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Sedimentary Processes in the Altered Geum Estuary with an Estuarine Dam

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01 Introduction

Estuaries are coastal indentations with a horizontal salinity gradient due to river runoff. Estuaries are subject to both natural and anthropogenic changes over time. With respect to natural changes, large shifts in estuary location have occurred during the Holocene sea level rise (11,700 years BP – present; Dyer, 1997). With respect to anthropogenic changes, humans have modified estuaries through coastal engineering projects such as land reclamation, dredging, and groins (Wang et al., 2015). The recent and widespread anthropogenic changes to estuaries is consistent with the concept of the Anthropocene, a proposed division of geologic time, generally considered to begin around the mid-twentieth century, in which humans have a dominant impact on the Earth's geology and ecosystems (see Zalasiewicz et al., 2015).

An additional modification of estuaries through coastal engineering is the construction of estuarine dams. Estuarine dams are dams constructed within either the salt or tidal intrusion limits. This places them typically within 1 – 1,000 km from the coast (Figueroa et al., in review). Estuarine dams

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block the upstream propagation of tides and salt, like tidal weirs. However, estuarine dams contain sluice gates which can discharge freshwater in discrete events whereas tidal weirs operate by freshwater overflow. Estuarine dams and tidal weirs have been constructed since at least the nineteenth century. Early examples include tidal weirs on the Thames (1811) and Ems (1899) estuaries. At present, estuarine dams and tidal weirs can be found worldwide. They are especially common in China where there are around 320 estuarine dams (Zhu et al., 2017) and in South Korea where about half of the estuaries along the coast are closed (Lee et al., 2011; Jung et al., 2021). While estuarine dams and tidal wiers share some similarities, this article focuses primarily on estuarine dams.

Estuarine dams can cause significant changes to estuaries' hydrodynamic and sedimentary processes such as by altering the tide, freshwater discharge, and transport of sediment. Sediment transport in estuaries is important because it controls the water depth and coastline. It also is important because it controls the water quality by affecting the water turbidity, light intensity, chlorophyll concentration, and dissolved oxygen concentration. Despite the significant changes that estuarine dams can cause to the hydrodynamic and sedimentary processes in estuaries, their impact is not well studied and not well understood.

To better understand the hydrodynamic and sedimentary processes in an estuary altered by an estuarine dam, extensive field measurements from Geum estuary, Korea, were recently collected and analyzed (Figueroa et al., 2019; 2020a; 2020b). These measurements focused on understanding 1) how freshwater discharge from the estuarine dam affects the fine cohesive sediment flocculation, which is important for understanding the sediment mobility, and 2) what are the driving forces and sediment flux mechanisms responsible for the increased deposition in Geum estuary that has occurred after the construction of the Geum estuary dam.

This article focuses on the sedimentary processes in Geum estuary altered by the estuarine dam. The next sections provides an overview of the study area, previous research, and the recent methodology used in Figueroa et al (2019; 2020a; 2020b). Section 3 presents the keypoints of that research. Finally, Section 4 presents a summary of the new insights into Geum estuary as well as implications for other estuaries with an estuarine dam..

02 Study Area and Methodology

The main channel of Geum estuary is about 20 km long, 2.0 km wide, and less than 20 m below the lower low water (Figure 1). Midway along the main channel is a shallow distributary channel called the Gaeya channel. The estuary has a spring tidal range of about 6.0 m. The average significant wave height is 1.2 m in winter and 0.7 m in other seasons. The construction of the Geum estuary dam began in 1983, and the operation of the dam began operation in 1994. The dam has 20 vertically rising sluice gates. When closed, there is no overflow, and when open, discharge occurs near the channel bed. Discharge occurs during ebb to prevent the salt intrusion and lasts on average 2.4 hours. The gates open on average 233 times a year, more often during the rainy summers than the dry winters. The annual average freshwater discahrge is 170 m^3 s^{-1} (Kim et al., 2006).

The estuarine dam resulted in many physical and geological changes such as blocking the tidal propagation and salt intrusion upstream, reducing the mean sea level, amplifying the tides, decreasing the tidal currents, increasing tidal asymmetry, decreasing the suspended sediment concentration (SSC), and shifting the surficial sediments from sandy to muddy (Kwon and Lee, 1999; Kim et al., 2006). In addition sediment depositional rates increased considerably, up to 20 cm yr^{-1}, resulting in the siltation of harbors and channels and the accretion of mud flats (Lee and Lee, 2007).

While it was known that the depositional rates increased after the construction of the estuarine dam, a detailed analysis of the sediment flux mechanisms and the factors that control them had not been investigated. Furthermore the effect of freshwater discharge on the cohesive sediment flocculation was not known. To better understand these sedimentary processes, field observations were conducted during 2015-2018. The primary considerations were of the freshwater discharge, tides, and waves and the resulting currents, salinity stratification, SSC, and floc size. Floc size was measured using a Laser In-Situ Scattering and Transmissometer (LISST). Acoustic Doppler current profilers (ADCPs) were used to measure the currents and the acoustic backscatter was calibrated to SSC. Using current (u) and SSC (c), the along-channel sediment flux ($F = u \cdot c$) was analyzed. To better understand the sediment flux mechanism, the sediment flux was decomposed as:

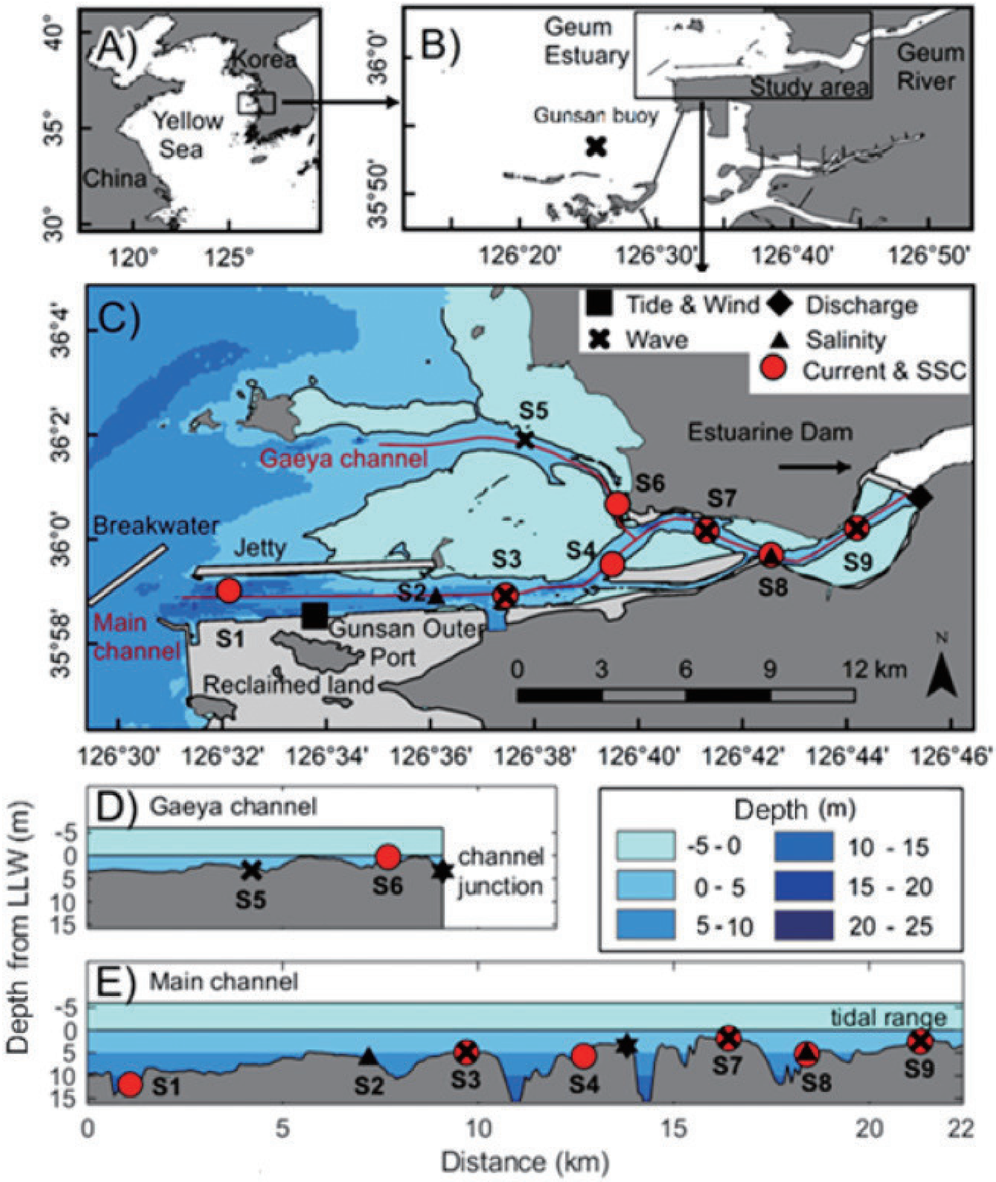

Figure 1. Study area and measurement stations. Depth is relative to a lower low water (LLW) vertical datum. Reprinted from Marine Geology, 429, Figueroa, S., Lee, G., Chang, J., Schieder, N., Kim, K., and Kim, S.Y., Evaluation of along-channel sediment flux gradients in an anthropocene estuary with an estuarine dam, 106318, copyright (2020), with permission from Elsevier.

$$\overline{F} = \underbrace{\overline{\overline{u} \cdot \overline{c}}}_{F_{mean}} + \underbrace{\overline{u' \cdot c'}}_{F_{corr}} \quad (1)$$

where an overbar represents a tidal average resulting from the application of a 36 hour Lanczos low-pass filter and a prime represents a tidal fluctuation resulting from the application of a 36 hour Lanczos high-pass filter (Geyer et al., 2001; Sommerfield and Wong, 2011). F_{mean} is the mean flow flux component occurring on timescales longer than the tidal cycle and F_{corr} is the correlation flux component occurring on the tidal timescale. F_{mean} can be seen as fluxes due to tidally averaged processes like river discharge, whereas F_{corr} can be seen as fluxes due to asymmetric processes like tidal pumping. For the field observations, Geum estuary was divided conceptually into the outer estuary (S1, S2, and S3), the central estuary (S4, S5, and S6), and the inner estuary (S7, S8, and S9; see Figure 1). It can be noted that during 2015-2018, observations began in the inner estuary (Figueroa et al., 2019; 2020a) and eventually covered the entire estuary (Figueroa et al., 2020b). Summer conditions were investigated during 2015 and 2016 (Figueroa et al., 2019; 2020a) and winter conditions were investigated during 2018 (Figueroa et al., 2020b).

03 Results

3.1 Summer 2015: Periodic stratification and floc asymmetry

Traditionally, estuaries can be classified by salinity structure as salt wedge, strongly stratified, partially mixed, and well-mixed. Simpson et al. (1990) recognized the potential for an addition type: a periodically stratified estuary. In this type, periodic vertical shear due to the tides acts on the horizontal salinity gradient resulting in stratified ebb phases and well-mixed flood phases. This was observed two days after a freshwater discharge in Geum estuary at Station S7 (Figure 2). During ebb (in grey), the water column was stratified, whereas during flood (in white) the water column was well-mixed (Figure 2C). During the stratified ebb, the turbulent shear rate was lower which allowed for the growth of larger cohesive sediment median floc sizes (Figure 2F, 2H). On the other hand, during the well-mixed flood, the turbulent shear rate was higher which broke up flocs and resulted in smaller median floc sizes (Figure 2F, 2H). These observations are important because they reveal that freshwater discharge can result in periodic stratification and in turn a floc size tidal asymmetry. The floc asymmetry is important because the settling velocity scales with floc size, and thus it suggests that sediment will be preferentially transported in the direction the water flows when flocs are smaller.

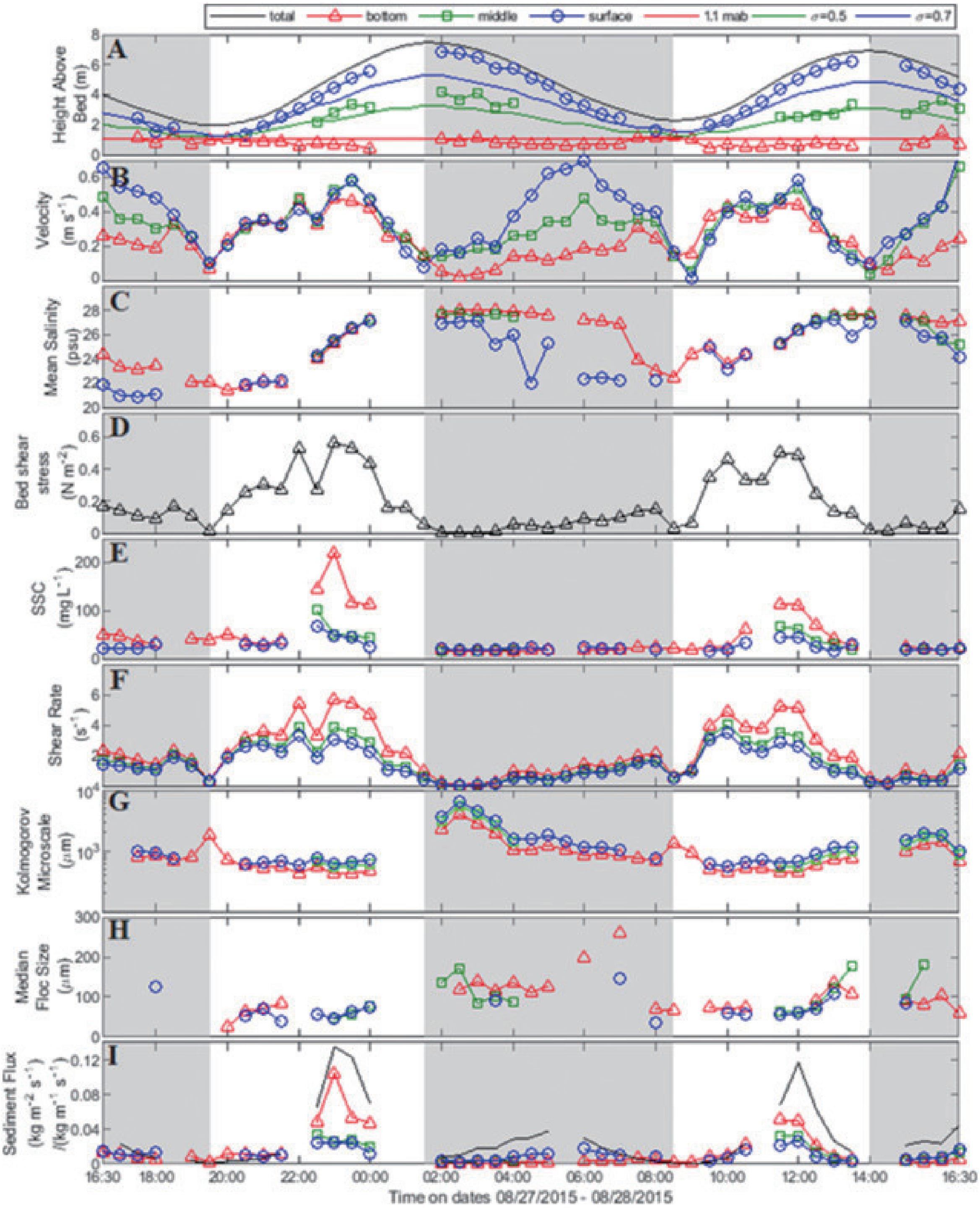

Figure 2. Times series of hydrodynamics and sediment dynamics data during two tidal cycles in summer 2015/08/27-2015/08/28 in Geum estuary at Station S7. A) Height above the bed of the water surface and measurement locations (m); B) Velocity magnitude (m s-1); C) Salinity (psu); D) Bed shear stress (N m-2); Suspended sediment concentration (SSC, mg L-1); F) Turbulent shear rate (s-1); G) Kolmogorov microscale (μm); H) Median floc size (μm); I) Suspended sediment flux magnitude (kg m-1 s-1). Reprinted from Marine Geology, 412, Figueroa, S., Lee, G., and Shin H.J., The effect of periodic stratification on floc size distribution and its tidal and vertical variability: Geum Estuary, South Korea, 12, copyright (2019), with permission from Elsevier.

3.2 Summer 2016: Importance of inner estuary spring tidal pumping

Observations at Stations S7 and S9 (also called M2 and M1, respectively) are shown in (Figure 3). It can be seen that in summer the discharges are relatively frequent (6 discharges; Figure 3A-3B) and the seaward discharge currents decrease from S9 to S7 (negative spikes in Figure 3C-3D).

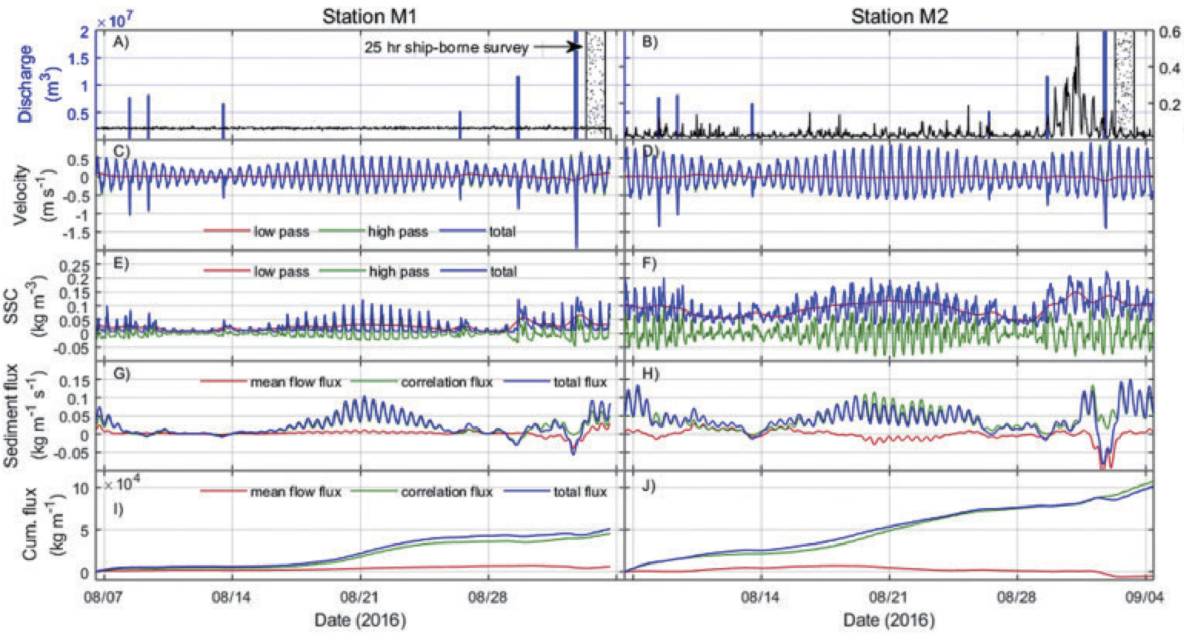

Figure 3. Along-channel sediment flux time series in summer 2016/08/07-2016/09/04 in Geum estuary at Stations S9 (here called M1) and S7 (here called M2). A and B) Freshwater discharge (m3) and significant wave hieght (m); C and D) Depth averaged velocity (m s-1); E and F) Depth averaged suspended sediment concentration (SSC); G and H) Depth integrated suspended sediment flux (kg m-1 s-1); I and J) Cumulative sediment flux (kg m-1). Positive velocities and fluxes are landward. Reprinted from Estuarine, Coastal and Shelf Science, 238, Figueroa, S., Lee, G., and Shin H.J., Effects of an estuarine dam on sediment flux mechanisms in a shallow, macrotidal estuary, 106718, copyright (2020), with permission from Elsevier.

The waves were negligible in summer (Figure 3A-3B). On the other hand the tidal current and SSC decrease toward the dam from S7 to S9 (Figure 3C-3F). This is because, when the sluice gates are closed, the currents must disappear at the closed boundary. The most important results from this survey are related to the along-channel sediment fluxes. The fluxes at both stations were landward and were greatest during spring tides (Figure 3G-3H). The sediment flux decomposition showed that tidal pumping due to tidal asymmetry (F_{corr}) was the main sediment flux mechanism (Figure 3G-3H; correlation flux, green). Time integrating the sediment fluxes showed that the landward flux was greater at S7 than S9, indicating that tidal pumping was resulting in a flux convergence, or deposition.

It was found that tides tend to pump sediment landward whereas the freshwater discharge tends to flush sediment seaward. The landward tidal pumping was proportional to the tidal range, and the seaward river runoff was proportional to the discharged volume. Therefore, in the inner estuary there was a competition between the effect of tide and freshwater discharge, however it was clear that the tides were the more dominant effect.

3.3 Winter 2018: Spatial segregation of sediment flux mechanisms and forcing

The winter observations extended throughout the estuary (Figure 4). An overall negative along-channel sediment flux gradient was again observed, indicating that sediments were being brought from offshore and deposted (Figure 4A). Considering the sediment flux mechanism, it was found that while the shallow, inner estuary was dominated by tidal pumping/correlation fluxes, the deeper outer estuary was dominated by tidally averaged mean flow fluxes (Figure 4B).

Also, it was revealed that there was a change in direction of the mean flow fluxes along channel. In the inner estuary they were seaward, which indicated the influence of the freshwater discharge. However, in the deeper outer estuary, they were landward under the influence of offshore flows. With respect to the driving hydrodynamic forcing, it was found that the tides drove the sediment fluxes throughout the estuary (Figure 4C). The freshwater discharge effect was limited to the inner estuary, and the wave effect was limited to the outer estuary, particularly the exposed Gaeya channel (Figure 4C). Overall, this survey identified the spatial segregation of sediment flux mechanisms and driving forces. In the deep outer estuary, mean flow fluxes bring sediment from the shelf which is pumped further landward in the shallow, inner estuary by tidal asymmetry. Tides are the dominant forcing, particularly during the spring tides. The freshwater discharge effect is only limited to the inner estuary. And, the winter waves are not the main forcing driving the sediment fluxes, but they likely contribute to some import of sediment, such as in the Gaeya channel.

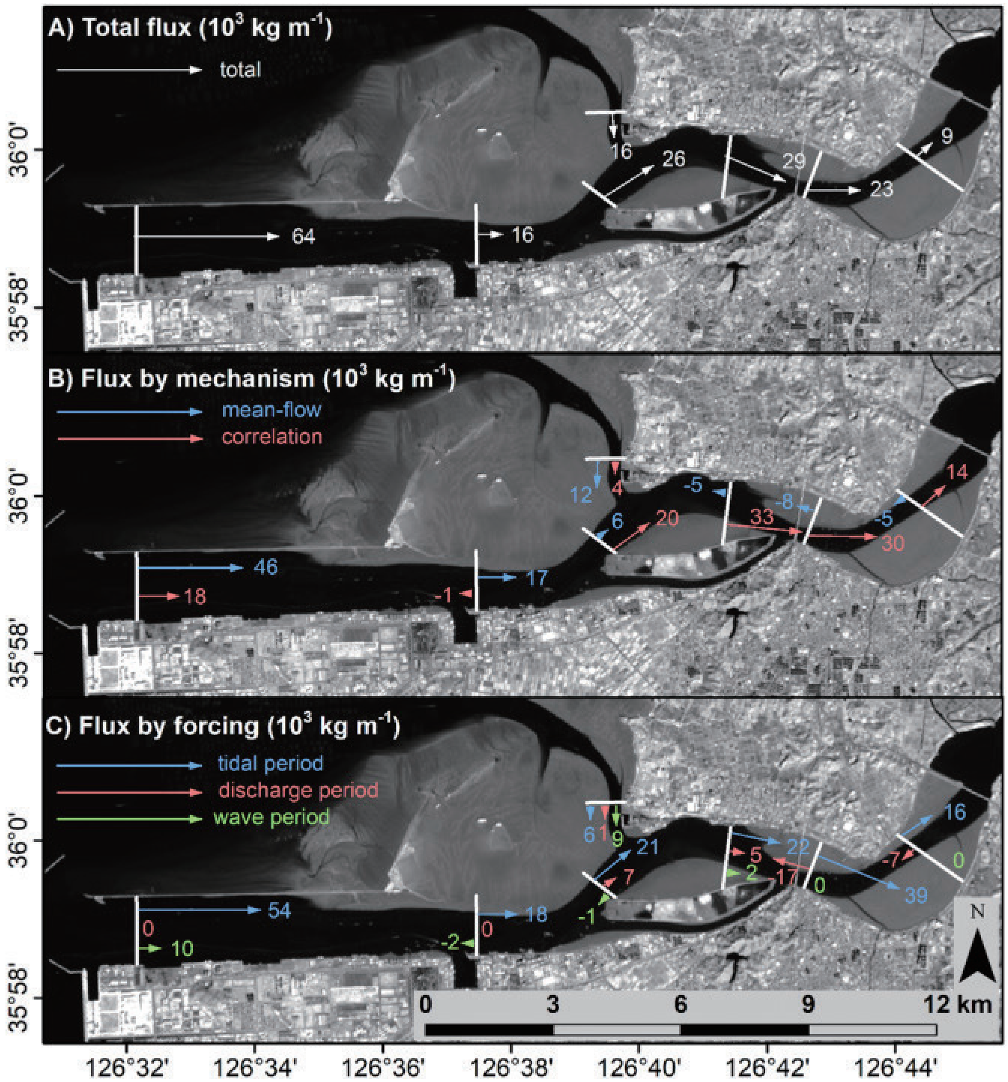

Figure 4. Map of the cumulative, depth-integrated sediment flux vectors over a neap-spring cycles in winter 2018/01/04-2018/01/18 in Geum estuary at Stations S1-S9. A) Cumulative, depth-integrated total sediment flux (103 kg m-1); B) Cumulative, depth-integrated sediment flux (103 kg m-1) decomposed by sediment flux mechanism; C) Cumulative, depth-integrated sediment flux (103 kg m-1) decomposed by forcing period. Landsat 8 basemap image provided by United States Geological Survey (earthexplorer.us.gs.gov). Image corresponds to low tide on 2018/03/06. Reprinted from Marine Geology, 429, Figueroa, S., Lee, G., Chang, J., Schieder, N., Kim, K., and Kim, S.Y., Evaluation of along-channel sediment flux gradients in an anthropocene estuary with an estuarine dam, 106318, copyright (2020), with permission from Elsevier.

04 Summary

This research has identified that freshwater discharge in the altered Geum estuary can result in periodic stratification and flocculation asymmetry in the inner estuary. It has also shown that the along-channel sediment flux convergence is driven primarily by the spring tides and occurs by the tidally averaged flows in the deep outer estuary and by tidal pumping in the shallow, inner estuary. The seaward estuarine dam freshwater discharge is not enough to counteract the landward tidal pumping, and the extent of freshwater discharge influence is mostly limited to the inner estuary. While no pre-dam measurements were presented here, Park et al. (1986) suggested that for the pre-dam estuary the shelf was a sink of sediment. However for the post-dam estuary, observations presented here (e.g. Figure 4) suggest that the shelf is a source of sediment. Thus there is some evidence that there has been a switch in the sediment flux direction at the mouth. Recent research suggests that switches in sediment flux direction can be due to changes in tidal asymmetry due to changes in both residual currents and tidal amplitudes effected by estuarine dams (Figueroa et al., in review). A conceptual diagram of the switch in sediment flux direction and other results presented here shown in Figure 5.

Finally, it should be noted that the results presented here may be applicable to other shallow, macrotidal estuaries. However, in other estuarine types the dominant forcing and sediment flux mechanisms may be different. For example,

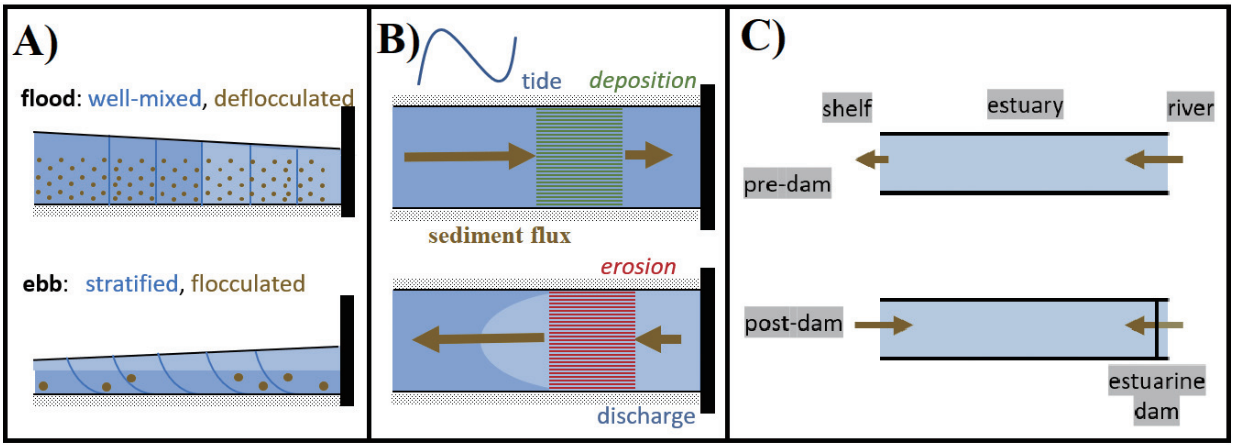

Figure 5. Conceptual diagrams. A) Periodic stratification and floc asymmetry after freshwater discharge. B) Competition between landward tidal pumping and seaward river runoff in the inner estuary. In Geum estuary, generally landward tidal pumping is greater. C) Simplified change of sediment flux direction at the mouth from the pre- to post-dam estuary.

in the microtidal Nakdong estuary, research suggests that enhanced deposition in the main channel after the estuarine dam is driven primarily by freshwater discharge and results from a seaward decrease in the mean flow sediment fluxes (Chang et al., 2020; Williams *et al*., 2015).

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