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Spatial and Temporal Variability of Residual Volume Transport according to Artificial Freshwater Discharge in Yeoungsan River Estuary, South Korea

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ABSTRACT

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To determine the effect of artificial freshwater discharge on the spatial and temporal variability of residual current and residual volume transport, current and density profile data have been analyzed in the Yeoungsan River estuary (YRE), South Korea. Current and density data were obtained from three transects during no freshwater discharge and during freshwater discharge. The residual current structure is complex (*e.g.,* vertically multi-layer) during no freshwater discharge, due to the combined influence of tides, wind, and topography. In contrast, strong freshwater discharge influences vertical mixing at the surface layer and no mixing at the bottom layer. This mixing characteristic causes a salinity gradient with depth and significant stratification. The direction of residual volume transport is flood-direction during no freshwater discharge and ebb-direction during freshwater discharge. Residual volume transport and stratification are shown to be dependent on artificial freshwater discharge in the YRE.

ADDITIONAL INDEX WORDS: *Artificial freshwater discharge, residual current, volume transport, Yeoungsan River Estuary.*

INTRODUCTION

In 1981, a dyke was built on the Yeoungsan River estuary (YRE) in South Korea for water supply and flood control, which has since changed the estuary environment. The magnitude of tidal currents decreased due to the blocking by the dyke, and the residence time in the estuary increased because of low freshwater discharge (Kang, 1998).

Mixing or stratification by freshwater in the estuary causes changes in vertical and horizontal density. This process has an important role in estuarine circulation and mass flux. Water column temperature in front of the YRE dyke occurs as either a two-layer structure (common in estuaries) or a multi-layer structure after freshwater discharge (Cho *et al.,* 2004). The dyke is in an area where the estuary environment changes drastically due to freshwater discharge. Therefore, freshwater influx due to water being discharged from the YRE dyke has become an important factor controlling the estuary's environment (Bang *et al.,* 2013). Various studies have been conducted to investigate the effects of the freshwater influx. Despite a decrease in the area of the tidal flats, ebb dominance intensified at Mokpo Port due to the construction of the dyke (Kang, 1999). Kim *et al.* (2013) suggested that salinity stratification develops at the front of the YRE dyke due to freshwater discharge and that discharge does not substantially contribute to vertical mixing between the surface layer and the bottom layer.

The vertical salinity structure and the strong current flow during freshwater discharge are important factors that affect stratification and mixing phenomena in the estuary. They are also very important for the horizontal transport of sediments and biotic matter both toward the open sea and within incoming seawater.

Previous studies focused mainly on making observations at fixed points, which is advantageous for identifying temporal environmental changes over a long time period. However, the movement of dissolved matter and sediments in an estuary causes complex spatial changes within the channel. This spatial variation has direct and indirect effects on the exchange of materials. Therefore, it is necessary to consider both temporal changes and spatial changes in order to identify the mechanisms of material circulation in an estuary.

In this study, observation of the spatial and temporal changes of current and salinity were performed simultaneously to identify the characteristics of three-dimensional estuarine circulation within the channel. Three-dimensional flow and salinity were reconstructed based on the data obtained from on-site observations. These data were used to calculate tidal residual current and total mass flux during no freshwater discharge and freshwater discharge.

METHODS

The locations of the mooring observation points and a topographical cross section through the study area are presented in Figure 1. The topography and water depth information are based on a digital chart provided by the Korea Hydrographic and Oceanographic Administration. Cross-sectional velocity was observed at the YRE using a 600 kHz acoustic Doppler current

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profiler (ADCP) on April 29 and July 20, 2012. Observations were performed repeatedly each hour for 13 hours along each transect, and ship speed was maintained at 4–5 knots to maintain stability for the observation tool and data integrity. The ADCP was mounted at 1 meter (m) under the water surface (MUS), and flow direction and speed data per water layer were measured at intervals of 0.5 m. Observations of the cross-sectional velocity of the channel were conducted at the channel junction inside Gohado, and three transects, which correspond to the entrances of each river junction, were observed (Figure 1). Temperature and salinity data were measured per water layer using an IDRONAUT Ocean Seven 304 Conductivity-Temperature-Depth.

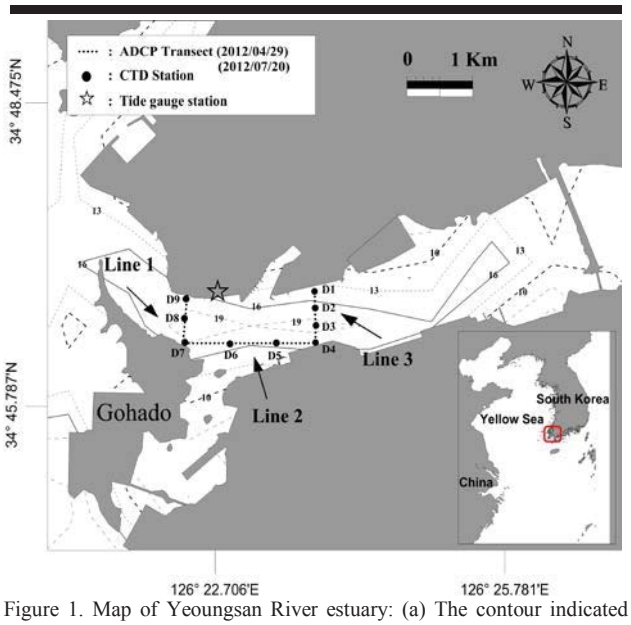


Figure 1. Map of Yeoungsan River estuary: (a) The contour indicated spatial distribution of depth. The dashed line indicated tidal current transects (Line 1, 2, and 3) and black dot indicated a CTD profile point (D1–D8).

The water levels observed on April 29 and July 20, 2012, are presented in Figure 2. Water level and freshwater discharge data were used to analyze change in the hydrodynamic environment. The water levels were collected from the Mokpo tidal gauge, and freshwater discharge data from YRE dyke were provided by the Korea Rural Community Corporation. The observations were conducted when freshwater was not discharged, and when freshwater was discharged, to observe any difference in the environment by artificial discharge.

The ADCP data was processed for error value elimination, true north direction correction, principal component analysis (PCA), and conversion into sigma coordinates to improve accuracy and reliability. The magnetic north direction used as a benchmark in the ADCP measurements was corrected to true north. In addition, as current direction and flow velocity measurements can be affected by the ship speed, this was corrected using the method of Joyce (1989). In this study, flow velocity in the raw data was rotated using PCA to define the main axis direction, and an analysis of dominant elements was then conducted (Preisendorfer and Mobley, 1988).

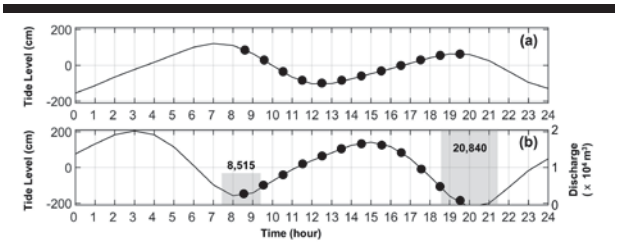


Figure 2. Tide level during no freshwater discharge in April 29, 2012 and tide level during freshwater discharge in July 20, 2012 at the Mokpo tide gauge station. The gray boxs indicate the daily-averaged freshwater discharge from dyke.

Finally, a normalization method (sigma coordinate) was used to facilitate the elimination of tidal elements within the surface and bottom layers, and the calculation of material volume transport (Kim *et al.,* 2013). When using the normalization method, the absolute water depth of the surface layer appears to be different due to tidal changes. The longitudinal flow was normalized vertically and horizontally for considers large tidal changes. ADCP water level is referred to as 0 m water depth at the time of observation.

Tidal propagation characteristics vary according to the characteristics of the estuary and change according to external forcing, such as non-linear tidal constituents, freshwater influx, and wind. Tidal residual current also vary according to the characteristics of the estuary (Yanagi *et al.,* 2003). Tidal residual current is defined as the flow after the tidal component is removed from the water circulation flow. Due to the short period of observation of 13 hours we could not identify short-period propagation characteristics that change daily (*e.g.,* K_1 and O_1). However, we could identify the characteristics of the spatial tidal residual current distribution during the tidal period by decomposing the M_2 and M_4 constituents, for which the cycle is less than 13 hours (Valle-Levinson and Atkinson, 1999). A harmonic analysis was conducted using the least square method (Lwiza *et al.,* 1991).

$$u = u_0 + \sum A_{M2}\, cos(\omega_{M2} - \emptyset_{M2}) + \sum A_{M4}\, cos(\omega_{M4} - \emptyset_{M4}) \quad (1)$$

In equation (1), u is the along-channel velocity of the main axis, u_0 is the residual current, A is the amplitude of M_2 and M_4, ω is angular velocity, and $\emptyset$ is phase angle. Considering the amplitude and the phase of the M_2 and M_4 tidal constituents, the difference in the raw data (u) was defined as the tidal residual current (*e.g.,* Choi *et al.,* 2012; Lee *et al.,* 2012; Valle-Levinson and Atkinson, 1999).

For a cross section having M grid cells, each with an instantaneous cross-sectional area of a_m and a normal velocity component of p_m, the residual volume transport rate may be expressed as (Sylaios and Boxall, 1998):

$$\langle \sum_{m=1}^{M} p_m a_m \rangle = \sum_{m=1}^{M} \langle p_m \rangle \langle a_m \rangle + \sum_{m=1}^{M} \langle P_m A_m \rangle \quad (2)$$

In equation (2), < > refers to a time longer than the tidal period, and P and A are defined as $P(=p-\langle p\rangle)$ and $A(=a-\langle a\rangle)$, respectively. The left side of this equation is the Lagrangian residual volume transport. The first term on the right side is the Eulerian residual volume transport, and the second term is Stokes drift volume transport rate.

RESULTS

The tidal residual current at each transect was calculated during no freshwater discharge (Figures 3a, 3b, and 3c). Positive values of velocity refer to flood directional flow, and negative values indicate ebb-directional flow. The black dotted line indicates a flow velocity of 0 m/s.

On the north side of Gohado is the river channel, which has a complex flow structure (Line 1, Figure 3a). Overall, flood-directional flow was dominant. Ebb-directional flow was well-defined on the surface layers. In Line 2, residual current was towards the flood-directional flow in the 400–800 m section (Figure 3b). Ebb-directional flow was seen in the other sections within the surface layer. During no freshwater discharge, the ebb-directional flow was seen within the surface and bottom layers, and the flood-directional flow within the middle layer (Line 3, Figure 3c). Residual current in the flood-direction was clear within the middle layer. However, the ebb tidal pattern was dominant within the lower layer.

During no freshwater discharge, the tide dominantly affected the longitudinal flow direction. Furthermore, the ebb-directional flow was dominant within the surface layer. During the observation period, there were continuous southeasterly winds in the study area, which likely affected the ebb-directional flow within the surface layer. We infer that the effect of wind is important during no freshwater discharge.

When freshwater was discharged, the longitudinal residual current was distinctly different to the periods of no discharge (Figures 3d, 3e, and 3f). In Line 1, overall residual current was ebb-directional in the northern channel and flood-directional in the southern channel at the middle and bottom layer (Figure 3d). Residual current in the ebb-direction was dominant overall. However, residual current in the flood-direction prevailed within the southern channel. We infer this residual current distribution to have been caused by seawater influx through the deep water.

In Line 2, a slight change in residual current distribution changed when freshwater was discharged (Figure 3e). Residual current in the flood-direction developed within the middle and lower layers in the 400–800 m section when there was no freshwater discharge. In contrast, residual current in the flood-direction developed in the surface and middle layers in the 0–800 m and in the lower layer in the 1600–2000 m section when freshwater discharge was occurring.

In Line 3, a multi-layer structure developed with residual velocity towards the ebb-direction in the surface layer, the flood-direction in the middle layer, and the ebb-direction in the bottom layer when freshwater was discharged (Figure 3f). During freshwater discharge, a two-layer circulation with ebb directed current at the surface layer and flood directed flow at the bottom layer occurred. When discharge stopped, a multi-layer flow with ebb flow at the surface layer, flood flow within the middle layer, and ebb flow at the bottom layer develops.

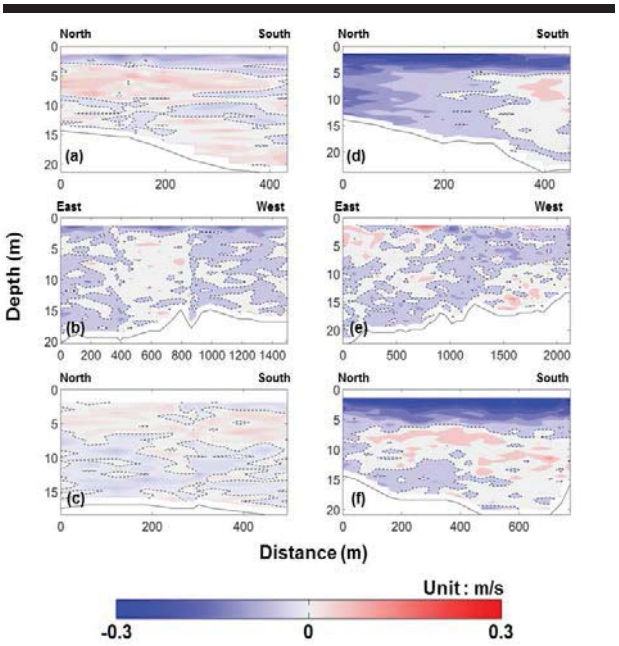


Figure 3. Distribution of residual flow velocity during no-freshwater discharge (a, b, c) and during freshwater discharge (d, e, f) at Line 1, Line 2, Line 3. Negative and positive value indicate ebb and flood direction of residual current, respectively. Dashed contour represents zero velocity.

When freshwater was discharged from the estuary dyke (mainly through Line 3), the environment changed rapidly due to the longitudinal flow velocity. The subsequent multi-layer structure was maintained for about five hours and a multi-layer flow also appeared in the residual current.

During no freshwater discharge, there was no significant vertical difference in the tidal mean salinity distribution (Figures 4a, 4b, and 4c). The mean salinity was approximately 30 psu during no freshwater discharged. Salinity decreased by about 10 psu down to 3 MUS. However, salinity below 3 m remained at approximately 2 psu. In contrast to other transects, the average salinity of the surface layer of the D1–D2 section of Line 3 was approximately 25 psu, and it did not appear in D8 (Figure 4c). The 25 psu salinity distribution occurred in deep water in D1, and we infer that a water mass of relatively low salinity moved through the northern channel.

When water was discharged, a large vertical gradient in tidal mean salinity occurred (Figures 4d, 4e, and 4f). Salinity at the surface layer was 4–5 psu due to the water discharge. However, it changed significantly between 5 and 10 m deep. At the beginning of the water discharge, a salinity distribution greater than 10 psu developed at 1–2 m deep. However, the effect of the freshwater extended down to 4–5 m deep during discharge.

After the discharge, the salinity in the surface layer recovered due to the flood-directional flow. Mean tidal salinity values confirm that salinity changes from water discharge were limited to a maximum depth of 10 m. Mean salinity

below 10 m was approximately 29 psu, which is only 1 psu lower than during no freshwater discharge, suggesting minimal influence from discharge.

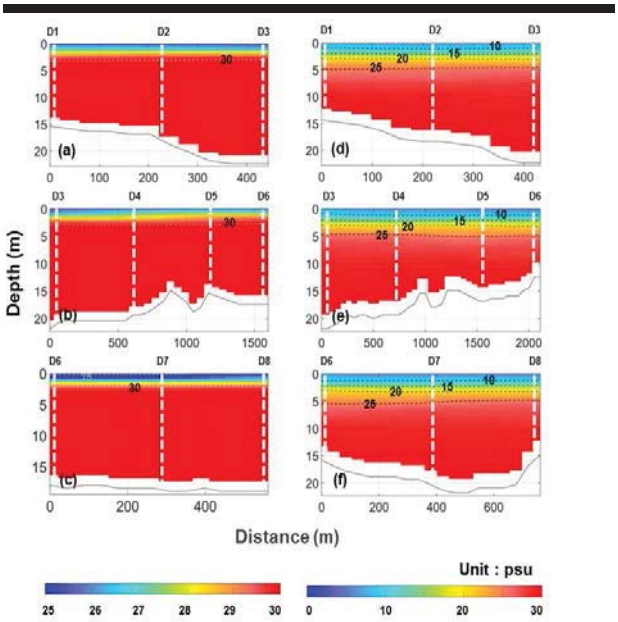


Figure 4. Average salinity across transect in no-freshwater discharge (a, b, c) and freshwater discharge (d, e, f) at Line 1, Line 2, Line 3. A contour of salinity intervals is 5 psu. D1 to D8 (white lines) are the CTD casting stations.

Figure 5 presents the residual volume transport calculation values during no freshwater discharge and freshwater discharge. During no freshwater discharge, the Stokes drift term value was close to 0 m^3/s in Lines 1, 2, and 3 (Figure 5a). The Eulerian transport value was 43 m^3/s and -90 m^3/s in Lines 1 and 2, respectively. Line 3, which was the closest transect to the estuary dyke, had the lowest value of 4 m^3/s. The residual volume transport was towards the interior of Gohado in Line 1, and towards the exterior in Line 2.

During freshwater discharge, the Stokes drift term value was 57 m^3/s, 13 m^3/s, and 55 m^3/s and the Eulerian term was -449 m^3/s, 19 m^3/s, and -563 m^3/s in Lines 1, 2, and 3, respectively, indicating greater values than those of no freshwater discharge (Figure 5b). The volume transport at each transect was directed towards the open sea in Lines 1 and 3 due to the effect of water discharge, and toward the interior of Gohado in Line 2. The magnitude and direction of the Eulerian and the Stokes drift terms, and the channels for seawater exchange, were different between the no discharge and discharge scenarios.

During no freshwater discharge, transport was toward to flood-direction through Line 1 and to ebb-directional through Line 2. Line 3, the closest cross section to the estuary dyke, had virtually no transport. During freshwater discharge, seawater exchange near the estuary dyke occurred through Lines 1 and 3. The freshwater discharged from the estuary dyke was discharged mostly through Line 1, and some volume transport was directed towards Gohado in Line 2.

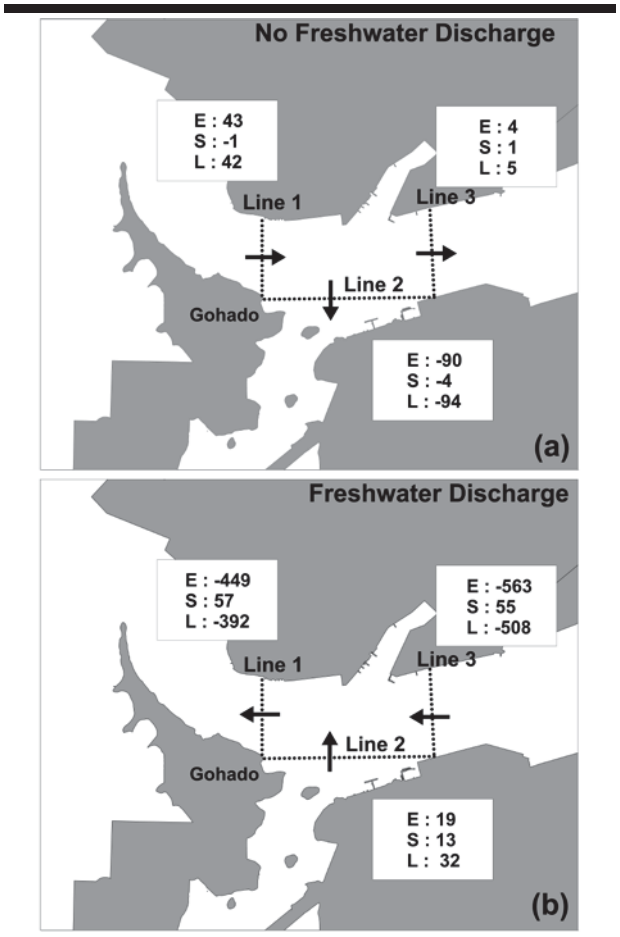


Figure 5. Residual volume transport rates at three cross sections in the no freshwater discharge (a) and freshwater discharge (b). Arrow indicate transport direction, and positive and negative values indeicate flooding and negative directions, respectively.

DISCUSSION

During freshwater discharge, the tidally residual current magnitude was relatively low. Slow residual current was due to the environment being blocked by the dyke, causing a complex tidal residual current structure. In Lines 1 and 3, a two-layer circulation developed with a vertically opposite directional structure. We infer that the effect of the wind was more significant, than that of the tide, due to the semi-closed topography during no freshwater discharge. In Line 2, there was a tidally residual current directed towards the flood-direction from the center of the cross section.

The mean salinity near the estuary dyke during no freshwater discharge was as high as 30 psu. The vertical salinity gradient was relatively low, approximately 3–5 psu. Salinity was usually maintained at approximately 30 psu below 3 m depth.

During freshwater discharge, the tidal residual current varied between the transects. In Line 1, the tidal residual current was in opposite directions in the deep and shallow water areas. In Line 2, the tidal residual current was in the flood-direction on the western surface layer and the eastern bottom layer of the channel, and in the ebb-direction elsewhere. In Line 3, ebb directional flow was dominant in the surface layer, flood directional flow occurred within the middle layer, and ebb directional flow was again dominant in the bottom layer, forming a multi-layer flow structure. These findings are consistent with previous research (*e.g.,* Kim *et al.,* 2013) that indicates a multi-layer residual current after freshwater discharge.

There was a significant vertical salinity difference due to freshwater influx during discharge. However, no significant horizontal salinity difference was observed. Strong freshwater discharge influences vertical mixing at the surface, however, the bottom layer remains unaffected. This causes a salinity gradient with depth and significant stratification.

The total volume transport at the junction of the channel near Gohado was calculated using data obtained by observing the cross-sectional flow velocity during no freshwater discharge and freshwater discharge. During no freshwater discharge, the volume transport ratio of Lines 1:2:3 was 1:2.2:0.1. During freshwater discharge, the ratio was 1:0.1:1.2. Artificial freshwater discharge caused changes in the total volume transport near the dyke. During no freshwater discharge, seawater exchange near the dyke mainly occurred through Lines 1 and 2. In contrast, seawater exchange mainly occurred through Lines 1 and 3 during freshwater discharge.

CONCLUSIONS

The characteristics of tidal residual current and total volume transport vary with freshwater discharge from the dyke at the Yeoungsan River estuary in South Korea. In the absence of freshwater discharge, the impacts of other external forcing (*e.g.,* wind and tide) were dominant, and seawater was exchanged through the channel that is close to the open sea. With freshwater discharge, the impact of the tide and freshwater was clear, and the tidal residual current and total volume transport were both directed towards the open sea. Therefore, we infer that the characteristics of residual volume transport, tidal residual current, and salinity stratification at the Yeoungsan River estuary are dependent on the presence or absence of freshwater discharge from the dyke.

Changes in net volume transport have a major impact on the erosion and transport of sediments and the formation and destruction of tidal flats. However, there are many limitations to identifying the mechanisms of net volume transport and making quantitative calculations. The data used in this study were collected for only a short period of time (13 hours) within the study area. Therefore, in a future study, we plan to identify the residual volume transport mechanism and change per season using a long period simulation in a numerical model.

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