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An Investigation of the Change in Tidal Signal in an Estuary as a Result of Sea Level Rise and Development at Short-Medium Time Scale

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ABSTRACT

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This paper highlights the impact of man-made and natural changes on the evolution of tidal signal at short-medium timescale in a subtropical estuary. The study area is the Coomera River Estuarine system located on the eastern coast of Australia. Coomera River Estuary has been impacted by a range of developments at its lower reaches over the past 20 years. Sea level rise is expected to be another source of change for the estuary. Earlier studies suggest that Sea level can rise 81 cm over the next 70 years. Similar to man-made changes, sea level rise has potential impact on tidal signal and all the tidally influenced parameters. This study is focused on investigating the tidal regime change and potential bank stability implications resulting from the above mentioned natural and man made impacts. The results of harmonic analysis show that Coomera Estuary responses non-linearly to tidal forcing and is dominated by frictional forces. The non-linear response of the estuary has reduced over the past 20 years and is expected to remain relatively unchanged under sea level rise condition. Tidal analysis of the study area under sea level rise condition indicates that the Estuary will become more flood-dominant over the next 70 years and as a result the balance between flood tide influenced sediment infilling and ebb tide induced sediment flushing out of the estuary may shift towards having more sand deposited in the estuary.

ADITIONAL INDEX WORDS: *Tide, Coastal development, Sea level Rise*

INTRODUCTION

Coomera River Estuary is positioned in a major coastal growth area and, as a result, it has been under substantial development stress in recent years, including construction of canal estates with potential impacts on the tidal prism of the estuary. In addition to the impacts resulting from man-made changes in the estuary, sea level rise is expected to have some impacts on the tidal signal and consequently on the morphological and ecological processes of the study area. An earlier study (WALSH et al., 1998) shows that the sea level in the study area will rise up to 58 cm and 81 cm by years 2050 and 2070, respectively. This study is undertaken in four stages. The first stage of the study deals with collection and sourcing hydrographic and sendimentological data for the study area. In the second stage of the study a calibrated and validated hydrodynamic model of the study area (MIRFENDERESK et al., 2008) is used to provide an in-depth understanding of the tidal dynamics and in particular non-linear mechanisms within the Coomera Estuary. Third stage of the study is dedicated to the examination of available historic tidal data, aiming at resolving the evolution of tidal regime of the Coomera Estuary over the past 20 years. At this stage of the study the examination of the tidal signal evolution is extended to future (under a sea level rise scenario for year 2070). Fourth stage of the study investigates the impact of sea level rise on the sediment transport regime changes of the estuary.

Study Area

Figure 1 shows the extent of the study area. Coomera River Estuary is located in the southeast corner of Queensland, Australia. $(153.4098^0 E, 28.0175^0 S)$. It drains runoff from the Coomera River catchment into the Pacific Ocean via a coastal water body named the Broadwater. The depth of the estuary varies between –6 meters (at lower reaches of the estuary) and close to 0.5 meters at its tidal limit. Tidal and fresh waters of the Coomera River are separated by Oxenford Weir approximately 28 km upstream from the Gold Coast Seaway. Base flow of the Coomera River is negligible for the most part of the year and the main portion of the catchment rainfall occurs during the summer period in a few heavy storm events. Therefore tidal movement is the main driving force for the horizontal water flow, for most part of a year.

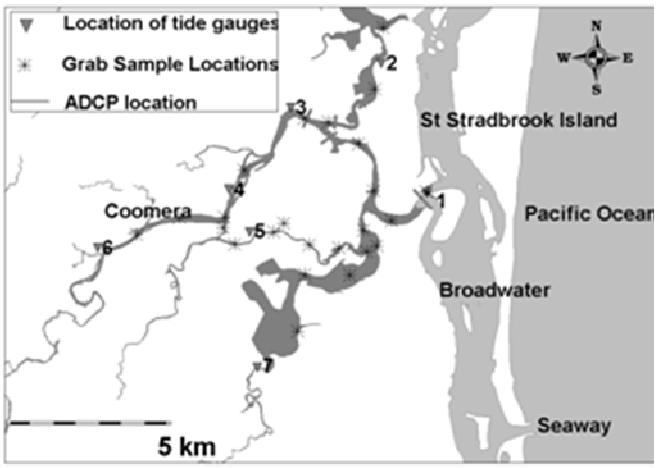

Figure 1. Layout of the study area and approximate locations of measurement stations.

DATA COLLECTION

Required data for this study was sourced as follows:

- Sediment logical data was collected using a grab-sampler at 24 locations as shown in figure 1. The collected samples were sieved to determine grain size distributions of the bed sediment within the study area.
- Hydrographic data was sourced from an earlier study (MIRFENDERESK et al., 2008). This includes water level measurements at seven stations and current measurements at 4 locations as shown in figure 1.
- Historical tide data was sourced from the Queensland Maritime Safety Department.

TIDAL DYNAMIC OF THE COOMERA ESTUARY

Numerical Modeling

A MIKE11 one-dimensional hydrodynamic model was set up for the simulation of tidalal flow within the Estuary. Mike11 (hydrodynamic module) solves the vertically integrated equations of conservation of mass and momentum (Saint Venant) equations. The equations are solved by implicit, finite difference techniques. Solution of these equations are based on the assumption that the wave lengths are large compared to the water-depth, implying that flow is always parallel to the bottom, vertical accelerations are negligible and pressure variation along the vertical is hydrostatic. The model can be applied to branched and looped networks and quasi two-dimensional flow simulations on floodplains. Given the configuration of the Coomera estuary, which is in the form of a system of narrow natural and man made channels, this modelling tool is regarded appropriate for this exercise.

The model was run for a few days to establish the tidal momentum within the estuary prior to the calibration. Model was run using the recorded water level variations at the mouth of the Estuary. Calibration was achieved by adjusting the Manning 'n' for different sections of the model. To this end the model was run for a number of different values of Mannings 'n'. The best correlation of the model and the recorded data was obtained using a combination of Manning coefficients generally between 0.02 and 0.03 for various reaches of the estuary. A variable value of Manning's 'n' was adopted for each cross-section, depending on the variation of roughness at various parts of the cross section. Tidal water level, measured simultaneously for a period of minimum 35 days during January and February 2005 at six stations within the study area, is used for calibration of the model.

Tidal water level, measured for a period of minimum 35 days at station 4 during January 2005, and also flow current measurements at four stations, as shown in figure 1, during January 2005 are used for validation of the model. Comparisons between the results from the calibrated model and the measured water level show that the model simulates water level and current variations satisfactorily (MIRFENDERESK et al., 2008).

Tidal study of the estuary

Tidal characteristics at the Coomera River Estuary have been identified as mixed predominantly semi diurnal using the form number as defined by (Pugh, 1987):

$$N = \frac{O_1 + K_1}{M_2 + S_2} \quad (1)$$

The form number for the Coomera River Estuary varies between 0.5 and 0.6 at the seven measurement stations. A form number between 0.25 and 1.5 is regarded as mixed semidiurnal regime.

Figure 2 shows variations of water level and discharge at a representative station (Brygon Creek) for an arbitrary 48 hours tidal cycle during spring tide. Similar graphs were prepared for a number of locations along the estuary and the following general observations were noted. 1) During ebb tide and after the flow reversal, discharge reaches its maximum quickly. It remains relatively constant for a few hours and then drops sharply again. During flood tide and after the flow reversal, discharge increases more slowly and it takes a few hours to reach its peak. Unlike the ebb tide situation, the discharge curve shows a distinct peak during the flood tide. 2) In all the stations duration of ebb discharge is longer than the duration of flood discharge. 3) In all stations the maximum flood discharge is higher than the maximum ebb discharge. 4) Flow reversal at low slack water seems slightly faster than that at high slack water.

Non-linear Response of the Estuary

In shallow estuarine waters tidal range is comparable with average depth, resulting in nonlinear mechanisms distorting the tidal wave profile. One of the important nonlinear mechanisms is the generation of M_2 over-tides such as M_4 as a result of bottom friction and continuity constraints (FRIEDRICHS, and AUBREY, 1998); (PARKER, 1991); (WALTERS, and WERNER, 1991), (SPEER; AUBREY and FRIEDRICHS, 1991). To highlight the relative importance of frictional dissipation and spectral energy transfer from M_2 to M_4, the variations of amplitude of the M_4 and M_4/M_2 components of the tide are depicted in Figure 3. The M_4 constituent is generated due to the nonlinear interaction of the M_2 constituent with itself. The physical manifestation of M_4 is the asymmetric distortion of the tide curve, which results in differences between ebb and flood current velocities. Figure 3 shows that the M_4 amplitude increases sharply over the first 5 kilometers from the Gold Coast Seaway to station 1 at the southern arm of the Coomera Estuary (from 0.1 cm to 2 cm); then it increases slowly from 2 cm to 3 cm over the next 15 km. The figure shows a sharp increase in the M_4 constituent over the last 5 km of the estuary (from 3 cm to 6 cm). To highlight the strength of the non-linear response of the estuary to tidal forcing the ratio of the amplitude of M_4 to M_2 has been presented on the same figure. It can be seen that the ratio of M_4/M_2 along the estuary

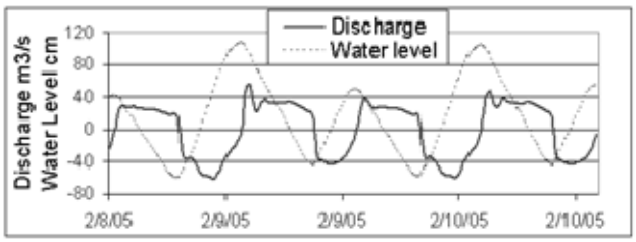

Figure 2. An example of a figure considered to one column. (The caption of a figure should be in Times New Roman 9 font)

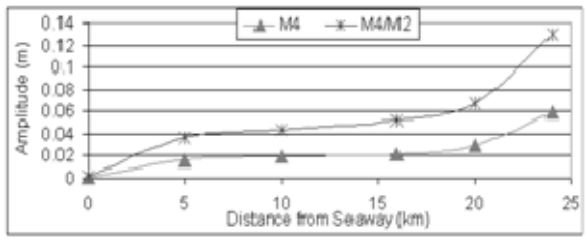

Figure 3. Amplitude variations of M_4/M_2 and M_4 at the Coomera River Estuary

varies almost with the same trend as that of M_4 with a slightly higher rate of change. The growth of the ratio of M_2 to M_4 reflects the combined frictional decay of the M_2 component and also spectral energy transfer from M_2 to M_4. This is evidence for a non-linear response of the estuary to tidal forcing over its entire length.

One of the outcomes of non-linear distortion of tidal current is flood or ebb dominance of the estuary (FRIEDRICHS, and AUBREY, 1998); (PARKER, 1991), (AUBREY and SPEER, 1985). Examination of the tidal elevation time history at the Coomera River estuary shows that in general the duration of the rising tide for each tidal cycle is shorter than the duration of the falling tide, indicating that the Coomera River is a flood dominant estuary.

EVOLUTION OF TIDAL REGIME WITHIN THE COOMER ESTUARY

Figures 4, 5, 6 and 7 show the variations of semidiurnal (M_2 and S_2) and diurnal (O_1 and K_1) tide constituents of the Coomera Estuary over the past 20 years for four representative locations. One of the major developments in the region over the past 20 years has been the construction of the Gold Coast Seaway in 1985. The seaway, which is a navigation channel, 250 meters wide with an average depth of 10 meters, replaced an unstable and shallow tidal inlet that connected the Broadwater to the Pacific Ocean. Figure 4 shows more than 20% increase in the amplitude of M_2 constituents between 1985 (after construction of the Seaway) and 2005 at the mouth of the southern arm of the Coomera River (station 1). Variations associated with S_2, O_1 and K_1 constituents for this station seem to be minimal. Figure 5 shows more than 30% increase in the amplitude of the M_2 constituent at the mouth of the northern arm of the Coomera River estuary (station 2) between 1985 and 2005. Figure 7 shows the same trend. Figure 6 shows that at station 6 the amplitude of M_2 constituent remains relatively unchanged. The same trend can be observed in station 7. In general, substantial reduction in rate of change of the tidal constituents between 1998 and 2005 suggest that the estuary adjusted itself to the construction of the Gold Coast Seaway before year 2000 to a substantial degree.

Figures 4, 5 and 7 show a drop of M_4/M_2 between 1985 (construction of the Seaway) and 1998. The reduction in M_4/M_2 ration varies between 10% and 70%. This indicates a substantial reduction in non-linear response of the estuary due to more effective connection of the estuary to the open ocean. These results show that tidal asymmetry and non-linear response of the Coomera River Estuary has changed over the past 20 years. They also indicate an increase of tidal range all over the estuary and almost across the spectrum of the tide wave. These changes can potentially have impact on the morphology and ecology of the estuary.

Figures 4 to 7 show that tidal range reduces across the spectrum due to an increase in sea level. In this case 81 cm sea level rise associated with projected sea level rise in year 2070 has been examined. The figures show a dramatic reduction in M_2 amplitude compared with other tidal constituents. The ratio of M_4/M_2 remains relatively similar to that in year 2005 for stations 1 and 2 that are in lower reaches of the estuary but changes substantially at stations 6 and 7 that are at the upper reaches of the estuary.

CHANNEL STABILITY IMPLICATIONS RESULTING FROM SEA LEVEL RISE

Coomera River and Saltwater Creek have experienced substantial bank instability in the past. Channel instability can be caused by a number of factors such as: Development activities, natural tendency of a river to meander by scouring one bank and allowing a build up of sediment on the other side, or wind and boat generated waves. There is a concern that as a result of an increase in tidal prism (as a consequence of sea level rise), the bank instability in this area will worsen.

Calculation of total volume of water moving past the throat of the Coomera Estuary during the flood tide (referred to as tidal prism) shows that the tidal prism for a typical spring tide is approximately 14,000,000 m3. The estimated tidal prism for 27 cm, 58 cm and 81 cm sea level scenarios are expected at 17,000,000, 21,000,000 and 24,000,000 m3 respectively.

This section of the study uses hydrodynamic modeling to extend our understanding of the present condition of the Coomera River and the adjustment to the estuary that might occur as a result of various sea level rise scenarios. Figure 8 shows the variations of bed shear stress over two full tidal cycles at the Southern arm of the Coomera River (stations 1) under current regime, 27, 58 and 81 cm sea level rise scenarios. It can be seen that every tidal cycle includes four peaks in bed shear stress. The first peak is associated with maximum current during a low amplitude flood tide. The second peak is associated with maximum current during the following low amplitude ebb tide. The higher shear stresses are associated with maximum current during the following high amplitude flood and ebb tides.

Model results for current and future situations at a number of cross sections have been related to the sediment characteristics at the same sections in order to determine if the cross-section is likely to erode, stay the same or be subject to silt deposition under future sea level rise scenarios.

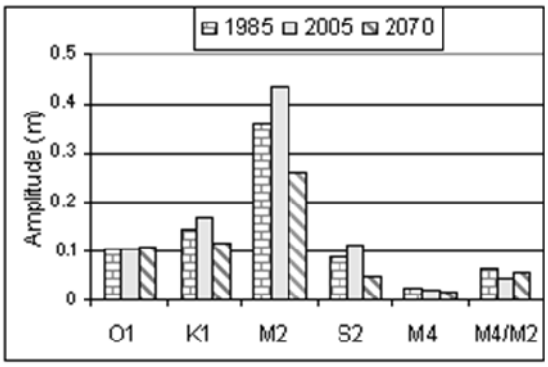

Figure 4. Amplitude variations of tidal constituents at Coomera mouth (station 1)

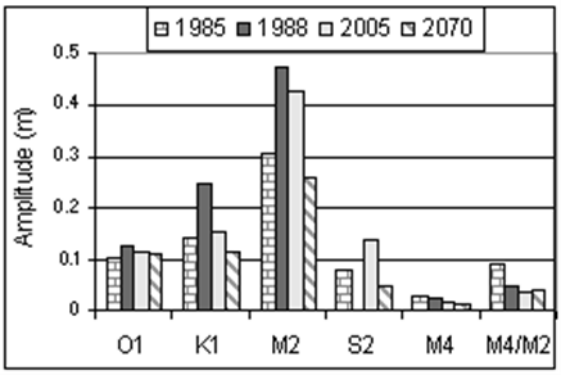

Figure 5. Amplitude variations of tidal constituents at North Arm (station 2)

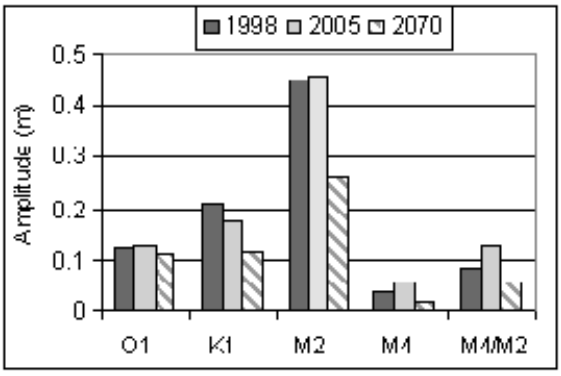

Figure 6. Amplitude variations of tidal constituents at Brygon Crreek (station 6)

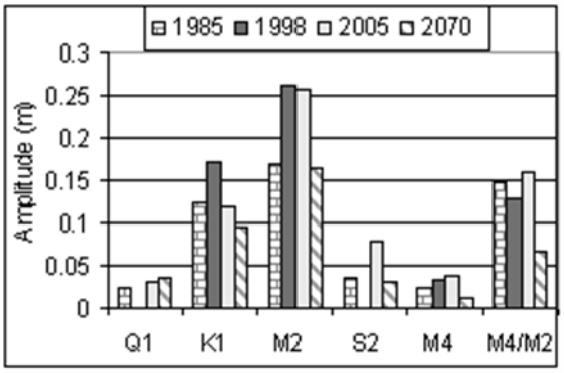

Figure 7. Amplitude variations of tidal constituents at Coombabah Lake (station 7)

The relation between the tidal model results such as velocities and sediment characteristics have been established by the Entrainment Function Diagram (Shields Diagram). The Entrainment Function Diagram comprises a dimensionless plot of Entrainment function (Fs) against particle Reynolds Number (Re*). The Entrainment Function is calculated from:

$$F_s = \frac{\tau}{g(\rho_s - \rho)d} \qquad (2)$$

where ρ_S = grain density,

ρ = water density,

d = grain diameter, and

g = acceleration due to gravity

The particle Reynolds Number is determined from

$$R_e^* = \sqrt{\frac{\tau}{\rho}}.\frac{d}{\upsilon} \qquad (3)$$

where τ = average shear stress, and υ = kinematics viscosity of water

On the Entrainment Function Diagram there is a line called threshold of movement. If at a particular channel location the value of the sediment and flow parameters falls below the Threshold of Movement, no movement of material is expected. Therefore, if sediment is washed into this area, it should settle and remain. This cross-section would gradually be filled up by sediment until the point moves over the Threshold of Movement. If the point is above the Threshold of Movement, material is moved back and forth by the tide and, if there is a net outflow of water, there is a net loss of sediment at this cross section and erosion of the channel is likely to be active. Erosion is expected to continue until the section has become armored by larger sized sediment.

Figure 9 shows that the plotted points representing Entrainment Numbers every 15 minutes during a full tidal cycle at a cross section at station 1 (under 2005 flow condition) have largely fallen above the Threshold of Movement line. From a sediment transport point of view, the cross section seems to be active and the sediments are moved back and forth by tidal flow. To gain a better insight into the sediment transport regime at this cross section, Entrainment Numbers associated with two hours peak flow over a tidal cycle under 2005 flow condition are plotted in Figure 10 for this cross section. The Entrainment Numbers associated with ebb flow varies between 0.31 and 0.4 and that of flood flow varies between 0.4 and 0.45. Figure 11 shows Entrainment Numbers associated with the two hours of peak flow over a tidal cycle under 81 cm sea level rise condition for the same cross section. In this case, the Entrainment Numbers associated with ebb flow vary between 0.43 and 0.46, whereas the Entrainment Numbers associated with flood flow vary between 0.63 and 0.7. These findings indicate more bed sediment movement and possibly more bank instability under the assumed sea level rise scenario. Plotted points in Figures 10 and 11 shows that the behavior of the estuary during flood and ebb tides are different under current and future sea level conditions. Under current climate the Entrainment Number associated with ebb and flood flow conditions are very close to each other. This situation indicates likely weak flood dominance as more particles are expected to pass this cross section and be moved into the estuary by the flood tide than flushed out by the ebb tide. Under the future climate scenario there is a distinct difference between ebb flow and flood flow Entrainment Numbers indicating a more flood dominant sediment transport regime under future climate change. The same analysis for other stations along the estuary shows the same behavior.

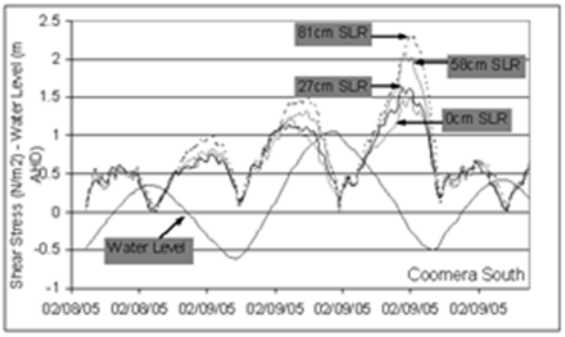

Figure 8. Change in bed shear stress at station 1 for 0, 27, 58 and 81 cm Sea Level Rise (SLR) scenarios for two arbitrary tidal cycle.

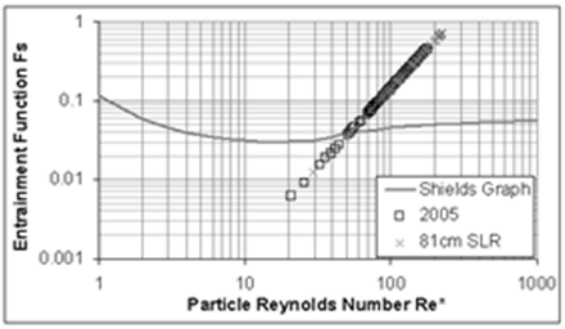

Figure 9. Entrainment Number at station 1 for a full tidal cycle under current climate.

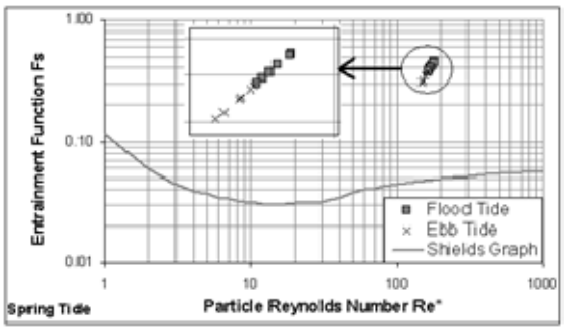

Figure 10. Entrainment number at station 1 during two hours peak flow, no sea level rise

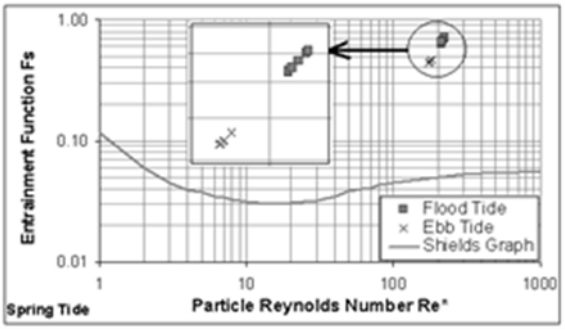

Figure 11. Entrainment number at station 1 during two hours peak flow, 81 cm sea level rise

CONCLUSION

The Coomera River Estuary has a mixed predominantly semidiurnal tidal regime. The estuary is currently flood-dominant and has a nonlinear response to tidal forcing. The strength of this nonlinear response increases at upper reaches of the estuary. The M_4 tidal constituent experiences amplification over the whole length of the estuary with an increased rate towards the upper reaches, indicating an increasing energy transfer from M_2 constituents to its over-tides as tide progresses towards the upper reaches of the estuary.

As a result of the construction of the Gold Coast Seaway, the estuary shows a reducing nonlinear response to tidal forcing over the past twenty years. Tidal range has been increasing within the estuary and as a result the volume of water, discharge and current velocity within the estuary has changed. The study shows that the non-linear response of the estuary does not change substantially as a result of the sea level rise at its lower reaches but it will experience some changes at its upper reaches. An increase in sea level (81 cm) results in an increase in hydrodynamic entrainment of sediments during both flood and ebb tides. However, the level of increase during flood tide is far greater than that during ebb tide. This finding indicates that the estuary will become more flood-dominant under the future climate condition. This will possibly result in more sediment being transported into the estuary during flood tides than sediment transported out during ebb tides.

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