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Simulation of typhoon-induced hydrodynamic conditions in the Hai Phong coastal area: a case study of Son Tinh typhoon 2012 and 2018

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ABSTRACT

The Hai Phong coastal area is one of the places that is often affected by storms and tropical depressions, with significant impacts on hydrodynamics and geomorphological changes. The influence of typhoons on hydrodynamic conditions in the Hai Phong coastal area has yet to be thoroughly studied. Accordingly, the above study has evaluated the influence of storms with different trajectories on the hydrodynamic field in the Hai Phong coastal area under complex, non-linear impacts to contribute to a better understanding of the influence of storms on hydrodynamic processes and to improve research capacity on hydrodynamic regimes in coastal estuaries using modeling tools. Observational and reanalysis data from global sources were collected systematically and homogeneously to create open boundary conditions (time-serial) for the model. The NESTING method created sea boundary conditions for the model from another model with a larger grid outside. The Delft3D model system was set up with five vertical layers in Sigma coordinates and was validated, showing a fair agreement with measurement data at some places in the study area. Results of scenarios showed typhoons have an extreme impact on hydrodynamic conditions in the Hai Phong coastal area, especially raising the water level and increasing the flow velocity and wave height in the coastal area. Different typhoons effect the hydrodynamics differently, but they all share that the estuary areas with narrow channels are more strongly affected than the remaining areas. When the typhoons make landfall at the Lach Huyen estuary in Nam Trieu, the flow velocity can be up to 0.8–1.2 m/s (an increase of 0.5 m/s compared to the flow velocity in normal conditions), and the wave height can be up to 1.2–2.5 m (a rise of 0.4–2 m compared to the wave height in without typhoon).

Keywords: Hydrodynamic, Delft3D, Hai Phong coastal area, typhoons Son Tinh.

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INTRODUCTION

The Hai Phong coastal area (Fig. 1) is characterized by complex hydrodynamic conditions and substantial seasonal variation [1, 2]. The area's unique shape gives rise to a typical tidal pattern, with a maximum tidal range of up to nearly 4 m, and it benefits from a significant sediment supply from the Red River-Thai Binh system. However, these features also lead to frequent deposition areas, primarily the alluvial phenomenon in the port of Hai Phong, which negatively impacts on economic-social development and national defense security in Hai Phong, particularly Vietnam in general [2, 3]. Therefore, the study of hydrodynamic conditions in the Hai Phong area is not only crucial for understanding the causes of sedimentation in the Hai Phong port area but also for providing solutions to this problem for designing coastal works such as breakwaters, port-serving works such as wharves, and shipping lanes.

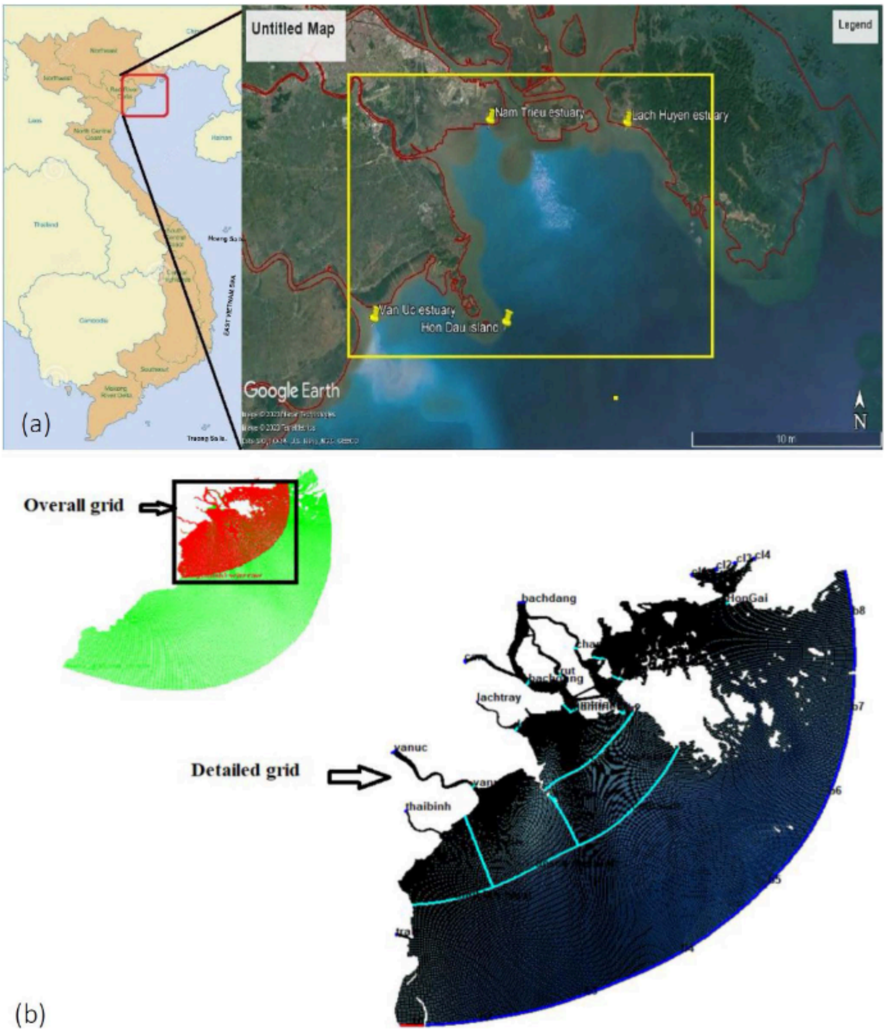

Figure 1. Model domain (in the yellow box, a) and the model grid (b) for Hai Phong coastal area

While there have been numerous sedimentation studies with different approaches (geology, geomorphology, dynamics) in the Hai Phong port area in particular and the hydrodynamic conditions in this area in general [1–7], there is a noticeable gap in-depth studies or comprehensive evaluations of the reciprocal impacts of natural conditions on hydrodynamic conditions in extreme weather conditions, especially the impacts and effects of typhoons in the Hai Phong area, considering that each typhoon occurence can disrupt the balance maintained over a long period. Cyclones and their consequences (floods, typhoons, surges, etc.) are among the most powerful factors affecting hydrodynamic conditions, sediment transport, and coastal erosion [8]. Typhoons cause water levels to rise, creating waves with strong intensity and a large amplitude. This effect is more evident in the estuarine area, the impact of waves on the seabed increases and forms currents in the direction of the shore. The impact of waves in typhoons increases the erosion-accretion process and sediment transport in the estuarine area and is an important cause of changing the shape of the shoreline. The total water level induced by typhoons is a combination of tidal, storm surge, and wave surge. The degree of impact of each factor depends on the typhoons, the specific position of the shoreline, and the time of the flood tide and ebb tide.

Using a 3D numerical model with the support of modern computational and technological tools (increasing grid resolution and processes), combining various methods such as GIS to process geographic data, statistical analysis to process data as input for the model, numerical modeling to simulate the hydrodynamic regime of the Hai Phong coastal area during the northeast and southwest monsoon seasons and the Son Tinh typhoons in 2012 and 2018, this study aims to provide an understanding of the impacts of typhoons on the Hai Phong coastal area.

DATA AND METHODS

Hai Phong coastal area

The study area is located in the region, bounded by the coordinates 20°5′N–20°9′N latitude and 106°5′E–107°1′E longitude (Fig. 1). The Hai Phong estuarine area is formed by the dynamic processes of rivers, seas, and river-sea interactions [2]. It is a coastal area with an extensive tidal range in the humid subtropical climate belt. It is influenced by two monsoon systems: The Northeast monsoon in the dry season and the Southwest monsoon in the rainy season [1]. Hai Phong City's coastline is curved, relatively low, and flat, mainly composed of sand due to the five estuarine outlets. The topography of the Hai Phong estuarine area is shallow and has a slight slope, and the seabed is composed of fine particles with many shallow trenches, which are the old rivers that now serve as channels for ships [3, 8].

The Hai Phong coastal area is strongly affected by its hydrological regime. River flow encompasses strong seasonal variations, with 71–79% of the total annual water discharge in the rainy season and only 9.4–18% during the dry season [9[. In addition, this area is influenced by diurnal tide, with an amplitude of 2.6–3.6 m in spring tide and about 0.5–1.0 m in neap tide[3]. Some recent studies have also shown that the coastal area of Hai Phong is where the manifestation of climate change: sea surface warming trend of 0.02°C/year for the period 1995–2020 and 0.093°C/year for the period 2008–2020 [10]; the average annual rate of sea-level was 7.78 mm/year over the periods 2002–2020 [11].

According to the Ministry of Natural Resources and Environment, Hai Phong belongs to Typhoon Zone I - the zone with the most typhoons and impacts, accounting for 31% of the total entering the country annually. The direct typhoon pouring period into Hai Phong is prevalent from July to September, with a total frequency of 78%, 28% in July, 21% in August, and 29% in September. When typhoons land, Hai Phong coastal areas not only cause economic damage and significantly affect the area's topography, especially morphological change, and can cause sedimentation of the port channel area [8].

Data

Shoreline and Bathymetry

Bathymetric data and shoreline were digitized from two sources, including field surveys conducted under the framework of the International VAST-IRD project (Research on the relationship between the dynamical creation of estuary maximum sediment settling in Cam - Nam Trieu estuary and the deposition of sediment in the Hai Phong navigation channel) and UTM-based geographical coordinates of VN 2000 (1:50,000 scale) issued by Vietnam Mapping and Geodesy Department. In addition, bathymetric data and geographical data of the outer areas and East Vietnam Sea were based on GEBCO - 1/8 (General Bathymetric Chart of the Ocean) of the UK Hydrographic Office with a resolution of 15 seconds, which were processed from satellite imagery combined with actual depth data[12, 13]. To synchronize these data, we remove GEBCO data in the coastal area and calibrate the GEBCO data (offshore) to the same chart datum of VN2000 data.

Meteorological Data

Wind data (*u*-*v* wind components with a 0.2° × 0.2° resolution) and pressure (0.2° × 0.2° resolution) of the whole East Vietnam Sea are updated from the reanalysis database of global climate model CFSR (Climate Forecast System Reanalysis) of the United States National Centers for Environmental Prediction with a six hourly frequency (00 h - 06 h - 12 h - 18 h UTC) as the forcings of the model.

In this study, we selected typhoons: Son Tinh in 2012 and Son Tinh in 2018. Information about these typhoons (maximum wind speed, maximum wind radius, typhoon center pressure, etc.) was referenced from the Japan Meteorological Agency: Typhoon Information and the Center for Environmental Forecasting NCEP [14], which was included in the model as a whole domain. In order to evaluate the influence of different typhoons on the hydrodynamic regime in the coastal area of Hai Phong, the study simulated two typhoons representing the landfall conditions in different periods and carrying different properties and characteristics. Typhoon Son Tinh 2012, a severe cyclone with a prolonged evolution and a complex track, caused heavy rain and floods and landed during the low tide. In contrast, Typhoon Son Tinh 2018 was a medium-intensity typhoon - a level 6 - but a fast-moving typhoon that made landfall during the high tide period. After that, it caused heavy rain and continued to recur before making a second landfall in China.

Hydrological data

We collected river discharge measurements data (with a frequency of 1 hour/time) and suspended sediment data (with a frequency of average monthly) at Cam Stations and Trung Trang Station on Cam and Van Uc rivers in 2012 and 2018 collected from the National Hydrological Meteorological Centre. In addition, measurements of the flow and suspended sediment content of some related topics in this area of the recently carried out projects of IMER have also been used. These projects include:

Hai Phong's scientific and technological research project 2020–2022: Load assessment and transportation of pollutants from upstream to major rivers in Hai Phong coastal area;

VAST-IRD Project 2020-2021: Research on the relationship between the dynamical creation of estuary maximum sediment settling in Cam - Nam Trieu estuary and the deposition of sediment in the Hai Phong navigation channel.

Oceanographic data

Include water level, flow, wave, sea water temperature, and salinity. Among them, the tidal data is analyzed from 13 tidal constituents, including M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, MF, MM, M_4, MS_4, MN_4 based on tidal harmonic constants dataset with a spatial resolution of 0.25° × 0.25° based on data from the TOPE in the software package OTIS (OSU Tidal Inversion Software) database [15]. The water level, flow, and wave measurements at several surveyed locations within the study area have been collected and processed to calibrate and verify the hydrodynamic model. In addition, to calculate the boundary condition in the East Vietnam Sea, the temperature and salinity data are reprocessed from World Ocean Atlas 2013 [16].

Methods

The main method used in the research is mathematical modeling. The hydrodynamic conditions are modeled by the Delft3d Flow module in the Delft3d modeling system of the Detalres Netherlands [17]. This model is widely used in the world, including Vietnam, and can simulate hydrodynamic conditions and wave refraction of the coast. The hydrodynamic model for the Hai Phong estuarine area uses a curvilinear grid with an area of water of about 2,100 km^2, divided into 468 × 628 points, with grid cell sizes ranging from 3.9 m to 264.5 m (Fig. 1-b). Vertically, the whole water column is divided into 5 layers of depth according to the coordinate system σ. The model is set up and run according to the time of the scenarios with a time step of 15 seconds.

Initial conditions (water level, temperature, and salinity) were averaged over several years in the Hai To evaluate the impacts of typhoons on the dynamic conditions of the coastal area in Hai Phong, different scenarios were established for conditions with and without typhoons:

Scenario for conditions without typhoons: Two characteristic seasons of the year were considered: the rainy season (from June to September) and the dry season (from November, December, and January of the following year) in 2012 and 2018 (these are two years of strong monsoon season with recorded intensity higher than the average for many years). The purpose was to simulate the hydrodynamic characteristics during these seasons.

Scenario for conditions with typhoons: Several scenarios were developed to assess the conditions before, during, and after the typhoons as follows:

Scenario for evaluating the impact of Typhoon Son Tinh in 2012: October (typhoon made landfall on 27–29 October 2012) - the typhoon hit during the dry season;

Scenario for evaluating the impact of Typhoon Son Tinh in 2018: July (typhoon made landfall on 18–22 July 2018) - the typhoon hit during the rainy season.

The model has ocean and river boundaries: the ocean boundaries include the Southern section of Tra Ly, the South-Eastern and South-Western Cat Ba Islands, and the South-Eastern Tuan Chau - Quang Ninh. The river boundaries include cross-sections at Bach Dang River, Cam River, Lach Tray River, Van Uc River, Thai Binh River, and Tra Ly River. Data for the ocean boundaries are the results from the outer model. Then, the NESTING method creates data files for temperature, salinity, and water level at the boundaries. These are time-series data with a frequency of 1 hour per time. The salinity and temperature data for boundary conditions are averaged monthly for the river boundaries. The water discharges for the river boundaries are time-series data calculated from measured data with a frequency of every hour.

To assess the level of reliability in the calculations, this study used the efficiency index of the forecast - the Nash - Sutcliffe efficiency index (*NSE*), the mean square error (*MSE*) and the correlation coefficient (R^2):

$$NSE = 1 - \frac{\sum_{i=1}^{n} \left(O_i - P_i\right)^2}{\sum_{i=1}^{n} \left(O_i - O_{ave}\right)^2} \qquad (1)$$

$$MSE = \frac{1}{n} \sum_{i=1}^{n} \left(O_i - P_i\right)^2 \qquad (2)$$

$$R^2 = \left\{ \frac{\sum_{i=1}^{n} \left(O_i - O_{ave}\right) \times \left(O_i - P_i\right)}{\left[\sum_{i=1}^{n} \left(O_i - O_{ave}\right)^2\right]^{0.5} \times \left[\sum_{i=1}^{n} \left(P_i - P_{ave}\right)^2\right]^{0.5}} \right\}^2 \qquad (3)$$

in which: O_i is the calculated value from the model; P_i is the observed value; $\overline{O}$ is the average observed value.

When the *NSE* and R^2 approach 1, the simulation results from the model are most accurate, on the other hand, when the *NSE* and R^2 approach 0, the results are not reliable. When the *NSE* is negative, the average characteristics calculated from the monitoring sequence give better forecast results from the model [18].

RESULTS AND DISCUSSION

Model validation and calibration

The model results of water level, flow velocity, and wave height were calibrated and verified through comparison with observed data. Specifically, the parameter set used in the study is presented in Table 1. The simulation results successfully captured the hydrodynamic regime in the Hai Phong area with the given parameter set. For the water level modeling result, after the final calibration, the comparison result shows a certain degree of agreement regarding phase and amplitude between the modeled and observed data. The correlation coefficient between the observed and modeled water levels during the dry and wet season are 0.89 and 0.91, respectively; the Nash coefficient ranges from 0.86 to 0.88; the mean square errors are 0.26 m and 0.24 m, respectively (Fig. 2). The observed flow velocity was analyzed into the u and v components of total flow before comparison with the modeled result from the model. After the final calibration, the comparison result shows an agreement between the observed and modeled flow velocity and wave in this region (Fig. 3). The final parameters used for the model in this study are given in Table 1.

Table 1. Summary of some calculated parameters of the model

Module	Parameters	Values
Flow	Roughness: manning	0.022
	Horizontal eddy viscosity	7 m^2/s
	Horizontal eddy diffusivity	14 m^2/s
	Vertical eddy viscosity	$1.0 \times 10^{-5} m^2/s$
	Vertical eddy diffusivity	$1.0 \times 10^{-5} m^2/s$
Wave	Spectrum	JONSWAP
	Friction	Madsen et al., (1978)
	Breaking	Bettjes & Janssen (1978)
	Alfa	1.0
	Gamma2	0.73

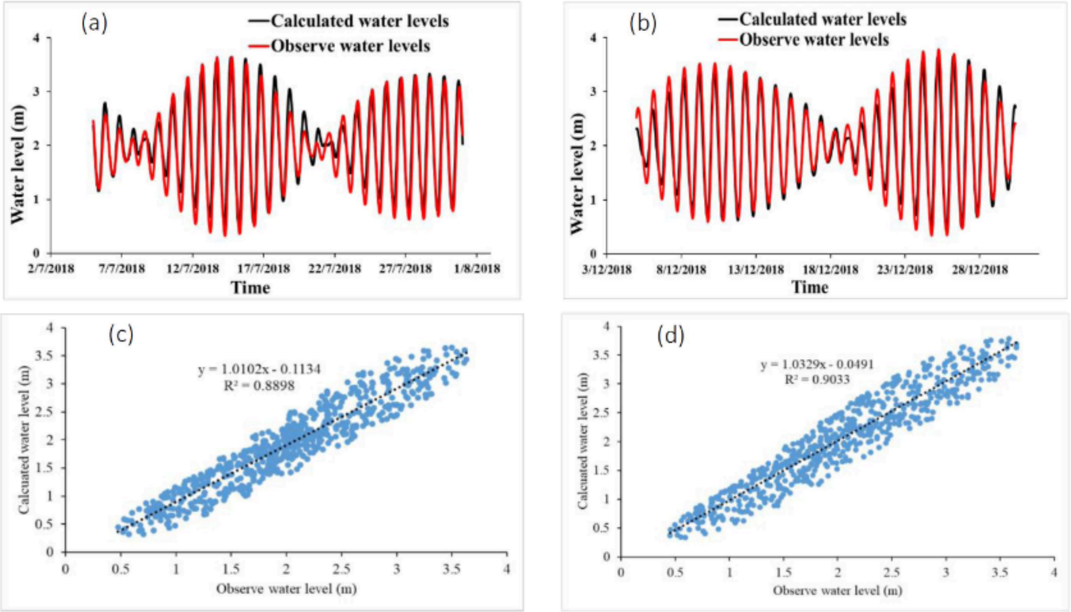

Figure 2. Comparison of observed and calculated water levels at Hon Dau between the two seasons of wet season (a, c) and dry seasons (b, d). (a) - compare the measured and computed water levels during the rainy season, from 1st July to 31st July 2018; (b) - compare the measured and computed water levels during the dry season, from 1st December to 31st December 2018; (c) - correlate the measured and computed water levels during the rainy season; (d) - correlate the measured and computed water levels during the dry season

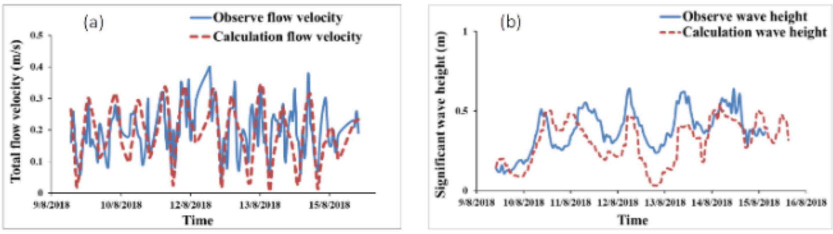

Figure 3. Comparison of flow velocity (a) and wave height (b) between field measurements and model calculations at Do Son - Hai Phong of wet seasons. (a) - compare the measured and computed flow velocities during the wet season, from 9th August to 16th August 2018; (b) - compare the measured and computed wave heights during the wet season, from 9th August to 16th August 2018

Hydrodynamics conditions in the Hai Phong coastal area

Without typhoons, the variations of the wind field and river water load are the leading causes of the seasonal changes in the river flow. In the rainy season, the flow velocity from the sea to the river mouths has a relatively low velocity with a dominant south-southeast direction; the flow velocity ranges from 0.25 m/s to 0.58 m/s. At Van Uc estuary, where the discharge from the river is the highest compared to the other rivers, the flow rate can reach up to 1.1 m/s. Besides, in the narrow section, such as Nam Trieu estuary and Lach Huyen estuary, the flow velocity can reach 0.5–0.63 m/s, while the flow velocity is relatively low in the outer area (Figs. 4, 5). In the dry season, the flow velocity fluctuates strongly following the tide oscillation. However, the change in the wind field and the significant reduction of discharge from the rivers also create relative differences in the river flow in the dry season compared to the rainy season. The comparison of the surface and bottom layer of the river in the region shows that the impact of the discharge from the river mouths is great; the velocity and flow direction of the surface layer depend on the direction and discharge from the river mouths, while the bottom layer is affected by the tide flowing in the opposite direction (Figs. 6, 7).

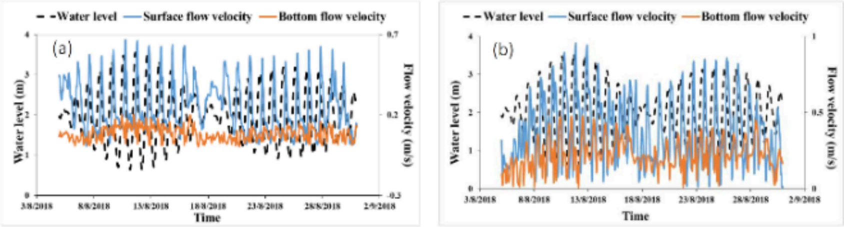

Figure 4. Variations of flow velocity and water level at the Nam Trieu estuary (a) and Lach Huyen estuary (b) during a typical month of the rainy season

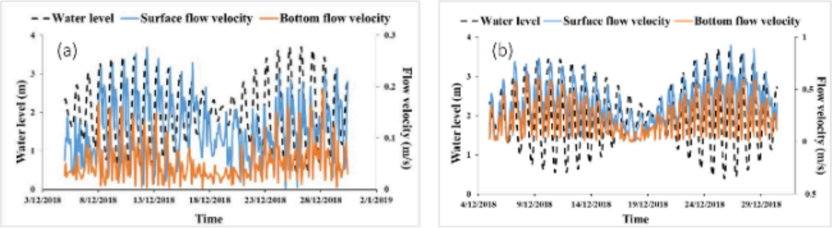

Figure 5. Variations in flow velocity and water level at Nam Trieu estuary (a) and Lach Huyen estuary (b) during a typical month of the dry season

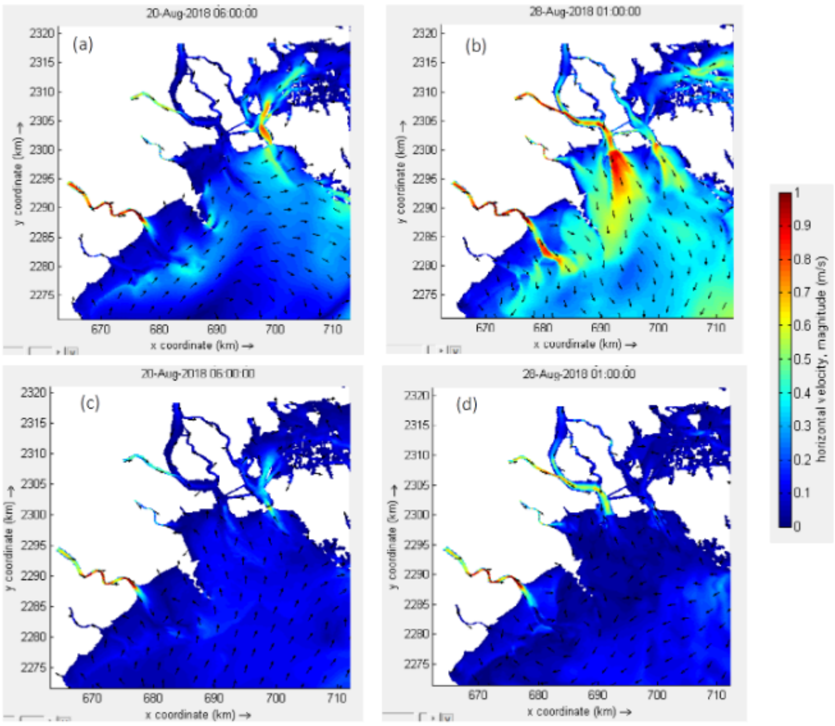

Figure 6. Surface (a, b) bottom (c, d) flow fields during the flood tide phase (left) and the ebb tide phase (right) at typical times in the rainy season

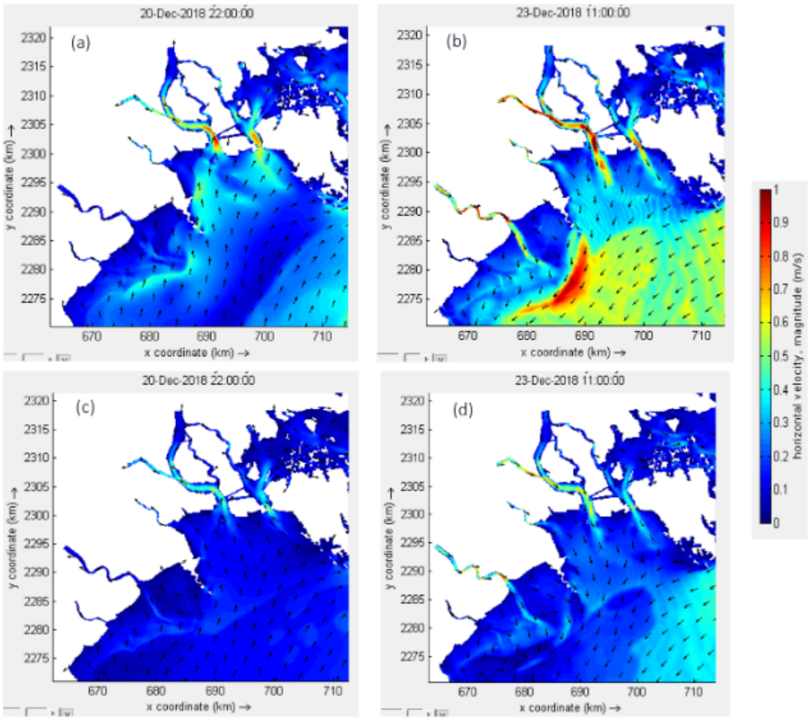

Figure 7. Surface (a, b) bottom (c, d) flow fields during the flood tide phase (left) and the ebb tide phase (right) at typical times in the dry season

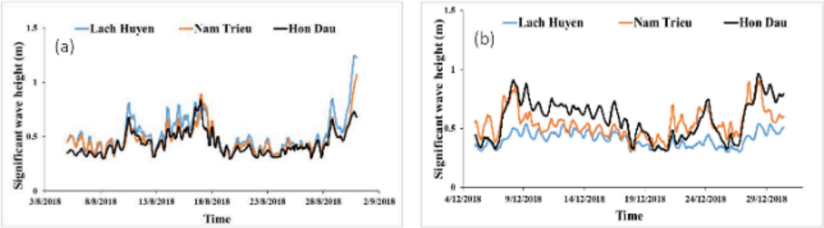

Figure 8. Wave height at Lach Huyen, Nam Trieu, and Hon Dau estuaries in a typical month of the rainy season (a) and dry season (b)

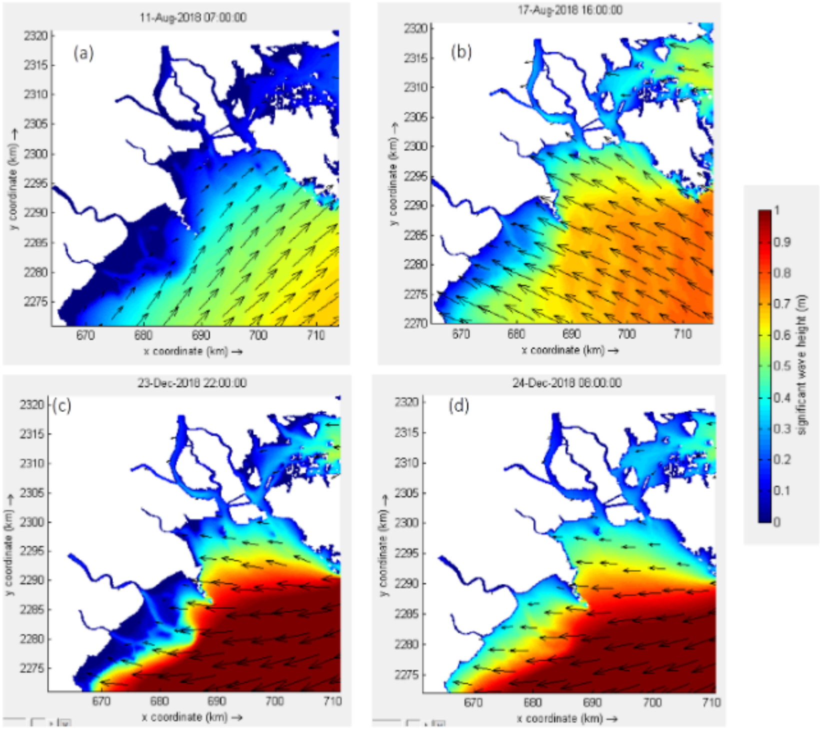

Figure 9. Wave fields at some typical time points in the rainy season (a, b) and dry season (c, d)

As for the wave field, during the rainy season, the prevailing wave directions in the offshore area are South, Southeast, and Southwest; coastal areas are Southeast and Southwest. The average wave height offshore ranges from 0.4 m to 0.65 m; the coastal area is 0.1–0.18 m (Fig. 8). The maximum height can reach 1.2 m in the coastal area and 1.8 m in the offshore area. In contrast to the rainy season, during the dry season, the Northeast monsoon is active in both frequency and speed; however, the wind energy is significantly reduced due to the shelter of Cat Hai and Cat Ba. In addition, the wavelength is short in shallow water conditions, so the offshore swell height is lower than the offshore area. The main wave directions are East and Northeast, with average wave heights of 0.35–0.55 m offshore, ranging from 0.22–0.38 m in coastal areas. The maximum wave height can reach 1.55 m offshore and 0.9 m inshore (Fig. 9).

Hydrodynamic condition in the Hai Phong coastal area during the typhoons

Under the influence of the typhoon, the sea level in the Hai Phong coastal area surged to 0.47 m for Typhoon Son Tinh 2012 (at 20:00 on Oct 28th, 2012) and to 0.35 m for Typhoon Son Tinh 2018 (at 18:00 on July 18th, 2018) (Fig. 10).

Under the impact of a large typhoon (Son Tinh 2012), the average flow velocity was relatively high, ranging from 0.6 m/s to 1.1 m/s (an increase of 0.5 m/s compared to the flow velocity under normal conditions) with an East-North direction in the nearshore. The highest flow velocity was observed in the Van Uc estuary, the Nam Trieu - Lach Huyen estuary, and the offshore area 20 km from the coast (especially in the area near the center of the typhoon, the flow velocity was over 1.2 m/s); the lowest was in the Southern part of Do Son Peninsula (Fig. 11). In the average typhoon (Son Tinh 2018), the average flow velocity only reached 0.3 m/s to 0.8 m/s (an increase of 0.3 m/s compared to the flow velocity under normal conditions).

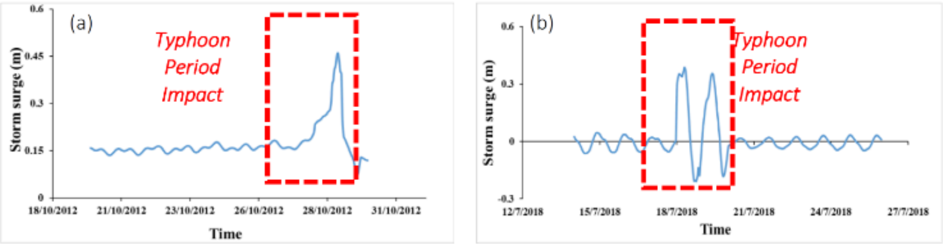

Figure 10. Typhoon surge at Hon Dau in Hai Phong during typhoons Son Tinh in 2012 (a) and 2018 (b)

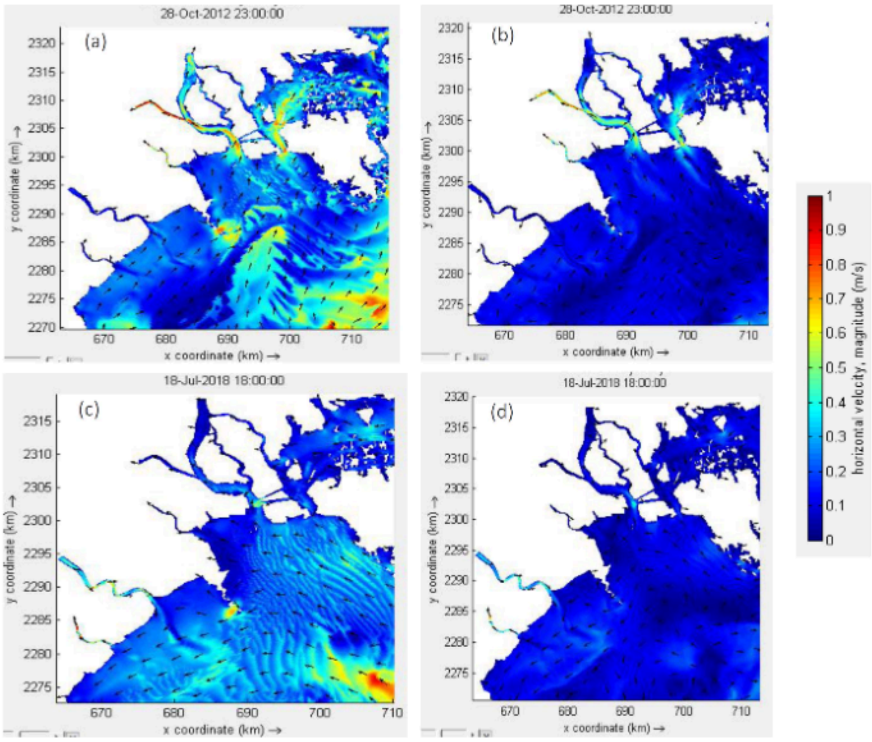

Figure 11. Surface and bottom flow fields during typhoon Son Tinh 2012 (a, b) and 2018 (c, d)

After the typhoon dissipated completely, the flow velocity at Nam Trieu and Lach Huyen gates tended to increase but insignificantly (increase from 0.05–0.15 m/s). Overall, the large flow velocity combined with the large wave height during the typhoon changed the balance maintained for a long time (Fig. 12).

A comparison of the area's surface layer and bottom layer flow fields showed that the typhoon's influence on the current stratification was huge. The speed and direction of the surface layer flow depended on the direction and intensity of the wind in the typhoon. In contrast, the bottom layer still suffered from a relatively significant influence from ocean dynamic processes in the opposite direction. At the time of the typhoon's attack, the surface current speed was greater than the bottom current speed from 0.3–0.5 m/s (especially in the Nam Trieu estuary); the bottom layer flow had a dispersed direction with a relatively small speed value, especially in the mid-sea area of Hon Dau, Cat Ba, and Cat Hai.

For waves, when a typhoon surge occurs, the wave height in the typhoon can reach a high intensity such as in typhoon Son Tinh 2012, the offshore area (63 km from the shore) can reach up to 3.7 m (an increase compared to normal conditions from 2.1–2.3 m). The wave in the typhoon quickly decreases when entering the coastal zone; the wave height during the typhoon coastal zone also only reaches 0.9 m (an increase compared to normal conditions from 0.3–0.5 m). At Hon Dau - Cat Ba, the wave height is higher than the entrance to Van Uc, Lach Huyen, and Lach Tray (Fig. 13). Due to islands in the estuary areas and Ha Long and Cat Ba coastal areas, the height waves in the typhoon are quickly reduced and not transmitted to the mainland. The wave height at the mouth of Nam Trieu, Lach Tray only reached 0.22 m (an increase compared to normal conditions of 0.05–0.1 m). For an average-intensity typhoon such as typhoon 2018, although it did not directly land in Hai Phong City, due to its relatively complex trajectory combined with its peak period, it has caused significant impacts on the Hai Phong coastal area (Figs. 14, 15). The wave height of Typhoon 2018 in the offshore area can reach up to 1.9m (an increase compared to normal conditions of 1.2–1.5 m), and in the coastal zone, 0.62m (an increase compared to normal conditions from 0.1–0.3 m).

After the typhoon dissipated, the wave height did not change much compared to the period before the typhoon, fluctuating within the range of 0.5–0.6 m depending on the time of weather and seasonal wind (Fig. 15).

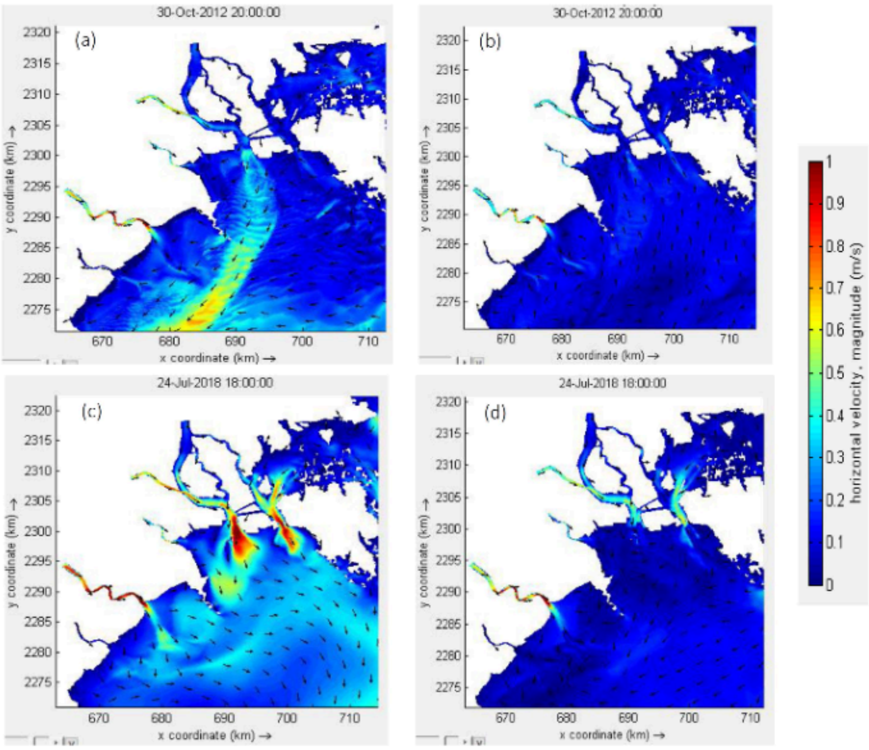

Figure 12. Surface and bottom layer flow fields at 72 h after typhoon Son Tinh 2012 (a, b) and 2018 (c, d)

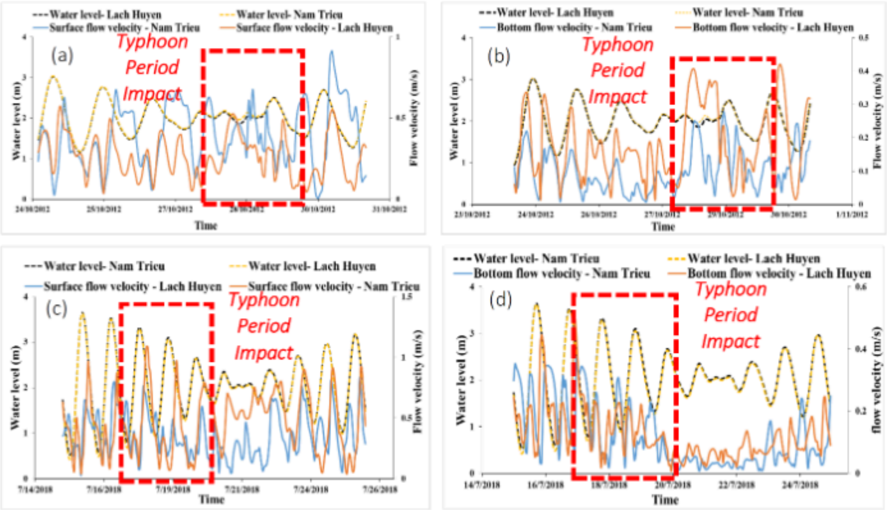

Figure 13. Flow velocity at the surface and bottom layers at the Nam Trieu and Lach Huyen entrances during Typhoons Son Tinh 2012 (a, b) and 2018 (c, d) at times: 72 hours before, during, and after the typhoons 72 hours

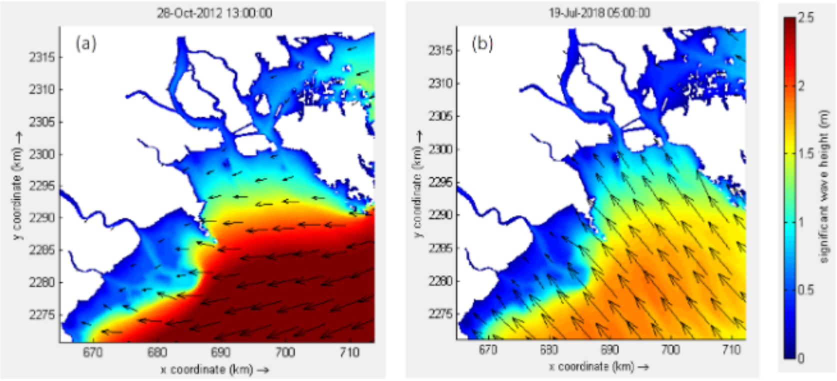

Figure 14. Wave field at the time of landfall of typhoon Son Tinh in 2012 (a) and 2018 (b)

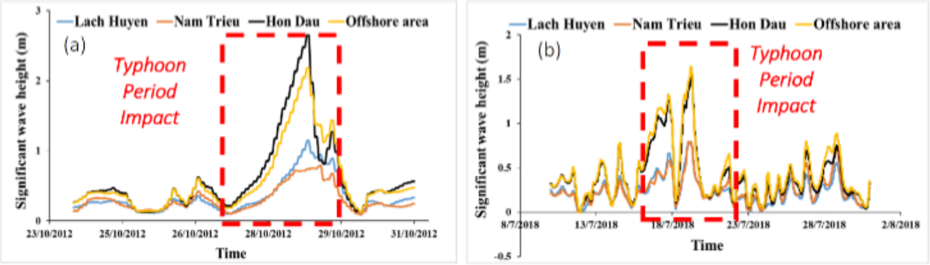

Figure 15. Wave height during typhoon Son Tinh 2012 (a) and 2018 (b) at points before, during, and after the typhoon

Discussion

Compared with the rating index NSE and MSE by Moriasi et al., [19], the results of the calibrated Delft3D model in this study are fairly good, with average R^2 values of 0.9, *NSE* values of 0.87 and *MSE* values of 0.25. This result is acceptable in the context of limited data included in the model, as in Vietnam. The research results show that typhoons have definite impacts on the hydrodynamic forces of the Hai Phong estuarine system. In the absence of typhoons, the flow velocity in the rainy season is higher than that in the dry season, with the difference in flow velocity at some estuaries, such as Nam Trieu estuary and Lach Huyen estuary, fluctuating between 0.3 m/s and 0.5 m/s. This is related to the flow from upstream and is relatively consistent with previous authors' studies on the seasonal hydraulic regime [1, 4, 8]. Under the influence of the typhoon, the typhoon surge in the estuary area ranges from 0.3 m to 0.5 m (depending on the magnitude of the typhoon). However, the surge calculation results have relatively low values compared to the intensity of the typhoon, which may be due to the shape of Hon Dau - Hai Phong Island's coastline and the sea floor extending to the sea. The highest surge caused by the typhoon usually ranges from a few tens to a hundred kilometers away from the typhoon center. In addition, the extent of the surge also depends on the range of influence and size of each typhoon.

The high flow velocity and the high wave height during the typhoons changed the balance maintained for a long time. In particular, typhoons often bring accompanying consequences such as heavy rain, floods from upstream, and high-speed river flow (current velocity of 1.5 m/s) carrying a large amount of sediment into the lower part of the river, which then flows into the estuary, leading to a significant increase in the amount of suspended sediment in the estuaries. When these flows reach the estuary, the flow velocity decreases, the sediment settles to the bottom, and submerged sandbars are formed, leading to the formation of the accretion of creeks in the Hai Phong area, potentially causing risks to the development of seaports and affecting the socio-economic development and national security in the area [2, 6].

CONCLUSION

The research results show that the current velocity at the estuarine zone of Hai Phong (especially at the Nam Trieu, Lach Huyen estuary) is strongly seasonal and closely depends on the monsoon. In the rainy season, due to the large discharge of water from the river, the current velocity is in the range of 0.25–0.63 m/s. In the dry season, due to the change in the monsoon climate and the considerable decrease in the water discharge from the rivers, the current velocity is 0.2–0.45 m/s. During the high tide phase, waves and winds from the Southeast and Northeast increase the diffusion of suspended sediments from the lower layers to the upper layers in the outer water. Additionally, the northeast wave direction enhances the movement of sand and mud flows from the Northeast to the Southwest.

Typhoons have an extreme impact on hydrodynamics conditions in the Hai Phong coastal area, Especially raising the water level and increasing the flow velocity and wave height in the coastal area. Different typhoons affect the hydrodynamics differently, but they all share that the estuary areas with narrow channels are more strongly affected than the remaining areas. When the typhoon makes landfall at the Lach Huyen estuary in Nam Trieu, the flow velocity can be up to 0.8–1.2 m/s (an increase of 0.5 m/s compared to the flow velocity in normal conditions), and the wave height can be up to 1.2–2.5 m (a rise of 0.4–2 m compared to the wave height in without typhoons).

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REFERENCES

[1] Vinh, V. D., and Uu, D. V., 2013. The influence of wind and oceanographic factors on characteristics of suspended sediment transport in Bach Dang estuary. *Vietnam Journal of Marine Science and Technology*, *13*(3), 216–226.

[2] Vinh, V. D., Hai, N. M., and Lan, T. D., 2019. Proposal for appropriate solutions to reduce influences of sediment dumping activities in the Hai Phong open waters.

Vietnam Journal of Marine Science and Technology, *19*(2), 199–213.

[3] Duy Vinh, V., Ouillon, S., and Van Uu, D., 2018. Estuarine Turbidity Maxima and variations of aggregate parameters in the Cam - Nam Trieu estuary, North Vietnam, in early wet season. *Water*, *10*(1), 68.

[4] Cuong, H. V., Tu, T. A., and An, P. H., 2015. Simulation of seasonal turbidity transmission in Do Son - Hai Phong coastal area and surrounding sites by 3D calculation model. *Vietnam Journal Science and Technology*, *58*(7), 19–23. (in Vietnamese).

[5] Vinh, V. D., and Thanh, T. D., 2014. Characteristics of current variation in the coastal area of Red river delta-results of resaerch using the 3D numerical model. *Vietnam Journal of Marine Science and Technology*, *14*(2), 139–148.

[6] Vinh, V. D., and Ouillon, S., 2021. The double structure of the Estuarine Turbidity Maximum in the Cam-Nam Trieu mesotidal tropical estuary, Vietnam. *Marine Geology*, *442*, 106670.

[7] Vinh, V. D., and Ouillon, S., 2014. Effects of Coriolis force on current and suspended sediment transport in the coastal zone of Red river delta. *Vietnam Journal of Marine Science and Technology*, *14*(3), 219–228.

[8] Vinh, V. D., and Lan, T. D., 2018. Influences of the wave conditions on the characteristics of sediments transport and morphological change in the Hai Phong coastal area. *Vietnam Journal of Marine Science and Technology*, *18*(1), 10–26.

[9] Vinh, V. D., Ouillon, S., Thanh, T. D., and Chu, L. V., 2014. Impact of the Hoa Binh dam (Vietnam) on water and sediment budgets in the Red River basin and delta. *Hydrology and Earth System Sciences*, *18*(10), 3987–4005.

[10] Duy, V. V., Ouillon, S., and Minh, H. N., 2022. Sea surface temperature trend analysis by Mann-Kendall test and sen's slope estimator: a study of the Hai Phong coastal area (Vietnam) for the period 1995-2020. *Vietnam Journal of Earth Sciences*, *44*(1), 73–91.

[11] Nguyen, H. M., Ouillon, S., and Vu, V. D., 2022. Sea level variation and trend analysis by comparing Mann–Kendall test and innovative trend analysis in front of the Red River Delta, Vietnam (1961–2020). *Water*, *14*(11), 1709.

[12] Becker, J. J., Sandwell, D. T., Smith, W. H. F., Braud, J., Binder, B., Depner, J., Fabre, D., Factor, J., Ingalls, S., Kim, S-H., Ladner, R., Marks, K., Nelson, S., Pharaoh, A., Trimmer, R., von Rosenberg, J., Wallace, G., and Weatherall, P., 2009. Global bathymetry and elevation data at 30 arc seconds resolution: SRTM30_PLUS. *Marine Geodesy*, *32*(4), 355–371.

[13] Weatherall, P., Marks, K. M., Jakobsson, M., Schmitt, T., Tani, S., Arndt, J. E., Rovere, M., Chayes, D., Ferrini, V., and Wigley, R., 2015. A new digital bathymetric model of the world's oceans. *Earth and space Science*, *2*(8), 331–345.

[14] Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., Behringer, D., Hou, Y-T., Chuang, H-Y., Iredell, M., Ek, M., Meng, J., Yang, R., Mendez, M. P., van den Dool, H., Zhang, Q., Wang, W., Chen, M., and Becker, E., 2014. The NCEP climate forecast system version 2. *Journal of climate*, *27*(6), 2185–2208.

[15] Egbert, G. D., and Erofeeva, S. Y., 2002. Efficient inverse modeling of barotropic ocean tides. *Journal of Atmospheric and Oceanic technology*, *19*(2), 183–204.

[16] World Ocean Atlas, 2013. Version 2. https://www.nodc.noaa.gov/OC5/woa13; accessed on 20 April 2023.

[17] Deltares Systems, 2017. Delft3D-FLOW User Manual: Simulation of Multi-Dimensional Hydrodynamic Flows and Transport Phenomena, including Sediments; Technical Report; Deltares: Delft, The Netherlands, 2017.

[18] Nash, J. E., and Sutcliffe, J. V., 1970. River flow forecasting through conceptual models part I—A discussion of principles. *Journal of hydrology*, *10*(3), 282–290.

[19] Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., and Veith, T. L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, *50*(3), 885–900.