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Calculations of Environmental Capacity and Pollutant Load Reduction by the Delft3d Model for the Development of Aquaculture in the Bach Dang Estuary Area

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Abstract: This study presents the results of research on water exchange and the environmental capacities of total suspended sediment (TSS), inorganic nutrients (PO_4^{3-}, NO_3^- and NH_4^+), and heavy metals (As, Hg, Cu, Cd, Pb, and Zn) in the receiving water of the Bach Dang estuary area. The database used in this study is from a collaboration project between Vietnam and China called "Comparative study of Holocene sedimentary evolution of the Yangtze River Delta and Red River Delta". The data were collected in Vietnam during another project by the Institute of Marine Environment and Resources (IMER). The results of the environmental carrying capacity of water are used to manage the carrying capacity to ensure sustainable development. The simulation was performed by using numerical models, and the patterns were established by applying the three-dimensional Delft3D model (Delft3D) to verify the water level data. The data were calculated in July and March, which represent the wet and dry seasons in the region, respectively. The results showed that the volumes of TSS, nutrients, and heavy metals in the waters met their potential carrying capacities. During the aquaculture processes in the wet season, the TSS and NO_3^- factors polluted the water in Vietnam, with average values of 98 g/m^3 and 0.081 gN/m^3, respectively, while the other factors did not cause pollution in the study area. During the dry season, only the NO_3^- factor was polluted in the water body, with an average value of 0.096 gN/m^3, and the other factors were not polluted in the water environment.

Key words: delft3D, environmental capacity, bach dang estuary, TSS, nutrients, heavy metals

1. Introduction

Water pollution caused by material pollution is a major global problem that requires continuous evaluation. In recent years, the water quality degradation associated with the rapid socioeconomic development in the Bach Dang estuary area, Vietnam, has attracted increasing attention from both the public and the Vietnamese government. It is well known that it is very important to study and assess the environmental factors that cause accidents as well as the many factors related to river discharge that cause environmental pollution of sea water from land waste. Therefore, these types of studies are very important in estuaries that have strong interactions with rivers and sea water. For this reason, the three-dimensional Delft3D model was used to evaluate the self-purification capacity of water through the impacts of tides and sea water bodies.

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Many different environmental factors may cause accidents. The major pollution in the Bach Dang estuary is dominated by domestic wastewater, industrial wastewater, agricultural wastewater and total suspended sediment (TSS) in river water. A technical report called "Analysis of Pollution from Manufacturing Sectors in Vietnam" [1], found that although the biochemical oxygen demand (BOD) and TSS loads represent the largest loads in terms of their relative share of the overall water pollution, chemicals and metals represent the greatest concern. The persistence of chemicals and metals in the environment and the potential health linkages make them a high priority in the short term. However, TSS is similar to particulates and provides attachment sites for heavy metals, such as cadmium, mercury and lead, and many toxic organic contaminants and pesticides. Therefore, the pollution factors evaluated in this study include TSS, inorganic nutrients (PO_4^{3-}, NO_3^- and NH_4^+), and heavy metals (As, Hg, Cu, Cd, Pb, and Zn). Multivariate statistical analysis was applied to assess the spatial and temporal changes caused by natural dynamic processes in the study area. Therefore, it is necessary to propose technical solutions to reduce both the total waste and socioeconomic activities and enhance the self-purification capacity of water to protect and improve the quality of the environment and ensure sustainable development.

There have been several previous studies on this topic both in Vietnam and throughout the world [2-16]. The results of these studies were based on observed data from measurements at stations, which were both continuous day-night measurements and instantaneous measurements at some stations in the area. The calculated results were not based on basic calculations or fully expressed average values of the pollution factors in water; the application of the approaches and the use of management tools were mostly in their initial stages. Instead of performing basic calculations by hand, a mathematical model is a versatile tool that can help calculate and simulate water environmental parameters across multiple time series and locations, as the results of these models provide full expressions of parameters with improved accuracy.

2. Methods

2.1 Study Area

The Bach Dang estuary is located in the northeastern part of the Red River Delta and receives water from the Lach Tray River as well as the Cam and Bach Dang Rivers, whose confluence is located 10 km from the mouth of the estuary (Fig. 1).

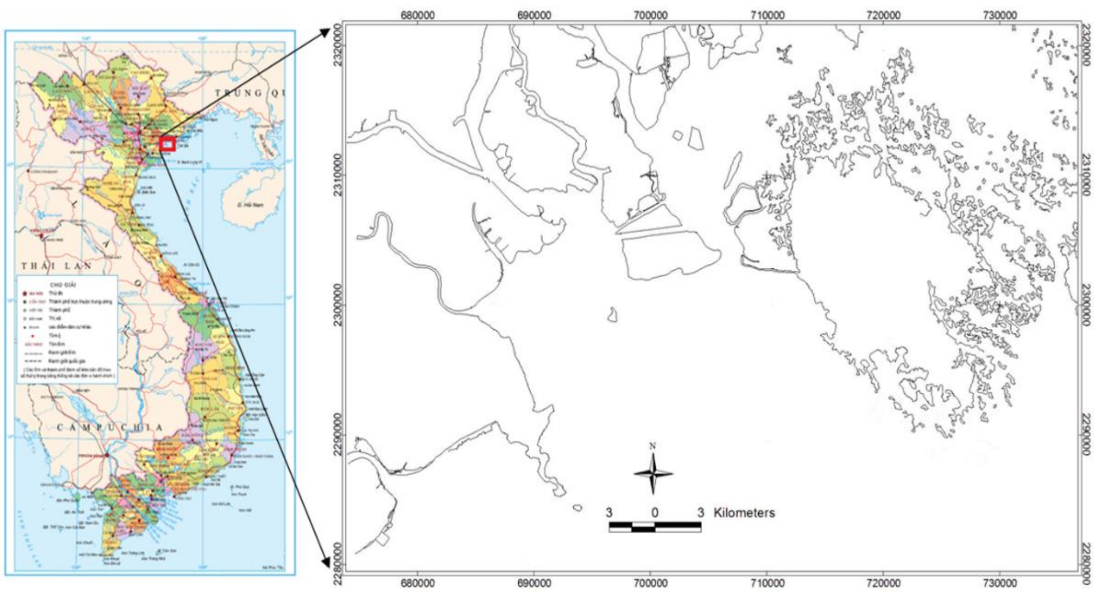


Fig. 1 Study area.

The Bach Dang estuary is characterized by a funnel-shaped estuary and an intricate tidal flat and creek system. The tide is a dominant dynamic factor that regulates the morphology and sedimentology in the estuary. The tide is diurnal, and its range in Haiphong is approximately 4 m during spring tide. The hydrological regime strongly depends on the monsoon regime, with the northeast monsoon occurring from November to May during the dry season and the southwest monsoon occurring from May to November during the wet season. The total average rainfall is ~1500 mm/year. The average wind speed is 3-4 m/s and reaches up to 45 m/s during typhoons. The average wave height is 0.5-1.0 m, and the prevalent directions (east, southeast and south) follow the wind climate, which depends on the monsoon regime. The average annual water temperature is 23.50°C. The average annual river discharge into the Bach Dang estuary area lies within the range of 350-440 m^3/s, and the average TSS concentration is between 290 and 360 mg/l [17].

2.2 Materials

+Coastline and bathymetry data: published by the Geodesy and Cartography Department in Vietnam.

+River discharge, salinity, and water temperature data: calculations based on observation data from a project implemented by the Institute of Marine Environment and Resources (IMER), Vietnam. The gridded salinity and temperature data were acquired from the National Oceanographic Data Center (NODC) [18].

+Tidal harmonic constants within a large boundary area: extracted from Finite Element Solutions 2004 (FES2004) [19] with the harmonic constant predictions of eight main constituents (M2, S2, K1, O1, N2, P1, K2, Q1). FES2004 has a 7.5 km resolution (0.125° grid).

+Wind data: recorded at the Hon Dau station during the dry and wet seasons.

+TSS, inorganic nutrients, and heavy metals at specific sections of the rivers: calculations based on observation data from a project implemented by Institute of Marine Environment and Resources (Vietnam) during the wet season in 2013 and dry season in 2014 “Assessment of environmental carrying capacity of some coastal typical water-bodies in Viet Nam in order to serving the sustainable development; code KC09.17/11-15; 2013-2015”

+Water level data used for the calibration and verification of the models: recorded at the Hon Dau station during the wet and dry seasons

2.3 Methods

+ Delft3D model [20]: the numerical hydrodynamic modeling system Delft3D-FLOW can be used to solve unsteady shallow water equations in two (depth-averaged) or three dimensions.

The system of equations consists of the horizontal equations of motion, the continuity equation, and the transport equations for conserved constituents [20]. The depth-averaged continuity equation is given by:

$$\frac{\partial\zeta}{\partial t}+\frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\left[(d+\zeta)U\sqrt{G_{\eta\eta}}\right]}{\partial\xi}+\frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\left[(d+\zeta)V\sqrt{G_{\xi\xi}}\right]}{\partial\eta}=Q$$

where ξ and η represent the horizontal coordinates in the orthogonal curvilinear coordinate system;

$\sqrt{G_{\xi\xi}}$ *and* $\sqrt{G_{\eta\eta}}$ represent the systems used to convert the parameters from the orthogonal curvilinear coordinate system to the Cartesian coordinate system;

d represents the depth at the point of calculation (compared with 0 m on the charts);

ζ represents the water level at the point of the calculation (compared with 0 m on the charts);

U and V represent the average velocity components in the ξ and η directions, respectively;

+ The land-ocean interactions in coastal zones [21] model is a block model used to evaluate the retention times of water bodies and the material balance, and the nutrition status in coastal water areas is applied in this model. The material balance process in a water body can be defined using the following model:

$$\frac{dV}{dt} = \sum V_{in} - \sum V_{out} + \sum V_{sources-sinks}$$

where $\frac{dV}{dt}$ represents the water exchange rate (volume per unit of time);

$\sum V_{in}$ represent the total volume of water in rivers and seas in an area (m^3);

$\sum V_{out}$ represents the total volume of water that is output from the area in sections (m^3);

$\sum V_{sources-sinks}$ represents the total change in water volume caused by the sinks (i.e., rain)

The material balance within a system according to the model by Gordon et al. (1996) [22] is:

$$\frac{d(VS)}{dt} = \sum V_{in}S_{in} - \sum V_{out}S_{out}$$

where $\sum V_{in}$ and $\sum V_{out}$ represent all of the hydrographic inputs and outputs, respectively, and S_{in} and S_{out} represent the salinities of the corresponding water masses.

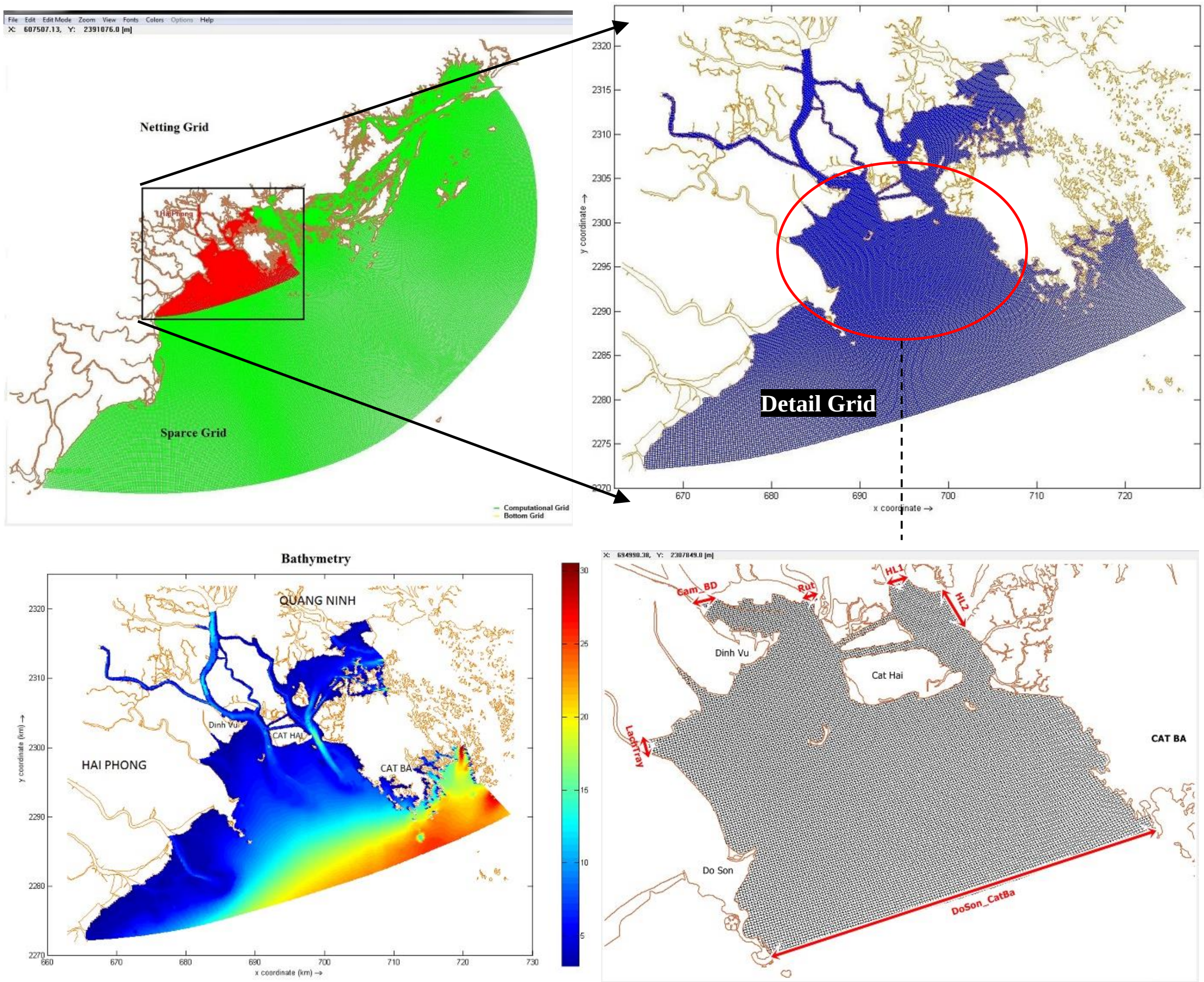


Fig. 2 Depths and grid used in the model.

2.4 Calibration and Verification

In this study, we use the root mean square error (RMSE) [23] for calibration and verification. The RMSE is a metric that is frequently used to measure the differences between the values (sample and population values) predicted by a model or an estimator and the values actually observed. To simplify, we assume that we already have n samples of the model errors ε calculated as follows (i.e., i = 1, 2, ..., n). The uncertainties brought by the observation errors or the methods used to compare the model results and observations are not considered here. We also assume that the error sample set ε is unbiased. The RMSE and mean absolute error (MAE) are calculated for the data set as follows [23]:

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n} e^{i}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} e_i^2}$$

Linear regression was used to compare the relationship between the observed data and the model results by fitting a linear equation to the observations. The model parameters were calibrated by trial and error until the simulated results agreed well with the observed data for the heavy metals.

$$R^2 = 1 - \frac{SSE}{SST}\ (0 \le R^2 \le 1)\ [24]$$

SSE: sum of square error; R^2 = 0 indicates that the calculated result is not exact, and R^2 = 1 indicates that the calculated result is exact.

To compare the observed data and modeled shifts in the study area, we used 48-hour observation data for the TSS, phosphate and nitrate nutrients during the wet and dry seasons. On average, during the wet season, the model validation using the observed data showed fair to good TSS values of ±3.13 mg/l, which corresponded to an error of 4.48%; very good phosphate nutrient values (error ±1.645 mg/l, ~5.59%); and good NO_3^- (±17.178 mg/l, ~9.52%) and NH_4^+ (±5.8 mg/l, ~4.39%) nutrient values. On average, during the dry season, the model validation using the observed data showed fair to good TSS values of ±0.64 mg/l, with a corresponding error of ~2.39%; very good phosphate nutrient values (±5.29 mg/l, ~4.27%); and good NO_3^- (error ±2.765 mg/l, ~11.59%) and NH_4^+ (±14.862 mg/l, ~13.34%) nutrient values.

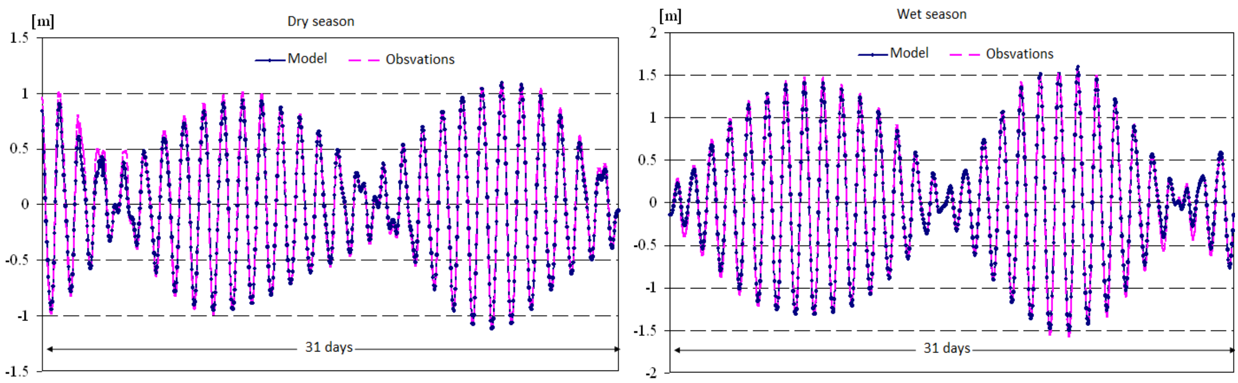


Fig. 3 Water level data recorded at the Hon Dau station and the difference between the observed and modelled TSS ranges.

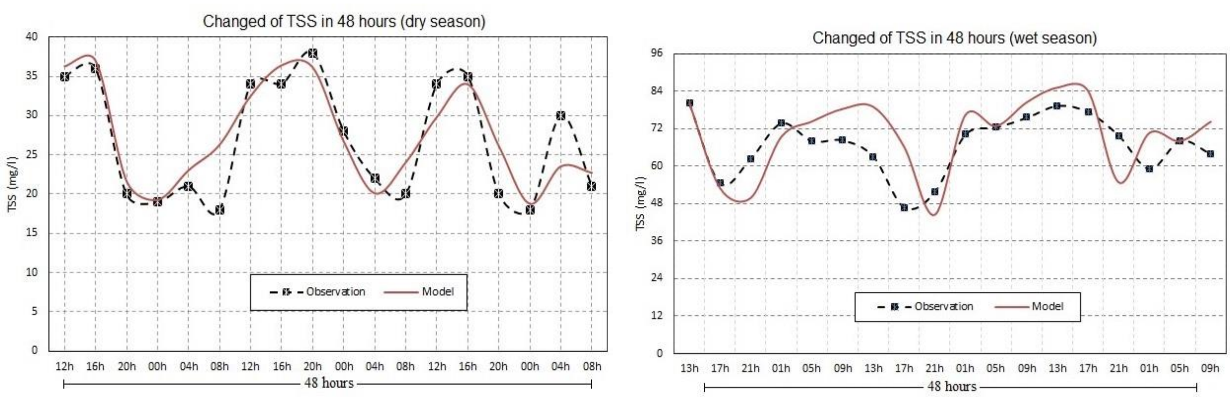


Fig. 4 TSS range in accuracy between the observed and modelled results.

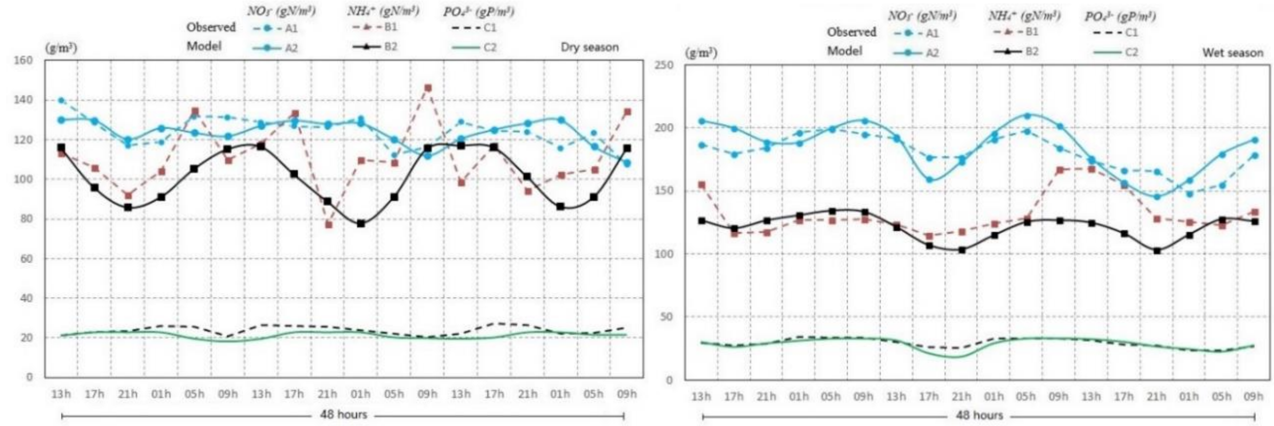


Fig. 5 Average nutrient values range in accuracy between the observed and modelled results.

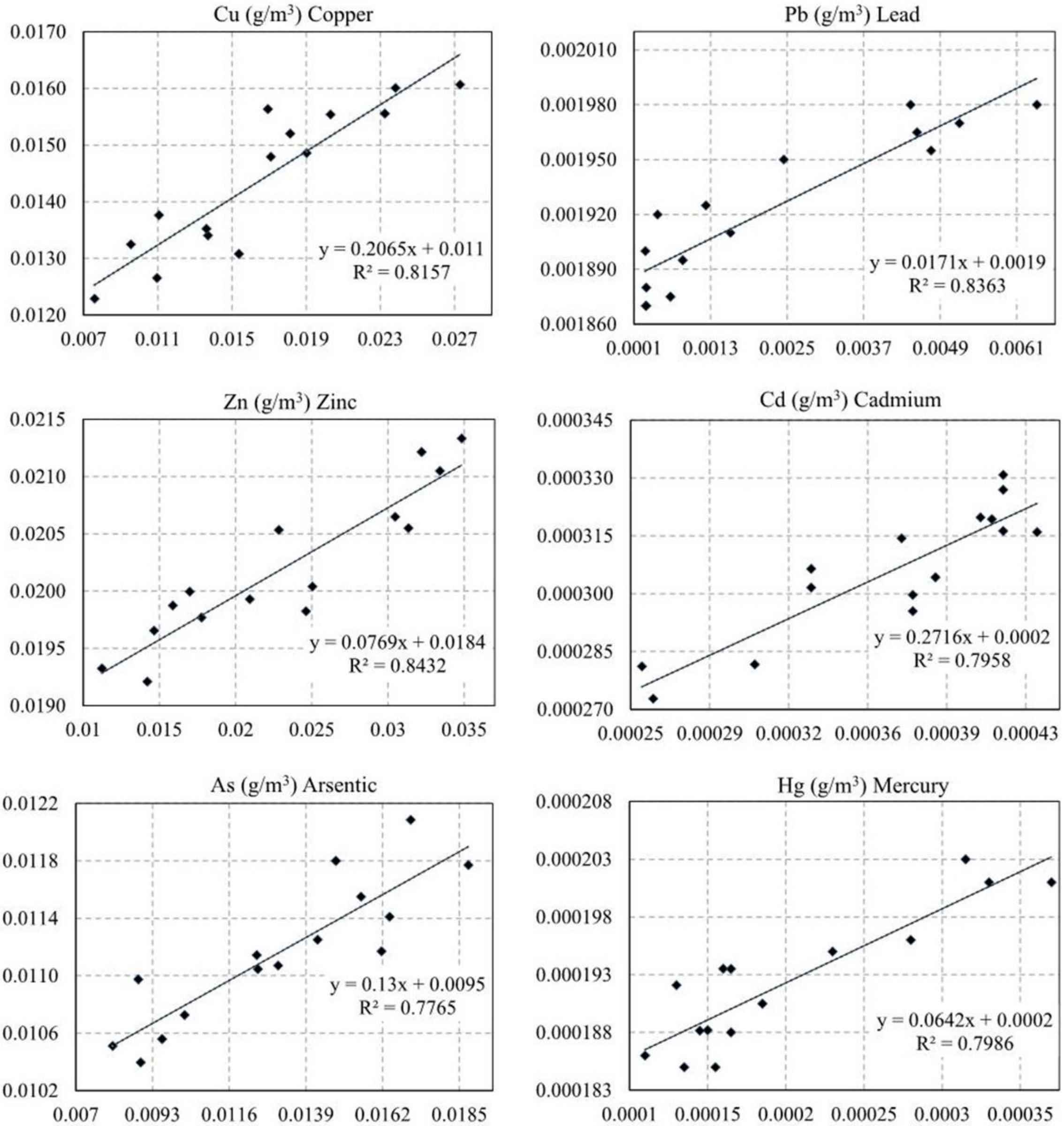


Fig. 6 Correlation graphs of heavy metals between the data measured at 15 observation points and the modelled results.

Due to missing information in the heavy metal time series, we used observed data of the mean heavy metal values at 15 points in the study area.

3. Results

The calculated water quality resulted in almost all scenario simulations having high NO_3^-levels (a measure of inorganic pollution) that caused pollution in the water body, while some inorganic matter did not cause pollution. The TSS factor caused pollution during the wet season, and in almost all scenarios, the heavy metal parameters did not pollute the water body (see Table 2). Currently, the worst pollution was caused by NO_3^- nutrients (see Table 3) and, in decreasing order, the average concentrations of NO_3^- nutrients were found during the dry season at high tide (0.09678 gN/m^3) and low tide (0.09618 gN/m^3), followed by those during the wet season at low tide (0.08904 gN/m^3) and high tide (0.07428 gN/m^3).

Table 1 Ability to receive TSS mass (tons) in the area.

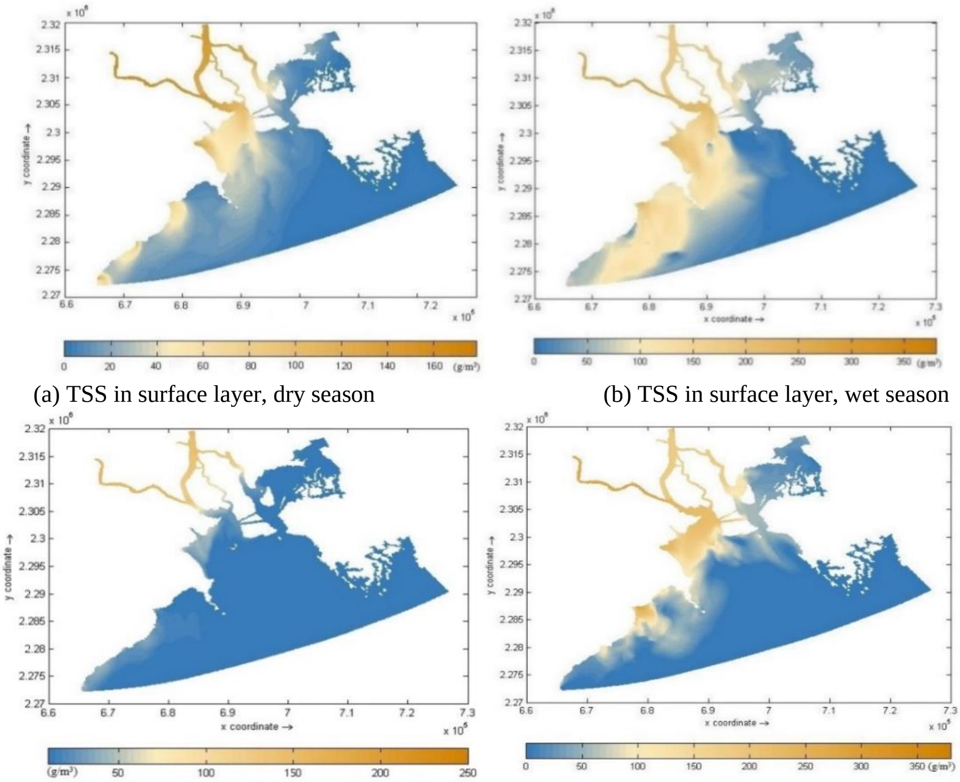
Factors	Dry season		Wet season	
	High tide	Low tide	High tide	Low tide
Volume of area (m^3)	1633503780	1179743396	1324121700	1066303300
TSS mass in standard level	66206	53315	81675	58987
Currently TSS mass	40306	37758	154693	119968
Current ability to receive TSS	25900	15557	-73018	-60981
Ability to receive TSS in 2025	17839	8006	-103956	-84975

Table 2 Ability to receive pollution matter in the study area (tons).

Factors	Current				In future 2025			
	Dry season		Wet season		Dry season		Wet season	
	High Tide	Low Tide	High Tide	Low Tide	High Tide	Low Tide	High Tide	Low Tide
NH_4^+	72.50	55.25	85.55	50.75	42.55	29.55	46.66	17.13
NO_3^-	-48.70	-38.58	-23.33	-34.27	-112.77	-89.86	-83.99	-86.79
PO_4^{3-}	45.87	36.66	47.69	32.11	39.01	31.00	34.78	21.63
Cu	26.79	21.34	35.02	24.51	20.32	16.01	28.03	19.07
Pb	64.88	52.23	80.09	57.72	64.22	51.69	79.30	57.08
Zn	49.94	39.97	62.39	43.88	41.80	33.30	52.75	36.32
Hg	1.19	0.96	1.47	1.04	1.13	0.90	1.38	0.98
As	6.49	5.09	8.03	4.93	3.12	2.31	3.88	1.50
Cd	6.47	5.21	7.93	5.70	6.40	5.15	7.81	5.60

Table 3 Average value of some factors in the water body

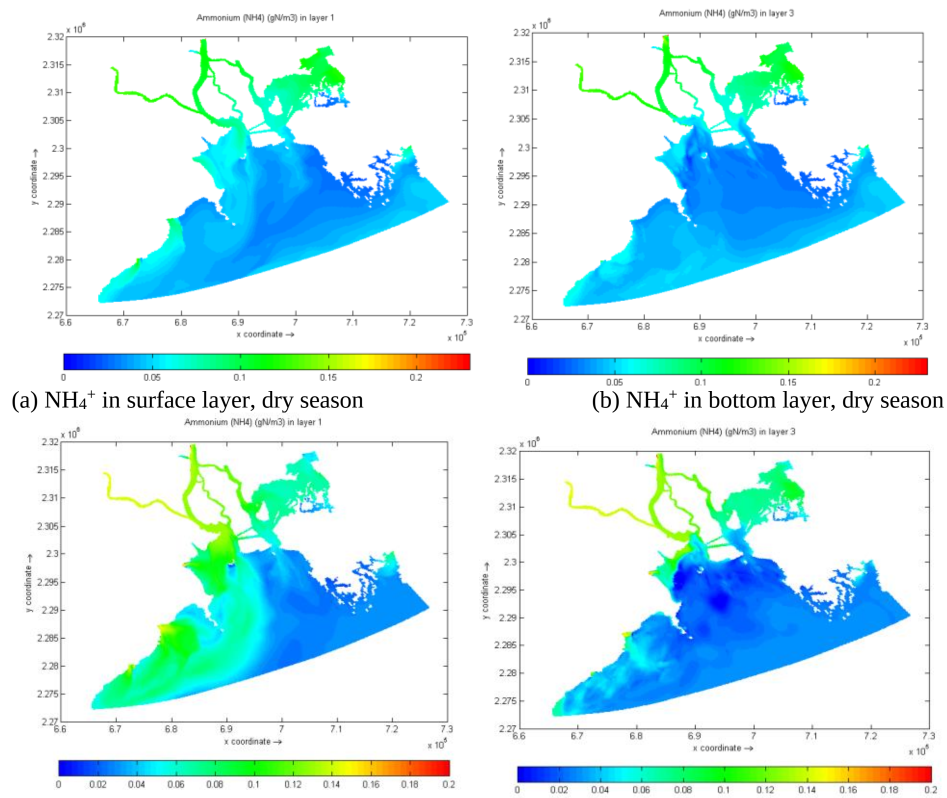
Factors	QCVN	Dry season		Wet season	
		High Tide	Low Tide	High Tide	Low Tide
NH_4^+ (gN/m^3)	0.1	0.04524	0.04819	0.04763	0.05698
NO_3^- (gN/m^3)	0.06	0.09678	0.09618	0.07428	0.08904
PO_4^{3-} (gP/m^3)	0.045	0.01036	0.01062	0.01581	0.01778
Cu (g/m^3)	0.03	0.00977	0.00999	0.00856	0.00922
Pb (g/m^3)	0.05	0.00100	0.00102	0.00097	0.00108
Zn (g/m^3)	0.05	0.01229	0.01251	0.01180	0.01281
Hg (g/m^3)	0.001	0.00010	0.00010	0.00010	0.00011
As (g/m^3)	0.01	0.00510	0.00522	0.00508	0.00582
Cd (g/m^3)	0.005	0.00011	0.00012	0.00015	0.00017
TSS (g/m^3)	50	30.44	35.41	94.7	101.69



(a) TSS in surface layer, dry season (b) TSS in surface layer, wet season

(c) TSS in bottom layer, dry season (d) TSS in bottom layer, wet season

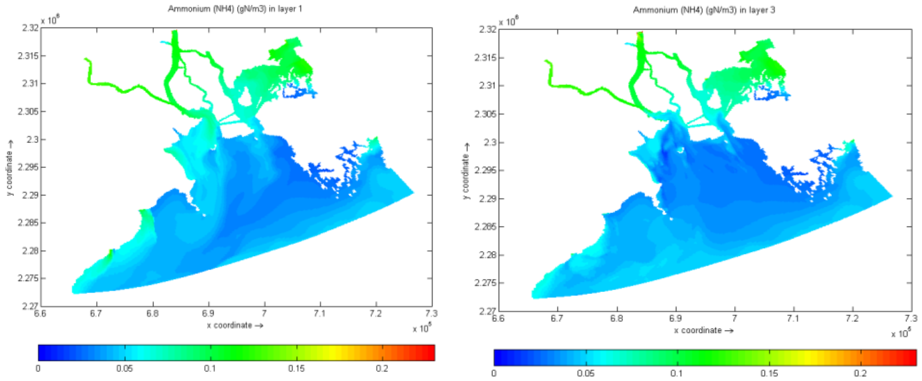
Fig. 7 Simulation results of the TSS distribution field (g/m³).



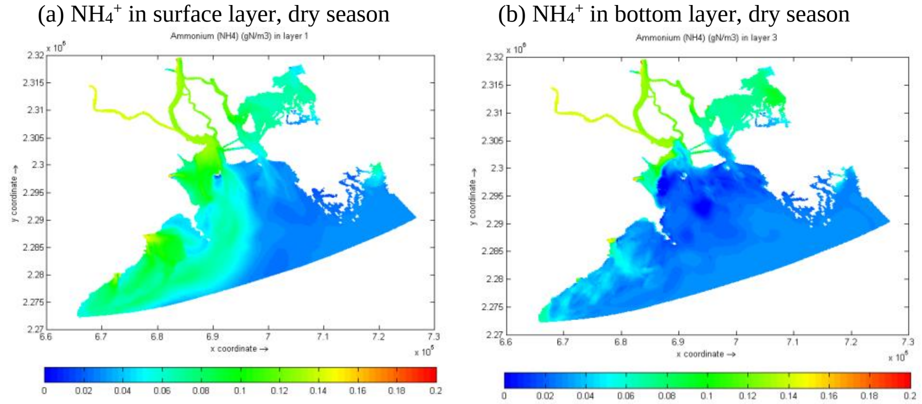
(a) NH_4^+ in surface layer, dry season (b) NH_4^+ in bottom layer, dry season

(c) NH_4^+ in surface layer, wet season (d) NH_4^+ in bottom layer, wet season

Fig. 8 Simulation results for the NH_4^+ nutrient distribution field (gN/m³).

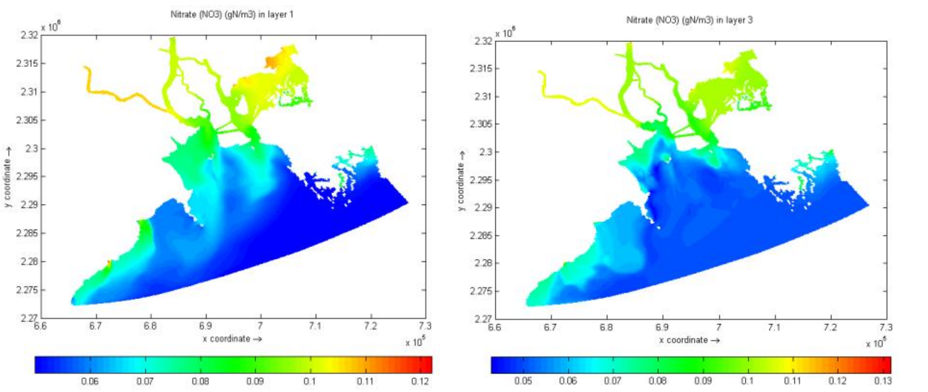


(a) NH_4^+ in surface layer, dry season (b) NH_4^+ in bottom layer, dry season

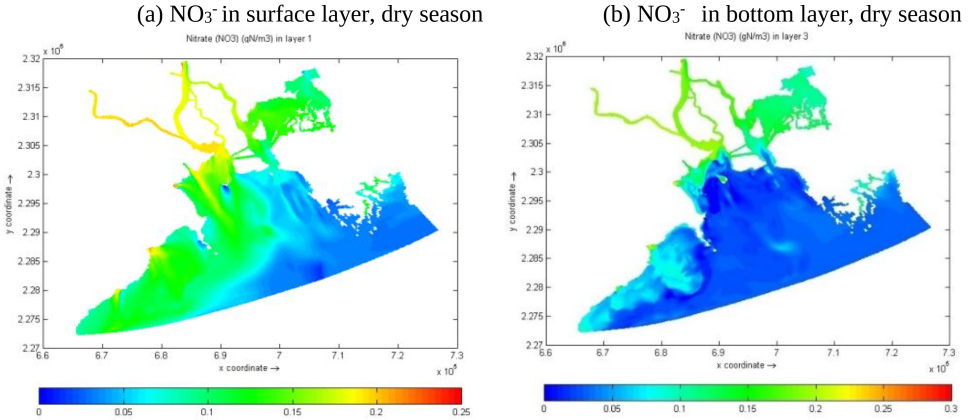


(c) NH_4^+ in surface layer, wet season (d) NH_4^+ in bottom layer, wet season

Fig. 9 Simulation results for the PO43-nutrient distribution field (gN/m^3)



(a) NO_3^- in surface layer, dry season (b) NO_3^- in bottom layer, dry season



(c) NO_3^- in surface layer, wet season (d) NO_3^- in bottom layer, wet season

Fig. 10 Simulation results for the NO3- nutrient distribution field (gN/m^3).

The pollution load emissions were compared with the environmental capacity of the water in the studied area, and the pollution load reduction required to meet the water quality objectives for the river was obtained. The results are shown in Tables 2 and 3.

The pollution load reductions required to satisfy the water quality objectives were calculated by subtracting the water environmental capacity from the pollution load emissions of the studied river reach [24]. Positive values indicate that the pollution load exceeds the environmental capacity and needs to be reduced; negative values indicate that the environmental capacity remains in surplus and can accommodate a greater pollution load. The NO_3^- nutrients in almost all cases caused pollution, and the TSS caused pollution during only the wet season. The TSS and NO_3^- nutrient pollution loads in the headwaters need to be reduced by 73018 tons/month during the wet season. The NO_3^- nutrient load reductions were 48.7 tons/month during the dry season and 34.27 tons/month during the wet season.

The goal was to achieve the water quality objectives under the water environment standard for aquaculture in Vietnam (QCVN) [15, 26-29]. According to the water quality objectives for the Bach Dang estuary, the pollution loads of the NO_3^- nutrients and TSS during the wet seasons greatly exceeded the environmental capacity. Particulates also provide attachment sites for heavy metals such as cadmium, mercury and lead, as well as many toxic organic contaminants and pesticides. High concentrations of particulate matter can modify light penetration, which causes shallow lakes and bays to fill faster and smooths benthic habitats [26].

4. Discussion

The methods used in this study were similar to those applied in other estuaries or lagoons, and these results are very important for the management of aquaculture water quality. Effective strategies for water environmental management need to be implemented in these rivers to improve the water quality of the Bach Dang estuary area and ensure sustainable development in the region. The aim of this study was to provide a basis for water environmental management decision-making. In this study, the Delft3D model for river and stream water quality was applied to predict the water quality and environmental capacity of the Bach Dang area.

The results showed that the pollution load reductions required to meet the water quality targets were calculated to be 73018 tons/month during the wet season and 48.7 tons/month during the dry season for TSS and 34.27 tons/month during the wet season for NO^{3-}. Thus, additional water pollution control measures are needed to control and reduce the pollution loads in the Bach Dang area watershed. The methods applied in this study should provide a basis for water environmental management decision-making. The results of this study provide a scientific basis that will allow water quality and environmental management to be effectively addressed at the legal and institutional levels.

5. Conclusions

In this study, the Delft3D model was calibrated and validated using data from field observations carried out during the wet season in 2013 and the dry season in 2014. The simulated results were strongly correlated with the measured data. The water quality in the Bach Dang estuary was simulated by the Delft3D model for the TSS, inorganic nutrients (PO_4^{3-}, NO_3^- and NH_4^+), and heavy metals (As, Hg, Cu, Cd, Pb, and Zn). The reductions in TSS pollution loads required to meet the water quality targets were calculated to be 3018 tons/month during the wet season; while the necessary reductions in the NO_3^- nutrient loads were calculated to be 48.7 tons/month during the dry season and 34.27 tons/month during the wet season. For the forecasted scenario in 2025, the necessary reductions in TSS loads were calculated to be 103956 tons/month during the wet season, while the necessary reductions in NO_3^- nutrient loads were calculated to be 112.77 tons/month during the dry season and 86.79 tons/month during the wet season. Therefore, economic instruments or macrophyte purification are required to control the pollution in the Bach Dang estuary watershed in the long term.

The land-water interface along the coastline is always in a highly dynamic state, and nature works towards maintaining an equilibrium condition. The mechanisms that operate along a coastline bring about various combinations of deposition, dispersion and suspended matter transportation. The deposition, dispersion and transportation processes of suspended matter in the Bach Dang estuary that are most directly affected by hydrodynamic forces are tides, waves, wind and currents.

The analysis and prediction of TSS and matter transport have great commercial, aesthetic, social, and scientific importance owing to the desire for sustainable development and coastal zone management. The results of this study should provide a basis for water environmental management strategies that will be taken on by the government.

Acknowledgments

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