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Comprehensive evaluation of the groundwater–seawater interface and submarine groundwater discharge

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Abstract Comprehensive studies of the groundwater–seawater interface and submarine groundwater discharge (SGD) have been made at Yatsushiro, Kumamoto, Japan, and other areas, by use of automated seepage meters with conductivity sensors to evaluate SGD and fresh/saline components of SGD continuously, and resistivity measurements to evaluate the relationship between temporal changes in the location of the saltwater–freshwater interface and SGD composition. The processes of SGD differ between the landward and offshore sides of the saltwater–freshwater interface. SGD in the nearshore can be mainly explained by connections of terrestrial groundwater, while offshore SGD is controlled mostly by oceanic process such as recirculated saline groundwater discharge. Global evaluations of SGD based solely on observational data (>25 000 automated flux measurements) showed that fresh groundwater discharge is estimated to be 2600 km^3/year (from the coast to 200 m offshore) and is equivalent to 7% of the global river flux.

Key words submarine groundwater discharge; terrestrial groundwater; recirculated saline water; saltwater–freshwater interface; global assessment of groundwater discharge

INTRODUCTION

Submarine Groundwater Discharge (SGD) is increasingly recognized as an important pathway for water and dissolved materials moving from the land to the ocean (Moore, 1996; Burnett *et al*., 2001; Taniguchi *et al*., 2006). Recent field work has revealed that SGD contains Submarine Fresh Groundwater Discharge (SFGD) and Recirculated Saline Groundwater Discharge (RSGD) (Taniguchi *et al*., 2002), and that there are tidal effects on SGD (Taniguchi, 2002; Kim & Hwang, 2002).

Saltwater–freshwater interfaces have been intensively studied in hydrological sciences for many years, because saltwater intrusion due to excessive groundwater pumping is a serious problem for water resources in coastal areas. SGD from aquifers on the land into the ocean, and seawater intrusion from the ocean into aquifers on land, are complementary processes, functioning in opposite flow directions as a result of the hydraulic gradient across the coastal freshwater–saltwater interface being directed away from shore, or towards shore, respectively. The quality of SGD at locations along a shore-perpendicular transect depends on the location of the freshwater–saltwater interface (Taniguchi *et al*., 2006a). However, there are many uncertainties on the relationship between SGD and the location of the interface.

Some global-scale estimates are based on hydrological or hydrogeological assumptions (Nace, 1970; COSODII, 1987). Others are based on water balance methods, which are the most widely used for global-scale estimation of the role of SGD. Global estimates of SGD vary widely, but most estimates range from 6 to 10% of surface water inputs (Taniguchi *et al.*, 2002). However, thus far there has been no attempt to estimate global SGD based solely on experimental data.

The purposes of this study are to evaluate: (1) the processes of SFGD and RSGD in the coastal zone, (2) the relationship between SGD and the freshwater–saltwater interface, and (3) a global assessment of SGD made solely by use of seepage meters

METHODS

Comprehensive studies on SGD and saltwater–freshwater interfaces have been made in Yatsushiro Sea in Kyushu Island, Japan (Fig. 1). Aquifers in this study area consist of permeable Quaternary volcanic rocks (andesite lava and tuff breccia) and pyroclastic flow deposits. The basin area is 4.5 km^2, and the length of the basin from the top (elevation is 400 m above sea level) to the coast is 4 km. The annual precipitation is about 1800 mm year^{-1}, and average annual air temperature is about 17°C. The Yatsushiro Sea is an inland sea, and the average tidal change is from 3 to 5 m.

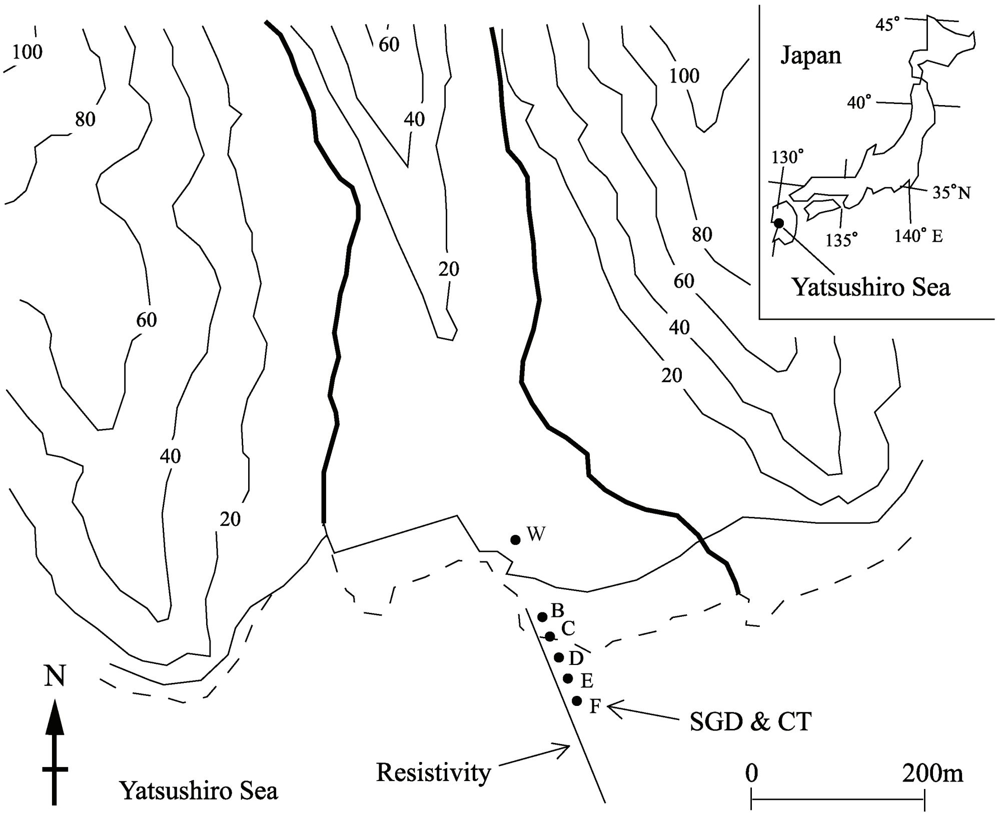

Fig. 1 Locations of seepage meters and resistivity cable at Shiranui, Kumamoto, Japan. (The broken line shows the location of the coast at low tide).

Five continuous heat-type automated seepage meters (Taniguchi & Iwakawa, 2001) were located at 30, 60, 90, 120 and 150 m distance offshore from the coastal line at high tide in Yatsushiro, Japan (Fig. 1). Seepage meters B and C are located between the high tide coast and low tide coast. The automated seepage meter is based on the effect of heat convection due to water flow by measuring the temperature gradient of the water flowing between the downstream and upstream positions in a horizontal flow tube with a diameter of 1.3 cm, which is connected to the chamber. The principle of the automated seepage meter is described in detail by Taniguchi & Iwakawa (2001) and Taniguchi *et al.* (2003). Measurements of SGD using the continuous heat type automated seepage meter have been made every 10 minutes from 2 to 7 August 2003. Tidal (sea) levels were recorded every 10 minutes at F using a pressure transducer which was attached to the outside of the seepage meter chamber. Conductivities and temperatures of water within the chambers were also measured continuously by Conductivity-Temperature-Depth (CTD) sensors (DIK 603A CTD, Daiki Rika Kogyo, Co., Ltd) which were installed inside the five seepage meters.

Resistivity under the seabed and land surface at the transect line, which is perpendicular to the coast (Fig. 1) were measured by Sting R1 IP/Swift (AGI). There are 28 probes along the 270 m transect (interval length between probes was 10 m). The Wenner method and RES2DINV ver. 3.50 (Geotomo Software) were used for the resistivity analyses.

We also provide here a global assessment of the magnitude of SGD by using data directly obtained in the field via automated seepage meters (Taniguchi *et al.*, 2003). We analysed measurement data from 10 countries, 17 locations, 97 observation points, and more than 25 000 individual data points. In each case, we evaluated the average total SGD. In most cases (13 out of 17 locations) we also had continuous conductivity measurements inside the measurement chambers and were able to separate the fresh (Submarine Fresh Groundwater Discharge, SFGD), and saline (Recirculated Saline Groundwater Discharge, RSGD) flow components. These were examined as functions of distance from shore.

RESULTS AND DISCUSSION

Location of saltwater–freshwater interface and SGD changes

The cross-section results of resistivity measurements along the transect line (Fig. 1) at the lowest and highest tides on 18 September 2003, are shown in Fig. 2(a) and (b), respectively. The darker colour shows fresher water (higher resistivity), and lighter colour shows saltier water (lower resistivity). As can be seen from Fig. 2(a), seepage meters B, C and D are located at a relatively fresher seepage area (darker colour in figure); on the other hand, E and F are located in a relatively saltier area (lighter colour). The freshwater–saltwater interface is not usually sharp, but has a transient zone. Although we cannot define the location of the sharp interface, we can see the fresher water seepage face at B, C and D. However, the locations E and F may be seaward of the freshwater–saltwater interface.

Changes in tide, SGD rate, and temperature of SGD at D (near shore) and F (offshore) are shown in Fig. 3(a) and (b), respectively. As can be seen from Fig. 3(a),

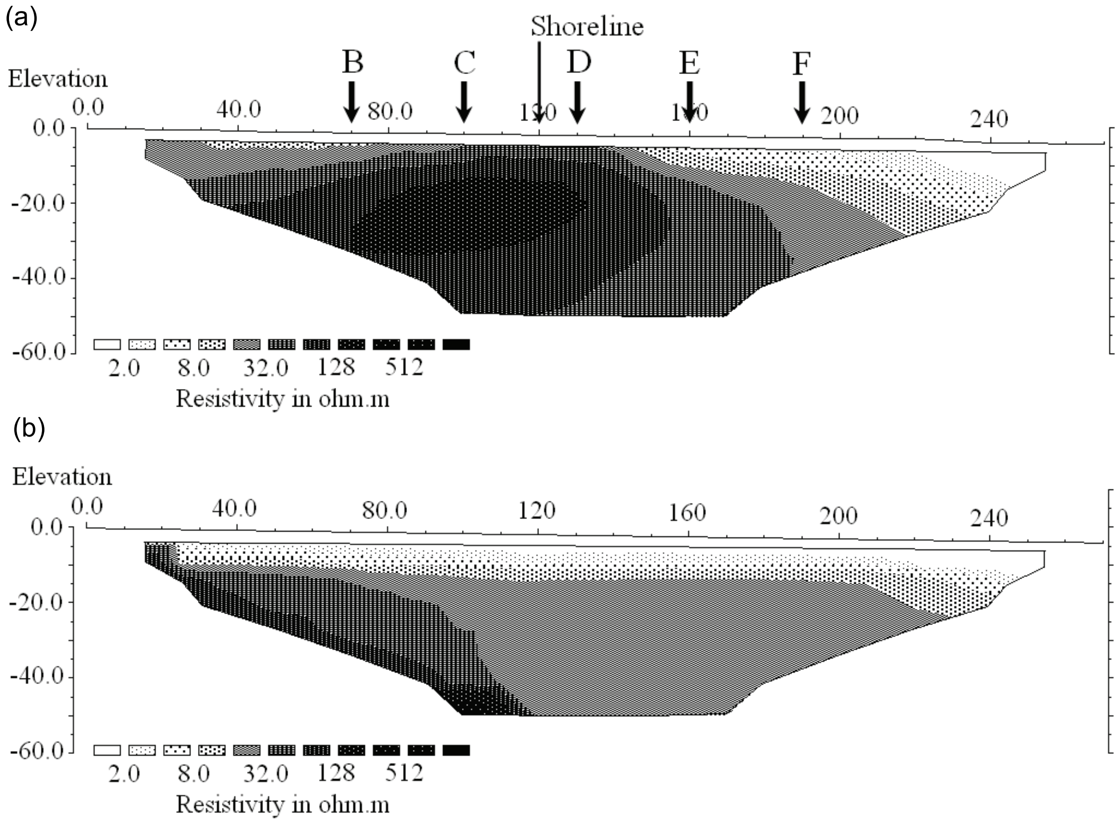

Fig. 2 Resistivity at: (a) high tide, and (b) low tide.

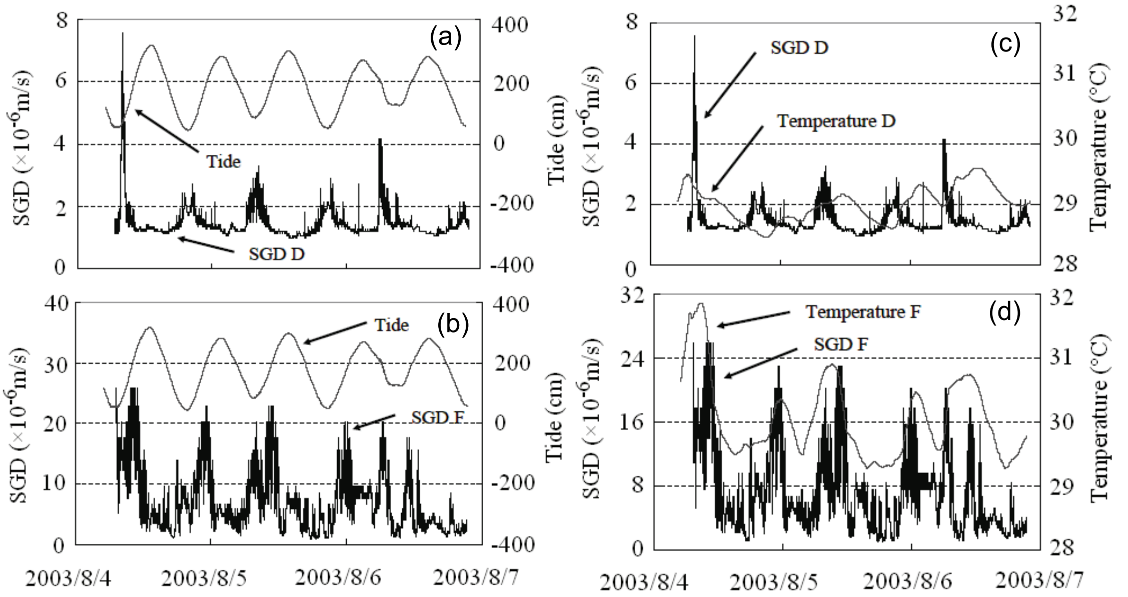

Fig. 3 Changes in: (a) tide and SGD rate at D, (b) SGD rate at F, (c) temperature of SGD at D, and (d) temperature of SGD at F.

negative correlations were found between tide and SGD at location D, however there is a time lag between tidal change and SGD changes at Location F (Fig. 3(b)). These results show that the changes in the hydraulic gradient between land and sea directly cause the changes of SGD nearshore (location D), but not offshore (location F). The negative correlations between temperature of SGD and SGD rate were also found near shore (location D), but not offshore (location F). The groundwater temperature is relatively cooler than that of the seawater during the summer in the field site. This result also supports the view that terrestrial groundwater is directly connected to the coastal water nearshore (location D), but not offshore (location F). These differences were found not only between D and F, but also between the nearshore group (B, C and D) and offshore group (E and F). As can be seen from Fig. 2, the nearshore group (B, C and D) is located landward from the seawater–freshwater interface, on the other hand, offshore group (E and F) is located seaward from the interface. Therefore, the SGD process is different on the landward side of the seawater–freshwater interface compared to that from the seaward side of the interface.

Recently collected detailed and continuous seepage flux and salinity measurements, together with tidal change and precipitation data at Shiranui, Japan, show that changes of Submarine Fresh Groundwater Discharge (SFGD) are likely related to changes in the hydraulic gradient between land and sea after an increase of groundwater recharge resulting from precipitation. Variations in Recirculated Saline Groundwater Discharge (RSGD), however, are related to tidal change and thus presumably caused by seawater exchange due to tide/wave pumping. Therefore, RSGD causes a phasing out of total SGD with the tide. Our automated measurements of groundwater flux suggest that precipitation and wave pumping appear to be important controls of terrestrial (fresh) and marine-induced (recirculated seawater) subterranean flows, respectively.

Global assessment of SGD

Observed SGD rates by seepage meters show that the total SGD distribution generally decreases, depending upon the distance from shore. The higher SGD flow closer to shore is likely a result of both SFGD, which is terrestrial fresh groundwater discharge, and RSGD due to wave set-up being elevated. SFGD observations clearly show that the ratio of the fresh groundwater discharge to the total discharge decreases systematically with distance from shore. This is attributed to a general decreasing hydraulic connection between terrestrial groundwater and seawater. The average flux of SFGD from the coast to 200 m offshore was 0.059 m/d. Therefore, fresh groundwater discharge per unit shoreline length from the coast to 200 m offshore is 12 m^3 m^{-1} d^{-1}. Using an estimated shoreline length of 600 000 km, we calculate that the SFGD flux to the world's ocean would be 2600 km^3/year within the first 200 m. This estimate of SFGD from the coast to 200 m offshore agrees well with a previous global estimation for fresh groundwater of 2400 km^3/year (or 11 m^3 m^{-1} d^{-1}) by hydrograph separation and water balance methods (Zektser, 2000). Although comparisons of SFGD between water balance methods and direct measurements have been done before on a local scale (Taniguchi *et al.*, 2006b), this is the first attempt on a global scale.

Figure 4 shows the magnitude of SFGD (solid bars) and RSGD (open bars) per unit shoreline length and location map of all known SGD observations cited in the

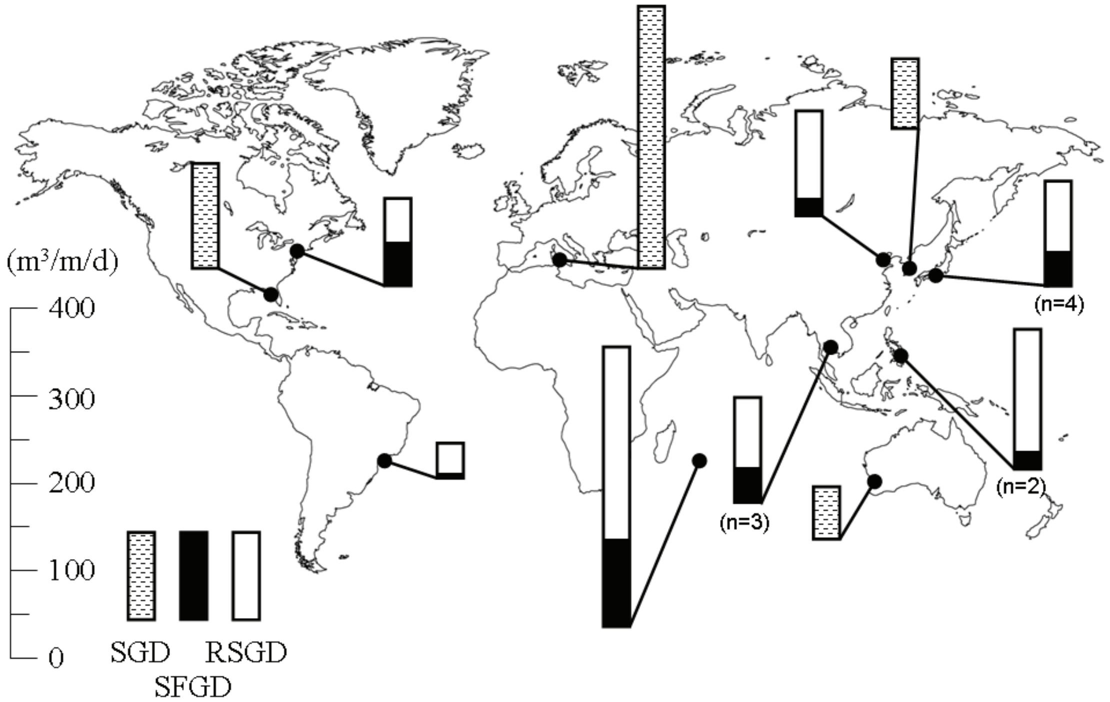

Fig.4 Global assessment of SGD, SFGD, and RSGD.

literature (closed circles). Total SGD (crossed-hatched symbol) given when separation of fresh and saline components was not possible. The numbers next to each circle refer to locations given in Taniguchi *et al.* (2002).

The geographical distribution of SFGD and RSGD estimates per unit shoreline length shows considerable spatial heterogeneity. Higher SFGD was found in east and south-east Asia, Long Island (New York), and Mauritius, areas where precipitation is also high and/or the sediments are very permeable (Emery, 1968). On the other hand, areas with low SFGD are found in deltaic areas such as near the mouths of the Yellow River (China) and Chao Phraya River (Thailand). The two areas we have measured that have the very highest SGD (= SFGD + RSGD) per unit shoreline length (>300 m^3 m^{-1} d^{-1}) are located on the coasts of Sicily and Mauritius, both characterized by high rainfall, steep topography, and an absence of well-developed rivers

CONCLUSION

The main conclusions of this study are:

1. SGD variations within the saltwater–freshwater interface had negative correlations with tidal variations, because of the connections of terrestrial groundwater on the land and the ocean. On the other hand, there is a time lag between tidal change and SGD changes offshore from the interface.
2. The negative correlations between temperature of SGD and SGD rate were also found landward from the freshwater–saltwater interface, but not offshore. This is attributed to the direct connection of nearshore coastal water to the terrestrial groundwater.

3. The processes of SGD differ between seaward and landward of the saltwater–freshwater interface. SGD landward of the interface can be explained mainly by connections of terrestrial groundwater; however, SGD seaward of the interface is controlled mostly by oceanic process such as recirculated saline groundwater discharge.
4. Global evaluations of SGD based solely on observational data showed that fresh groundwater discharges is estimated to be 2600 km^3/year (from the coast to 200 m offshore) and is equivalent to 7% of the global river flux. There is heterogeneity in the distribution of SGD depending on hydrogeology and precipitation.

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REFERENCES

Burnett, W. C., Taniguchi M. & Oberdorfer, J. A. (2001) Assessment of submarine groundwater discharge into the coastal zone. *J. Sea Res.* **46**, 109–116.

COSOD II (1987) *Fluid Circulation in the Crust and the Global Geochemical Budget*. Report of the Second Conference on Scientific Ocean Drilling (Strasbourg, France, July, 1987).

Emery, K. O. (1968) Relict sediments on continental shelves of the world. *Am. Assoc. Petroleum Geol*. **52**, 445–464.

Kim, G. & Hwang, D. W. (2002) Tidal pumping of groundwater into the coastal ocean revealed from submarine Rn-222 and CH_4 monitoring. *Geophys. Res. Lett*. **29**, 1–4.

Moore, W. S. (1996) Large groundwater inputs to coastal waters revealed by ^{226}Ra enrichments. *Nature* **380**, 612–614.

Nace, R. L. (1970) World hydrology: status and prospects. In: *World Water Balance*, vol. I.(IAHS-UNESCO symposium, Reading, August 1970), 1–10. IAHS Publ. 92. IAHS Press, Wallingford, UK.

Taniguchi, M. (2002) Tidal effects on submarine groundwater discharge into the ocean. *Geophys. Res. Lett*. **29**, 1–3, 10.1029/2002GL014987.

Taniguchi, M. & Iwakawa, T. (2001) Measurements of submarine groundwater discharge rates by a continuous heat – type automated seepage meter in Osaka Bay, Japan. *J. Groundwater Hydrol.* **42**, 271–277.

Taniguchi, M., Burnett, W. C., Cable, J. E. & Turner, J. V. (2002) Investigations of submarine groundwater discharge. *Hydrol. Processes* **16**, 2115–2129.

Taniguchi, M., Burnett, W. C., Cable, J. E. & Turner, J. V. (2003) Assessment methodologies of submarine groundwater discharge. In: *Land and Marine Hydrogeology* (ed. by M. Taniguchi, K. Wang, & T. Gamo), 1–23. Elsevier, Amsterdam, The Netherlands.

Taniguchi, M., Ishitobi, T. & Shimada, J. (2006a) Dynamics of submarine groundwater discharge and freshwater–seawater interface: *J. Geophys. Res*. **111**, C01008, doi:10.1029/2005JC002924.

Taniguchi, M., Ishitobi, T. & Shimada, J. (2006b) Evaluation of spatial distribution of submarine groundwater discharge, *Geophys. Res. Lett.* **33**, L06605, doi:10.1029/2005GL025288.

Zektser, I. S. (2000) *Groundwater and the Environment*. Lewis Publishers, Boca Raton, Florida, USA.