A New Focus on Groundwater–Seawater Interactions
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Basin-wide groundwater flow study in a volcanic low permeability bedrock aquifer with coastal submarine groundwater discharge

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Abstract The purpose of this study is to reveal the basin-wide groundwater flow system in a Quaternary pyroclastic bedrock aquifer by using several hydrological methods: catchment hydrometric observations, environmental isotope study of the spring water and observation borehole levels including in-land, on-shore and offshore boreholes, basin-wide groundwater potential monitoring, geophysical methods to understand the aquifer distribution, water balance for the representative paired catchments in the study basin including micro-meteorological evapotranspiration measurements, direct submarine groundwater discharge (SGD) measurements by automatic seepage meters, and three-dimensional groundwater flow simulations based on observed hydrological data. The results clearly show that topographically driven groundwater flow systems with different flow dynamics and residence times exist in the study catchments and strongly support the hydrological characteristics of local springs and a river discharge system including coastal SGD. Also, a stagnant fresh groundwater system exists under the present sea bed which is completely separate from the land-based groundwater flow systems, and is thought to be a kind of remnant palaeo groundwater recharged during the previous regression era. This has no direct relation to the present SGD in the area.

Key words groundwater flow system; environmental isotopes; groundwater potential; submarine groundwater discharge; observation borehole; remnant palaeo groundwater

INTRODUCTION

Quaternary pyroclastic flow deposits are widely distributed in Japan, but their groundwater flow systems have not been studied much. The relatively steep morphology and humid temperate hydrological conditions of Japan should create active groundwater flow including coastal groundwater seepage-out. A 5.2 km^2 mountainous pyroclastic catchment has been selected in Uto peninsula, Kumamoto, Japan (Fig. 1) for this purpose, and the following four major themes have been taken to reveal the regional groundwater flow system:

1. Precise hydrometric study in the headwater catchments relating the rainfall–runoff process.

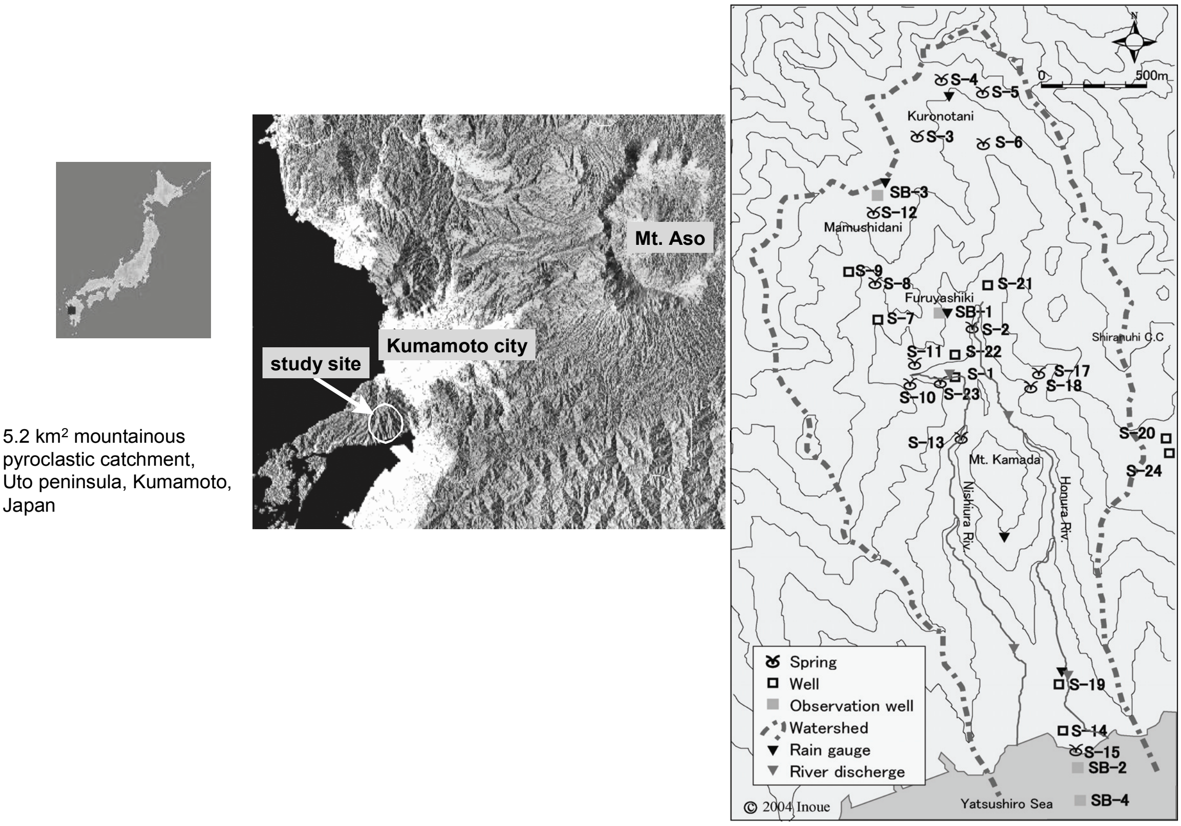

Fig. 1 Location of study site and major hydrological feature in the study catchments.

2. Isotope hydrological study with the help of groundwater potential measurements using deep observation boreholes of different depth and the self potential survey in the study catchments.
3. Self potential survey, resistivity survey, seepage meter measurements and groundwater potential measurements in the observation boreholes have been conducted in the on-shore and off-shore area during the tidal fluctuation period.
4. Three dimensional groundwater flow simulation in the study catchments, including river water discharge and evapotranspiration.

The study started in 2002 and a major hydrological observation system including four river discharge gauging stations and nine boreholes of different depth were installed in the study basin for monitoring purposes (Fig. 1). The groundwater flow regime characteristics observed during the four year period since, allow study of the relation between coastal groundwater seepage and the inland groundwater flow system and a multi-scale groundwater flow system has been confirmed.

STUDY AREA

The study basin is about 4 × 2 km in area with an elevation range of 0–400 m, which we call the Shiranui study site. It mainly consists of Tertiary/Quaternary lava and volcanic tuff-breccias. The Palaeozoic sedimentary rock, a hydrogeological basement boundary to the above volcanic rocks, exists about 200 m below the ground surface.

The major land uses of this basin are citrus farming, paddy field and bamboo/cedar forest. There are many natural springs in the mid-basin area, and an artesian spring in the tidal flat area of the coastal zone is also a feature. We established four observation borehole sites, including the tidal flat and the offshore site below the present sea bed, to monitor the groundwater potential and to collect water samples. Two sites in the mountain area have several boreholes with different depths down to 200 m. Another two sites in the coastal and offshore area have 50 m deep boreholes divided into several zones by multi-packer systems to obtain groundwater potential data and water samples at the different depths (Fig. 1). Two major river systems are gauged to monitor the discharge rate and nearly 20 natural springs and domestic wells are also seasonally sampled to understand the groundwater flow system of the study area.

GROUNDWATER FLOW SYSTEM IN THE STUDY BASIN

Seasonal change of groundwater potential and stable isotope content in the groundwater of the observed boreholes

Figure 2 shows the seasonal fluctuation of the groundwater potential for the observation boreholes. In the case of SB3 boreholes, which are located at the highest elevation in the basin, the shallow well (25 m; SB3-1) has groundwater only in the wet season and clearly shows perched groundwater characteristics. However, the 120 m deep well (SB3-3) did not show any seasonal trend. However, the elevation of the water level of this deep borehole (SB3-3) is clearly higher than that of the mid basin observation well, and it is considered that these headwater areas function as the groundwater recharge area of the basin-wide regional groundwater system. In the case of the SB1 boreholes, the shallowest (SB1-3, 25 m deep) shows a perched aquifer

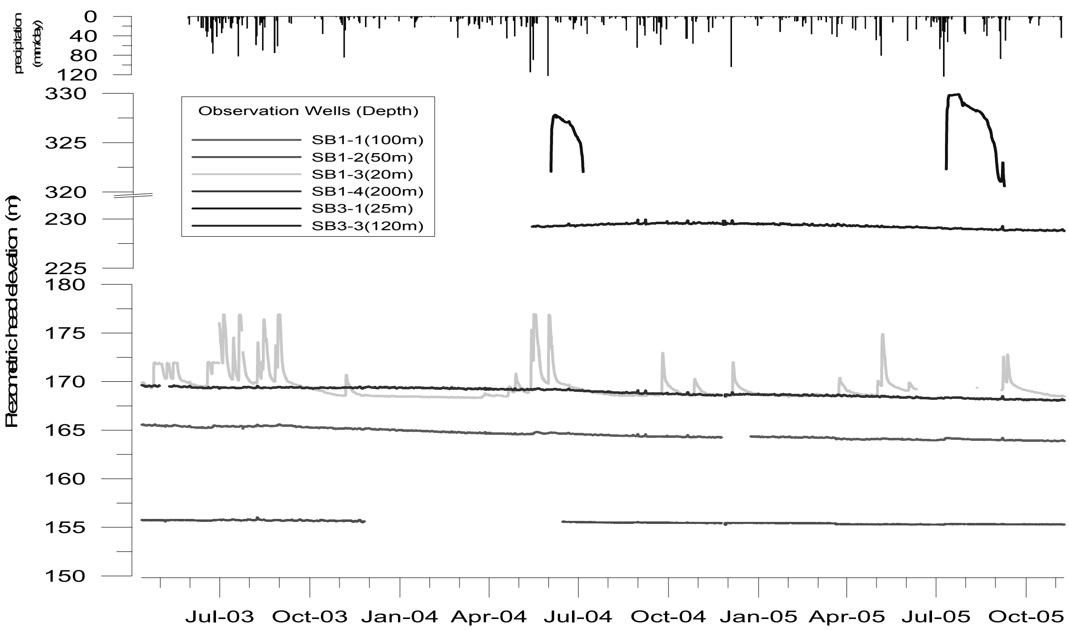

Fig. 2 Seasonal fluctuation of groundwater potential in the observation boreholes.

fluctuation. While the other three boreholes with much deeper depths have no seasonal trend, a clear upward groundwater flux depends on the difference of their groundwater potentials. This upward flux can explain the relatively large discharge rate of the local spring in the mid basin area (Fig. 5). The observation well at the coastal area (SB2) with a multi-packer system shows daily fluctuations associated with tidal movement, but only a little seasonal trend. This coastal well also shows an upward groundwater flux.

Figure 3 shows the stable oxygen isotope content in groundwater/spring water sampled at different altitudes in the study catchments. Seasonally fluctuating spring water, which has a relatively short residence time (within one year), and represents relatively small catchments with different altitudes, clearly shows an isotopic altitude effect in the study area. Using the isotopic altitude trend from Fig. 3, the isotopic content of spring water and borehole groundwater with no seasonal isotope trend, was used to estimate recharge elevations, which were found higher than the sampling altitudes.

Using the observed groundwater data, two dimensional groundwater potential distributions have been constructed in Fig. 4. The groundwater system of the studied area is clearly affected by both the local topography and geology. The flow characteristics obtained are also supported by previously estimated recharge altitudes, which depend on the stable isotope content of groundwater.

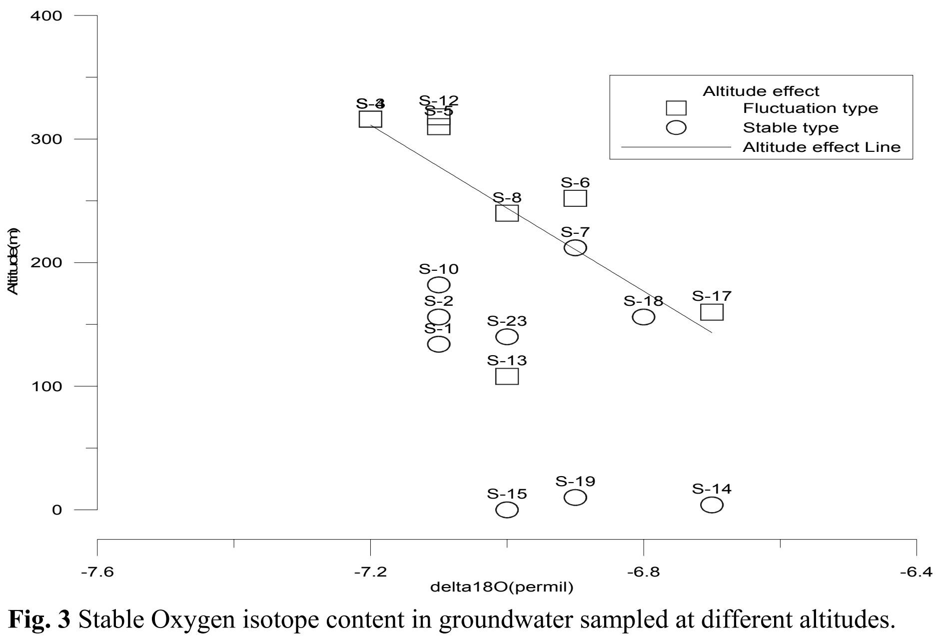

Fig. 3 Stable Oxygen isotope content in groundwater sampled at different altitudes.

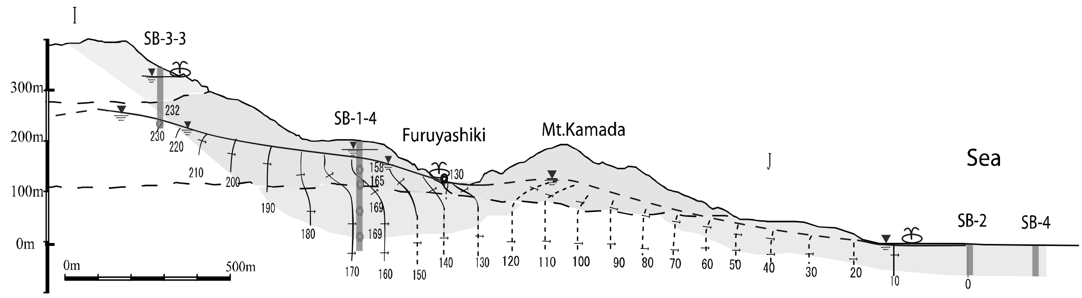

Fig. 4 Cross sectional groundwater potential distribution of the study basin.

Rainfall–runoff characteristics of the head water catchments

Three representative small spring sites were selected to monitor rainfall–runoff processes in the headwater catchments in the study area: Mamushi (S-12), Yozaemon (S-2), and Suzure (S-18), Fig. 1. Specific discharge rates for each catchment are shown in Fig. 5 for the two year period. The Mamushi site discharges only during the wet season, and responds quickly to rainfall events, while the other two sites have continuous discharge throughout the year. The Yozaemon site, situated in the mid-basin, shows discharge fluctuations with the highest base runoff of the three monitored catchments. Annual runoff percentages for these catchments are 9% for Mamushi, 156% for Yozaemon, and 72% for Suzure. The annual runoff percentage differences explain the differences in groundwater conditions of the catchments. Mamushi site is a perched groundwater catchment, which also works as a regional-scale groundwater recharge area, while Yozaemon site works as a regional groundwater discharge area in the mid-basin.

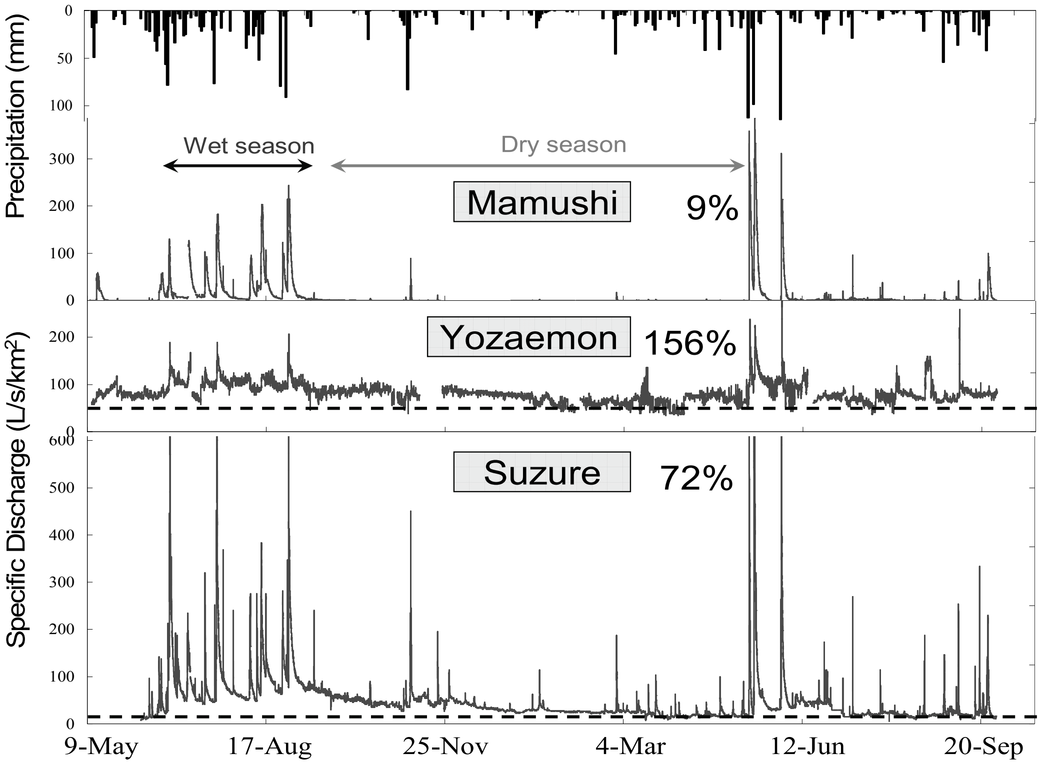

Fig. 5 Comparison of hydrograph in three representative head water catchments.

Basin-wide self potential (SP) survey

Surface self potential surveys have been used for better understanding of subsurface fluid movement in geothermal areas, as well as for the detection of groundwater flow (Fournier, 1989; Fagerlund & Heinson, 2003; Revil *et al.*, 2004), showing characteristics of groundwater recharge to discharge areas. Figure 6 shows the regional scale SP distribution along the valley line in the study area. The SP at the top basin area in both

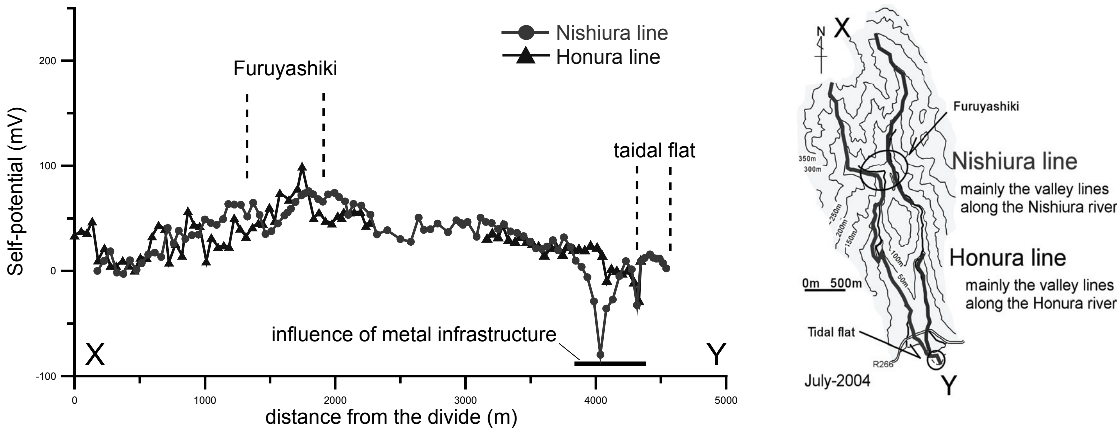

Fig. 6 Self potential distribution along the valley line of Nishi-ura and Hon-ura rivers.

valleys show a relatively low voltage, which gradually increases toward the mid-basin of the Furuyashiki area, where it is characterised by the regional-scale groundwater discharge (Fig. 5). Below the Furuyashiki area, SP does not show any increasing trend, but shows a weak decreasing tendency toward the coastal discharge areas. This regional-scale SP trend could be explained by the three dimensional groundwater flow system in the study area (Sato *et al*., 2005).

Apparent groundwater age determination using radioactive tritium and carbon isotopes

To better understand the groundwater flow system in the study area, the groundwater samples from wells and springs were used to estimate apparent groundwater ages. Figure 7 shows tritium content in the groundwater along a N–S transect of the basin. The higher recharge elevation area has a relatively higher tritium content, which represents a relatively young age, while the lower discharge elevation or deep groundwater, has a low tritium content which represents an old age. Because the tritium method has a detection age limit of only 100 years, C^{14} analysis has also been carried out in this area, as shown in Fig. 8. The estimated apparent age distributions support well the groundwater flow system presented previously in Fig. 4.

If we look at Fig. 8 more carefully, we see that sub-sea groundwater with over 2000 year ages is not directly related to the present-day groundwater flow regime, but it should be considered to be a “remnant” palaeo-fresh groundwater.

REGIONAL WATER BALANCE AND SUBMARINE GROUNDWATER DISCHARGE

Water balance of the paired catchments in the study basin

For understanding the regional groundwater flow system, it is necessary to know the precise water balance. Two parallel river basins were gauged (Fig. 1) to calculate the

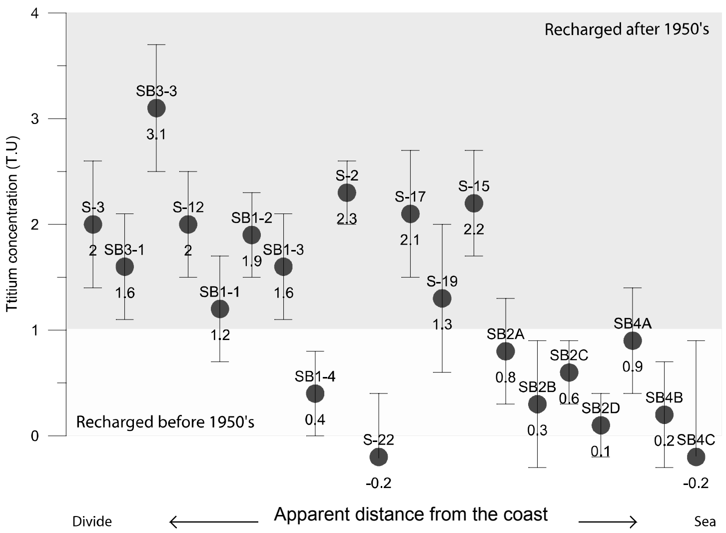

Fig. 7 Tritium content in the groundwater along the N-S line of the study basin.

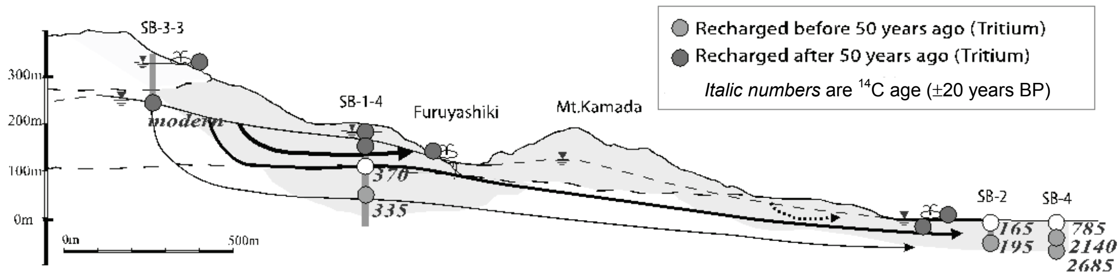

Fig. 8 Apparent groundwater ages from tritium and radioactive carbon isotopes.

regional water balance which measured the actual evapotranspiration at five meteorological stations in the study catchments during the three year period July 2003 to September 2006. Here, the water year is defined as from October to the next September. Figure 9 shows a schematic water balance of the study catchments for each of the three year periods (Sueda *et al.*, 2006). In spite of similar amounts of precipitation and evapotranspiration, the eastern Hon-ura River basin always shows a higher groundwater discharge rate than the western Nishi-ura River basin. This is due to the regional geological setting affecting the groundwater flow system in the study area.

Evaluation of the spatial distribution of submarine groundwater discharge

Continuous heat-type automated seepage meters (Taniguchi *et al.*, 2003) were installed at about 50, 100, and 150 m distance offshore from the coastal line at high tide. All the seepage meters were located between the high tide coast and the low tide coast, which is the representative area for the fresh submarine groundwater discharge. A previous seepage study was carried out at this study area along the transect line from the landward coast to the open sea (Taniguchi *et al.*, 2005). The spatial distribution of

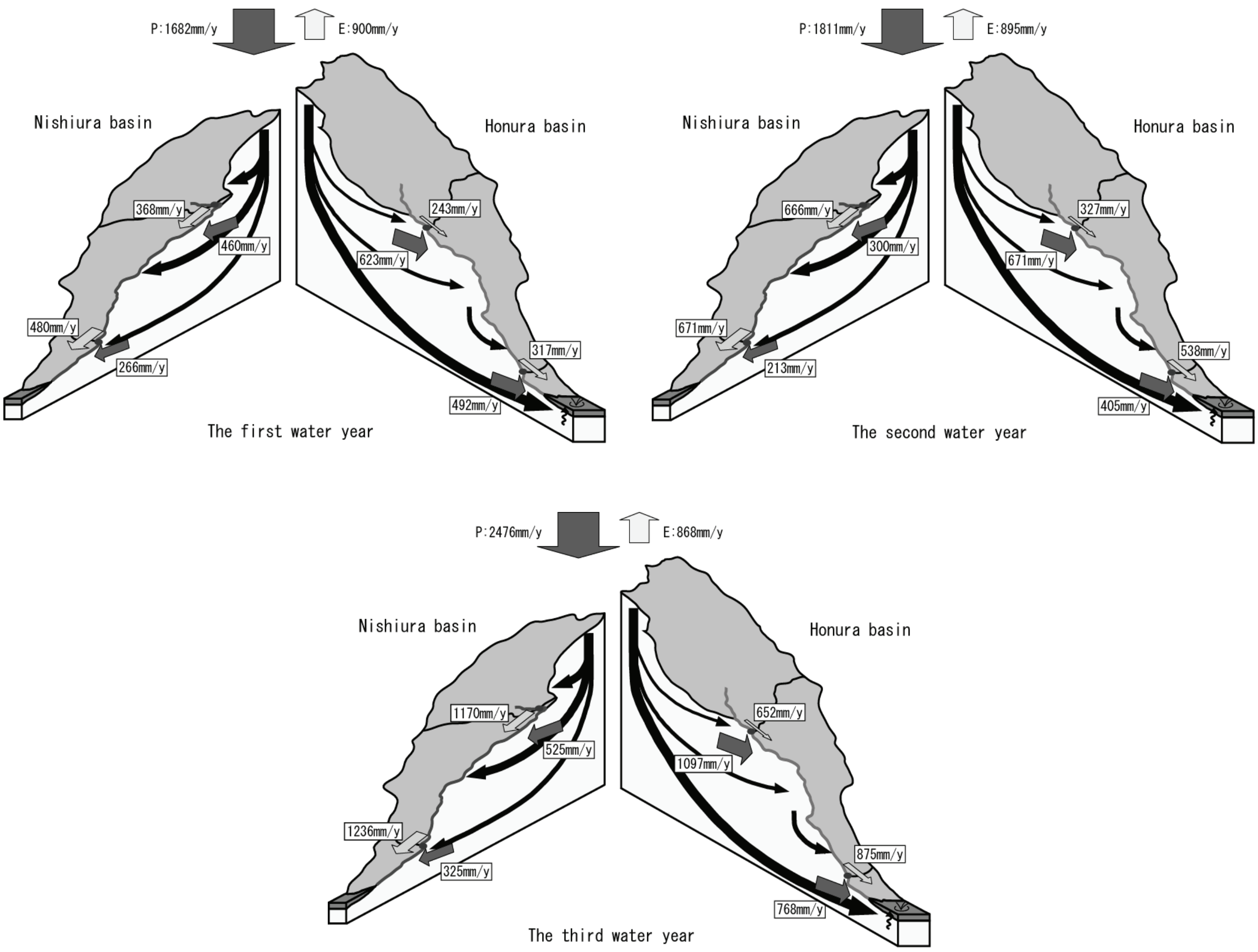

Fig. 9 Schematic water balance for the paired river basins in the study area.

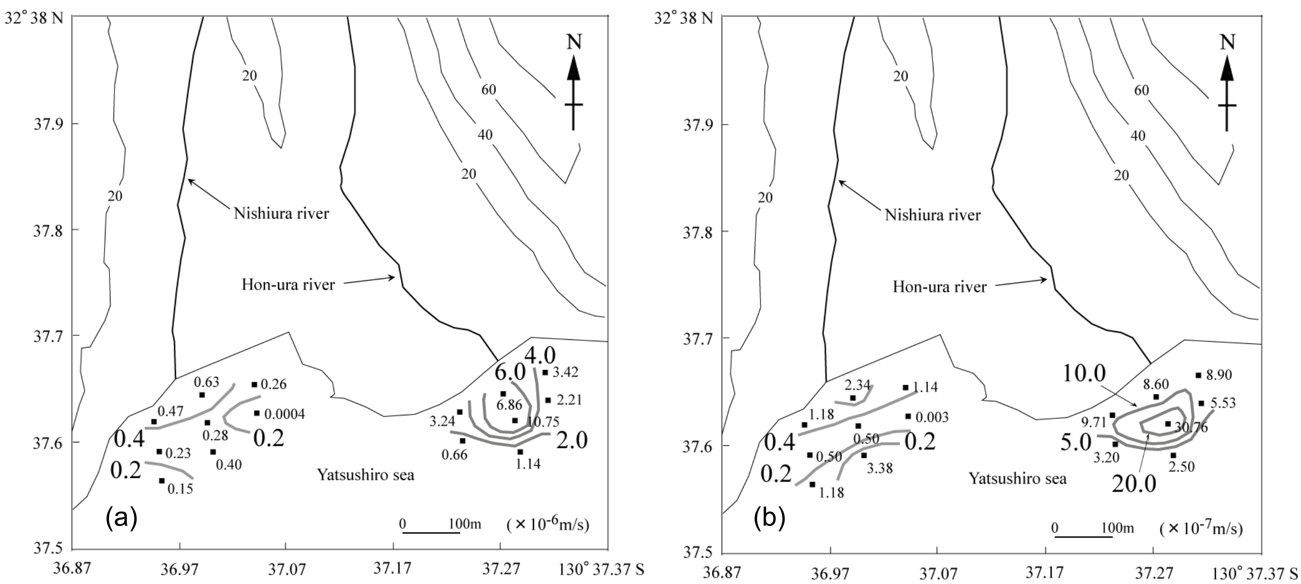

Fig. 10 Spatial distribution of: (a) SGD, and (b) SFGD in the coastal area of the study basin (modified after Taniguchi *et al.*, 2006).

daily-averaged SGD (Fig. 10(a)) shows that the SGD rate offshore 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, indicating that the dominant process of SGD depends on the distance from the coast. Based on the observed SGD conductivities during the SGD monitoring, the spatial distribution of the terrestrial fresh groundwater discharge (SFGD) is shown as Fig. 10(b). As can be seen from this figure, SFGD is also larger at offshore Hon-ura basin than that in Nishi-ura basin. The spatial integration of SFGD as measured by seepage meters agrees relatively well with the groundwater discharge estimated by water balance calculations in the paired sub-catchments (Taniguchi, *et al.* 2006).

3-D GROUNDWATER FLOW SIMULATIONS

In order to understand the three dimensional groundwater flow regime, a steady state three dimensional groundwater flow simulation was conducted in the study area. The model code used is the Visual Modflow Pro(Version 3.1) by Waterloo Hydrogeologic, and the boundary conditions and model validations are as follows:

The Palaeozoic sedimentary rock is selected as a hydrogeological basement boundary which exists about 200 m below the ground surface.

1. Impermeable side boundary is selected at the same location with topographical river basin boundary.
2. Groundwater recharge rate is 900 mm/year, depending on the water balance calculation of the study basin.
3. The model used does not cover the perched groundwater system and the seawater–freshwater boundary condition in the coastal area.
4. Permeability distribution used in the model is adjusted as to match the estimated groundwater residence time, to fit the estimated apparent groundwater ages.
5. Model results are validated by the observed groundwater potential at the observation boreholes, the location of the highest permanent spring connecting to the two major river systems in the study catchments, and the groundwater flow line and its residential time.

Figure 11 shows an example of the model results along the N–S vertical cross-section for the groundwater potential distribution and the flow line with estimated residence times. Except for the perched groundwater system in the headwater region and the stagnant palaeo fresh groundwater under the present sea bed, the regional-scale groundwater flow system can be explained by these results.

DISCUSSION AND POSSIBLE FUTURE WORK

The conceptual diagram of the subsurface environment of the studied area is shown in Fig. 12. In the headwater region, the perched groundwater system with accompanying local seasonal spring discharges has developed even at high elevations. This local flow system, with a residence time of a few years, is mainly caused by the local geology. However, the area itself mostly works as a major recharge area either for the

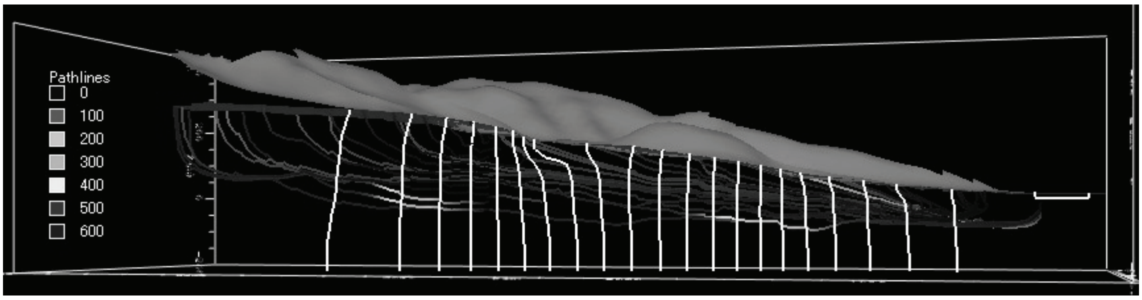

Fig. 11 Groundwater potential distribution and flow line along the cross section of the study basin by the 3D groundwater flow simulation.

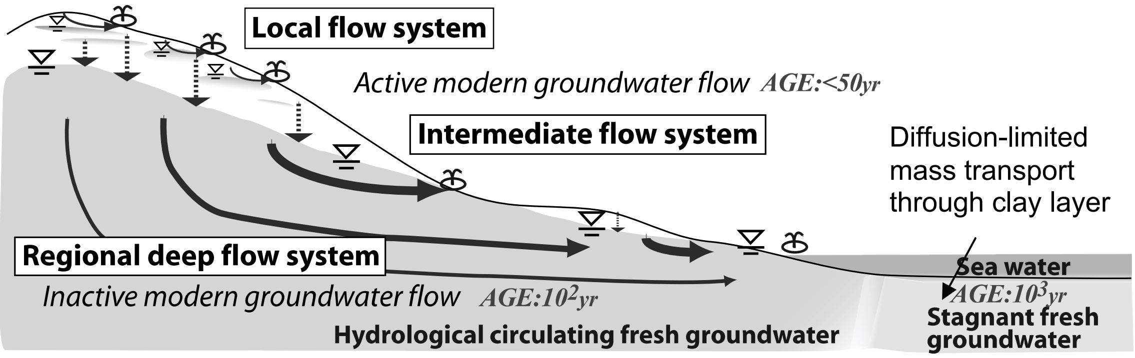

Fig. 12 Conceptual diagram of the subsurface environment of the study area.

intermediate groundwater flow system or for the regional deep groundwater flow system. These concepts are confirmed by the groundwater potential distribution, the recharge elevation analysis using stable isotopes, specific discharge rates of local springs, river water discharge-related regional water budget study, regional scale SP survey, and the radioactive isotope age analysis of groundwater in the study area.

The intermediate groundwater, aged less than 50 years, mostly flows out of the mid basin springs, and supports the base flow of two local rivers, while the regional groundwater, aged 100+ years, mostly flows out of the coastal area, including natural springs and submarine groundwater discharges at the tidal flat zone. The evidence to support those regional-scale groundwater flow systems is the results of the resistivity survey, SP survey, groundwater potential distribution of the observation boreholes, water chemistry and environmental isotope contents in groundwater, and on-site seepage measurements.

This study also shows evidence of stagnant fresh groundwater under the present sea bottom. This seems to be remnant palaeo fresh groundwater formed during a different geological era (Tokunaga *et al*., 2006). An inland sea, such as the Ariake Sea and the Yatushiro Sea, is expected to have similar subsurface conditions as in the present study area because of the similarity of the local geological settings. In this case, the effective submarine groundwater discharge might be limited only to the area close to the coast. To confirm this, we need to develop a technique to detect the submarine groundwater discharge not at a single point, but as a much wider range of its spatial distribution.

CONCLUSIONS

The basin-wide groundwater flow system in the Quaternary pyroclastic bedrock aquifer was studied using many hydrological methods. The major results of this study are:

1. The shallow seasonally fluctuating perched groundwater flow system dominates in the headwater catchments and also contributes to the regional-scale groundwater recharge area.
2. The intermediate groundwater flow system has been confirmed by the groundwater potential distribution, the isotope content, the annual runoff ratio in the headwater catchments and the regional-scale SP survey.
3. The coastal area shows distinctive submarine groundwater seepage which has been confirmed by resistivity survey and direct seepage measurements. This submarine groundwater discharge, which is mainly supplied by the large-scale regional groundwater flow system was evaluated quantitatively by a basin-scale water balance.
4. Under the present sea floor, remnant palaeo fresh groundwater formed during a different geological era is present.
5. The schematic groundwater flow system of the studied pyroclastic aquifer has been confirmed and is mainly controlled by local topography and geology.

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