD flux. It is represented by the dashes line shown in Figures 7 and 8.

The estimated mixing losses are between 29.4 to 89.0 Bq/m^2·hr during neap tide and between 64.0 to 125.0 Bq/m^2·hr during spring tide.

SGD Flux

As mentioned, the net ^{222}Rn flux is a balance between supply from SGD and mixing loss to the open sea. After correcting for mixing loss, the ^{222}Rn flux is solely attributed to SGD. The average ^{222}Rn flux solely attributed to SGD is 52.8 Bq/m^2·hr, which is about 130 times larger than the flux diffused from sediment. Although Hu et al. (2001) and Xu et al. (2004) suggested that significant amount of nutrients was diffused from seabed sediments and supplied to the phytoplankton in Tolo Harbour, nutrients discharged with SGD are conceived to be much more significant than diffusion from sediment in Plover Cove.

In order to convert ^{222}Rn fluxes to SGD fluxes, the ^{222}Rn fluxes solely attributed to SGD have to be divided by the concentration of ^{222}Rn in the SGD fluid. Determination of the SGD fluid requires an understanding of the discharge characteristic: If slow seepage through sediment is dominant, ^{222}Rn in porewater will be a good guess of that in SGD; otherwise ^{222}Rn in groundwater will be more representative if fast groundwater flow is dominant. ^{222}Rn in porewater was determined by sediment equilibration experiment to be 3052 Bq/m^3. Groundwater was collected from two private wells near Plover Cove, the concentrations of ^{222}Rn are 6858 Bq/m^3 ($n = 28$; $\sigma = 3728$) for Po Sum Pai private well and 16790 Bq/m^3 ($n = 5$; $\sigma = 4188$) for Chim Uk private well.

The SGD fluxes are plotted on Figures 9 and 10 and summarized in Table 2. The inverse relationship between tidal height and SGD is verified. Precisely the peaks of SGD coincide with the transitions from flood tide to ebb tide. With porewater being selected to represent the SGD fluid, the mean SGD fluxes are 30.3 and 63.0 cm/day for neap and spring tides respectively. The mean SGD fluxes are 7.8 and 16.3 cm/day for neap and spring tides with groundwater from the two wells averaged to represent the SGD fluid.

The SGD fluxes based on terrestrial groundwater are chosen for calculating the nutrient loading to Plover Cove through SGD so as to obtain the most conservative estimates of SGD and the corresponding nutrient loading to Plover Cove. These values are also comparable to the mean SGD fluxes measured directly by seepage meter, which are 8.0 and 9.3 cm/day for neap and spring tides respectively.

The width of the seepage face is difficult to estimate. During the field studies, neap tide, the exposed sandy beach face during neap tide is about 30 m from the high water mark. In the following calculation, it is assumed that the width of the seepage face is 30 m. With the length of the shoreline approximately about 3.5 km, the amount of SGD should be around 8,000 m^3/day for neap tide and 17,000 m^3/day for spring tide. Result in nutrient analysis and nutrient loading to Plover Cove through SGD are given in Table 3.

Conclusion

Within Tolo Harbour, Plover Cove has been selected for SGD study. SGD flux has been estimated via continuous ^{222}Rn measurements and seepage meter. ^{222}Rn flux attributed to SGD has been obtained after correcting for tidal effect, atmospheric loss, sediment diffusion and mixing loss to the open sea. With terrestrial groundwater being selected, the amount of SGD is 8,000 m^3/day during neap tide and 17,000 m^3/day during spring tide. It has to point out that the estimated SGD include both components of terrestrial groundwater discharge as well as recirculated seawater.

Management of algal blooms has emphasized on external nutrient loading from rivers. Even most of the nutrient loading from rivers has been removed through the Tolo Harbour Action Plan, the total phytoplankton densities are still the highest among Hong Kong waters. In this study, nutrients discharged with SGD are conceived to be much more significant than all the other pathways in Plover Cove. Taking the width of the seepage area to be 30 m, nutrient loading on Plover Cove through SGD during neap tide and spring tide are: Total inorganic nitrogen 1,241 and 2,599 mol/day; Orthophosphate phosphorus 27.8 and 58.2 mol/day; Silica 185.9 and 388.5 mol/day. In terms of nutrient loadings per unit area, the amount of nitrate-nitrite nitrogen loading through SGD is about twice of that released from sediment diffusion obtained by Hu et al. (2001). Transformation along the groundwater flow path in the sediments may attenuate nutrient composition in the SGD fluid but still, based on the result from this study, the current practice for the management of algal blooms in Tolo Harbour has to be reviewed and the control measures of groundwater contamination are obviously required.

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Tables

Table 1 Measurements of ^{222}Rn in ambient air on 16th July 2005

Time	Conc. of ^{222}Rn (Bq/m^3)
01:23	47.73
02:23	14.80
03:23	29.23
04:23	18.50
05:23	37.37
Average	**29.53**

Table 2 Estimated SGD fluxes

During neap tide period

Approach	SGD fluxes	Mean (cm/day)
^{222}Rn (SGD fluid represented by)		
• Porewater	0-67.5	30.3
• Groundwater from nearshore wells	0-17.4	7.8
Seepage meter	0.9-40.1	8.0

During spring tide period

Approach		
^{222}Rn (SGD fluid represented by)		
• Porewater	0-236	63.0
• Groundwater from nearshore wells	0-60.8	16.3
Seepage meter	1.0-144	9.3

Table 3 Nutrients in porewater and nutrient loading to Plover Cove through SGD

Nutrients	**Concentration (μmol/L)**	**Nutrient Loading to Plover Cove through SGD (mol/day)**	
		Neap Tide	**Spring Tide**
Nitrite Nitrogen	0.8	6.6	13.7
Nitrate Nitrogen	78.6	643.7	1345.2
Ammonia Nitrogen	72.1	590.5	1234.0
Orthophosphate Phosphorus	3.4	27.8	58.2
Silica	22.7	185.9	388.5

Figures

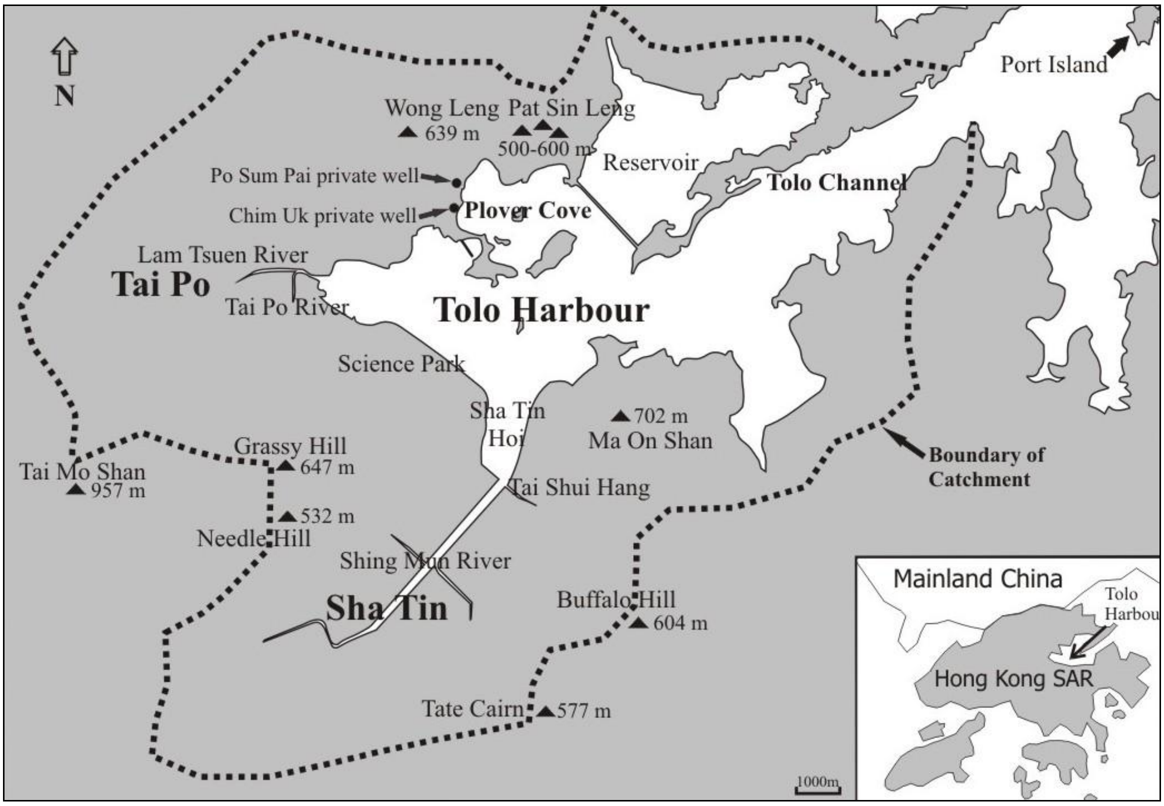

Figure 1 Map of Tolo Harbour

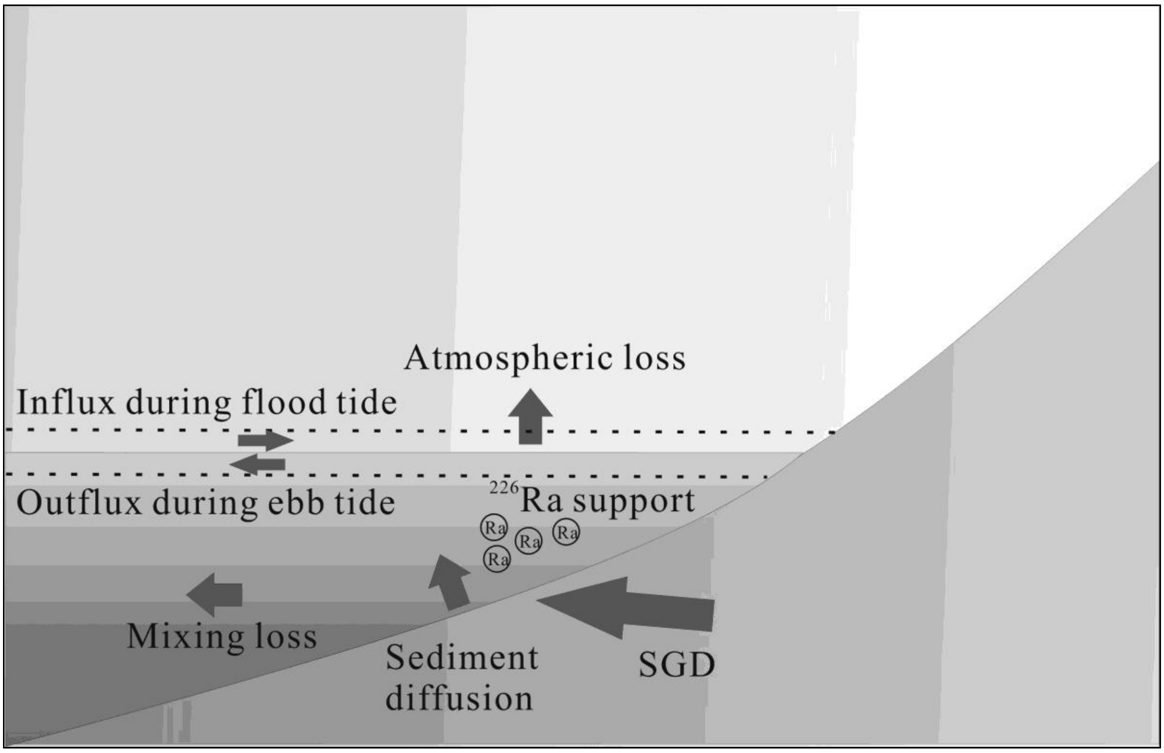

Figure 2 Sources and sinks of ^{222}Rn in coastal waters (modified from Lambert and Burnett 2003)

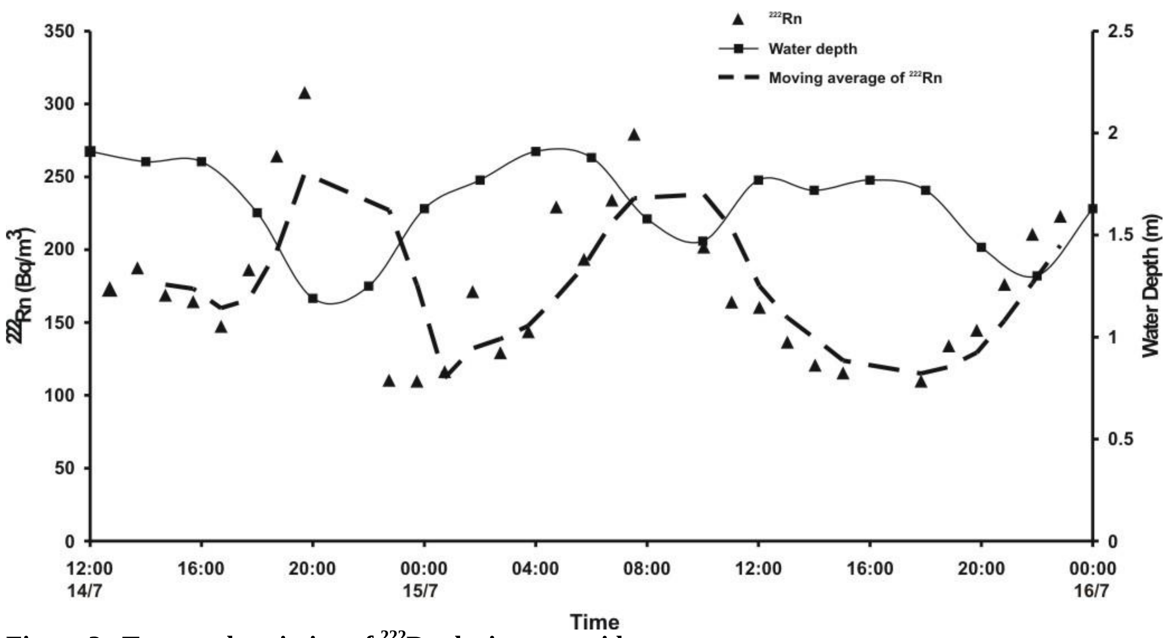

Figure 3 Temporal variation of ^{222}Rn during neap tide

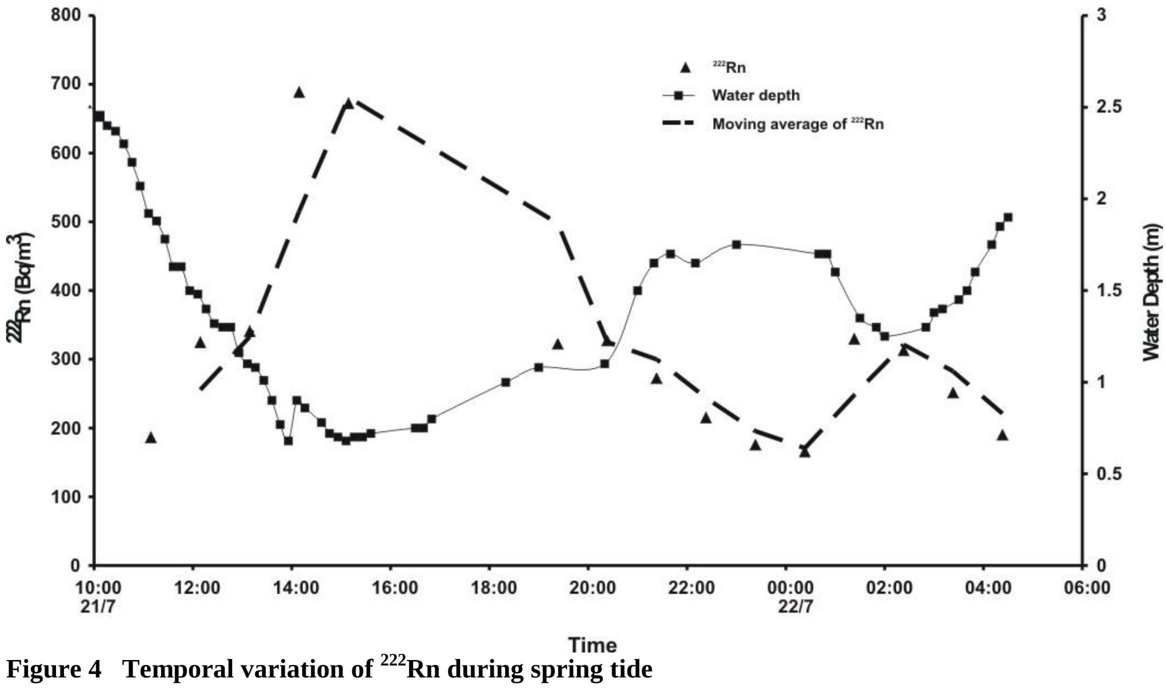

Figure 4 Temporal variation of ^{222}Rn during spring tide

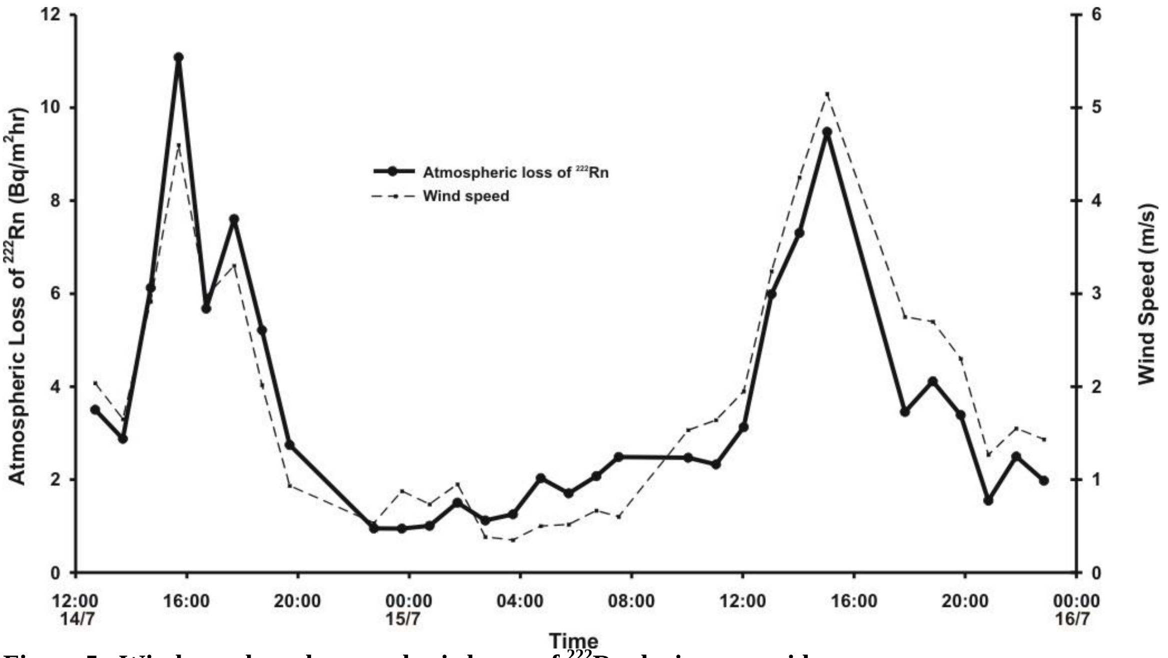

Figure 5 Wind speeds and atmospheric losses of ^{222}Rn during neap tide

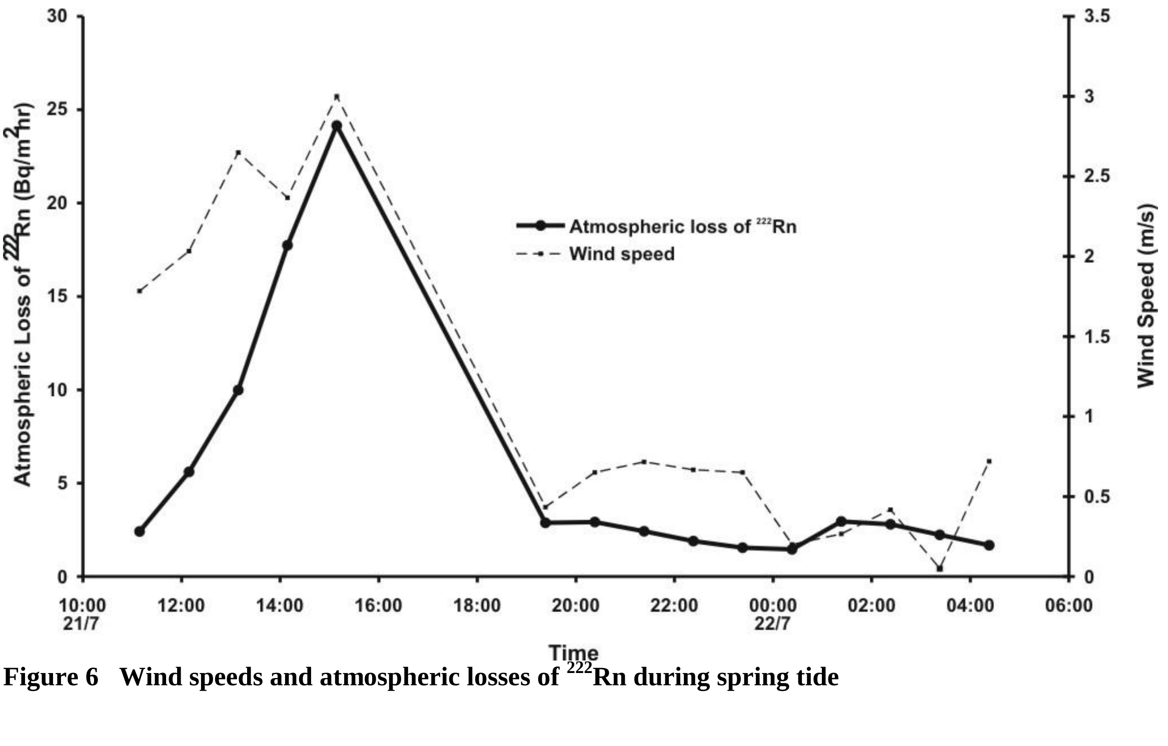

Figure 6 Wind speeds and atmospheric losses of ^{222}Rn during spring tide

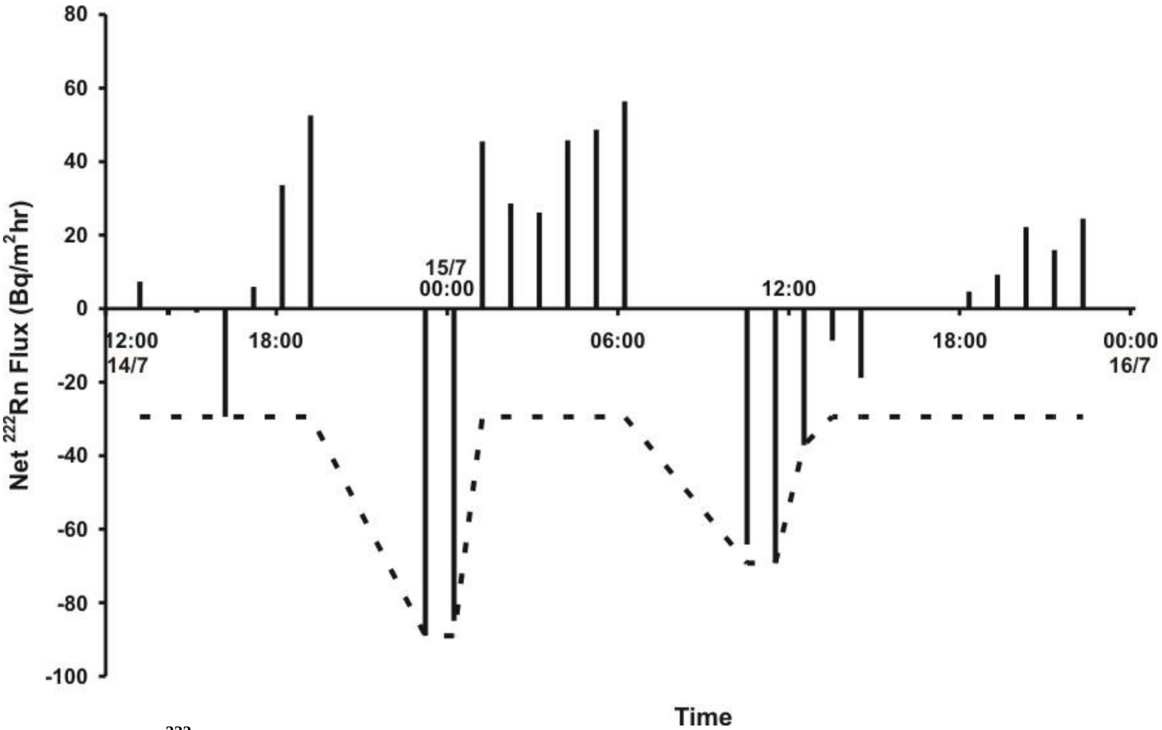

Figure 7 Net ^{222}Rn flux during neap tide (The dashed line represents the mixing loss)

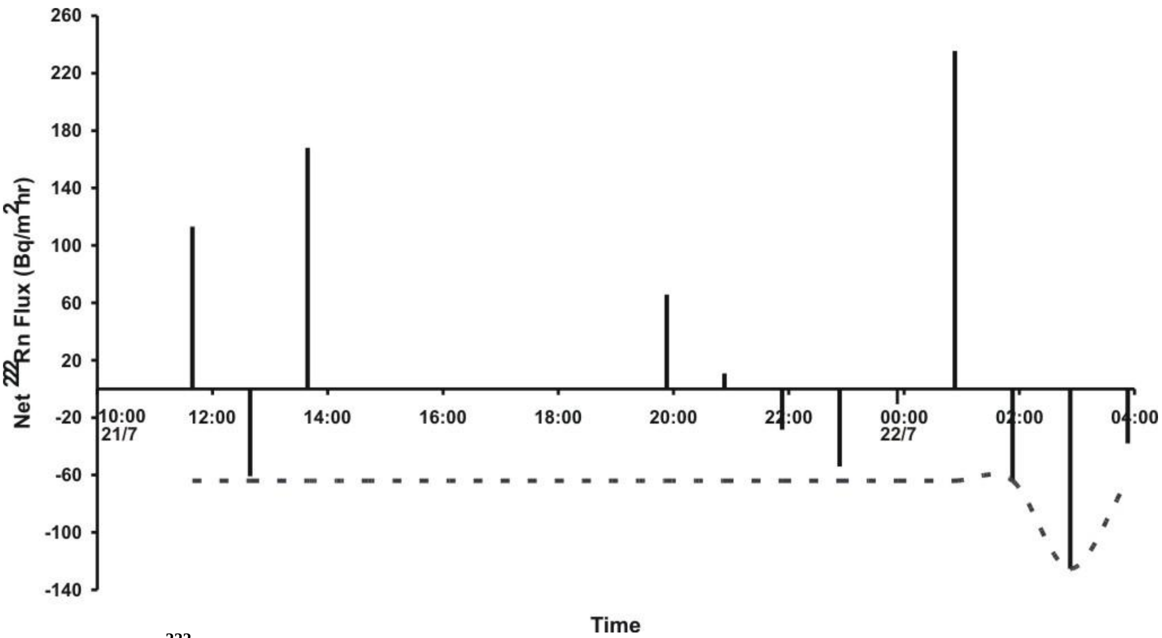

Figure 8 Net ^{222}Rn flux during spring tide (The dashed line represents the mixing loss)

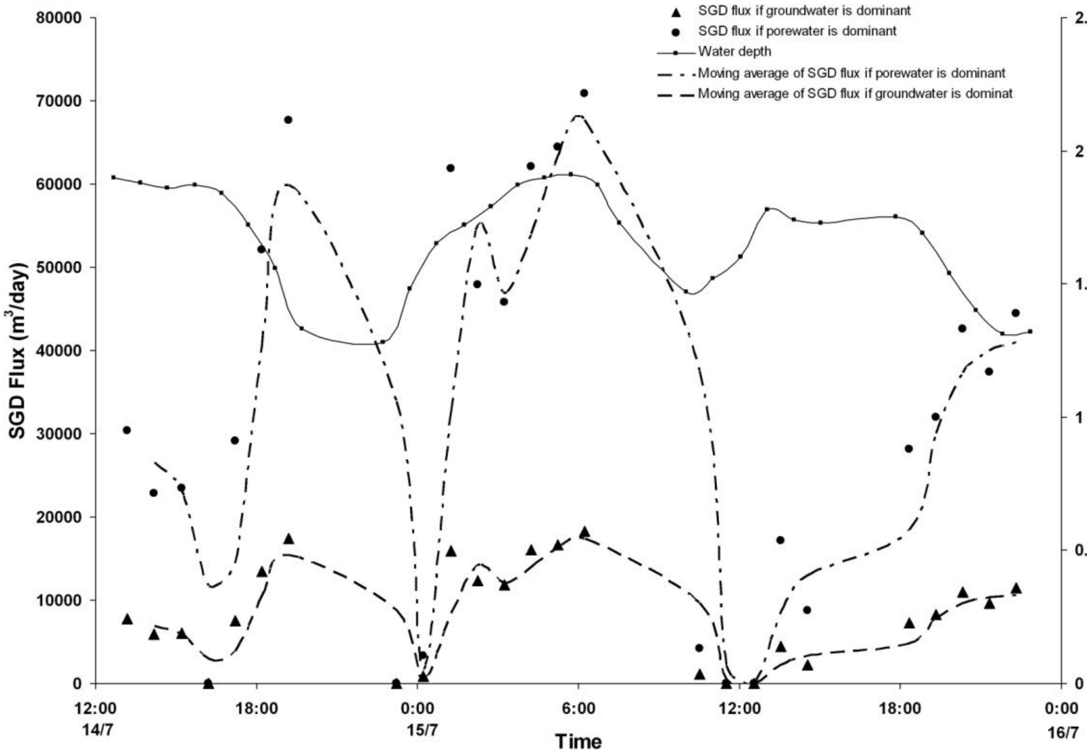

Figure 9 SGD fluxes during neap tide

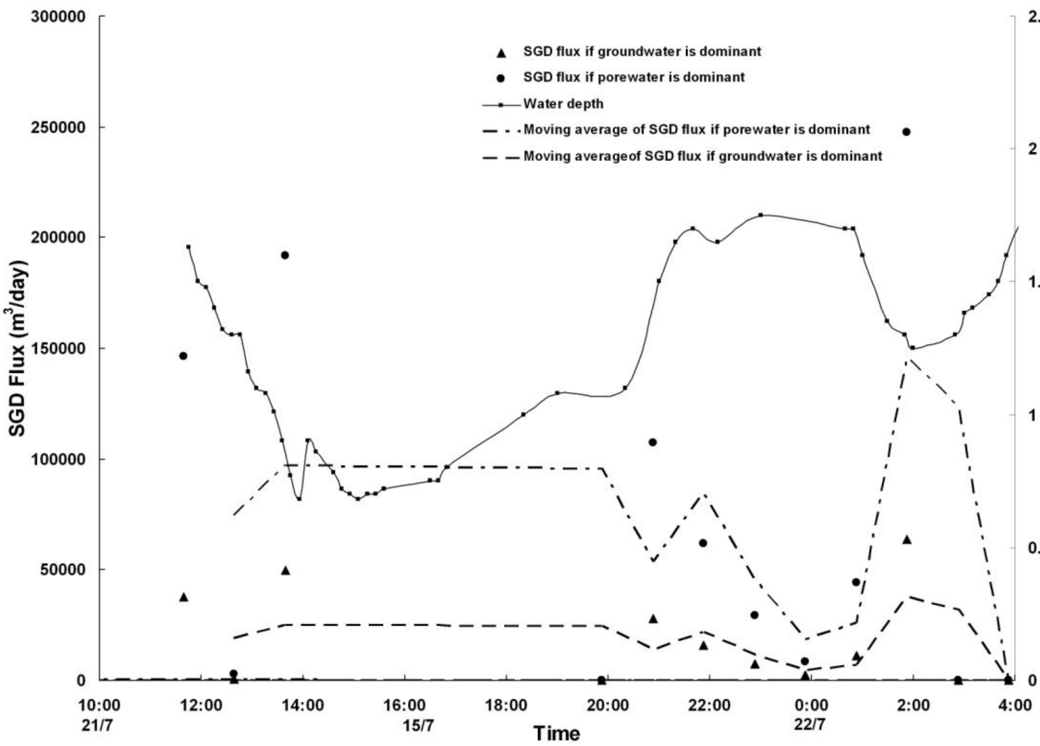

Figure 10 SGD fluxes during spring tide