INFLUENCE OF COASTAL GROUNDWATER ON BRACKISH WATER ENVIRONMENT IN A TIDAL ESTUARY

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Inflow and outflow of water and salt into a shallow tidal estuary were estimated using a modified box model. Snapshots of the salinity profile were obtained using the variation in tide depth using an installed measurement device. The water circulation budget and geochemical components in the estuary may be affected by coastal groundwater discharge.

INTRODUCTION

Understanding the hydrological dynamics of brackish water bodies is considered important for the effective conservation and management of the natural environment of tidal estuaries. Especially, fresh water inflows and residence times have a marked effect on the salinity within an estuary. Residence time, which refers to the mean time required to transport dissolved or suspended matter out of a water body, can be one of the limiting factors affecting phytoplankton abundance within a system (Monbet, 1992). Howarth *et al*. (2000) reported that a decrease in river inflows results in increased residence times and primary production in estuaries. Moreover, since the settlement and deposition of suspended matter is dependent on residence time, short residence times are considered to improve the water quality of estuarine water. A box model using salt as a conservative tracer is often applied to estimate both fresh water inflows and residence time within a system, both of which are considered important indicators of the physical condition of the estuarine environment. However, while the box model is simple in principle, the cases to which it can be applied are relatively limited, particularly in tidal estuaries because of its non-steady flow.

Tidal flats along the periphery of tidal estuaries are important habitats for a variety of coastal organisms, particularly as nurseries for fish. The tidal flats of Ota River Estuary support numerous benthic fauna (16 *Eucrustacea* spp., 14 *Pelecypoda* spp. and *Gastropoda* spp., and 6 *Polychaeta* spp.) (Hibino *et al*., 2006). The salinity and dissolved oxygen concentration of the pore water in these areas and the particle size of the bed material has been shown to restrict the habitat preference of these species (Lalli and Persons, 1993). Submarine groundwater discharge is also important for material circulation in coastal region (Simmons, 1992; Moore, 1996; Burnett, 2003). Nonetheless, the groundwater environment of tidal flats is relatively poorly understood.

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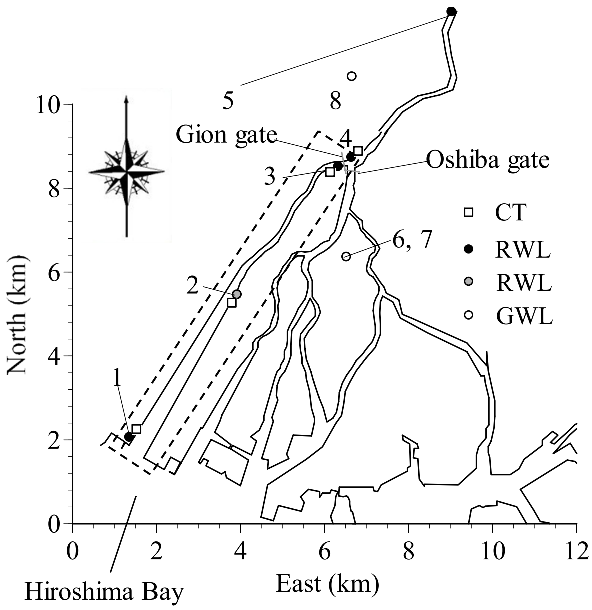

Figure 1. Samples sites in the Ota River Estuary. RWL (●) and GWL (○) were observed by Ministry of Land, Infrastructure, and Transport, Japan. Dashed box contains the Ota River Floodway (calculation domain).

Therefore, in order to conserve the waterfront environment in tidal estuaries, we need to investigate the influence of not only the residence time of river runoff water, but also the circulation of groundwater in brackish water environments. The Ota River Estuary (Fig. 1) at the head of Hiroshima Bay has a large astronomical tide variation, fluctuating by a maximum of approximately 4 m (Japan Meteorological Agency, 2001), and the tidal flats on the Ota River Floodway (ORF) provide a variety of habitats to coastal organisms. This study describes the application of a new box model to estimate fresh water inflow into a large tidal estuary such as Ota River Estuary. In addition, the fresh water budget and formation mechanism of brackish water, including groundwater circulation, is also described by observing groundwater level (GWL) and salinity in the tidal flats and coastal aquifer of the Ota River Delta.

OBSERVATION AND ANALYSES

Continuous observation for water budget analysis

Figure 1 shows a map of Ota River Delta. The Ota River empties into the ORF (dashed box) and old rivers (so called "Shinai-hasen" rivers). To analyze the water budget of the ORF using a box model, salinities of river water at St. 1 to 3 were taken at hourly intervals from August to October in 2004 (Fig. 1). Each sensor was installed on a riverbank in the main channel as shown in Table 1. Salinity in the tidal flat beds was measured simultaneously to other stations at hourly intervals at St. 2. The salinity meter at St. 4 measured the inflow of river water from upstream river reaches. River water levels (RWL) at St. 1, 3, 4, and 5 are measured hourly by the Ministry of Land, Infrastructure, and Transport, Japan (MLIT). Moreover, the fluctuations in GWL were measured using observation wells at St. 6, 7, and 8, which had depths of -34 m (measured hydraulic head below silty-sand layer), -16 m (above silty-sand layer), and -10 m (below the silty-sand layer), respectively.

The box model is a simple method for estimating the amounts of inflow water or suspended/dissolved materials in estuary using salt as a tracer. If water budget analysis using a box model can be adapted to a tidal river, we can investigate the contribution of fresh water inflow to salinity in the brackish water body. Furthermore, if the model can be used to determine the hydraulic gradient, estimated from the relationship between the GWL from different sites around the coastal area, then it should be possible to clarify the relationship between salinity in the beds of the tidal flats and shallow/deep groundwater flow in the Ota River Delta.

Observations of velocity and salinity profiles

A slight meander of the channel in an upstream part of the ORF may cause the streamline to deviate. In order to characterize the velocity and salinity profile characteristics of the ORF for analysis with the box model, transverse salinity profiles were measured every hour at St. 2 on October 10 (spring tide) and October 18 (neap tide), 2003, for half a day. In addition, the cross sections of five velocity and salinity profiles were measured at St. 2 on February 3 in 2007 at hourly intervals for half a day.

Principles of the box model and assumptions

Several box models have been employed in hydrological studies to date. For example, Alber *et al*. (1999) proposed a robust model for various time step, which can be applied to both large and small flow rates. Hagy *et al*. (2000) proposed a box model that considers the temporal variation of salinity and river water without assuming static water flow. Furthermore, Sheldon *et al*. (2002) modified a box model that considers the downstream variations in channel area and varying the number of box separation to improve the accuracy. However, in the Ota River Estuary, where tidal range is approximately 4 m and where stratification varies markedly, previously reported box models cannot be utilized without modification. Consequently, water budget analysis using a box model that is suitable for tidal estuaries is needed.

Using continuous salinity and water level data measured at St. 1 to 3 shown in Fig. 1, we consider a box model in which calculation domain consisted of the ORF. Inflow and outflow rates from the up- and down-stream ends of the box are calculated by solving the continuity equation (1) and salt conservation equation (2) for Q_1 and Q_3, simultaneously.

Table 1. Installation height of salinity meters		
	Depth	Deepest riverbed depth
St. 1	-0.93 m	-5.92 m
St. 2	-0.82 m	-3.64 m
St. 3	-0.4 m	-1.5 m

Reference: mean sea level of Tokyo Bay

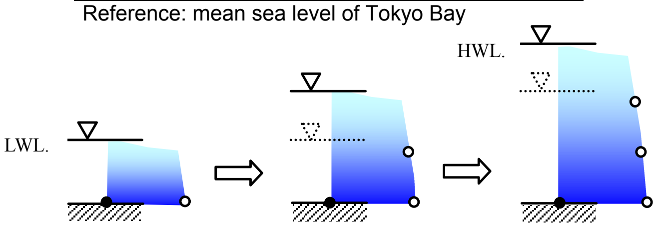

Figure 2. Estimation method for determining salinity profiles using data from the fixed sensors (●: sensor position, ○: salinity datum)

$$\frac{\partial V_B}{\partial t} = -Q_1 + Q_3 \quad (1)$$

$$\frac{\partial}{\partial t} C_B V_B = -\overline{C}_1 Q_1 + \overline{C}_3 Q_3 \quad (2)$$

$$\overline{C}_i = \frac{1}{A_i} \int_{-D_i}^{\eta_i(t)} \int_{b_i(z)} C_i(z) dydz \quad (3)$$

where, i: station number, t: time, y: cross-sectional axis, z: vertical axis, L: longitudinal length of box, V_B: water volume of box, Q_1, Q_3: discharges at the up- and down-stream ends of the box, C_B: salinity in box, C_1, C_3: salinities at the up- and down-stream ends of the box, D_i: depth, b_i(z): channel width, η_i(t): water level, and A_i: cross-sectional area. The bar in equation (2) refers to the cross-sectional average, expressed as equation (3). Channel width b_i(z) was obtained from annual longitudinal survey data by the MLIT. Cross-sectional velocity was assumed to be uniformly.

Salinities at the up- and down-stream ends of the box were obtained at St. 1 and 3. Since the salinity meters were fixed at the low water level (LWL) mark at spring tide, the salinities measured at different depths varied vertically due to variation in the tides. These variations salinity depth data were used to estimate salinity profiles at each station from LWL to high water level (HWL) or from HWL to LWL. In this estimation, as shown in Fig. 2, it is assumed that the high salinity water intruding/discharging from the bottom displaces any low salinity (low density) water, while remaining stratified. Therefore, the temporal variation in measured salinity between the ebb tide and the flood tide can be converted to a spatial component representing measured salinity, that is, a vertical profile of salinity can be created. In this process, since the calculation time step Δt was determined based on tidal variation, the salinity profile at the time of the flood tide could be estimated from the data obtained from high tide to low tide of the M_2 tidal component. Consequently, the semi-diurnal variation in flow will not be addressed here.

However, because St. 3 is located near the fresh water upstream inlet, and since its cross-sectional area is less than that of St. 1 at the river mouth, the contribution of the inflow water volume and salinity variation at St. 3 is relatively low compared to the entire channel. Thus, the cross-sectional shape at 1 km-intervals was considered in terms of the water volume shown on the left hand side of equations (1) and (2). Conversely, the salinity of the channel will be obtained from the observed salinities at St. 1 to 3, which was weighted-mean by channel width at each section as follows:

$$C_B(z) = \frac{1}{\sum_i b_i(z)} \sum_i b_i(z) C_i(z) \quad (4)$$

Therefore, the total amount of salt in the box was obtained from the vertical-integration of C_B(z) multiplied by water surface.

To verify the inflow amount Q_3 estimated from the box model, the discharge through water gate (Gion gate) between St. 3 and 4 was also estimated using another method. Here, the discharge Q_{gate} was inferred using the relationship between the water level at St. 3 and 4, and the open height of the gate, by applying the empirical equation for free flow and submerged flow from the sluice gate (Japan Society of Civil Engineers, 1999). In addition, according to the hourly records from 2004, the frequency of salinity below 0.5 and 5.0 psu at the upstream gate of St. 4 was more than 80% and 95%, respectively. This means that most of runoff water through the water gate is fresh water. In addition, the run-up of seawater through the gate Q_{gate} was considered to improve the accuracy of water volume.

RESULTS

Characteristics of salinity profiles

Figure 3 shows the cross-sectional distribution of downstream velocity and salinity at St. 2 on February 3, 2007 (spring tide) at the time of the (a) maximum velocity and (b) low water level at spring tide. Salinity meter dried up on spring low tide, however, depth meter was always submerged. Salinity meter measured at a middle layer of water on spring flood tide. However, in case of small tidal range due to neap tide or diurnal inequality of tide, there can be an immeasurable domain in salinity profile. Since salinity profile at St. 2 distributes uniformly in cross-section, even on spring tide in which flow velocity becomes large, cross-sectional salinity distribution can be estimated from salinity measured at riverbank. Velocity differs between riverbank and riverbed by more than 30 cm/s, and the maximum core of velocity moves from the deepest column in the direction of the left bank of about 25 m. Figure 4 shows the relation among depth-mean velocity at the deepest point, cross-sectional mean discharge, and mean salinity flux. Velocity and salinity were almost uniform in

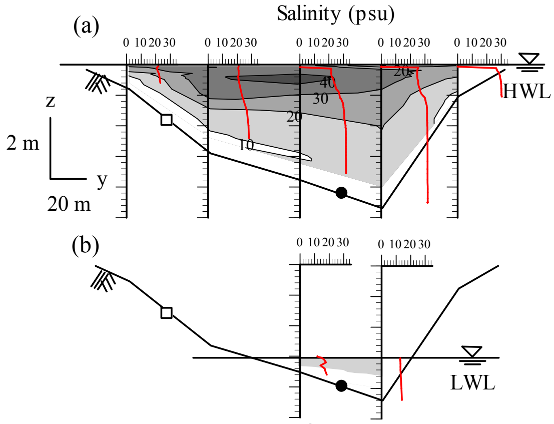

Figure 3. Cross sectional river velocity profile (unit: cm/s) and salinity at St. 2 at the time of (a) maximum velocity and (b) spring ebb tide on February 3 in 2007. ●: depth meter. □: salinity meter

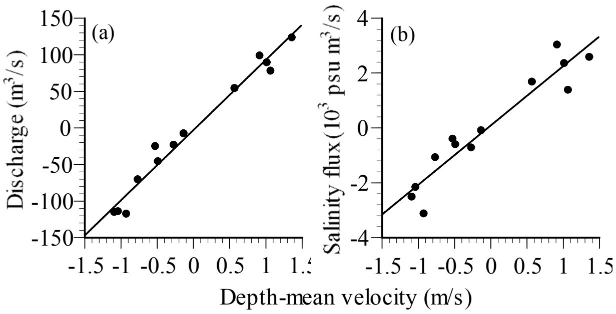

Figure 4. Relationship between mean velocity at the deepest column and mean cross sectional discharge at St. 2 (left) and salinity flux (right).

the cross sectional direction, and depth-mean velocity correlates well with mean discharge and mean salinity flux (R^2=0.97, and 0.90). Thus, it is suggested that mean discharge and salinity flux can be estimated from salinity at the riverbank and depth at the deepest point in the water budget analysis of box model.

Figure 5 shows the relationship between river depth and the depth-mean salinity on October 11 (spring tide) and October 18 (neap tide) in 2003. Hourly observation data of STD (salinity, temperature, and depth) (○) and two estimation data at twice of tide by the fixed salinity meter on the riverbank (●) are also shown. In addition, mean daily river discharges at the upstream station (St. 5) during the observation period were 19 and 17 m^3/s. An estimated depth indicates a depth on a high tide making a salinity profile. When estimating the salinity profile, any salinity data not measured by the fixed sensor near water surface/bottom was extrapolated uniformly using measured salinity at the edge of the measured range. From these results, during neap tide, hourly

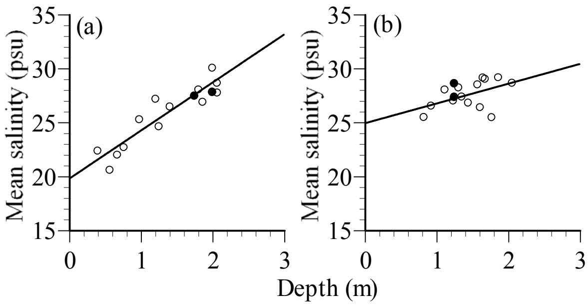

Figure 5. Relationship between depth and mean salinity at St. 2 during spring and neap tides. ○: Hourly data of STD observation. ●: estimated values (twice of tide).

measurements of mean salinity varied slightly by 25 to 30 psu, and estimations correspond to average values. During spring tide, hourly measurements of mean salinity varied between 20 and 30 psu, and estimated salinities corresponded to levels measured during high tides at approximately 27 psu. This means that salinity profile was not asymmetric between flood tide and ebb tide during spring tide, although mean salinity was estimated assuming that tidal variation does not affect stratification. That is, seawater intrudes from the bottom layer and becomes stratified during spring flood tide, and low salinity water discharges (runs off) using entire depth during spring ebb tide.

Salinity environment of riverbed in main channel

Figure 6 shows temporal variations in (a) RWL and discharge at St. 5, (b) salinity at St. 2 (surface water at the deepest point and pore water in the beds of the tidal flats), (c) difference in GWL (St. 6: confined groundwater, St. 7: unconfined groundwater), water level difference (WL dif.) of the tidal flat beds minus the deepest point at St. 2, and GWL at St. 8, and (d) inflow amount Q_3, through flow amount Q_{gate} estimated by the box model and discharge the difference between them (Q_3-Q_{gate}, with a moving average of two M_2 tidal cycles) from August to October in 2004. Since the estimated discharge at St. 5 is not affected by the tidal fluctuations it represents the total (mean) fresh water discharge of the ORF and Shinai-hasen rivers. The dashed line in Figure (c) shows the difference in water level between the RWL and GWL of the tidal flats in late August, before the river discharge increases markedly.

In Fig. 6 (a) and (b), even if river flooding decreased the salinity of the surface waters in the main channel, the salinities in tidal flats remain at about 22 psu (the data without submerged has been deleted because they does not indicate the state of pore water). This means that, even during flooding, surface river water intrudes into the riverbed and pore water and river water are not exchanged completely. Consequently, saline water is restored in the bottom

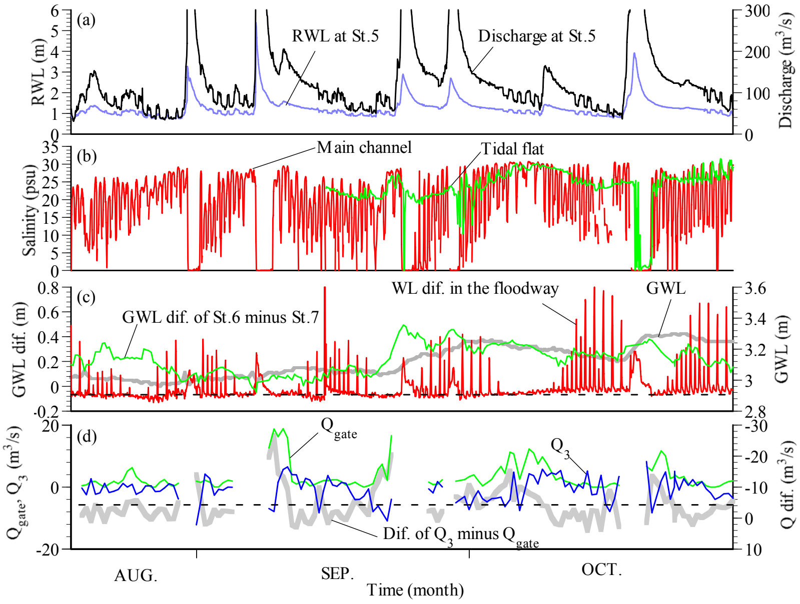

Figure 6. Temporal variations of (a) RWL and discharge at St. 5, (b) salinity at St. 2 (surface water at deepest point and pore water in tidal flat bed), (c) difference in GWL (St. 6: confined groundwater, St. 7: unconfined groundwater), water level difference (WL dif.) in tidal flat bed minus deepest point at St. 2, and GWL at St. 8, and (d) inflow Q_3, through flow amount Q_{gate} estimated by the box model, and difference in discharge (Q_3-Q_{gate}, with a moving average of two M_2 tidal periods) from August to October in 2004. Dashed line in figure (d) shows mean difference of Q_3 minus Q_{gate}.

layer, or seawater recycled from the open sea resupplies the water under the tidal flats.

From Fig. 6 (c), after late September, the pressure head may also rise in the coastal aquifer, because the confined GWL at St. 6 (GWL dif.) and GWL at St. 8 rise. On the other hand, since the GWL in the tidal flats at St. 2 rises to 20 cm higher than the RWL during the ebb tide (WL dif.), groundwater supplies to tidal flat beds may increase. Consequently, subsurface flow water in the coastal aquifer may increase the height of the water table and the salinity of the tidal flat beds.

Freshwater inflow and formation mechanisms of blackish water

Continuous estimation of fresh water inflows at upstream river reaches by the box model is shown in Fig. 6 (d); data for the flooding associated with the opening of the Gion water gate have been deleted. Except for this period of flooding, estimation of inflow and the variation therein correlate closely with the through flow at Gion gate. This is because the model considers the following physical conditions:

1. Detailed riverbed morphology as a function of tide level to show the variation of tides in box water volume.
2. Variation in the cross sectional and longitudinal salinity profiles to accurately examine total salt concentration along the river profile.

There were a several occasions when the inflow amounts determined using the box model (0 to 10 m^3/s) were estimated to be less than the discharge (Q_{gate}, 0 to 20 m^3/s). Mean difference between these inflows (Q dif.) is about 4 m^3/s. This is because salinity in the box remained high, even when fresh river water inflowed Q_{gate} from upstream river. This means that inflow water from the upstream river therefore only actually has the effect of decreasing salinity corresponding to Q_3. On the other hand, since salinity in the tidal flat beds of the main channel remain above 20 psu, saline groundwater may be restored as coastal aquifer moves up into the channel. The difference between GWL in tidal flats and RWL having a period of half a month (Figure 6 (c)), provides evidence for the groundwater flow from the coastal aquifer as being essential for maintaining the water environment of the estuary and tidal flats.

CONCLUSIONS

Characteristics of salinity profiles

An estimation method has been proposed for conducting water budget analysis in a large tidal estuary, and the mechanism for maintenance of the brackish water environment has been described.

1. A data analysis method for estimating salinity profiles using river depth and salinity data measured at the riverbank during tidal variations in the water level of an estuary was proposed. In this method, assuming that seawater intrudes from the bottom layer and stratification remains, the temporal variation in salinity was converted to spatial (vertical) variation. The depth-mean salinity estimated by this method agreed well with the depth-mean salinity measured by STD observations at spring high tide and neap tide.
2. Based on continuity and salt conservation equations, a box model utilizing the characteristics of large-tidal estuary was derived. In this model, riverbed and riverbank morphology were considered as a function of tidal level for the integration of longitudinal salinity distribution. The applicability of the model was verified by continuous estimation of inflow amounts into the tidal estuary.
3. The disparities observed in fresh water inflows estimated by the box model and discharge measured at the water gate which amounted 0 to 10 m^3/s, are thought to have occurred due to salinity increases from the groundwater in the coastal aquifer to the river water, or because of river water intrusion into the riverbed. These water paths may be important in the transport of water and various materials in tidal estuaries.

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