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Eutrophication Monitoring for Sustainable Development in Nha Trang Marine Protected Area, Vietnam

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Abstract: Environmental monitoring is essential to assess and, if possible, anticipate the consequences of various marine economic developments. This study describes progress in environmental monitoring by developing and applying a eutrophication index (EI) for marine protected areas (MPAs). The EI combines available data, such as biological oxygen demands, dissolved inorganic nitrogen and phosphorus, and chlorophyll-a, with the weighting factors calculated from principal component analysis to assess environmental quality. Its effectiveness was tested using nearly three decades of environmental data (since 1996) from the Nha Trang MPA in Vietnam. The EI revealed clear trends in environmental quality. In the period 1996–2006, environmental conditions deteriorated, negatively impacting aquaculture. In the later period, 2007–2024, improved environmental protection policies, technological developments, expanding tourism, and heightened public awareness contributed to a reversal of this trend. During the earlier period, the EI indicated poor environmental quality (Level V), while in the later years, it improved significantly, approaching Level II. This study also identified the spatial eutrophication patterns and helped to determine the causes of specific eutrophication levels. These included port development, aquaculture activities, and domestic waste discharge. These findings highlight the close relationship between environmental quality and economic activities in the bay. Overall, the new EI and its sensitivity maps enhance environmental monitoring capabilities. They provide valuable tools for decision-makers, aiding in the strategic planning of marine economic development, ecosystem protection, and sustainable resource use. The approach supports long-term environmental stewardship and more informed, adaptive management of coastal and marine areas.

Keywords: water quality monitoring; eutrophication index (EI); water quality; marine protected area (MPA); Nha Trang Bay

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1. Introduction

Environmental monitoring and assessment have become important tools for environmental management [1]. Programs for monitoring and assessing trends in natural resources or environmental quality have been developed in various countries and continents [2–7]. The

trends established through environmental monitoring and assessment enable the control and management of environmental quality [8].

Environmental quality in marine, coastal, and freshwater environments can be monitored and assessed with various chemical [9–12] and/or biological [6] parameters. Carlson [13], for example, pioneered the development of a freshwater index suitable for fresh waters, using chlorophyll-a (Chl-a), total phosphorus (TP), and Secchi disk depth. The Chl-a concentration is a measure of photosynthetic biomass, which is the basis of the natural food chain in aquatic ecosystems [14,15]. Chl-a and TP indicate potential productivity, and this relationship helps to evaluate the load of nutrients in water bodies and predict ecological changes [16]. Secchi disk depth is a measure of turbidity [17]. Together, these parameters also indicate water quality [16,18].

Following this idea, researchers have successfully developed and applied various eutrophic or eutrophication indices using several other integrated methods [11,19–27]. Bricker et al. [4] conducted an integrated assessment approach for the eutrophic status in estuaries. Their approach relates pressure (overall human influence), state (overall eutrophic conditions), and response (including future management activities) indicators. Its results and applications were reviewed by the NEEA [28], who concluded that such an integrated approach could well inform environmental managers. Selman et al. [29] reviewed and examined 415 eutrophic and hypoxic coastal waters worldwide. Niu et al. [30] have analyzed the way in which eutrophication affects the health of ecosystems, underlining the need for composite indexes that incorporate more ecological variables. In Asia, specifically, the exploration of eutrophication is under-reported [27,30–33]. Environmental and resource managers require aggregated information from these integrated environmental monitoring and assessment approaches, and the resulting indices, to simplify complex data [34,35]. They provide a simple yet robust product by reducing the complexity of abundant, multiple, and varying parameter combinations [34,35]. Peyman et al. [36] explored the characteristics of eutrophication in these areas but indicated that much more regional research is needed. Borja et al. [5], moreover, suggested that in the future, marine environmental assessment should not only be based on integrated indices but also involve ecosystem-based approaches, which consider the ecological interactions of target species within their habitat, interactions between economic activities and these species and habitats, and the consequences of economic development on these ecosystems. Most environmental monitoring and assessment approaches that were applied to estuaries and/or coastal waters addressed severely environmentally stressed systems [27,30,33,37,38]. Additionally, the approaches used to assess marine protected areas used less appropriate methodologies and therefore had limited practical applicability.

In Vietnam, marine environmental monitoring and assessment have been applied to assess the consequences of economic development and integrated coastal zone management [39–44]. These studies used many environmental parameters to recognize the environmental status and trends, but environmental quality could only be quantified by individual parameters [39,40]. Unfortunately, some studies targeted environmental impact with such integrated indicators [33,45]. The indices TRIX [22] and UNTRIX [46] were used to evaluate eutrophication levels in coastal waters [33,47]. Son [45] developed a protocol which integrated Chl-a, biological oxygen demand (BOD), and dissolved inorganic nitrogen (DIN) and phosphorus (DIP) to assess water quality in shrimp culture in the Mekong Delta, which likely caused eutrophication, whereas the nutrient uptake of mangrove forests and high water exchange substantially reduced the water's eutrophication levels.

Nha Trang Bay in central Vietnam consists of a nice archipelago with islands, beaches, and coastal landscapes, and therefore has high tourist appeal. Formerly, Nha Trang Bay, established as a marine reserve, was oriented towards developing the tourism economy

and conserving marine life [48,49]. Thus, monitoring and management of the coastal and marine environment in this bay would support both environmental and economic development, aiding managers, authorities, and farmers in ensuring proper water-quality management [48,50]. However, the long-term monitoring of water quality and eutrophication in Nha Trang Bay remains limited. Much of the existing data are fragmented or collected for short-term regulatory purposes, lacking integration across the temporal and spatial scales. Furthermore, the application of consistent eutrophication assessment frameworks, such as the Trophic State Index (TRIX) or UNTRIX, is not yet widespread in Vietnam's coastal monitoring programs [22]. There is a critical need for robust scientific assessments to understand the extent, trends, and drivers of eutrophication in the region and to inform evidence-based management strategies.

The use of EI in monitoring and assessing water quality in Nha Trang Bay to inform management strategies is underlined in the context of marine protected areas, supporting the sustainability of tourism, which is essential for the local economy [51,52]. This study aimed to improve this and use an EI to quantify the status of and trends in the bay's water quality and determine the factors that caused changes in water quality over three decades. The study also reviewed the possibilities to monitor water quality for emerging coastal and marine economies by developing and applying a new eutrophication index (EI) that is suitable for rapidly developing coastal areas and that is not limited by the disadvantages of the earlier approaches.

2. Materials and Methods

2.1. Sampling, Collection, and Analysis

Nha Trang Bay, situated in central Vietnam, has experienced profound economic and environmental changes over the past few decades (Figure 1). In the 1990s, the local economy was primarily based on agriculture and small-scale fisheries, but by the 2000s, marine aquaculture became increasingly prominent, and in recent years, tourism has emerged as the dominant sector driving economic growth [48]. This progression has brought substantial improvements in infrastructure and income opportunities but has also imposed mounting stress on the bay's coastal and marine ecosystems [53]. The rapid expansion of tourism, particularly mass tourism, has fueled extensive shoreline development, leading to the destruction of natural habitats, increased waste discharge, and deterioration of water quality. Coral reefs and seagrass beds, which are critical to biodiversity and fisheries' productivity, have suffered from sedimentation, pollution, and disturbances caused by unregulated tourism and recreational activities [54]. Meanwhile, the intensification of marine aquaculture has led to localized environmental degradation, including organic pollution and habitat modification [47,55]. Although Nha Trang Bay is designated as a marine protected area (MPA), regulatory enforcement remains weak, and integrated coastal zone management has yet to be effectively implemented [56]. Going forward, sustainable development and adaptive environmental governance will be essential to reconciling economic aspirations with the preservation of the bay's ecological health and resilience.

Multiple surveys were conducted to collect samples in Nha Trang Bay from 1996 to 2024 (Figure 2) in the NCB95 verseera (1996–2014) [33,57] and with other ships (2014–2024). In every survey, water samples were collected at the surface layer (about 1 m water layer) and, if the depth was larger than 5 m, also at the bottom water layer (1 m from the bottom) within 3 h of high tide. At the environmental monitoring station (EMS, located at 12°12′45″ N and 109°13′12″ E, Figure 1), water samples were collected four times a year or twice a year at the surface and bottom layers during high and low spring tides.

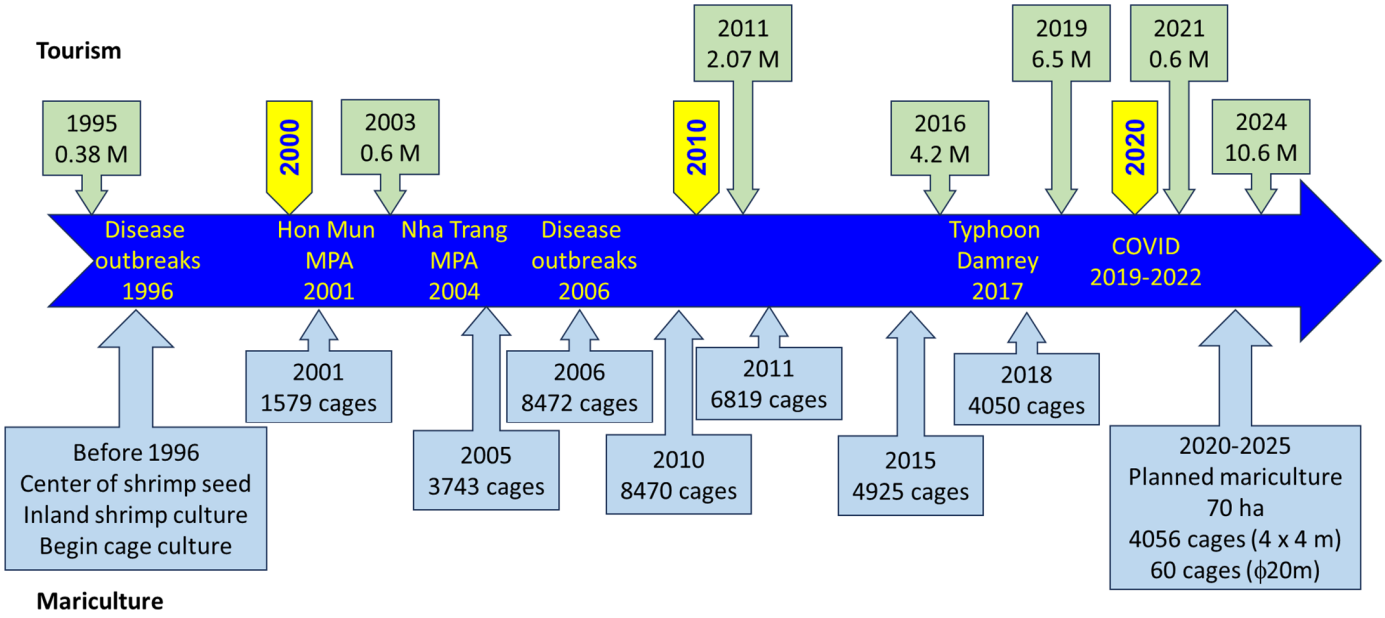


Figure 1. Tourism and mariculture trends in Nha Trang Bay over three decades. The trend of tourism is presented by the number of visitors (in million people), whereas the trend of mariculture is the number of cages (4 × 4 m) and HDPE cages (ϕ 60 m).

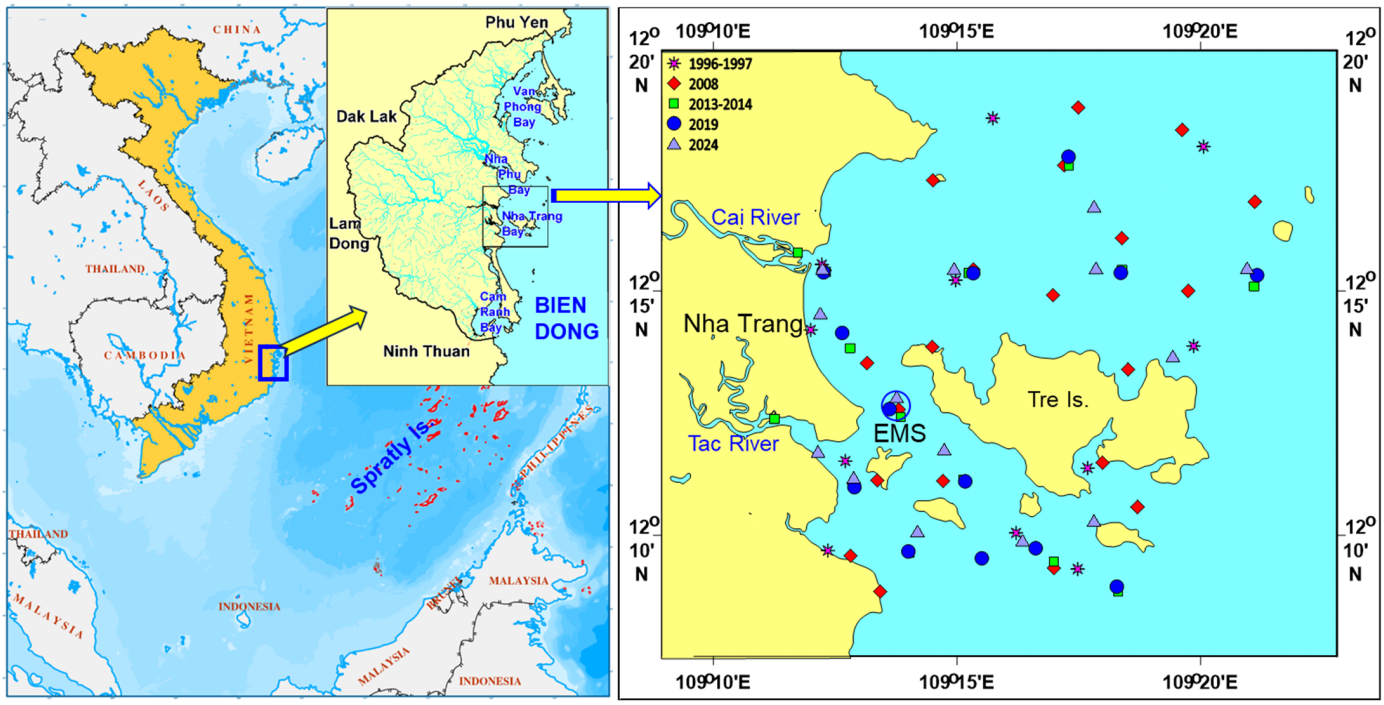


Figure 2. Sampling stations in Nha Trang Bay (1996–2024).

Water samples were collected with a 6 L Niskin bottle. Water temperature and salinity were determined directly at all in situ stations. Samples for biological oxygen demand (BOD) were prepared at the same time as DO and kept in the dark but analyzed after 5 days. DO samples were prepared immediately on the ship and analyzed by the Winkler method [58] later in the laboratory. Water samples were collected with 5 L gray plastic cans for total suspended matter (TSM) and Chl-a measurements, and with 0.5 L plastic bottles for nutrient measurements. These cans and bottles were immediately stored at 4 °C in the dark and transported to the laboratory, where all TSM and Chl-a samples were filtered

using glass microfiber filters (GF/F membranes with a pore size of 0.45 µm) within six hours from their collection time. Nutrient samples were kept at −20 °C until they were analyzed, i.e., within one week of collection.

BOD was analyzed by using the difference in DO. BOD samples were kept in the dark over a five-day period [58]. The TSM value was weighed after the samples were dried at 105 °C for 24 h [58]. Chl-a was measured by the acetone method with a spectrophotometer [59]. NH_4^- concentrations were measured by the indophenol method [60,61]. NO_2^-, NO_3^- (which together determine DIN), and PO_4^{3-} concentrations were measured by the 4500-NO_2^- B, 4500-NO_3^- E, and 4500-P E ascorbic acid methods, respectively [58]. Chl-a, N, and P nutrients were measured using a UV–vis spectrophotometer (1996–1997) and a U2900 double-beam Hitachi (2008–2024).

This study also used the Chl-a climatology data from NASA's Giovanni (https://giovanni.gsfc.nasa.gov/ (accessed on 20 March 2025)) to help design the sampling strategy. This showed that the Chl-a concentration in Nha Trang Bay reaches the peak (Figure 3) in November (about 1.9 mg per m^3). The lowest values occur between April to August. To ensure representative sampling, environmental quality was monitored during the periods of lowest (April to June) and highest (November to December) Chl-a concentrations.

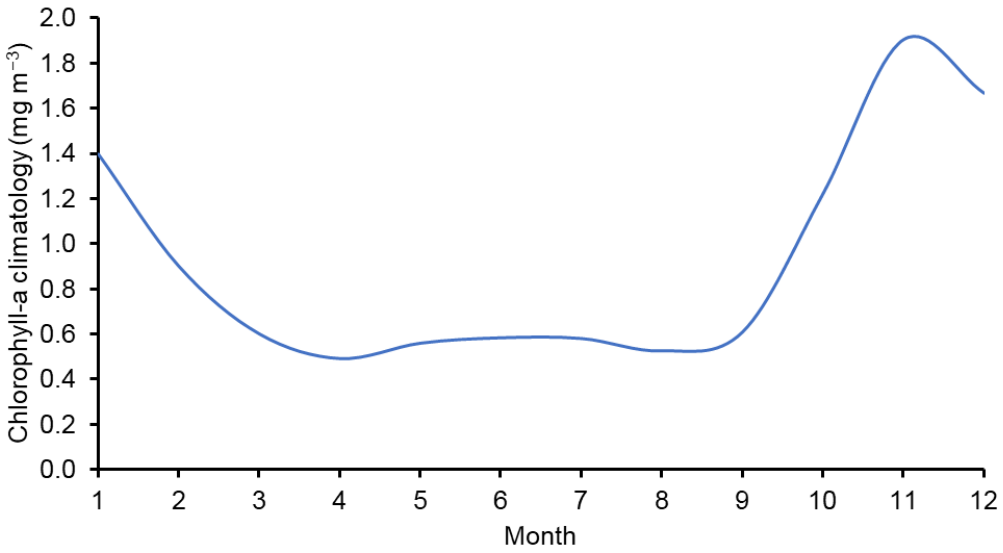


Figure 3. Average concentration of Chlorophyll-a climatology in Nha Trang Bay from MODIS data (Data from https://giovanni.gsfc.nasa.gov/ accessed on 20 March 2025).

2.2. Data Analysis

2.2.1. EI Calculation

To assess the environmental quality, we used a new eutrophication index (EI) approach. The EI for each station was calculated as follows

$$EI = \sum W_i(U_i/U_{Si}) \quad (1)$$

where EI is the eutrophication index (unitless), W_i is the weight coefficient for each environmental variable i in such a way that the sum of all weight coefficients is 1, U_i is the measured concentration of environmental variable i, and U_{Si} is the criterion or threshold concentration of environmental variable i. The weight coefficients (W_i) are determined as follows

$$W_i = F_i/\sum F_i \quad (2)$$

where F_i represents the first principal component (PCA1) obtained from the principal component analysis of variable i. The sum of all F_i values equals the sum of all PCA1 values of the environmental variables used for *EI* calculation. The principal component analysis [62] was applied with the parameters of seawater temperature, salinity, DO, Chl-a, BOD, DIN, and DIP in the software Origin Pro 2024 (OriginLab Corporation, Northampton, MA, USA).

The parameters used to calculate the *EI* in Nha Trang Bay included Chl-a, DIN, DIP, and BOD. On the basis of the *EI* ranges, water quality was classified into seven levels (Table 1), each associated with specific limitations on economic activities.

Table 1. Eutrophic classes (above) and the criterion concentration of parameters for Level V (EI = 1, below).

Category	*EI*	Level	Goods and Services
Oligotrophic	<0.25	I	All activities but limiting aquaculture
Low mesotrophic	0.25–0.50	II	Good for swimming, aquaculture, and biodiversity protection
Mesotrophic	0.50–0.75	III	Good for aquaculture, limiting swimming
High mesotrophic	0.75–1.00	IV	Controlling aquaculture and limiting biodiversity, but good for port activities, shipbuilding, and navigation
Eutrophic	1.00–2.00	V	Limiting aquaculture and reducing biodiversity but good for port activities, shipbuilding, and navigation
Polluted	2.00–5.00	VI	Controlling port activities and navigation; no aquaculture
Heavy polluted	>5.00	VII	Limiting port activities and navigation
Parameter	**Vietnamese environmental standard (VNES)**		**Criterion [63]**
Chl-a (mg m^{-3})	No data		1–10
DIN (mgN m^{-3})	No data		200–300
DIP (mgP/m^{-3})	15		15
BOD (mg O_2 L^{-1})	10		1–3 (for COD concentration (used for comparison))

2.2.2. EI Validation

To validate the eutrophication index (EI), the UNTRIX index (unitless) was applied using the following Equation (3) [46] with the dataset in 2019–2024.

$$UNTRIX = \log_{10}(Chla \times aD\%O \times DIN \times DIP) \quad (3)$$

where Chla is the factor expressing the productivity concentration of Chl-a in ug/L, aD%O is the oxygen as the absolute percentage of deviation from saturation, DIN is the dissolved inorganic nitrogen (N-NO3 + N-NO2 + N-NH3) in ug/L, and DIP is the dissolved inorganic phosphorus in ug/L.

The relationship between the *EI* and UNTRIX is presented in Figure 4. A strong positive linear correlation was observed, with the regression equation y = 2.4334x + 2.495 and a coefficient of determination R^2 = 0.7145. This indicates that the developed EI aligns well with the established UNTRIX index, supporting the validity of the EI as a reliable tool for assessing eutrophication in coastal waters and MPAs.

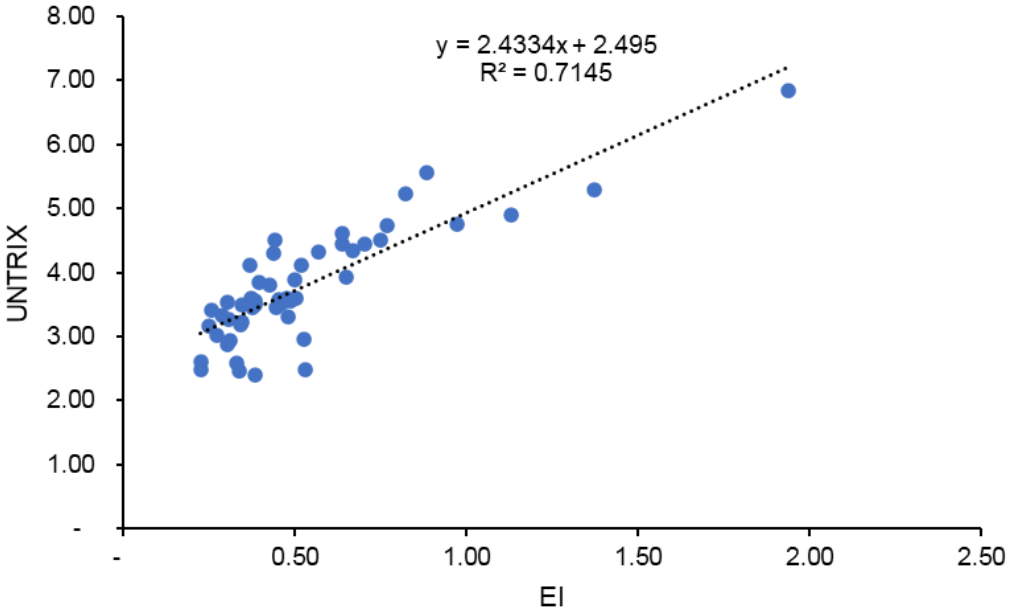


Figure 4. Relationship between EI and UNTRIX for validation.

3. Results

3.1. Distribution of Water Quality Parameters

During the observational period, the oxygen concentration in Nha Trang was in the range of 4.38–6.86 mg L^{-1}. The other parameters of water quality are summarized in Table 2.

Table 2. Mean ± standard deviation of environmental parameters in Nha Trang Bay.

Survey Time	Number of Stations/Number of Samples	TSM (g m^{-3})	Chl-a (mg m^{-3})	DIN (mgN m^{-3})	DIP (mgP m^{-3})	BOD (mgO_2 L^{-1})
December 1996	11/22	4.35 ± 4.37	1.33 ± 1.45	194 ± 154	31.6 ± 13.5	0.85 ± 0.33
April 1997	11/22	1.97 ± 1.29	0.17 ± 0.11	26 ± 15	19.9 ± 6.1	0.79 ± 0.45
November 1997	11/22	10.64 ± 9.47	0.56 ± 0.57	81 ± 96	19.1 ± 6.7	0.65 ± 0.18
March 1998	11/22	1.76 ± 1.07	0.23 ± 0.13	107 ± 127	13.9 ± 10.8	0.86 ± 0.31
April 2008	23/82	2.22 ± 1.89	0.50 ± 0.29	46 ± 73	8.9 ± 6.6	0.23 ± 0.20
July 2013	13/45	1.57 ± 1.08	0.64 ± 0.73	64 ± 22	10.0 ± 11.3	0.49 ± 0.23
January 2014	13/45	1.80 ± 1.92	0.75 ± 0.41	65 ± 43	10.4 ± 11.9	1.04 ± 1.18
August 2019	13/24	2.50 ± 2.71	0.94 ± 0.60	99.19 ± 28.97	26.19 ± 14.22	0.37 ± 0.16
November 2024	14/29	2.84 ± 1.95	1.92 ± 1.67	96.64 ± 72.18	16.84 ± 13.19	0.48 ± 0.23
VNES	-	80	No data	No data	15	10
ECEI	-	No data	1–10	200–300	15	1–3

Notes: VNES, Vietnamese environmental standard as defined in 1995 for surface coastal water; ECEI, environmental criteria of the eutrophication index in Table 1.

In the Nha Trang Bay, the in situ Chl-a concentration varied from 0.05 to 10.70 mg per m^3, averaging in the range of 0.23 ± 0.13 to 3.66 ± 2.39 mg per m^3. The highest concentration was found at the Tac River mouth. The Chl-a median concentration in most datasets met the environmental criteria. The Chl-a concentration increased at stations close to aquaculture activities, fishing, traffic ports, and/or domestic wastewater discharge.

Unlike Chl-a, the bay's concentration of TSM was appropriate for swimming and aquaculture. The mean TSM concentration ranged from 0.73 to 10.64 mg per m^3 and met the requirement of Vietnamese environmental standards for coastal surface waters (Table 2). The concentration in the rainy season (December 1996, November 1997, January 2014, November 2024) was significantly higher than in the dry season (April 1997, March 1998, July 2013, August 2019) due to erosion processes in the catchment. The average concentration of DIN and DIP ranged from 25.8 to 194.4 mg N per m^3 and from 8.92–31.64 mg P

per m^3, respectively (Table 2). Median concentrations of DIN varied slightly, while those of DIP sharply decreased. DIN and DIP concentrations during the rainy seasons were higher than those in the dry seasons. The BOD values demonstrated the organic pollution level in the bay's waters. The concentration of BOD in Nha Trang Bay (Table 2) catered to rich marine ecosystems. However, in some short periods, marine water quality was threatened by serious environmental problems.

This chemical analysis shows that the water quality passed through a deterioration period and has recently started to improve (Figure 5) because the local government tried to meet the requirements of the Vietnamese national environmental standard (VENS). Thus, the changing water quality advanced the development of the bay's aquatic ecosystems. The role of nutrients in the bay's aquatic ecosystems has changed (according to the W_i of DIN and DIP changes) (Table 3). Initially, photosynthesis was limited by phosphorus, and nitrogen was relatively abundant. Now, as the VENS standards have been met, the limiting factor has become nitrogen.

3.2. Classification of Water Quality in Nha Trang Bay

Table 3 and Figure 5 show that water quality conditions in Nha Trang Bay were satisfactory. Thom and Tuan [64] reported that the bay's water quality was clear and suitable for coral reef ecosystems, suggesting that the EI should ideally be below Level II. The average EI values, however, range from Levels II to III (Table 3). These results also indicate that water quality in the rainy season was worse than that in the dry season (c.f. Figure 5a–d,f–i). This lower water quality mainly occurred near estuaries, where large nutrient and sediment inputs are released through erosion in the catchment by the rainy season's heavy rains. This was evident, for example, in the high EI at the Cai River mouth in November 1997, when untreated domestic waste from Nha Trang City was flushed by rainwater, directly impacting nearby marine areas. Such large values were also found in waters near the Tac and Lo Rivers' mouths, but here, the nutrient waste mainly originated from marine aquaculture. In the dry season, the accelerated photosynthesis processes of phytoplankton enhanced self-purification capacity, and this contributed to the bay's water quality recovery. As a result, the bay's water quality was best in this season (as displayed by its low EI; Figure 5b,e), although the northwestern part of the bay was affected by polluted fresh water and domestic waste input (c.f. Figure 5e).

However, in some special cases, bad water quality was reported as the result of the negative impacts of specific activities. The most remarkable event occurred in December 1996, when EI indicated eutrophic conditions (i.e., Level V; Table 3 and Figure 5a). This was caused by the release of untreated waste and pollutants from collapsed shrimp aquaculture in the Tac River catchment. Other eutrophic conditions were found near the Cai and Tac Rivers' mouths. They were also frequently impacted by domestic, aquaculture, and industrial waste and waste from port activities and ships. In addition, marine aquaculture in open waters also contributed to eutrophication (c.f. Figure 5e).

Further offshore from the Cai River's mouth, eutrophic conditions (i.e., EI at Level V) often occurred in dry seasons (Figure 5d–f,h). This is explained by the spring bloom of green seaweed, followed by biomass decomposition and the reproduction of brown seaweed. As a result, nutrients in the coastal waters increase rapidly, and their algal spores likely increase phytoplankton pigments (i.e., Chl-a levels). In addition, the degradation of organic materials from the Cai catchment, which accumulated here, increased nutrient concentrations in these waters.

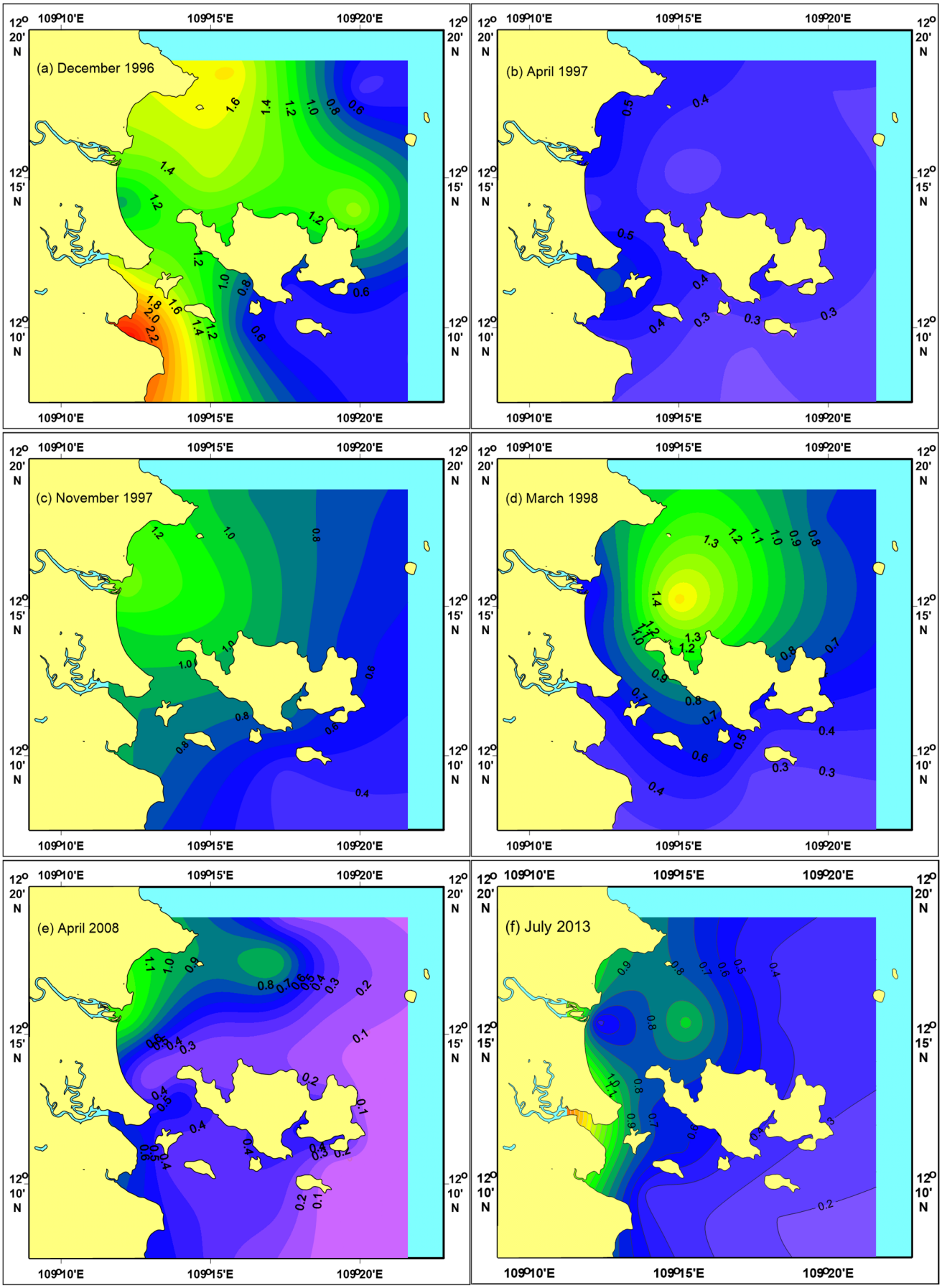


Figure 5. *Cont.*

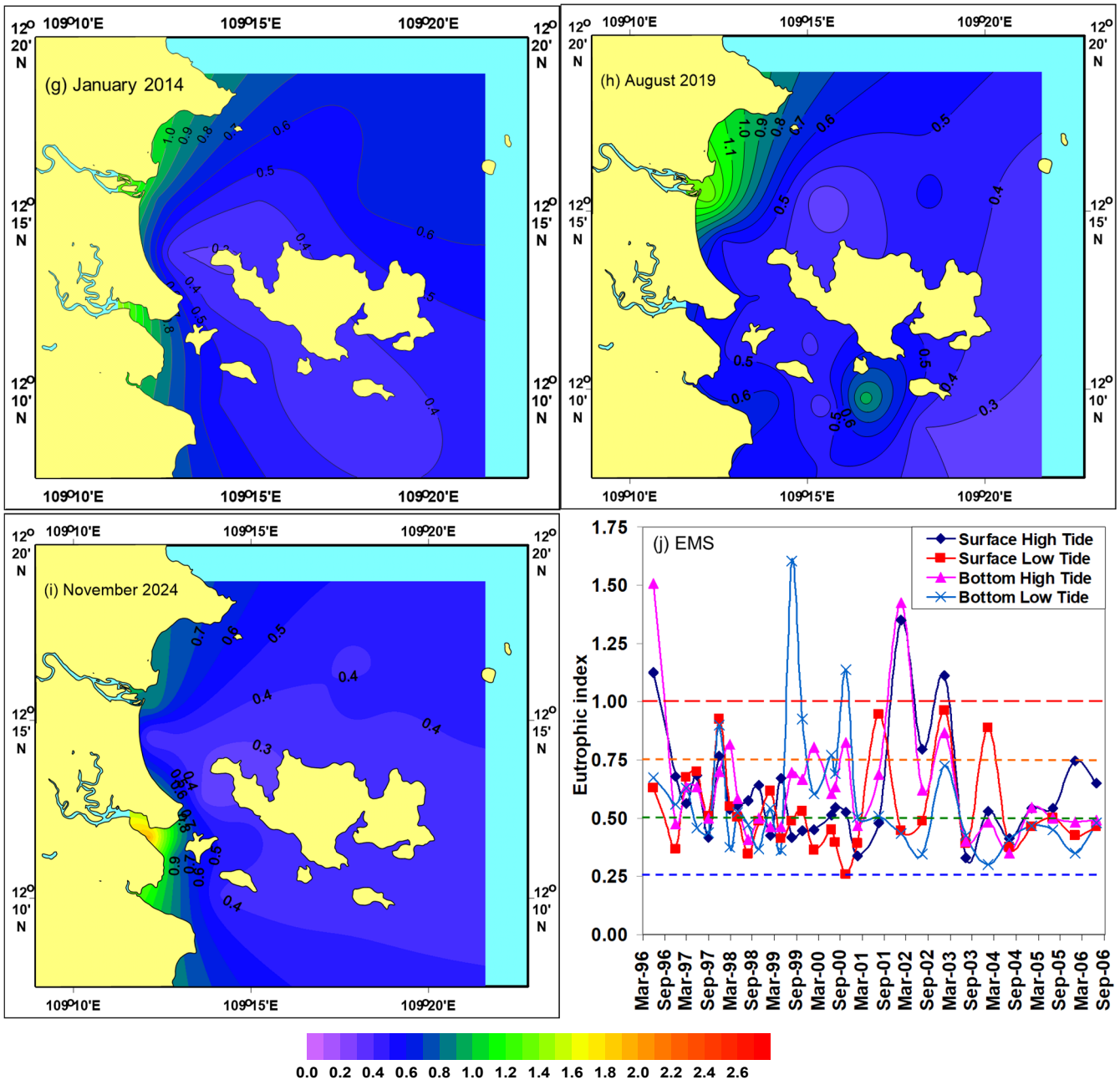


Figure 5. Water quality in Nha Trang Bay based on the eutrophication index (EI) in the surface layer for spatial distribution (**a**–**i**) and at MES (j). Maps (**a**,**c**) show higher eutrophication levels during the rainy season, influenced by runoff and waste from domestic and aquaculture sources. Maps (**b**,**d**) show lower eutrophication levels during the dry season, with peaks potentially due to seaweed spores. Map (**e**) indicates increased EI due to runoff from the Cai River after heavy rain. Maps (**f**,**h**) show the impact of domestic waste during the dry season. Maps (**g**,**i**) indicate the low domestic waste impact during the rainy season. Map (**j**) shows variable EI levels at the environmental monitoring station (EMS), fluctuating between Levels II and III, with occasional peaks at Levels IV or V.

Although not all water quality data at specific sampling points were available in the general surveys in the bay between 1998 to 2007, the EI at the official EMS station demonstrated these temporal changes in water quality. The average EI generally indicates mesotrophic conditions (i.e., EI Level III; Table 3), but the actual EI ranged from low mesotrophic to mesotrophic conditions (i.e., Levels II and III), although sometimes eutrophic conditions (i.e., Level V) emerged when environmental problems were obvious. For example, the EI peaked at Level V at EMS in 2002 because monitoring samples were taken

immediately following a major algal bloom. This was also demonstrated by the high TSM measurements and BOD, and low Chl-a, as well as the unbalanced N:P ratio. In addition, the imbalance in the N:P ratio also caused a eutrophic event [21,65]. Another eutrophic status was noted with high EI at the surface layer at high tide (Figure 5j) when most of the wild fish and cultured fish were killed in the Tac River mouth in February 2006 [40].

Table 3. Status of water quality in Nha Trang Bay.

Period	W_i (sum W_i = 1)				EI				Status
	Chl-a	DIN	DIP	BOD	Min	Max	Average	±SD	
December 1996	0.264	0.338	0.041	0.357	0.30	2.68	1.07	0.58	V
April 1997	0.270	0.263	0.170	0.297	0.20	0.86	0.44	0.18	II
November 1997	0.378	0.276	0.278	0.068	0.29	1.34	0.72	0.29	III
March 1998	0.199	0.322	0.250	0.229	0.21	1.75	0.65	0.33	III
April 2008	0.121	0.408	0.382	0.089	0.17	1.15	0.40	0.24	II
July 2013	0.415	0.076	0.243	0.266	0.20	1.18	0.59	0.28	III
January 2014	0.212	0.354	0.296	0.138	0.30	0.81	0.47	0.13	II
August 2019	0.245	0.252	0.234	0.251	0.21	1.26	0.55	0.24	III
November 2024	0.244	0.252	0.262	0.242	0.23	1.94	0.46	0.34	II
Average	0.261	0.282	0.239	0.215	0.17	2.68	0.59	0.20	III
Environmental monitoring station	0.121	0.408	0.382	0.088	0.16	1.69	0.58	0.24	III
Low tide	0.116	0.475	0.400	0.009	0.14	1.60	0.55	0.24	III
High tide	0.140	0.349	0.346	0.165	0.17	1.51	0.62	0.25	III

Notes: W_i, weight coefficient of parameter i (dimensionless), calculated from the PCA1 of DO, Chl-a, DIN, DIP, and BOD according to Equation (2). The eutrophication index (EI; unitless) was estimated using Equation (1). The status level came from Table 1.

In general, water quality was good enough for the development of ecotourism and aquaculture, although eutrophic marine areas were frequently observed near the Cai and Tac Rivers' mouths. Water quality was threatened by increasing pressures of domestic waste, untreated waste from aquaculture in coastal and marine regions, industrial waste, navigation, and tourism activities and services, as well as urbanization. Further, analyzing the results from monitoring data indicated that water quality in Nha Trang Bay sometimes faced a eutrophic/polluted status, but these phenomena occurred in relatively short periods.

4. Discussion

4.1. EI Approach

Eutrophication, which is known as nutrient enrichment in waters [29], causes an increase in microalgae and provides organic matter [66,67] as well as reducing DO in water bodies. Whereas it occurs naturally over geological timescales, modern eutrophication is largely a result of anthropogenic nutrient enrichment stemming from agriculture, urbanization, and industrialization [68]. When it rains, nutrients flow into nearby rivers and could cause eutrophication of the marine and coastal waters [69]. In marine and coastal systems, eutrophication often leads to a cascade of environmental changes. The process of eutrophication typically follows a sequence: increased nutrient loading, elevated chlorophyll-a concentrations (indicative of phytoplankton biomass), decreased dissolved oxygen levels, and eventual impacts on biodiversity and ecosystem functioning. These stages can be influenced by various physical and biological factors [70].

Assessing eutrophication effectively requires the integration of both chemical and biological indicators to capture nutrient dynamics and ecological responses. Key parame-

ters commonly monitored include total nitrogen (TN), total phosphorus (TP), DIN, DIP, chlorophyll-a, dissolved oxygen (DO), biochemical oxygen demand (BOD), and water transparency [71]. Nitrogen is the main controlling factor of eutrophication in coastal waters [72], but that role might seasonally shift to phosphorus in estuaries, influenced by the rain and nutrient flow of the Earth [73]. During rainy seasons, the nutrient load increases, resulting in higher concentrations of chlorophyll-a, which are essential changes, as high chlorophyll levels can signal potential hypoxia [74]. Moreover, eutrophication is caused by an unbalanced N:P ratio [21,65,75]. Chl-a acts as a measurable indicator of phytoplankton biomass [76]. DO levels signify the oxygenation state of the water column, with low DO (hypoxia) indicating the collapse of oxygen availability due to organic decomposition [77]. BOD, which quantifies the oxygen consumed by microbial activity during organic matter decomposition, is elevated in nutrient-rich waters and serves as an early warning of potential hypoxia [78]. Some water quality indexes were estimated by using Chl-a [4,13,22,79,80], whereas others suggested assessing the status of environmental quality by integration of Chl-a, TN, TP, and DO for marine and coastal waters in the USA, Italy, the Philippines, and the Adriatic Sea [4,22,31,46] or by integration of COD, DIN, and DIP for marine and coastal waters in China and Taiwan [37,38,81]. Sotto et al. [31] reported that high nutrients in the water layer of the near-bottom layer could be related to low DO. They also indicated that where eutrophication existed, hypoxia was also observed [4,22,31,46,74]. This relationship is not exclusive to Nha Trang; similar observations have been made in coastal lagoons around the world, which also face nutrient-induced eutrophication [82]. The impact of nutrient load is critical due to the sensitivity of the local marine life to changes in water quality [36]. However, in Nha Trang, although eutrophication was reported [40] and could be assessed with TRIX in mariculture [47] or UNTRIX in the bay [33], DO reported a concentration higher than 4 mg m^{-3} [40]. The dual monitoring of DO and BOD provides a robust diagnostic tool for distinguishing between natural biogeochemical fluctuations and anthropogenic impacts. Elevated BOD values often co-occur with depleted DO in systems under nutrient stress, reinforcing the detection of eutrophic conditions [83,84]. In our study of the Nha Trang MPA, the DO concentration was also higher than 4 mg m^{-3}, even though eutrophication occurred by macroalgae [85], increasing the BOD value. Thus, in the case of Nha Trang Bay, a marine protected area, we suggest that EI should be estimated on the basis of the interaction of Chl-a, DIN, DIP, and BOD.

The proper calculation of EI is often based on the range and the available set of parameters. Some studies used national environmental standards as the input parameters [39,40,64,86], but these results only identified polluted areas. Others built a list of parameters for eutrophication assessments [4]. These criteria were set up on basis of the special conditions of the study areas. For this study, the criteria were built up according to previous research in coastal waters, as well as the characteristics of the natural and economic systems in Nha Trang. Antoine et al. [87] classified marine regions on the basis of chlorophyll-a concentrations in the water body, in which oligotrophic, mesotrophic, and eutrophic levels have a Chl-a of <0.1 mg m^{-3}, 0.1–1 mg m^{-3}, and >1 mg m^{-3}, respectively. Fisher et al. [63], however, suggested that the threshold for the chlorophyll-a concentration in coastal waters should be in the range of 1–10 mg m^{-3}. Thus, the chlorophyll-a concentration was selected to be 1 mg m^{-3} as a eutrophic threshold value. Other environmental criteria were referenced from national environmental standards.

4.2. The Weighting Method in the Eutrophication Index

An essential consideration in the development of an EI is the assignment of variable weight coefficients, which reflect the relative importance of each environmental parameter involved in the assessment. Eutrophication, typically driven by excessive nutrient enrich-

ment, manifests differently across ecosystems and time periods, necessitating a flexible and robust weighting approach to capture the complexity of environmental responses.

Historically, some studies have employed equal weighting schemes ($W_i = 1/n$, where n is the number of variables) [13]. While this method simplifies calculations and avoids subjective bias, it also assumes that all variables contribute equally to eutrophication, which contradicts ecological reality. Other studies suggested that the weight coefficient should be given a specific value for tested variables [4,88]. For example, nutrients like dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) typically exert more direct influence on algal growth than others such as biological oxygen demand (BOD) or chlorophyll-a (Chl-a), especially in systems with nutrient-specific limitations.

To better reflect real environmental conditions, recent studies advocate data-driven weighting schemes that derive weights based on the statistical contribution of each variable. Among these, principal component analysis (PCA) has become a widely used method [62,89–91]. PCA simplifies complex datasets by reducing multidimensional variables into a smaller set of principal components (PCs), which explain most of the dataset's variance. Variables with high loadings on the first principal component (PCA1) are considered more influential and are assigned greater weight. Shin and Lam [91], for example, identified six significant variables from a dataset of 24 using PCA to develop a sediment pollution index. Son [45] applied PCA to environmental data during shrimp culture collapse events in the Mekong Delta and found that BOD, DIN, DIP, and Chl-a were the most critical variables. The PCA1 scores were used as weight coefficients in the EI, demonstrating how real-time environmental collapse events can refine parameter prioritization. In a related example, Morsy et al. [92] analyzed the eutrophication risk in the Mediterranean Sea, using PCA to identify key indicators and assign differentiated weights. This allowed the authors to highlight interlinked environmental variables and the cascading effects that one parameter may have on others, reinforcing the need for a system-based analytical perspective [93]. In our study, we adopted a similar PCA-based approach to determine the weights of selected variables, ensuring that the most impactful contributors to eutrophication were emphasized.

In our findings, PCA1 scores were used as the weight coefficients for each studied variable. The results revealed that weight coefficients (Ws) varied significantly across temporal and seasonal scales. The average weight of DIN (0.291) was higher than those of Chl-a (0.266), DIP (0.237), and BOD (0.206). However, these values fluctuated depending on the seasonal dynamics. For instance, during the rainy season, Chl-a concentrations peaked, resulting in a higher weight coefficient for Chl-a, indicating its increased contribution to eutrophication. Conversely, during aquaculture disease outbreaks in 1996, DIN and BOD were dominant contributors to poor water quality, showing their greater relevance under pollution stress. In areas like the EMS (environmental monitoring site), tidal dynamics and pollution sources influenced weight allocation. During low tide, eutrophication was largely affected by nutrient and organic matter input from ports, aquaculture, and riverine discharge (e.g., higher weights for DIN and DIP). During high tide, however, ocean inflow and tourism-related pollution increased the relative weights of Chl-a and BOD.

Looking forward, machine learning techniques such as random forests and artificial neural networks (ANNs) offer powerful tools for determining variables' importance. These models can detect nonlinear interactions and context-specific variability, often missed by traditional statistical approaches. Additionally, incorporating expert-based multi-criteria decision analysis (MCDA) allows for the integration of empirical findings with stakeholder insights, which are especially relevant in the context of environmental policy and governance.

A crucial component of EI development is sensitivity analysis. By comparing multiple weighting approaches, such as equal, PCA-derived, expert-based, or machine-learned, researchers can assess the robustness and reliability of the index. Sensitivity testing helps

reveal whether the EI maintains consistent responses under varying conditions or is overly reliant on specific variables. As emphasized by Wu and Tang [94], such evaluations are instrumental in setting effective regulatory thresholds and designing adaptive water quality management strategies.

Thus, in our case study, variable weighting is both a technical and strategic process in the construction of a eutrophication index. It influences how accurately the index reflects ecosystem dynamics and determines the reliability of derived policy interventions. A comprehensive approach that combines data-driven methods, machine learning algorithms, expert judgment, and rigorous sensitivity testing is essential for developing scientifically robust and practically applicable EIs.

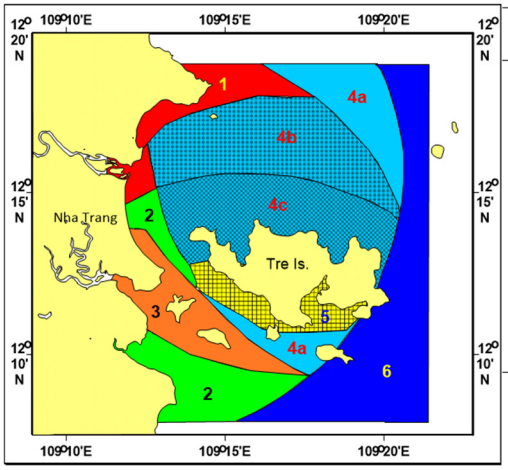
4.3. EI as a Tool for Water Quality Monitoring in MPAs

Water quality in Nha Trang Bay has been studied since the 1970s. Tac-An [95,96] introduced the status of water quality, combining with the development of phytoplankton in marine regions. Other research presented a water quality analysis in Nha Trang Bay in terms of contamination. Tac-An [95] built a database of water and sediment quality, including physical, chemical, and biological parameters. The status of water quality was reported and identified the causes of water degradation [33,39,40,64,86]. In addition, Bai [39,86] considered the national monitoring program, which first reported on the changes in environmental parameters in a temporal fashion. Further, a risk quotient was used as a pollution index for water assessment [39], but the results targeted the pollution assessment of heavy metals both in water and sediments. Linh et al. [97] provided an early description of the quality of the coastal waters, analyzing factors such as temperature, salinity, and nutrient concentrations. Du and Kunzmann [98] have explored the relationship between sediment loads and organochlorine pesticide pollution, linking terrestrial activities with marine degradation. However, most of the results above only reported on the status of and changes in environmental factors in a separate and non-integrated manner.

Other studies used integrated methods for environmental assessment. For example, Thi et al. [99] tried to assess sediment quality on the basis of toxicity testing, but this research did not indicate which parameters caused sediment pollution in ports. Tac-An [95] reported an assessment of environmental quality in Nha Trang Bay, both in water and sediments, by using integrated risk quotient indices. His results targeted polluted parameters, including heavy metals, COD (chemical oxygen demand), and BOD, and within this approach, all parameters were assigned an equal coefficient weight. Researchers have used several indices to measure the levels of contamination of heavy metals and nutrients [33,100]. Phuong [100] investigated the bioaccumulation of heavy metals in marine organisms, indicating the potential risks for both the ecosystem and human health. Giao et al. [101] highlighted the importance of understanding the relationship between water quality and zooplankton diversity, which indicates broader ecological implications. These results were not able to indicate the interactions among environmental parameters, human activities, and natural processes. Tkachenko et al. [102] approached how human pressures, such as tourism and coastal development, negatively influence coral reefs in the area. This underlines the need for robust integrated studies that consider anthropogenic and natural factors that affect water quality.

In this contribution, we use the EI as an integrated index for water quality monitoring. Our results predict effects in a more integrated fashion in comparison with the above-mentioned work, because the EI preserves the cause-and-effect relationship of the environmental parameters, resulting in eutrophication of the marine waters. Consequently, Table 3 and Figure 5 show the status and trends of water quality in Nha Trang Bay during the observational period. The results also allow an assessment of which environmental

parameter has a more important contribution than the others (Table 3). Furthermore, interactions of EI, economic development, and natural processes allow a spatial mapping approach to sensitive environmental zones (Figure 6). In the northern part of the bay, water quality is considerably affected by domestic waste (Zone 1) and tourism activities (Zone 2) while in another part, the quality is affected by waste from aquaculture in the Be catchment, seafood processing manufactories, fishing, and traffic ports (Zone 3); tourism activities (Zone 2); and marine aquaculture (Zone 5). In addition, some transitional zones between coastal and ocean waters exist (Zone 4a, 4b—with increased runoff influence from the Cai River, and Zone 4c—impacted by tourism). Additionally, a distinct zone was near the EMS. During the dry season, seawater from the southern part had more influence than in the northern part. Seawater contained high eutrophic levels due to high phytoplankton concentrations, nutrients, and organic matter. Conversely, during the rainy season, water in the northern part contained high TSM, organic matter, and nutrients.



Zone	Affected by	Eutrophic level
1	Runoff, domestic waste, and other waste sources from Nha Phu Lagoon	IV–VI
2	Tourism	I–III
3	Inland aquaculture, ports, and factories	II–IV
4a	Transitional zone	I and II
4b	Transitional zone, but more affected by water from Zone 1	I and II
4c	Transitional zone and tourism	I and II
5	Marine aquaculture	II and III
6	Open water	I

Figure 6. Relationship between economic activities and water quality in Nha Trang Bay.

5. Conclusions

In conclusion, water quality in Nha Trang Bay over the observational period (since 1996) was sufficient to stimulate marine economic development and biodiversity protection. In general, water quality in the bay towards the end of the observations tended to be clear and supported the development of aquatic ecosystems. The water quality, however, was still threatened by the increasing pressure of economic development in coastal and marine regions of the bay, as well as urbanization. Water quality in Nha Trang Bay changed considerably over three decades, depending on the restructuring efforts of the economy, but from 2003, the water quality could be considered as appropriate for marine economic development and biodiversity protection.

The EI is used as a method of water quality monitoring in Nha Trang Bay. This index reveals the interaction of contributing parameters, which are the cause/effect of eutrophication. The status of and changes in EI are related to the economic development in coastal and marine regions, as well as natural processes in the bay. Further, by combining the impact of economic restructuring and natural processes, the EI is able to predict a map of spatially distributed water quality. The EI is thus an effective and relatively simple parameter summarizing environmental effects using a complete set of variables of water quality, so the EI can be used for water quality monitoring and considerably support policy-makers, scientists, and farmers to understand the status and trends of the aquatic environment in general.

Implementing a future strategy for integrated coastal zone management in Nha Trang's marine protected area will result in improving living standards for the local people, a

developing economy, and protecting the environment and biodiversity at the same time. Even in case of extreme events, such as a severe environmental problem occurring, the EI is capable of identifying pollution hot-spots as well as their causes within a short response time. Economic losses, therefore, can be reduced to an acceptable minimum. We thus propose the use of EI as a water quality index to assess and monitor environmental quality for the sustainable development of the economy as well as to protect and improve marine water quality.

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References

1. Jacobson, C.; Carter, R.W.; Thomsen, D.C.; Smith, T.F. Monitoring and evaluation for adaptive coastal management. *Ocean Coast. Manag.* **2014**, *89*, 51–57. [CrossRef]
2. Udy, J.; Gall, M.; Longstaff, B.; Moore, K.; Roelfsema, C.; Spooner, D.R.; Albert, S. Water quality monitoring: A combined approach to investigate gradients of change in the Great Barrier Reef, Australia. *Mar. Pollut. Bull.* **2005**, *51*, 224–238. [CrossRef] [PubMed]
3. Hu, C.; Chen, Z.; Clayton, T.D.; Swarzenski, P.; Brock, J.C.; Muller-Karger, F.E. Assessment of estuarine water-quality indicators using MODIS medium-resolution bands: Initial results from Tampa Bay, FL. *Remote Sens. Environ.* **2004**, *93*, 423–441. [CrossRef]
4. Bricker, S.B.; Ferreira, J.G.; Simas, T. An integrated methodology for assessment of estuarine trophic status. *Ecol. Model.* **2003**, *169*, 39–60. [CrossRef]
5. Borja, A.; Bald, J.; Franco, J.; Larreta, J.; Muxika, I.; Revilla, M.; Rodríguez, J.G.; Solaun, O.; Uriarte, A.; Valencia, V. Using multiple ecosystem components, in assessing ecological status in Spanish (Basque Country) Atlantic marine waters. *Mar. Pollut. Bull.* **2009**, *59*, 54–64. [CrossRef]
6. Borja, Á.; Franco, J.; Valencia, V.; Bald, J.; Muxika, I.; Jesús Belzunce, M.; Solaun, O. Implementation of the European water framework directive from the Basque country (northern Spain): A methodological approach. *Mar. Pollut. Bull.* **2004**, *48*, 209–218. [CrossRef]
7. Hossain, T.; Adams, M.; Walker, T.R. Role of sustainability in global seaports. *Ocean Coast. Manag.* **2021**, *202*, 105435. [CrossRef]
8. Artiola, J.; Pepper, I.; Brusseau, M. *Environmental Monitoring and Characterization*; Elsevier: Amsterdam, The Netherlands, 2004; p. 410.
9. Jingzhong, Z.; Liping, D.; Baoping, Q. Preliminary studies on eutrophication and red tide problems in Bohai Bay. *Hydrobiologia* **1985**, *127*, 27–30. [CrossRef]

10. Lin, R. Review of assessing methods for coastal eutrophication. *Mar. Environ. Sci.* **1996**, *15*, 28–31.
11. Cloern, J.E. Our evolving conceptual model of the coastal eutrophication problem. *Mar. Ecol. Prog. Ser.* **2001**, *210*, 223–253. [CrossRef]
12. Yao, Y.; Shen, Z. A review on eutrophication research of coastal waters. *Mar. Sci.* **2005**, *29*, 53–57. (In Chinese)
13. Carlson, R.E. A trophic state index for lakes. *Limnol. Oceanogr.* **1977**, *22*, 361–369. [CrossRef]
14. Bennett, M.G.; Lee, S.S.; Schofield, K.A.; Ridley, C.E.; Washington, B.J.; Gibbs, D.A. Response of chlorophyll a to total nitrogen and total phosphorus concentrations in lotic ecosystems: A systematic review. *Environ. Evid.* **2021**, *10*, 23. [CrossRef]
15. Kasprzak, P.; Padisák, J.; Koschel, R.; Krienitz, L.; Gervais, F. Chlorophyll a concentration across a trophic gradient of lakes: An estimator of phytoplankton biomass? *Limnologica* **2008**, *38*, 327–338. [CrossRef]
16. Saragih, F.S.; Djamil, H.; Juanda, J.; Mubarak, A.S.; Hasan, V.; Sihombing, A.; Satyantini, W.H. Nutrient Concentration, Water Brightness, Chlorophyll-a, and Phytoplankton Abundance as Indicators for Determining the Trophic Status of Lake Toba, North Sumatera—Indonesia. *J. Aquac. Fish Health* **2024**, *13*, 366–374. [CrossRef]
17. Gomes, A.C.; Alcântara, E.; Rodrigues, T.; Bernardo, N. Satellite estimates of euphotic zone and Secchi disk depths in a colored dissolved organic matter-dominated inland water. *Ecol. Indic.* **2020**, *110*, 105848. [CrossRef]
18. Harvey, E.T.; Walve, J.; Andersson, A.; Karlson, B.; Kratzer, S. The Effect of Optical Properties on Secchi Depth and Implications for Eutrophication Management. *Front. Mar. Sci.* **2019**, *5*, 496. [CrossRef]
19. Smith, V. Eutrophication of freshwater and coastal marine ecosystems a global problem. *Environ. Sci. Pollut. Res.* **2003**, *10*, 126–139. [CrossRef]
20. Borja, A.; Dauer, D.M. Assessing the environmental quality status in estuarine and coastal systems: Comparing methodologies and indices. *Ecol. Indic.* **2008**, *8*, 331–337. [CrossRef]
21. Heisler, J.; Glibert, P.M.; Burkholder, J.M.; Anderson, D.M.; Cochlan, W.; Dennison, W.C.; Dortch, Q.; Gobler, C.J.; Heil, C.A.; Humphries, E.; et al. Eutrophication and harmful algal blooms: A scientific consensus. *Harmful Algae* **2008**, *8*, 3–13. [CrossRef]
22. Vollenweider, R.A.; Giovanardi, F.; Montanari, G.; Rinaldi, A. Characterization of the trophic conditions of marine coastal waters with special reference to the NW Adriatic Sea: Proposal for a trophic scale, turbidity and generalized water quality index. *Environmetrics* **1998**, *9*, 329–357. [CrossRef]
23. Dell'uomo, A.; Torrisi, M. The Eutrophication/Pollution Index-Diatom based (EPI-D) and three new related indices for monitoring rivers: The case study of the river Potenza (the Marches, Italy). *Plant Biosyst. Int. J. Deal. All Asp. Plant Biol.* **2011**, *145*, 331–341. [CrossRef]
24. Alonso Fernández, J.R.; García Nieto, P.J.; Díaz Muñiz, C.; Álvarez Antón, J.C. Modeling eutrophication and risk prevention in a reservoir in the Northwest of Spain by using multivariate adaptive regression splines analysis. *Ecol. Eng.* **2014**, *68*, 80–89. [CrossRef]
25. Yu, H.; Zhao, M.; Agarwal, R.P. Stability and dynamics analysis of time delayed eutrophication ecological model based upon the Zeya reservoir. *Math. Comput. Simul.* **2014**, *97*, 53–67. [CrossRef]
26. Bonometto, A.; Ponis, E.; Cacciatore, F.; Riccardi, E.; Pigozzi, S.; Parati, P.; Novello, M.; Ungaro, N.; Acquavita, A.; Manconi, P.; et al. A New Multi-Index Method for the Eutrophication Assessment in Transitional Waters: Large-Scale Implementation in Italian Lagoons. *Environments* **2022**, *9*, 41. [CrossRef]
27. Li, W.; Ye, J.; Gao, X.; Zhang, Y.; Li, Y.; Li, H. Integrated ecological quality assessment of the sea area adjacent to the Yellow River estuary under multiple pollutants. *Front. Mar. Sci.* **2025**, *12*, 1542611. [CrossRef]
28. NEEA. *Effects of Nutrient Enrichment in the Nation's Estuaries: A Decade of Change*; National Estuarine Eutrophication Assessment: Silver Spring, MD, USA, 2007; p. 160.
29. Selman, M.; Greenhalgh, S.; Diaz, R.; Sugg, Z. Eutrophication and hypoxia in coastal areas: A global assessment of the state of knowledge. In *WRI Policy Note: Water Quality: Eutrophication and Hypoxia*; World Resources Institute: Washington, DC, USA, 2008; pp. 1–6.
30. Niu, L.; Zou, G.; Guo, Y.; Li, Y.; Wang, C.; Hu, Q.; Zhang, W.; Wang, L. Eutrophication dangers the ecological status of coastal wetlands: A quantitative assessment by composite microbial index of biotic integrity. *Sci. Total Environ.* **2022**, *816*, 151620. [CrossRef]
31. Sotto, L.P.A.; Jacinto, G.S.; Villanoy, C.L. Spatiotemporal variability of hypoxia and eutrophication in Manila Bay, Philippines during the northeast and southwest monsoons. *Mar. Pollut. Bull.* **2014**, *85*, 446–454. [CrossRef]
32. Wu, H.Y.; Chen, K.L.; Chen, Z.H.; Chen, Q.H.; Qiu, Y.P.; Wu, J.C.; Zhang, J.F. Evaluation for the ecological quality status of coastal waters in East China Sea using fuzzy integrated assessment method. *Mar. Pollut. Bull.* **2012**, *64*, 546–555. [CrossRef]
33. Thu, P.M.; Hieu, N.T.D.; Thao, P.T.P. Variation of water quality in Nha Trang Bay. *Vietnam J. Mar. Sci. Technol.* **2016**, *16*, 144–150. [CrossRef]
34. Ferreira, J.G.; Andersen, J.H.; Borja, A.; Bricker, S.B.; Camp, J.; Cardoso da Silva, M.; Garcés, E.; Heiskanen, A.-S.; Humborg, C.; Ignatiades, L.; et al. Overview of eutrophication indicators to assess environmental status within the European Marine Strategy Framework Directive. *Estuar. Coast. Shelf Sci.* **2011**, *93*, 117–131. [CrossRef]

35. Maúre, E.d.R.; Terauchi, G.; Ishizaka, J.; Clinton, N.; DeWitt, M. Globally consistent assessment of coastal eutrophication. *Nat. Commun.* **2021**, *12*, 6142. [CrossRef] [PubMed]
36. Peyman, N.; Tavakoly Sany, S.B.; Tajfard, M.; Hashim, R.; Rezayi, M.; Karlen, D.J. The status and characteristics of eutrophication in tropical coastal water. *Environ. Sci. Process. Impacts* **2017**, *19*, 1086–1103. [CrossRef] [PubMed]
37. Zhou, J.; Wang, Y.-S. A comprehensive approach to assessing eutrophication for the Guangdong coastal waters in China. *Front. Mar. Sci.* **2024**, *10*, 1280821. [CrossRef]
38. Liu, T.-K.; Chen, P.; Chen, H.-Y. Comprehensive assessment of coastal eutrophication in Taiwan and its implications for management strategy. *Mar. Pollut. Bull.* **2015**, *97*, 440–450. [CrossRef]
39. Bai, L.V. The marine environmental status in the coastal waters of south Vietnam (2002–2006). In Proceedings of the National Conference "Bien Dong 2007", Nha Trang, Vietnam, 12–14 September 2007; pp. 451–459.
40. Vinh, L.T.; Kiem, D.T.; Thu, N.H.; Tam, P.H.; Ngoc, P.H. Some remarks on water environment in Nhatrang City. In Proceedings of the National Conference "Bien Dong 2007", Nha Trang, Vietnam, 12–14 September 2007; pp. 272–280.
41. Doan, Q.T.; Nguyen, T.M.L.; Quach, T.T.T.; Tran, A.P.; Nguyen, C.D. Assessment of water quality in coastal estuaries under the impact of an industrial zone in Hai Phong, Vietnam. *Phys. Chem. Earth Parts A/B/C* **2019**, *113*, 100–114. [CrossRef]
42. Trang, C.T.T.; Thanh, T.; Thanh, T.D.; Vinh, V.D.; Tu, T.A. Assessment of the environmental carrying capacity of pollutants in Tam Giang-Cau Hai Lagoon (Vietnam) and solutions for the environment protection of the lagoon. *Sci. Total Environ.* **2021**, *762*, 143130. [CrossRef]
43. Phu, L.H.; Kim-Hong, P.T.; Chung, T.V.; Binh, T.V.; Dung, L.T.; Ngoc, P.H.; Thu, N.H.; Thu, N.T.T.; Anh, N.T.H.; Nguyen, A.L.; et al. Environmental Concerns for Sustainable Mariculture in Coastal Waters of South-Central Vietnam. *Sustainability* **2022**, *14*, 8126. [CrossRef]
44. Souda, K.; Minami, T. Analysis of water pollution in Halong Bay, Vietnam using a comprehensive water quality index. *Environ. Technol.* **2020**, *49*, 209–213. (In Japanese) [CrossRef]
45. Son, V.D. Environmental state in Mekong Delta, South of Vietnam. In Proceedings of the International Symposium on Marine Pollution, Monaco, Monaco, 5–9 October 1998; pp. 674–675.
46. Pettine, M.; Casentini, B.; Fazi, S.; Giovanardi, F.; Pagnotta, R. A revisitation of TRIX for trophic status assessment in the light of the European Water Framework Directive: Application to Italian coastal waters. *Mar. Pollut. Bull.* **2007**, *54*, 1413–1426. [CrossRef]
47. Du, H.T.; Hieu, N.M.; Kunzmann, A. Negative effects of fish cages on coral reefs through nutrient enrichment and eutrophication in Nha Trang Bay, Vietnam. *Reg. Stud. Mar. Sci.* **2022**, *55*, 102639. [CrossRef]
48. Nguyen, A.D.; Zhao, J.x.; Feng, Y.x.; Hu, W.p.; Yu, K.f.; Gasparon, M.; Pham, T.B.; Clark, T.R. Impact of recent coastal development and human activities on Nha Trang Bay, Vietnam: Evidence from a Porites lutea geochemical record. *Coral Reefs* **2013**, *32*, 181–193. [CrossRef]
49. Khuu, D.T.; Jones, P.J.S.; Ekins, P. Governance analysis of Nha Trang Bay and Cu Lao Cham Marine Protected Areas, Vietnam. *Mar. Policy* **2021**, *127*, 104330. [CrossRef]
50. Minh-Thu, P.; Sang, H.M.; Thao, L.T.T.; Hieu, N.M.; Tram, D.T.T.; Ngoc, D.T.H.; Mien, P.T. A SWOT Analysis of Aquaculture for Sustainable Management in Coastal Waters of Ba Ria—Vung Tau Province, Vietnam. *Asian J. Fish. Aquat. Res.* **2023**, *25*, 127–138. [CrossRef]
51. Giang, P.Q.; Khanal, R. What next for marine ecosystem management in Vietnam: Assessment of coastal economy, climate change, and policy implication. *Environ. Res. Commun.* **2024**, *6*, 25002. [CrossRef]
52. Huong, D.T.T.; Ha, N.T.T.; Do Khanh, G.; Van Thanh, N.; Hens, L. Sustainability assessment of coastal ecosystems: DPSIR analysis for beaches at the Northeast Coast of Vietnam. *Environ. Dev. Sustain.* **2022**, *24*, 5032–5051. [CrossRef]
53. Pham-Do, K.H.; Pham, T.T.T. Tourism in marine protected areas: A view from Nha Trang Bay, Vietnam. *Tour. Manag. Perspect.* **2020**, *33*, 100623. [CrossRef]
54. Tkachenko, K.S. Degradation of Coral Reefs under Complex Impact of Natural and Anthropogenic Factors with Nha Trang Bay (Vietnam) as an Example. *Biol. Bull. Rev.* **2023**, *13*, 442–459. [CrossRef]
55. Anh, P.T.; Kroeze, C.; Bush, S.R.; Mol, A.P.J. Water pollution by intensive brackish shrimp farming in south-east Vietnam: Causes and options for control. *Agric. Water Manag.* **2010**, *97*, 872–882. [CrossRef]
56. Khuu, D.T.; Jones, P.J.S.; Ekins, P. Development of Marine Protected Areas (MPAs) in Vietnam from a coevolutionary governance perspective: Challenges of unholy alliances between the state, businesses and NGOs. *Environ. Sci. Policy* **2023**, *149*, 103560. [CrossRef]
57. Sam, H.H.; Huan, N.H. Distribution of dissolved and particulate organic carbon in Nha Trang—Binh Cang Bay. *Collect. Mar. Res. Work.* **1998**, *8*, 86–97.
58. APHA. *Standard Methods for the Examination of Water and Wastewater*, 23rd ed.; American Public Health Association: Washington, DC, USA, 2017.
59. Jeffrey, S.W.; Mantoura, R.F.C.; Wright, S.W. *Phytoplankton Pigments in Oceanography: Guidelines to Modern Methods*; UNESCO Publishing: Paris, France, 1997; p. 661.

60. Riley, J.P.; Sinhaseni, P. The determination of ammonia and total ionic inorganic nitrogen in sea water. *J. Mar. Biol. Assoc. UK* **1957**, *36*, 161–168. [CrossRef]
61. Bower, C.E.; Holm-Hansen, T. A salicylatehypochlorite method for determining ammonia in seawater. *Can. J. Fish. Aquat. Sci.* **1980**, *37*, 794–798. [CrossRef]
62. Greenacre, M.; Groenen, P.J.F.; Hastie, T.; D'Enza, A.I.; Markos, A.; Tuzhilina, E. Principal component analysis. *Nat. Rev. Methods Primers* **2022**, *2*, 100. [CrossRef]
63. Fisher, T.R.; Peele, E.R.; Ammerman, J.W.; Harding, L.W.J. Nutrient limitation of phytoplankton in Chesapeake Bay. *Mar. Ecol. Prog. Ser.* **1992**, *82*, 51–63. [CrossRef]
64. Thom, P.V.; Tuan, V.S. Characteristics of chemistry environment and possible relation to coral reef degradation in Nha Trang bay. In Proceedings of the First National Conference on Marine Biology, Nha Trang, Vietnam, 1996; Science and Technological Publishing House: Ha Noi, Vietnam, 1996; pp. 54–61.
65. Arrigo, K.R. Marine microorganisms and global nutrient cycles. *Nature* **2005**, *437*, 349–355. [CrossRef]
66. Nixon, S. Eutrophication and the macroscope. In *Eutrophication in Coastal Ecosystems. Developments in Hydrobiology*; Andersen, J.H., Conley, D.J., Eds.; Springer: Dordrecht, The Netherlands, 2009; Volume 207, pp. 5–19.
67. Nixon, S. Coastal marine eutrophication: A definition, social causes, and future concerns. *Ophelia* **1995**, *41*, 199–219. [CrossRef]
68. Anderson, D.M.; Glibert, P.M.; Burkholder, J.M. Harmful algal blooms and eutrophication: Nutrient sources, composition, and consequences. *Estuaries* **2002**, *25*, 704–726. [CrossRef]
69. Wurtsbaugh, W.A.; Paerl, H.W.; Dodds, W.K. Nutrients, eutrophication and harmful algal blooms along the freshwater to marine continuum. *WIREs Water* **2019**, *6*, e1373. [CrossRef]
70. Paerl, H.W.; Hall, N.S.; Calandrino, E.S. Controlling harmful cyanobacterial blooms in a world experiencing anthropogenic and climatic-induced change. *Sci. Total Environ.* **2011**, *409*, 1739–1745. [CrossRef]
71. Smith, V.H.; Tilman, G.D.; Nekola, J.C. Eutrophication: Impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. *Environ. Pollut.* **1999**, *100*, 179–196. [CrossRef] [PubMed]
72. Howarth, R.W. Coastal nitrogen pollution: A review of sources and trends globally and regionally. *Harmful Algae* **2008**, *8*, 14–20. [CrossRef]
73. He, Y.; Zhang, P.; Xu, F.; Zhao, L.; Zhang, J. Seasonal nutrients variation, eutrophication pattern, and Chlorophyll a response adjacent to Guangdong coastal water, China. *Front. Mar. Sci.* **2023**, *10*, 1236609. [CrossRef]
74. Pérez-Ruzafa, A.; Campillo, S.; Fernández-Palacios, J.M.; García-Lacunza, A.; García-Oliva, M.; Ibañez, H.; Navarro-Martínez, P.C.; Pérez-Marcos, M.; Pérez-Ruzafa, I.M.; Quispe-Becerra, J.I.; et al. Long-Term Dynamic in Nutrients, Chlorophyll a, and Water Quality Parameters in a Coastal Lagoon During a Process of Eutrophication for Decades, a Sudden Break and a Relatively Rapid Recovery. *Front. Mar. Sci.* **2019**, *6*, 26. [CrossRef]
75. Glibert, P.M.; Burkholder, J.M. The Complex Relationships Between Increases in Fertilization of the Earth, Coastal Eutrophication and Proliferation of Harmful Algal Blooms. In *Ecology of Harmful Algae*; Granéli, E., Turner, J.T., Eds.; Springer: Berlin/Heidelberg, Germany, 2006; Volume 189, pp. 341–354.
76. Boynton, W.R.; Garber, J.H.; Summers, R.; Kemp, W.M. Inputs, transformations, and transport of nitrogen and phosphorus in Chesapeake Bay and selected tributaries. *Estuaries* **1995**, *18*, 285–314. [CrossRef]
77. Diaz, R.J.; Rosenberg, R. Spreading Dead Zones and Consequences for Marine Ecosystems. *Science* **2008**, *321*, 926–929. [CrossRef]
78. Chapman, D. *Water Quality Assessments—A Guide to Use of Biota, Sediments and Water in Environmental Monitoring—Second Edition*; UNESCO/WHO/UNEP: Cambridge, UK, 1996; p. 656.
79. Anderson, D.M.; Burkholder, J.M.; Cochlan, W.P.; Glibert, P.M.; Gobler, C.J.; Heil, C.A.; Kudela, R.M.; Parsons, M.L.; Rensel, J.E.J.; Townsend, D.W.; et al. Harmful algal blooms and eutrophication: Examining linkages from selected coastal regions of the United States. *Harmful Algae* **2008**, *8*, 39–53. [CrossRef]
80. Borja, A.; Ranasinghe, A.; Weisberg, S.B. Assessing ecological integrity in marine waters, using multiple indices and ecosystem components: Challenges for the future. *Mar. Pollut. Bull.* **2009**, *59*, 1–4. [CrossRef]
81. Luo, Y.; Liu, J.-W.; Wu, J.-W.; Yuan, Z.; Zhang, J.-W.; Gao, C.; Lin, Z.-Y. Comprehensive Assessment of Eutrophication in Xiamen Bay and Its Implications for Management Strategy in Southeast China. *Int. J. Environ. Res. Public Health* **2022**, *19*, 13055. [CrossRef]
82. Gooday, A.J.; Jorissen, F.; Levin, L.A.; Middelburg, J.J.; Naqvi, S.W.A.; Rabalais, N.N.; Scranton, M.; Zhang, J. Historical records of coastal eutrophication-induced hypoxia. *Biogeosciences* **2009**, *6*, 1707–1745. [CrossRef]
83. Wang, Y.; Liu, D.; Xiao, W.; Zhou, P.; Tian, C.; Zhang, C.; Du, J.; Guo, H.; Wang, B. Coastal eutrophication in China: Trend, sources, and ecological effects. *Harmful Algae* **2021**, *107*, 102058. [CrossRef] [PubMed]
84. Camargo, J.A.; Alonso, Á. Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: A global assessment. *Environ. Int.* **2006**, *32*, 831–849. [CrossRef] [PubMed]
85. Tuan, V.S. Biodiversity dynamics of coral reefs in Nha Trang Bay and management measures. In Proceedings of the National Conference on Marine Science and Technology: Volume 4—Marine Biology and Resources, Ha Noi, Vietnam, April 2011; pp. 29–39.

86. Bai, L.V. Environmental status in the coastal waters of South Vietnam (1996–2002). *Collect. Mar. Res. Work.* **2003**, *13*.
87. Antoine, D.; Andre, I.M.; Morel, A. Oceanic primary production 2: Estimation at global scale from satellite (Coastal Zone Color Scanner) chlorophyll. *Glob. Biochem. Cycles* **1996**, *10*, 57–69. [CrossRef]
88. Aguilar-Manjarrez, J.; Nath, S.S. *A Strategic Reassessment of Fish Farming Potential in Africa*; FAO: Rome, Italy, 1998; p. 170.
89. Allen, J.I.; Somerfield, P.J. A multivariate approach to model skill assessment. *J. Mar. Syst.* **2009**, *76*, 83–94. [CrossRef]
90. Primpas, I.; Tsirtsis, G.; Karydis, M.; Kokkoris, G.D. Principal component analysis: Development of a multivariate index for assessing eutrophication according to the European water framework directive. *Ecol. Indic.* **2010**, *10*, 178–183. [CrossRef]
91. Shin, P.K.S.; Lam, W.K.C. Development of a Marine Sediment Pollution Index. *Environ. Pollut.* **2001**, *113*, 281–291. [CrossRef]
92. Morsy, A.; Ebeid, M.; Soliman, A.; Halim, A.A.; Ali, A.E.; Fahmy, M. Evaluation of the water quality and the eutrophication risk in Mediterranean sea area: A case study of the Port Said Harbour, Egypt. *Environ. Chall.* **2022**, *7*, 100484. [CrossRef]
93. Hughes, B.B.; Haskins, J.C.; Wasson, K.; Watson, E. Identifying factors that influence expression of eutrophication in a central California estuary. *Mar. Ecol. Prog. Ser.* **2011**, *439*, 31–43. [CrossRef]
94. Wu, J.; Tang, D. Correlation Model-Based Principal Component Analysis on the Application on Water Body Eutrophication Evaluation. In Proceedings of the 3rd International Conference on Bioinformatics and Biomedical Engineering, Granada, Spain, 11–13 June 2009; pp. 1–4.
95. Tac-An, N. *The Contamination Status in Coastal Zone of NhaTrang Bay. The Ecological Effects and Preventive Means*; Institute of Oceanography: Nha Trang, Vietnam, 1996; p. 128.
96. Tac-An, N.; Minh-Thu, P.; Cherbadji, I.I.; Propp, M.V.; Odintsov, V.S.; Propp, L.H. Primary production of coral ecosystems in the Vietnamese coastal and adjacent marine waters. *Deep. Sea Res. Part II Top. Stud. Oceanogr.* **2013**, *96*, 56–64. [CrossRef]
97. Linh, V.T.T.; Kiem, D.T.; Ngoc, P.H.; Phu, L.H.; Tam, P.H.; Vinh, L.T. Coastal sea water quality of Nha Trang bay, Khanh Hoa, Viet Nam. *J. Shipp. Ocean Eng.* **2015**, *5*, 123–130.
98. Du, H.T.; Kunzmann, A. The sediment load and deposition by river discharge and their relation to organochlorine pesticides pollutants in the sediment bottom of Nha Trang Bay, Vietnam. *Ocean Sci. J.* **2015**, *50*, 455–466. [CrossRef]
99. Thi, V.H.; Tac-An, N.; Huong, L.H. Sediment quality assessment of some marine ports in Nha Trang Bay by biotoxycity testing. In Proceedings of the National Conference "Bien Dong 2007", Nha Trang, Vietnam, 12–14 September 2007; pp. 182–186.
100. Phuong, T.T.M. Bioaccumulation of Heavy Metals in Nha Trang bay, Khanh Hoa, Viet Nam. Ph.D. Thesis, Université Nice Sophia Antipolis, Nice, France, 2014.
101. Giao, N.T.; Dien, N.T.C.; Nguyen, H.T.; Nhu, T.N.; Mi, L.T.D.; Nhien, H.T.H. Evaluating Relationship between Surface Water Quality and Zooplankton Diversity in Coastal Areas of Tien Giang Province, Vietnam. *J. Appl. Sci. Environ. Manag.* **2024**, *28*, 841–851. [CrossRef]
102. Tkachenko, K.S.; Britayev, T.A.; Huan, N.H.; Pereladov, M.V.; Latypov, Y.Y. Influence of anthropogenic pressure and seasonal upwelling on coral reefs in Nha Trang Bay (Central Vietnam). *Mar. Ecol.* **2016**, *37*, 1131–1146. [CrossRef]

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