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STUDY ON SALINITY INTRUSION PROCESSES INTO HAU RIVER OF VIETNAMESE MEKONG DELTA

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Field studies in the DinhAn branch of the Hau River, belonging to the Vietnam Mekong Delta, were conducted at spring tides (4 March 2018 and 21 to 22 April 2019) to examine the vertical and longitudinal salinity distribution along the DinhAn branch as well as the vertical salinity distribution at two typical cross-sections. The measured data were used to classify mixing and stratification of the DinhAn estuary during a tidal cycle. The results indicate that along the Hau River (1) the salinity intrusion length at flood tide is 15 km longer than that at ebb tide and (2) the maximum salinity appears at the river mouth and irregularly reduces toward upstream during flood tide. Moreover, at the cross-section far from the river mouth 22km, (3) the peak of salinity lags one hour after the peak of water level and (4) the maximum salinity during one tidal cycle occurs at ebb tide. Finally, all three stratification parameters, including Pritchard, Froude, and Richarson numbers show that the partial mixing and moderate stratification condition prevailed in the DinhAn branch during a tidal cycle. These results are useful in operating the salinity control gates in terms of timing and duration.

Key Words: *Mekong Delta, salinity intrusion, estuarine stratification, salt-wedge, mixing, tide*

1. INTRODUCTION

The Mekong River (MR) has a basin area of 795,000 km^2 and a mainstream length of about 4,800 km from the Tibetan Plateau. The MR is divided into two branches as Tien River and Hau River in Vietnamese territory. Firstly, major flow (85%) is carried by the Tien River but later transfers to the Hau River through Vam Nao linking channel. The Tien and Hau Rivers flow into the East Sea of Vietnam through eight estuaries. This research concentrates on the Hau River which contributes 41.8%[1)] of the freshwater discharge among all rivers in Vietnamese Mekong Delta (VMD). The Hau River splits into DinhAn and TranDe distributaries, starting from the CuLaoDung Island before flowing into the ocean (**Fig.1**). Nowadays, the VMD is facing with so many problems such as flooding, subsidence, river and coastal erosion, climate change, and salinity intrusion. Especially, salinity intrusion causes serious impacts on the environment, water supply and economy. For instance, during the dry season 2016, the salinity of 4.0 intruded up to 60 km and 65 km into the Hau and Tien Rivers, respectively. That affected 52.7% area of the VMD with a total economic loss of approximately US$360 million[2)].

Salinity intrusion process is a natural phenomena

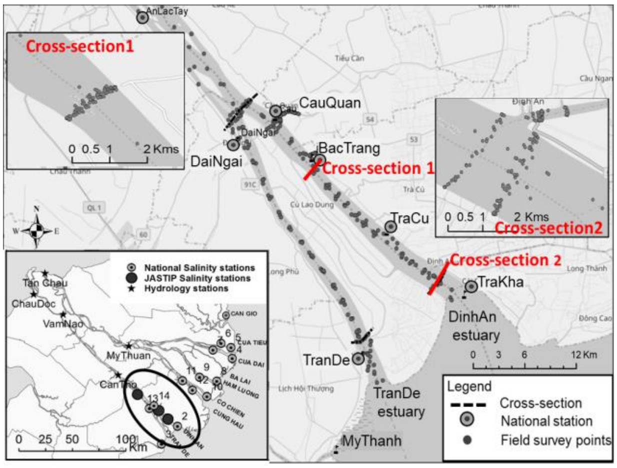

Fig.1 Study area

occurring in the lands, estuaries, and aquifers adjacent to the sea[3]. These processes are controlled by river discharges, tides, sea level rise, flow currents, winds and geomorphology factors (topography, bathymetry). The difference of these controlling factors is used to define and delineate the type of mixing and stratification of salinity intrusion in estuaries. For instance, salt wedge conditions were observed only in the lowermost of the DinhAn channel at high discharges while at low discharges, the Hau River is partially mixed estuarine[4]. Additionally, Mekong estuaries are meso-tidal (the tidal amplitude from 2 m to 4 m)[1]. Recent studies have examined the impact of sea level rise (SLR) and upstream inflow changes on salinity intrusion in the VMD and their results showed serious consequences for water supplies and agriculture production. For instance, Mai et al.[2] found that 12% reduction of the upstream discharge would increase the maximum salinity (S_{max}) from 14% to 23% at all of 30 km points from the estuaries. Other authors revealed that a combination of 20 cm SLR and 15% upstream flow reduction may increase salinity intrusion length by 10 km in the main stream and 20 km in the paddy field[5].

These studies, however, have not yet paid particular attention to vertical and longitudinal distribution of salinity intrusion in Mekong estuaries under the impact of tidal regime. The tide is a powerful source of mixing between fresh and saltwater and thus plays an important role in saltwater intrusion processes. Because, the tidal amplitude of the semi-diurnal tidal in the VMD has increased over the past 27 years such as: change of the yearly maximum sea level was 3.2mm/year along the East Sea[6]. The maximum amplitudes at the mouth increases from 3.2m[7] to 3.8m[8]. That is a cause of intrusion length increasing.

Therefore, different hydraulic engineering measures were constructed to mitigate the adverse impacts of seawater intrusion into the rivers. For instance, earth embankment along the river bank and many sluice gates which were located along the river bank and the intake of small channels were constructed to collect freshwater. During the dry season, most of sluice gates are closed to control the saltwater intrusion. Theoretically, the stratification of saltwater may have freshwater or slightly saline water in the surface that can be collected by sluice gate operation. The aims of this research are (1) to examine the spatial and temporal salinity distribution and (2) to classify mixing and stratification of the DinhAn estuary. The results of such analyses are meaningful in operations of sluice gates for irrigation and salinity intrusion management.

2. METHODOLOGY

(1) Theoretical approach

There are three types of vertical mixing and stratification of water revealed in the zone of river and sea water mixing: type I is complete mixing and weak stratification; type II is partial mixing and moderate stratification; type III is weak mixing and strong stratification, saltwater wedge[8].

Stratification parameter n (Pritchard's number) is used for such classification and is calculated as:

$$n = \frac{\Delta S}{S_m} = \frac{S_{bot} - S_{surf}}{0.5(S_{bot} + S_{surf})} \tag{1}$$

where ΔS is the vertical gradient of water salinity, S_m is depth averaged water salinity, S_{bot} and S_{surf} are saline water at the bottom and on the surface, respectively.

The second parameter is densimetric Froude number[9,10] which is used in hydromechanics of stratified flow and calculated by:

$$Fr_\rho = V / \sqrt{\frac{\Delta\rho}{\rho_m}.gh} \tag{2}$$

where V is mean river flow velocity[11], Δρ is the density difference between sea ρ_s and river ρ_{riv} water, $\rho_m = 0.5(\rho_s + \rho_{riv})$, h is flow depth.

The third parameter is Richardson's number Ri_L[9,10] which is computed as:

$$Ri_L = Fr_\rho^{-2} = gh\Delta\rho / V^2 \rho_m \tag{3}$$

The ranges of n, Fr_ρ, and Ri_L are shown in **Table 1.**

(2) Field survey

Two field surveys were conducted during spring tide. The first field survey was to measure salinity along the Hau River from the DinhAn river mouth on March 4, 2018 by four instruments. Which have namely (i) Infinity- ACTW – USB-0628, (ii) Pro30, (iii) ProDSS of YSI Professional Series

Table 1 Quantitative criteria of different types of vertical mixing, stratification of salinity intrusion into river mouth[9,10)]

Type of Seawater intrusion	Character of vertical mixing	Character of stratification	n	Fr_p	Ri_L
I	Well mixing	Weak	0 to 0.1	> 0.7	< 2
II	Partial mixing	Moderate	0.1 to 1.0	0.71 to 0.22	2 to 20
III	Weak mixing	Strong (Salt Wedge)	1.0 to 2.0	< 0.22	> 20

instrument (these three instruments can measure at a fixed point) and (iv) CastAway – CTD version 1.5 made by SonTek/YSI Inc which can record vertical data. The first three instruments were mounted on a side boat and set up at 1.35m below the surface. Salinity concentrations along the DinhAn river were measured twice, once during the low tide started from 10:49 at the CauQuan station (30 km from the river mouth) toward ebb tide, heading downstream. The other during the high tide started from 15:24 at the river mouth, the boat returned to the upstream during flood tide.

The second field survey was to measure salinity concentration, discharge, and velocity at 2 cross-sections. The cross-section1 (at 22 km from the river mouth) was hourly measured from 9:15 to 21:25 on April 21, 2019. The cross-section2 (at 3km) was conducted from 9:10 to 21:00 on April 22, 2019. Each cross-section was measured at 8 to 10 vertical profiles; each vertical profile was measured 12 times during 12 hours (one tidal cycle) by CastAway – CTD and GPS-equipped Acoustic Doppler Current Profiler (ADCP). The ADCP was mounted securely on a side boat, connected to a computer for in-situ measurement.

3. RESULTS AND DISCUSSIONS

(1) Longitudinal salinity distribution

Fig.2 shown the longitudinal salinity distribution in the DinhAn branch. The timing of the returning way was 2 hours before the flood tide reached its peak at the DinhAn estuary so the maximum salinity was not so high. The salinity values at 1.35m deep recorded by four instruments are good matching (**Fig.2**), indicating that the recorded data are reliable. Only Pro30 data are slightly lower than the others because the sensor was set up 0.1 m higher.

The blue line in **Fig.2** showed that maximum salinity (S_{max}) at the bottom increased from 0.43 at a location of 30 km from the river mouth to 8.92 at the river mouth during ebb tide. During flood tide, the red line (**Fig.2**) indicated that S_{max} irregularly reduced from 20.2 at the estuary

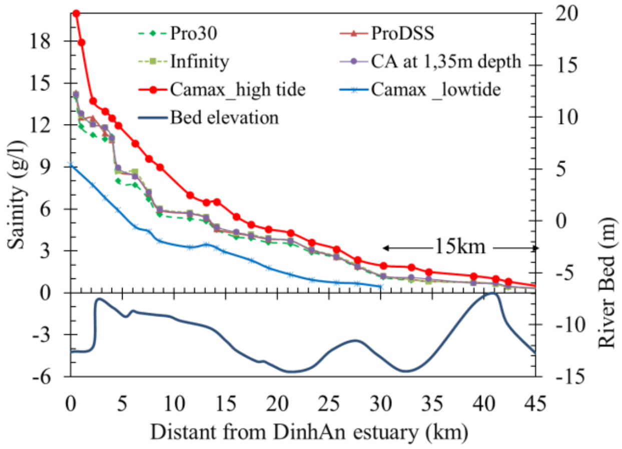

Fig.2 Longitudinal Salinity distribution in the DinhAn branch

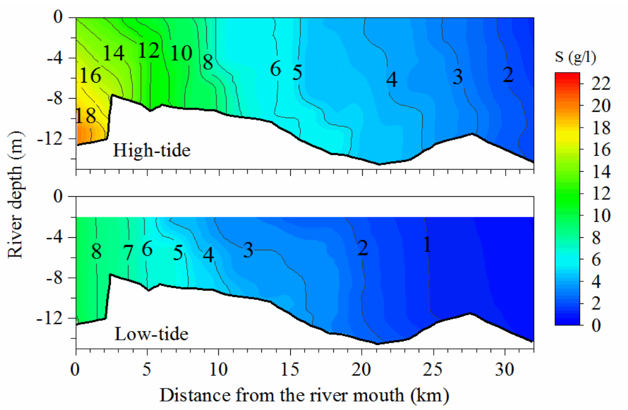

Fig.3 The vertical and longitudinal distribution of salinity in the DinhAn branch

to 0.4 at a location of 45 km from the river mouth. Hence, the intrusion length during flood tide was about 15 km longer than that during ebb tide. Salinity difference (ΔS) between the bottom and the surface was 0.05-2 at low tide and 0.4-8.8 at high tide. Maximum difference of salinity value at high tide appeared at the river mouth while maximum difference of salinity value at low tide occurred in between 5 km and 22 km from the river mouth. Additionally, vertical salinity distribution indicated partial mixing and moderate stratification because the Pritchard's number, n, ranging from 0.11 to 0.68 was in the range of 0.1-1. Along the left bank of DinhAn branch, six sluice gates have been constructed before 2007, after the drought 2016, two more sluice gates have proposed[12)] to be implemented because the intrusion length of 4concentration line in 2016 at Hau River was 60 km from the river mouth[2)]. The bottom elevation of gates from -6.5m to -3.0m. These gates can open when the salinity is less than 2because that concentration can be accepted for rice crop and fruit trees. **Fig.3** shows that all gates located far from the estuary 22 km can open in ebb tide but the question is how long the gates should be open? So the next section will analyze and discuss the impact of tidal regime on salinity distribution at 2 cross-sections during 12 hours (one tidal cycle).

(2) The spatial and temporal salinity distribution in two surveyed cross-sections

Fig.4 shows the measurement results at every two hours. From 9:15 to 13:00, the tide receded; as a result, salinity concentrations reduced from 0.89 to 0.14 g/l. The salinity was at its minimum value at 13:00 during the low water of -0.97 m **(Fig.4).** Then water level rose up from -0.97 m to its maximum level (WL_{max}) of 1.67 m at 18:00, leading to salinity concentrations increasing from 0.14 to 1.69 g/l. S_{max} in the surface of 1.04 occurred at 18:00 (**Fig.4**). While **Fig.5** indicates that S_{max} at the bottom of 1.74 was at 19:00 and S_{max} at the bottom is observed in case of slack water when velocity changes from flood tide to ebb tide and close to the high water. That means that S_{max} at the surface coincided with WL_{max} and S_{max} at the bottom lagged one hour after WL_{max} at a location of 22 km from the river mouth (cross-section 1) (**Fig.4 and 5**). A similar observation was revealed by Fischer et al.[13]. **Fig.5** also indicates that S_{min} occurs when ebb tidal velocity changes from flood tide and close to low water. The value of mean velocity during one tidal cycle at cross-section 1 was used for calculating the stratification parameters.

Beside**, Fig.4** also shows that reductions in the salinity in the left bank were faster than the right bank during 9:15-13:00, indicating that the reversal flow velocity (seaward) in the left bank was faster than that in the right bank. On the other hand, increasing of salinity during flood tide from 15:00 to 18:00 in the right bank was faster than the left bank as a result of high flow velocity (riverward) in the right bank compared to that in the left bank. Then at 18:00, the flow velocity direction shifted from the middle of the river to the left bank. Thus, the flow ran toward downstream on the left bank and the S_{max} occurred at the bottom of the left bank.

Fig.4 also indicates that the duration to open the sluice gates near the cross-section1 to take water with S_{max} less than 2 is 9 hours during one tidal cycle from 9:00 to 17:00.

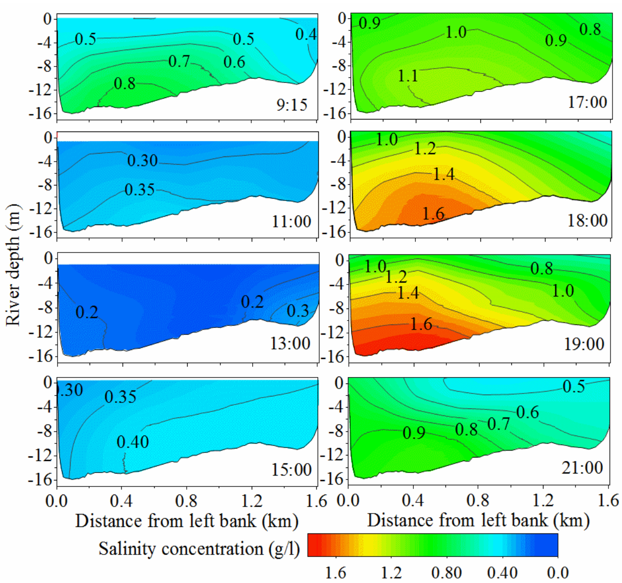

Fig.4 The vertical distribution of salinity at cross-section 1 during one tidal cycle.

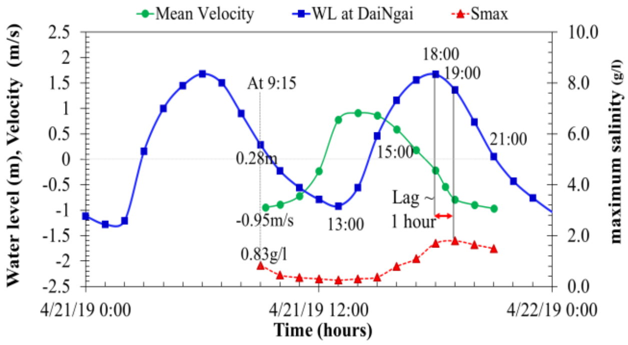

Fig.5 The water level, mean velocity, and maximum salinity (Smax) at cross-section 1 during a tidal cycle

Fig.6 represents a schematic that summaries step-by-step salinity intrusion processes, describing the special features of dynamics in the river mouth by the relationship between the tide, the freshwater and velocity and illustrates the changing of intrusion length during one tidal cycle.

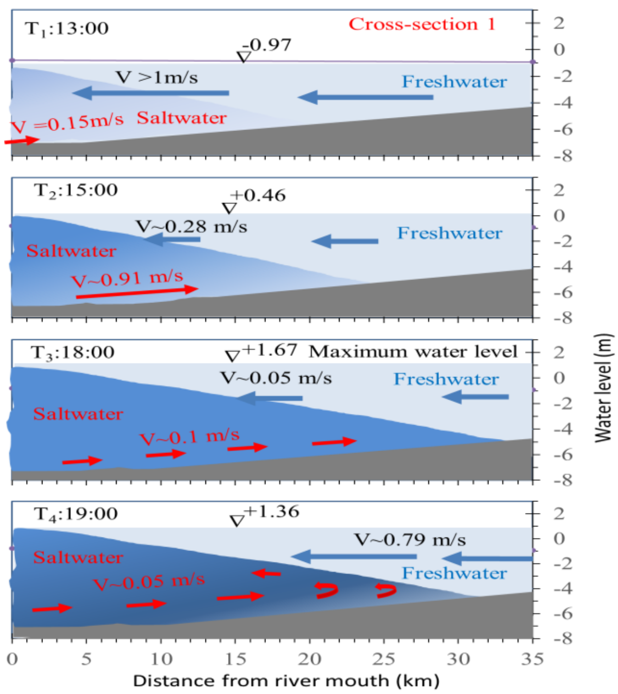

Fig.6 The salinity intrusion processes along the river during the half of a tidal cycle on 21, April 2019

Table 2 Stratification parameters for Hau River (S = Strong stratification, M = Partially mixing or Moderate stratification, W= Weak stratification)

Approach method	Cross-section1		Cross-section2	
	Middle point	Deepest point	Middle point	Deepest point
Pritchard's number: n	0.11 to 0.61	0.18 to 0.66	0.16 to 0.89	0.53 to 1.57
Froude number: Fr_r	0.45	0.41	0.51	0.42
Richardson's number: Ri_L	4.9	6.0	3.9	5.6
Classification (n, Fr, Ri)	(M, M, M)	(M, M, M)	(M, M, M)	(W, M, M)

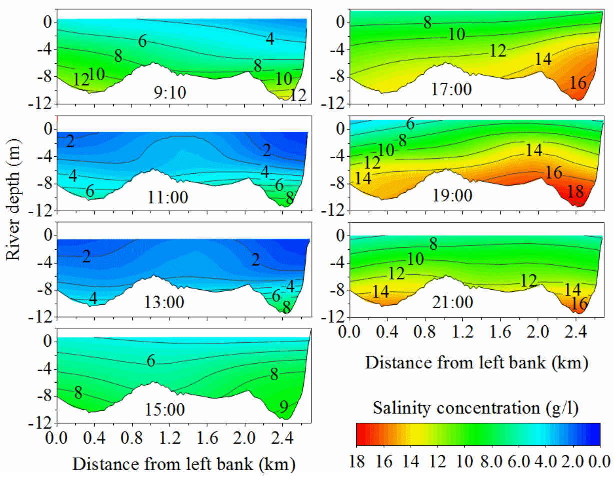

Fig.7 The vertical distribution of salinity at cross-section 2 during one tidal cycle.

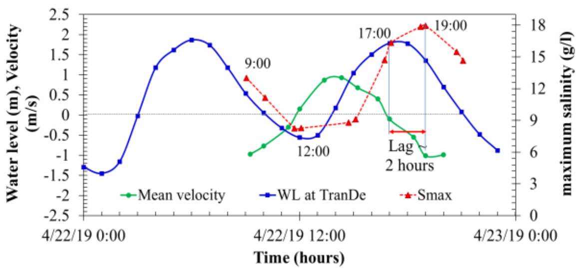

Fig.8 The water level and mean velocity at cross-section 2 during 12 hours in 22, April 2019

At cross-section 2 (3km from the estuary), the salinity value also depends on the tidal regime with 2.77m of amplitude tide at measurement time. Because salinity also gradually decreases and increases following the flood and ebb tide respectively. For instance in **Fig.7**, salinity reduces 1.54 (61%) during low tide (from 9:10 to 12:00) and increases 3.89 (32%) during food tide (12:00 to 17:00). The S_{max} in the surface occurs at the same time with WL_{max} at 17:00 as shown in **Fig.7** and **Fig.8**, while the S_{max} at the bottom appears at 19:00, two hours lag compares with the time of WL_{max} (**Fig.8**). Moreover, S_{max} at the bottom occurs in ebb tide when velocity changes from flood tide to ebb tide and close to the high water while S_{min} appears at low water.

Last but not least, the salinity values near the bank and at the middle point of the river are quite different. The salinity near the bank is smaller than that at the middle point or at the deepest one and has only a slight change from the surface to the bottom.

On the contrary, at the middle point and at the deepest one, the different value between the surface and the bottom (ΔS) is high, for instance, at a cross-section 2, ΔS at the deepest point is 7.22 to 9.8 at the ebb tide and at the flood tide respectively. In practice, salinity measurement stations are located permanently near river banks, thus the data collected cannot represent for all cross-sections but we can refer those data for the operation of the sluice gates located along the river banks.

(3) The mixing and stratification at cross-section

The mixing and stratification were controlled by the wind, the tide and the river flow, but influenced by the wind is only significant in the shallow river. Thus, in this case, only the effects of the river flow and the tide are considered.

We consider the different of salinity at one cross-section during ebb tide at one elevation during ebb tide (9:00 to 13:00) as shown in **Fig.4**. Salinity different between two river banks at the same depth (at -4m elevation) is less than 0.1 while at flood tide (15:00 to 18:00) it is from 0.1 to 0.4. That means at cross-section 1, the advection was more influenced by tide than river flow. Whereas, the changes in river flow at ebb tide have more control over the advection at cross-section 2 as shown in **Fig.7** indicating that at -4m elevation, the salinity values at ebb tide are more fluctuating than that in flood tide.

The results in **Table** 2 indicate that the mixing and stratification in both cross-sections reveal partial mixing and moderate stratification with the value of n, Fr_ρ, Ri_L parameters being always in the range of type II of salinity intrusion in **Table 1**. However, at the deepest point of cross-section 2, the ΔS between surface and bottom in the ebb tide becomes so high with Pritchard's number over 1. Thus, this location occurs salt wedge during 6 hours of ebb tide in the right bank at the deepest point. Further researches in the future need to take into account the effects of river morphology on estuarine mixing and stratification.

4. CONCLUSION

Along the Hau River, the intrusion length in flood tide is about 15km longer than ebb tide on 2, April 2019. The CastAway data indicate the partial mixing and moderate stratification condition with Pritchard's number, n = 0.11-0.68.

In one tidal cycle, S_{max} at the bottom occurred at the transition from flood tide to ebb tide and close to the high water while S_{min} were observed when ebb tidal currents change to flood tide and close to low water. The peak of water level came 1 hour and 2 hours sooner than the peak of salinity at cross-section 1 and 2, respectively.

At a cross-section, among the water columns, S_{max} appears at the bottom of the deepest one. This value is much higher than that near the bank. Thus, the salinity data collected at fixed salinity stations along the bank cannot represent for salinity of the wide and deep rivers like the Hau River.

The rising speed of flood tide in the right bank is higher than that in the left bank and vice versa, the reducing speed during ebb tide in the left bank is faster than the speed in the right bank.

The Pritchard's number (n), Froude number (Fr_ρ) and Richarson's number (Ri_L) also indicate that the partial mixing and moderate stratification condition prevailed at two cross-sections during one tidal cycle. Sometimes in the ebb tide, the salt wedge occurred in the lowermost of the DinhAn branch. That results suggest all the gates which are located from 22km far from the estuary can open during 9 hours to take water for irrigation.

Salinity distribution in an estuary depends on the estuarine response to river discharge, wind and tidal mixing over time scales ranging from days (flood – ebb tide) to weeks (spring-neap tide) and months (seasonal river discharge change). In this paper we consider only the day time scales, therefore, the future research, we need considering the salinity mixing and stratification in fortnightly, month time scales and changing of estuary morphology.

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