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Temporal variations of groundwater salinity and temperature in a tidal flat in front of a tide pool

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ABSTRACT

A tidal flat in an estuary is a complex hydrological system, which is characterized by interactions between surface water in river and groundwater and is particularly driven by tides. Small-scale variability in the discharge or inflow could lead to variable results of surface groundwater salinity and temperature. In particular, there is a high possibility that a hydraulic head difference due to the presence of a tide pool, lagoon, or seep would cause the generation of small-scale spatial submarine groundwater discharge.

This study investigates the spatio-temporal variations in surface groundwater salinity and temperature (0–50 cm depth) and the groundwater table in a tidal flat in the presence and absence of a tide pool. A tide pool formed in the Ota River diversion channel at the study observation site following the construction of a masonry revetment in the intertidal zone. We established observation sites at three locations to consider the effects of the presence or absence of a tide pool. Specifically, we measured the surface water in river and groundwater salinity, temperature, and level in the presence and absence of a tide pool in 2007 and 2009. Reviewing the past data based on these results, we found the characteristic variation of groundwater salinity around the tide pool during flood event in 2004. Groundwater salinity and temperature were directly measured by setting conductivity-temperature meters in the tidal flat.

We conclude that the groundwater table in the presence of the tide pool was 20 cm higher than in areas where no tide pool existed. The temporal variation of groundwater salinity in the presence of the tide pool was 5 psu lower than those where a tide pool was absent. Moreover, we confirmed the increase in groundwater salinity up to 8 psu in the tidal flat during flood, when river water salinity was at 0 psu and groundwater salinity in the tide pool was at 10 psu.

We consider that the high groundwater table, the low salinity, and the increase of groundwater salinity were caused by water discharge from the tide pool, and that the groundwater salinity was increased by groundwater discharge during a flood event.

We expect the groundwater flow around masonry revetment has important roles of substance transportation and formation of tidal flat environment. The consideration of this phenomenon will be important for construction of artificial tidal flat and improvement of tidal flat environment.

1. Introduction

A tidal flat in an estuary is a complex hydrological system, which is characterized by interactions between the river surface water and groundwater, and is particularly driven by tides. In the tidal flat environment, the inflow of tidal water toward the tidal flat at high tide and the discharge of groundwater into the surface water at low tide cause periodic variations in the quality of the surface water and groundwater, which affects the conditions of the habitat for its benthos and vegetation communities (Montalto et al., 2006; Werner and Lockington, 2006). Discharge of groundwater into the surface water can occur wherever an aquifer with an elevated water table is hydraulically connected to surface water (Emery and Foster, 1948; Johannes, 1980).

Several studies have been conducted on dealing with the quantified groundwater discharge (Burnett et al., 2001; Peterson et al., 2010); however, little is known about small-scale spatio-temporal variations in groundwater discharge. Small-scale variability in the discharge or inflow could lead to variable results in the surface groundwater quality. This zone has been termed a “subterranean estuary” (Moore, 1999). Urish and McKenna (2004) showed that temporal (over tidal cycles) and spatial (over tens of meters) patterns of groundwater discharge from a sandy beach are highly site-specific and can vary greatly even within one site. On

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an intertidal sand flat, Miller and Ullman (2004) revealed that there is significant spatial variability in the groundwater discharge in the cross-shore direction along a 16–24 m transect. Dale and Miller (2007) found that groundwater temperatures were much lower in groundwater discharge than in the nearby sediment, by as much as 8–9 °C at 30 cm sediment depth.

There is a high possibility that small-scale spatial groundwater flux will be generated by a hydraulic head difference caused by the presence of a tide pool, lagoon, or seep. Austin et al. (2013) revealed that groundwater conductivity changed periodically because of a hydraulic head difference between the tidal and lagoon water levels.

Specific phenomena in a tidal river include periodic variation in the river water caused by tides, associated flood events, and continuous salinity degradation as a result of the floods. A few studies have reported specific phenomena in tidal rivers. Groundwater quality (e.g., salinity and temperature) in a tidal river varies differently than it does in river water because of the presence of SGD (Carol et al., 2012). Extreme flooding events have significant effects on the structure and function of macrobenthic communities (Cardoso et al., 2008; Norkko et al., 2002). The continuous degradation of salinity is a heavy stress on benthos in a tidal flat (Ritter et al., 2005).

A groundwater flux in subterranean estuary is expected to mitigate the low salinity for the surface groundwater because of the presence of a tide pool, lagoon, or seep. Thus, the groundwater flux improves a benthos habitat in a tidal flat. However, very few studies exist about the variation of the groundwater quality in front of a tide pool, lagoon, or seep. Our study area, the Ota River diversion channel (tidal river), is a compound channel that has a masonry revetment in the main channel. A tide pool is formed in the flood plain. Hence, the groundwater flux between the flood plain and the main channel is expected to occur because of the hydraulic head difference. The purposes of this study are to present the spatio-temporal variations in groundwater salinity and temperature in the tidal flat surface (0–50 cm depth), and to consider the role of river structure in the tidal flat.

A priori knowledge of spatio-temporal variation of intertidal groundwater inflow and discharge should lead to more accurate discharge measurements and greater appreciation of their inherent variability.

2. Methods

2.1. Study site

The Ota River estuary is located at approximately 34.4°N latitude in the western area of the Seto Inland Sea, and flows into Hiroshima Bay, Japan (Fig. 1(a)). The Ota River branches into the Ota River diversion channel and five branch rivers at a distance of 10 km upstream from the river mouth. The Ota River diversion channel is an artificial channel constructed for the rapid discharge of flood water, and is characterized by the periodic intrusion of salt wedges (Kawanisi et al., 2010). The annual tidal range of Hiroshima Bay is almost 4 m. The slope of the tidal flat is on the order of 10–2. The wide tidal range and mild river bed gradient have formed a tidal flat of over 60 ha in area in the Ota River diversion channel.

The river water pouring into the Ota River diversion channel is normally controlled by an array of sluice gates at Gion, located near the branch area. The flow ratio between the Ota River diversion channel and other branch rivers is kept at 1:9 on normal days. During flood events, the river water discharge dynamically increases as the Gion sluice gates are opened. Since the 1980s, the Ota River diversion channel has experienced more than 25 floods with peak flow rates greater than 1000 m^3/s. The Ota River diversion channel can be said to be impacted extensively by flooding because the floods have caused rapidly decreasing river water salinity to continue for several days, and have been accompanied by large amounts of sediment transportation.

2.2. Tide pool and tidal flat

A masonry revetment was constructed between 3 and 7 km upstream from the river mouth about 40 years ago. As a result, a tidal flat has formed in the main channel. A tide pool formed in the flood plain only at a distance of 5.4 km upstream from the river mouth. The tide pool was formed by erosion at the back of a revetment that was built in response to a big flood event about 30 years ago. River water, whose salinity exceeds 30 psu, flows into the tide pool during high tides because the height of the revetment was constructed at Tokyo Peil (T.P.) +0.65 m, which is approximately at mean sea level. Generally, the formation of a tide pool along a shoreline is less likely than in the river. The sediment on the tidal flat is mainly sand, and the fine fraction content is under 1% with a horizontal hydraulic conductivity on the order of 0.1 cm/s. The sediment of the tide pool is mainly fine sand, and the fine fraction content is approximately 3% with a horizontal hydraulic conductivity on the order of 0.04 cm/s.

To investigate the variation mechanism of groundwater quality and the role of river structure for the tidal flat, field observations were carried out in the Ota River diversion channel, as shown in Fig. 1(b) and Picture1. Several observations conducted in 20042009 and all observations were carried out during spring tide. The observation site of St. 1 was set at a distance of 5.4 km upstream from the river mouth because the tide pool and the tidal flat are formed in the flood plain and main channel, respectively, as shown in Fig. 2(a) and Pictures 1 and 2(a). The water level of the tide pool at St. 1 is kept at T.P. −0.1 m at low tide during spring tide. Other observation points were set at a distance of 100 m (St. 2) and 150 m (St. 3) downstream from St. 1 to consider the effects of the presence or absence of the tide pool. Cross sections of each observation site are show in Fig. 2(b) and (c) and Pictures 2(b) and (c). The tide pool was present at both St. 2 and St. 1, although the ground level of the tide pool at St. 2 was 0.3 m higher than at St. 1. Therefore, the tide pool water flows from St. 2 to St. 1, and the tide pool at St. 2 dried out during low tide. Conversely, the tide pool was not present at the St. 3 because of the deposited sand, as shown in Fig. 2(c) and Picture 2(c).

2.3. Monitoring of surface groundwater and river water quality

To clarify the variation of groundwater quality in the tidal flat, the distribution of the groundwater salinity profile and the variation of groundwater quality with tidal cycle were measured at 25 m in front of the revetment in the tidal flat at St. 1. These observations were carried out on June 1 and August 1, 2007. The distribution of the groundwater salinity profile and quality profile (water temperature, salinity, pH, DO) were measured from the tidal flat surface to a depth of 0.5 m by multiple water quality meters (JFE-Advantech Co., Ltd., AAQ-1183). First, a vinyl pipe (diameter 12.5 cm) installed until 0.05 m below the groundwater level. The groundwater quality was measured using AAQ-1183 after removing the sand in the pipe. Next, the pipe installed until 0.1 m below the groundwater level. The quality of discharge groundwater was measured after removing the sand and groundwater in the pipe. The profiles of groundwater quality were made repeat this process from surface to the depth of 0.5 m.

The variation of the groundwater salinity and temperature with the tidal cycle were measured using a conductivity-temperature meter (JFE-Advantech Co., Ltd., CT meter) on the river bed and at