A New Focus on Groundwater–Seawater Interactions
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Investigation of submarine groundwater discharge using several methods in the inter-tidal zone

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Abstract To accurately estimate the flux of terrestrial groundwater discharge into the sea, a study using several methods was done in the coastal zone of Osaka Bay, Japan. The seepage-meter method and the measurement of temperature near the seabed were applied based on the hypothesis that seawater temperature in summer would decrease, reflecting the extent of active mixing with colder fresh groundwater. As a result, it was confirmed from the seepage-meter method that submarine groundwater discharge rates decreased with the distance from the coast. Evaluations of groundwater discharge rates from seabed temperature showed similar values to the results using the seepage meter, which means that the values were reasonable. Finally, the total groundwater discharge flux from this beach was estimated at 36.7% of the river discharge rate.

Key words submarine groundwater discharge; inter-tidal zone; seepage meter; seabed temperature

INTRODUCTION

Recognition of the importance of submarine groundwater discharge (SGD) is increasing in the studies of water and dissolved-material transport from the land to the sea. According to recent studies from hydrology and coastal oceanography, SGD consists of both terrestrial groundwater and recirculated seawater (Taniguchi *et al.*, 2002; Burnett *et al.*, 2003). However, there are many uncertainties about SGD, because it is invisible and difficult to evaluate quantitatively. Therefore, further study is needed to better estimate submarine fresh–groundwater discharge (SFGD) in coastal areas.

Our study area is located in the coastal zone of Omaehama, Osaka Bay, Nishinomiya city, Japan (Fig. 1). Osaka Bay is located next to Osaka city, the second capital of Japan. The annual precipitation and air temperature are about 1300 mm/year and 16.5°, respectively. Several rivers flow into the Osaka Bay and the largest of them

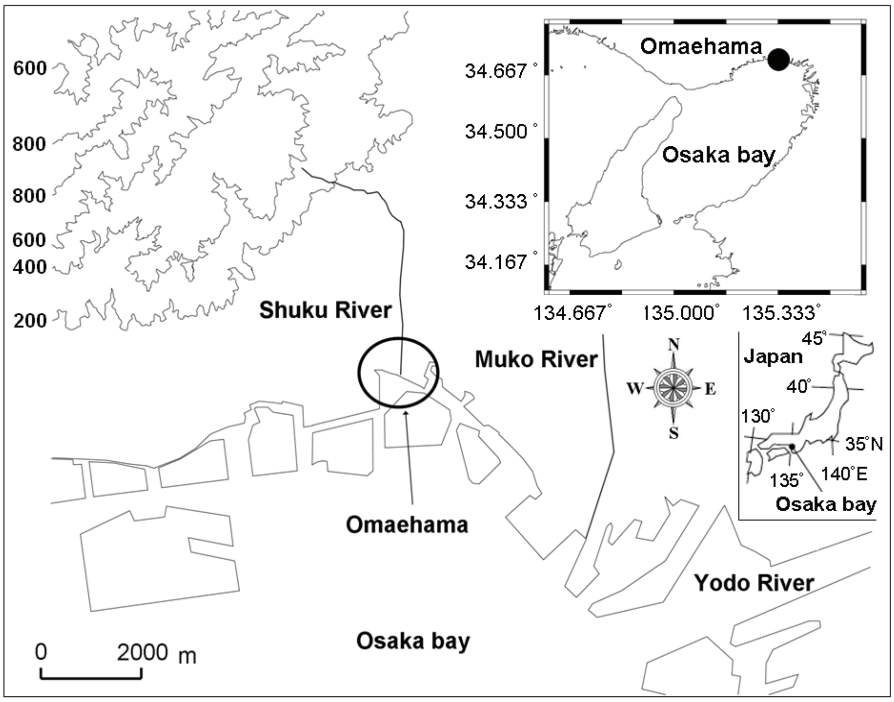

Fig. 1 The study area for measuring SGD.

is the Yodo River with an average discharge rate of about 250 m^3/s. The smaller, the Shuku River, also directly flows into the Osaka Bay, and the river mouth is located near the centre of this beach. The area near Omaehama is well-known because groundwater is abundant and there are many Japanese sake (alcoholic drink) breweries, which need good quality water for making the Japanese sake. Therefore, it was worth monitoring how much fresh groundwater actually contributes to the terrestrial water flux into the ocean in this area. However, some problems such as deposition of organic matter and degradation of the seabed are occurring with the recent developments of the coastal area, although Omaehama is a natural coastal area near a mega-city. Therefore, some environmental assessments have been undertaken in this area (Kasahara, 2005). However, quantitative research on groundwater discharge to the sea has not been done here, despite the possibility that the groundwater transports a certain amount of contaminating materials. The purposes of this study are: (1) to quantitatively evaluate groundwater discharge to the sea by using several methods including a seepage meter and a fibre-optic cable, and (2) to compare groundwater and river discharge.

STUDY METHODS

According to some previous studies, it is thought that SGD rates decrease with the distance from the coast (Bokuniewicz, 1992; Taniguchi *et al.*, 2002). Therefore, seepage meters were deployed along a transect set perpendicularly to the coast line to evaluate the SGD rates from the seabed (Fig. 2). Lee-type seepage meters (Lee, 1977) were used in the inter-tidal zone (A, B and C) and continuous heat flow type seepage meters (Taniguchi & Iwakawa, 2001) were used in the subtidal zone (D and E). Electric conductivity measurements of SGD were done with CT (conductivity-temperature, “Compact-CT” Alec Electronics, Co., Ltd) sensors in the chamber of the seepage meter to evaluate the amount of terrestrial groundwater in SGD. Measurements of tidal change were made concurrently using a Diver sensor (Daiki-rikakogyo, Co., Ltd).

In general, the temperature of terrestrial groundwater is lower than seawater in the summer season. Therefore, it is assumed that the temperature near the seabed will be lower than its surroundings if groundwater discharge from the seabed is actively occurring. In fact, there are some studies which mention a good correlation between SGD and temperature (Banks *et al.*, 1996). In this study, therefore, temperature measurements on the seabed and coastal land surface were taken using a fibre-optic cable (Hitachi, Co., Ltd) to evaluate the change of temperature of the pore water caused by SGD. However, it was also considered that the seabed temperature could be easily influenced by various factors such as the sunlight and marine currents. Therefore, temperature measurements under the seabed (5 cm below the seabed surface) were also collected using a temperature data logger (“tidbit” HOBO, Co., Ltd). The locations of these instruments at the site are shown in Fig. 2.

The measurement period was from 21 to 24 August 2006. Three measurements using the Lee-type seepage meters (A, B, and C) were done at low and high tide. Measurements by continuous a heat-type seepage meter (D and E) were taken every 1 minute during this period. Temperature measurements of the seabed by a fibre-optic cable, and under the seabed by the temperature data logger, were taken every 5 minutes from 6:30 to 18:30 and every 1 minute from 13:00 to 18:30 on 23 August. In addition to these measurements, river discharge rates were also estimated by multiplying the velocity and the cross-section of the river near the mouth on 22 and 23 August to compare the discharge of groundwater from this beach.

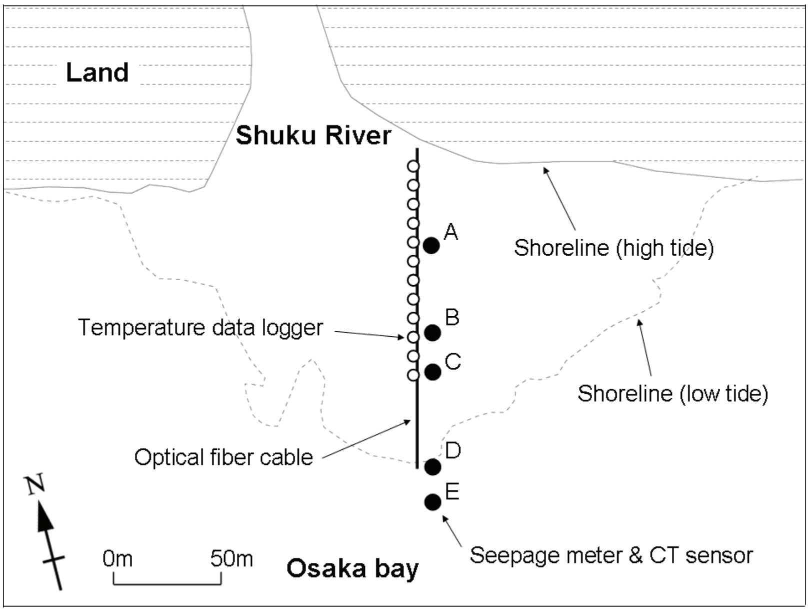

Fig. 2 Location of the instruments measuring SGD.

RESULTS AND DISCUSSION

Results

Table 1 shows the measurement results of discharge rates and electric conductivity of the SGD compensated at 25°. The SGD rates at location C was higher than those at the other locations, and electric conductivity was about 40 mS/cm at all the locations.

Figure 3 shows results of temperature measurements on the seabed and under the seabed by the fibre-optic cable and temperature data logger at high tide (18:00 on 23 August). Temperature on the seabed was higher near to the coast, and decreases with distance from the coast. Temperature under the seabed here was about 31° and lower than those on the seabed by about 2–3°.

River discharge rates were estimated to be 3456 m^3/d and 7776 m^3/d on 22 and 23 August, with an average rate of 5616 m^3/d.

Table 1 Measurement results of discharge rates and electric conductivity (EC) of SGD.

Point	Distance (m)	Average depth (m)	SGD (cm/d)	EC (mS/cm)
A	45	0.5	11.04 ± 3.95	39.24 ± 1.65
B	95	0.6	11.41 ± 2.12	40.74 ± 0.93
C	110	0.7	37.64 ± 7.48	40.63 ± 1.00
D	150	1.0	4.76 ± 6.63	40.59 ± 0.37
E	165	3.1	2.72 ± 9.84	39.47 ± 0.65

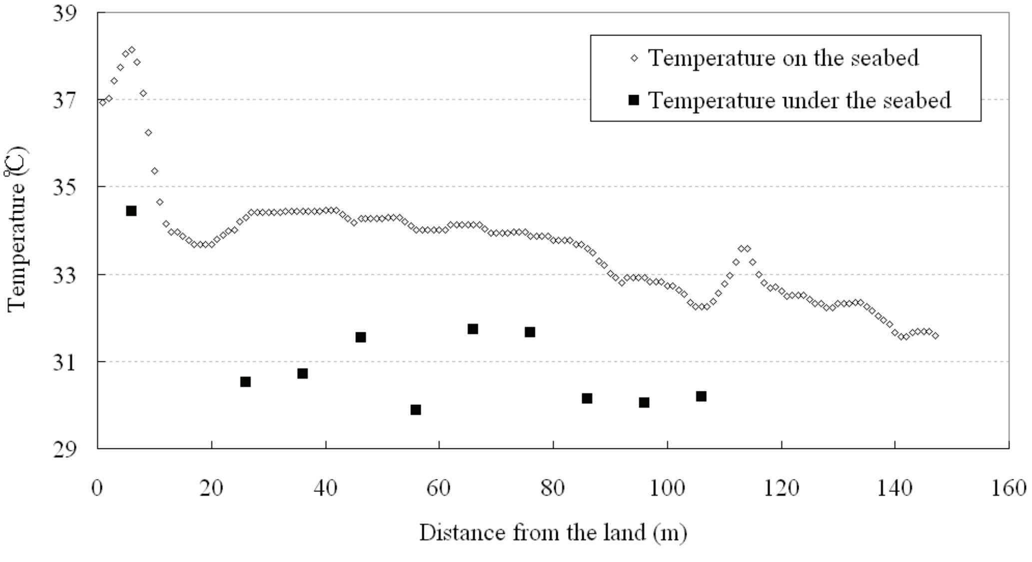

Fig. 3 Results of temperature measurements on the seabed and under the seabed.

Evaluation of terrestrial groundwater discharge rates at each point

SGD can consist of terrestrial groundwater (SFGD = Submarine Fresh Groundwater Discharge) and recirculated seawater (Taniguchi *et al.*, 2002). Separation of the two components was accomplished by using SGD rates and the electric conductivity of SGD (Table 1), the known conductivities of terrestrial groundwater (0.38 mS/cm) and seawater (46.01 mS/cm) as expected end-members to estimate the amount of SFGD from the land to the sea. Figure 4 shows the result of the separation and it is seen that SFGD rates decrease with the distance from the coast, and the highest SFGD rate was still found at location C. Negative correlation between SFGD rates and distance from the land has frequently been seen in previous studies (Bokuniewicz, 1992). If the result at location C is excluded, a regression line that is calculated from the results of each point gives a high correlation coefficient. However, Taniguchi *et al.* (2006) indicate that higher SFGD rates are found near the seaward edge of the inter-tidal zone, and it is assumed that the location of the fresh–salt water interface under the seabed correlates with the position of high SFGD rates. Therefore, the location of the fresh–salt water interface is likely the cause of the high SFGD rates at location C.

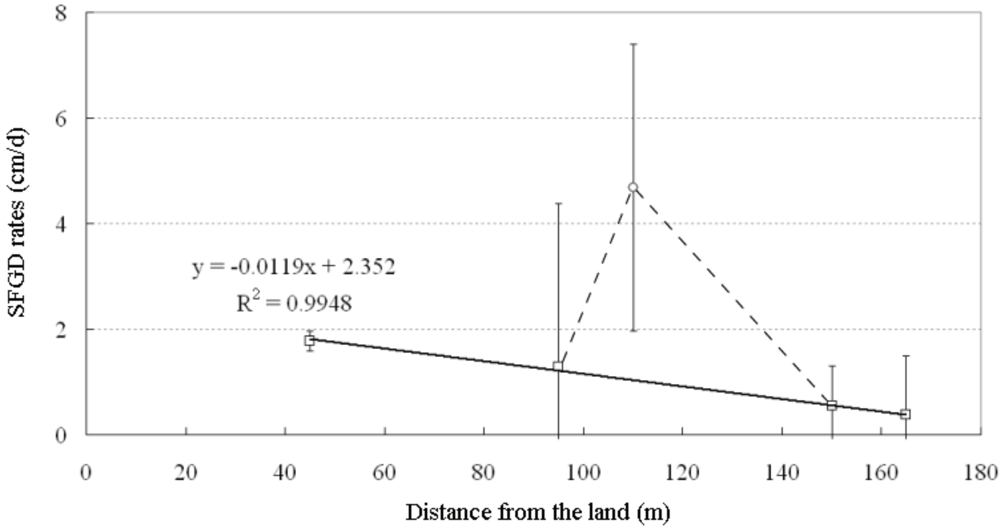

Fig. 4 Average of SFGD rates by seepage meters.

Evaluation of groundwater discharge flux per unit shoreline length

A scale-up of the observed SFGD rates (Fig. 4) is needed to evaluate the total groundwater discharge rate from the land to the coastal zone at Omaehama. Therefore, a scale-up of the observed SFGD rates was attempted in order to estimate the total "area" SFGD rates using the "point" SFGD rates evaluated by the seepage meters (Fig. 4). The intercept of the regression line on the Y-axis can be used to estimate how far terrestrial groundwater discharge occurs from the coastline. Therefore, the estimated SFGD rate of 2.35 cm/d along the shoreline (0 m) gradually decreased with the distance from the shore, and reached zero flux at 197 m offshore from the coast. It is estimated by integration of the SFGD rates estimated from the regression line that SFGD flux per unit shoreline length is 23 100 cm^3/cm/d. To consider the observed higher SFGD rate at location C, however, estimation using the modified regression line (broken line in Fig. 4) was also attempted, because it was also likely that the SFGD flux was large at a point a little away from the coast (Taniguchi *et al.*, 2006). From this result, the SFGD per unit shoreline length was estimated as 33 200 cm^3/cm/d, which is about 1.5 times higher than the first estimate of the groundwater discharge rates.

Scale-up of groundwater discharge rates from results of temperature measurement

For the evaluation of accurate terrestrial groundwater discharge flux from Omaehama, scaling-up of SFGD rates using the results of the temperature measurements was also applied to compare with the results for SFGD flux from seepage meters. Here we applied two techniques for this evaluation, one using a regression line between temperature on the seabed and SFGD rates in the same location, and the other using a regression line between SFGD rates and the difference in temperature between the seabed and under the seabed. The latter is based on the assumption that the difference in temperature decreases if the groundwater discharge rate is higher.

Figure 5(a) shows the relationship between temperature on the seabed and SFGD rates, and Fig. 5(b) shows the relationship between SFGD rates and difference in temperature between the seabed and 5 cm under the seabed. Although the numbers of data points are limited, it can be seen that temperature and SFGD rates have negative correlations and Fig. 5(b) showed better correlation than Fig. 5(a).

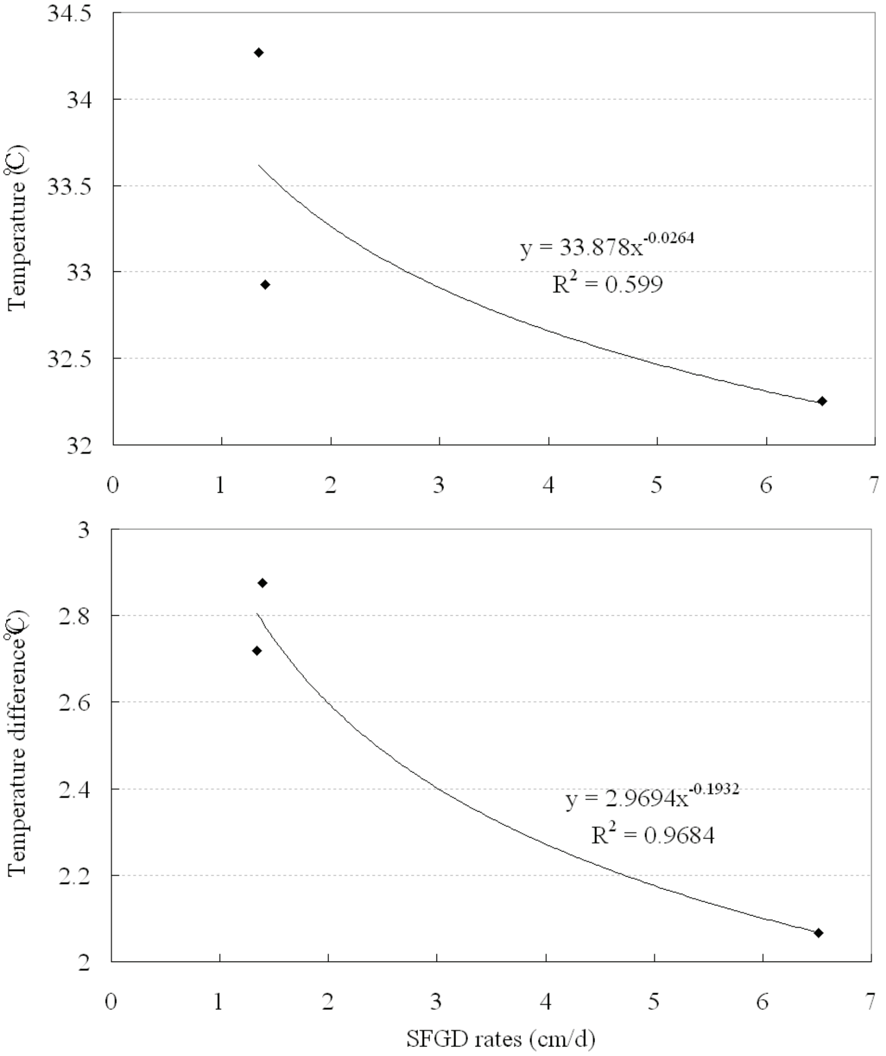

Fig. 5 (a) Relationship between temperature on the seabed and SFGD rates. (b) Relationship between SFGD rates and difference in temperature between the seabed and under the seabed.

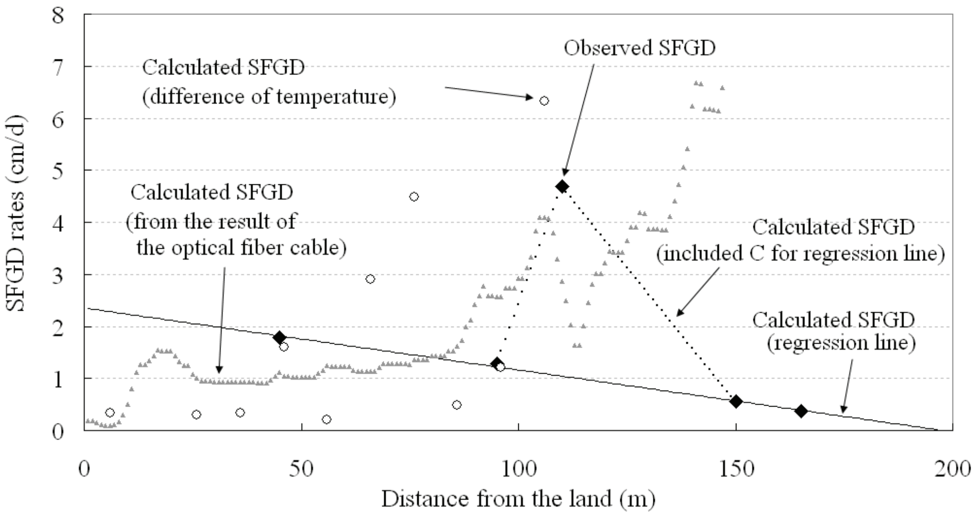

Fig. 6 SFGD rates estimated from several different methods.

Figure 6 shows SFGD rates calculated using the three regression lines from Figs 4, and 5(a) and (b). In this result, differences in the spatial variation of SFGD rates are related to the difference in evaluation techniques. However, all the results indicate that the location of the higher SFGD rates is at the point 110 m from the coast.

Comparison of SFGD rates by each technique was done in the region out to 106 m from the coast, because the data sets for all SFGD rates coexist in this region. From this comparison, the SFGD flux per unit shoreline length are 18 100 cm^3/cm/d by the regression line of the observed SFGD from seepage meters (except for C), 19 700 cm^3/cm/d by the regression line of the observed SFGD (including C), 14 700 cm^3/cm/d by the regression line of the SFGD rates and temperature on the seabed, and 15 300 cm^3/cm/d by the regression line of SFGD rates and differences in temperature.

From these results, the evaluation of the SFGD rates per unit shoreline length appears valid, because no great difference was found between calculated SFGD rates up to 106 m offshore using several different methods.

Comparison of groundwater discharge and river discharge

The processes of water movement from land to sea can be divided into river discharge and groundwater discharge. In order to compare groundwater and river discharge, the total groundwater discharge rates to the sea from Omaehama was roughly estimated by multiplying the SFGD rates per unit coast line out to 197 m from the land, and the length of the coast at Omaehama (620 m). As a result, the total groundwater discharge rate to the sea is 2062 m^3/d, equivalent to 36.7% of the river discharge (see result). According to previous studies, the groundwater discharge rate is assumed to be only a few to 10% of the river discharge on a global scale (Taniguchi *et al.*, 2002). Therefore, this study has shown that the ratio of groundwater to total water discharge to the sea is relatively high in this area. As well as the river discharge, terrestrial groundwater discharge can strongly influence the coastal zone of Omaehama with regard to both water and material (contaminant) transport. However, the estimation of groundwater discharge rates in this study is rough, and more accurate estimation including spatial variations of SGD rates is expected from future work.

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