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Assessing the Impact of Industrial Zones on the Environmental Pollution in Hai Phong's Coastal Areas, Vietnam

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Abstract

Pollution in the coastal areas negatively affects biochemical indicators of seawater, human health and marine organisms. Hai Phong is a coastal city of Vietnam with the development of socio-economic activities, representing through an increasing number of industrial zones. This study is to evaluate the pollution of large industrial zones in Hai Phong city using numerical models. The numerical simulation (MIKE 21 SW, FM, ECO Lab) models were applied to simulate the wave propagation, hydraulic regime, water quality in coastal Hai Phong area. The MIKE 21 ECO Lab model was used to evaluate sources of waste from the large coastal industrial zones to some aquaculture zones. The calibration and validation results of wave propagation and the hydrodynamic models were resonably good, with Nash coefficient ranging from 0.65 to 0.90 and a percent bias (PBIAS) from 5.6% to 9.4%. The simulation results of water quality and concentration of pollutants (DO, BOD_5, COD, TSS, Fe, and Coliform) in 2023 at the aquaculture locations show that the BOD_5, COD, and TSS concentrations were higher than the allowable limits stated in the national technical regulation on surface water quality (QCVN 08:2023/BTNMT) and lower than the allowable limits stated in the national technical regulation on marine water quality (QCVN 10:2023/BTNMT). The outcomes of this study will provide more information to support managers to come up with a better socio-economic development plan for Hai Phong city to achieve sustainable development.

Keywords

Coastal Areas, Water Quality, MIKE 21, Industrial Zones, Costal Pollution

1. Introduction

Nowadays, there have been many studies about coastal pollution in the world (Zhou et al., 2021; Xu & Zhang, 2022; Das, 2022; Luo et al., 2022). Ocean pollution from land-based sources, such as terrestrial runoff and wastewater discharge through point sources has significant environmental, social, and economic repercussions (Liu et al., 2011; Thompson-Saud & Wenger, 2022; Xu et al., 2023). The impact of heavy metals has caused environmental problems on coastal ecological systems (Elsagh et al., 2013; Yang et al., 2020; Jeong & Ra, 2023; Şener et al., 2023; Gülşen-Rothmund et al., 2023). Sediment pollution in coastal and marine environments has emerged as a pressing concern due to its far-reaching ecological, environmental, and human health impacts (Thiyagarajan et al., 2010; Mandour et al., 2021; Rangel-Buitrago et al., 2023; Tyre et al., 2023). Two typical examples are the increasing pollution load from shrimp farms in the intensive cultivation system and the pollution status of coastal waters (Sumantra et al., 2022; Sivanandan et al., 2023). Ocean water quality (OWQ) monitoring provides insights into the quality of water in marine and near-shore environments. OWQ measurements can contain the physical, chemical, and biological characteristics of oceanic waters and indicate the health of the ecosystem, for example, low OWQ values indicate an unhealthy ecosystem (Slama et al., 2021; Mohseni et al., 2022).

A lot of research has used different numerical models to simulate and evaluate water quality in the coastal and marine environments. Abbott & Ionescu (1967) assessed water quality for the southern coastal edge (SCF) of the Inner Plata River based on MIKE 21 model to simulate the evolution of water quality parameters. Baghdad et al. (2015) assessed marine pollution in the Gulf of Oran with pollution parameters such as zinc, copper, iron, and lead. Serviere-Zaragoza et al. (2021) accessed the effect of cadmium, lead, copper, zinc, and Iron concentration patterns in three marine fish species from two different mining sites inside the Gulf of California, Mexico. This study was part of a pollution assessment on the west coast of Algeria to protect the marine environment. Arne & Dagmar (2014) used statistical analysis for large-scale coastal areas to assess water quality based on a weighted geographic neural network (GNNWR) model. Yusal et al. (2019) examined water quality based on meiofauna abundance and pollution index in the coastal zone of Losari Beach, Makassar used measurement and statistical methods to calculate the water pollution index. Xiong et al. (2023) performed a holistic analysis based on three-dimensional hydrodynamic and water quality modeling used for quantifying the impact of climate change on the salinity and concentrations of total nitrogen (TN), total phosphorus (TP) and chlorophyll a (Chl.a) in Shenzhen Bay between Shenzhen and Hong Kong, the two most developed megacities in South China.

Marine pollution has also been studied in Vietnam in terms of identifying socio-environmental conflicts and quantifying through tools and models (Doan & Chen, 2016; Doan et al., 2018, 2019a, 2019b, 2019c; Le et al., 2023a, 2023b). Trang et al. (2012) identified the environmental conflicts between port development (the expansion port and construction of Hai Phong port) with biodiversity protection industrial development with environmental protection in Hai Phong, and tourism development in Cat Ba with environmental protection. Tran et al. (2013) analyzed conflicts mainly focusing on the nature of conflicts, the parties involved in the social construction of the conflicts, their typological classification, and the ranking of conflicts in two case studies, namely Hai Phong and Nha Trang. Doan et al. (2015) applied an environmental sensitivity index (ESI) map of shoreline for the coastal oil spills in Cat Ba Island. Duc & Thang (2018) developed a sensitivity index for marine pollution ESI environmental sensor to assess the level of damage when an oil spill occurs to identify sensitive areas to take appropriate response measures and minimize the impact on the environment. Duong & Le (2019) studied the coastal water quality in the northern part of Vietnam. Duong et al. (2020) analyzed water quality results from monitoring stations along the coast in the Northern Vietnam Vu et al. (2020) applied hydrodynamic and water quality models (the Delft3D model) based on the measured data and the estimated pollution discharges from Dinh Vu industrial zones to Nam Trieu estuary.

There are many studies on the problem of coastal pollution, but there are none which assess the current status of coastal water quality pollution in Hai Phong city from large industrial zones. Pressure from the development of socio-economic activities on the coast of Hai Phong comes from urbanization and population growth, industrial development, seaport development, tourism development, aquaculture development, and livestock development. This study will: 1) apply the MIKE 21 (SW, FM, ECO Lab) models to simulate wave propagation, hydraulic regime, and coastal water quality in Hai Phong city; 2) assess sources of waste from the large coastal industrial zones in Hai Phong to water quality in some aquaculture zones.

2. Materials and Methods

2.1. Description of Study Site

Hai Phong is a city of vibrant economic development and high population density. It has an area of 1519.2 km^2 with 15 administrative units (7 districts, 6 coastal districts and 2 island districts). Hai Phong's population in 2008 was only in 10 years (in 2018) it was 2,013,800 people. In the inter-continental relationship between the continent and the sea, the development of socio-economic activities has caused great impacts on the marine environment. The coastal of Hai Phong area has a very wide range of water pollution risk values (**Figure 1**).

2.2. Methods

The study structure is presented in **Figure 2**. This study uses MIKE 21 SW model to simulate and evaluate wave propagation, MIKE 21 FM in 2D model to analyze the hydraulic regime, and MIKE 21 ECO Lab to simulate pollution transport in Hai Phong coastal area.

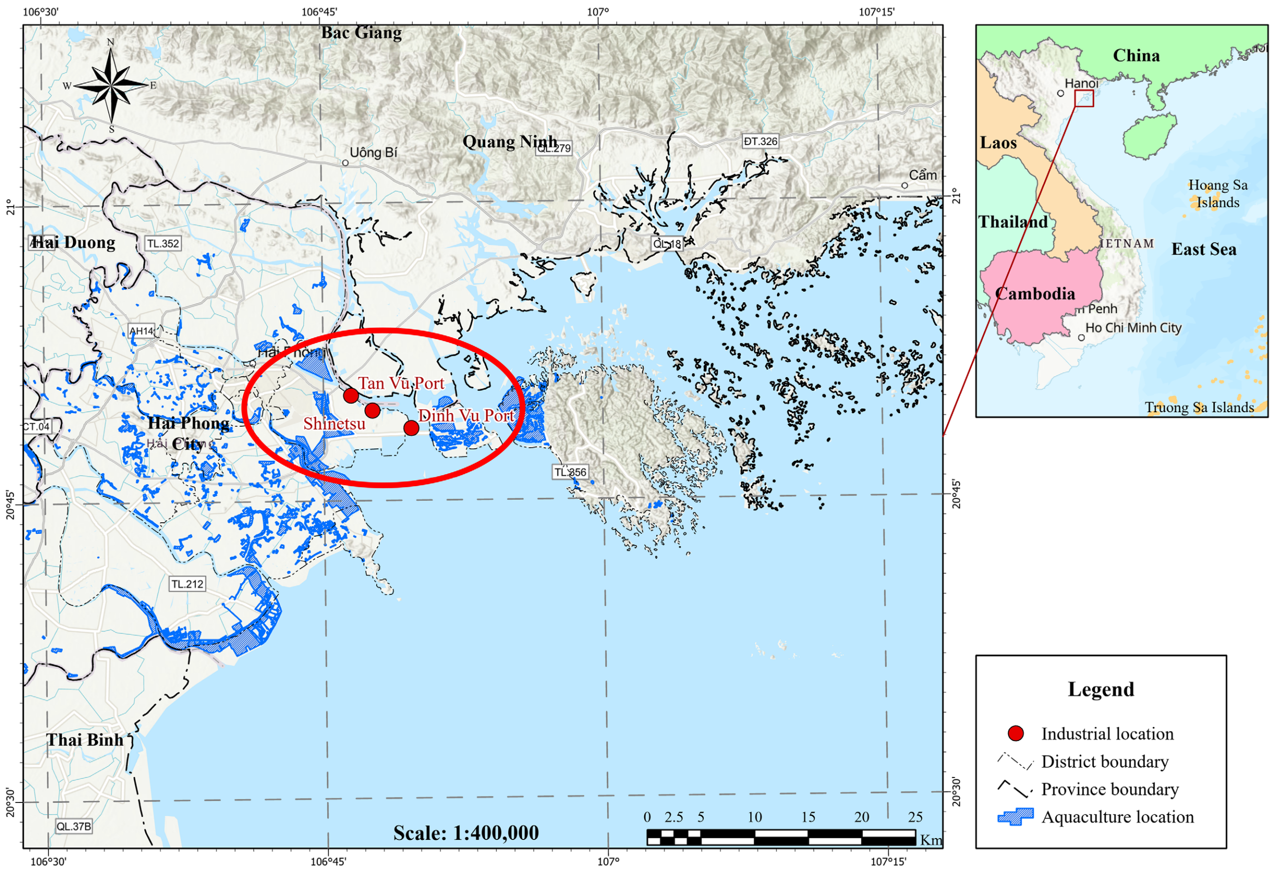

Figure 1. Study location map.

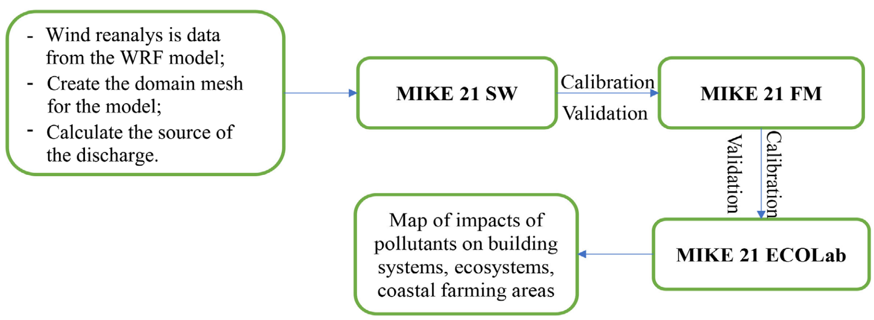

Figure 2. The flowchart of study structure.

2.2.1. Description of MIKE 21 SW Model

The dynamics of the gravity waves are described by the transport equation for wave action density. For small-scale applications, the basic transport is usually formulated in Cartesian coordinates, while spherical polar coordinates are used for large-scale applications. The wave action density spectrum varies in time and space and is a function of two wave phase parameters (DHI, 2017b). The two wave phase parameters can be the wave number vector $\boldsymbol{k}$ with magnitude, k, and direction, θ. Alternatively, the wave phase parameters can also be the wave direction, θ, and either the relative (intrinsic) angular frequency, $\sigma = 2\pi f a$, or the absolute angular frequency, $\omega = 2\pi f a$. In the present model a formulation in terms of the wave direction, θ, and the relative angular frequency, σ, has been chosen (Abbott & Ionescu, 1967). The action density, $N(\sigma, \theta)$, is related to the energy density $E(\sigma, \theta)$ by Equation (1):

$$N = \frac{E}{\sigma} \tag{1}$$

For wave propagation over slowly varying depths and currents the relation between the relative angular frequency (as observed in a frame of reference moving with the current velocity) and the absolute angular frequency ω (as observed in a fixed frame) is given by the linear dispersion relation.

$$\sigma = \sqrt{gk \tanh(kd)} = \omega - \boldsymbol{k} \cdot \boldsymbol{U} \tag{2}$$

where g is the acceleration of gravity, d is the water depth and $\boldsymbol{U}$ is the current velocity vector. The magnitude of the group velocity, c_g, of the wave energy relative to the current is given by Equation (3):

$$c_g = \frac{\partial \sigma}{\partial k} = \frac{1}{2}\left(1 + \frac{2kd}{\sinh(2kd)}\right)\frac{\sigma}{k} \tag{3}$$

The phase velocity c of the wave relative to the current is given by Equation (6):

$$c = \frac{\sigma}{k} \tag{4}$$

The frequency spectrum is limited to the range between a minimum frequency, σ_{min}, and a maximum frequency, σ_{max}. The frequency spectrum is split up into a deterministic prognostic part for frequencies lower than a cut-off frequency and an analytical diagnostic part for frequencies higher than the cut-off frequency. A dynamic cut-off frequency depending on the local wind speed and the mean frequency is used as in the WAM Cycle 4 model (Wamdi Group, 1988). The deterministic part of the spectrum is determined by solving the transport equation for wave action density using numerical methods. Above the cut-off frequency limit of the prognostic region, a parametric tail is applied.

$$E(\sigma, \theta) = E(\sigma_{\max}, \sigma)\left(\frac{\sigma}{\sigma_{\max}}\right)^{-m} \tag{5}$$

where m is a constant. In the present model m = 5 is applied. The maximum prognostic frequency is determined as

$$\sigma_{\text{cut-off}} = \min\left[\sigma_{\max}, \max\left(2.5\bar{\sigma}, 4\sigma_{PM}\right)\right] \tag{6}$$

where $\sigma_{\max}$ is the maximum discrete frequency used in the deterministic wave model, $\bar{\sigma}$ is the mean relative frequency and $\sigma_{PM} = g/(28u_{10})$ is the Pierson-Moskowitz peak frequency for fully developed waves (U_{10} is the wind speed at 10 m above the mean sea level). The diagnostic tail is used in the calculation of the non-linear transfer and in the calculation of the integral parameters used in the source functions. Below the minimum frequency the spectral densities are assumed to be zero (Abbott & Ionescu, 1967).

2.2.2. Two-Dimension Hydraulic MIKE 21 HD Model

The MIKE 21 FM HD module is a two-dimensional flow calculation model in a vertically homogeneous fluid layer. The flow modulus is solved by the finite element grid method. This module is based on the solution of the Reynolds mean Navier-Stokes equations for 2- or 3-dimensional incompressible fluids combined with the Boussines q hypothesis and the hydrostatic pressure hypothesis. In the case of two-dimensional elements can be triangular or quadrangular elements. Integration of the horizontal momentum equations and the continuity equation over depth $h = \eta + d$ the following two-dimensional shallow water equations are obtained.

$$\frac{\partial h}{\partial t}+\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=S \tag{7}$$

where t is time, x, y and z are the direction in Cartesian coordinate, η is the surface elevation, d is the still water depth, $h = \eta + d$ is total water depth, u, v, and w are the velocity components in the x, y and z direction, S is the magnitude of the discharge due to point sources and (u_s, v_s) is the velocity by which the water is discharged into the ambient water (Komen et al., 2010).

2.2.3. Water Quality MIKE 21 ECO Lab Model

MIKE ECO Lab is a numerical lab for Ecological Modelling. It is a generic and open tool for customizing aquatic ecosystems models to describe for instance water quality and eutrophication. DHI's expertise and know-how concerning ecological modelling has been collected in predefined ecosystem description (ECO Lab templates) to be loaded and used in ECO Lab. The ECO Lab templates describe physical, chemical, and biological processes related to environmental problems and water pollution (DHI, 2017a).

2.3. Setting up the Models

2.3.1. Input Model

- Discharge data was collected from four hydrographic stations, namely Don Son, Cua Cam, Kien An, Quang Phuc (**Figure 3(a)**).
- Meteorological and water level data was collected from Hon Dau station (**Figure 3(a)**).
- At some estuaries where there is no monitoring station, tide prediction in MIKE 21 Toolbox was used as the lower boundary for the calculation model (**Figure 3(b)**).
- The topographic data (Digital Elevation Model—DEM) used for constructing the grids in hydraulic calculations was processed from the nautical chart data of the Vietnam Navy Command and from the surveying studies in the past projects with a spatial solution of 30 × 30 m.
- The study established an integrated mesh of wave, hydraulic and water quality and a detailed mesh coupling of rivers and the sea (**Figures 3(c)**).
- Industrial zone-point sources include location, pollution parameter concentrations and wastewater discharges.

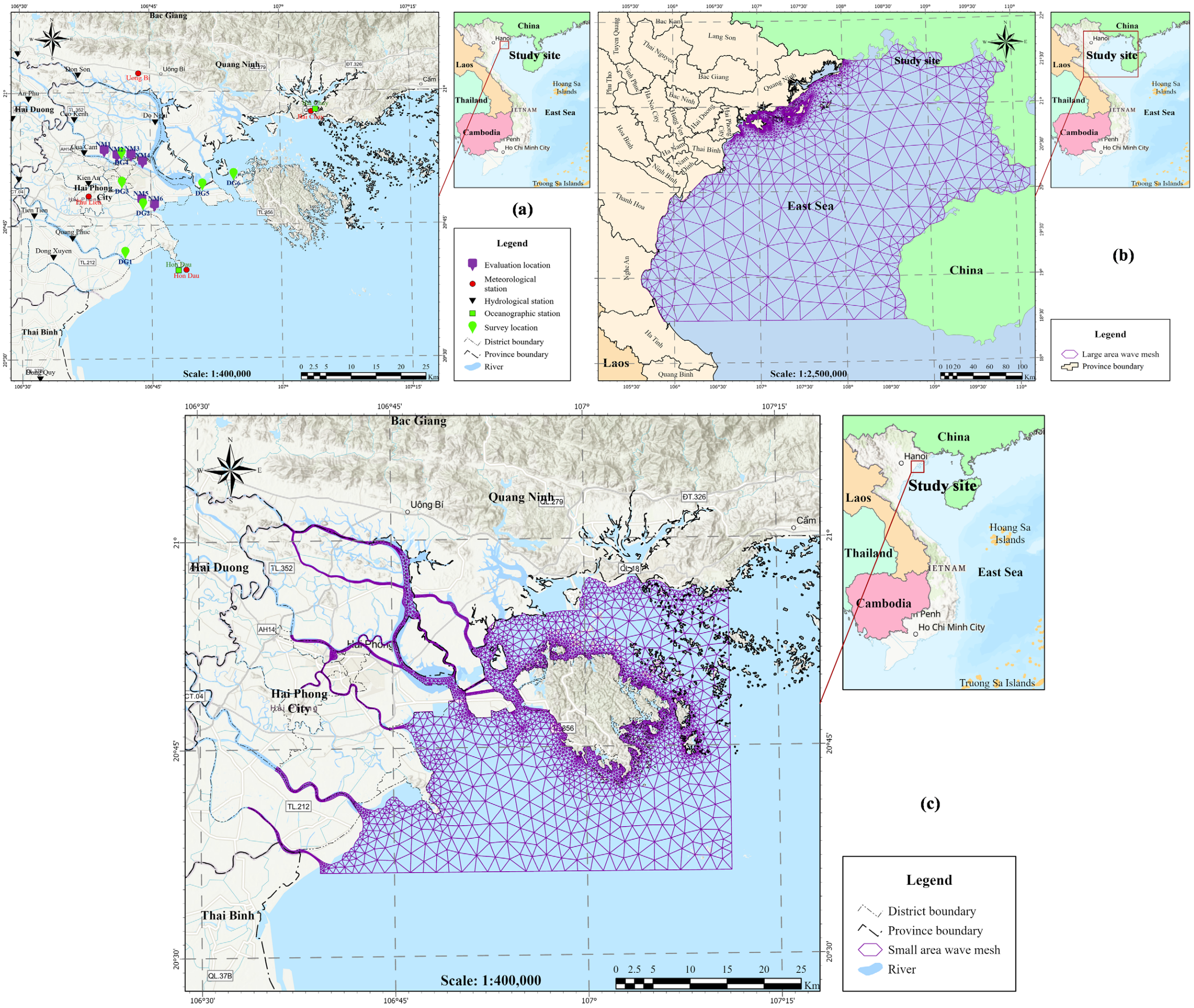

Figure 3. (a) Meteorological, hydrological and ocenographical stations; (b) Establised mesh of tidal prediction; (c) Established mesh of wave propagation, hydraulic and water quality.

2.3.2. MIKE 21 SW Model

To get a wave field for the study area, it is necessary to simulate the wave field for the wide area. Therefore, the calculation range of the selection model is shown in section 3. The area of wide-area wave simulation ensures that the scale of wind momentum is large enough to form a wave mode that propagates into the coastal area to create a high-precision wave field. The domain used for the MIKE 21 SW modeling area is limited from longitude 105˚44'E to 111˚1'E, and latitude from 18˚30'N to 21˚45'N. After simulating the waves for the whole large area, setting the domain for the study area, the wave transmission function from the deep-water wave model to the study area with the margins scaled was used (Figure 3(b)).

The small grid area was modeled from 20˚01'N to 21˚31'N and 106˚38'E to 107˚14'E. The grid is built with a combination of unstructured grid and square grid with a total of 10,512 cells and 7047 grid nodes. The calculated area is simulated by an unstructured mesh. The length of the smallest mesh edge is 20 m (the coastal area of Hai Phong city), the largest is about 3000 m (the sea area off the coast of Hai Phong city). In particular, the area is set up with a relatively detailed grid which is a smooth resolution in the coastal area with the smallest mesh edge of about 10 m. The zone is set up with a rough grid in the offshore area with the largest mesh edge of 1000 m (**Figure 3(c)**).

2.3.3. MIKE 21 FM Model

MIKE 21 FM model is set up using the same mesh as MIKE 21 SW model with marginal data being tidal level using DHI's MIKE 21 Toolbox. Combining computational grids will produce detailed results in the study area with small and fine grid cells and reduce the calculation step when using sparser grid cells offshore. The location of the grid cells and the specific marine topography of the simulated area are presented in **Figure 3(c)**.

2.3.4. MIKE 21 ECO Lab Model

MIKE 21 ECO Lab model is set up using the same mesh as MIKE 21 FM model. This study selected temple MIKE 11 WQ Level 1 and Coli, heavy metals to simulate pollutions parameters, and point sources were added in to mesh in **Figure 3(c)**.

3. Results

3.1. Calibration and Validation of the MIKE 21 SW Model

The calibration and validation of wave height used the data from the Hon Dau station with the periods from January to April 2020 and January to April 2021 (**Figure 4(a)** and **Figure 4(b)**). An assessment of the results of calibration and validation with the Nash coefficient ranged from 0.65 to 0.76 and PBIAS ranged from 5.6 to 9.4 (PBIAS < ±10%) for both calibration and validation (**Table 1**).

3.2. Results of Calibration and Validation of the MIKE 21 FM

The calibration and validation of the MIKE 21 FM used the water level at the Hon Dau station from January to March 2020, and January to March 2021 (**Figure 5(a)** and **Figure 5(b)**). The results of calibration and validation based on the Nash and R^2 criteria showed high similarity in the phase and amplitude of oscillations (**Table 2**). **Table 2** shows that the MIKE 21 FM model can simulate relatively accurately with Nash coefficient ranging from 0.85 to 0.90, showing a good match between simulation results and observation data. The results for the offshore water levels and flow rates in the river showed that the hydraulic parameters

Table 1. Assessment of correlation values for calibration and validation of the MIKE 21 SW model.

Station	Calibration		Validation	
	NSE	PBIAS	NSE	PBIAS
Hon Dau	0.76	5.6	0.65	9.4

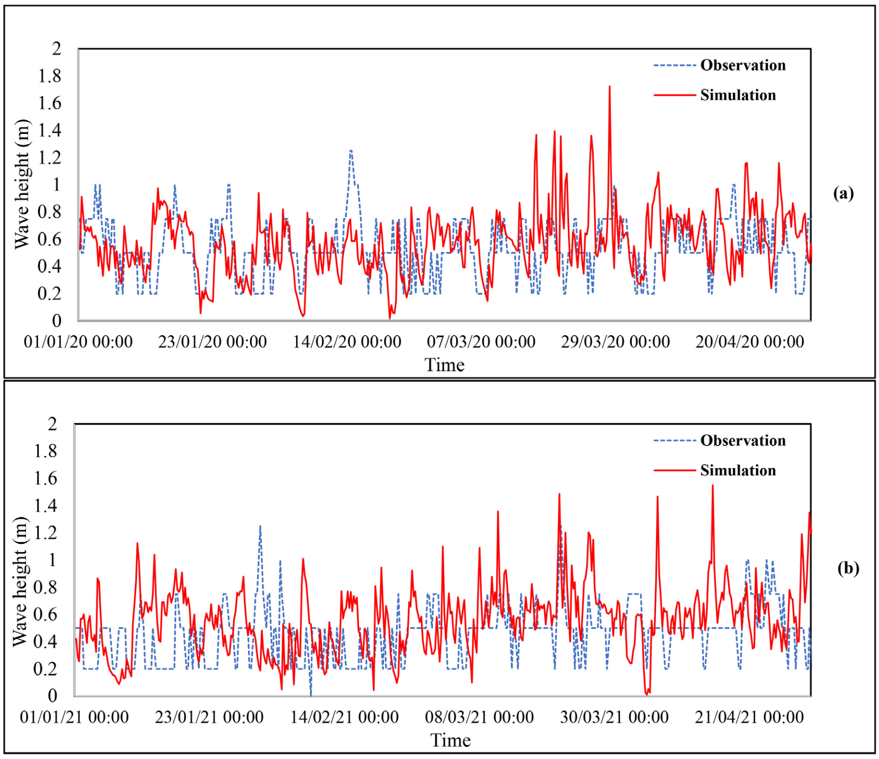

Figure 4. The calibration (a) and validation (b) results of wave height at Hon Dau station.

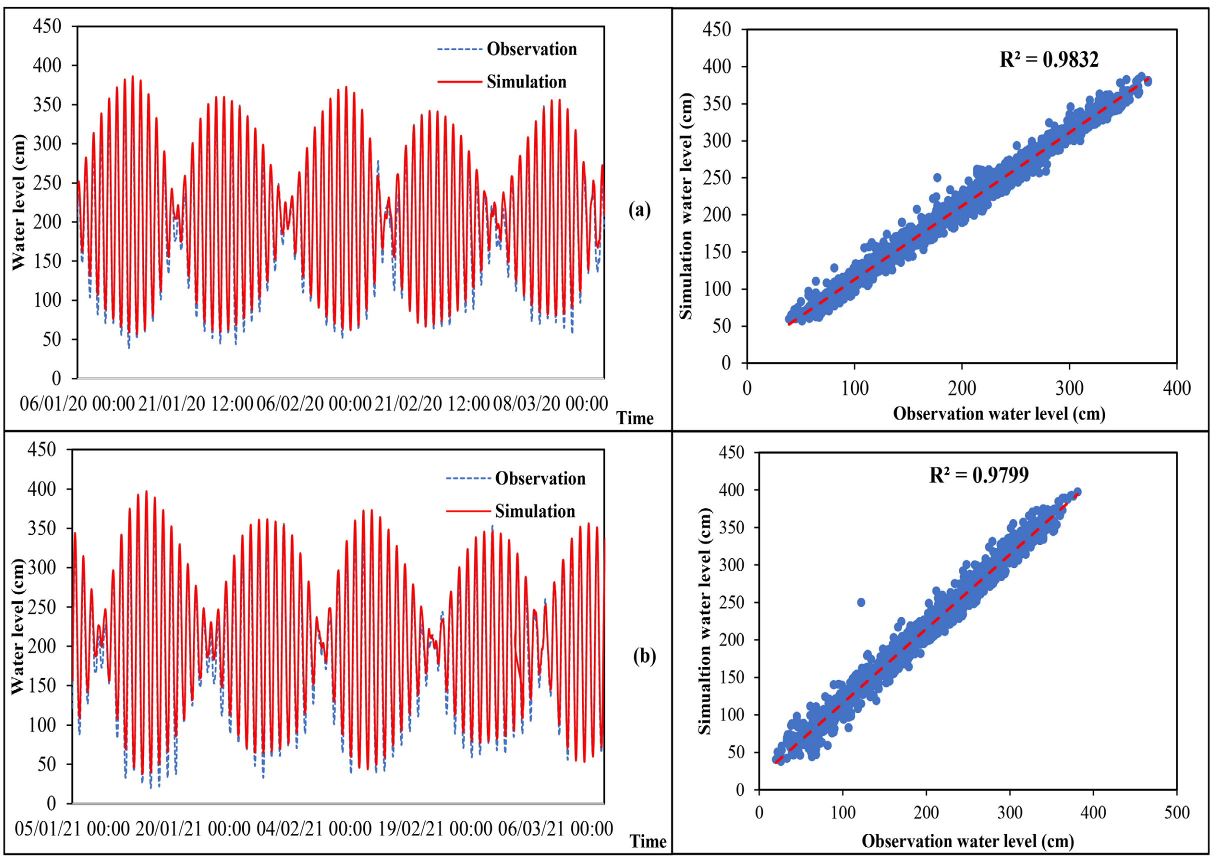

Figure 5. The calibration (a) and validation (b) results of water level at Hon Dau station.

Table 2. Assessment of correlation values for calibration and validation of the MIKE 21 FM model.

Station	Calibration			Validation		
	NSE	R^2	PBIAS	NSE	R^2	PBIAS
Hon Dau	0.90	0.98	6.13	0.85	0.97	9.17

of the MIKE 21 FM model were relatively suitable for the study area. Therefore, it would be possible to use the MIKE 21 FM model to simulate the impact of the hydraulic regime of water quality in the study area.

3.3. Calibration and Validation of the MIKE 21 ECO Lab Model

3.3.1. Calibration of Water Quality Model

Calibration results show that the correlation values between the simulated and observed concentrations of pollution ranged from 5% - 19% (**Figure 6**). It can be seen that the water quality model parameter set was relatively suitable for the study area. However, to be able to evaluate accurately and objectively, this study used these parameters to simulated for the 2016 data. Six locations for calibration and verification of the water quality model are shown in **Table 3**.

The assessment of the calibration and calibration results used the water quality model are presented in **Table 4**.

3.3.2. Validation of Water Quality Model

Validation results show that correlation values between the simulated and observed pollution parameter concentrations ranges from 6% to 24% (**Figure 7**). It can be seen that the water quality model parameters were relatively suitable for the study area.

3.4. Simulation Results of the Current Pollution Situation in Hai Phong's Coastal Areas

The results of water quality simulation in the coast of Hai Phong used the survey data of some coastal locations in 2023 are shown in **Figures 8(a)-(f)**.

Evaluation results of simulated transmission of pollution parameters are represented for 06 aquaculture areas (DG1 - DG6) (**Figures 8(a)-(f)**); in which there are four locations in rivers, namely DG1 to DG4 and 2 locations at DG5-Cat Hai and DG6-Cat Ba islands. Based on the national regulations QCVN 08:2023/BTNMT and QCVN 10:2023/BTNMT, only TSS has different allowable limits and Fe is only applied for coastal areas. The details of the simulation results in 2023 are evaluated in **Figures 9(a)-(f)**.

- DO concentration at some aquaculture sites is below B level—QCVN 08:2023 as average water quality. This water can be used for production industrial and agricultural output after treatment.
- The concentration of BOD_5 at the aquaculture sites exceeded B level—QCVN 08:2023. Only at Cat Ba Island the concentration was still below A level, identifying that water quality was good.

Table 3. Assessment of the calibration and validation locations.

No.	Location	Description
1	NM1	Bach Dang shipyard
2	NM2	
3	NM3	Tan Vu port
4	NM4	
5	NM5	Hai Phong Cement Factory
6	NM6	

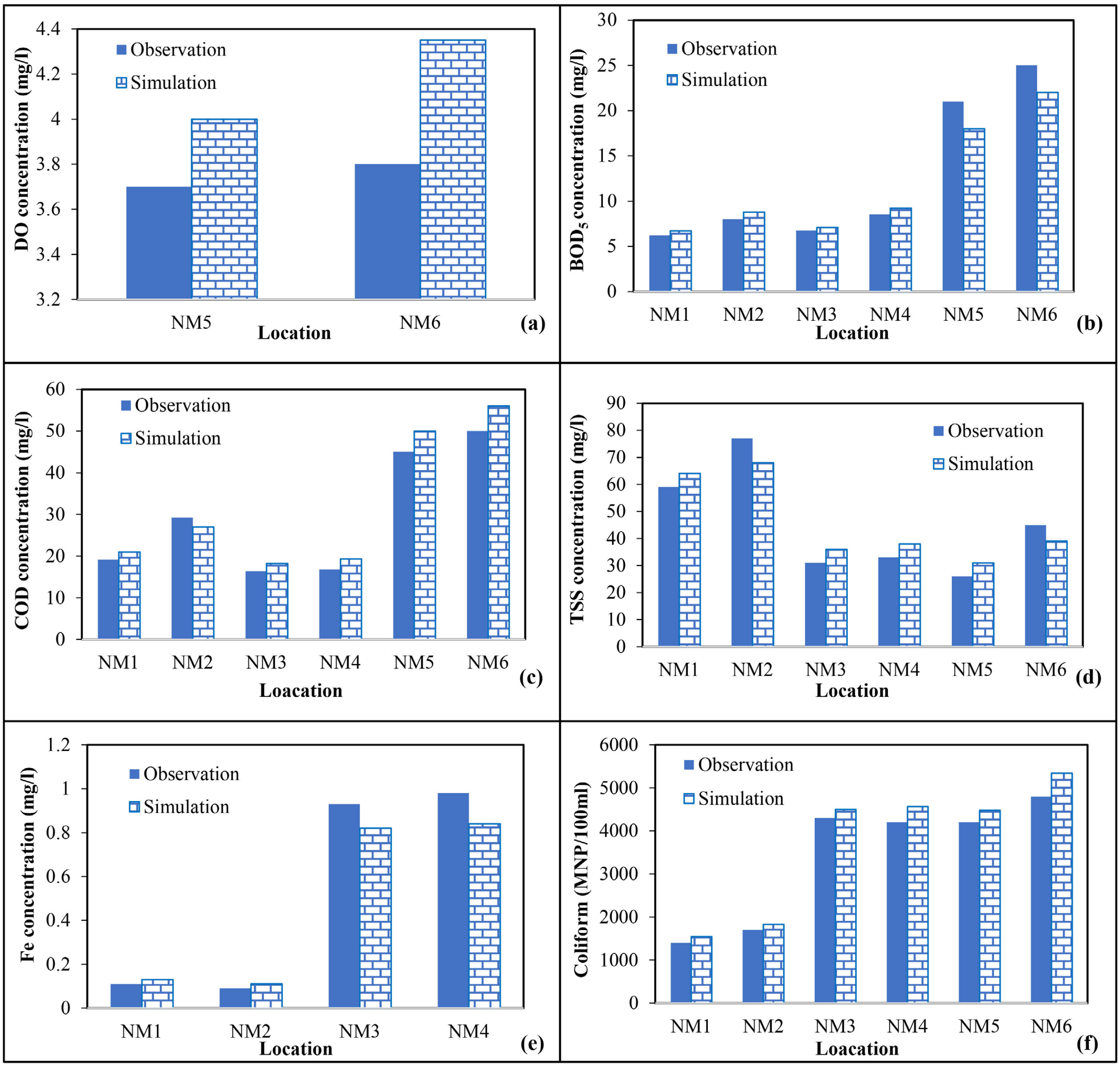

Figure 6. Calibration result of water quality model in 2016; (a) DO; (b) BOD_5; (c) COD; (d) TSS; (e) Fe; (f) Coliform.

Table 4. Assessment of the calibration and validation results used the water quality model.

Process	Evaluation location	Pollution concentrations					
		Coliform	BOD_5	COD	TSS	Fe	DO
Calibration	NM1	−10%	−8%	−10%	−8%	−18%	
	NM2	−8%	−10%	8%	12%	−22%	
	NM3	−5%	−5%	−11%	−16%	12%	
	NM4	−9%	−8%	−15%	−15%	14%	
	NM5	−7%	14%	−11%	−19%		−8%
	NM6	−11%	12%	−12%	13%		−14%
Validation	NM1	−8%	−13%	−17%	6%	−19%	
	NM2	−7%	−7%	−19%	9%	−21%	
	NM3	−7%	−9%	−15%	−24%	−13%	−16%
	NM4	−7%	−7%	−14%	−21%	−11%	−15%
	NM5	−10%	−11%	9%	−19%		15%
	NM6	−15%	−10%	6%	13%		8%

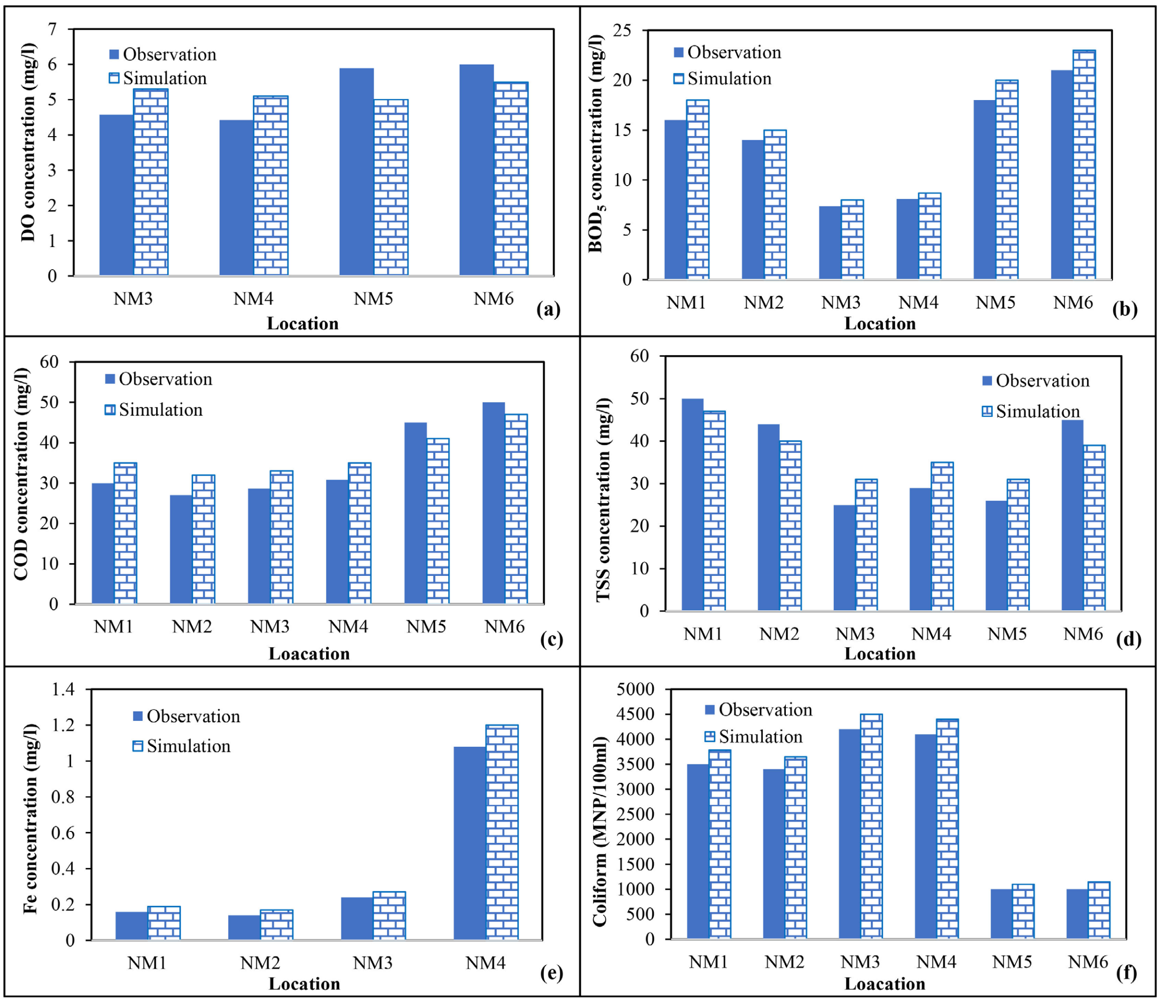

Figure 7. Calibration result of water quality model in 2016; (a) DO; (b) BOD_5; (c) COD; (d) TSS; (e) Fe; (f) Coliform.

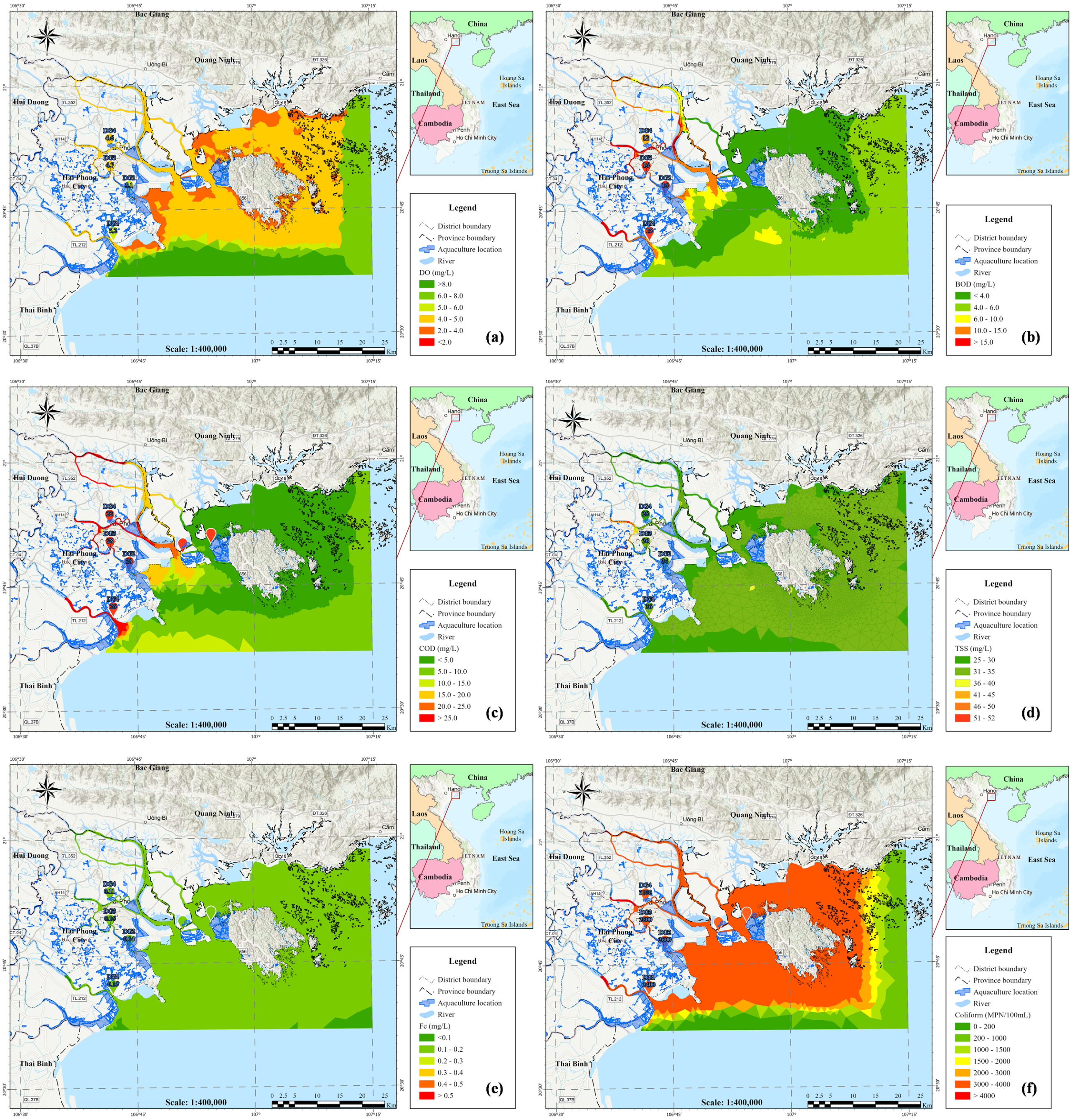

Figure 8. Simulation result of water quality model in 2023; (a) DO; (b) BOD_5; (c) COD; (d) TSS; (e) Fe; (f) Coliform.

- COD concentrations at all locations in rivers are above level B, only 2 coastal locations DG5 and DG6 are below level B.
- TSS concentrations at all locations in the river exceeded B level; However, the two coastal locations are still below allowable limits for the marine water quality (QCVN 10:2023/BTNMT).
- Fe concentrations were below the allowable limit at two locations near the shore based on QCVN 10:2023/BTNMT.
- Coliform concentration was below B level at all locations.

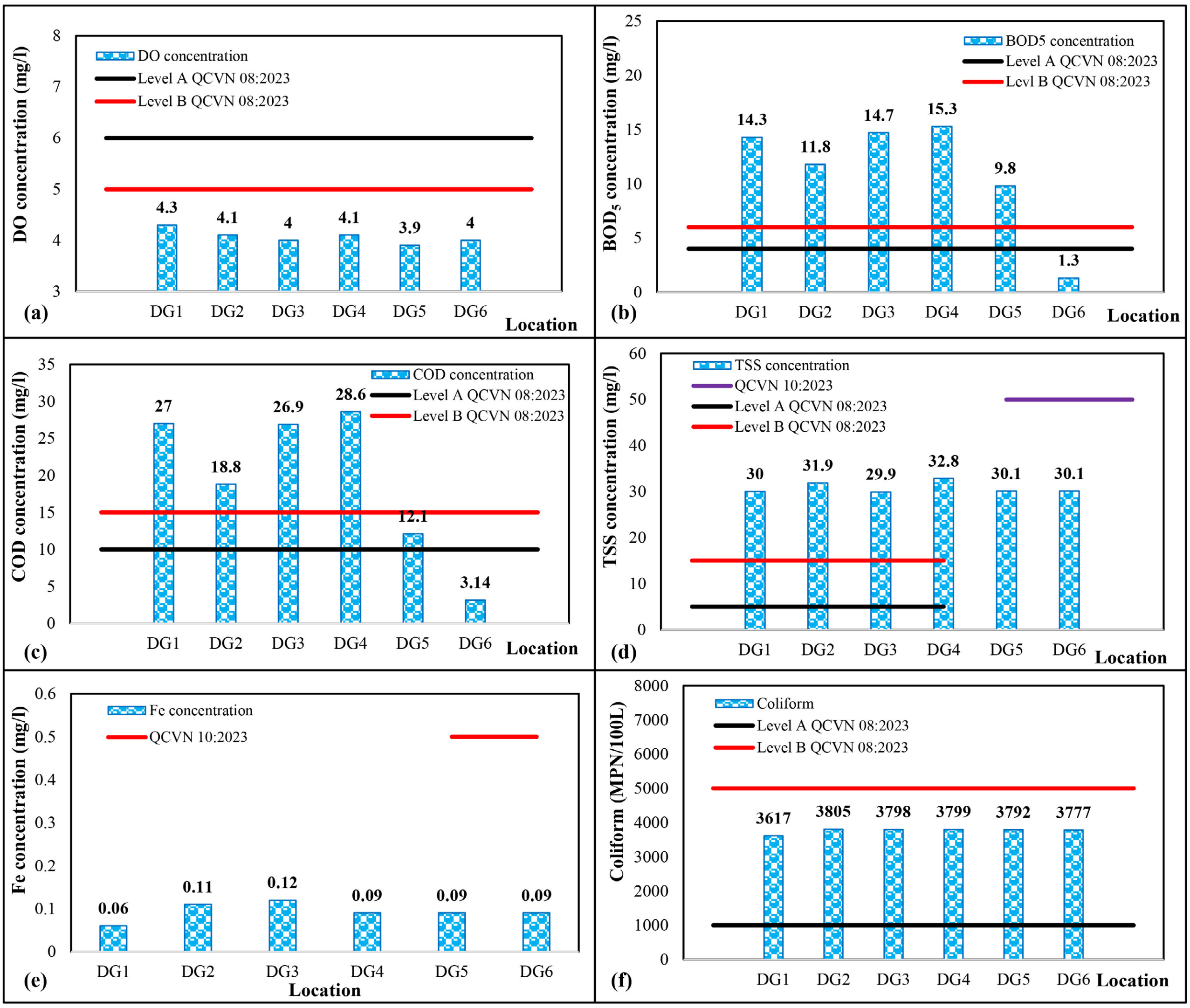

Figure 9. Concentration of pollutant parameters at aquaculture location; (a) DO; (b) BOD_5; (c) COD; (d) TSS; (e) Fe; (f) Coliform.

Based on the results above, a concentration distribution map of some pollution parameters in the coastal area and an assessment of the status of water quality in some aquaculture zones were done in the study area. This study assessed the impact of some sources of waste from the large coastal industrial zones in Hai Phong to open water bodies. The study results will support managers in working towards a socio-economic development plan for Hai Phong city to achieve sustainable development.

4. Conclusion

This study simulated water quality in the coastal area of Hai Phong city in relation to pollution sources from large industrial zones in Hai Phong city. The application of MIKE 21 SW model to simulate waves, MIKE 21 FM model to simulate hydraulic regimes and MIKE 21 ECO Lab model to simulate pollutant transmission was applied in the case study. Hai Phong is one of the coastal cities in Vietnam highlighted with increasing socio-economic activities. More and more industrial parks and industrial zones are invested and built along the coast of Hai Phong, leading to an increase in the sources of waste discharged into the coastal areas. Hydraulic simulation results with Nash coefficient from 0.85 to 0.90 and R^2 of 0.97. The results of calibration and verification of the water quality model in the study area with a correlation value of less than 20% are acceptable for the study area.

The research results show that the aquaculture area in the river is currently polluted by discharges from industrial zones, thus, it is necessary solute to minimize the impact of pollution sources as required by all industrial zones. It is necessary to raise the waste treatment threshold instead of just meeting the grade A standard of QCVN 40:2011/BTNMT—National Technical Regulation on industrial wastewater before discharging into the environment. At the same time, there is a plan to redistribute the aquaculture area accordingly.

The simulation results of the current state of water quality in the coastal of Hai Phong city are quite consistent with observation data. The models applied in this study can be widely applied to many coastal industrial zones. Vietnam has a long coastline, so the widespread application of water quality simulation models to assess the impact of pollution sources on coastal estuaries is meaningful not only for the aquaculture but also for the coastal economic activities. The results of the study will be widely applied to coastal areas with similar conditions, the systematic assessment of coastal water quality under the impact of discharge sources will help managers make policies to improve and protect water quality and the coastal environment to promote effective marine economic development.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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