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Seasonal variation of currents in the Cam-Nam Trieu estuary (Hai Phong, Vietnam): results from a 3D modelling

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ABSTRACT

This paper employs the Delft3D numerical model to characterize the seasonal variation of currents in the Cam-Nam Trieu estuary during 2015. Model outputs were validated and calibrated against measured water level and current velocity data at Hon Dau. The convincing performance of Delft3D in replicating natural conditions is evident from the high Nash-Sutcliffe Efficiency (NSE) (up to 0.972), low Root Mean Squared Error (RMSE), and strong R-squared (R) values for both water level and current velocity. Current magnitudes in the wet and early wet seasons significantly exceed those observed during the dry season. Peak ebb tide velocities can reach 1.6 m/s. While river discharge to the sea is diminished in the dry season, the impact of tides becomes more pronounced, with a clearer stratification of water velocity during spring tides compared to neap tides. The influence of strong river flow in the dry season is apparent in higher current velocities during ebb and low tides relative to flood and high tides, particularly during neap tide conditions. The successful replication of the Cam-Nam Trieu estuary's hydrological regime by the Delft3D model positions it as a valuable tool for future predictive simulations in the region. These simulations will make substantial contributions to coastal and marine management. The findings of this research serve as a foundational reference for subsequent studies.

Keywords: Delft3D, Cam-Nam Trieu estuary, currents, velocity, direction.

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Introduction

The mesotidal Cam-Nam Trieu estuary (Fig. 1), which is a part of the Thai Binh River and Red River basins and is situated in Hai Phong City, Northeast Vietnam, is a fascinating place to study estuarine dynamics in a tropical climate because it is subject to both a strong seasonal river signal and a monsoon regime. This area is affected by natural and anthropogenic activities. Agriculture and industrial activities from upstream can cause pollution for the area due to contaminant spreading out by field currents. The estuary is further submitted to atmospheric and oceanic variability at a large range of scales (flooding, seasonal monsoon, climate change, storm surges, wave and tidal forcing, large scale circulation, etc.) [1–3].

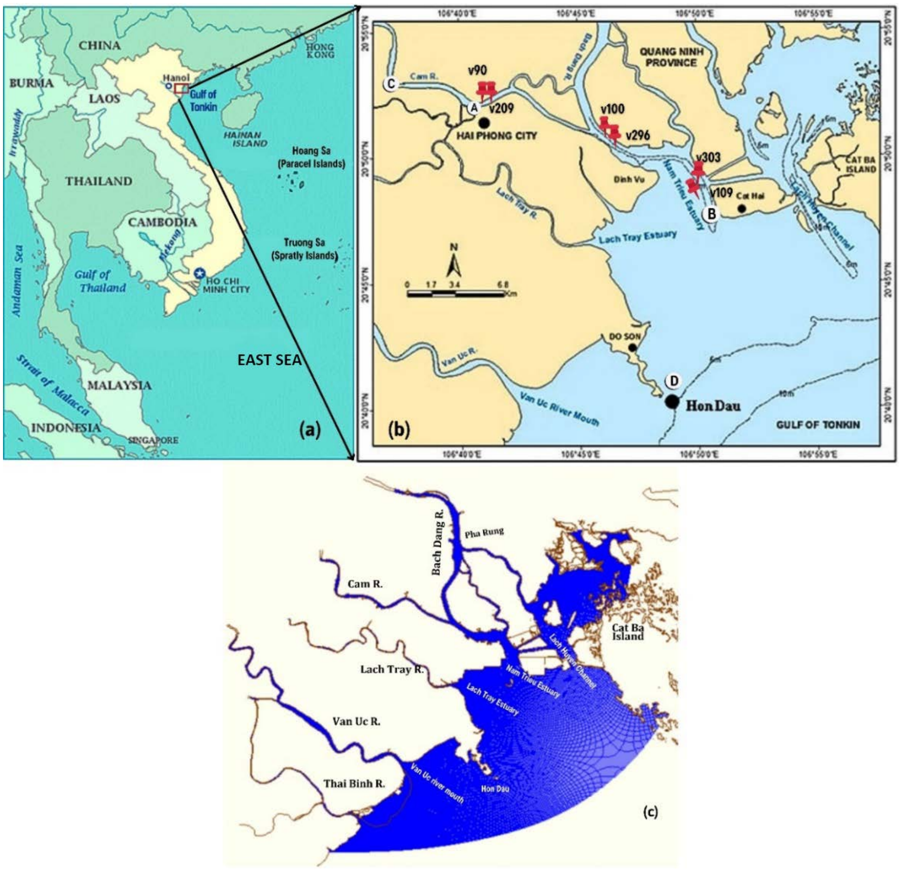


Figure 1. (a) Location of Cam-Nam Trieu estuary; (b) Sampling transects were mostly performed between stations A and B (from v90 to v303), C is the hydrological station, D is the tide gauge at Hon Dau [2]; (c) The grid for the hydrodynamics model in the Cam-Nam Trieu

The hydrodynamic regime here is critical for carrying sediment, regulating topography variations, and dispersing pollutants from coastal areas to the sea [4, 5]. One factor which influences coastal erosion is currents. Sediment particles are affected by their turbulence and velocity [6, 7] Currents then move the eroded sediment particles downstream or along the shore. Although larger and heavier particles like sand and gravel settle closer to the source or roll downstream, finer particles like silt and clay can be suspended and moved over vast distances [8]. In comparison to smaller currents, stronger ones move sediment farther. Sediment patterns can be dispersed in response to current direction changes. The sediment particles are lost from suspension as the current's strength diminishes or it comes into contact with obstructions. Deposition results from these particles settling down [9]. Currents have the ability to physically carry pollutants away from their source. Turbulence accelerates dispersion and works especially effectively when there is mixing water. While pollutants settle on the seafloor in areas with inconsistent flow directions or weaker currents, strong currents have the capacity to resuspend them in water columns, thereby extending their reach, enhancing pollution [10]. As a result, studying hydrodynamic conditions is crucial. The Cam-Nam Trieu estuary has been studied from a variety of perspectives, in both doing analyzing measured data and numerical models [5–7].

Most hydro-sedimentary processes in coastal waters occur in 3D in nature [3]. As a result, scientists adapt 3D numerical models to solve the mathematical models of fluid dynamics applied to estuaries. The mass balance [11] or convective diffusion equations of sediment particle matter [12, 13] are the foundation for the 3D model which provides the most comprehensive inclusion of variables of any hydrodynamic system. In fact, the programs are required to reflect processes of the hydrodynamics occurring in 3D, model calibration also necessitates a significant amount of data and is typically complex. 3D sediment transport-hydrodynamic models shed light on the development and the interplay of processes occurring in bodies of water. Numerous 3D models have been used at various scales. Due to the lengthy computing time, it is usually only simulated within a few days or a tidal cycle, which is not particularly advantageous for the large area scale. NOPP Community Sediment Transport Model (ROMS), ECOMSED, SEDTRANS, and Delft3D are a few of the most popular models [14].

In Vietnam, numerical models have been applied to simulate water quality in some bays and coastal areas. For example, MIKE and Delft3D models have used to simulate the spread of pollutants in some coastal areas such as Dinh Vu, Do Son-Hai Phong, Dong Nai-Saigon River basin [14–16], Ha Long-Cat Ba waters, Bai Tu Long Bay, Hai Phong coastal waters, Thi Nai lagoon, and Tam Giang-Cau Hai lagoon [17–20]. Studies on hydrodynamics have been conducted recently in the Cam-Nam Trieu estuary. Still, there are not many studies available. In 2008, Vinh et al. [5] used Delft3D model to simulate the hydrodynamic and sediment transport in Hai Phong estuary. The result of the model is dependable and in line with actual situations. Water level oscillations and the flow regime in the Hai Phong coastal area are closely associated. In 2011, Nguyen Kim Cuong [20] applied HUS-VNU modelling system to simulate the circulation and shed light on factors that have impacted on flow fields in Hai Phong estuary. According to the results of their simulation, at ebb tide in Nam Trieu, the river flows southward, changing from a northward flow at flood tide. At the deepwater depth, the change in concentration of particles is largely influenced by wind waves. Onshore–offshore sediment movement is driven by the tide's current velocity, while longshore sediment transport is significantly influenced by waves. When it comes to modify the distribution of sediment, the overall volume of river discharge matters. In 2021, from measured data, Vu Duy Vinh and Sylvain Ouillon [2] reported that at the Cua Cam station, the average river discharge reached its peak during the flood season (averaged 783 m^3s^{-1}), its lowest during the low-flow season (297 m^3s^{-1}), and its intermediate point during the start of the rainy season (459 m^3s^{-1}, 10th–13th May 2015). The studies, however, did not provide any insight into seasonal variations in the field current and its fluctuation along the water column.

In this study, seasonal variation of currents in the Cam-Nam Trieu estuary in 2015 is to be simulated horizontally and vertically by a numerical modelling called Delft3D. The intended outcomes of this study will be calibrated and validated with measured data. The validated model can be applied for study sediment transport and other future researches in this study.

Data and methods

The study area

The Cam-Nam Trieu estuary, located in the northeastern part of Hai Phong City (Vietnam's third-largest city), is influenced by the Cam and Bach Dang rivers [2–6]). These rivers, tributaries of the Thai Binh River, also receive water and sediment from the Red River via the Duong River (Fig. 1). The estuary receives approximately 20 × 10^9 m^3year^{-1}, accounting for 16.5% of the total discharge from the Red-Thai Binh River system into the Tonkin Gulf.

Prior to the construction of the Hoa Binh dam in the 1980s, sediment flux from the Red-Thai Binh River system through the Cam and Bach Dang rivers to the coastal zones was around 13.2 million tons per year. After the dam's completion, sediment trapping in the reservoirs reduced this flux to 6.0 million tons per year, representing 17% of the total sediment transported by the Red-Thai Binh River to the Red River coastal area [21].

The Cam-Nam Trieu estuary experiences a tropical monsoon climate with distinct wet and dry seasons. Annual rainfall in the region averages 1,161 mm (data reported in Hon Dau, 1978–2007), with 83% occurring during the summer monsoon (May to October). Wind patterns are predominantly easterly (NE, E, SE) and southerly (SW, S, SE) during the summer and northerly (NE, N, NW) and easterly (SE, E, NE) during the dry season (wind data measured at Hon Dau (1960–2011) [3].

As part of the Red River system, the Cam and Bach Dang rivers are subject to its hydrological regime. Historical data from 1960 to 2010 indicate that the Red River discharge at Son Tay varied between 80.5 and 160.7 × 10^9 m^3year^{-1}, with an average of 110.0 × 10^9 m^3year^{-1}. Seasonal variations of discharges are significant, with 71–79% of annual amount occurring during the rainy season and only 9.4–18% during the dry season [21].

The Cam-Nam Trieu estuary is also influenced by tides, primarily diurnal. Tide gauge measurements at Hon Dau station show tidal amplitudes ranging from 2.6 to 3.6 m during spring tides and 0.5 to 1.0 m during neap tides. Sediment sampling in the estuary has revealed a predominance of clay and fine silt in the Cam River and a higher concentration of fine sand in the estuary itself [2, 3].

Data

The digital bathymetry data for the Hai Phong coastal estuary area was obtained from UTM topographic maps of the VN 2000 geographic coordinate system, which were published in 2015 by the Ministry of Natural Resources and Environment’s Department of Survey, Mapping, and Geographic Information Vietnam at the scale of 1:50,000 in the coastal and 1: 25,000 in the river/estuaries region. The bathymetry of the study area was also updated by the measurement from the project ĐT.MT.2020.852 - Assessing the load and transportation of pollutants from upstream to major rivers in Hai Phong. The British Oceanographic Data Center’s GEBCO-1/8 database is used to determine the topography and depth of the Gulf of Tonkin and its surrounding areas [22].

Additionally, information about the water levels at open sea boundaries have been gathered and analysed [23]. The Center National d’Études Spatiales’ Collected Localization Satellites and Toulouse’s FES2004 of the Laboratoire d’Etude en Géophysique et Océanographie Spatiales are the sources of the tidal data [24]. The data pertaining to seawater temperature and salinity in Hai Phong’s coastal estuary are the outcome of numerous connected issues and projects being monitored and researched in the area. Additionally, the seaward open boundary conditions for the East Vietnam Sea region are gathered from the World Oceans Atlas 2013 [25].

Six-hour of temporal resolution was used in the collection of weather observations (wind, air pressure, temperature) at the National Centers for Environmental Prediction. There is a 2.5-longitude/latitude degree horizontal resolution in this dataset [26].

Over the course of the early wet season (10^{th}–13^{th} May 2015) and wet season (23^{rd}–25^{th} September 2015), 2 field investigation compaigns were conducted in the Cam-Nam Trieu estuary at spring tides [2, 3]. In approximately three to four hours each, river transects were carried out from the Nam Trieu mouth (position B, Fig. 1b) to the upper estuary of the Cam River (position A, Fig. 1b), or the other way around. Velocity profile was measured by 600Hz Acoustic Doppler Current Profiler (ADCP) at each station, for example, from V90 (position A) to V109 (position B) in May 2015, and from V209 to V303 in

September 2015. Data are available for water height (hourly), wind (every 6-hour), and rainfall (daily) at the Hon Dau station on Hon Dau Island (position D, Fig. 1b).

The National Hydro-Meteorological Service (NHMS)'s periodic monitoring data of river discharge on the Cam River (position C, Fig. 1b) have been gathered to create the model's open boundary. They consist of water river discharge (measured hourly). These measurements and calculations were made in accordance with the Vietnam Meteorological Hydrological Administration's standard 94 TCN17-99, which is used in all Vietnamese gauging stations using the same methodology.

Set up model

A package of integrated modelling applications called Delft3D can simulate both two- and three-dimensional flow, waves, water quality, sediment transport and morphology, and ecology. It can also handle the interactions that arise from these natural processes [27].

A detailed curvilinear grid (Fig. 1c) with 5 depth layers of sigma coordinate system was applied to the study area. In this work, the open sea boundary conditions of the model were generated using the NESTING method. The orthogonalize number always must be lower than 0.02 with aspect ratio no larger than 1:3. The coarse mesh model uses an orthogonal curved grid structure and has a point count of 704 × 703. The grid cells' sizes range from 39 to 540 m. Bathymetry data was used for this model.

With the reference date is 1st January 2015, a hydrodynamic model for the Cua Cam - Nam Trieu was set up and operated with wet and dry seasons as well as varied scenarios. Two current scenarios are used to calibrate and validate the model: rainy season (May-August-September 2015) and dry season (January–February 2015). The hydrodynamic model's running time step is 0.25 minute.

The model necessitates the simultaneous coupling of wave and hydrodynamic principles. Salinity, temperature, the impact of surface winds, waves, and their interactions are the primary variables considered. The hydrodynamic model simultaneity combined with the wave model here is known as an online coupling model.

Through restart files, the model's starting conditions can be obtained from the outcomes of earlier runs. The outcomes of the last day in the restart files serve as the starting conditions for the scenarios when applying to Hai Phong's estuary [27].

The model has open sea and river boundaries: the open sea border includes the southern borders of Thai Binh mouth, the southeast and south of Cat Ba Island and southeast of Tuan Chau. River boundaries include cross sections at Bach Dang River: Pha Rung; Cam River (near Cau Binh bridge), Lach Tray (near Phan Dung); Van Uc (near Duong Ao ferry); Thai Binh River (Tran Duong area). Delft3D- NESTHD was used to create boundary files of temperature, salinity, and water level. These are time serial data with a frequency of 1 h/time. For river boundaries, salinity and temperature data for boundary conditions are monthly average characteristics. The water flow used for the river boundary conditions in the study is a series of data calculated from measured data with a frequency of 1 h/time, based on the measured data at Cua Cam Station (Cam River) and Trung Trang Station and measured data from the ĐT.MT.2020.852 project.

The model takes into account the effects of wind, cloud, pressure, radiation, and air temperature, which were acquired at Hon Dau in 2015. The uniform Manning coefficients (n) of 0.02 $m^{-1/3}s$ were chosen as the bottom roughness parameter. Background horizontal and vertical of viscosity and diffusivity are uniform and are 0.5 and 10^{-5} m^2/s, respectively. The turbulence conditions were calculated by using the HLES (Horizontal Large Eddy Simulation). The HLES model in Delft3D is a 2-D entangled closed model. The k-ϵ model is the 3D closed model used in this work.

Model calibration and validation

Simulated results like water level and current were compared with measured data.

One commonly used metric to quantify the discrepancy between simulated values and observed data is the Root Mean Square Error (RMSE). The amount of error between two data sets is measured by the RMSE. Put another way, the RMSE makes a comparison between an observed or known value and a predicted value [28]:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} X_{obs,i} - X_{sim,i}}{n}} \qquad (1)$$

where: $X_{obs,i}$, $X_{sim,i}$, are i^{th} observational, simulated values; n is the total number of observations.

An essential statistical metric in regression models is the R-squared correlation, which expresses how much of the statistical variance or difference for a dependent variable can be accounted for by one or more independent variables, was applied to compare water levels as well. R-squared correlation, to put it simply, measures how well the modelled data fits the observed data or how well the data fits the regression model. The square of the correlation coefficient is known as R-squared correlation. The Pearson correlation must first compute and then square it to determine R-squared correlation [29]:

$$R = \frac{n\left(\sum xy\right) - \left(\sum x\right)\left(\sum y\right)}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right]\left[n\sum y^2 - \left(\sum y\right)^2\right]}} \qquad (2)$$

where: R is Pearson correlation; n is the number in the given dataset; x is the first variable in the context (or observational data); y is the second variable (or modelled data).

To determine the relative magnitude of the observed and simulated data, the Nash-Sutcliffe efficiency (NSE) was applied [30]. NSE is very commonly used [31–33] which provides extensive information on reported values and can be the best objective function for reflecting the overall fit of a hydrograph. NSE ranges between −∞ and 1.00 (1.00 inclusive), with NSE = 1.00 being the optimal value (theory). Values between 0.00 and 1.00 are generally viewed as acceptable levels of performance, whereas values ≤ 0.00 indicates that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance. For NSE in range of 0.75 to 1.00, performance rating is very good, and the simulation is very reliable. NSE is computed as shown in equation (4):

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{mean}\right)^2} \qquad (3)$$

where: Y_i^{obs} is the i^{th} observation for the constituent being evaluated; Y_i^{sim} is the i^{th} simulated value for the constituent being evaluated; Y^{mean} is the mean of observed data for the constituent being evaluated; and n is the total number of observations.

Results and discussion

Model validation and calibration

In this study, the results of simulations are compared with observational data of water level at Hon Dau station from 2015. This one is located near central of the model frame, about 8km from the closet point on the sea boundary of the model. Hon Dau is also the only station with water level measurement data of NHMS in area Hai Phong coastal area. It shows a very good match of simulations and observations with NSE above 0.80 every month, especially it reaches 0.97 in May 2015. The values for R^2 are above 0.95 every month, especially it reaches 0.972 in May 2015, showing a very matching of simulation and observation. The smaller RMSE the better simulation. RMSE of measured and simulated water level ranging from more than 12 to less than 25 (Table 1, Fig. 2).

Table 1. RMSE, NSE and R coefficient between simulated and measured water levels (cm) in 2015

Months	RMSE	NSE	R
January	12.012	0.970	0.972
February	18.125	0.955	0.957
May	12.791	0.971	0.972
August	18.125	0.963	0.965
September	24.853	0.845	0.9513

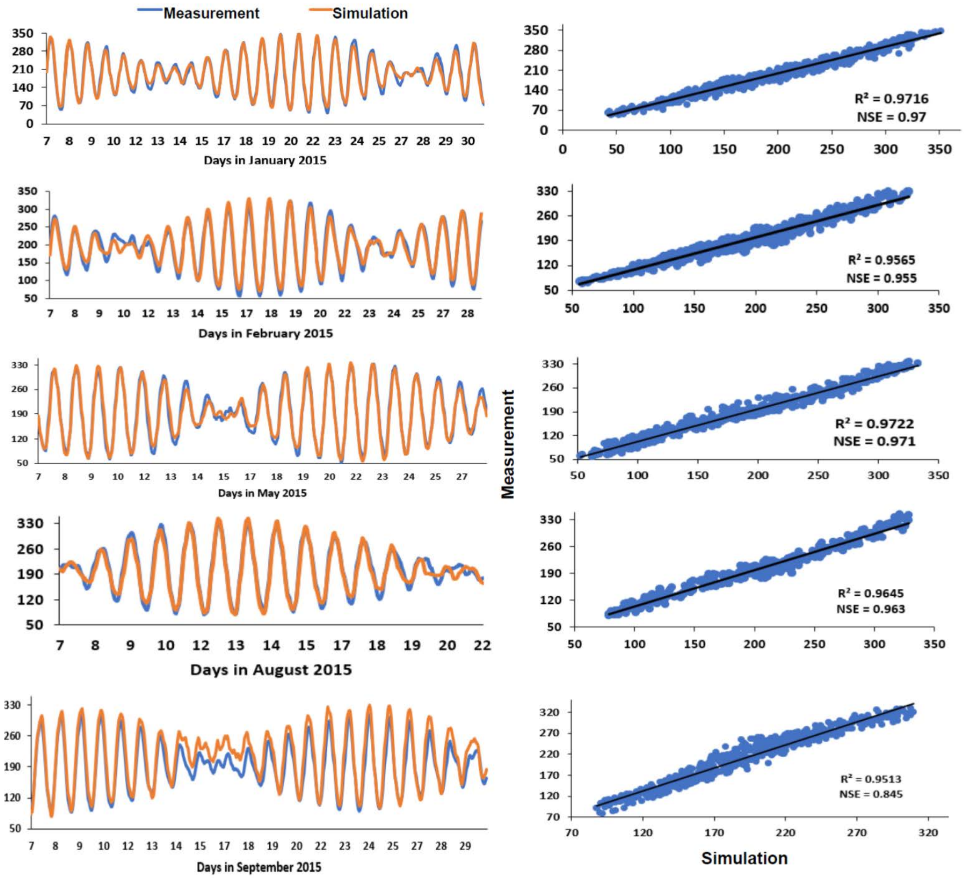


Figure 2. Simulated and measured water levels (cm) comparison, at Hon Dau station in 2015

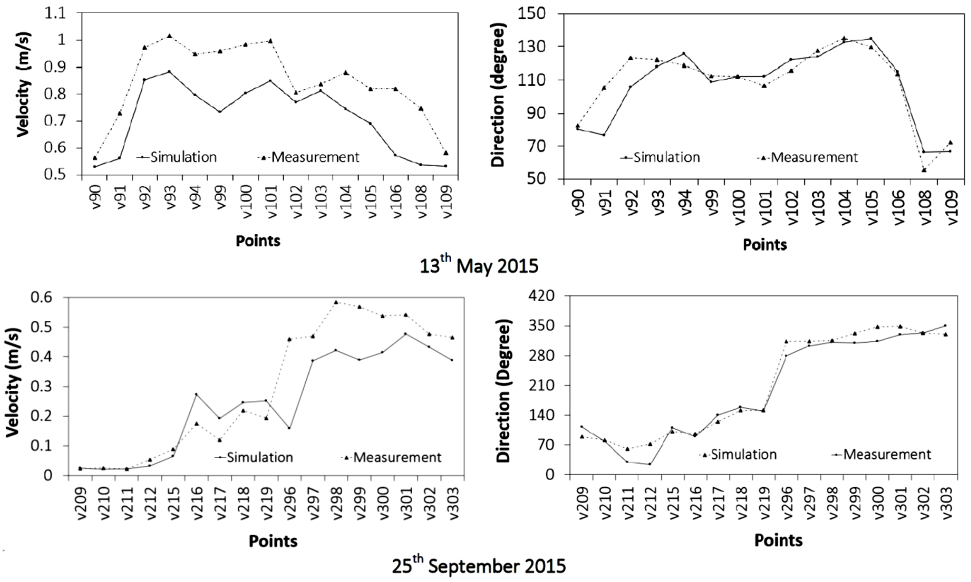


Figure 3. Simulated and ADCP measured velocity (m/s) and direction (degree) in surface layer in May and September 2015 seaward in the Cam-Nam Trieu estuary

Table 2. RMSE, NSE and R^2 coefficient between simulated and ADCP measured velocity (m/s) and direction (Degree) in surface layer in May and September 2015

Velocity	Months	RMSE	NSE	R^2
Magnitude	13th May	0.159	0.655	0.7
	25th September	0.109	0.738	0.811
Direction	13th May	0.154	0.595	0.593
	25th September	0.217	0.74	0.91

Due to there are no survey data during the dry season, in this study, the flow calculation results are verified with measurements in May and September 2015. Figure 3 and Table 2 show a relatively good matching of simulation and ADCP measurement of current velocity and direction. At first glance, the simulated results and measured data shared a relative closed trend in velocity magnitude. NSE, RMSE and R values are all in accepted range. Therefore, the results obtained from the models are match with the natural situations.

Seasonal variation of horizontal currents

Horizontal current in the dry season

In general, due to river discharge, current flows with bigger magnitude during wet and early wet season than that during dry season, especially in the surface layer. Figure 4 shows current field (m/s) in the area during dry season with flow velocity varies greatly according to tide phases and primary nearshore direction is SE-NW. Current velocity during spring tide commonly changes between 0.1–0.8 m/s. During high water, the flow velocity is quite small (especially outside the estuary). The influence of freshwater flow by this time is very limited, so the sea water intrudes deeper into the estuary. It is noteworthy that at the time of high water, freshwater flow still appears in the estuary with a velocity ranging from 0.1 to 0.4 m/s even the flow velocity is very offshore. During neap tide, flow velocity has a relatively small velocity and is strongly dispersed in magnitude and direction. Due to the magnitude of freshwater flow is small, slack tide duration is shortened and the flow quickly changes into flood tide. During neap tide, flow velocity changes more dramatically during flood and ebb tides than that during high and low tides.

Horizontal current in transitional season

Figure 5 shows current field in the area during early wet season. Flood tide causes seawater to migrate inland during the early wet season. On the nearshore, the predominant flow direction is SE-NW. Because of the combination of freshwater and saltwater, especially in the surface layer, flow velocity in ebb tide is significantly greater than that in flood tide. Current velocity in this tidal phase commonly fluctuates between 0.2-1 m/s and significantly drops in high water. The flow velocity is comparatively small and widely distributed in both direction and magnitude in neap tide. The flow is small because the slack tide lasts less and transitions into flood tide more quickly. The flow velocity is comparatively small and widely distributed in both direction and magnitude during neap tide.

Horizontal current in the wet season

Figure 6 shows current field (m/s) in the area during wet season. In the wet season, although the discharge of river water is larger than in the dry season, but due to the influence of the wind field, the flow of seawater landwards is quite large. During flood tide, the flow velocity value varying from 0.1–0.7 m/s. Witnessing the same trend in dry season, during flood tide in wet season, seawater flows landwards deeply in the river with a velocity value of about 0.4–0.7 m/s while flow velocity offshore is quite small. Around 1–2 hours after flood tide, the value of flow velocity is minimum and changes direction and creates ebb tide. The flow velocity at the end of flood tide increases from the outside to the inside of the estuary, while the beginning of ebb tide tends to decrease from the inside of the estuaries to the sea. During neap tide, freshwater flows seaward rapidly, however, because the area topography is strongly differentiated when the water level is low, the flow scattered in both direction and magnitude values.

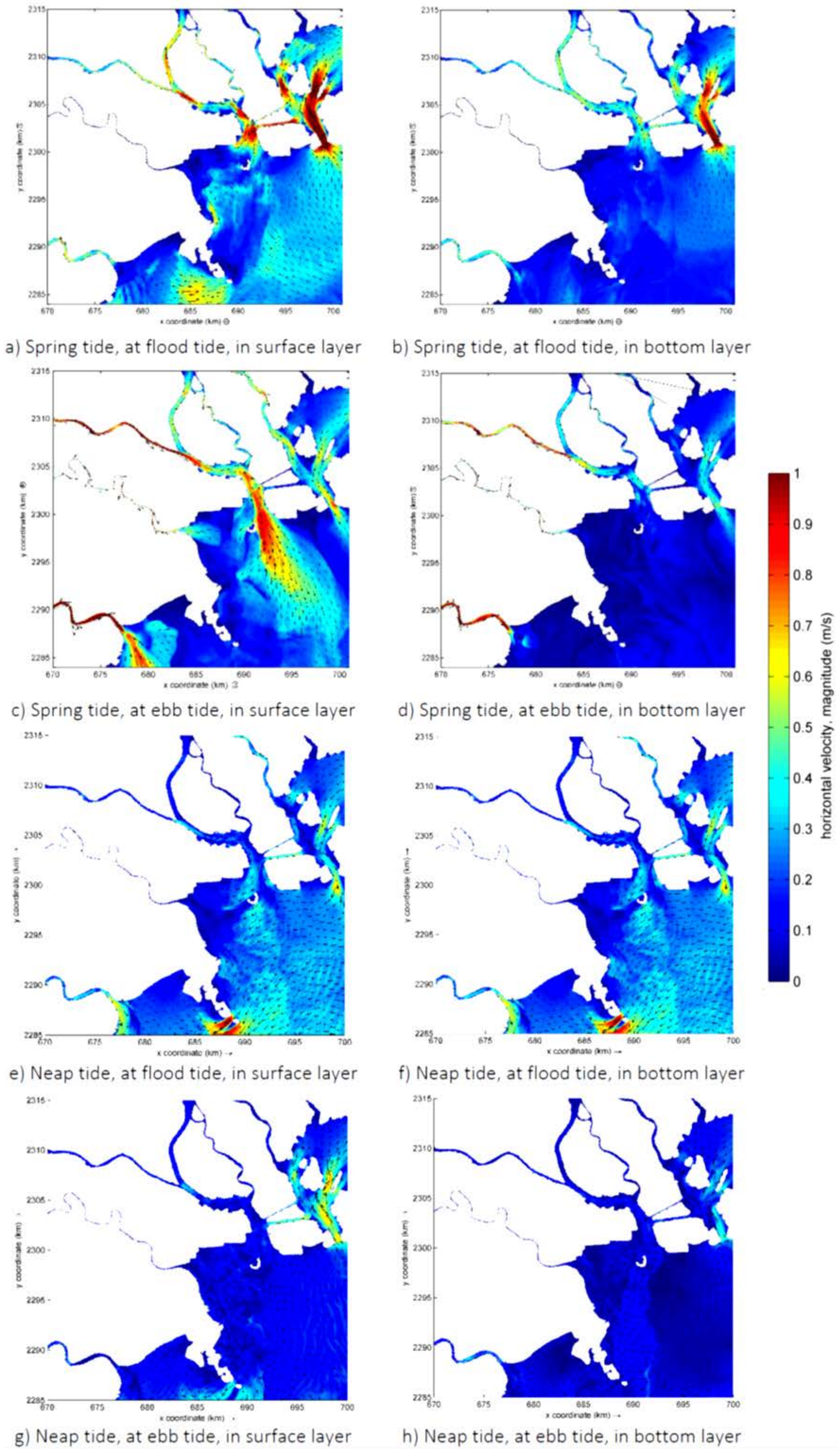


Figure 4. Current field (m/s) in Hai Phong's estuaries during dry season, on 21st (spring tide) and 27th (neap tide) January 2015

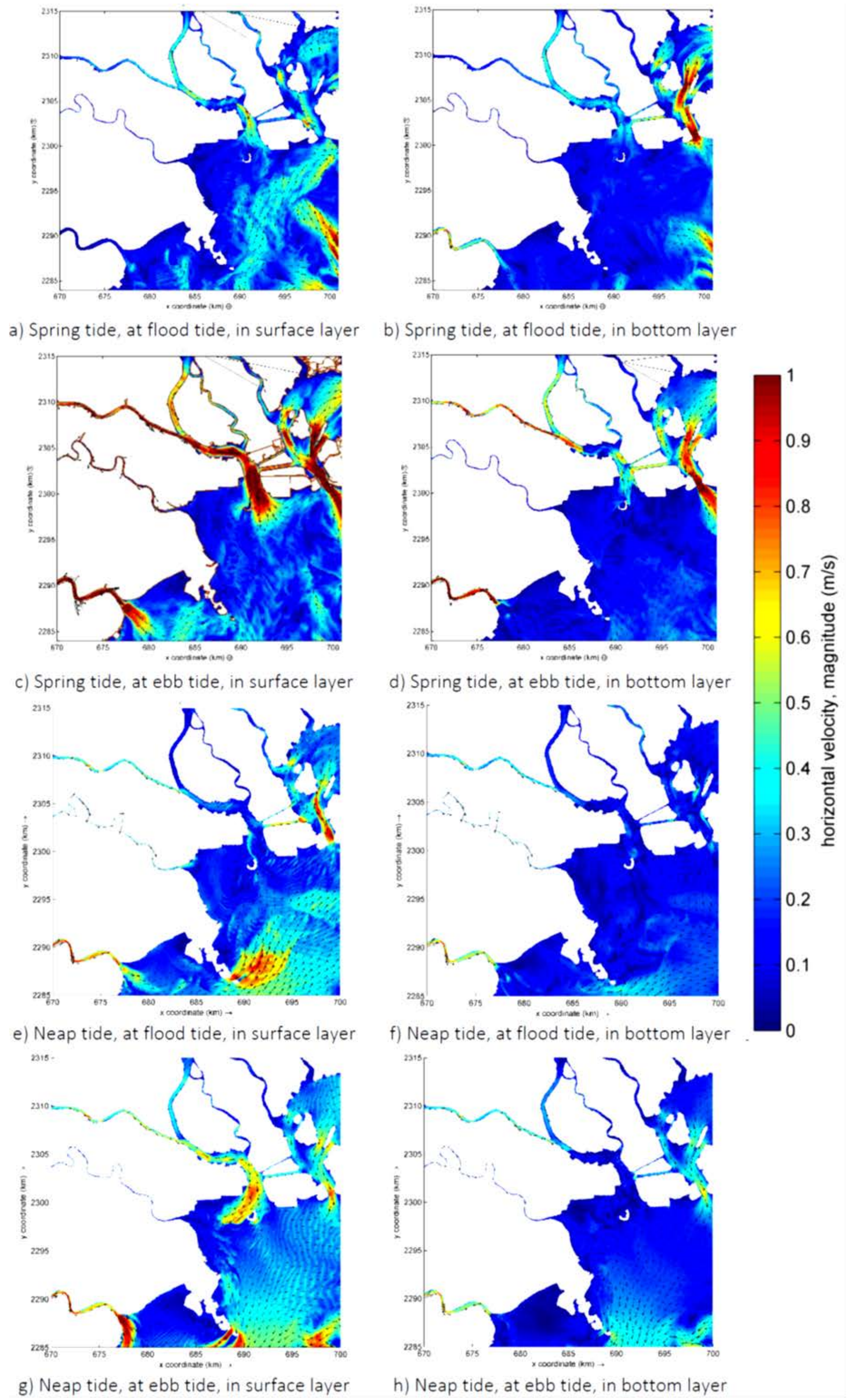


Figure 5. Current field (m/s) in Hai Phong's estuaries during early wet season, on 12th (spring tide) and 15th (neap tide) May 2015

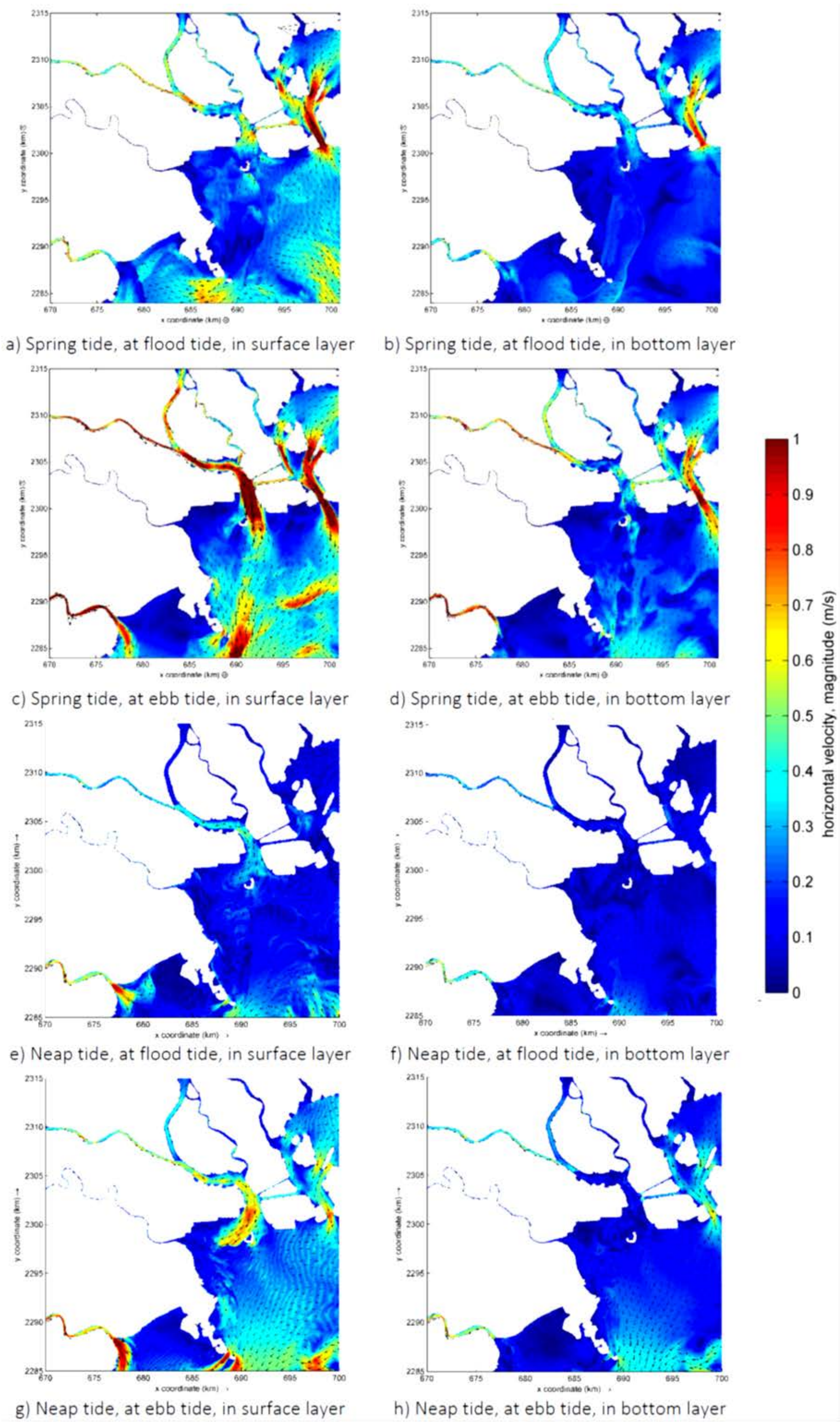


Figure 6. Current field (m/s) in Hai Phong's estuaries during wet season, on 24th (spring tide) and 17th (neap tide) September 2015

Seasonal variation of current profile along Cam-Nam Trieu estuary

The simulation successfully replicates currents profile in nature which reviews two different parts of water in river and outside of the estuary. In the former part, current along water column is less stratified than that in the later one. Due to narrow river and a certain amount of water flows from Bach Dang River (around the middle of transect), water velocity inside is bigger than that near and outside the estuary (Fig. 1). Water velocity stratification in spring tide is more significant than that in neap tide. Because river discharge is pronounced in dry season, during neap tide, current velocity is bigger in ebb and low tides than that in flood and high tides.

Hourly water discharge measurements at the Cua Cam hydrographic station revealed a significant increase in river discharge from the dry to the wet season (Figs. 7, 8). This transition marked a distinct shift between high-flow (wet season) and low-flow (dry season) regimes. Figures 9–11 depicts variation of current profile in 2015 in the cross-section from position A to position B (Fig. 1). The water column exhibited varying degrees of stratification, ranging from fully mixed to highly stratified, influenced by tidal cycles and freshwater influx (Figs. 9–11).

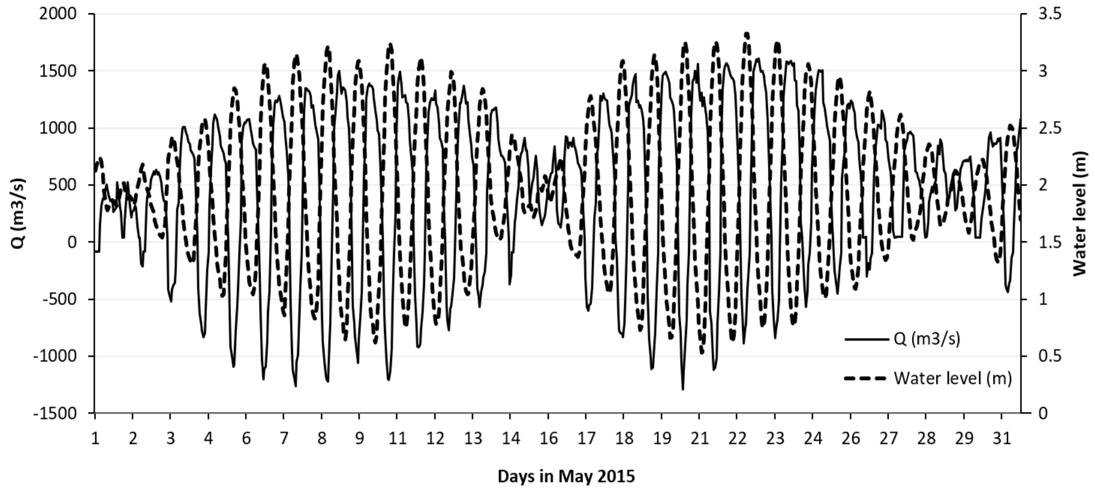


Figure 7. Water levels (m) and river discharges (m^3/s) in the Cam river in May 2015

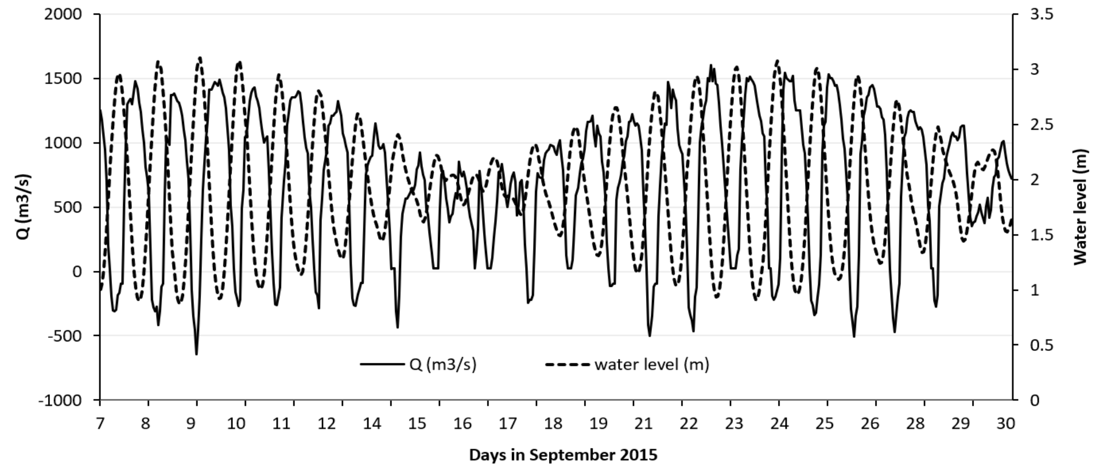


Figure 8. Water levels (m) and river discharges (m^3/s) in the Cam river in September 2015

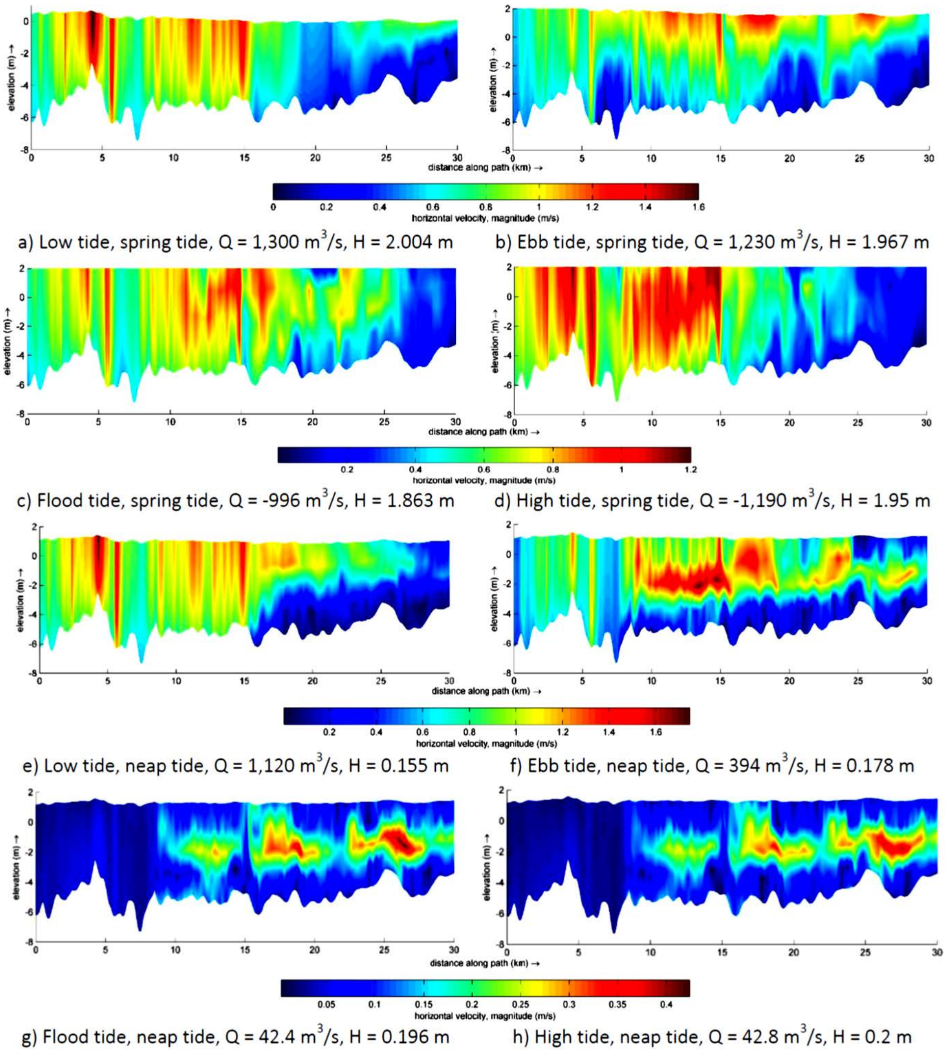


Figure 9. Variation of current profiles along Cam-Nam Trieu estuary on 21st (spring tide) and 28th (neap tide) Jan 2015

In dry season

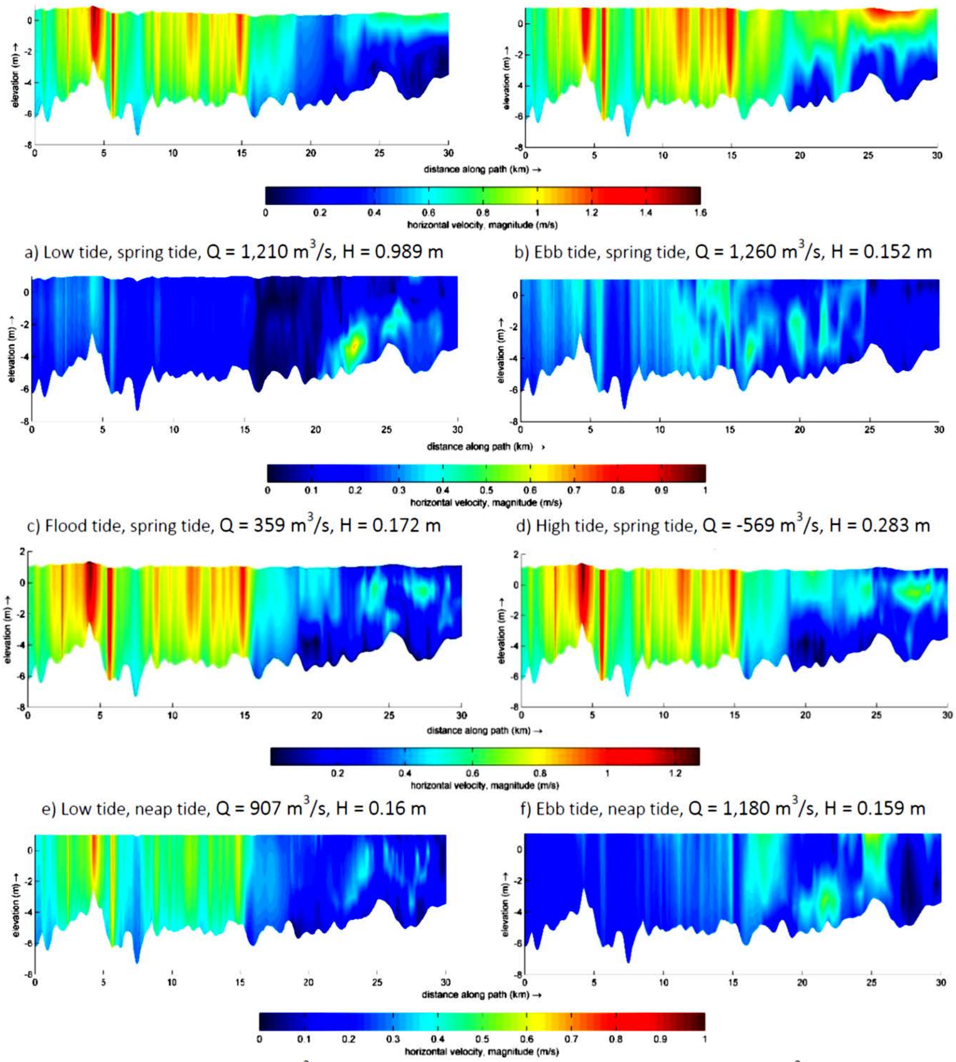
Figure 9 shows the variation of current profile in dry season. In spring tide, the flow velocity can be higher than 1.6 m/s on surface layer, that could not exceed 1.2 m/s during neap tide. In neap tide, the flow velocity is extremely low in the bottom, below 0.2 m/s even it can be extremely high in the middle of the water column. It can be explained by a certain amount of water flows from the Lach Huyen to the Cam River through two 2 channels (Figs. 4e-h).

In transitional season

Figure 10 shows the variation of current profile in Cam-Nam Trieu estuary in early wet season. The flow variation occurs during neap tide and is smaller in amplitude than it is during spring tide. The current velocity fluctuates significantly with depth in near and outside of the estuary.

In wet season

Figure 11 shows the variation of current profile in Cam-Nam Trieu estuary in wet season. Freshwater flows fast from the river seawards, in the begging of the transect. During flood and high tide, freshwater tends to stay still with velocity less than 0.2 m/s.



a) Low tide, spring tide, Q = 1,210 m^3/s, H = 0.989 m
b) Ebb tide, spring tide, Q = 1,260 m^3/s, H = 0.152 m
c) Flood tide, spring tide, Q = 359 m^3/s, H = 0.172 m
d) High tide, spring tide, Q = -569 m^3/s, H = 0.283 m
e) Low tide, neap tide, Q = 907 m^3/s, H = 0.16 m
f) Ebb tide, neap tide, Q = 1,180 m^3/s, H = 0.159 m
g) Flood tide, neap tide, Q = 733 m^3/s, H = 0.166 m
h) High tide, neap tide, Q = -88.8 m^3/s, H = 0.217 m

Figure 10. Variation of current profiles along Cam-Nam Trieu estuary on 12th (spring tide) and 14th (neap tide) May 2015

Discussion

Fluctuations in freshwater input from the Cam and Nam Trieu rivers throughout the year significantly impact current strength and direction. Higher discharge during the rainy season (May to October) leads to stronger currents (flowing out to sea) and weaker currents (flowing towards the estuary). In contrast, the dry season (November to April) experiences lower discharge, resulting in weaker currents overall and potentially stronger currents, especially with tidal influences.

Throughout the day and month, the interaction between these tides and river discharge determines the direction and speed of the stream. River discharge may not have as much of an impact as tidal currents, which are strongest during spring tides (when the moon and sun line up). Within the estuary, tidal forcing produces alternating tidal currents in flood and ebb tide. At high tide, currents flow upstream as water pushes landward from the sea. Currents move back towards the ocean when the tide recedes. The dominance of tidal currents in the lower estuary is highlighted by [2], especially during spring tides when their influence can even outweigh that of river discharge. Vertical mixing caused by tidal forcing can affect the salinity and sediment transport in the estuary. Vu Duy Vinh et al. [3] noted that strong tidal currents might occasionally result in well-mixed conditions throughout the water column, whereas weaker currents may allow for stratification with differing salinities at different depths. The Cam-Nam Trieu estuary exhibits tidal asymmetry, where flood tide are shorter and weaker than ebb tide. This phenomenon, documented by Lefebvre et al [28], emerges as a result of the interaction between the estuary and the Gulf of Tonkin as well as tidal forcing. The duration of flood and ebb tide, currents are affected by tidal asymmetry, which also affects overall sediment movement and estuary morphology.

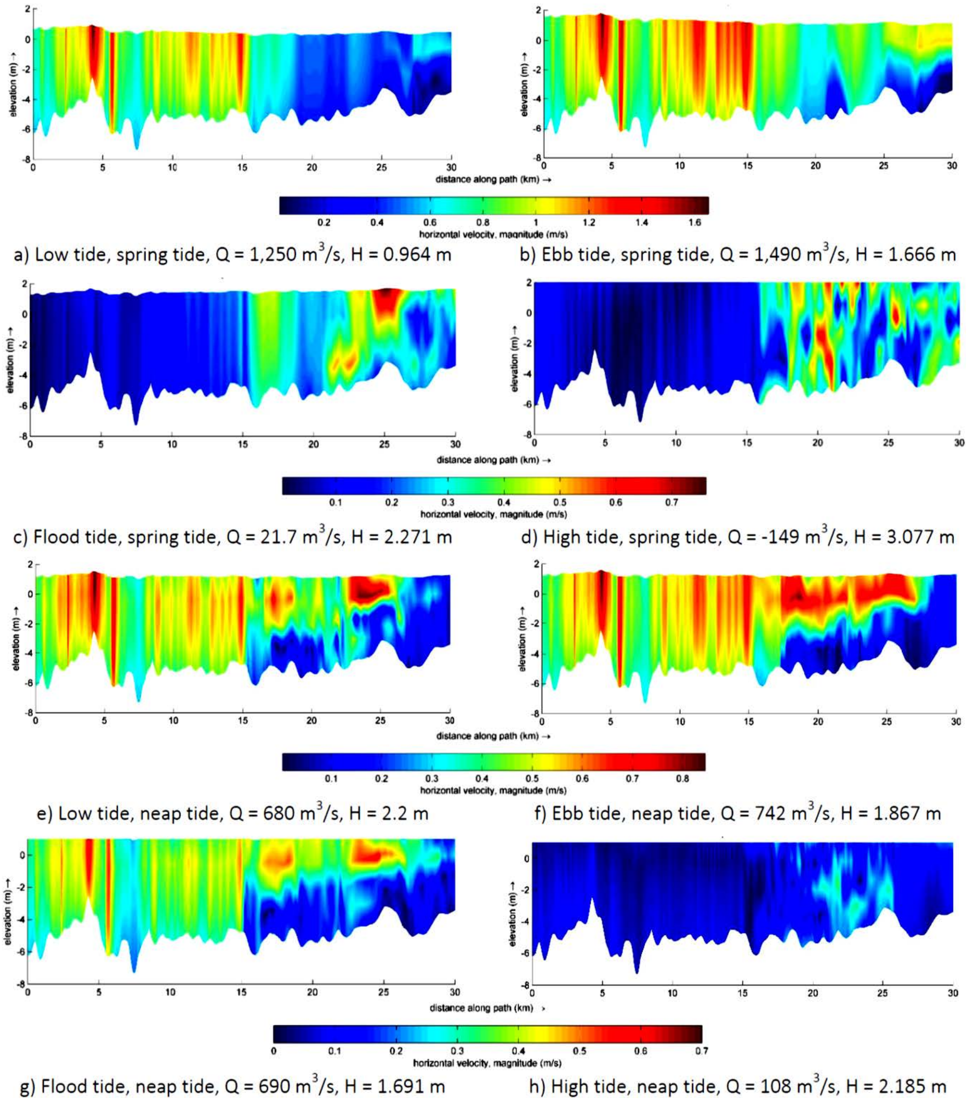


Figure 11. Variation of current profiles along Cam-Nam Trieu estuary on 17th (neap tide) and 24th (spring tide) Sep 2015

Meteorological factors such as wind and rainfall effects on the variation of currents. Wind stress on the water surface can contribute to near-surface current patterns. Prevailing winds in the region during different seasons can cause additional fluctuations in current speed and direction. For example, strong Northeast monsoon winds during the winter months might promote stronger surface currents flowing southward within the estuary. Although included in the hydrological category, seasonal variations in rainfall, particularly intense events, can cause sudden changes in river discharge and subsequent current patterns [2, 3, 33].

The shape and depth of the estuary bed can influence how currents flow and interact with each other. Shallow areas might experience stronger frictional effects, slowing down currents, while deeper channels might experience faster-moving currents. The Cam-Nam Trieu estuary exhibits a funnel-shaped geometry, expanding significantly as it approaches the open sea. This configuration causes significant changes in current velocities throughout the estuary. Vu Duy Vinh et al. [34] show that current speeds decrease as the estuary widens, leading to greater sedimentation accumulation towards the seaward regions. Deeper channels act as conduits for faster-moving currents, while shallow areas experience increased frictional drag and slower velocities. The presence of tidal flats and shoals within the estuary, which significantly influence near-bed current patterns and contribute to sediment trapping and erosion dynamics. The erosion and deposition of sediments within the estuary can also affect current dynamics. As sediments move with the currents, they can alter the channel morphology and influence the flow patterns. Dredging and channel modifications that are currently happens in the area can change the depth and shape of the estuary bed, potentially leading to alterations in current patterns.

During the high-flow season, the upper estuary experienced predominantly mixed conditions with low salinity levels [2, 3, 9]. Conversely, the low-flow season witnessed a gradual transition from partially stratified to highly stratified conditions, particularly in the middle and lower estuary, primarily driven by the combined effects of neap-spring tidal cycles, diurnal tides, and reduced discharge. Spring tides resulted in partial stratification at high tide and mixing at low tide, while neap tides consistently maintained strong stratification.

Conclusion

The model of hydrodynamic processes in Cam-Nam Trieu estuary was developed successfully by Delft3D. Simulated and observed water levels and current velocity share a similar trend with high and very high results of NSE. Results obtained from the model are reliable and the model can be applied to further sediment-related studies in the future.

During ebb tide in the spring tide period, the current velocity can exceed 1.6 m/s. The river's flow into the sea is less during the dry season than it is during the rainy season. During spring tide, there is a more noticeable stratification of water velocity compared to neap tide. Because of the strong river flow during neap tide, which happens throughout the dry season, the current velocity is higher during ebb and low tides than during flood and high tides.

Current velocity and direction fluctuate with tide cycles and seasons. The flow usually has high value and fluctuates strongly during high tide. The maximum flow magnitude during the ebb tide is usually bigger than that during flood tide. The minimum flow velocity occurs after the maximum water level of about 1–2 hours, in which the minimum flow in during high tide is usually smaller than the minimum flow during the low water.

In wet season, the difference in maximum flow magnitude between ebb tide and flood tide phase is often larger than that difference in the dry season. The maximum flow velocity in the rainy season is also usually bigger than that in dry season. The number of hours of flow with high velocity values in the wet season is also larger than that in the dry season.

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