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The impact of the COVID-19 pandemic on the seawater quality of Ha Long Bay, Vietnam

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ABSTRACT

Ha Long Bay is a UNESCO World Heritage Site in Vietnam with unique natural scenery. Development and socio-economic activity impact its water quality. In the context of the Vietnam National Standards, historical follow-up data taken over a five-year period (2016 to 2020), for twenty-eight widely dispersed sampling sites, has been used to carry out a temporal assessment of seawater quality utilizing a Water Quality Index (WQI) method. The analysis shows that the seawater quality is generally acceptable over this period. However, the calculated WQI values for the "pandemic year" of 2020 compared to the data for 2016 to 2019, demonstrate a significantly lesser impact for the bay overall and, more specifically, for seventeen individual sites. Ten sites remain unaffected, and one site shows a significantly higher impact. This study demonstrates how the occurrence of the pandemic in 2020 may be exploited for the interrogation of anthropogenic impacts around the bay.

1. Introduction

Ha Long Bay (HLB), Vietnam, is a UNESCO World Heritage Site (Mai et al., 2016) with unique natural scenery, including thousands of limestone islands, Fig. 1. It is also an area of diverse anthropogenic activities, all of which have sustainability implications. For example, HLB is a prime tourism area in the Quang Ninh province bordering China and is part of the strategic economic development triangle, Ha Noi-Hai Phong-Quang Ninh (Duong et al., 1999).

HLB is also in the area where the major deep-sea port at Cai Lan is operational. Due to the ongoing influence of so many socio-economic activities, the seawater quality in HLB is becoming increasingly threatened (Nguyen and Sevando, 2019). Therefore, there is a requirement for the ongoing monitoring of seawater quality, as well as its spatial-temporal variation, to protect and control the water quality of the bay into the future.

A wide range of parameters may be used to assess and monitor seawater quality including pH, dissolved oxygen, total suspended solids, oil and grease, coliform, ammonium, phosphate, and metals such as iron, zinc and manganese (El Zrelli et al., 2018). Although the analysis and evaluation of each individual parameter may allow comparison to existing regulations, this does not provide a comprehensive picture of the overall marine environment.

An established method for achieving this involves the employment of the Water Quality Index (WQI) (Brown et al., 1970; Ott, 1978; Noori et al., 2019). Thus, the WQI has been widely used to assess surface and groundwater water quality (Salim et al., 2009; Rubio-Arias et al., 2012; Khalik et al., 2013; Tirkey et al., 2013; Effendi et al., 2015; Naubi et al., 2016; Bora and Goswami, 2016; Cymes and Glińska-Lewczuk, 2016; Roy et al., 2017; Ewaid and Abed, 2017; Mora-Orozco et al., 2017; Nong et al., 2020) and, to a lesser extent, coastal seawater (Gupta et al., 2003; Al-Mutairi et al., 2014; Ma et al., 2020; Jha et al., 2015). Although there are several variations of the WQI method, the NSF-WQI, developed by the National Sanitation Foundation (NSF) (Tirkey et al., 2013; Noori et al., 2019), has been demonstrated to be particularly effective and useful. A recent comprehensive review of WQIs (Chidiac et al., 2023) discusses the perceived advantages and shortcomings of different variations of this method and advocates that more work be done to affirm its general validity.

For Vietnam, the sea is one of its most valuable natural resources and most socio-economic development activities are concentrated in Vietnam's easily accessible coastal zone (Nguyen and Sevando, 2019). Therefore, the risk of environmental pollution in coastal and marine areas is high. This is particularly true of HLB, which is routinely assessed over time by the authorities (Quang Ninh DONRE/EPA, 2020) for various water quality parameters. This has created an established

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Fig. 1. Ha Long Bay (Countryliving, 2021).

database that is an ideal resource for the effective application of the WQI method. Therefore, this method has been applied to historical follow-up data taken over a five-year period from 2016, up to and including the COVID-19 pandemic year of 2020, for twenty-eight sampling sites around HLB (Fig. 2). More specifically, this temporal assessment of seawater quality across HLB utilizes a modified version of the NSF-WQI method (Tirkey et al., 2013; Noori et al., 2019) to explore the long-term environmental health of the bay and to assess whether any effects of the 2020 pandemic lockdown on HLB can be identified. The geographical locations of the sampling sites, together with the site characteristics, are given in Table 1.

Thus, the NSF-WQI method provides a convenient way for evaluating the water quality of a coastal zone over time and allows a year-by-year comparison of overall water quality as well as between the different sampling locations. As mentioned previously, *vide supra*, of particular interest in this study is the inclusion of the data for the first COVID-19 pandemic year of 2020, where a decrease in anthropogenic activities, due to pandemic control measures such as lockdowns (Minh et al., 2021), is expected to be reflected in comparison with the data for the non-pandemic years of 2016 to 2019. In this regard, the Quang Ninh province of Vietnam, that includes HLB, endured four lockdown periods from 2020 through 2021, including: Phase 1 (January 23, 2020–July 24, 2020), Phase 2 (July 25, 2020–January 27, 2021), Phase 3 (January 28, 2021–April 26, 2021) and Phase 4 (April 27, 2021–to December 30, 2021). Significantly, the HLB area was in lockdown for almost the whole of 2020 (Phases 1 & 2), providing a unique opportunity to compare up to ten water quality parameters that were measured over the course of 2020, from 28 sampling sites around the Bay, with those collected in the previous non-lockdown years of 2016 to 2019. A comparison of each individual water quality parameter with the Vietnam National Standards (MONRE, 2015) across all sampling sites has also been carried out for 2020, to pinpoint any sites where human activity is known to have a significant impact. Taken together, such an analysis will enable more informed environmental management and the potential development and implementation of an evidence-based sustainability strategy.

2. Methodology

2.1. Database characteristics

Water quality data were sourced from the Environmental State Report of Quang Ninh, 2016 to 2020 (Quang Ninh DONRE/EPA, 2020). According to regulatory procedures, water samples were taken by the local Quang Ninh DONRE/EPA four times a year from 2016 through 2020 for each of the twenty-eight sampling sites (D1 to D28) shown in Fig. 2 and Table 1. For monitoring purposes, ten water quality parameters were determined by the EPA for each sample (Table 2). Standard literature methods were used to determine the individual and microbiological indicators, and these are listed in Table 2. For this paper, the four yearly values were averaged for each site from 2016 to 2020. These average values were used in both the NSF-WQI calculations[1] and for Vietnam National Standards comparisons.

2.2. The Water Quality Index (WQI)

The Water Quality Index (WQI) combines several water quality parameters into a single parameter (Shweta et al., 2013; Tirkey et al., 2013; Chidiac et al., 2023). Each water quality parameter is assigned an appropriate weight (Table 3).

There are various methods for calculating the WQI (Noori et al., 2019) and, for this study, a modified NSF-WQI method was used according to the National Sanitation Foundation (NSF) model (Tirkey et al., 2013; Noori et al., 2019). In this study, five parameters were used; namely, pH, DO, TSS – rather than TS or TDS (Azami et al., 2015; Trikoilidou et al., 2017), phosphate – rather than total phosphate (Gupta et al., 2003, 2017; Trikoilidou et al., 2017) and coliform – rather than fecal coliform (Pham, 2016); consistent with existing literature and current Vietnamese regulations (Table 2).

The NSF-WQI formula that was employed is:

$$\mathrm{WQI} = \sum_{i=1}^{n} (\mathrm{W_i}\ \mathrm{Q_i})$$

[1] Five of these parameters were selected for the modified WQI calculations.

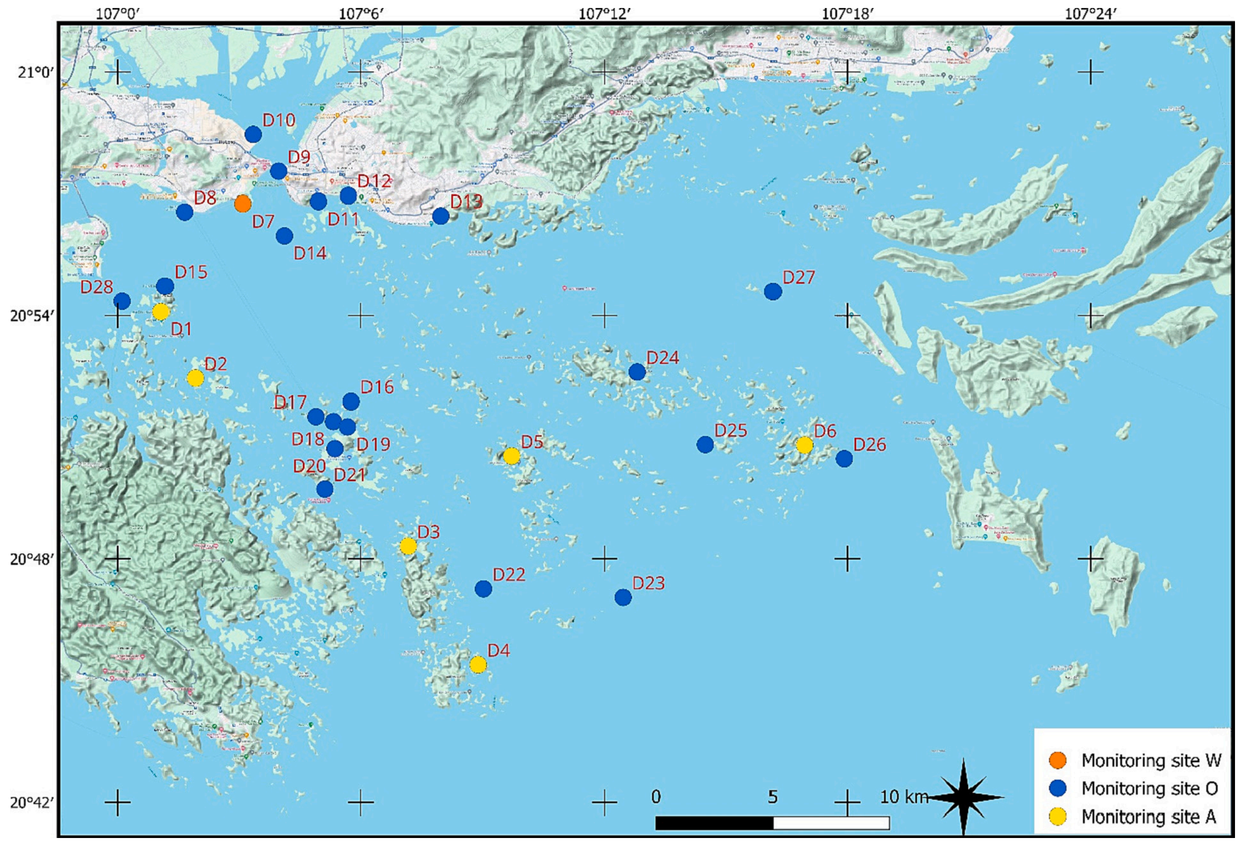

Fig. 2. Locations of the 28 sites (D1 to D28) in Ha Long Bay that were sampled for 10 water quality parameters over the 5-year period of 2016 to 2020. The general area characteristics of the monitoring sites are classified as W (water sports — orange); O (other — blue); A (aquaculture — yellow); see legend. More detailed characteristics of sites D1 to D28 are listed in Table 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

where: W_i = the weight of parameter; Q_i = the sub index for water quality parameter *i* is obtained by interpolating the appropriate rating curve (Ott, 1978).

When a reduced number of parameters are used, as is the case here (five parameters), the WQI value is scaled (DMRWQN — Des Moines River Water Quality Network, 2021) as follows:

$$WQI = WQI_o/a$$

where: WQI = final WQI value; WQI_o = calculated WQI value for the reduced number of parameters and a = the total weight of the calculated parameters = 0.17 + 0.16 + 0.11 + 0.10 + 0.07 = 0.61.

In conjunction with the WQI analyses, each site may also be assessed by comparison with the Vietnam Technical Regulation (Pham, 2016) with respect to each of the *individual* ten parameters listed in Table 2, employing the same parameters that are used in the WQI calculations.

2.3. Seawater quality assessment on a "per parameter" basis

This allows the individual parameters for each site to be compared to the National Vietnamese Standard (MONRE, 2015) (Pham, 2016; Nguyen and Sevando, 2019). For example, Fig. 3 shows a *representative* assessment for ammonium concentrations across all the twenty-eight sites for the year of 2020. Note that, for this year, all parameters listed in Table 2 meet the required QCVN 10 - MT: 2015/BTNMT standards and that this is consistent with the "acceptable" 2020 WQI data found for each site (Table 4). However, it must be emphasized that such outcomes do not mean that further improvements cannot be made. For example, the ammonium level almost reaches the QCVN-10 limit for the fishing/aquaculture areas D1 to D6 and it would be advisable for measures to be taken to control this into the future. Analogous assessments and commentary for the other nine individual parameters for the year 2020 are provided, for reference, in the Supplementary Material, Part 1, Figs. A to J.

2.4. Field investigation and personal communication and consultation

Observational fieldtrips were also made to glean relevant information such as land-based pollution sources near sampling sites such as the Ha Long Market 1, D11 (Fig. 4). Also, frequent personal communication and consultation with the staff from the HLB Management Board and Quang Ninh Department of Natural Resources and Environment was carried out to help validate the relevant information and data for this research project.

3. Results and discussion

3.1. Comparative calculated WQI values for all sites from 2016 through 2020

The calculated NSF-WQI values, from 2016 to 2020, for each of the twenty-eight sampling sites, are given in Table 4 and compared graphically in Fig. 5. The 100-point index can be divided into several ranges corresponding to the general descriptive terms shown in Table 5 (Ott, 1978).

3.2. WQI values in relation to location

From Tables 4 and 5, from 2016 to 2020 inclusive, 3.6 % of the sites

Table 1
The characteristics and geographical locations of the 28 sampling sites shown in Fig. 2. Sites D1 to D6 are broadly designated as "aquaculture", D7 as "water sport" and the remaining sites, D8 to D28, as "other". Within the latter category, sites with well-defined tourist activities are highlighted.

Site	Area characteristics	Sampling Site Characteristics	Location	
			Longitude	Latitude
D1	Aquaculture	Ba Hang - fishing village.	107°1'4.21"E	20°54'5.67"N
D2		Hoa Cuong - fishing village.	107°1'54.55"E	20°52'27.09"N
D3		Cua Van - fishing village, with aquaculture activities.	107°7'9.63"E	20°48'18.97"N
D4		Cong Tau - fishing village, with aquaculture activities	107°8'53.48"E	20°45'24.28"N
D5		Vong Vieng - fishing village, with aquaculture activities.	107°9'43.27"E	20°50'32.70"N
D6		Cong Dam -fishing village with aquaculture activities.	107°16'56.38"E	20°50'48.82"N
D7	Water Sports	Bai Chay – beach, with tourist activity.	107°3'4.9"E	20°56'45.4"N
D8	Other	Bai Chay - tourist pier.	107°1'38.5"E	20°56'33.3"N
D9		Under the Bai Chay Bridge.	107°3'58.17"E	20°57'32.99"N
D10		Cai Lan – port.	107°3'20.37"E	20°58'27.50"N
D11		In the vicinity of Ha Long Market 1.	107°4'57.29"E	20°56'48.73"N
D12		Cot 3 - sewage discharge point.	107°5'41.80"E	20°56'57.11"N
D13		Nam Cau Trang - coal loading port.	107°7'57.88"E	20°56'27.48"N
D14		Cua Luc fairway - within the bay but far from the shore.	107°4'6.75"E	20°55'58.09"N
D15		Thien Cung-Dau Go - cave with daily tourist activity.	107°1'10.01"E	20°54'43.50"N
D16		Hon Mot area fairway - within the bay but far from the shore.	107°5'45.79"E	20°51'52.87"N
D17		Titop Island - daily tourism activity.	107°4'53.57"E	20°51'30.90"N
D18		Cat Lan Resort - resort with daily tourist activity; people can stay overnight.	107°5'19.54"E	20°51'23.68"N
D19		Luon cave – resort with daily tourist activity; people can stay overnight.	107°5'40.50"E	20°51'15.88"N
D20		Bo Nau-Sung Sot cave with daily tourist activity.	107°5'21.92"E	20°50'43.63"N
D21		Lom Bo night resort with daily tourist activity.	107°5'6.86"E	20°49'43.65"N
D22		Ang Du fairway - within the bay but far from the shore.	107°9'1.37"E	20°47'15.50"N
D23		Near Trong cave, with daily tourist activity	107°12'27.62"E	20°47'02.81"N
D24		Cong Do resort, daily tourist activity; people can stay overnight.	107°12'48.56"E	20°52'36.21"N
D25		Tra Gioi fairway - within the bay but far from the shore.	107°14'29.83"E	20°50'49.66"N
D26		Dong Trang fairway - within the bay but far from the shore.	107°17'55.18"E	20°50'28.68"N
D27		Hon Net port - shipping activity.	107°16'9.86"E	20°54'35.52"N
D28		Tuan Chau harbor - daily tourist activity.	107°0'6.7"E	20°54'21.3"N

Table 2
The 10 marine water quality parameters measured by the Quang Ninh DONRE/EPA four times a year from 2016 through 2020, for each of the 28 sampling sites that are shown in Fig. 2 and listed in Table 1. Also shown are the standard analytical methods used and the Vietnam Ministry of Natural Resources and Environment (MONRE, 2015) recommended values for these parameters over three arbitrary area characteristics, broadly designated as "aquaculture" (A), "water sport" (W) and "other" (O). Namely, QCVN 10 — MT:2015/BTNMT(A), QCVN 10 — MT:2015/BTNMT(W) and QCVN 10 — MT:2015/BTNMT(O), respectively.

	Measured parameter	Units	Analytical methods	MONRE recommended values		
				Aquaculture (A)	Water sport (W)	Other (O)
1	pH	–	TCVN 6492:2011 (ISO 10523:2008)	6.5–8.5	6.5–8.5	6.5–8.5
2	Dissolved oxygen (DO)	mg/L	TCVN 7325:2004 (ISO 5814:1990)	≥5	≥4	–
3	Total suspended solids (TSS)	mg/L	SMEWW 2540.D: 2012	≤50	≤50	–
4	Total coliforms	MPN/100 mL	TCVN 6187–2:1996 (ISO 9308-2:1990E)	≤1000	≤1000	≤1000
5	Ammonium (N-NH_4^+)	mg/L	TCVN 6179–1:1996 (ISO 7150-1:1984)	≤0.1	≤0.5	≤0.5
6	Phosphate (P-PO_4^{3-})	mg/L	TCVN 6202:2008 (ISO 6878: 2004)	≤0.2	≤0.3	≤0.5
7	Iron (Fe)	mg/L	SMEWW-3111.B:2012	≤0.5	≤0.5	≤0.5
8	Zinc (Zn)	mg/L	SMEWW-3111.B:2012	≤0.5	≤1.0	≤2.0
9	Manganese (Mn)	mg/L	SMEWW-3111.B:2012	≤0.5	≤0.5	≤0.5
10	Oil and grease	mg/L	SMEWW-5520.B:2012	≤0.5	≤0.5	≤0.5

Table 3
Water quality parameters and assigned NSF-WQI weight scores (Tirkey et al., 2013; Noori et al., 2019).

NSF-WQI parameter	NSF-WQI weight
Dissolved oxygen (DO) (mg/L)	0.17
Fecal coliforms (MPN/100 mL)	0.16
pH	0.11
Biochemical oxygen demand (BOD) (mg/L)	0.11
Water temperature (°C)	0.10
Total phosphate (mg/L)	0.10
Nitrates (mg/L)	0.10
Turbidity (NTU)	0.08
Total dissolved solids (TDS) (mg/L)	0.07
Total	1.0

scored "excellent" (blue) ratings, 86.4 % scored "good" (green) ratings and 10.0 % of the sites scored "medium" (yellow) ratings. No sites were rated "bad" or "very bad". Based on this broad-brush WQI analysis, most of the Bay over the 2016 to 2020 period is environmentally acceptable with respect to water quality. From Tables 4 and 5 and in Fig. 5, the majority of the lower "medium" (yellow) ratings represent the sites D11, D12 and D13, which are in the vicinity of the Ha Long Market 1 (Figs. 4 and 5), the Cot 3 sewage discharge point and the Nam Cau Trang coal loading port, respectively, Table 1. These sites, amongst others, dramatically improve for the pandemic lockdown year of 2020 and this will be discussed in more detail later, *vide infra*. The cluster of higher values from D21 to D26, that encompass the majority of the "excellent" (blue) ratings are sites that are further from the shore (Fig. 2) and are less impacted by anthropogenic factors *per se*. It can be seen from Table 5 and Fig. 5 that the WQI scores for 2020 are generally higher than for 2016 to 2019, as reflected in the green entries of Table 4 and the red bars of Fig. 5.

3.3. Whole bay considerations

The relative average NSF-WQI values over all sites, for each year from 2016 to 2020 (Table 4) are presented in Fig. 6 together with appropriate confidence intervals. The average 2020 WQI of 83 is significantly higher (at a 94 % confidence level)[2] than the average WQI values of 77, 79, 76 and 76, for 2019, 2018, 2017 and 2016, respectively. Notably, the average overall WQI values for the pre-pandemic period of 2016 to 2019 are not significantly different in themselves, suggesting that the Bay has maintained a consistent overall water quality over this period.[3] However, it is notable that Fig. 6 reveals a dramatic and highly significant *improvement* in overall water quality for HLB for the pandemic lockdown year of 2020, compared to the previous four years. Indeed, this is expected to be the case and it is gratifying to see it borne out by the application of the modified WQI method to this data.

Given that the twenty-eight individual sampling site characteristics are well known and characterized (Table 1), we surmise that a more detailed comparative analysis of pre-pandemic (2016 to 2019) and pandemic (2020) data, may offer unique and important insights into factors that could contribute to reducing anthropogenic impacts across the bay.[4]

3.4. Conducting a site-by-site analysis

The following discussion demonstrates how a site-by-site analysis may be conducted based on such temporal WQI data. To discern where the major contributions to improvements for 2020 are located with respect to the twenty-eight sites, the differences in WQI-NSF values between the 2020 values and the average values for the years 2016 to 2019 have been calculated for each site. This data is represented in Fig. 9 and Tables 6 and 7. In relation to this data, a positive significant difference (now at 95 % level of confidence) indicates an improvement in water quality for 2020 at a given site, no significant difference indicates no improvement for 2020 at that site, while a negative significant difference indicates an actual decline in water quality for 2020 at that site. It can be seen from Fig. 9 and Tables 6 and 7, that seventeen out of twenty-eight individual sites (61 %) have a statistically significant improvement in WQI for 2020 compared to the 2016 to 2019 period. Ten sites (36 %) are not considered to be statistically different and just one site, D4, is statistically worse. In relation to the characteristics of the twenty-eight sites, as described in Table 1, it is informative to relate such differences to what anthropogenic activities were likely to be curtailed, or otherwise affected, at each site during the pandemic lockdown in 2020.

It is, perhaps, not surprising that the WQI for D4 shows a significant deterioration for 2020 since this is a fishing village with aquaculture activities. During the pandemic lockdown, activities at such locations were maintained or even intensified with fishermen spending more time on their boats. In this regard, the remaining sites that are designated as fishing villages, with or without aquaculture, show no significant improvement (D1, D2, D5, D6), with one being only marginally

[2] 94 % is the maximum confidence level where the value for the pandemic year of 2020 may be deemed significantly higher than for all the years of 2016 to 2019.

[3] This is consistent with the Vietnam Technical Regulation data for 2020 provided in the Supplementary Material.

[4] Following this proof of principle study, such detailed investigations will be followed up in further research.

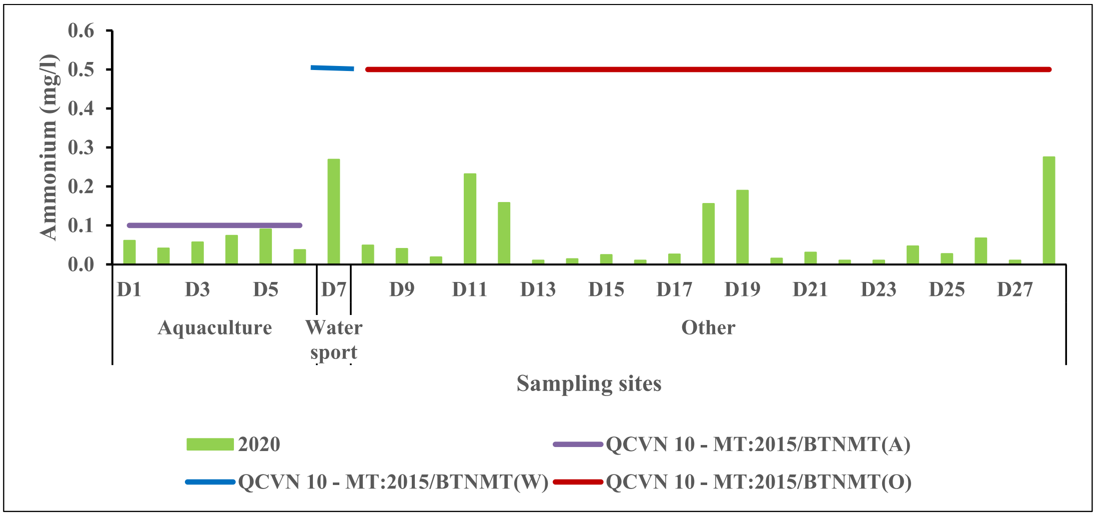

Fig. 3. Representative example of the evaluation of the ammonium (N-NH_4^+) concentrations across all 28 sites for the year 2020 — demonstrating that the ammonium concentration meets the required standard, as represented by the horizontal lines (see Table 2). QCVN 10 — MT:2015/BTNMT(A), QCVN 10 — MT:2015/BTNMT(W) and QCVN 10 — MT:2015/BTNMT(O) represent the Vietnam Ministry of Natural Resources and Environment (MONRE, 2015) recommended values for such parameters over three arbitrary area characteristics, broadly designated as "aquaculture" (A), "water sport" (W) and "other" (O).

improved (D3); despite these sites being geographically dispersed across the bay, Fig. 2.

As alluded to previously, the sites D11, D12 and D13 are in the vicinity of the Ha Long Market 1 (Figs. 4 and 8), the Cot 3 sewage discharge point and the Nam Cau Trang Coal Loading Port, respectively, Table 1. These sites, amongst others, dramatically improved during the pandemic lockdown year of 2020 (Tables 6 and 7). This is entirely understandable for the Market site where less people would be out and about and for the Coal Loading Port that, although still partly in operation, was under strict pandemic prevention rules. However, the improvement for the sewage discharge obviously requires more investigation as the reason(s) for improvement at this site is less obvious, since the site was still receiving wastewater from residents who were locked down at home. Intriguingly, it is possible that the nature of the discharge was affected by the circumstances of the pandemic. Such observations could provide new leads into improved environmental practices at such sites.

A consideration of the designated tourist sites (Tables 1 and 6), namely, D7, D8, D15, D17, D18, D19, D20, D21, D23, D24 and D28, reveals that out of eleven of these sites, eight (*i.e.*, 73 %) have significantly improved WQI values for 2020. This is entirely consistent with the downturn in tourism for 2020. However, the tourist sites D21, D23 and D24, show no significant change, even though such an expected downturn would also have occurred at these sites for 2020. This is, perhaps, suggestive of better environmental management practices at these three sites over time in comparison with the other eight. However, other explanations could be possible such as the fact that these sites are further from the shore. Such clues could prompt further informative and potentially advantageous comparisons — although such a detailed analysis is beyond the scope of this publication.

It can be seen from Fig. 2 that D9 and D10 (bridge and port, respectively) are coastal sites that are influenced by a wide range of anthropogenic activities, such as sewage discharge, stormwater runoff, industrial waste, and indirect tourism activities. The pandemic year of 2020 saw a reduction in socio-economic activities, with an almost complete shutdown of tourism in Vietnam. It is therefore not surprising that sites such witnessed significant improvements for 2020 (Tables 6 and 7). Similarly, the fairway sites D14, D16 and D27 also witnessed improvements in water quality for 2020, suggesting that these sites are normally influenced by anthropogenic factors. However, as expected, the fairway sites that are further from the mainland, namely, D22, D25 and D26, showed no significant change in water quality.

4. Conclusions

The application of a modified WQI method to the analysis of an established temporal database of seawater quality parameters, from twenty-eight sampling sites across Ha Long Bay (HLB), Vietnam, from the year 2016 up to and including the pandemic year of 2020, has confirmed that the overall environmental condition of the seawater around the bay and at each of the twenty-eight individual sites across the bay is within acceptable standards. However, this study has also demonstrated that, for the overall bay and for 61 % of the individual sampled sites across the bay, the water quality significantly improved for the pandemic year of 2020 compared to the previous four years. Since the characteristics of these site are well-known, it is possible to rationalize the results and to interrogate those factors that might contribute to the enhancement of the water quality at each site. In this way, given such a database, we have demonstrated how the occurrence of the pandemic may be exploited to glean useful environmental information. In the light of the perceived advantages and shortcomings of different variations of the WQI method (Chidiac et al., 2023), these compelling results also serve to validate both the modified NSF-WQI method (particularly with a reduced number of parameters) and the quality of the data. We surmise that there is likely to be numerous related databases worldwide that cover a similar period to that used herein, and we suggest that the same or a similar method might also be advantageously applied to these.

A more detailed investigation of each site, informed by this research, will be carried out under the auspices of the broad management measures listed as follows:

- Conventionally, it is considered desirable to increase investment in environmental protection as well as to diversify the resources used in the management and protection of areas such HLB. The present study demonstrates that such environmental protection measures can become more focused by the application of innovative research. For example, the exploitation of the COVID lockdowns and the judicious application of the WQI method to existing temporal data, allow greater insight into the relative impact of anthropogenic activities across multiple sites. This has opened the way for further research

Table 4
Summary of seawater quality indices (WQI) for the period of 2016–2020. These WQI values, projected onto the site maps of Fig. 2, for each of the years 2016 to 2020, are given in the Supplementary Material, Part 2, Figures K to O.

Sites	2016	2017	2018	2019	2020
D1	73	74	76	74	74
D2	73	76	76	75	78
D3	68	68	72	71	75
D4	88	83	86	83	75
D5	68	70	74	72	75
D6	90	85	73	88	81
D7	76	74	75	75	80
D8	74	76	77	73	88
D9	74	76	80	76	84
D10	73	73	78	72	86
D11	63	63	69	66	80
D12	64	63	68	69	81
D13	69	65	72	70	77
D14	76	77	80	78	87
D15	70	71	75	72	83
D16	79	79	81	79	87
D17	72	78	78	75	88
D18	79	79	80	78	88
D19	73	74	75	74	79
D20	73	73	77	75	88
D21	80	85	85	84	82
D22	84	84	90	83	88
D23	91	85	87	83	88
D24	79	84	84	83	81
D25	85	85	90	84	88
D26	90	83	87	83	88
D27	75	77	78	77	88
D28	69	70	74	71	76
Average	**76**	**76**	**79**	**77**	**83**

Fig. 4. Example of a land-based pollution source behind Ha Long Market 1, sample site D11.

where the WQI method will be applied to new and ongoing data. It will also inform improvements on the collection of the data itself.

- Strengthening the monitoring and patrol activities within the bay, thereby taking measures to reduce the input of seawater pollution, is desirable but obviously requires additional resources. Based on research such as that presented herein, such activities could be made more efficient by focusing on areas identified as showing the greatest improvements during lockdown, *i.e.*, those areas that are more susceptible to human impact.
- Research such as the beneficial exploitation of the COVID lockdowns captures the imagination of the public. Thus, it can be used to enhance environmental communication and education and to raise the awareness and responsibility of authorities and residents in environmental protection. Within this context, consideration could also be given to the engagement of "Citizen Scientists".
- The pro-active incorporation of research results in the environmental planning for HLB, Ha Long City, and Quang Ninh province, with a vision to 2030, should include extending the WQI studies to include more recent and ongoing data for these areas. This project is already underway in our research group.
- Develop a multi-sectoral management mechanism for HLB, since the bay is affected by many different activities. In the light of research to date, further research would involve a comprehensive stock-take of such activities on a site-by-site basis. This would feed into the results of existing and continuing WQI investigations, where the relative anthropogenic impacts have been quantified. When interrogating the sites, it is also important to consider whether the handling of waste from land-based sources is a major issue. More specifically, ensure that all domestic wastes are treated before being discharged into the sea and that this is closely monitored by competent state agencies.
- The quantification of the relative anthropogenic impacts on different sites, as is evident from our current research, is a major advance towards improving the health of the environment. In this regard, further quantitative parameters may also be gleaned from the data.

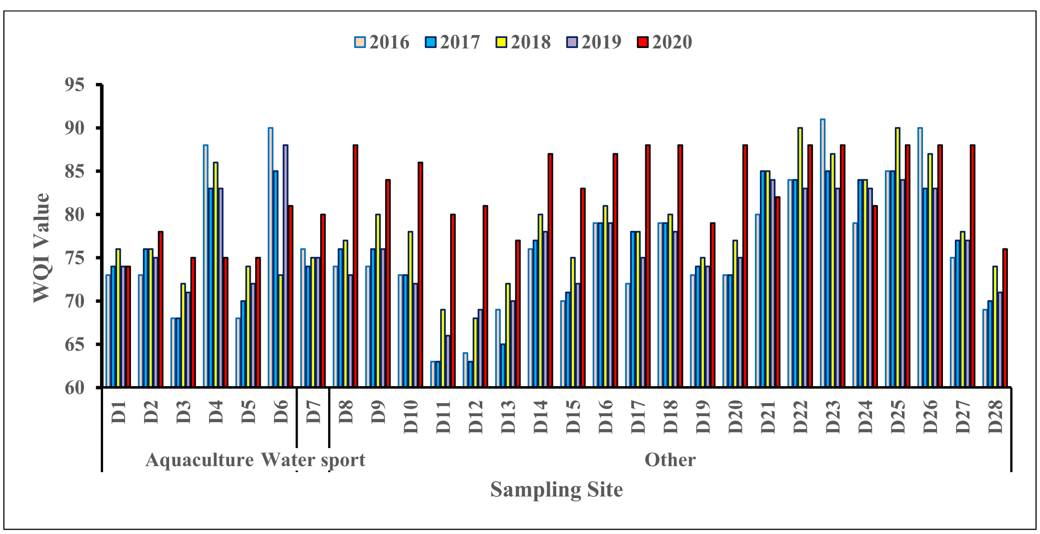

Fig. 5. The calculated NSF-WQI values, from 2016 to 2020, for each of the twenty-eight sampling sites. The distribution of the water quality across the sites and the distribution of improvements for 2020 (red bars) may be seen from this plot. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5
Water quality rating according to the NSF-WQI method.

NSF-WQI value	Rating of Water Quality	Grading
90-100	Excellent	A
70-90	Good	B
50-70	Medium	C
25-50	Bad	D
0-25	Very bad	E

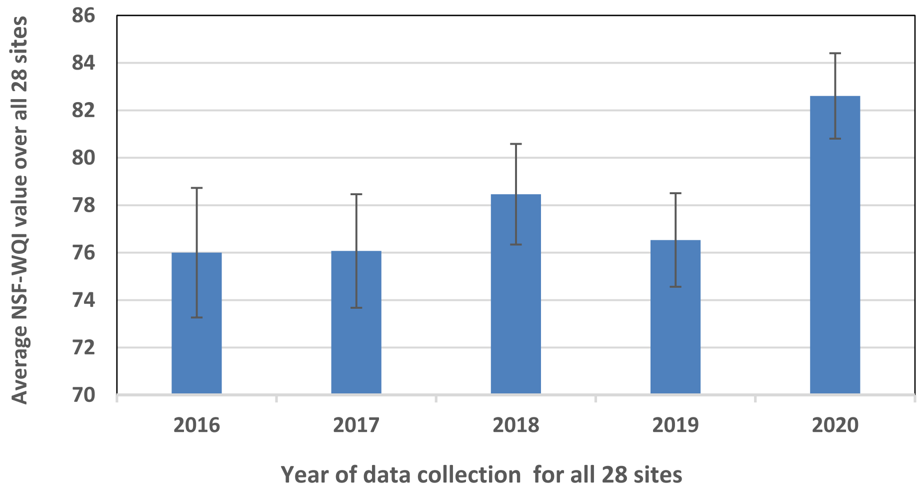

Fig. 6. A comparison of the average NSF-WQI values over all 28 sites (representing the whole bay) for each year from 2016 to 2020. Error bars represent confidence intervals of 94 %, which is the maximum level of confidence where the value for the pandemic year of 2020 may be deemed significantly higher than for all the years of 2016 to 2019.

Table 6
A quantitative evaluation of Fig. 6. The 2020 WQI status compared to 2016–2019 has been assessed by comparing the relative bar heights in Fig. 6 for each site. The errors for the average values from 2016 to 2019 represent 95 % confidence intervals and the errors for the 2020 values represent an estimated experimental error of 2 % in each calculated WQI value. Note that site D4 is the only site where the WQI value for 2020 is significantly lower than the average value for 2016 to 2019. The asterisked sites are designated tourist areas.

Sites	Average 2016–2019 values	2020 values	Differences	Significantly Higher/lower 2020 values
D1	74 ± 1	74 ± 2	0	No
D2	75 ± 1	78 ± 2	3	No
D3	70 ± 2	75 ± 2	5	Yes
D4	85 ± 2	75 ± 2	−10	Yes, lower (−)
D5	71 ± 3	75 ± 2	4	No
D6	84 ± 8	81 ± 2	−3	No
D7*	75 ± 1	80 ± 2	5	Yes
D8*	75 ± 2	88 ± 2	13	Yes
D9	77 ± 3	84 ± 2	7	Yes
D10	74 ± 3	86 ± 2	12	Yes
D11	65 ± 3	80 ± 2	15	Yes
D12	66 ± 3	81 ± 2	15	Yes
D13	69 ± 3	77 ± 2	8	Yes
D14	78 ± 2	87 ± 2	9	Yes
D15	72 ± 2	83 ± 2	11	Yes
D16	80 ± 1	87 ± 2	7	Yes
D17*	76 ± 3	88 ± 2	12	Yes
D18*	79 ± 1	88 ± 2	9	Yes
D19*	74 ± 1	79 ± 2	5	Yes
D20*	75 ± 1	88 ± 2	13	Yes
D21*	84 ± 2	82 ± 2	−2	No, lower (−)
D22	85 ± 3	88 ± 2	3	No
D23*	87 ± 3	88 ± 2	1	No
D24*	83 ± 2	81 ± 2	−2	No, lower (-−)
D25	86 ± 2	88 ± 2	2	No
D26	86 ± 3	88 ± 2	2	No
D27	77 ± 1	88 ± 2	11	Yes
D28*	71 ± 2	76 ± 2	5	Yes

Table 7
A qualitative assessment of WQI site statuses ., 2020 WQI individual site statuses are compared to individual average 2016 to 2019 values. An arbitrary distinction has been made to distinguish between the degree of site improvement (WQI difference of 5 to 9 — significant improvement and WQI difference of 10 to 15 — significant major improvement). See Table 6 for the corresponding quantitative data.

2020 WQI individual site statuses compared to individual average 2016 to 2019 values (95 % confidence level)	Sites
No significant improvement of site	D1, D2, D5, D6, D21, D22, D23, D24, D25, D26
Significant improvement of site (WQI difference of 5 to 9)	D3, D7, D9, D13, D14, D16, D18, D19, D28
Significant major improvement of site (WQI difference of 10 to 15)	D8, D10, D11, D12, D15, D17, D20, D27
Significant major deterioration of site (WQI difference of −10)	D4

For example, a further investigation is underway to measure the relative rate of improvement for each site during 2020, which is a quantification of the relative sensitivity of each site to anthropogenic factors. This is possible because samples are taken quarterly each year; namely, February (Quarter 1), May (Quarter 2), August (Quarter 3) and November (Quarter 4). Rather that averaging these measurements over the whole year of 2020, as has been done in the present study, the WQI values could also be calculated for each Quarter and the rate of improvement assessed as the lockdown takes hold.

CRediT authorship contribution statement

Dao Van Hien: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Dong Ha My:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. **John D. Orbell:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no conflicts of interest.

Data availability

Data will be made available on request.

Fig. 8. The three sampling sites near the coastal residential areas which have lower water quality from 2016 to 2019, but which show highly significant improvements in 2020.

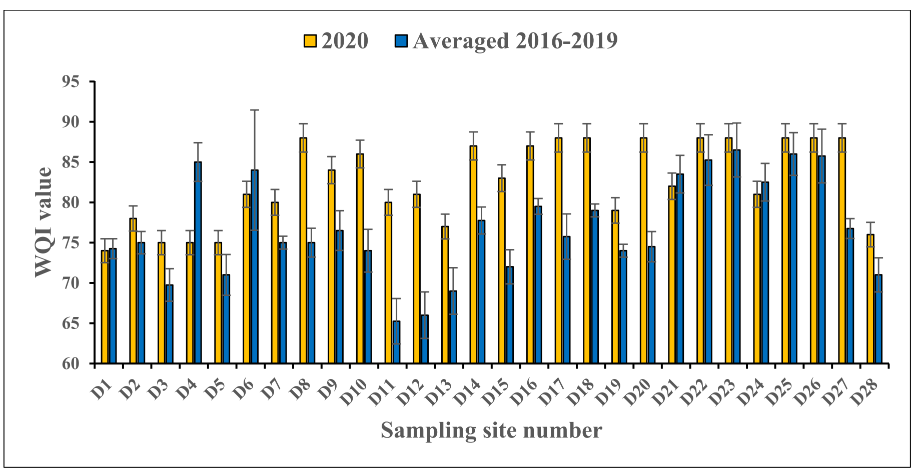

Fig. 9. Relative water quality index (WQI) for 28 sampling sites in Ha Long Bay for the period of 2016 to 2020. Error bars for the 2016 to 2029 averaged data (blue) represent 95 % confidence intervals, error bars for the 2020 data represent an estimated 2 % error in the individually derived WQI values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2024.116242.

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