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THE PROCESSES OF SALTWATER INTRUSION INTO HAU RIVER

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ABSTRACT: Saltwater intrusion is getting more serious in the Vietnam Mekong Delta (VMD) under the impact of upstream dams' development, water demand increasing, complicated tidal regime that extend 15-25km further of the intrusion length in 2016 compared to the previous years at 8 estuaries. Field investigations were conducted at 500 points to measure salinity concentration longitudinally and transversally (i.e. at five cross-sections) in the Hau River during high tide and low tide conditions.

Vertical and longitudinal salinity distributions along two branches of the Hau River are very complicated. At cross-section 3 which is 5km from the river mouth, the difference in salinity concentration between the surface and bottom is approximately 6g/l. The maximum salinity concentration appears at the deepest point and occurs 1 hour after the peak of the water level at the ebb tide. Moreover, the vertical velocity gradually reduces from the surface to the bottom at ebb tide but during the flood tide, vertically maximum velocity appears near the bottom, at the middle of the cross-section. Importantly, various stratification parameters, including Pritchard, Simmon and Richarson numbers show that the partial mixing and moderate stratification condition prevails in the DinhAn branch during a tidal cycle. This finding is helpful in proposing the locations and intake levels of saltwater control works and building operation rules for the existing sluice gates.

Keywords: saltwater intrusion, tidal regime, high tide, low tide, salt wedge, Hau River, Vietnamese Mekong Delta.

1. INTRODUCTION

Saltwater intrusion is the intrusion of seawater into rivers and land. That is a typical phenomenon of river mouths where two different water masses, riverine and marine, are interacting. The intrusion length of seawater into rivers is controlled by the river flow, tidal amplitude and river morphology.

Processes of saltwater intrusion is the processes of the sea and river water mixing and the estuarine stratifications are the combinations of small-scale turbulent diffusion and large-scale variation of the field of advective mean velocities not constant either in time, space and direction. The turbulent diffusion is to transfer mass among streamlines, depending on the velocity of streamlines. The velocity record obtained at a single point in the middle of the river contains semidiurnal tidal variation, wind variation, tributary flow, and fluctuation during a tidal cycle or seasonal variations. Moreover, the flow is going in different directions at different depths. Thus, the analysis of saltwater intrusion processes in terms of the interaction of advection and diffusion is much more complicated in estuaries (Fischer 1979)

Furthermore, saltwater intrusion processes in the estuaries of the Vietnamese Mekong Delta (VMD) depend on many factors such as river flow, tides, sea level rise, flow currents, winds, water use, activities humans and geomorphological factors (topography, bathymetry) (Fig.1). However, saltwater intrusion processes in the estuaries of the VMD can be simply evaluated by considering the sole effect of the tide, which is a powerful source of mixing between fresh and saltwater, that also plays an important role in a saltwater intrusion. The tidal regime of the VMD in the East Sea is semi-diurnal with maximum amplitudes at the mouth of 3.2m in 1993 (Wolanski et al. 1996) and increases to 3.8m in 2015-2016 (Gugliotta et al. 2017) (the rising rate is 2.61mm/year). Nhan (2016) concluded that annual maximum and mean sea levels along the East coastal areas have risen by 8.1mm/year and 3.2mm/year, respectively.

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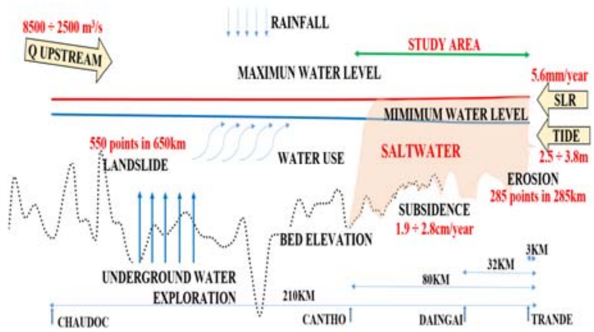

Fig. 1 Systematic causes of saltwater intrusion in the Hau River

2. STUDY AREA

The Mekong River (MR) has a basin area of 795,000km^2 and a mainstream length of about 4,800km from the Tibetan Plateau. The VMD is located at the lowermost of the MR with a total area of 39,000km^2 from the Vietnam-Cambodia border to the East Sea (Fig. 2). The MR is divided into two branches as the Tien and Hau Rivers in Vietnamese territory. The Tien River carries 85% of the total flow volume of which 26.8% is transferred to the Hau River through the Vam Nao linking channel (Nguyen et al. 2008). The Tien and Hau Rivers flow into the East Sea of Vietnam through 8 distributaries.

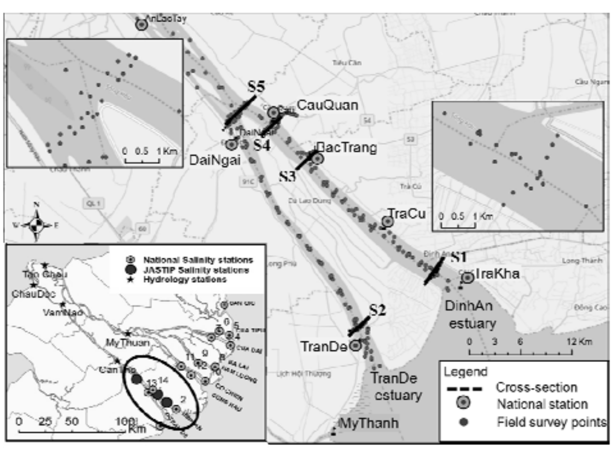

Fig 2. Spatial maps of the VMD and Hau River estuary

This research concentrated on the Hau River which discharges 41.8% of the total freshwater volume of the VMD to the East Sea (Nguyen et al. 2008). The Hau River splits into the DinhAn and TranDe distributaries, starting from the Cu Lao Dung Island before flowing into the ocean. In the dry season 2016, saltwater intrusion had an extreme effect on the environment, water supply, and the economy of VMD. For instance, the salinity concentration of 4.0g/l intruded up to 60km and 65km into the Hau and Tien Rivers, respectively. Consequently, it affected 52.7% area of the VMD with a total economic loss of about US$360 million (Mai et al. 2018). Therefore, understanding the longitudinal and vertical salinity distribution and classification of the salinity stratification in the Hau River are very necessary and useful. The results can be used to suggest the location and the operation of saltwater control structures.

3. METHODOLOGY

The theoretical and survey method is considered the impact of tidal regime on the mechanism of saltwater intrusion to find specific features of the process of seawater intrusion into Hau river mouth. The results of the studies may be subdivided into two parts: (1) evaluation the vertical and horizontal salinity concentration distribution of the Hau River and (2) typification of mixing processes and stratification of water at river mouths.

Field survey

Two field surveys were conducted during spring tide. The first field survey was to measure salinity concentrations along the Hau River from the river mouth on March 2÷4, 2018. The CastAway – CTD version 1.5 made by SonTek/YSI Inc was used to record vertical data along DinhAn and TranDe branches and five cross-sections in the Hau River. Salinity concentrations along the river were measured twice, once during the low tide and once during the high tide.

The second field survey was conducted during April 21÷22, 2019 to measure salinity concentrations, discharge, and velocity at two cross-sections: one is at 5 km (cross-section 2) and other is at 22 km (cross-section 3) from the DinhAn river mouth (Fig.2). Each cross-section was measured 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 of the boat, connected to a computer for in-situ measurements.

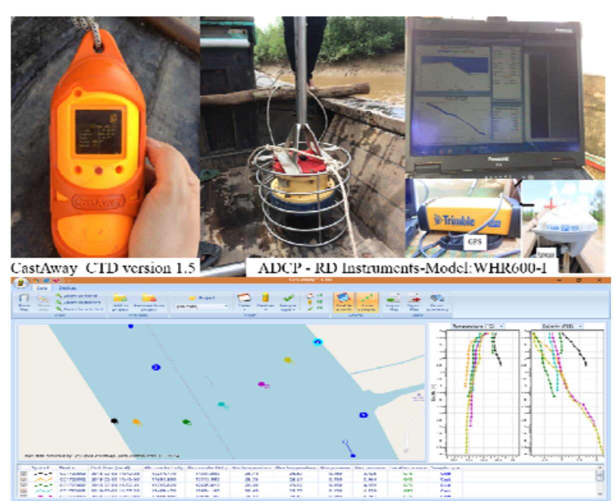

Fig. 3 The instruments used in two field surveys and examples of preliminary results

Theoretical approach

Table 1.1 Quantitative criteria of different types of vertical mixing, stratification of salt intrusion into the river mouth

Type of Seawater intrusion	Character of vertical mixing	Character of stratification	n	α	Ri_L
I	Well mixing	Weak	0 ÷ 0.1	0 ÷ 0.1	< 2
II	Partial mixing	Moderate	0.1 ÷ 1.0	0.1 ÷ 1.0	2 ÷ 20
III	Weak mixing	Strong (Salt Wedge)	1.0 ÷ 2.0	>1	> 20

There are three types of vertical mixing and stratification of water revealed in the zone of river and seawater mixing: type I is complete (well) mixing and weak stratification; type II is partial (moderate) mixing and moderate stratification; type III is weak mixing and strong stratification, saltwater wedge (Mikhailova 2013), (Tuin, H.van der 1951).

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

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

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

The second parameter is Simmon's number,is the flood tidal parameter and calculated by:

$$\alpha = \frac{W}{P} = \frac{Q_m.\tau}{P} \quad (2)$$

where W is the volume of water runoff over the tidal cycle, Q_m is the river flow during the tidal period τ.

The third parameter is Richardson's number Ri_L which is computed as:

$$Ri_L = gh\Delta\rho / V^2 \rho_m \quad (3)$$

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

The ranges of n, α, and Ri_L showed in Table 1.1.

4. RESULTS AND DISCUSSION

4.1 The vertical and longitudinal salinity distribution in the Hau River

4.1.1 Observations on March 2nd, 2018 in the TranDe branch

After setting the instruments at the DaiNgai station which is about 28km from the river mouth, the survey on March 2nd began at 9:08 from here toward ebb tide, to the downstream and ended at 0km point (river mouth) at 13:53. As shown in Fig. 4, maximum salinity concentration (S_{max}) gradually increases from 0.83g/l to 15.49g/l in the ebb tide and S_{max} is recorded at the bottom of the river by CastAway-CTD equipment (CA_{max}). S_{min} is recorded at the surface (CA_{min}) and increases from 0.4g/l to 12.42g/l. Then the boat returned toward flood tide from 16:23 to 19:34 heading upstream from the 0km point to the 42.3km point. S_{max} reduces from 21.5g/l to 0.8g/l.

During the ebb and flood tides, salinity concentration between the surface and bottom from the river mouth to the 20km point varies from 5.2g/l to 1.94g/l (Fig. 5) with the Pritchard number (n) always lower than 1, indicating that partial mixing and moderate stratification prevail over the TranDe branch. Furthermore, the intrusion length of 42.3km at flood tide is 14.3km longer than that at ebb tide.

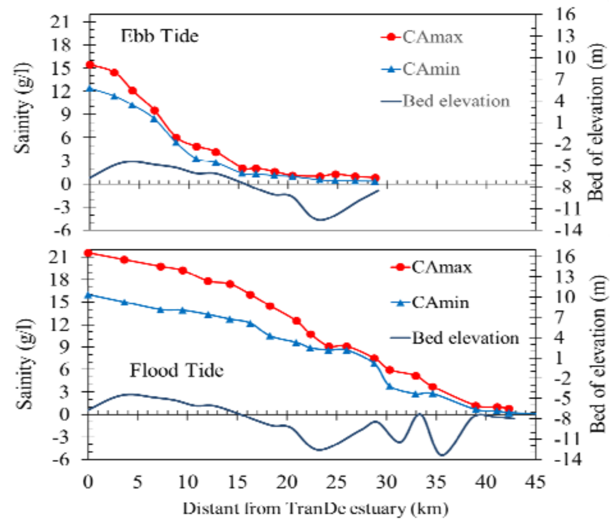

Fig. 4 Longitudinal distribution of salinity in the TranDe branch on March 2nd, 2018

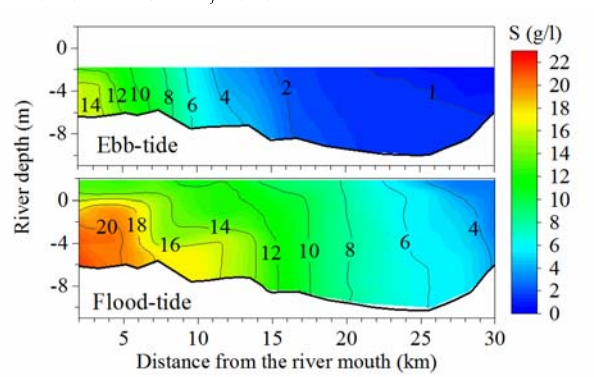

Fig. 5 Vertical and longitudinal distribution of salinity in the TranDe branch on March 2nd, 2018 in ebb - flood tide

4.1.2 Observations on March 4nd, 2018 in the DinhAn branch

Fig. 6 shows longitudinal salinity distribution in the DinhAn branch, conducted from 10:49 at the 30km point at the CauQuan station toward ebb tide, heading downstream. During ebb tide, salinity concentration at the bottom increases from 0.43g/l at the 30km point to 8.92g/l at the 0km point. The boat then returned to the upstream during flood tide from 15:24 that was 2 hours before the flood tide reached its peak. Therefore, salinity concentration values at the bottom are not so high and regularly reduce from 20.2g/l at the river mouth to 0.4g/l at the 45km point. The reduction gradient (slope) depends on the riverbed slope. Fig. 6 also shows that the intrusion length at flood tide is 15km longer than that at ebb tide.

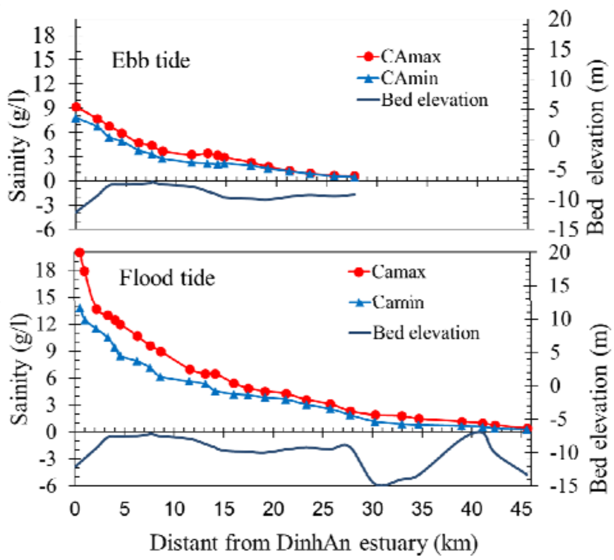

Fig. 6 Longitudinal distribution of salinity in the DinhAn branch on March 4th, 2018

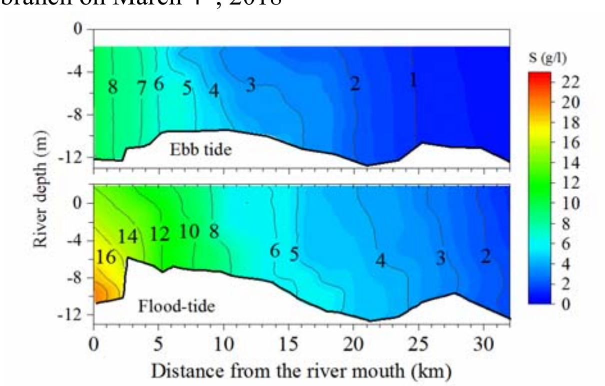

Fig. 7 Vertical and longitudinal distribution of saltwater in the DinhAn on March 4th, 2018 in ebb - flood tide.

Vertical and longitudinal distribution of salinity along the DinhAn branch in Fig. 7 verifies that partial mixing and moderate stratification prevail over the DinhAn branch with the Pritchard number ranging from 0.1 to 0.7, belonging to type 2 (Table 1.1). Furthermore, a much different salinity concentration between the surface and bottom occurs at the estuary in the flood tide while that appears in between the 10km and 25km points in the ebb tide.

Fig. 4 and Fig. 6 show that salinity concentration collected in the TranDe branch is higher than those in the DinhAn branch. However, this finding might be not completely correct because of the difference of the date measurement in the two branches, therefore a direct comparison between the two branches may have some uncertainties. In fact, the salinity values in the DinhAn branch at the CauQuan station are usually higher than that at the DaiNgai station in the TranDe branch (Fig. 8). Noting that distances of the CauQuan and DaiNgai stations from the river mouths are relatively similar. Salinity values at CauQuan and DaiNgai are controlled by the sea water level and river discharge at the CanTho station. Sometimes the peak of daily maximum salinity concentration ($S_{max}{}^{d}$) at CauQuan appears sooner than that at DaiNgai. That means the speed of tidal propagation in the DinhAn branch is faster than that in the TranDe branch. The peak of $S_{max}{}^{d}$ at DaiNgai lags two hours after the daily maximum water level ($WL_{max}{}^{d}$).

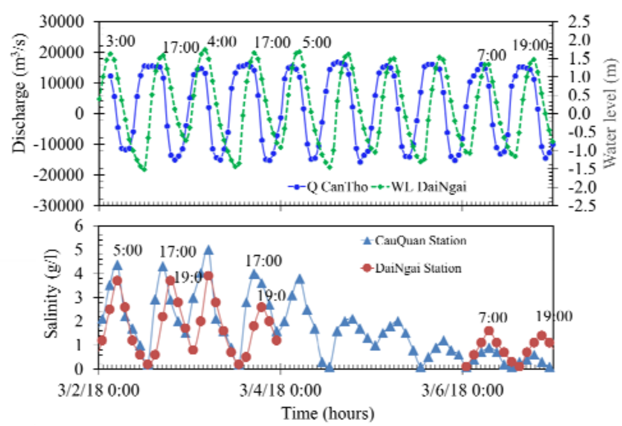

Fig.8 Salinity concentrations at the DaiNgai and CauQuan stations, water levels at the DaiNgai station, and discharges at the CanTho station.

4.2 The vertical salinity distribution at cross-sections

4.2.1 Observation on cross-section 1 in Tran De branch

The measurements at cross-section 1 (5km from the river mouth) in the in Tran De branch were conducted from 11:42 to 12:15 (during ebb tide) and from 15:34 to 16:03 (during flood tide). Fig. 9 shows the vertical salinity distribution.

Salinity amplitudes in the ebb tide and flood tide are about 5g/l and 14g/l in the surface and the bottom respectively. S_{max} at cross-section 1 appears at the deepest point and higher than salinity concentration in the surface about 2.3g/l and 8.2g/l at the ebb and flood tide respectively.

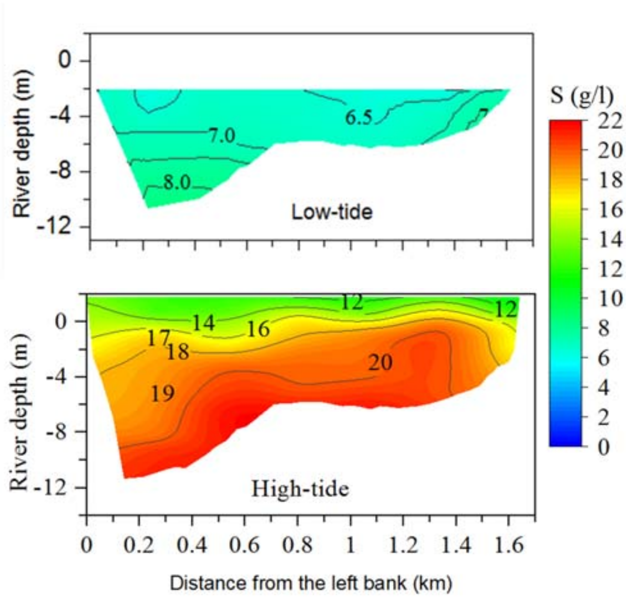

Fig. 9 Vertical salinity distribution at cross-section 1 at ebb and flood tides in the TranDe branch

4.2.2 Observation on cross-section 2 in DinhAn branch

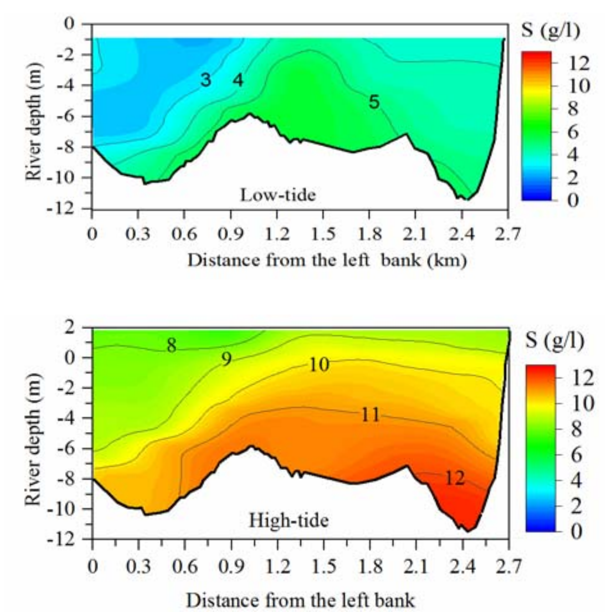

Fig. 10a, b Vertical salinity distribution at cross-section 2 at the low and high tides in the DinhAn Branch

The measurements at cross-section 2 (5km from the river mouth) were conducted from 14:07 to 14:37 (at low tide) and from 16:00 to 16:32 (at high tide). Fig 10 shows that the right bank is deeper than the left bank; therefore, S_{max} occurs at the bottom of the right bank. The difference of salinity concentrations between the surface and bottom is 2g/l and 8.58 g/l at the ebb and flood tide, respectively.

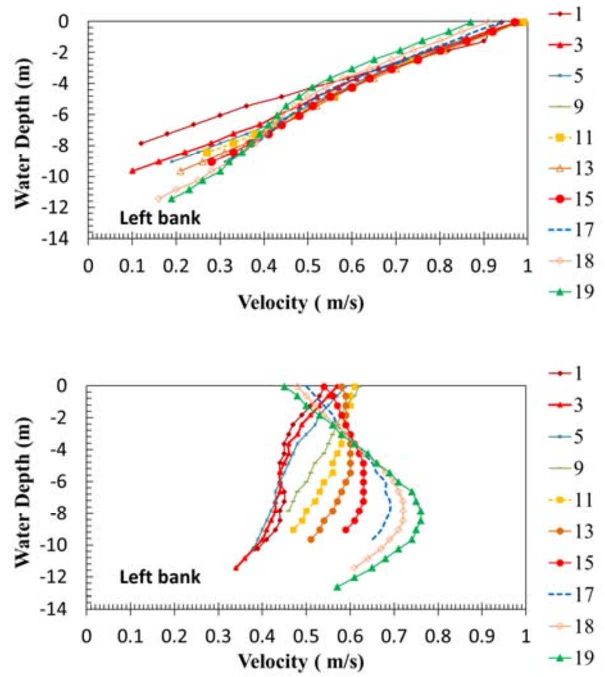

Fig. 11a, b Vertical velocity distribution at ebb tide and high tide at cross-section 2 in the DinhAn Branch (number 1,3,5, et al is the order of velocity profiles which start from the left bank and distance between each profile is 0.13m)

The vertical salinity distribution was controlled by the value and direction of flow velocity at this cross-section. Fig.11a shows the vertical velocity distribution at ebb tide. At cross-section 2, 20 velocity profiles were conducted from the left bank to the right bank. The results indicated that at ebb tide, the maximum velocity (V_{max}) is at the surface and minimum velocity is at the bottom with velocity magnitude being up to 0.9m/s. Vice versa, at flood tide (Fig. 11b), V_{max} occurs in the right bank and closes to the bottom while a part of cross-section 2 occurs reversal flow (seaward). Therefore S_{max} always happens in the bottom and closes to the right bank (Fig.10b).

4.3 The mixing and stratification at a cross-section

Mixing in the estuary is a complicated process, which is controlled by the wind, the tide and the river flow. In this research, only the effect of the tide and the river flow are considered. The mixing changes over the time scales ranging from days (flood – ebb tide) to weeks (spring-neap tide) and months (seasonal river discharge variations). The authors consider only the daily time scales.

Salinity concentrations at cross-section 3, 22km from the DinhAn estuary (Fig. 1), were hourly measured from 9:15 to 21:25 on April 21st, 2019. 8÷10 vertical profiles were measured during each measurement period,

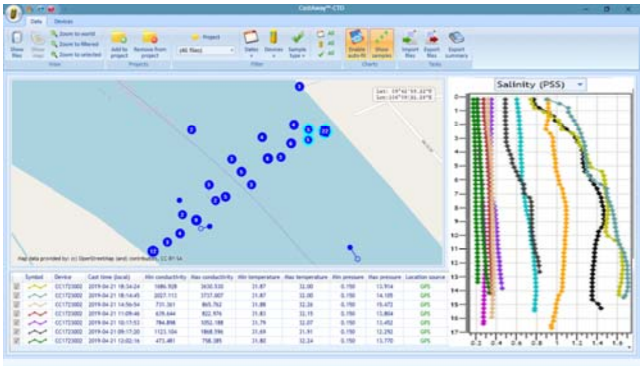

Fig. 12 Locations and vertical salinity concentrations at 12 measurement times at the deepest point of cross-section 3 during 12 hours

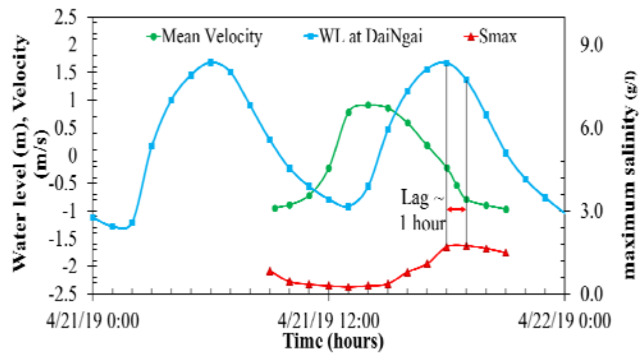

Fig.13 Mean velocity, water level and maximum salinity during 12 hours at the cross-section 3

Table 4.1 The result of three stratification parameters at the deepest point of cross-section 3 during 12 hours

Time	Q (m^3/s)	V(m/s)	Depth(m)	S max (g/l)	S min (g/l)	n	α	Ri_L
4/21/19 9:00	-0.950	0.95	0.37	0.89	0.83	0.62		
4/21/19 10:00	-0.890	0.89	0.38	0.54	0.35	0.56		
4/21/19 11:00	-0.720	0.72	0.27	0.36	0.29	0.44		
4/21/19 12:00	0.230	0.23	0.20	0.32	0.46	0.14		
4/21/19 13:00	0.780	0.78	0.16	0.20	0.22	0.48		
4/21/19 14:00	0.910	0.91	0.21	0.30	0.35	0.54		
4/21/19 15:00	0.860	0.86	0.31	0.41	0.28	0.50	0.3	6.0
4/21/19 16:00	0.590	0.59	0.55	0.81	0.38	0.34		
4/21/19 17:00	0.150	0.15	0.94	1.13	0.18	0.09		
4/21/19 18:00	-0.300	0.30	0.98	1.70	0.54	0.18		
4/21/19 18:30	-0.540	0.54	1.25	1.74	0.33	0.32		
4/21/19 19:00	-0.790	0.79	0.96	1.40	0.37	0.47		
4/21/19 20:00	-0.880	0.88	0.75	1.49	0.66	0.54		
4/21/19 21:00	-0.900	0.90	0.70	1.02	0.37	0.55		

Table 4.2 Stratification parameters in the Hau River (S = Strong stratification, M = Partially mixing or Moderate stratification, W= Weak stratification)

Approach method	Cross-section 3	
	Middle point	Deepest point
Pritchard's number: n	0.11 to 0.61	0.18 to 0.62
Simmon number: α	0.3	0.3
Richardson's number: Ri_L	4.9	6.0
Classification (n, α, Ri_L)	(M, M, M)	(M, M, M)

starting from the left to the right bank. Fig.12 shows the measurement results at every hour. From 9:15 to 13:00 (Fig. 13), the tide receded and salinity concentration reduces from 0.89g/l to 0.14g/l. The salinity concentration is at its minimum value at 13:00 at the same time as the low water of -0.97m (Fig. 13). Then water level rises up from -0.97m to its maximum level (WL_{max}) of +1.67m at 18:00, leading to salinity concentrations increasing from 0.14g/l to 1,69g/l. But S_{max} of 1.74 occurs at 19:00 (Fig. 13) at the deepest point, therefore, the peak time of S_{max} lags one hour after WL_{max} at a location of 22km from the river mouth.

Three stratification parameters in Table 1.1 are used to classify the mixing and stratification during one tidal cycle (12 hours) at cross-section 3 in the Hau River. The results in Table 4.1 and Table 4.2 indicate that the mixing and stratification in cross-section 3 reveal partial mixing and moderate stratification with the value of n, α and Ri_L parameters being always in the range of type II of salinity intrusion in Table 1.1.

All the results are useful for integrated water resources management and salinity control measurements. Along the left bank there are six completed and two under construction sluice gates, those have bottom elevation varies from -3m to -6.5m. Most of the gates are used to take freshwater and control salinity, therefore, the gates will be closed in the dry season when salinity is very high. However, during the period between the high slack water and the low slack water, the gates can open to take freshwater for irrigation. For instance, the Can Chong gate, located in the left side at the 29km point far from the DinhAn estuary, is opened to take water when S_{max} is less than 1g/l. The threshold of this gate is -6.5m. Fig. 5 and Fig. 13 collectively suggest that the Can Chong gate should be open from 9:00 to 16:00 (eight hours) to take water when maximum salinity concentration is less than 1g/l.

Furthermore, the annual mean sea level along the Eastern coastal areas would increase in the average amplitude of 3.2 mm/year (Nhan 2016). Therfore, the projected intrusion length should be predicted to propose locations of new gates and the threshold of gates to control salinity in the future.

5. CONCLUSION

The intrusion length in flood tide is about 15km longer than that in the ebb tide. Longitudinal salinity distribution along the Hau River indicates the partial mixing and moderate stratification condition with Pritchard's number, n = 0.11÷0.68.

At a cross-section, S_{max} appears at the bottom of the deepest position. This value is much higher than that at the surface and near by the bank from 2g/l to 8,58 g/l.

At the estuaries, during the ebb tide, the vertical velocity gradually reduces from the surface to the bottom. Vice versa, during the flood tide, maximum vertical velocity appears near the bottom.

At cross-section 3, the peak of water level occurs 1 hour sooner than the peak of salinity concentration, which occurs at the transition from flood tide to ebb tide and close to the high water. On the other hand, minimum salinity concentrations are observed when ebb tidal currents change to flood tide and close to low water.

The Pritchard's number (n), Simmon's number (α) and Richarson's number (Ri_L) indicate that the partial mixing and moderate stratification condition prevail in along the Hau River during one tidal cycle.

The research results are helpful in the operation of sluice gates along the left bank of the DinhAn branch and the right bank of the TranDe branch.

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