

## **Spatial Variation of Submarine Groundwater Discharge (SGD) in the Central Part of Seto Inland Sea, Japan**

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**Abstract**—We measured the spatial distribution of salinity and radon-222 (<sup>222</sup>Rn) concentration within seawater in the Hiuchi-Nada, a small bay located in central part of the Seto Inland Sea, to clarify the groundwater discharge distribution in weak stratification period of 2009. The results suggest that the shallow (unconfined) groundwater discharged near the coastline, while deep (confined) groundwater discharged from offshore seabed in southwestern area of the study area. The average contribution of groundwater to seawater in the study area is estimated to be about 2%.

**Keywords:** submarine groundwater discharge (SGD), spatial variation, Seto Inland Sea, Radon-222 (<sup>222</sup>Rn)

### INTRODUCTION

Submarine groundwater discharge (SGD) represents all direct discharge of subsurface fluids across the land-ocean interface (Taniguchi *et al.*, 2002). Recent studies have revealed that SGD is one of the important pathways for nutrients and the other dissolved materials such as carbon and trace metals from terrestrial area to the marine environment (Moore, 2010). On the global scale, Zektser and Loaiciga (1993) estimated that the amount of dissolved material load by direct groundwater discharge is more than 50% of that from rivers. Accordingly, the effect of groundwater cannot be negligible in considering nutrient environment of coastal area.

Based on the conceptual figure shown by Taniguchi *et al.* (2002), submarine fresh groundwater discharge (SFGD) includes shallow (unconfined) groundwater and deep (confined) groundwater. In addition, shallow groundwater generally discharges near the coast line, while deep groundwater would discharges from the seabed of offshore area because it has higher water pressure than shallow groundwater. However, in the previous studies, discharge area and its flux of the

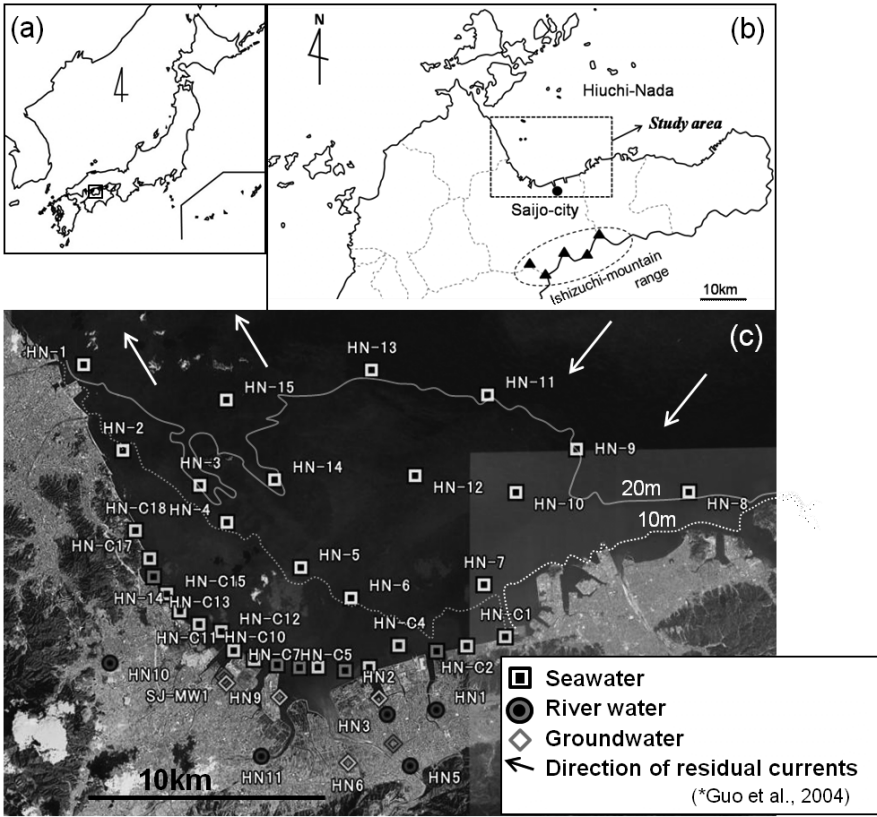


Fig. 1. Study area (a: location of the study area and b: sampling stations).

deep groundwater in the coastal areas were not well evaluated.

Seto Inland Sea is the largest semi-enclosed coastal sea in Japan. Recently, some researchers tried to evaluate SGD at the specific area of the Seto Inland Sea. For example, Taniguchi and Iwakawa (2004) evaluated shallow groundwater discharge in the Osaka Bay using seepage meters. Onodera *et al.* (2007) examined shallow groundwater discharge and derived nutrient transport in a small tidal flat located on an island. Shimizu *et al.* (2009) estimated the shallow groundwater discharge along the coast line of Bisan-Seto using topographic model. Nevertheless, deep groundwater discharge was not evaluated in these studies.

The objective of the study is to confirm the presence of SGD including both of shallow and deep groundwater and its spatial distribution in the central area of Seto Inland Sea.

### STUDY AREA

The Hiuchi-Nada is a semi-enclosed bay in the central part of the Seto Inland

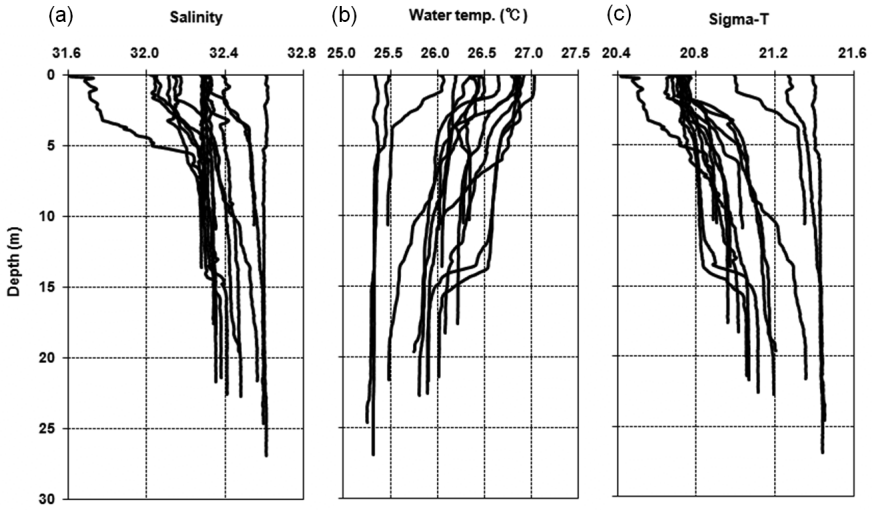


Fig. 2. Vertical profiles of (a) salinity, (b) temperature and (c) sigma-t measured at all stations.

Sea. The bay has a size of about  $50 \text{ km} \times 30 \text{ km}$  and an average depth of approximately 20 m. Kurushima Strait, a narrow and deep strait ( $>50 \text{ m}$ ), is located at its western side, and Bisan Strait, a wide and shallow strait, at its eastern side.

The study area (Fig. 1) is southwestern part of the Hiuchi-Nada and has a size of approximately  $30 \text{ km} \times 13 \text{ km}$ . Based on the horizontal distribution of residual current in the Hiuchi-Nada (Guo *et al.*, 2004), we know that dominant diurnal current flows from east to west along coastal line. Only some small rivers (Kamo River, Nakayama River etc.) flow into the study area, whereas the terrestrial area is characterized by abundant volume of groundwater recharged in the catchment of mount Ishizuchi, which is the highest mountain (max. 1982 m amsl.) in western Japan.

## METHOD

We conducted the measurement of vertical profiles in salinity, water temperature and chlorophyll and sampling of sea water at intervals of 5 m from the surface to the bottom at 15 stations with depth of from 10 m to 25 m in September 2009 (Fig. 1). River water samples and terrestrial groundwater samples were collected around the study area. Radon-222 ( $^{222}\text{Rn}$ ) concentration was measured at surface and bottom layers of the sampling station using electronic radon detector (RAD7, DurrIDGE Co.).  $^{222}\text{Rn}$  is one of the radioactive isotopes of radon in the uranium-238 ( $^{238}\text{U}$ ) series. It is unreactive in nature with short half-life ( $t_{1/2} = 3.83 \text{ d}$ ). Burnett *et al.* (1996) pointed out that the Radon-222 ( $^{222}\text{Rn}$ ) is a useful tracer of SGD because groundwater has extremely high

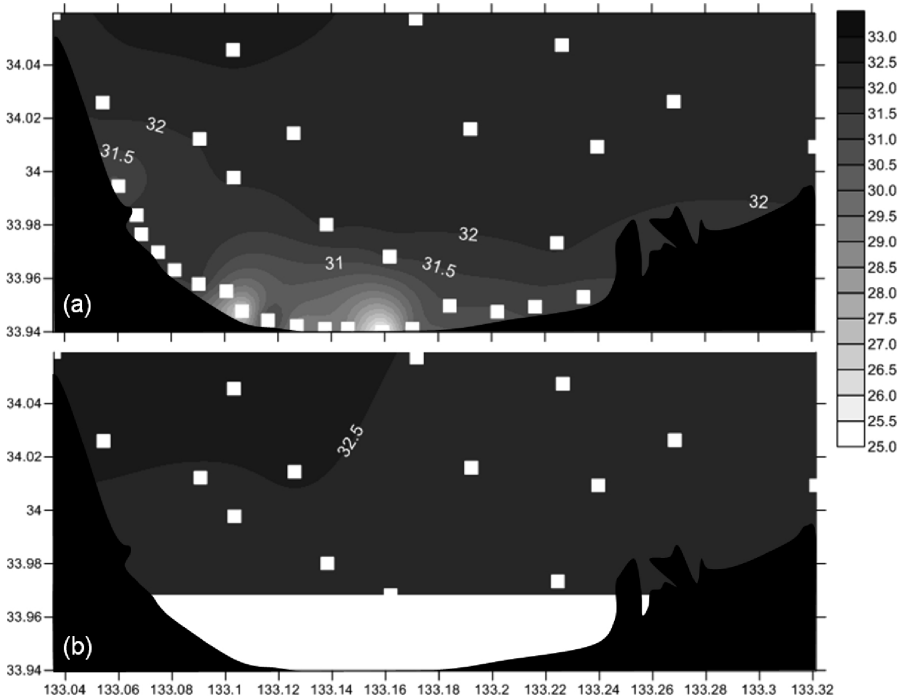


Fig. 3. Salinity distribution in surface (a) and bottom (b) seawater.

concentration in  $^{222}\text{Rn}$  compared with river water and seawater. Therefore, relatively high  $^{222}\text{Rn}$  concentration in seawater suggests groundwater discharge area.

## RESULTS AND DISCUSSION

### *Spatial distribution of groundwater discharge area*

Figure 2 summarized vertical profiles of (a) salinity, (b) water temperature and (c) sigma-t at all sampling stations. Salinity and sigma-t were relatively low while temperature was high in the upper layer. These results indicate the presence of stratification with a pycnocline at depth of about 5 m.

Salinity in the surface layer was relatively low near the coastline, indicating the influence of river water inflow. Figure 3 shows horizontal distribution of salinity in (a) surface and (b) bottom seawater. In the surface layer, low salinity less than 26 was detected at some stations near the coastline; in the bottom layer, salinity was about 32–33 with a smaller spatial variation than in surface layer.

Figure 4 is the horizontal distribution of  $^{222}\text{Rn}$  concentration in (a) surface and (b) bottom seawater. Here,  $^{222}\text{Rn}$  concentration is expressed as the ratio of the

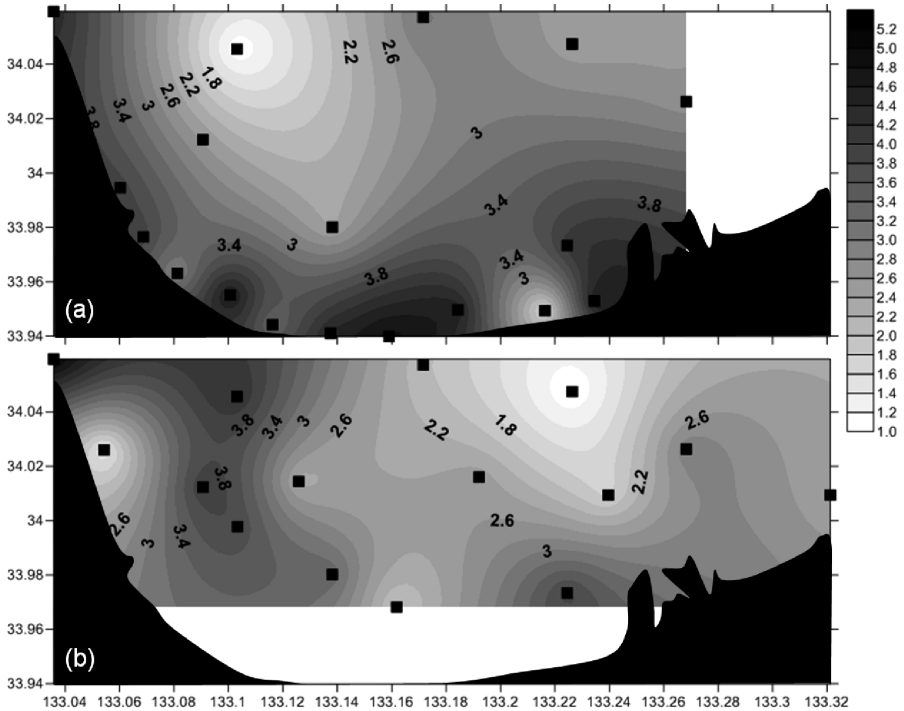


Fig. 4.  $^{222}\text{Rn}$  distribution in surface (a) and bottom (b) seawater.

concentration in each station to the lowest concentration (HN-11).  $^{222}\text{Rn}$  concentration in the surface layer was relatively high along the coast line. This result suggests the effect of river inflow and shallow (unconfined) groundwater discharge near the coast line. Meanwhile, in the bottom layer, high  $^{222}\text{Rn}$  concentration was detected in the offshore area at southern part of the study area. As mentioned above, the observation was conducted in stratification period (Fig. 2). Therefore, the result indicates that deep (confined) groundwater discharged more offshore area than the shallow groundwater.

The spatial variation of salinity and  $^{222}\text{Rn}$  concentration presented almost the same trend, which was more significant in  $^{222}\text{Rn}$  than in salinity. This can be easily understood from the fact that salinity is almost same between river water and groundwater, whereas  $^{222}\text{Rn}$  concentration is generally higher in groundwater than in river water (Burnett *et al.*, 1996). For this reason,  $^{222}\text{Rn}$  is a good tracer for separating the effect of river water and groundwater within seawater, as shown by our measurement results. It must be noted that our measurements confirmed presence of deep groundwater discharge in the coastal area (Fig. 4b), which correspond well to the concept of SGD given by Taniguchi *et al.* (2002).

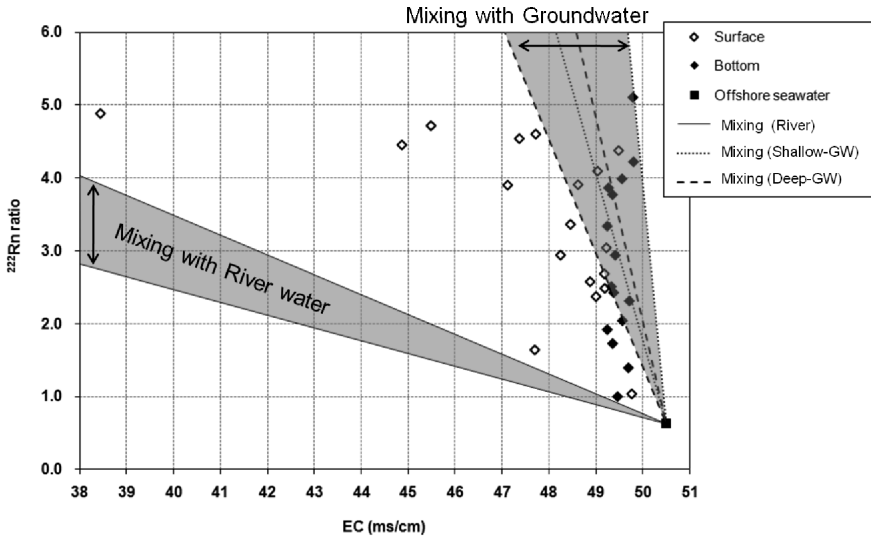


Fig. 5. Relation between salinity and  $^{222}\text{Rn}$  in the seawater, groundwater and river water.

*Estimation of groundwater contribution in the seawater*

Figure 5 shows the relation between salinity shown as electric conductivity (EC) and  $^{222}\text{Rn}$  concentration in the surface and bottom seawater. Surface seawater is characterized by lower salinity than bottom seawater. Here, we hypothesized that the seawater in the study area is composed of simple binary mixing between offshore seawater and terrestrial water (river water or groundwater). The offshore seawater is assumed to be the bottom seawater at station HN-11 located in the northeastern area (Fig. 1c). According to the distribution of residual currents in the Hiuchi-Nada given by Guo *et al.* (2004), offshore seawater would flow in the study area from eastern part, and flow out from western part (Fig. 1c). Since the bottom seawater at station HN-11 is characterized by the lowest  $^{222}\text{Rn}$  concentration and relatively high salinity among all stations, it should be little influenced by fresh terrestrial water inflow.

The gray color zone in Fig. 5 shows the mixing between offshore seawater and river water or that between offshore seawater and groundwater. Here, the mixing is not given as a single “line”, because the  $^{222}\text{Rn}$  concentration in terrestrial water has spatial variations among sampling sites (Fig. 1c). The result suggests that the bottom seawater in the study area would be originated by the mixing between offshore seawater and the groundwater, while the surface seawater would be influenced by river water. The average contribution of groundwater is estimated to be about 2% among all sampling stations.

## CONCLUDING REMARKS

To confirm the groundwater discharge area in the Hiuchi-Nada, we have measured the spatial distribution of salinity and radon-222 ( $^{222}\text{Rn}$ ) concentration in the surface and bottom seawater during the stratification period of 2009. Significantly low salinity in the surface seawater indicates the effect of river inflow. Spatial distribution in  $^{222}\text{Rn}$  concentration suggests that shallow (unconfined) groundwater discharges near the coastline, while deep (confined) groundwater discharges from the offshore seabed in southwestern area of the study area. The average contribution of groundwater to the seawater in the study area is estimated to be about 2%.

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