Spatial Variation of Asymmetry in Velocity and Sediment Flux along the Artificial Aam Tidal Channel

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Abstract: Tidal flats, crucial for biodiversity and ecosystem services, are facing significant alterations due to human activities such as reclamation. In South Korea, over 65% of tidal flats have been reclaimed since the 1970s, resulting in morphological changes and altered sediment transport dynamics. This study investigates sediment transport processes in the artificial Aam tidal channel, created as part of the megacity development project in Incheon, Korea. Using data from Acoustic Doppler Current Profiler and Vector instruments deployed in 2019 and 2021, we analyzed tidal asymmetry, current velocities, shear stress, and suspended sediment concentration. Our results reveal a pronounced tidal asymmetry influencing sediment transport, with ebb-dominant currents near the channel entrance and flood-dominant currents in the interior. We observed significant sediment deposition in the landward section of the channel, driven by tidal mixing asymmetry and rainfall events. These findings highlight the complex interactions between artificial structures and natural sediment dynamics, informing future coastal development and management strategies.

Keywords: asymmetry; anthropogenic; reclamation; tidal channel; sediment flux; eddy viscosity; eddy diffusivity

1. Introduction

Tidal flats provide vital biological resources and ecosystem services that support human well-being [1]. However, they have been directly affected by development for commercial, agricultural, and industrial purposes due to ever-increasing population growth and economic development. Reclamation is the most common form of human development that has changed tidal flat morphology [2,3]. In South Korea, for instance, over 65% of tidal flats along the west coast have been reclaimed since the 1970s [3,4].

The extensive reclamation of tidal flats has induced morphologic alterations in the estuarine and coastal regions. These morphologic changes, alongside shifts in land use, have affected hydrodynamics and sediment transport pattern around the reclaimed tidal flats and within estuaries. The nature of these alterations varies depending on the type of development. For example, harbor development that involved reclamation and dredging in the North Harbor of Incheon, Korea, resulted in rapid siltation over a meter per year at the harbor entrance due to the exchange flow by horizontal entrainment [5,6]. On the other hand, in the Geum estuary, altered by an estuarine dam and land reclamation, tidal mixing asymmetry under strain-induced periodic stratification due to the freshwater discharge from the Geum estuarine dam plays an important role in sediment transport process [7,8]. Various examples of shifting sediment dynamics are observed worldwide, including in countries such as China, the United States, and the Netherlands [9–13].

While sediment transport processes have been extensively studied in various coastal developments, artificially constructed tidal channels have rarely been documented in the literature. In natural tidal channel environments, bidirectional tidal currents over flood...
and ebb tides control the redistribution of sediments. The asymmetry of tidal flow rates causes differences in the magnitude of the maximum shear stress during the tidal cycle, affecting sediment transport in tidal channels [14]. Vertical tidal asymmetry causes horizontal tidal current asymmetry, but it also depends on the tidal prism, storage width, and cross-sectional area during the tidal cycle [15]. Therefore, the evolution of morphology in tidal channels reflects the outcome of nonlinear processes across both space and time. Nonetheless, these processes remain largely unexplored in artificially constructed tidal channels.

In the Songdo tidal flats of Incheon, Korea, an artificial tidal channel, named the Aam tidal channel, began to take shape in 2003 and was completed in 2013 as part of a series of reclamation projects associated with harbor and new town developments in the rapidly expanding city of Incheon. Over the past decade, sediment deposition has been observed within the 5-km-long artificial tidal channel, with higher deposition occurring in the landward section (Figure 1C). This study aims to examine the sediment transport processes responsible for the deposition in the artificial tidal channel. The specific objectives include the understanding of (1) spatial variation of sediment transport along the artificial tidal channel, especially near the entrance and farther inside of the channel and (2) sediment transport mechanisms responsible for the deposition in the artificial tidal channel.

![Image of the Aam tidal channel](image-url)

**Figure 1.** Location map of the Aam tidal channel. (A) Plan view of the study area before reclamation in 2005. (B) Study area after the formation of the Aam tidal channel in 2015. (C) Depth along the thalweg of the channel. The locations of ADCPs and Vector are also shown in (B,C). Symbols V, S, and X in (B) represent Nortek Vector, Signature, and Aquadopp Side, respectively. Moreover, ‘19’ and ‘21’ indicate observations conducted in 2019 and 2021, respectively. C1 and C2 represent profiling survey stations. For a more detailed explanation of these symbols, please refer to text Section 2.2.

2. Materials and Methods

2.1. Study Area

The Aam tidal channel is a 4.5 km long semi-enclosed artificial channel with an area of about 2 km², located in the city of Incheon, Korea (Figure 1). This channel was developed on the tidal flats of Gyeonggi Bay as part of the Songdo International Business District (SIBD) megacity development project. The project includes two phases: land reclamation and channel development, completed in 2013, and the Songdo Waterfront project that connects 16 km-long waterways around the SIBD by 2027.

The Aam tidal channel was an open-ocean tidal flat until 2003 when reclamation was initiated (Figure 1A). As the reclamation started, breakwaters for reclamation were
constructed on the northern and southern sides and reclaimed land was built in between the breakwaters in 2006. Afterwards, a tidal channel began to form between the reclaimed land and the existing seawalls to the north and east of the reclaimed land. Now, a flipped L-shape channel has formed with a width of about 0.3 km and an average spring high tide depth of 5 m (Figure 1B).

At the channel entrance, sandy sediments prevail, and numerous oyster shells are found in the channel at the entrance and where the waterway bends. Landward of the bend, muddy sediments dominate. The main channel is typically 2–3 m deeper than the surrounding tidal flat, with a width ranging from 30 to 100 m. The seaward end of the channel connects to the tidal flats of Gyeonggi Bay, while the landward end is closed by a sluice gate that links to the Aam waterfront lake. Along the tidal channel, about 30 rainwater outlets discharge small amounts of freshwater, and secondary tidal channels develop from these outlets. Additionally, five bridges have been built along the tidal channel.

The tide in Gyeonggi Bay is macrotidal with a mean tide range of 6.5 m. The mean spring tidal range is 8 m, but the maximum tidal range of 10 m occurs during spring tides. The winds are monsoonal, with strong northwesterly winds in winter and gentle southerly winds in summer. Although waves are relatively stronger in winter, their height rarely exceeds 1 m on the tidal flats due to wave-energy dissipation over the extensive sand shoals in the Gyeonggi Bay [16].

Sediments on the tidal flat are primarily derived from the Han River during high freshwater discharges in the summer flood season [16]. The suspended sediment concentration (SSC) ranges from about 100 to 1000 mg/L in a nearby channel of the Han River estuary [17,18]. In Gyeonggi Bay, further seaward of the Han River estuary, the concentration is higher during flood tides than ebb tides due to the turbid fringe along the tidal flats [6]. The maximum concentration exceeds 1 g/L during spring tides and winter seasons, while the minimum occurs during neap tides and the non-discharge period of summer [6,17].

2.2. Field Experiments and Data Collection

Field experiments were conducted in 2019 and 2021 to examine the sediment transport processes responsible for deposition in the artificial Aam tidal channel. The first experiment took place at two locations (S19 and V19) between 19 July and 22 August 2019 (Figure 1B). S19, located at the entrance of the channel, was chosen to measure the incoming and outgoing sediment fluxes. V19, situated about two-thirds along the length of the channel, aimed to examine sediment transport behavior within the channel.

At S19, a 1-MHz Nortek Signature ADCP (acoustic doppler current profiler), referred to hereafter as Signature, was deployed at about 8-m depth in the channel, looking upward on a TRBM (Trawl Resistant Bottom Mount). The Signature collected 4096 velocity datapoints in burst mode with a sampling rate of 8 Hz and a burst interval of 30 min. The bin size was 0.5 m with a blanking distance of 0.1 m. The nominal height of the Signature on the TRBM was 0.47 m. At V19, a 6-MHz Nortek Vector (Vector hereafter) was installed on an H-frame on the slope of the tidal flat. The Vector sampled 4096 velocity datapoints at 8 Hz with a burst interval of 30 min. The nominal height of the measuring volume was about 30 cm above the bed. The coordinates and settings of the instruments are tabulated in Table 1.

The second field experiment, conducted between 11 August and 31 August 2021, included three stations (S21, X21, and V21) at different locations from those in 2019 to observe previously unexamined areas. A 6-MHz Nortek Vector was deployed on an H-frame at V21, located on the tidal flat outside the channel, to measure flow and SSC on the tidal flats. A 1-MHz Nortek Signature was deployed at S21, situated about 1.6 km landward from the channel entrance. The deployment configuration and data collection scheme at V21 and S21 were the same as those in 2019. At X21, located about 3.5 km from the channel entrance, a 1-MHz Nortek Aquadopp Profiler Side (Side hereafter) was deployed on a flat frame. The Side collected 1024 velocity datapoints at a sampling rate of 2 Hz with a burst
interval of 30 min. The bin size of the Side was 0.25 m with a blanking distance of 0.23 m. The nominal height of the Side on the flat frame was 0.48 m.

<table>
<thead>
<tr>
<th>Station</th>
<th>Coordinate</th>
<th>Depth (m)</th>
<th>Instrument</th>
<th>Sensor Height (m)</th>
<th>Sampling Rate (Hz)</th>
<th>Sampling per Burst (#)</th>
<th>Burst Interval (min)</th>
<th>Blanking Distance (m)</th>
<th>Bin Size (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S19</td>
<td>37°25′42.06″ N 126°36′49.68″ E</td>
<td>8.5</td>
<td>Signature 1 MHz</td>
<td>0.37</td>
<td>8</td>
<td>4096</td>
<td>30</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>V19</td>
<td>37°25′12.54″ N 126°38′9.66″ E</td>
<td>2.3</td>
<td>Vector</td>
<td>0.55</td>
<td>8</td>
<td>4096</td>
<td>30</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S21</td>
<td>37°25′46.29″ N 126°37′40.44″ E</td>
<td>3.4</td>
<td>Signature 1 MHz</td>
<td>0.37</td>
<td>8</td>
<td>4096</td>
<td>30</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>X21</td>
<td>37°24′55.40″ N 126°38′13.71″ E</td>
<td>2.0</td>
<td>Aquadopp Profiler 1 MHz</td>
<td>0.20</td>
<td>2</td>
<td>1024</td>
<td>30</td>
<td>0.23</td>
<td>0.25</td>
</tr>
<tr>
<td>V21</td>
<td>37°25′45.24″ N 126°36′28.82″ E</td>
<td>3.3</td>
<td>Vector</td>
<td>0.55</td>
<td>8</td>
<td>4096</td>
<td>30</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

To calibrate the optical backscatter sensor (OBS) and acoustic backscatters, 13-h CTD profiling surveys were conducted at two stations, C1 and C2, on 14 and 16 August 2019, respectively, and at station C2 on 25 August 2021. The stations are located on two bridges shown in Figure 1B, and the casts were performed from the bridges. The 2019 profiling survey took place during the neap tide, while the 2021 survey occurred during the spring tide. Note that the profiling survey at C2 did not cover the full 13 h due to the shallow water during low tide. For the profiling, a Seabird SBE 19plus SeaCAT profiler fitted with a Seapoint OBS was used along with a water pump for water sampling. The Seabird SBE 19plus measured conductivity, temperature, and depth profiles during the downcast at 4 Hz every 30 min, along with turbidity (in NTU). During each upcast, 1-L water samples were taken by pump at the surface, middle, and bottom layers of the water column to calibrate the OBS turbidity to SSC. However, during low tide when the water depth decreases significantly, only one water sample was taken.

To characterize the environmental conditions during the field experiments, various oceanographic and meteorological data were obtained. Tide data were acquired from the Incheon Port tidal gauge station of the Korea Hydrographic and Oceanographic Agency (KHOA). Precipitation data from the rain gauging station in Incheon, located 5 km north of the channel, were obtained from the Korean Meteorological Administration (KMA).

2.3. Data Processing and Analysis

The burst-averaged water depth from the flow sensors (Signature, Side, and Vector) was obtained by averaging \( h(t) \), which is the burst time series of hydrostatic depth computed from the pressure series \( p(t) \) as:

\[
h(t) = \left[ p(t) - \frac{p_a(t)}{\rho g} \right] + z_p \tag{1}
\]

where \( p_a \) is the atmospheric pressure obtained by the Korea Meteorological Administration (KMA), \( \rho \) is the water density, \( g \) is the gravitational acceleration, and \( z_p \) is the elevation of the pressure sensor [16]. Waves were obtained by using the manufacturer’s wave analysis program. Since the waves were insignificant, they are not considered further in this study.

Raw ADCP and Vector data were burst averaged and then rotated to the channel coordinates as the Aam tidal channel has a flipped L-shape. This study uses a right-handed channel coordinate system \((x,y,z)\) with time \( t \), where the origin is located on the bed, the positive \( x\)-axis is directed toward the channel head, and the positive \( z\)-axis is directed upward. The corresponding 3D flow velocity vectors are denoted as \( \mathbf{u} = (u,v,w) \) (m/s).
To calibrate OBS (optical backscatter sensor) and ADCP backscatters, water samples were filtered at the site by vacuum filtration and subsequently dried and weighed in the lab to measure the SSC. For the OBS calibration, all water samples collected at two bridges over two different years were used, resulting in the regression curve, $\text{SSC}_{\text{OBS}} = 1.229 \text{ NTU} + 3.65$, with an $R^2$ value of 0.84 (Figure 2A, Table 2). It is noted that three datasets, shown with different colors in Figure 2A, agree with each other.

![Figure 2. Calibration of OBS turbidity (NTU) against water sample-derived SSC (A). Comparison between acoustically derived suspended sediment concentration (SSC) and reference SSC for each measurement instrument (B–D). The dotted line represents the one-to-one line, while the solid line is the regression line for (B–D).](image)

**Table 2.** Error analysis of acoustically derived suspended sediment concentration (SSC) and comparison of shear velocities of various instruments.

<table>
<thead>
<tr>
<th>Station</th>
<th>OBS</th>
<th>S19</th>
<th>V19</th>
<th>S21</th>
<th>X21</th>
<th>V21</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SSC calibration</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of samples</td>
<td>55</td>
<td>13</td>
<td>12</td>
<td>18</td>
<td>16</td>
<td>-</td>
</tr>
<tr>
<td>Slope of regression eq.</td>
<td>0.87</td>
<td>1.23</td>
<td>1.32</td>
<td>1.38</td>
<td>1.07</td>
<td>-</td>
</tr>
<tr>
<td>Correlation</td>
<td>0.84</td>
<td>0.80</td>
<td>0.74</td>
<td>0.76</td>
<td>0.84</td>
<td>-</td>
</tr>
<tr>
<td><strong>Shear velocity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of samples</td>
<td>-</td>
<td>165</td>
<td>190</td>
<td>161</td>
<td>69</td>
<td>58</td>
</tr>
<tr>
<td>Slope of regression eq.</td>
<td>-</td>
<td>1.10</td>
<td>1.06</td>
<td>0.85</td>
<td>1.14</td>
<td>0.86</td>
</tr>
<tr>
<td>Correlation</td>
<td>-</td>
<td>0.97</td>
<td>0.92</td>
<td>0.88</td>
<td>0.86</td>
<td>0.87</td>
</tr>
</tbody>
</table>

The SSCs, denoted as $c$ (mg/L), were obtained from the calibration of the acoustic backscatter intensity. The water sample-derived SSC ($\text{SSC}_{\text{water sample}}$) obtained during the
CTD profiling surveys was used to calibrate the backscatter signal. The acoustic backscatter calibration was done following [18]. The validation of the acoustically derived SSCs (SSC_{ADCP} and SSC_{ADV}) vs. reference SSC (SSC_{water sample}) is shown in Figure 2 and Table 2. Measured SSCs varied between 0–80 mg/L, and the acoustically derived SSC showed a similar variation (Figure 2). Overall, the data followed the one-to-one relationship, and the correlation values exceeded 0.86 (Table 2).

2.4. Tidal Asymmetry, Eddy Viscosity, and Eddy Diffusivity

To examine the tidal forcing on the sediment flux along the various locations in the Aam artificial tidal channel, the tidal asymmetry is evaluated for tidal elevation, current velocity, and sediment flux. Tidal asymmetry for tide is quantified as the normalized sample skewness, $\gamma_1$, of the tidal elevation time derivative, $\dot{\zeta} = \partial \zeta / \partial t$ [19]:

$$\gamma_1 = \frac{\mu_3}{\sigma^3} = \frac{\frac{1}{\tau} \sum_{t=1}^{\tau} \left( \dot{\zeta} - \bar{\zeta} \right)^3}{\left[ \frac{1}{\tau} \sum_{t=1}^{\tau} \left( \dot{\zeta} - \bar{\zeta} \right)^2 \right]^{3/2}}$$

where $\mu_3$ is the third moment about the mean, $\sigma$ is the standard deviation (the square-root of the second moment about the mean), and $\tau$ represents the number of observations from time $t = 1$ to $t = \tau$. Ebb duration is shorter for $\gamma_1 < 0$ and flood duration is shorter for $\gamma_1 > 0$.

For velocity and sediment flux, skewness is calculated from time series without taking the time derivative [19]. In this case, currents and sediment fluxes are ebb-dominant for $\gamma_1 < 0$ and flood-dominant for $\gamma_1 > 0$.

In a tidal channel or an estuary, if the tidal elevation and velocity are in quadrature, the duration asymmetry leads to tidal current asymmetry [8,19]. However, this may not hold under the influence of river flow, stratification, or bathymetric effects. Other studies have shown that the tidal pumping could be driven by tidal mixing asymmetry [20,21]. Furthermore, the strength of eddy diffusion, which is responsible for suspended sediment concentration, is caused by turbulent mixing [22,23], which can be quantified by the eddy viscosity and eddy diffusivity. To further examine the tidal mixing asymmetries, we estimated the eddy viscosity and eddy diffusivity.

Assuming that, over sufficiently long times, the diffusional upward flux, characterized by a time-averaged eddy diffusivity $K_s$, is balanced by the downward flux with average speed of the settling particles, the theoretical value of eddy diffusivity can be obtained from one-dimensional vertical diffusion equation of suspended sediment:

$$w_s C + \frac{K_s}{\partial z} \frac{\partial C}{\partial z} = 0$$

where $w_s$ is the settling velocity and $C$ is the suspended sediment concentration at elevation $z$ above the bed. With a known settling velocity, the eddy diffusivity can be estimated from the profile of suspended sediment concentration [22]. In addition, the eddy viscosity profile, $K$, can be estimated from the law of the wall:

$$K \frac{\partial u_c}{\partial z} = \frac{\tau}{\rho}$$

where $u_c$ is the current velocity over turbulent timescales, $\tau$ is the bed shear stress, and $\rho$ is the seawater density. To obtain the eddy viscosity and eddy diffusivity, the settling velocity and the shear stress are known a priori, and the following section describes the methods to obtain these values from the observed data.
2.5. Estimation of Shear Stress and Settling Velocity

Bed shear stress is an important parameter which controls sediment resuspension and flux, and is closely related to turbulence in the water column. Shear stress can be obtained from the quadratic drag law:

$$\tau = \rho C_D u_c^2$$

(5)

where $C_D$ is the drag coefficient, typically $C_D = 0.0025$ [24]. The current velocity, $u_c$, is taken from the first bin in the Signature and Side. To verify the shear stress in Equation (5), the LP method is used to estimate the shear velocity, $u_s$, from the logarithmic velocity profile:

$$u_c = \frac{u_s}{\kappa} \ln \left( \frac{z}{z_o} \right)$$

(6)

where $z_0$ is the hydraulic roughness and $\kappa$ is the von Karman’s constant (~0.4) [22]. With an estimation of $u_s$, the shear stress is then estimated as $\tau = \rho u_s^2$. The LP method is based on Equation (4) and applied to the velocity profile data measured by the Signature and Side. For the Vector, the COV and TKE methods were used. The COV method provides the direct measurement of $\tau$ from $\tau = \rho \left( -u'w' \right)$, while the TKE method uses the intensity of velocity fluctuations to infer the shear stress through turbulent kinetic energy (TKE), $\tau = C_1 E$, where $C_1$ is constant (~0.19) and $E$ is the TKE, $E = \left( \overline{u'^2 + v'^2 + w'^2} \right) / 2$. Here, $u'$, $v'$ and $w'$ are fluctuating components of the velocity in x-, y-, and z-direction [22].

From Equation (3), the settling velocity can be solved for simply by dividing both sides by $C$. However, since we seek to determine eddy diffusivity, Equation (3) cannot be used directly. Instead, separating concentration into mean and fluctuating components provides an alternative expression of turbulent diffusion [23,25]:

$$w_C \overline{C} = -\overline{w'\overline{C}}.$$  

(7)

The fluctuating components of both vertical velocity and concentration are directly measured from the Vector, allowing the estimation of settling velocity from Equation (7).

2.6. Sediment Flux Decomposition

Time series of current velocity and derived SSC$_{ADCP}$ were used to compute instantaneous sediment flux at the Signature, Side, and Vector stations as:

$$F = U(z) \cdot SSC(z)$$

(8)

where $U$ and SSC are the instantaneous values of rotated along-channel velocity and sediment concentration, respectively. The instantaneous velocity is the sum of the tidally varying velocity ($U'$) and the tidally averaged velocity ($\overline{U}$). In a similar manner, the instantaneous SSC is found as the sum of the tidally varying SSC and the tidally averaged SSC. The total residual sediment flux per unit width of flow ($F_T$) is computed by integrating the instantaneous sediment flux with depth. To distinguish the mechanisms driving residual sediment flux between tidal and nontidal factors, the advective ($F_A$) and tidal pumping ($F_P$) components were decomposed from $F_T$, such that:

$$F_A = U(z) \cdot SSC(z)$$

(9)

and

$$F_P = U'(z) \cdot SSC'(z)$$

(10)

where the overbar indicates a tidally average, while the prime represents a deviation from the tidally average. To average $U$ and SSC over the tidal cycle, time series data were filtered utilizing a 36-h Lanczos low-pass filter [6,7].
3. Results

3.1. Estimation of Shear Velocity and Settling Velocity

Figure 3 shows the one-to-one relationship between shear velocities estimated by the quadratic drag law and those by the LP method for the Signature and Side. Also shown are the comparisons between shear velocities estimated by the quadratic drag law and those by the TKE and COV methods for the Vector. Overall, the data follow the one-to-one relationship and the correlation between them are reasonably good, all exceeding 0.86 (Table 2). Nonetheless, the shear velocities during the high-water and low-water slacks were disregarded as the regression coefficients were low for the LP method. Therefore, this study utilizes shear velocities estimated by the quadratic drag law.

![Figure 3. Comparison of the bed shear velocity.](image)

As indicated in Equation (7), the settling velocity was estimated using the Vector, which measured turbulent fluctuations in both vertical velocity and concentration, \( \omega' \) and \( C' \). Figure 4A, B show plots of \( \omega'C' \) vs. \( C \) for 2019 and 2021, respectively. The settling velocity, \( w_s \), was determined from the slope of the best-fit regression. The resulting slopes produced estimates of \( w_s = 0.23 \pm 0.03 \) mm/s for V19 and \( w_s = 0.57 \pm 0.03 \) mm/s for V21, respectively. The settling velocity of V21 is slightly larger than that of V19, which is reasonable as one can expect the slope to increase with relatively larger particles on the tidal flat outside the tidal channel. Moreover, the varying settling velocity from 0.23 to 0.57 mm/s did not significantly change the estimation of eddy viscosity and eddy diffusivity. Thus, we use a settling velocity of 0.23 mm/s in this study.

3.2. Flow, Shear Velocity, SSC, and Sediment Flux

In 2019, one ADCP (S19) and one Vector (V19) were deployed in the Aam tidal channel. Figure 5 shows the time-series of water depth, current velocity, shear velocity, suspended sediment concentration, and sediment flux at stations S19 and V19. Here, S19 was located at the channel entrance, while V19 was stationed on the slope from the channel to the flat, about 3 km landward from the channel entrance (Figure 1B). Although the instruments were deployed for over a month in 2019, only one spring-neap tidal cycle of data was usable due to significant battery power drop after two weeks. During the observation period, four rainfall events occurred; two of them during the neap tide and the other two during the early phase of the spring tide. The mean tide at the entrance of the channel (S19) was about 6 m with a maximum tide of approximately 9 m during the spring tide (Figure 5A). The current velocity was weaker at about ±25 cm/s during the neap tide, and increased during
the spring tide (Figure 5B). The currents were ebb-dominated (more detailed analysis in the following section) with the maximum current velocity reaching about 90 cm/s during the ebb of the spring tide. Following the trend of current velocity over the spring-neap tidal cycle, the shear velocity was generally low (1–2 cm/s) during the neap tide and increased to 5–6 cm/s during the spring tide (Figure 5C). The shear velocity was greater during the ebb than during the flood (Figures 5C and 6C). The suspended sediment concentration was also low (about 5–10 mg/L) during the neap tide and increased to about 50 mg/L during the spring tide (Figure 5D). Notably, the SSC was generally higher during the second spring tide (31 July–5 August) compared to the SSC during the first spring tide (21–24 July), for which difference is discussed later in relation to the rainfall events. Moreover, the SSC was higher during the low tide slack rather than at the peak of the flood or ebb (Figure 6D). The cumulative sediment flux was directed seaward, with a significant change occurring during the spring tide (Figure 5F).

Figure 4. Settling velocity calculations using Reynolds concentration flux versus predicted concentration of the Vector 2019 (A) and 2021 (B).

The maximum water level was about 5 m during the spring tide, and the sensor was exposed during the low tide at the far end of the channel (V19). The current velocities and shear velocities were lower compared to those at S19 (Figure 5B,C). However, the shear velocity appeared to be larger during the ebb rather than the flood. The SSC was generally higher than that at S19, ranging from about 20 mg/L during the neap tide to about 80 mg/L during the spring tide (Figure 5D). Over a tidal cycle, the SSC was larger during the flood (Figure 5D). The cumulative sediment flux was directed seaward during the waning phase, but turned to landward during the growth phase of the spring tide (Figure 5F), which is discussed later along with the flood-dominated nature of shear stress and SSC at V19.

In 2021, two ADCPs (Signature, S21, and Side, X21) and one Vector (V21) were deployed in the Aam tidal channel. Figure 7 shows the time-series of tide, current velocity, shear velocity, suspended sediment concentration, and sediment flux for S21, X21, and V21. Here, V21 was located on the tidal flat just outside of the artificial tidal channel. The Signature (S21) was moved to about 1.7 km from the channel entrance and the Aquadopp Side was located at 3.6 km from the channel entrance. The maximum tide during the spring tide was about 8 m at S21 and decreased to about 6 m at X21. The tidal range at V21 was
between S21 and X21 (Figure 7A). The peak current velocity during the flood and ebb ranged from 20 to 70 cm/s, but the current velocity at V21 was lower because the velocity was measure at 35 cm above the bottom, while the velocity measurements at S21 and X21 were performed at about 70 cm above the bed (Figure 7B). However, the shear velocity was in a similar range (Figure 7C). Nonetheless, the asymmetry existed in that the flood was dominant for X21, while the ebb shear velocity was stronger for S21. Likewise, the SSC was higher during the flood at X21, while it was higher during the ebb at S21. On the other hand, the shear velocity does not show any clear asymmetry for V21. However, the SSC is significantly larger right after the low tide slack (Figure 7D), for which the mechanism is discussed later. The sediment flux was directed landward for X21 and V21, while it was seaward at S21. The sediment flux was small in magnitude and symmetric during the neap tide for all stations. However, the sediment flux magnitude was larger and asymmetric during the spring tide (Figure 7E,F).

Figure 5. Time series data from S19 and V19 in 2019: (A) water depth and precipitation; (B) current velocity; (C) shear velocity; (D) suspended sediment concentration; (E) sediment flux; and (F) cumulative sediment flux. The shaded areas indicate the selected periods shown on Figure 6. The positive current and sediment flux indicate landward direction, while the negative values represent seaward direction.

3.3. Tidal Asymmetry for Tide, Current Velocity, and Sediment Flux

Tidal asymmetry for tide, current velocity, and sediment flux was calculated by using Equation (2) for Stations S19, S21, and X21, and the results are shown on Figure 8 with respect to the distance from the channel entrance. Here, positive values indicate flood dominance, while negative values represent ebb dominance. The tidal elevation time derivative (‘f’) was positively skewed at all stations, indicating that the tidal water surface rises faster during flood than ebb. Regarding tidal current, the far interior stations, S21 and X21, were positively skewed, while the station near the entrance, S19, was negatively skewed. On the other hand, the sediment flux was positively skewed for the far interior station, X21, but negatively skewed for the stations near the entrance, S19 and S21. If the current velocity were driven purely by the tide, all stations would show positive skewness, indicating flood dominance, because the elevation and current velocity are nearly 90 degrees out of phase. The switching of the skewness for current velocity and sediment flux is due to the increased velocity and concentration during the ebb, which is discussed later.
The maximum water level was about 5 m during the spring tide, and the sensor was exposed during the low tide at the far end of the channel (V19). The current velocities and shear velocities were lower compared to those at S19 (Figure 5B,C). However, the shear velocity appeared to be larger during the ebb rather than the flood. The SSC was generally higher than that at S19, ranging from about 20 mg/L during the neap tide to about 80 mg/L during the spring tide (Figure 5D). Over a tidal cycle, the SSC was larger during the flood (Figure 5D). The cumulative sediment flux was directed seaward during the waning phase, but turned to landward during the growth phase of the spring tide (Figure 5F), which is discussed later along with the flood-dominated nature of shear stress and SSC at V19.

Figure 6. Water depth, current velocity, shear velocity, suspended sediment concentration, and sediment flux during selected time windows of a rain event. These periods are highlighted in Figures 5 and 7.

In 2021, two ADCPs (Signature, S21, and Side, X21) and one Vector (V21) were deployed in the Aam tidal channel. Figure 7 shows the time-series of tide, current velocity, shear velocity, suspended sediment concentration, and sediment flux for S21, X21, and V21. Here, V21 was located on the tidal flat just outside of the artificial tidal channel. The Signature (S21) was moved to about 1.7 km from the channel entrance and the Aquadopp Side was located at 3.6 km from the channel entrance. The maximum tide during the spring tide was about 8 m at S21 and decreased to about 6 m at X21. The tidal range at V21 was between S21 and X21 (Figure 7A). The peak current velocity during the flood and ebb ranged from 20 to 70 cm/s, but the current velocity at V21 was lower because the velocity was measured at 35 cm above the bottom, while the velocity measurements at S21 and X21 were performed at about 70 cm above the bed (Figure 7B). However, the shear velocity was in a similar range (Figure 7C). Nonetheless, the asymmetry existed in that the flood was dominant for X21, while the ebb shear velocity was stronger for S21. Likewise, the SSC was higher during the flood at X21, while it was higher during the ebb at S21. On the other hand, the shear velocity does not show any clear asymmetry for V21. However, the SSC is significantly larger right after the low tide slack (Figure 7D), for which the mechanism is discussed later. The sediment flux was directed landward for X21 and V21, while it was seaward at S21. The sediment flux was small in magnitude and symmetric during the neap tide for all stations. However, the sediment flux magnitude was larger and asymmetric during the spring tide (Figure 7E,F).

3.4. Vertical Profiles of Current Velocity, Sediment Flux, Eddy Viscosity, and Eddy Diffusivity

The vertical profiles of velocity and sediment flux at three stations, S19, S21, and X21 (Figure 9), align with the trend of tidal asymmetry (Figure 8) and provide additional insight into the mechanisms of sediment transport along the tidal channel. The velocity
at X21 shows a typical circulation pattern with landward current in the bottom layer and seaward current in the surface layer (Figure 9C). The seaward velocity increases at S21 with the bottom current further reduced (Figure 9B). At the channel entrance at S19, the mean residual current has a maximum of about 20 cm/s in the mid depth, directed seaward. However, the sediment flux at X21 is directed landward throughout the depth, with high sediment flux in the bottom layer, while the velocity is directed seaward in the surface layer (Figure 9I). This differing behavior is mainly due to the asymmetry of SSC, which is twice as large during flood than ebb. In addition, the typical Rouse-type concentration profile results in a larger sediment flux profile in the bottom layer. Unlike X21, the concentration is larger during ebb than flood at S19 and S21 (Figure 9D,E). Therefore, the sediment flux is directed seaward at both stations (Figure 9G,H).

Figure 8. Tidal asymmetry for tide, current velocity, and sediment flux for Stations S19, S21, and X21.

Figure 9. Depth profiles of velocity, SSC, and sediment flux for Stations S19, S21, and X21. Velocity and sediment flux were decomposed into mean and correlation components, while the SSC was averaged for flood and ebb.
Moreover, the sediment flux decomposition showed that the sediment flux was mainly driven seaward by the mean component at S19, while it was driven by the tidal pumping component at S21 and X21. However, the sediment flux direction was landward at X21, but seaward at S21. Both sediment pumping observed near the bed are driven by tidal asymmetries in sediment concentration.

Figure 10 shows the profiles of eddy viscosity, segregated by the phase of the tide for S19, S21, and X21. There is a clear tidal asymmetry in eddy viscosity for all stations. At S19, significantly larger values are reported for the ebb tide (Figure 10B). At S21 and X21, the eddy viscosities were much smaller compared to S19. Surely, the eddy viscosity was larger during the ebb at S21, while it was greater during the flood at X21. The eddy diffusivity also followed a similar trend to eddy viscosity; it was larger during the ebb for S19 and S21, while it was larger during the flood for X21.

![Figure 10](image_url)

**Figure 10.** Profiles of eddy viscosity and eddy diffusivity during flood and ebb for S19 (A,B), S21 (C,D), and X21 (C,D).
4. Discussion

4.1. Asymmetry of Sediment Transport along the Artificial Tidal Channel

A tidal flat has been turned into an artificial tidal channel in the city of Incheon under the megacity development project of the Songdo International Business District (Figure 1). This transformation altered the sloping flat morphology (Figure 1A) into a tidal channel, resulting in sediment infilling at the channel’s far interior end and deepening at the entrance (Figure 1B). This morphological change can be explained by the asymmetry of sediment transport in relation to the tidal channel morphology along the artificial tidal channel.

Just outside of the channel entrance, the tide is flood-dominated, and so is the sediment flux, indicating sediment transport into the tidal channel (Figure 7F). The sediment flux asymmetry mainly results from the imbalance of suspended sediment concentration (Figure 7D). Figure 11A shows the SSC over water depth during flood and ebb at V21, while Figure 11B shows the SSC for V19. The highest concentration occurs during the first and last hours of immersion at V21, while peak SSC occurs during the peak of the flood and ebb at V19. This occurrence of high concentration during the first and last hours of immersion at V21 is called the turbid fringe, which occurs at the edge of rising or falling tide, sweeping up and down the intertidal flat [26]. Outside the channel entrance on the tidal flat, the turbid fringe is larger during the flood compared to the ebb (see Figure 12A). Consequently, the sediment flux is directed landward throughout the study period (Figure 7F).

![Figure 11](image-url)  
**Figure 11.** SSC vs. depth during flood and ebb for V21 (A) and V19 (B). The SSCs were color-coded for the spring and neap tide. Also shown are the bin average for each one-meter water depth (black circle) and an error bar of one standard deviation for each bin average.
In the tidal channel, the tide was flood-dominated at all stations due to the tidal deformation in the shallow channel (Figure 8). On the other hand, the depth-averaged current velocity was ebb-dominated at V21 and S19 but became flood-dominated in the interior tidal channel at S21, V19, and X21 (Figure 8). The vertical profile of the current velocity showed that currents were directed seaward throughout the water column at the low water (Figure 12A,B). Conversely, higher velocities are found around high water at the entrance of the channel entrance because of the draining of water through the inlet (Figures 8 and 9). Similarly, velocity is dominant during flood at the interior stations (Figures 8 and 9). As a result, a strong asymmetry in internal mixing is revealed, with higher eddy viscosity occurring during flood at the far interior station X21 and during ebb at the entrance of the channel (S19 and S21) (Figure 10). Consequently, the bed shear stress is stronger during ebb at stations S19, S21, and V19, but during flood at station X21.

While the flow and shear stress align with the channel morphology, the SSC is not in equilibrium with the local bed shear stress, indicating other processes beyond local resuspension are at work. As explained above, the SSC at the tidal flat outside of the channel entrance and shallow, wider tidal flat at the interior (Figure 1).
channel (V21) is driven by the turbid fringe, exhibiting peaks during low tide with higher SSC during flood (Figure 11). At the subtidal channel entrance (S19), the peak occurs during the low tide (Figures 5 and 6), indicating the peak SSC is induced by the turbid fringe in and outside of the tidal channel. At the far interior stations (V19 and X21), the SSC is higher during flood than ebb because of the scour and settling effect [28,29]. This is clearly evident at V19 where the SSC is higher during flood, while the shear stress is stronger during ebb (Figure 5). At S21, the SSC is higher during ebb in line with the flow. Consequently, the cumulative sediment flux is landward at the far interior station (X21), where the asymmetry in the velocity and SSC are directed to landward, resulting in the rapid sediment filling. On the other hand, the sediment flux was seaward around the channel entrance (S19 and S21), with the stronger ebb current due to water draining maintaining the deeper channel. Thus, the along-channel variation of the tidal asymmetry in velocity and SSC is responsible for the rapid filling in the interior region and the deepening of the man-made Aam tidal channel.

4.2. Rainfall Effect on Sediment Concentration

While the concentration was higher during flood than during ebb at V19, it was also observed that the SSC increased immediately following a rainfall. To illustrate the impact of rainfall, SSCs were plotted against the bed shear velocity for V19 (Figure 13). Here, the SSCs recorded during and just after a rainfall event are colored in red. It is evident that rainfall elevated SSCs at a given shear velocity. The observed doubling of SSC in this study aligns with the findings from other studies [30,31].

![Figure 13. SSC vs. shear velocity for V19. SSCs during and immediately after a rainfall event are shown in red, indicating higher values at a given shear velocity.](image_url)

Figure 13. SSC vs. shear velocity for V19. SSCs during and immediately after a rainfall event are shown in red, indicating higher values at a given shear velocity.
The elevated concentrations due to rainfall contribute to increased landward sediment flux. Our data indicate that rainfall affected erodibility during low tide slack when the tidal flat is exposed. Consequently, SSCs rose more during the flood phase than during the ebb (Figure 6D). The relatively larger SSC during the flood contributed to the landward sediment flux. Therefore, the cumulative sediment flux in parallel with rainfall events (Figures 5F and 7F). This contrasts with previous studies that found rainfall-induced runoff led to the seaward export of mud sediment in tidal channels [26,32]. However, at least in the artificial Aam tidal channel, rainfall contributed to the landward sediment flux.

5. Conclusions

This study provides a comprehensive analysis of sediment transport in the artificially constructed Aam tidal channel in Incheon, Korea. Our findings underscore the significant impact of tidal asymmetry on sediment dynamics within the channel. Specifically, we observed that sediment deposition is heavily influenced by tidal mixing patterns, with ebb-dominant currents near the entrance facilitating sediment export, while flood-dominant currents in the interior promote sediment accumulation. Additionally, rainfall events were found to elevate suspended sediment concentrations, further enhancing landward sediment flux and contributing to sedimentation within the channel. These insights into the sediment transport mechanisms in artificial tidal channels are crucial for informing the design and management of similar coastal developments worldwide. Effective management strategies must consider the complex interplay between tidal dynamics, sediment transport, and external factors such as rainfall to mitigate adverse impacts on coastal and estuarine environments. Future research could investigate the long-term effects of tidal asymmetry and sediment transport dynamics in artificial tidal channels under varying environmental conditions. Additionally, research could explore the impact of varying flow velocities and shear stress on sediment transport processes, aiming to optimize the design of artificial tidal channels to better manage sediment flux and channel stability.

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