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Development of a water quality index to assess and classify water quality in the coastal waters of Hai Phong (Vietnam)

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ABSTRACT

The method of developing the water quality index (WQI) to evaluate and classify the water quality of the coastal waters of Hai Phong (2019) includes the following steps: selecting parameters, calculating sub - indices, determining weights, calculating the WQI, building a classification scale, and testing the formula. The water quality of Hai Phong's coastal waters varied widely, ranging from very poor to excellent. The water quality of Hai Phong's coastal waters tended to improve from the river mouths to the sea. In the rainy season, the areas with very poor and poor water quality tended to expand, while the areas with medium and good water quality tended to shrink compared to the dry season. The area of excellent water quality showed little seasonal variation. During high tide, water quality was typically better than during low tide. The water quality at the Bach Dang, Lach Tray, Van Uc, and Thai Binh estuaries was very poor during low tide (WQI from 19 to 22) and poor during high tide (WQI from 43 to 45) in both the dry and rainy seasons. The South - Southwest area of the Hai Phong coastal estuary generally had worse water quality compared to the North and Northeast areas. The Ben Beo area (the main port of Cat Ba Island, where most of the island's large and small boats gathered) had medium water quality (WQI from 62 to 73). This area was at a higher risk of environmental pollution compared to other areas in the Cat Ba Island sea. The outside area had water quality ranging from good to excellent.

Keywords: Water quality index, Hai Phong coastal seawater, water quality zoning.

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INTRODUCTION

Hai Phong is a coastal city in the North and serves as the gateway to the sea for the Northern provinces of Vietnam. The coastal area of Hai Phong is situated between the Red River Delta and the Northeast coastal region, featuring a rich and diverse terrain and natural landscape. It includes mountains, forests, plains, seas, islands, rivers, and lakes. The diverse ecosystem of the Hai Phong coastal area encompasses most of the fundamental ecosystems found along Vietnam's coast [1]. Hai Phong has vibrant marine economic activities, including seaports, fishing, aquaculture, tourism, and services, which impact not only Hai Phong but also the entire northern coastal region. However, these economic activities have significantly affected the environment, leading to environmental pollution, a reduction in tidal flat areas, and challenges for the marine ecosystem.

Around the world, the approach to constructing water quality index models varies based on geographical location, natural conditions, current water quality status, and management regulations of each territory or country. Typically, there are three main directions for developing WQI models: (1) Applying an existing foreign WQI calculation method to the country or locality; (2) Adapting and improving an existing WQI calculation method to better suit the country or locality; and (3) Researching and developing a new WQI calculation method specifically for the country or locality. The US WQI calculation method (WQI-NSF) has been widely applied and enhanced by numerous studies for assessing water quality.

In Vietnam, WQI research is primarily focused on surface water environments. Notable studies include Pham Thi Minh Hanh's work in 2009, which improved the WQI calculation method for inland surface water in Vietnam. This research addressed limitations such as ambiguity and rigidity in the existing methods [2]. Pham Gia Hien (2009) developed the WQI-NSF index to support water resource planning for the Saigon River [3]. Nguyen Van Hop (2010) applied the WQI - Bhargava method to evaluate the water quality of the Bo River in

Thua Thien Hue Province [4]. Nguyen Le Tu Quynh (2015) developed a water quality index to classify the water quality of rivers in Thai Nguyen Province, based on the US Environmental Sanitation Foundation's method (WQI-NSF) [5]. Pham Ngoc Ho (2011) developed WQI formulas to evaluate the water quality of the Thanh Hoa coastal region [6]. Nguyen Thi The Nguyen (2014) developed WQI formulas to assess the water quality of Ha Long Bay in Quang Ninh [7]. Pham Huu Tam (2016) applied the WQI-NSF method to assess water quality at marine environmental monitoring stations in southern Vietnam over a five-year period (2011–2015) [8]. Truong Van Dan (2018) researched and developed the WQI-NSF method to assess the water quality of the Tam Giang - Cau Hai Lagoon [9]. Tran Thi Yen and Nguyen Thi Thanh Thuy (2019) studied and developed the WQI-NSF method, using both arithmetic weighted sum and geometric weighted mean, to assess the quality of coastal seawater at Cua Phu Beach in Dong Hoi, Quang Binh [10].

Research on developing a Water Quality Index (WQI) is practical because it allows for the assessment and reporting of information in a form suitable for all interested parties (including managers and communities who are not water environmental experts) regarding the quality of water environments in estuaries and coastal areas. In addition, the water quality index (WQI) for coastal waters - one of the effective tools for assessing, zoning, and managing water quality according to an integrated approach, has not been widely studied in Vietnam [7]. Zoning coastal waters based on the water quality index is scientifically and economically effective because it simplifies research results, helps managers grasp the situation, addresses pollution problems in coastal estuaries, and saves costs compared to traditional methods [5]. Water quality zoning is an important component of the process of planning and managing the use of coastal estuaries. The results of developing a water quality index to assess and zone water quality in coastal waters in Hai Phong are crucial for the zoning and planning of spatial management of coastal waters in Hai Phong, as well as for

supporting the zoning and management of seas in other coastal areas. However, previous studies have rarely addressed the application of the water quality index for evaluating and classifying water quality in the coastal waters of Hai Phong. Consequently, this article presents the results of developing a water quality index to assess and zone the water quality in the coastal waters of Hai Phong.

MATERIALS AND METHODS

Materials

The article uses survey data to study the aquatic environment in Hai Phong's coastal waters from state, ministerial and provincial level projects including:

Project: Assessment of the environmental carrying capacity of some typical water bodies along the coast of Vietnam for sustainable development (KC 09.17/11–15), 2011–2015.

Project: Research to build arguments for planning dredged sand and sediment dumps in the Hai Phong area, 2015–2017.

Project: Investigation, assessment and overall solution to protect the marine and island environment in Hai Phong City, 2017–2019.

Project: Monitoring and analysis of the coastal marine environment in northern Vietnam from 2010 to 2019.

Project: Research and assessment of the environmental carrying capacity of Dinh Vu industrial park for the ability to receive chemical and petrochemical projects (ĐT.MT.2017.788), 2017–2019.

Project: Research to build a green economic model for some typical island communities along the coast of Vietnam (KC.08.09/16–20), 2016–2020.

Methods

Study areas

The research space encompasses the entire tidal zone, coastal waters of Hai Phong City, from the shore to the outside of Cat Ba - Long Chau Archipelago. The total area of the study area is approximately 1,232 km². Research space includes 4 areas (Fig. 1):



Figure 1. Map of the study area

1. Coastal area in the southwest of Do Son Peninsula: Typical for the sea area along the river mouth of the delta.

2. Coastal area in the northeast of Do Son Peninsula, Nam Trieu Estuary: Typical for the sea area along the funnel-shaped estuary.

3. Coastal area of Cat Ba Island: Typical for the bay area of the island.

4. Outside area, this is the area affected by 3 areas: Southwest Do Son, Northeast Do Son and Cat Ba Island.

Method for developing a water quality index (WQI)

The method for developing the water quality index takes place in 6 steps:

Step 1: Select WQI calculation parameters

The parameters selected to calculate the WQI for the coastal waters of Hai Phong are parameters that describe the water quality characteristics of the coastal waters of Hai Phong. The parameters (10 parameters) selected to calculate WQI include: DO, NO_3^- , NH_4^+ , PO_4^{3-} , $\text{COD}_{\text{KMnO}_4}$, TSS, coliform, chlorophyll-a, oil and grease, Fe [11].

Step 2: Method for grouping water quality parameters

Use the cluster analysis method (cluster variables) to group water quality parameters. Cluster analysis is a tool for mining data and finding groups with similar characteristics. Cluster analysis can also be applied to group variables (parameters) with similar observed data. The goal of cluster analysis is to identify groups based on their similarity [12]. In the first step, the two closest observations are linked together. In the next step, either the third value is linked to the first two values or the next two values are combined into another group. This process continues until all groups are combined into one [13].

Step 3: Build sub-index (q_i)

The sub - index is determined based on QCVN 10:2015/BTNMT on coastal seawater quality of Vietnam and the seawater quality standards of ASEAN countries, Australia, Indonesia, the Philippines and Thailand. Refer to some water quality requirements for marine

ecosystems and other research documents on WQI applied to coastal seawater. Also refer to QCVN 08-MT:2015/BTNMT (Vietnam's national technical regulation on surface water quality).

The sub-index has a value from 1 to 100 (1 is the worst water quality and 100 is the best water quality) and is divided into 4 ranges as follows:

$q_i = 100$: corresponds to the allowable limit for "aquaculture and aquatic conservation areas" in QCVN 10-MT:2015/BTNMT standard (seawater quality section in coastal waters).

$q_i = 75$: corresponds to the allowable limit for "beaches and water sports areas" in QCVN 10-MT:2015/BTNMT (seawater quality section in coastal waters) and refers to the standard Coastal seawater of some countries around the world.

$q_i = 50$: Corresponds to the allowable limit "for other places" in the QCVN 10-MT:2015/BTNMT standard and refers to coastal sea water standards for port waters and navigation of some water in the world.

$q_i = 25$: When the value of the parameter exceeds the allowable limit for "Other places" water areas in QCVN 10-MT:2015/BTNMT standard, coastal sea water standards of some countries in the world and Some other sea water quality materials or corresponding to the allowable limits of surface water used for navigation and other purposes with low water quality requirements (QCVN 08-MT:2015/BTNMT, column B2).

$q_i = 1$: When the value of the parameter exceeds the allowable limit compared to the level $q_i = 25$.

Step 4: Determine the weights of the WQI calculation parameters

Apply the entropy method to determine the weight of the WQI calculation parameters [14–17]. Entropy is applied to measure the size of the amount of information; the more information contained in a specific indicator, the more important its influence in decision making becomes. Therefore, entropy is also used to assign weights to environmental indicators [14, 18].

Step 5: Evaluate and select the WQI calculation formula

Perform assessment of 1) ambiguous; 2) eclipsing and 3) sensitivity to 3 methods of synthesizing sub-indices:

Arithmetic weighted sum:

$$\sum_{i=1}^n w_i q_i$$

Geometric weighted mean:

$$\prod_{i=1}^n q_i^{w_i}$$

Solway modified weighted sum:

$$\frac{1}{100} \left(\sum_{i=1}^n w_i q_i \right)^2$$

in which: q_i : sub-index of parameter i ; w_i : weight of parameter i ; n : number of parameters used to calculate the WQI .

After the assessment process, the optimal and most suitable WQI form is selected for water quality assessment in the coastal waters of Hai Phong.

Step 6: Build a water quality classification scale according to WQI

The classification scale is built based on the level and number of parameters exceeding the allowable limit according to Vietnam's coastal sea water standards (QCVN 10:2015/BTNMT) and coastal sea water standards of some other countries (ASEAN, Australia, etc.). The water quality classification scale is divided into five ranges: excellent, good, medium, poor, very poor and shown in Table 1.

Table 1. Water quality classification scale

No.	Level for classifying water quality	Current status of selected parameters for calculating the WQI compared to QCVN 10:2015/BTNMT and seawater quality standards of some other countries
1	Excellent	All valid parameters are within the allowable limits for aquaculture and aquatic conservation areas ($q_i = 100$).
2	Good	All valid parameters are within the allowable limits for beaches and water sports areas ($q_i = 75$).
3	Medium	All valid parameters are within the allowable limits for the "other places" region ($q_i = 50$).
4	Poor	All parameters have values exceeding the allowable limits for water areas "other places" ($q_i = 25$).
5	Very poor	When the value of the parameter exceeds the allowable limit compared to the level $q_i = 25$ ($q_i = 1$).

Methods of investigation, water quality survey and laboratory analysis

Location and time of monitoring

The monitoring location (Fig. 2) is determined based on the characteristics of the waste source, hydrodynamic regime and aquatic dispersion of pollutants in the coastal waters of Hai Phong. Coastal sea area in the northeast of Do Son Peninsula, Nam Trieu Estuary, water sampling points from ĐBĐS 1 to ĐBĐS 27. Coastal sea area of the southwest of Do Son Peninsula, water sampling points from

TNĐS 1 to TNĐS 12. Coastal area of Cat Ba Archipelago, water sampling points from CB 1 to CB 11. Outside area, water sampling points from VN 1 to VN 7. Water samples were collected twice: March (dry season, 2019) and August (rainy season, 2019). Besides, continuous measurement of hydrological factors at three survey points evenly distributed from the river mouth to the sea over a 48-hour period. Collect water samples every three hours to measure and analyze water quality parameters, aiming to assess fluctuations in water quality throughout the day and simulate the spread of contaminants.

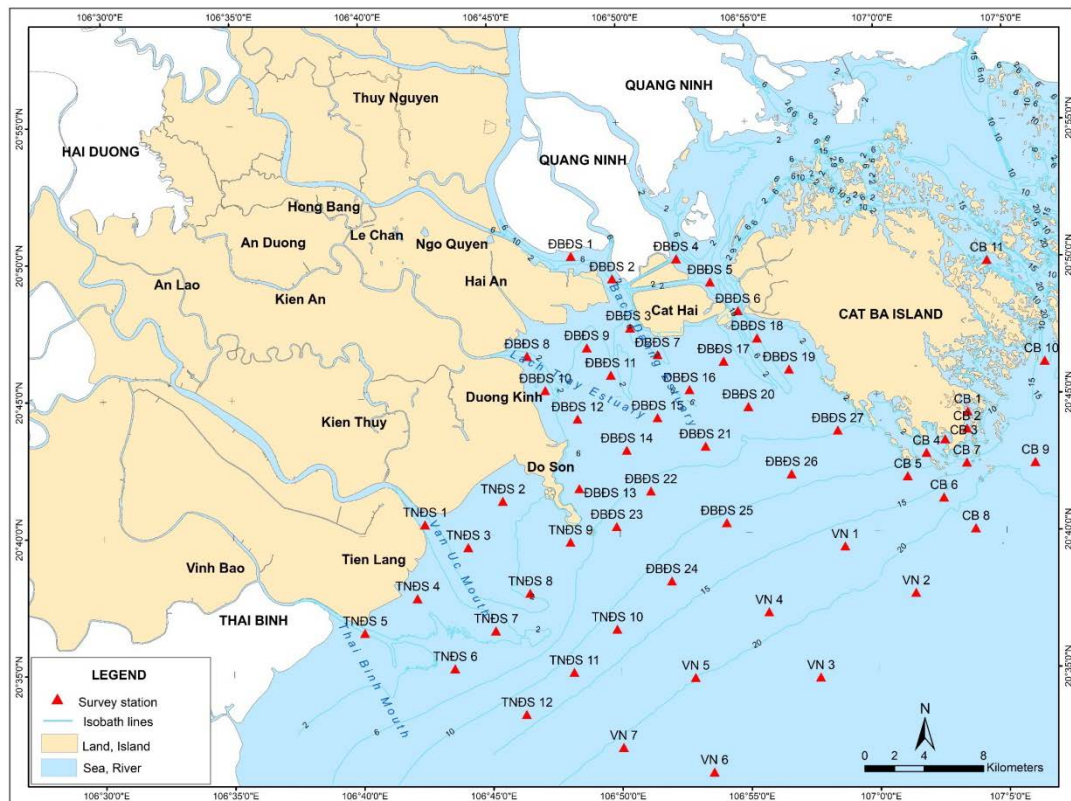


Figure 2. Location of water sampling points

Monitoring parameters

To assess the water quality in the coastal waters of Hai Phong, parameters were selected including: dissolved oxygen (DO), $\text{COD}_{\text{KMnO}_4}$, NO_3^- , NH_4^+ , PO_4^{3-} , total suspended solids (TSS), iron (Fe), oil and grease, coliforms, chlorophyll-a.

Methods of sample collection, sample preservation, field measurements and laboratory analysis

Collection and preservation of samples

Surface water samples (0.5 m from the surface) and bottom water samples (0.5 m from the bottom) were collected using a 5-liter Niskin Van Dorn Sampler according to the instructions of Circular 24/2017/TT-BTNMT-Technical regulations on environmental monitoring [19] and Circular No. 34/2010/TT-BTNMT-Technical regulations on oceanographic, chemical and environmental investigation and survey of coastal and island areas [20].

Treat and store samples for laboratory analysis according to the instructions of *Standard methods for Examination of Waster water, 23 Edition, 2017 APHA-AWWA-WPCF* [21]. Dissolved oxygen content in the water were measured using a DO meter (550A YSI - USA).

Method for analyzing samples in the laboratory

The analysis of the water samples was carried out using the following methods:

TSS was determined by the weight method (TCVN 6625:2000).

Chemical oxygen demand (COD) was determined by the oxidation method of potassium permanganate (KMnO_4) in alkaline environment [22].

The oil content in the water was determined by the infrared projection method (SMEWW 5520.B:2017 or SMEWW 5520.C:2017):

The content of nutrients (NH_4^+ , PO_4^{3-} , NO_3^-) in the water was determined using a

spectrophotometer DR/3900 HACH, USA (SMEWW 4500:2017).

The content of *Fe* was determined after sample treatment using flame atomic absorption spectrometry (SMEWW 3111.B: 2017).

The chlorophyll-a content in the water was determined by colorimetric method after filtration and extraction with acetone (SMEWW 10200.H: 2017).

The coliform index in water was determined using the multi-tube method (TCVN 6187-2:1996).

Water quality zoning method according to WQI

The coastal waters of Hai Phong are classified into water quality zones according to the *WQI* classification scale established for the coastal waters of Hai Phong and indicated in different colors. Using the spatial interpolation method to build a water quality zoning map in Hai Phong's coastal waters (using the spline interpolation method in ArcGIS 10.5 software based on water quality index values at monitoring points).

RESULTS

Formula for calculating the water quality index (WQI) for coastal waters

Analyze and select the aggregation functions (WQI)

According to the US Environmental Protection Agency [7, 23], the *WQI* calculation method must meet the following criteria: Easy calculation; describe the importance of calculation parameters; avoid eclipsing and ambiguity; sensitive to changes in water quality levels.

The sensitivities of the aggregation functions are determined and compared using ideal data sets, with one variable set to an extreme value of 0 or 1 (worst case) and the other variables set to 100 (best case) [2]. Table 2 presents the results of calculating the *WQI* using aggregate functions in the ideal case where one extreme sub-index is 0 or 1, while the other sub-indices are 100.

Table 2. Results of calculating *WQI* of aggregate functions in the ideal case when one extreme sub-index is 0 or 1, the other sub-indices are 100

No.	Method	Aggregation functions	<i>WQI</i>	
			$q_i = 0$	$q_i = 1$
1	Arithmetic weighted sum	$WQI = \sum_{i=1}^n q_i W_i$	88–92	88–92
2	Solway modified weighted sum	$WQI = \frac{1}{100} \left(\sum_{i=1}^n q_i W_i \right)^2$	77–85	78–85
3	Geometric weighted mean	$WQI = \prod_{i=1}^n q_i^{W_i}$	0	58–69

in which: W_i : weight of parameter i ; q_i : sub-index of parameter i ; n : number of parameters has been selected.

Eclipsing problem

Eclipse occurs when a parameter has a q_i that indicates poor water quality but a *WQI* value that does not reflect poor water quality (Table 2).

In the case where one sub-index is “0” and the others are 100: The *WQI* calculated by the geometric weighted mean (Equation 3) results in the last index equal to “0”.

When a parameter has a q_i value of “0” or “1”: the *WQI* calculated according to the arithmetic weighted sum (Equation 1) has the highest eclipse (high *WQI* value and still represents a good water quality level).

Similarly, Solway modified weighted sum (Equation 2) also has eclipse because these two forms of *WQI* formula are derived from Equation 1.

The Geometric weighted mean (Equation 3) has a non-severe eclipse and is reduced as the number of sub-indices decreases.

Ambiguity problem

The ambiguity of the aggregate functions is determined using an ideal data set, where all sub-index (q_i) of all parameters are equal to 50.

The results show that the 3 aggregate functions (arithmetic weighted sum, geometric weighted mean, weighted harmonic square index) give a WQI value of 50, while the Solway modified weighted sum gives a WQI value of 25. Thus, the weighted Solway sum form has great ambiguity.

Rigidity

Rigidity (difficulty in incorporating new parameters) occurs with weighted WQI aggregate functions.

Comment

Based on the consideration of the advantages and disadvantages of aggregate functions, it can be seen: The arithmetic weighted sum shows the greatest eclipse. However, in a group of parameters with similar values, the Arithmetic weighted sum does not show serious eclipse. The Geometric weighted mean has a non - severe eclipse and is reduced as the number of sub - indices decreases. Geometric weighted mean has greater sensitivity than the remaining aggregate functions. The Solway modified weighted sum has a high level of ambiguity.

Thus, the geometric weighted mean has many advantages over the remaining aggregate functions. To develop a suitable WQI to apply to the research area, we propose a WQI aggregate function combining geometric weighted mean and arithmetic weighted sum, WQI calculation parameters are divided into different groups.

Formula for calculating the water quality index (WQI) for coastal waters:

$$WQI = \left(\frac{\sum_{i_1=1}^{m_1} q_{i_1} W_{i_1}}{\sum_{i_1=1}^{m_1} W_{i_1}} \right)^{\sum_{i_1=1}^{m_1} W_{i_1}} \times \left(\frac{\sum_{i_2=1}^{m_2} q_{i_2} W_{i_2}}{\sum_{i_2=1}^{m_2} W_{i_2}} \right)^{\sum_{i_2=1}^{m_2} W_{i_2}} \times \dots \times \left(\frac{\sum_{i_n=1}^{m_n} q_{i_n} W_{i_n}}{\sum_{i_n=1}^{m_n} W_{i_n}} \right)^{\sum_{i_n=1}^{m_n} W_{i_n}} \quad (1)$$

$$\sum_{i_1=1}^{m_1} W_{i_1} + \sum_{i_2=1}^{m_2} W_{i_2} + \dots + \sum_{i_n=1}^{m_n} W_{i_n} = 1$$

in which: WQI : water quality index; m_1 : number of parameters in group 1; m_2 : number of parameters in group 2; m_n : number of parameters in group n ; n : number of parameter groups; q_{i_1} : the sub-index of parameter i_1 belongs to group 1, ($i_1 = 1-m_1$); q_{i_2} : the sub-index of parameter i_2 belongs to group 2, ($i_2 = 1-m_2$); q_{i_n} : the sub-index of parameter i_n belongs to group n , ($i_n = 1-m_n$); W_{i_1} : the weight of parameter i_1 belongs to group 1, ($i_1 = 1-m_1$); W_{i_2} : the weight of parameter i_2 belongs to group 2, ($i_2 = 1-m_2$); W_{i_n} : the weight of

parameter i_n belongs to group n , ($i_n = 1-m_n$);

$\sum_{i_1=1}^{m_1} w_{i_1}$: weight of parameter group 1; $\sum_{i_2=1}^{m_2} w_{i_2}$:

weight of parameter group 2; $\sum_{i_n=1}^{m_n} w_{i_n}$: weight of parameter group n .

Group of parameters

Apply the grouping method (cluster variables) to 10 parameters (DO , NO_3^- , NH_4^+ , PO_4^{3-} , COD , TSS , coliform, chlorophyll-a, oil and grease, Fe) to choose to calculate WQI , get the

results of grouping the parameters. Water quality numbers are as follows:

Group 1, includes parameters: DO, COD_{KMnO4}.

Group 2, including parameters: NH₄⁺, NO₃⁻, PO₄³⁻, chlorophyll-a.

Group 3, including parameters: TSS.

Group 4, including parameters: oil and grease.

Group 5, including parameters: Fe.

Group 6, including parameters: coliform.

Weight of parameters and parameter groups

Table 3. Weight calculation results (W_i)

No.	Parameter	Weight (W _i)
1	DO	0.10
2	COD _{KMnO4}	0.12
3	NH ₄ ⁺	0.11
4	NO ₃ ⁻	0.11
5	PO ₄ ³⁻	0.11
6	Chlorophyll-a	0.11
7	TSS	0.09
8	Oil and grease	0.09
9	Fe	0.08
10	Coliform	0.08
11	ΣW _i = 1	

Apply the Entropy weighting method and assess the importance of the parameters. Weight of 10 parameters: DO, NO₃⁻, NH₄⁺, PO₄³⁻,

COD_{KMnO4}, TSS, Coliform, chlorophyll-a, oil and grease, Fe (Table 3).

Determine the weights of the parameter groups to calculate the WQI: using the formula (the weight of the parameter group is equal to the total weight of the parameters in the group), the weights of the parameter groups (Table 4) are calculated from the weights of the parameters (Table 3).

Table 4. Weight calculation results of parameter groups

Group	Parameter	Weight
1	DO, COD _{KMnO4}	0.22
2	NH ₄ ⁺ , NO ₃ ⁻ , PO ₄ ³⁻ , chlorophyll-a	0.44
3	TSS	0.09
4	Oil and grease	0.09
5	Fe	0.08
6	Coliform	0.08
7	Total weight (group)	1

The WQI calculation formula applies to the coastal waters of Hai Phong

10 selected water quality parameters (parameter weight (Table 3) and parameter group weight (Table 4) for calculating the WQI for the coastal waters of Hai Phong. Formula 1 can be specifically written as follows:

$$WQI_{HP} = \left(\frac{q_{DO} \times 0.10 + q_{COD} \times 0.12}{0.22} \right)^{0.22} \times \left(\frac{q_{NH_4^+} \times 0.11 + q_{NO_3^-} \times 0.11 + q_{PO_4^{3-}} \times 0.11 + q_{chlorophyll-a} \times 0.11}{0.44} \right)^{0.44} \times q_{TSS}^{0.09} \times q_{Oil}^{0.09} \times q_{Fe}^{0.08} \times q_{coliform}^{0.08} \quad (2)$$

in which: q_{DO} : sub-index of parameter DO; q_{COD} : sub-index of parameter COD_{KMnO4}; $q_{NH_4^+}$: sub-index of parameter NH₄⁺; $q_{NO_3^-}$: sub-index of parameter NO₃⁻; $q_{PO_4^{3-}}$: sub-index of parameter PO₄³⁻; $q_{chlorophyll-a}$: sub-index of parameter chlorophyll-a; q_{TSS} : sub-index of parameter TSS;

q_{Oil} : sub-index of parameter oil and grease; q_{Fe} : sub-index of parameter Fe; $q_{coliform}$: sub-index of parameter coliform.

The sub index values

The sub index values for each parameter are listed in Table 5.

Table 5. The table gives the q_i subindex values that correspond to the C_i concentration

i	q_i	The C_i value corresponds to each parameter				
		%DO ₅ [7, 10]	Oil and grease (mg/L)	Fe (mg/L)	TSS (mg/L)	N-NH ₄ ⁺ (mg/L)
1	100	100	not detected	< 0.5	≤ 20	≤ 0.07
2	75	65	0.1	0.5	50	0.3
3	50	40	0.2	0.8	-	0.5
4	25	20	0.5	1.0	100	1
5	1	< 20	> 0.5	> 1.0	> 100	> 1
i	q_i	N-NO ₃ ⁻ (mg/L)	P-PO ₄ ³⁻ (mg/L)	Chlorophyll-a (μg/L)	COD (mgO ₂ /L)	Coliform (CFU/100 mL)
1	100	≤ 0.02	≤ 0.015	≤ 1.4	≤ 3	500
2	75	0.06	0.045	2	4	1,000
3	50	0.18	0.3	10	10	1,500
4	25	0.36	0.6	20	20	2,000
5	1	> 0.36	> 0.6	> 20	> 20	> 2,000

The sub-index value of parameter i (q') at any concentration C' is calculated according to the following formula [7]:

$$\frac{DF}{EF} = \frac{BD}{AB} \Leftrightarrow \frac{C_{i+1} - C'}{q' - q_{i+1}} = \frac{C_{i+1} - C_i}{q_i - q_{i+1}} \Rightarrow q' = (q_i - q_{i+1}) \frac{C_{i+1} - C'}{C_{i+1} - C_i} + q_{i+1}$$

in which: C_i : the content of monitoring parameters are specified in Table 5 corresponding to level i ; C_{i+1} : the concentration of monitoring parameters is specified in Table 5 corresponding to level $i+1$; q' : sub-index corresponding to C' concentration; q_i : the sub-index at level i given in Table 5 corresponds to the value C_i ; q_{i+1} : the sub-index at level $i+1$ given in Table 5

corresponds to the value C_{i+1} ; C' : the concentration of the monitored parameter is included in the calculation of WQI .

Water quality classification scale

Using Formula 2, the results of calculating the water quality classification levels are presented in Table 6.

Table 6. WQI calculation results according to the water quality classification level

No.	Level for classifying water quality	WQI_{HP}	Base
1	Excellent	100	The parameters for calculating the WQI all have $q_i = 100$
2	Good	75	The parameters have $q_i = 75$
3	Medium	50	The parameters have $q_i = 50$
4	Poor	25	The parameters have $q_i = 25$
5	Very poor	1	The parameters have $q_i = 1$

Note: maximum WQI level - good water quality ($WQI = 98$).

Table 7 presents the water quality classification scale, including the corresponding levels and intended uses of water.

Water quality zoning results in the coastal waters of Hai Phong

The water quality in Hai Phong's coastal waters varied over a wide range, from very poor to excellent.

Area of excellent water quality: This area included the "Outside area" sea area and Cat Ba Island. This area had seawater quality that could be used for all water uses. The content of

seawater environmental parameters were all within the permissible limits according to the QCVN 10-MT:2015/BTNMT regulations and the seawater quality standards of ASEAN, Indonesia, the Philippines, Thailand, Australia, Japan, and China, USA applicable to aquaculture areas and aquatic conservation.

Table 7. Water quality classification scale

No.	WQI_{HP}	Water quality	Colour	Note
1	$99 \leq WQI_{HP} \leq 100$	Excellent		Can be used for all water uses, including aquaculture and aquatic conservation areas.
2	$75 \leq WQI_{HP} \leq 98$	Good		Can be used for all water uses, including beaches and water sports. Cannot be used for aquatic conservation or aquaculture of certain special seafood species.
3	$50 \leq WQI_{HP} \leq 74$	Medium		Can be used for tourism, entertainment, sports (no direct contact with water), water transportation, and seaports.
4	$25 \leq WQI_{HP} \leq 49$	Poor		Can be used for water transportation, seaports or some other uses that do not require high water quality.
5	$1 \leq WQI_{HP} \leq 24$	Very poor		Can only be used for waterway and seaport transportation.

Area of good water quality: This area included the inner waters of the "area of excellent water quality". This area had seawater quality that could be used for all water uses (could not be used for aquatic conservation or aquaculture of some special seafood species).

Area of medium water quality: This area included the inner waters of the "area of good water quality". This area had sea water quality that could be used for: Tourism, entertainment, sports activities (no direct contact with water); water transportation and seaport activities.

Table 8. WQI values at survey points in the coastal waters of Hai Phong during the dry season

Region	Value	Low tide		High tide	
		WQI	Water quality	WQI	Water quality
Northeast of Do Son ($n = 27$)	Smallest	22	From very poor to good	44	From poor to good
	Highest	88		92	
	Average	57		79	
Southwest of Do Son ($n = 12$)	Smallest	38	From poor to good	56	From medium to good
	Highest	86		92	
	Average	63		78	
Cat Ba ($n = 11$)	Smallest	64	From medium to good	65	From medium to excellent
	Highest	98		100	
	Average	90		92	
Outside area ($n = 7$)	Smallest	90	Good	95	From good to excellent
	Highest	96		99	
	Average	94		97	

Table 9. WQI values at survey points in the coastal waters of Hai Phong during the rainy season

Region	Value	Low tide		High tide	
		WQI	Water quality	WQI	Water quality
Northeast of Do Son (n = 27)	Smallest	19	From very poor to good	43	From poor to good
	Highest	76		89	
	Average	45		69	
Southwest of Do Son (n = 12)	Smallest	21	From very poor to medium	45	From poor to good
	Highest	70		88	
	Average	41		70	
Cat Ba (n = 11)	Smallest	62	From medium to good	64	From medium to excellent
	Highest	98		99	
	Average	89		90	
Outside area (n = 7)	Smallest	88	Good	94	From good to excellent
	Highest	97		99	
	Average	93		97	

Area of poor water quality: This area included the inner waters of the “Area of medium water quality”. This area had sea water quality that

could be used for: Water transportation activities, seaports, or some other water uses (no high requirements for water quality).

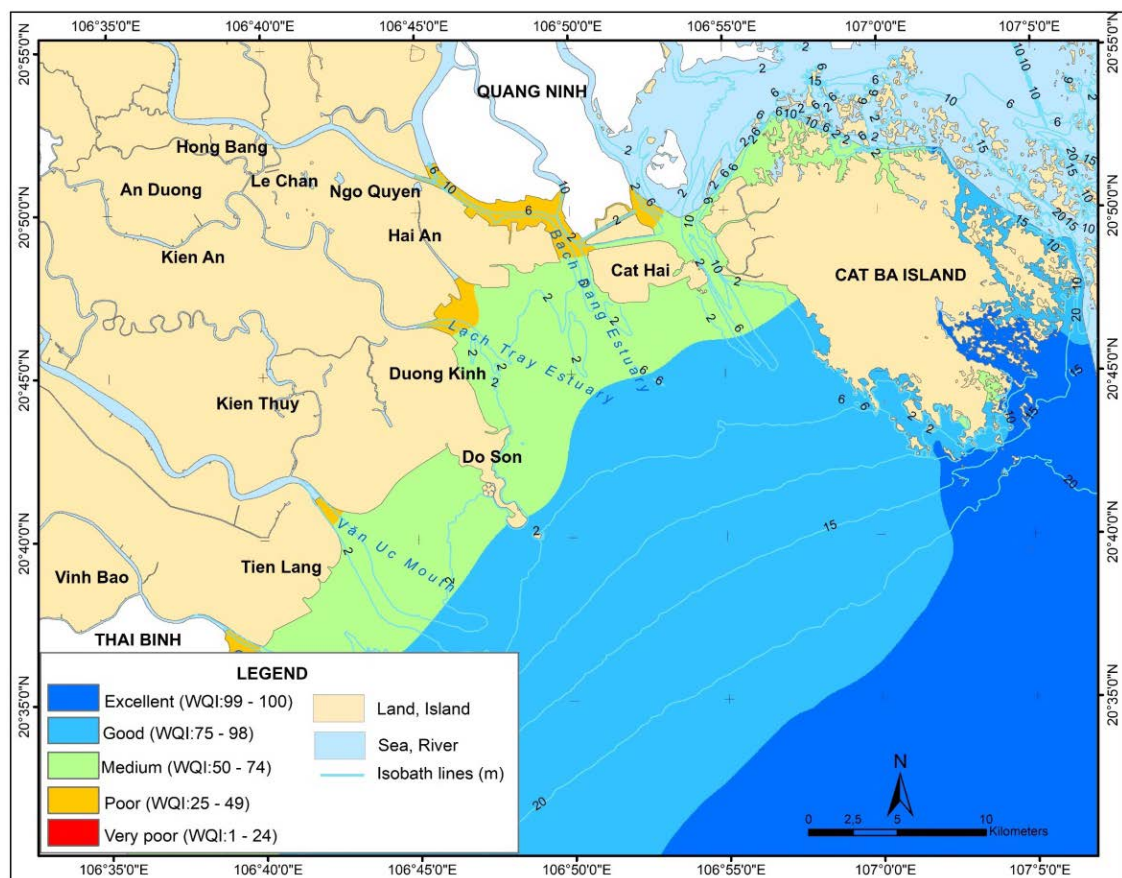


Figure 3. Results of water quality zoning in the coastal waters of Hai Phong during the dry season

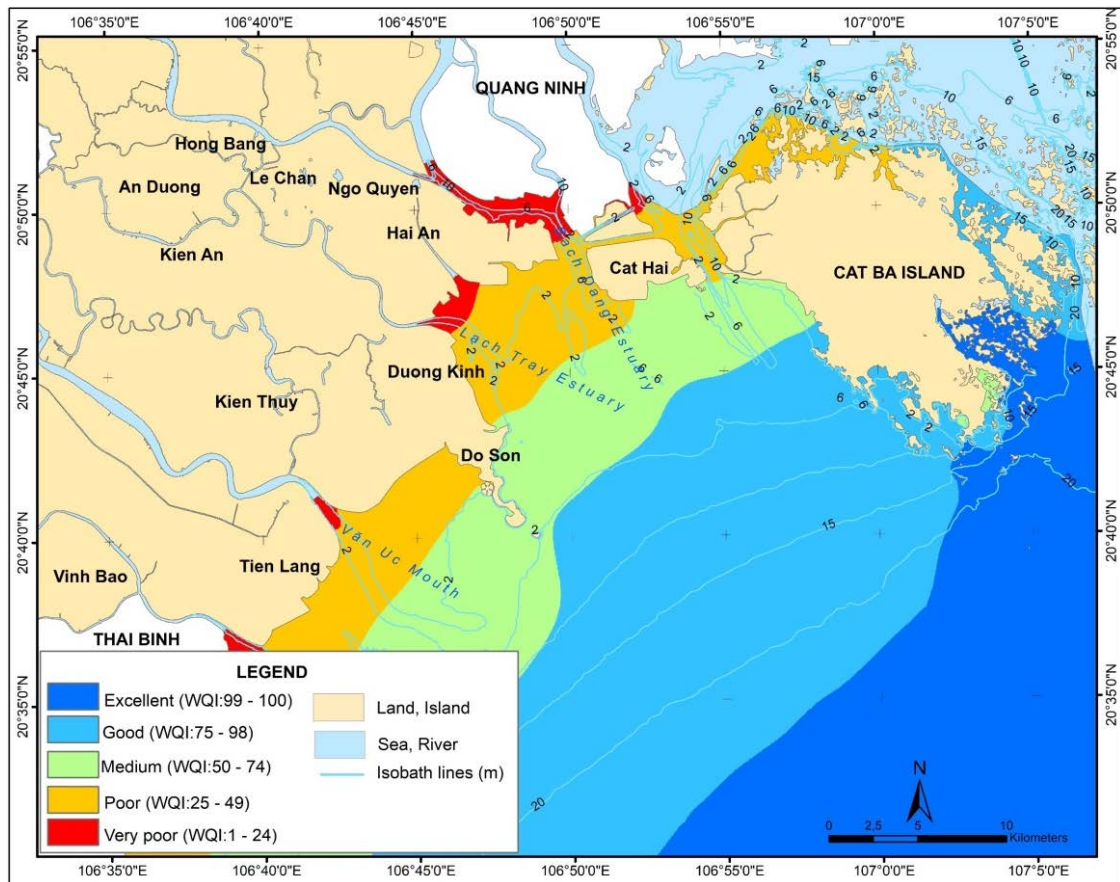


Figure 4. Results of water quality zoning in the coastal waters of Hai Phong during the rainy season

Area with very poor water quality: This area included the inner waters of the “Area of poor water quality”. This area had sea water quality that could be used for: Water transportation and seaport activities. This water quality area was polluted with high levels of oil, nutrients, $\text{COD}_{\text{KMnO}_4}$, Chlorophyll a, TSS, Fe, and coliform.

The water quality zoning results in the coastal waters of Hai Phong are presented in Tables 8, 9; as well as Figures 3, 4.

During the dry season, the Northeast Do Son area had water quality at low tide ranging from very poor to good ($WQI = 22-88$) and water quality at high tide ranging from poor to good ($WQI = 44-92$). The Southwest Do Son area had water quality at low tide ranging from poor to good ($WQI = 38-86$) and water quality at high tide ranging from medium to good ($WQI = 56-92$). The Cat Ba Island area had water quality at low tide ranging from medium to

good ($WQI = 64-98$) and water quality at high tide ranging from medium to excellent ($WQI = 65-100$). The outside area had good low tide water quality ($WQI = 90-96$) and high tide water quality ranging from good to excellent ($WQI = 95-99$). Water quality at high tide was better than water quality at low tide.

During the rainy season, the Northeast of Do Son area had water quality at low tide ranging from very poor to good ($WQI = 19-76$) and water quality at high tide ranging from poor to good ($WQI = 43-89$). The Southwest of Do Son area had water quality at low tide ranging from very poor to medium ($WQI = 21-70$) and water quality at high tide ranging from poor to good ($WQI = 45-88$). The Cat Ba Island area had water quality at low tide ranging from medium to good ($WQI = 62-98$) and water quality at high tide ranging from medium to excellent ($WQI = 64-99$). The outside area had

good low tide water quality ($WQI = 88\text{--}97$) and high tide water quality ranging from good to excellent ($WQI = 94\text{--}99$). Water quality at high tide was better than water quality at low tide.

In the rainy season, areas with very poor and poor water quality tended to expand (areas with medium and good water quality tended to shrink) compared to the dry season. The reason for this was that during the rainy season, the inflow of fresh water increased and the water mass had a higher concentration of pollutants than in the dry season.

The simulation results of hydrodynamic characteristics in the Hai Phong coastal estuary demonstrated the dominant and crucial role of water level fluctuations in the dynamic conditions in this area. In addition, another factor that strongly influenced material transport in this area was the strong seasonal variation of the flow field due to river water flow and wind regime. The influence of water level fluctuations could enhance the dispersal of material from the mainland to the outer coastal area of Hai Phong, but also limit or bring material back to the estuary during the high tide phase. This characteristic of the hydrodynamic regime in the Hai Phong coastal estuary could lead to the appearance of frontal areas - the concentration of pollutants introduced from the continent and the sea. The

movement of water masses to the south and southwest might have indicated that the movement of pollutants was greater south of the Hai Phong coastal estuary than to the north and northeast.

Therefore, the water quality was often better at high tide than at low tide. During both the dry and wet seasons, the areas of Bach Dang Estuary, Lach Tray Estuary, Van Uc Estuary, and Thai Binh Estuary had very poor water quality at low tide (WQI from 19 to 22) and poor water quality at high tide (WQI from 43 to 45). The South - Southwestern area of the Hai Phong coastal estuary had poorer water quality than the northern and northeastern areas.

The Ben Beo area (port on Cat Ba Island, where most of the island's large and small boats docked) had medium water quality (WQI from 62 to 73). This area had a higher risk of pollution than other areas in the waters of Cat Ba Island. The outdoor area had good to excellent water quality.

The area of the excellent water quality zone showed little seasonal variation because the excellent water quality zone was the outer area of the study area - a place less affected by coastal waste sources. The results of calculating the area (km^2) of water quality zones are presented in Table 10.

Table 10. Area (km^2) of water quality zones

Season	Tide	Water quality zones					
		Excellent	Good	Medium	Poor	Very poor	Total
Dry season	High tide	480.680	621.616	122.119	7.633	< 0.5	1,232.048
	Low tide	339.001	580.713	145.607	154.129	12.598	1,232.048
	Average	388.621	580.052	239.955	23.420	< 0.5	1,232.048
Rainy season	High tide	454.723	541.008	172.108	64.209	< 0.5	1,232.048
	Low tide	223.204	497.939	243.228	122.352	145.325	1,232.048
	Average	391.833	463.764	209.002	147.331	20.118	1,232.048

CONCLUSION

The study developed a formula for calculating the water quality index to assess and zone the water quality in the coastal areas of Hai Phong. The WQI results showed that the water quality of the coastal areas of Hai Phong

tended to improve gradually from the river mouths to the sea. In the rainy season, areas with very poor and poor water quality tended to expand (areas with medium and good water quality tended to shrink) compared to the dry season. The area of the zone with excellent water quality had little seasonal fluctuation.

When the tide was high, the water quality was usually better than when the tide was low. During both the dry and rainy seasons, the areas of Bach Dang Estuary, Lach Tray Estuary, Van Uc Estuary, and Thai Binh Estuary all had very poor water quality at low tide and at high tide. The Southern - Southwestern areas of the Hai Phong coastal estuary had poorer water quality than the Northern and Northeastern areas. The Ben Beo area (port on Cat Ba Island, where most of the island's large and small boats docked) had medium water quality. This area had a higher risk of pollution than other areas in the waters of Cat Ba Island. The outdoor area had good to excellent water quality.

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