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Development of Water Quality Index for Coastal Zone and Application in the Hạ Long Bay

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Abstract: In this study, a water quality index (WQI_{HL}) was developed in accordance with the nature of coastal zone and applied to assess the water quality in Ha Long Bay. Nine parameters, including $\%DO_{sat}$ (0.08), COD (0.11), TOC (0.08), oil and grease (0.17) total coliforms or feacal coliform (0.07), TSS (0.17), TN or NH_4^+ (0.11), TP or PO_4^{3-}(0.11) and chlorophyll a (0.11) are employed for the estimation of water quality. Numbers in the parentheses indicate weight of each parameter. Sub-indices are built based on the QCVN 10:2008/MONRE, the standards on coastal water quality of ASEAN, Australia, Japan … and other requirements for water quality in marine ecosystems. Assessment of the eclipsing and ambiguous effects and the sensitivity of four aggregation functions reveal that weighted geometric mean function is the most appropriate to calculate WQI_{HL} with selected weights. The application of the developed WQI_{HL} in the Hạ Long Bay shows that water quality in the core zone is good, except some tourist areas and fishing villages. The buffer zone of the Bay possesses poor water quality. The WQI_{HL} formula can be a good tool for water quality management and planning, which supports for the integrated coastal zone management.

Keywords: Water quality index, weighted geometric mean function, coastal zone, Hạ Long Bay.

1. Introduction

The use of water quality index gained acceptance in many years before. It is a tool to improve understanding of water quality issues by integrating complex data and generating different levels that describes water quality status and evaluates water quality trends [1] In this way, the index can be used to assess water quality relative to its desirable state (as defined by water quality objectives) and to provide insight into the degree to which water quality is affected by human activity. Although some information is lost when integrating multiple water quality variables, this loss is outweighed by the gain in understanding of water quality issues by the public and decision makers [2].

A review of studies and usages of water quality index around the world (by the authors) reveals that few studies involved in estuaries and coastal zone and the remainder was restricted to inland water or surface water. In

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Vietnam, there is not any study about WQI for the coastal area.

In this study, a WQI is developed suitably with coastal zone conditions and tried to apply in assessment of water quality in the Ha Long Bay. Coastal characteristics and issues in the Ha Long Bay are taken into account during the WQI development. Therefore, the study result is significant for tasks of environmental assessment, planning and management in the coastal zone.

2. Methodology

There are four steps involved in the development of most water quality indices [1, 3]. These include: (1) selecting the set of water quality parameters (indicators/variables) of concern, (2) weighting the indicators based on their relative importance to overall water quality, (3) developing sub indices for comparing indicators on a common scale (Indicator transformation), and (4) formulating and computing the overall water quality index (Aggregation function).

2.1. Indicator selection

There are six criteria for a meaningful variable [4], including: (1) Water quality variables that are widely and regularly measured; (2) Variables that have clear effects on aquatic life, recreational use, or both; (3) Variables that have man-made sources as opposed to natural sources; (4) Variables those are amenable to control through pollution abatement programs, (5) Realistic ranges of each variable - from no pollution to gross pollution, (6) Sensitivity to reasonably small changes in water quality. In addition, Dunnette (1979) and Tebbutt T.H.Y (2002) recommended that variables of concern should be selected from 5 commonly recognized impairment categories like (1) oxygen status and demand, (2) eutrophication, (3) health aspect, (4) physical characteristics, and (5) solid substances [5-7].

2.2. Indicator weighting

It is also generally acknowledged that some indicators are more important to “average water quality” than others [8]. It is thus necessary to weight the indicators appropriately. In this study, the weight of the indicator is determined through importance and roles of the indicator to aquatic system and current status of that parameter in the Ha Long Bay. Temporary weight is developed by dividing the significant rating by the average significance rating of individual parameters. Then, weighting scale for each parameter is defined as the ratio of temporary weight to the sum of temporary weights. Final weight (Weighting scale) is obtained by approximating the ratio of temporary weight for each variable to the sum of temporary weights [4].

2.3. Indicator transformation

Water quality indicators are generally in many different units. This makes simple aggregation impossible. As a consequence, another important step in developing an index involves a transformation of all indicators to an equal, dimensionless scale. This results in sub indices [3]. In this study, the sub indices are from 1 to 100 which represent the poorest and the highest water quality respectively. The development of the sub-index of each selected variable in this study bases on following information: (1) National technical regulation on coastal water quality - QCVN 10: 2008/BTNMT, (2) Marine and coastal water quality standards and criteria of ASEAN, Thailand, Indonesia, Japan, Australia [9], and (3) Requirements of water quality for coral reef and seabed grass.

2.4. Aggregation function

The aggregation process is one of the most important steps in calculating any environmental index. Generally, aggregation functions, either additive or multiplicative forms, are suffered from both eclipsing and ambiguous effects [1]. There are some kinds of functions to calculate an aggregated score (index score) for WQI. To minimize the ambiguity and eclipsing effect, it is necessary to identity an appropriate function for calculating an aggregated score. Four kinds of functions have been considered in this study. They are the weighted Solway function [8], the weighted arithmetic mean function [10], the weighted geometric function [10] and the weighted harmonic mean function [1].

3. Results and discussions

3.1. Variable selection

(1) Oxygen status and demand: Indicator for the oxygen status in water body is $\%DO_{sat}$. Organic matter has the greatest impact on dissolved oxygen concentrations [11]. Consequently, COD and oil and grease should be taken into account. Oil pollution prevents not only oxygen in atmosphere from dissolving into the sea water but also phytoplankton from catching carbonic in atmosphere for photosynthetic reaction. In addition, the process of biodegradation of oil makes some microorganisms more active and then reduces the amount of oxygen in the water. TOC is also an important parameter is selected as the Vietnamese coast receives many organic pollutants and grease. The TOC content is a measure of the concentration of organically bound carbon and is therefore a direct indication of the pollution levels by organic compounds [12].

(2) Eutrophication: the indicators for the eutrophication are: TN, NO_3^-, NO_2^-, NH_4^+, TP, PO_4^{3-} and chlorophyll-a. The chosen indicators are TN, TP, and chlorophyll-a. The two paramettеrs TN and TP can be replace by NH_4^+ and PO_4^{3-}. The two parameters NO_3^-, NO_2^- can be ignored in calculating the WQI for coastal waters for the following reasons: Due to tidal activity in the coastal zone, NO_2^- is not high and easily transformed into NO_3^-. High concentration of NO_3^- makes algae flourish and thereby causes adverse effects to the environment if the eutrophication occurs. Then, chlorophyll a is a more important parameter to measure the eutrophic state than NO_3^-.

(3) Health aspect: The parameters in this group include total coliform, fecal coliform and heavy metal [9, 11]. The heavy metal concentrations are not selected to develop WQI for the following reason: Theoretically, the ions of heavy metals in water are usually absorbed by clay particles and suspended sediment. Due to high salinity and pH in the coastal areas, the clay particles and suspended sediment flocculation is settle down and make the content of heavy metals in the water are much lower than those in the sediments. Therefore, the concentrations of heavy metals in coastal water do not adequately reflect the level of heavy metal pollution in coastal areas. That kind of pollution needs to be assessed by the accumulation of heavy metals in plankton, benthic organisms or bed sediment. Such assessment is beyond the scope of this study. For the reason above, the selected parameter is total coliforms (or Feacal coliform). This parameter needs to be controlled in the coastal areas having water sports activities [9]. Currently, the total coliforms is monitoring quite often so that it is convenient for evaluation of microbial pollution in general. However, to strictly control the quality of the coastal water used for aquatic sports activities such as swimming or water skiing, the fecal coliform parameter is more important and should be included in monitoring programs.

(4) Physical characteristics: While the importance of this category is evident for freshwater systems, the meaning of physical characteristics in term of coastal zone is not significant for coastal water [8].

Due to the dynamic nature of estuarine and coastal water masses under "normal" conditions, physical characteristics in that water bodies are highly variable and could not be controlled. The pH is strongly controlled by the mixing of marine and fresh water [5]. Given the buffering capacity of sea water, the pH of river water entering an estuary will be driven to 8. Thus, the pH of estuarine and coastal water generally increases towards the sea. Salinity (measure of total dissolved solids) is a much more important indicator of the extend of seawater mixing than water quality impairment [5]. In fact, it is the brackish nature of estuarine and coastal water that makes this habitat unique and contributes to its resource value. Temperature of coastal water greatly depends on solar energy, mixing of sea currents and other water than human impacts. Consequently, this parameter is not considered as pollutant. However, oxygen concentration in water body will decrease when the temperature raises. Thus, the temperature should be taken into account in process of oxygen concentration determination.

As a consequence of above, the parameters of the physical characteristics are not chosen for WQI in the coastal zone.

(5) Solid substances. The selected parameter is total suspended solids (TSS). In the water, TSS consists of organic matter, minerals, heavy metals, sulfur, algae (including toxic algae), and bacteria (including pathogenic bacteria). TSS contributes to turbidity of the water and reduces not only the amount of transmitted light needed for photosynthesis but also the landscape of the coast. High TSS concentration (above 20 mg/l) will degrade or can destroy mangrove, coral reefs, sea grass ecosystems.

The selected parameters for the WQI for the coastal zone are summarized in the table 1.

3.2. Indicator weighting

The weights of parameters are determined depending on whether they have direct or indirect effects on the ecosystem. Two types of parameters that directly affect aquatic ecosystems can be distinguished: those that are directly toxic to biota, and those that, while not directly toxic, can result in adverse changes to the ecosystem [11]. The parameters that directly affect aquatic ecosystems have higher weight than those that, while not directly toxic, can result in adverse changes to the ecosystem. The detail importance and final weights are shown in the table 1.

3.3. Sub-indices

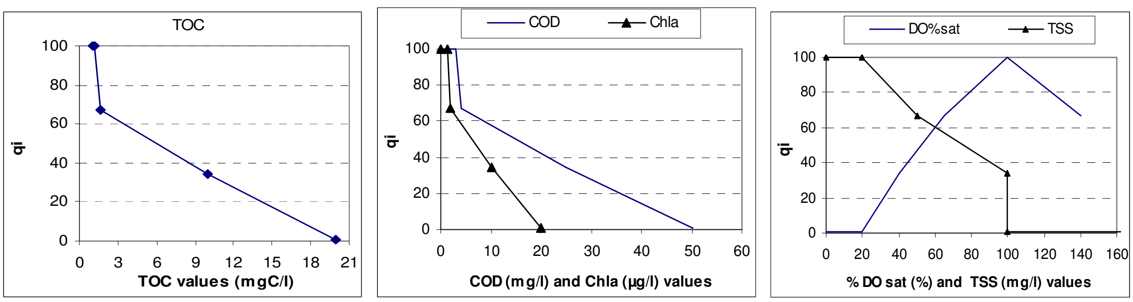
Sub-indices (q_i) are within the range 1-100 (1 is the worst and 100 is best). They are divided into 3 parts (1-34-67-100) which are followed the QCVN 10:2008/MONRE and other document listed in part 2.2. The sub-index transformation curses of each selected variable have been developed and shown in figure 1. They are developed based on criteria of protecting aquatic life in coastal water and human contact. The value of the sub-index at an any concentration Cq is calculated by referring to the sub-index transformation curses (Figure 1) or by the method of linear interpolation of the values in Table 2.

Table 1. The selected parameters for the WQI in the coastal zone and their weights

No.	Parameter	Importance	Temporary weight	Final weight	Note
1	Oil and grease; TSS	1	2.5	0.17	Stressors directly toxic to marine ecosystems [11]
2	COD, TN (or NH_4^+), TP (or PO_4^{3-}), chlorophyll a	1.5	1.7	0.11	Stressors that are not directly toxic but can directly affect marine ecosystems [9, 11]
3	TOC	2	1.3	0.08	- Assess the level of organic pollution which is major pollution problem in the Ha Long Bay
4	Total coliforms (or Feacal coliform), DO	2.5	1	0.07	- Total coliforms (or Feacal coliform) directly toxic to human being [9] - DO affect process of respiration of marine creature [9, 11]

Table 2. Sub-index values (q_i)

i	q_i	Concentration values (Ci) for each parameter					
		TOC (mg/l)	COD (mg/l)	DO%sat	Oil and grease (mg/l)	TN (mg/l)	TP (mg/l)
1	100	≤ 1.2	≤ 3	100	0	≤ 0.25	≤ 0.02
2	67	1.6	4	65 or 140	0.1	0.35	0.05
3	34	10	25	40	0.2	0.75	0.5
4	1	> 20	> 50	20	> 0.3	> 1.5	> 1
i	q_i	PO_4^{3-}-P (mg/l)	NH_4^+-N (mg/l)	Chla (µg/l)	T. Coli (MPN/100ml)	F. Coli (F.Coli/100ml)	TSS (mg/l)
1	100	≤0.015	≤ 0.1	≤ 1.4	≤500	≤100	≤ 20
2	67	0.045	0.3	3	1000	-	50
3	34	0.08	0.5	10	-	500	-
4	1	> 0.5	> 1	> 20	>2000	>1000	>100



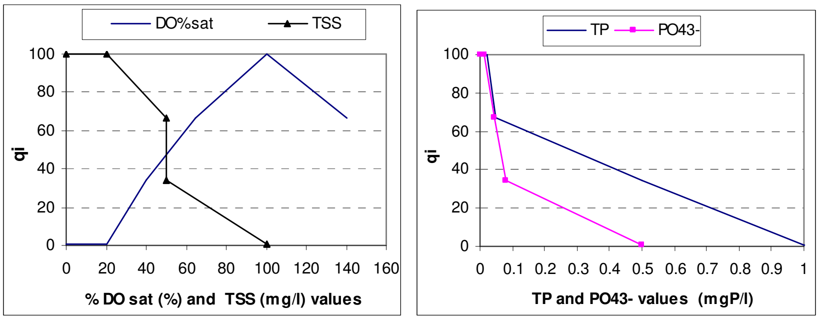


Figure 1. The sub-index transformation curses of each selected variable.

3.4. Aggregation function

In this study, for the purpose of minimizing the eclipsing and ambiguous effects on the formulation for WQI, the four aggregation functions, including the *Solway function, the weighted arithmetic mean function, the weighted geometric function and the weighted harmonic mean function*, were chosen to compare the eclipsing and ambiguous effects on the final results of WQI. These functions are widely used to develop WQI over the world. The aggregation function should be also sensitive to small changes in water quality.

The assessments of the eclipsing and ambiguous effects on the final results of WQI and the sensitivity of the aggregation function are done by verifying one of the q_i values from 1 to 100. Then, the eclipsing and ambiguous effects, the sensitivity and the nature of easy application of the four functions mentioned above are evaluated by scoring from 1 to 4. The more easily functions calculate, the higher score they have; the more ambiguous the functions are, the lower score they get; the more eclipsing the functions are, the lower score they get; the more sensitive the functions are, the higher score the functions are (Table 3).

Table 3. General assessment of the average functions

TT	Property	Weighted arithmetic	Weighted geometric	Weighted harmonic	Weighted Solway
1	Easy to apply	4	4	2	3
2	Ambiguous	4	3	2	1
3	Eclipsing	1	3	4	4
4	Sensitive	1	3	3	4
	Sum	10	13	11	12

Table 4. Thresholds of water quality classification

No.	Threshold	States of parameters in comparison with the allowance in the QCVN 10:2008/BTNMT and others
	Upper limit	100
1	Excellent	From good threshold to 100
2	Good	One water quality parameter exceed allowance for aquaculture and aquatic conservation ($q_i = 67$) or $q_{i\ min} \geq 67$
3	Medium	One water quality parameter exceed allowance for beach or areas for recreation activities with directed water contact ($q_i = 34$)
4	Bad	One water quality parameter exceed allowance for “other areas” like ports … ($q_i = 1$)
5	Very bad	Three water quality parameters exceeds allowance for “other areas” like ports …($q_i = 1$)
	Lower limit	1

Table 5. Water quality classification and usages

No.	WQI_{HL}	Water quality	Water use ability
1	97 - 100	Excellent	Can be used for any purpose.
2	92 – 96	Good	Can be used for any purpose, except protection of aquatic life or special aquaculture
3	70 - 91	Medium	Tourism, recreation without direct water contract, ports and navigation, industrial water supply
4	35 - 69	Bad	Ports and navigation, industrial water supply or other purposes which do not need high water quality.
5	1- 34	Very bad	Ports and navigation only

Based on the analysis results in Table 3, the weighted geometric mean function has the highest score. Consequently, the weighted geometric mean is use to build WQI for the coastal zone. With the selected weights in this study, the weighted geometric mean has a small eclipsing and ambiguous effects and a high sensitivity. In addition, the weighted geometric mean is easy to apply in the comparison to the harmonic mean or the Solway. Finally, the WQI for the coastal zone is following:

$$WQI_{HL} = \left(\prod_{1}^{n} q_i^{w_i}\right)^{1/\sum_{1}^{n} w_i}$$

In which, q_i and w_i are the sub-indices and weights of the chosen parameters which shown in the table 1.

3.5. Water quality classification and range scales

In order to evaluate water quality and environmental management effectiveness, it is necessary to have descriptor categories and ranges of WQI scores. Classification scale is determined based on the level and number of parameters violating the allowable limits. WQI values are divided into 5 ranges which are very good, good, medium, bad and very bad as shown in table 4. Water quality classification is calculated by the WQI_{HL} formula with the thresholds in the table 4. The final results of water quality classification are summarized in table 5.

3.6. Application in assessment of water quality in the Ha Long Bay

* *Data:* Monitoring data at 12 points in 4/2013 (table 6) and at 32 points in 8/2013 in the Ha Long Bay.

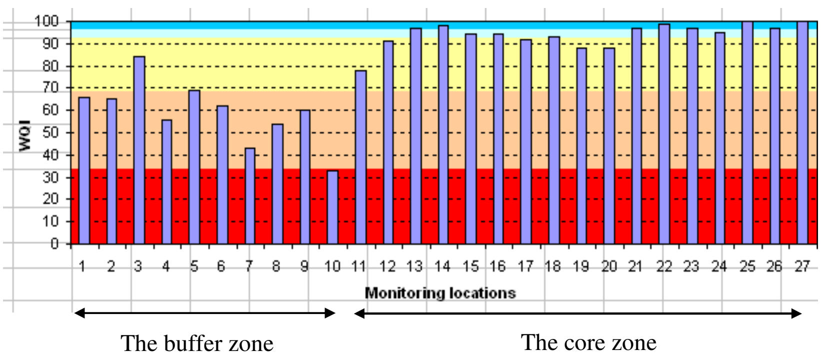
Results and discussions: The example results are shown in table 6 and figure 1. It can be seen that the water quality in the buffer zone of the bay is from very bad to medium, while that in the core is still good to very good. However, there is local pollution in the core zone, especially at the tourist areas and fishing villages. In the figure 1, that locations are monitoring point number 11 (Thien Cung – Dau Go islands), 12 (Titop island), 17 (Cong Do area), 19 (Hoa Cuong fishing village), 20 (Cua Van fishing village).

The calculation results also reveal that there are differences between the three calculation methods. For example at the monitoring point of Cua Van fishing village, the two formulas WQI_{HL} and WQI_{PNH} show that the water quality is very good, whereas the CWQI formula gives bad result. Monitoring results here show that most of the water quality parameters are within the allowable limits, only COD value (3.1 mg/l) was slightly higher than the allowance (3 mg/l) of QCVN 10:2008/BTNMT for aquatic conservation areas. The CWQI formula results in poor water quality due to the parameter F1 (% ratio between the number of failed parameters and the total number of parameters) affects largely to the final results. This is one of the limitations pointed out in the workshop on water quality indicators in Canada in 2003 [1].

It can be concluded that the usage of the WQI_{HL} to evaluate and classify the water quality in the Ha Long bay with monitoring data in 4/2013 and in 8/2013 gives quite reasonable results. Still it needs more testing with other monitoring sites in the coastal zone of Vietnam.

Table 6. Some examples of the water quality classification in the Ha Long Bay in 4/2013 with different WQI formula

No.	Monitoring point	WQI_{HL}		CWQI		$WQI_{P.N.H}$	
1	Bang bridge	69	Medium	37	Bad	88	Bad to Medium
2	At the middle of Cua Luc Bay	48	Bad	27	Bad	54	Medium
3	Bai Chay bridge	55	Bad	29	Bad	71	Medium
4	Bai Chay beach	60	Bad	20	Bad	32	Very bad
5	Bai Chay tourist wharf	30	Very bad	29	Bad	61	Medium
6	Tuan Chau beach	66	Bad to Medium	20	Bad	33	Very bad
7	Ha Long I market	22	Very bad	24	Bad	31	Very bad
8	Pillar 5 - pillar 8	56	Bad	33	Bad	75	Medium
9	Nam Cau Trang wharf	49	Bad	40	Bad	50	Bad
10	Islet 1	100	Excellent	100	Excellent	100	Excellent
11	Titop beach	96	Excellent	100	Excellent	100	Excellent
12	Cua Van fishing village	98	Excellent	41	Bad	97	Excellent



Color	WQI	Water quality clarification
	97-100	Excellent
	92-96	Good
	70-91	Medium
	35-70	Bad
	1-34	Very bad

Figure 1. Some examples of the water quality classification in the Ha Long Bay in 8/2013.

3.7. Overall assessment of the water quality index for the coastal zone

The WQI_{HL} is evaluated following 15 characteristics that an ideal water quality index should possess [10]. Evaluation results show that the WQI_{HL} formula has met 13 out of 15 characteristics for the ideal water quality index recommended by the Environmental Protection Agency of the U.S. This is due to the keeping abreast of the recommended characteristics in the construction of the WQI_{HL}. Thus, the WQI_{HL} formula can be used to assess the status and changes in water quality in the coastal zone and serve the management and conservation natural ecosystems here.

4. Conclusion

In this study, the water quality index has been built in accordance with the nature the coastal zone in Ha Long Bay. The index consists of 9 parameters, including $\%DO_{sat}$ (0.07), COD (0.11), TOC (0.08), oil and grease (0.17) total coliforms or feacal coliform (0.07), TSS (0.17), TN or NH_4^+ (0.11), TP or PO_4^{3-} (0.11) and chlorophyll a (0.11). The weighted geometric mean function is used to integrate sub-indices. The WQI_{HL} provides a convenient way for evaluating the water quality of the coastal zone in terms of the specific water use for marine ecosystem protection and human contact, and comparing water quality among different areas of the coast. The application of the developed WQI_{HL} shows that the water environment in the core zone of Ha Long Bay is good, except some points that concentrate tourist activities and fishing villages. The core zone currently is subjected to damage by the poor water quality in the buffer zone which is currently impacted by socio - economic activities in Ha Long city.

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Xây dựng chỉ số chất lượng nước cho vùng ven biển và áp dụng đánh giá chất lượng nước vịnh Hạ Long

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Tóm tắt: Trong nghiên cứu này, chỉ số chất lượng nước (WQI_{HL}) đã được xây dựng phù hợp với tính chất của vùng biển ven bờ và áp dụng để đánh giá chất lượng nước vịnh Hạ Long. Các thông số sử dụng để tính toán WQI là $\%DO_{BH}$ (0.07), COD (0.11), TOC (0.08), dầu và mỡ (0.17) tổng coliforms hoặc feacal coliform (0.07), TSS (0.17), TN hoặc NH_4^+ (0.11), TP hoặc PO_4^{3-}(0.11) và chlorophyll a (0.11). Trọng số của các thông số được ghi trong dấu ngoặc. Các chỉ số phụ được xây dựng dựa trên QCVN 10:2008/MONRE, các tiêu chuẩn chất lượng nước biển ven bờ của ASEAN, Australia, Nhật … và các yêu cầu chất lượng nước cho các hệ sinh thái biển. Quá trình đánh giá tính mơ hồ, tính che khuất, độ nhạy và mức độ dễ tính toán của các phương pháp tổng hợp chỉ số phụ thường dùng cho thấy hàm tích có trọng số là phương pháp tổng hợp thích hợp nhất để tính WQI_{HL}. Việc áp dụng công thức WQI_{HL} để đánh giá chất lượng nước vịnh Hạ Long cho thấy chất lượng nước vùng lõi vịnh còn tốt, trừ một số khu vực tập trung hoạt động du lịch hoặc làng chài. Tuy nhiên, vùng lõi vịnh đang chịu áp lực lớn bởi chất lượng nước khá xấu tại vùng đệm. Công thức WQI_{HL} là một trong những công cụ hiệu quả trong quản lí và phân vùng chất lượng nước nhằm phục vụ quá trình quản lí tổng hợp vùng bờ.

Từ khóa: Chỉ số chất lượng nước, tích có trọng số, vùng ven bờ, vịnh Hạ Long.