Evaluations of spatial distribution of submarine groundwater discharge

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[1] The paired catchments with the same basin size and meteorological condition but different geology were selected to compare the fresh submarine groundwater discharge (SGD) rate observed by seepage meters with value calculated from water balance method in Kumamoto, Japan. The fresh SGD rate decreases with the distance from the coast, on the other hands, recirculated saline SGD is higher at near shore due to wave set-up and at offshore due to tidal pumping. The spatial integrations of fresh SGD agree well with the water budget in both paired catchments. The difference of fresh component of SGD between two catchments may be caused by the difference of geology in the study area. **Citation:** Taniguchi, M., T. Ishitobi, J. Shimada, and N. Takamoto (2006), Evaluations of spatial distribution of submarine groundwater discharge, *Geophys. Res. Lett.*, *33*, L06605, doi:10.1029/2005GL025288.

1. Introduction

[2] Recognition of the importance of submarine groundwater discharge (SGD) is increasing for the studies on water and dissolved material transports from land to the ocean [e.g., *Moore*, 1996]. There are several methods to evaluate SGD, such as tracer methods using Rn [*Burnett et al.*, 2003; *Cable et al.*, 1997; *Kim and Hwang*, 2002], use of seepage meters [*Taniguchi et al.*, 2002], use of piezometers [*Martin et al.*, 2005], and water balance methods [*Taniguchi et al.*, 2005]. SGD consists not only of terrestrial fresh water (Submarine Fresh Groundwater Discharge; SFGD), but also of Recirculated Saline Groundwater Discharge (RSGD) of marine origin [e.g., *Taniguchi et al.*, 2002]. The water balance method or combination of seepage meter and CTD measurements of SGD can tell us the SFGD rates. On the other hands, tracer method such as Rn measurements, piezometer measurements, and seepage meter itself can tell us the total volume of SGD (SFGD and RSGD).

[3] Seepage meter is the only way to evaluate SGD rates directly, and automated seepage meters have been recently developed [e.g., *Paulsen et al.*, 2001; *Rosenberry and Morin*, 2004; *Taniguchi et al.*, 2003]. Although *Shinn et al* [2002] criticized the seepage meter measurements, recent field evaluations of the SGD using seepage meters showed that consistent and reliable results can be obtained even in the heterogeneous situations if one accounts for the potential problems [*Cable et al.*, 1997]. Temporal changes of SGD due to tidal effects were evaluated with semi-diurnal variation [*Paulsen et al.*, 2001; *Taniguchi*, 2002] and semi-monthly variation [*Taniguchi*, 2002; *Kim and Hwang*, 2002], however spatial integrations of SGD are limited to only the transect lines which are perpendicular to the coast [*Burnett et al.*, 2003].

[4] The water balance equation for a basin has been used to estimate SGD and is described as follows: $P = E_T + D_S + D_G + dS$, where P is precipitation, E_T is evapotranspiration, D_S is surface runoff, D_G is groundwater discharge, and dS is the change in water storage. Over extended periods (i.e., years), dS is usually assumed to be negligible. Therefore, one needs to know precisely the precipitation, evapotranspiration and surface runoff for an accurate estimation of D_G. When both the area and flux of SGD are known, one can calculate the SGD volume. Therefore spatial integration of observed (local) SGD estimates shown as Darcy's flux (e.g., $cm^3/cm^2/s$, cm/s, m/y) is needed to convert to the volume of SGD to compare the results from the water balance method.

[5] The purposes of this study are (1) to compare the fresh terrestrial SFGD observed from seepage meters with values calculated from water budget, (2) to evaluate spatial distributions of SFGD and RSGD, and (3) to compare the SGD in paired catchments with the same basin size and meteorological condition but with different geology.

2. Study Area and Methods

[6] Study area is a coastal zone of Yatsushiro Sea in Kyushu island, Japan (Figure 1). Aquifers in this study area consist of permeable quaternary volcanic rocks (andesite lava and tuff breccia) and pyroclastic flow deposits. The basin consists of two paired sub-catchments, Hon-ura basin and Nishi-ura basin, with the area of 2.867 km^2 and 2.198 km^2. The length of the basin from the top (elevation is 400 m above sea level) to the coast is about 4 km. The annual precipitation is about 1680 mm $year^{-1}$, and average annual air temperature is about 16.7°C. The Yatsushiro sea is an inland sea, and the average of tidal change is from 3 to 5m.

[7] Continuous heat - type automated seepage meters were installed at about 50m (a, d, g, i, k and n in Figure 1), 100 m (b, e, h, j, l, and o in Figure 1), and 150 m (c, f, and m in Figure 1) distance offshore from the coastal line at high tide along the 6 transect lines (A to F) in Yatsushiro. The all seepage meters are located between high tide coast and low tide coast. The principle of the automated seepage meter is described in detail by *Taniguchi et al.* [2003]. The depth of the seawater at high tide is 1.0, 1.8, and 2.5 m at the location of the seepage meter of 50 m offshore, 100 m offshore, and 150 m offshore, respectively. All chambers were exposed during the low tide. The area of the chamber

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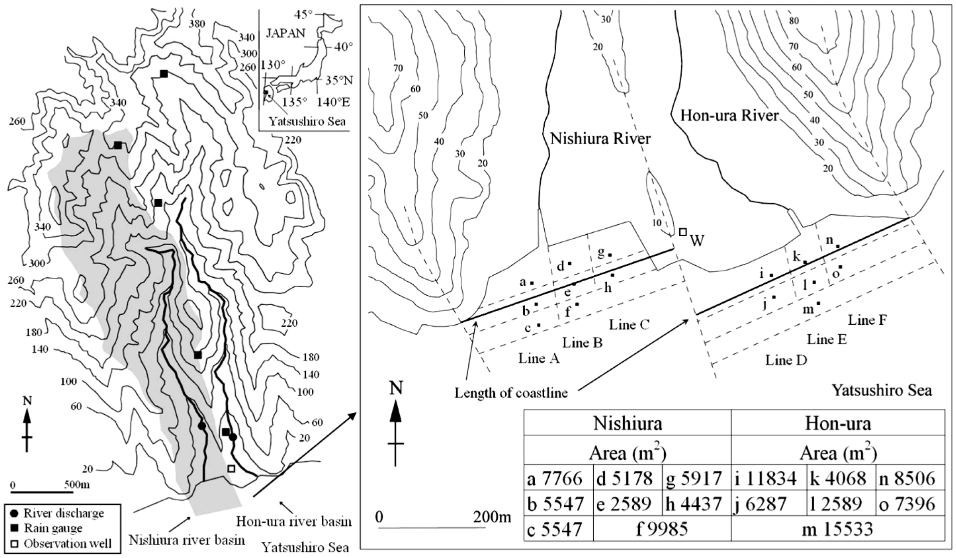

Nishiura			Hon-ura		
Area (m^2)			Area (m^2)		
a 7766	d 5178	g 5917	i 11834	k 4068	n 8506
b 5547	e 2589	h 4437	j 6287	l 2589	o 7396
c 5547	f 9985		m 15533		

Figure 1. Location map of the study area.

with the diameter of 0.5 m for the seepage meter is 0.196 m^2. Measurements of SGD using the continuous heat type automated seepage meter have been done every 10 minutes from August 8 to 11, 2005. Conductivities and temperatures of waters within the chambers were also measured continuously (every 10 min) by Conductivity-Temperature (CT) sensors (Compact-CT, Alec Electronics, Co., Ltd.) which were installed in the chamber of the seepage meters. Seepage meters with CTD sensors were located at the same location at least 24 hours (144 data) and moved to the next transect lines. The amplitude of the semi-diurnal sea level change is about 1.5 m during observation period. No precipitation was observed during last seven days before observation, therefore the SFGD should show the base flow from the land to the ocean.

3. Results

[8] Spatial distribution of daily-averaged SGD (Figure 2a) shows that SGD rate at off shore of Hon-ura basin is about ten times larger than that in Nishi-ura basin. The contour lines of SGD are parallel to the coast which indicates the dominant process of SGD is based on the distance from the coast.

[9] In order to separate SGD into terrestrial fresh groundwater discharge (SFGD) and recirculated saline water (RSGD), analyses of water and material budgets using two end members have been made. Water balance and material balance equations at the seabed are described as follows; SGD = SFGD + RSGD, and $C_{SGD} \times SGD = C_{SFGD} \times SFGD + C_{RSGD} \times RSGD$, where C_{SGD}, C_{SFGD}, and C_{RSGD} are conductivities of the water that compose the SGD, SFGD and RSGD, respectively. Conductivities of the SGD at each location as C_{SGD}, the fresh terrestrial ground water at observation well (shown as open square in Figure 1) as one end member of C_{SFGD}, and sea water as another end member of C_{RSGD} were used to separate SGD into SFGD and RSGD.

[10] Observed SGD conductivities range from 25.23 to 42.91 mS cm^{-1} (from 15.36 to 27.60 psu in salinity) in Hon-ura, and from 7.35 to 40.38 mS cm^{-1} (from 4.04 to 25.80 psu in salinity) in Nishi-ura basin. Incorporating average SGD (Figure 2a), C_{SGD}, C_{SFGD} of 0.200 mS cm^{-1} (0.10 psu) at the observation well, and C_{RSGD} of 48.66 mS

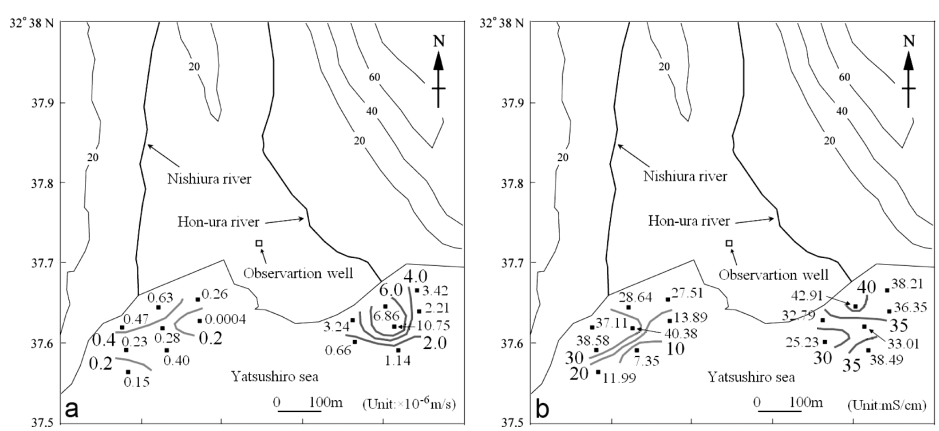

Figure 2. Spatial distribution of (a) SGD and (b) SFGD.

Table 1. Water Balances of the Nishi-ura and Hon-ura Basins[a]

P	Ds	E_T	D_G
	Nishiura River Basin		
1673	500	743	430
	Hon-ura River Basin		
1687	324	739	624

[a]Unit (mm/y).

cm^{-1} (31.76 psu in salinity) into above equations, SFGD and RSGD were calculated, and shown in Figure 2b. As can be seen from Figure 2b, SFGD is also larger at offshore of Hon-ura basin than that of Nishi-ura basin. The contour lines of SFGD show that the highest SFGD locates in the middle of the bay but not near the coast.

[11] Annual water budgets in two paired-catchments are calculated using monthly data of precipitation (P), evapotranspiration (E_T), and river discharge (D_S) from October 2003 to September 2004. SFGD were calculated from $P - E_T - D_S$ (Table 1). Monthly precipitation and air temperature data were collected at five meteorological stations for the water balance calculation in the basin (Figure 1). Thornthwaite method [*Thornthwaite*, 1948] for estimating evapotraspiration rates and Thiessen polygon method for evaluating basin scale precipitation and evapotraspiration were used for calculating water balance in the basin (three stations for Hon-ura basin and two stations for Nishi-ura stations shown by solid squares in Figure 1). River discharges were recorded at two locations (shown by solid circle in Figure 1). As can be seen from Table 1, river discharge is 1.54 times larger at Nishi-ura basin (500 mm year^{-1}) than that at Hon-ura basin (324 mm year^{-1}). As precipitation as well as evapotraspiration is almost the same in both sub-basins, SFGD is 1.45 times larger at Hon-ura basin (624 mm year^{-1}) than that at Nishi-ura basin (430 mm year^{-1}).

4. Discussion

[12] In order to compare SFGD flux (cm/day or m/s) measured by seepage meters with SFGD volume (m^3/y) calculated from water balance method, integrations of SFGD from seepage meter measurements have been made with two different ways. The first one is the integration

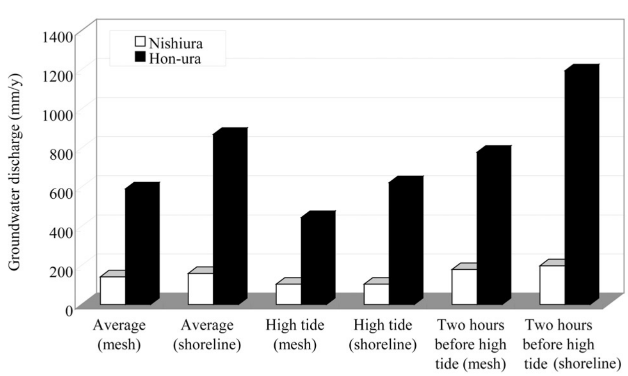

Figure 3. Comparisons of SFGD with two different ways (mesh and shoreline) and three different periods (average, high tide, and two hours before high tide).

Table 2. SFGD From Seepage Meter Measurements for the Integrations by "Shoreline Way"[a]

Period	Line: Nishiura River Basin A	B	C	Hon-ura River Basin D	E	F
50m						
Average (24 h)	1.7	2.7	1.2	11.6	8.0	16.1
High tide (12 h)	1.2	2.3	1.1	9.7	8.6	8.9
Two hours before high tide	4.0	3.8	1.1	14.8	12.1	25.8
100m						
Average (24 h)	0.6	0.9	0.004	3.2	40.4	9.3
High tide (12 h)	0.5	0.5	0.003	3.2	30.8	5.5
Two hours before high tide	0.6	1.0	0.003	3.1	46.2	13.5
150m						
Average (24 h)	4.6	3.4			2.4	
High tide (12 h)	1.2	3.4			2.5	
Two hours before high tide	4.9	3.4			1.6	

[a]Unit $\times 10^{-7}$m/s.

depending on the SFGD rates and meshed area where each seepage meter is representative (Figure 1). SFGD volume is calculated by multiplying SFGD flux by representative area. The representative area is divided with the same distance from each seepage meter, and it ranges from 2589 m^2 to 15533 m^2, which is shown in Figure 1. The second way is an integration of SFGD along the six transect lines (three lines in each basin) which are perpendicular to the coast, then it is multiplied by the length of the coast to be SFGD volume. The length of the transect line is 175 m. The length of the coast is 419 m (169m, 77m, and 173 m from west to east) and 426 m (169m, 69m, and 188 m from west to east) in Nishi-ura and Hon-ura basin, respectively. Three different observation periods of SFGD are chosen. The 24 hour average (lacunae of SGD data during some periods because of drying up of seepage meter), 12 hour average during high tide (no lacunae of SGD data), and 2 hour average before high tide (highest SGD) are used for SFGD evaluations. Therefore, six (two different ways and three different periods) spatial integrations of SFGD observed by seepage meters have been made, and are shown in Figure 3.

[13] SFGD rates obtained by each seepage meter at lines A to F during three different periods are shown in Table 2. Total SFGD in Nishi-ura basin and Hon-ura basin by the first way (mesh method) ranges from 104 to 179 mm/year, and from 446 to 779 mm/year, respectively. The total SFGD in Nishi-ura basin and Hon-ura basin by the second way (shoreline method) ranges from 103 to 198 mm/year, and from 622 to 1194 mm/year, respectively. The SFGD evaluated by seepage meters with six different ways ranges from 104 to 198 mm/year in Nishi-ura basin and from 446 to 1194 mm/year in Hon-ura basin. On the other hand, SFGD evaluated by water balance is 430 mm/year and 624 mm/year in Nishiura and Hon-ura basin, respectively (Table 1). Both water balance and seepage meter integration methods showed that SFGD in Hon-ura basin is higher than that of Nishi-ura basin. The SFGD evaluated by seepage meters always underestimates SFGD evaluated by water balance in Nishi-ura basin, however the SFGD evaluated by water balance in Hon-ura basin is within the range of SFGD evaluated by seepage meters in Hon-ura basin for both mesh and shoreline methods. Spatial

integration of SFGD measured by seepage meters agreed relatively well with the water balance calculation in both sub-catchments.

[14] The difference of the hydrogeology in the two sub-basins may be the reason of the different of SFGD. The difference of the main geological features of both basins is whether the amphibole pyroxene andesite (Nishi-ura basin) or the include amphibole pyroxene andesite (Hon-ura basin) overlies the amphibole andesite. The hydraulic conductivity is reported to be 1.6 to $\times 10^{-3}$ cm/s and 3×10^{-3} for amphibole andesite and the amphibole pyroxene andesite (Nishi-ura basin), respectively. The hydraulic conductivity of the include amphibole pyroxene andesite (Hon-ura basin) is not reported, however the permeability of the include amphibole pyroxene is assumed to be higher than that of amphibole pyroxene andesite [*Kumamoto University*, 2003]. Therefore the reason of the higher SFGD in Hon-ura basin is the high permeability of the aquifer.

[15] SGD consists of SFGD and RSGD [*Taniguchi et al.*, 2002]. SFGD is mainly controlled by terrestrial hydrological condition and hydrogeology mentioned above, however RSGD may be controlled by different processes. As can be seen from Figure 2a, the contour lines of SGD are parallel to the coast which indicates the dominant process of SGD is based on the distance from the coast. The distribution of SGD conductivity showed that the areas with high conductivity are located near shore and offshore for Hon-ura basin. Recirculated saline SGD occurred by several reasons such as wave set-up [*Li et al.*, 1999], tidal pumping, or thermal convection. The higher conductivity of SGD near shore may be caused by wave set-up, on the other hand, the higher conductivity of SGD at offshore may be caused by tidal pumping.

[16] The spatial distribution of SFGD may depend on the shape of the coastal line, such as bayment or peninsular. Effects of curvature of the bay on SGD were discussed by *Cherkauer and McKereghan* [1991]. They showed a genetic model of the bay effect, and generalized that SGD is higher with curvature in unit length of the bay than that without curvature, because of the convergence of the groundwater discharge. They also discussed that the convergence of the groundwater discharge is smaller with less curvature of bay. As can be seen in Figure 2b, the highest SFGD were found in the middle of the bay for both basins. This may be caused by the effect of curvature of the bay on SFGD.

5. Conclusions

[17] Submarine Groundwater Discharge (SGD) using different two methods, water balance method and seepage meter method, are evaluated and compared in the paired catchments with the same basin size and same meteorological condition but different hydrogeology. Two different methods (“mesh” and “shoreline” methods) and three different periods are used for integrations of the SGD by seepage meters to compare the results by water balance method. The conclusions of this study are summarized as follows; (1) The spatial integrations of fresh SGD by seepage meters relatively agree well with the water budget in both paired catchments, (2) Fresh component of SGD in Hon-ura basin is about 1.5 times larger than that of Nishi-ura basin, due to the difference of the permeability of the aquifer in both basins, and (3) The fresh SGD rate decreases with the distance from the coast, and recirculated SGD is higher at near shore due to wave set-up and at offshore due to tidal pumping.

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