A New Focus on Groundwater–Seawater Interactions
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Seasonal changes in the groundwater–seawater interaction and its relation to submarine groundwater discharge, Ise Bay, Japan

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Abstract The purpose of this study is to elucidate the conditions of seasonal changes in the fresh and salt water distribution, and the control factors of the relationship between the groundwater flow system and submarine groundwater discharge (SGD) at Ise Bay, Japan. The results indicate that the groundwater levels and qualities have different seasonal change patterns in each depth at the measurement sites. Deep freshwater discharges as SGD in the irrigation season. The water quality of the SGD changes is affected by groundwater–seawater interaction. Seasonal changes in the groundwater–seawater interaction are controlled by geology, recharge water, and tidal conditions.

Key words geological conditions; groundwater flow system; resistivity; seasonal changes; submarine groundwater discharge (SGD); tidal conditions

INTRODUCTION

Anthropogenic influences in inland areas can reach coastal areas where groundwater discharge areas are located (Tokunaga *et al.*, 2003). Rice fields are one of the most common types of land use in monsoon Asia. Rice fields are widely distributed over the coastal zone at Ise Bay, so the recharge rate from surface water to groundwater in the irrigation season is larger than during the non-irrigation season. This suggests that the nutrient flux and groundwater discharge rate have seasonal changes in the coastal zone located at the groundwater discharge area. Taniguchi *et al.* (2002) show that submarine groundwater discharge (SGD) is important to the seawater quality and ecosystem in the coastal area. Taniguchi *et al.* (2006) state that the SGD volume is large near to the coast, and is gradually reduced with distance from the coast. These previous studies are important for elucidating the actual conditions of three dimensional groundwater–seawater interaction. However, these studies do not consider the effects of seasonal factors such as rainfall and irrigation on the seasonal changes of groundwater–seawater interactions. The purposes of this study are twofold: to elucidate the actual conditions of seasonal changes in groundwater–seawater interaction, and to evaluate the factors that are related to groundwater–seawater interaction and SGD through the seasons.

STUDY AREA

Figure 1 show the location of the study area and the distribution of land use, geomorphology and geology. The study area is the coastal plain located at the mouth

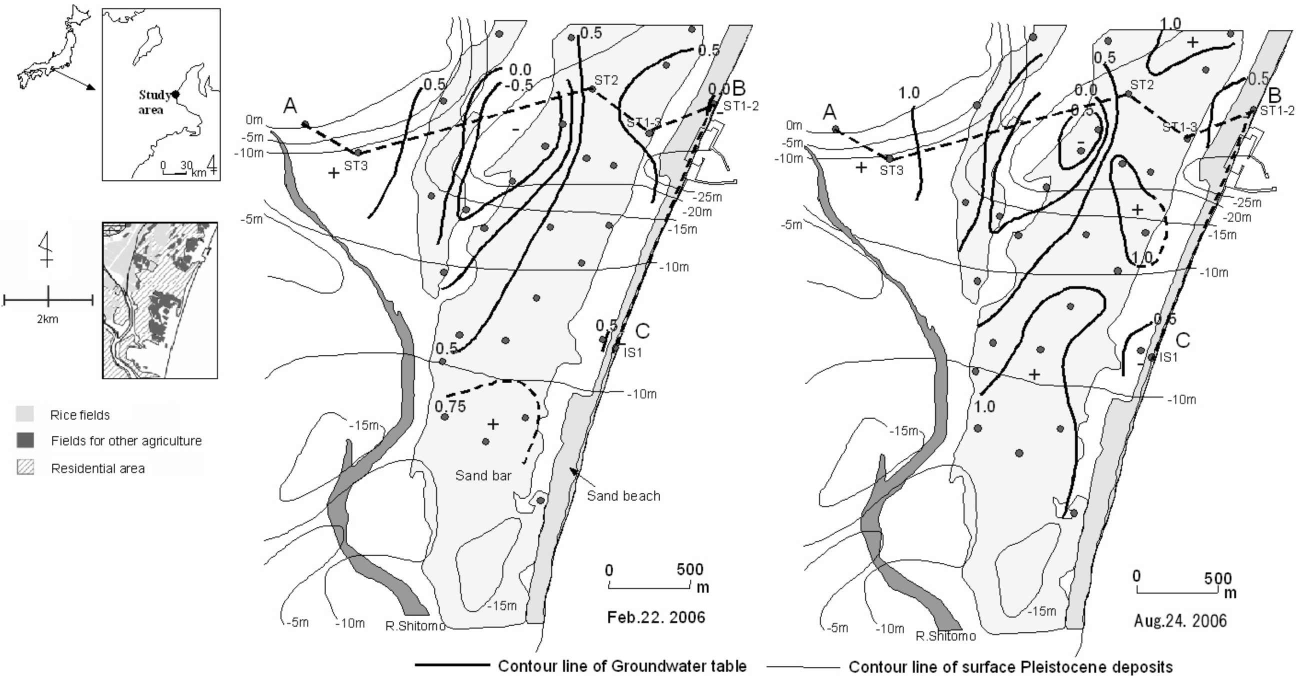

Fig.1 The location of the study area and cross-section measurement line, and the distribution of groundwater table contour lines, surface contour lines of Pleistocene deposits.

of the Shitomo River. Two sandbars are present, and there are residential areas and agricultural fields. Two lagoons are present, and there are rice fields and wetlands. An alluvial plain is present on the western side of the inland sandbar. A Pleistocene valley is present in the alluvial and coastal plain (Geological Survey of Japan, 1987, 1995). This valley is thought to be a palaeo river channel (Miyaoka & Yoshizaki, 2006). Rice fields are widely distributed across the alluvial plain and lagoon. The irrigation season is from March to August, and non-irrigation season is from October to February in the study area.

METHODS

Monitoring wells at depths of 5, 10, 20, and 30 m were installed at two sites in the tidal zone and four sites inland along the Pleistocene valley. Each well site in the tidal zone has a different geology; site ST1-2 is located in thick Holocene deposits where a palaeo river channel sand and gravel layer exists in the deep layer; site IS1 is located in thin Holocene deposits. A conductivity–temperature–depth (CTD) sensor was installed in each well, and continuous measurements of electrical conductivity, water temperature, and water level were made at 15-min intervals from 1 December 2005. Hourly measurements of resistivity from onshore to offshore were made using the Schlumberger method from low tide to the next low tide during the monthly spring tide beginning February 2006.

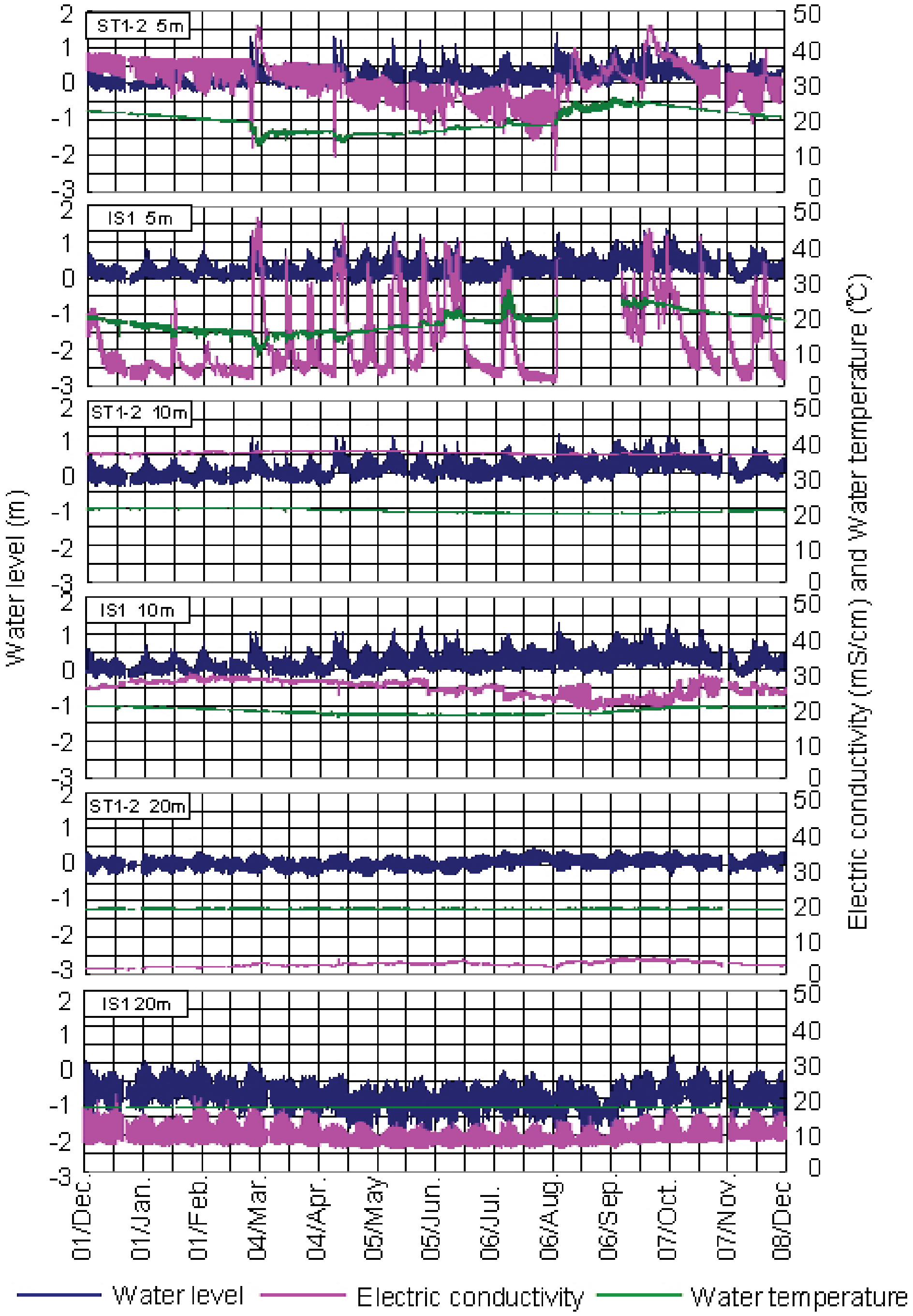

Fig. 2 Seasonal change of groundwater level, electrical conductivity and water temperature.

RESULTS AND DISCUSSION

Horizontal groundwater distribution measurements

Figure 1 shows the seasonal spatial variation of the water table in the non-irrigation and irrigation seasons. Water levels in the irrigation season are higher than in the non-irrigation season, so groundwater is being affected by irrigation and/or rainfall. The highest water level is in the sandbar area, and a trough and lowest point in the water table is in the lagoonal area. The location of the trough in the water table corresponds to the location of the geological valley of the Pleistocene deposits (Fig. 1). These suggest that the water table is controlled by geomorphological, geological and/or land use conditions.

Seasonal changes in the water level and electrical conductivity have been measured at two sites located in different geological conditions (Fig. 2). The patterns of the water levels and electrical conductivity are quite different, even at the same depth, at these sites. There are some important points to note here. First, freshwater exists in the deep layer at site ST1-2, but not at site IS1. Second, brackish water exists in the shallow layer at site IS1 in the non-irrigation season, and during neap tide in the irrigation season. Third, the range of water levels in the deep layer is larger than in the shallow, and is similar to the tidal change from high to low tide at both sites. These many different points suggest that the groundwater flow system, groundwater potential distributions, seawater intrusion, and other factors are controlled by the geological, geomorphological, and land use conditions.

Vertical groundwater distribution in the irrigation and non-irrigation seasons in the hydrogeological water path

The longitudinal-profile is located along the water table trough and geological Pleistocene deposits in the valley as shown in Fig. 1. The longitudinal-profile along the A–B line of the groundwater potential is shown in Fig. 3, and the longitudinal-profile of electrical conductivity in the non-irrigation and irrigation season is shown in Fig. 4.

In the deep layer along the coast, the groundwater potential shows seasonal changes between the irrigation and non-irrigation seasons, and between the high and low tides. High groundwater levels are present during the high tide through the year, but this location is different in that a high potential is present at a depth of 20 m during the non-irrigation season, but that changes to a depth of 30 m during the irrigation season.

At the upstream area, an electrical conductivity of 0.5 to 1.0 mS/cm is present at a depth of 10 to 20 m, i.e. in the Pleistocene deposits. The same range of electrical conductivity occurs at 20 to 30 m depth along the coast, and this electrical conductivity distribution is similar to the groundwater potential distribution (Fig. 3). High electrical conductivity occurs at the depth of 10 m, and is stable through the seasons, so it is suggested that salt water is constantly intruding to the inland area at this depth. At a depth of 5 m the electrical conductivity is high, the same as at the 10 m depth value in the non-irrigation season, but it gradually becomes lower when the irrigation season begins. The lowest electrical conductivity is present at the end of the rainy season (the end of July). According to the landform conditions in Figs 1 and 3, a sandbar is a recharge area of the local groundwater flow system. Therefore the groundwater at 5 m depth is also affected by some land surface conditions.

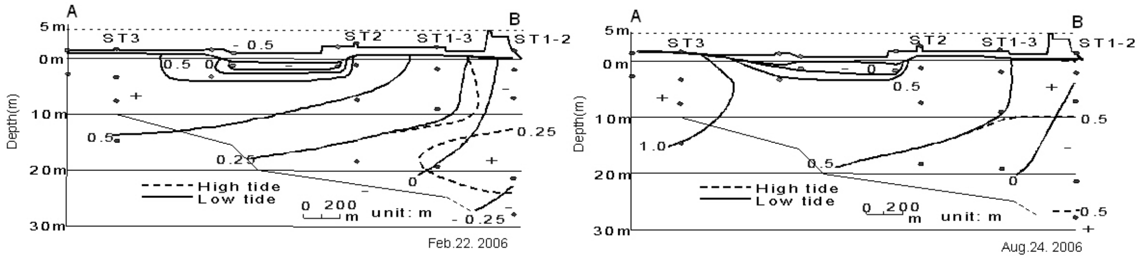

Fig. 3 Longitudinal-profiles of groundwater potential in the non-irrigation and irrigation season.

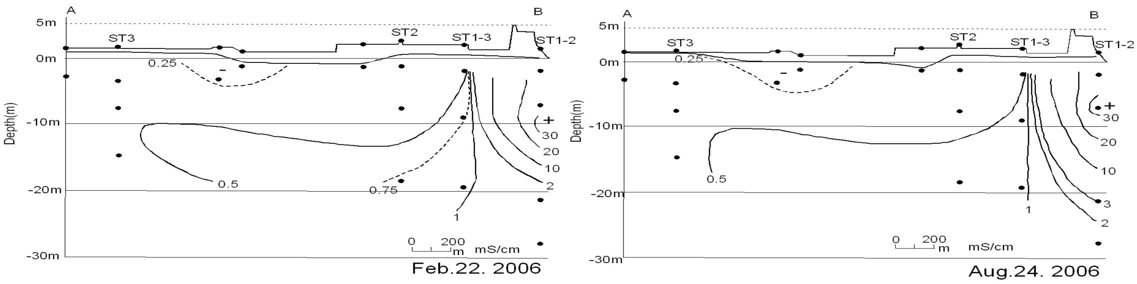

Fig. 4 Longitudinal-profiles of electrical conductivity in the non-irrigation and irrigation season.

Vertical groundwater distribution at the coastal zone during the irrigation and non irrigation season

The cross-section B–C of the groundwater potential is shown in Fig. 5. Upward flow occurs from deeper than 20 m in the thick Holocene deposits. Otherwise, downward flow is shown in all layers in the thin Holocene deposits. According to the seasonal change of electrical conductivity in site ST1-2 and site IS1 (Fig. 2), the freshwater distribution is different from the tidal conditions and irrigation conditions at each site. This shows that interactions between surface water, groundwater, and seawater have some patterns; i.e. via the recharge area, groundwater discharge, seawater intrusion, and geological conditions. This suggests a regional groundwater flow system exists in

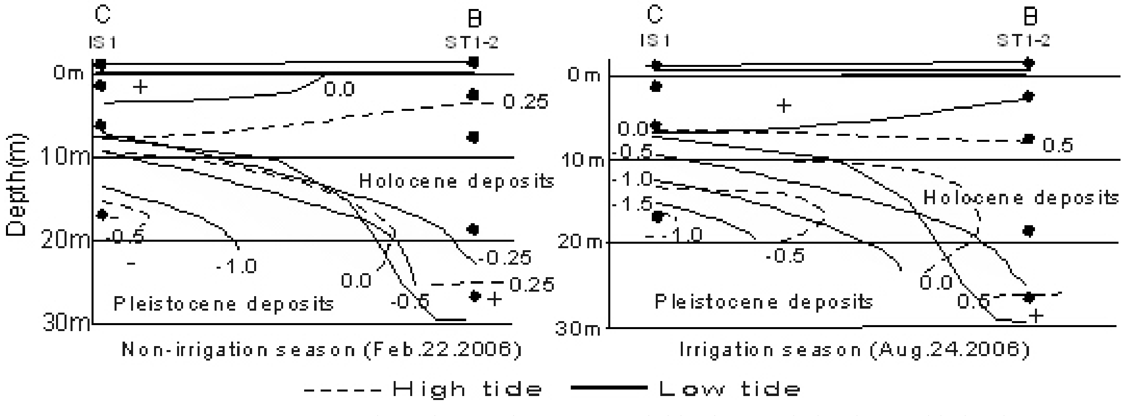

Fig. 5 Cross-section of groundwater potential in the non-irrigation and irrigation season.

Holocene deposits where the palaeo river channel is located. Finally, seawater may intrude easily into the shallow inland layer there because of the trough in the water table.

Estimation by resistivity measurements of the location of SGD and its seasonal variation

The resistivity and electrical conductivity distribution from high tide through low tide during both the non-irrigation (15 March 2006) and irrigation seasons (13 July 2006) were evaluated in order to estimate the seasonal change of the interaction between groundwater and seawater, and the SGD locations (Fig. 6). Both measurements were carried out under spring tide conditions. The seepage face is shown at the same location during low tide in both seasons, but the electrical conductivity in July is lower (29.5 mS/cm) than that in March (45.5 mS/cm). The seepage face is buried under seawater during high tide, but at the deep layer, freshwater rises up to the shallow layer during high tide. Furthermore, this freshwater zone reaches the seepage face at low tide

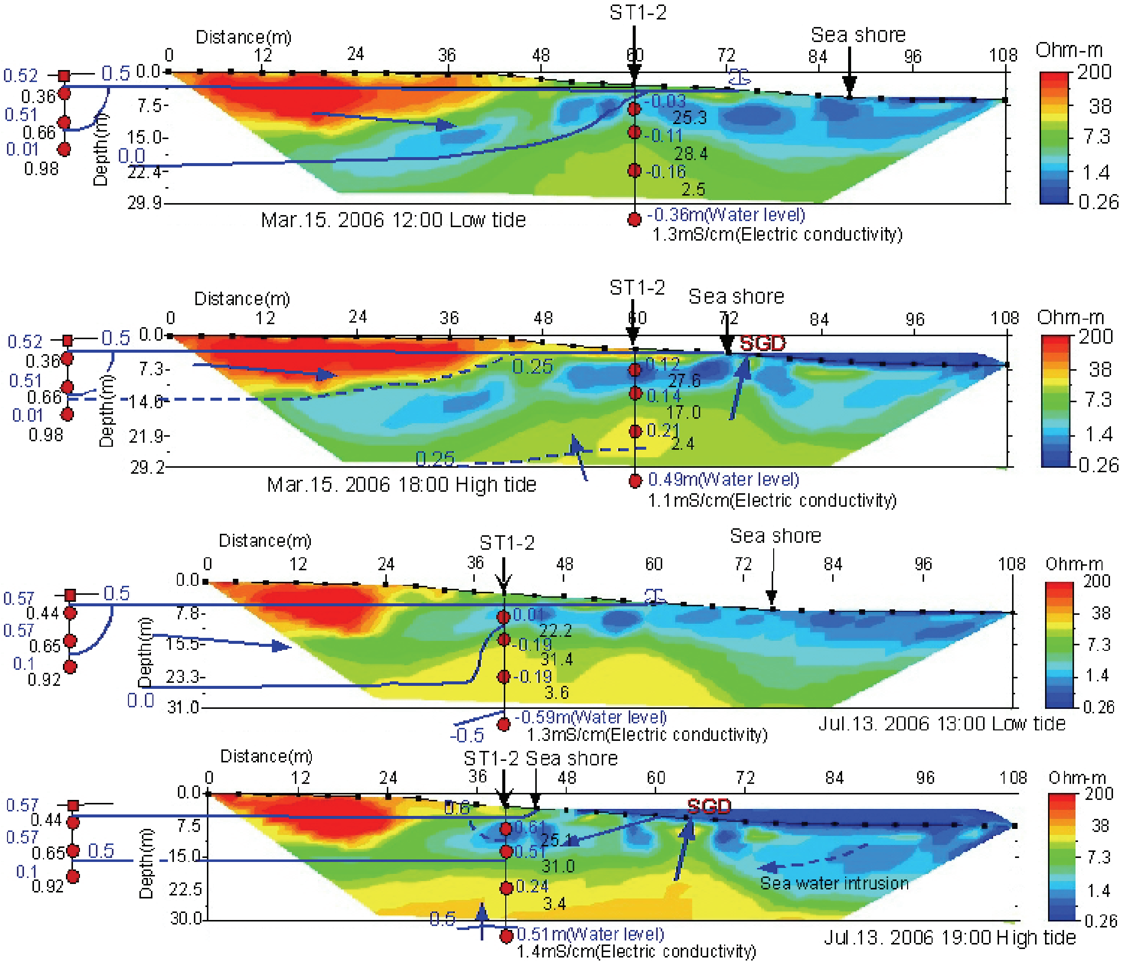

Fig. 6 Cross-section of resistivity distributions at the coastal zone in the high tide and low tide, in the non-irrigation season and irrigation season.

during the irrigation season. But during the non-irrigation season, deep freshwater does not reach the shallow depth and the seepage face. These seasonal variations of the freshwater flow condition show that the groundwater discharge rate is greater during the irrigation season. During high tide, freshwater flow is prevented by the seawater pressure, so strong upward flow occurs and discharges at the seepage face as SGD. At low tide, this seepage face acts as the shallow groundwater discharge point.

CONCLUSIONS

This study elucidated the seasonal changes of the horizontal and vertical distribution of fresh and salt water, and the relation between their seasonal changes and that of the SGD. The interaction between groundwater and seawater changes is affected by the seasonal condition. That is, the distributions of fresh and salt water in the aquifers depend on the geological conditions, especially the location of the Pleistocene valley in the coastal area. These seasonal variations in the freshwater flow condition shows that the groundwater discharge rate is large during the irrigation season. During the high tide, the seawater pressure interrupts freshwater flow, so strong upward flow occurs and discharges at the seepage face as SGD. The water quality of the SGD changes between high and low tide, and between the non-irrigation and irrigation seasons.

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