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Assessing the Impacts of Dike Systems on Water Quality in Natural Reserves of the Vietnamese Mekong Delta

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Abstract: Protected places such as nature reserves (NRs) are used to maintain ecological balance, biodiversity, and support surrounding ecosystems. However, the development and operation of infrastructure such as dikes and sluice gates in NRs, as seen in the Vietnamese Mekong Delta (VMD), often adversely affects the hydrological regime and water quality at both local and regional scales. This study analyzes the consequences of a constructed dike system on the hydrological regime and water quality in the NRs through an integrated approach including hydrochemical analysis (using descriptive statistics and weighted arithmetic water quality index (WAWQI) analysis), traditional interviews (face to face), using semi-structured questionnaires, field surveys, and secondary data. Results show that constructed infrastructure has helped maintain water supplies for both livelihoods and forest fire prevention. However, considerable impacts on the hydrological regime and water quality have occurred. From water quality assessments in three NRs, 29% of sampling sites in the My Phuoc melaleuca forest (MPMF) had WAWQI values over 100, while all sites in Lung Ngoc Hoang NR (LNHNR) and Mua Xuan Agriculture Center (MXAC) had WAWQI values over 100. This was to a large extent due to elevated concentration of chemical oxygen demand (COD), biological oxygen demand (BOD_5), and phosphate (PO_4^{3-}). Meanwhile, during the wet season, pollution was marginally reduced by dilution, with 42.86% of sites at Lung Ngoc Hoang NR, 28.57% of sites at MXAC, and 78.57% of sites at MPMF having WAWQI values of less than 100. These results show the issue of water pollution at spatio-temporal scales, and call for better holistic management options for improving the hydrological regime and water quality.

Keywords: Lung Ngoc Hoang Nature Reserve; WAWQI; water pollution; Mua Xuan Agriculture Center; My Phuoc melaleuca forest

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1. Introduction

The water resources of the Vietnamese Mekong Delta (VMD) are vulnerable to both anthropogenic and natural changes, affecting both the quantity and quality of the hydrological regime [1–3]. Furthermore, recent socioeconomic development and transformation of the delta has resulted in increased agricultural and aquaculture production; increased pollution; urban sprawl; and a scarcity of human, financial, and technical resources, which in turn have led to poor governance and challenges to nature protection and biodiversity conservation efforts. The state management of some fields between local and central government has shown overlapping issues and lacks close cooperation [4]. The most recent climate change scenarios for Vietnam forecast a sea level rise of between 0.75 to 1 m by year 2100. This would inundate about 20–38% of the VMD, seriously affecting 27% of Vietnam's listed critical natural habitats, 33% of protected areas, 23% of nationally and internationally important biodiversity sites, and 23 other important conservation sites. As the largest nature reserve (NR) in the VMD, Lung Ngoc Hoang Nature Reserve (LNHNR) is a wetland NR located in Phuong Binh commune, Phung Hiep district, Hau Giang province with a total area of ~3000 ha. LNHNR was created between the two ecological zones, west of Hau River (Bassac River) and Ca Mau Peninsula. The LNHNR was formed from the process of sea retreat, and exhibits rich alluvial accretion with mainly coastal sediments and swamps, leading to a low and quite flat topography dissected by a system of canals. The LNHNR was formed with the objectives of safeguarding a habitat for different species, maintaining the ecological balance, maintaining and increasing forest cover, and safeguarding the sustainable development of the VMD [5].

However, the construction and operation of hard engineering infrastructure aimed at regulating water in order to store water into channel to prevent the forest fires, such as dikes and sluices, has resulted in changes in tidal fluctuation and flow directions. Additionally, the conversion of forest land to agriculture has contributed to the above changes, as melaleuca forests are known to play an important role in ecosystem conservation and water regulation. Initially, sluices and dikes were erected as part of short-term plans to preserve water for forest fire prevention. However, after a short period of time, the water regime has changed; it no longer follows the natural tidal flow and is solely dependent on the structure's operation. To assess the spatial and temporal dynamics of water quality, the water quality index (WQI) is one of the most utilized and reliable used tools worldwide [6] Additional index systems, such as the National Sanitation Foundation Water Quality Index (NSFWQI) and the Canadian Council of Ministers of the Environment Water Quality Index (CCMEWQI), Oregon Water Quality Index (OWQI), and weighted arithmetic water quality index (WAWQI) are also widely used [7–12]. The WAWQI is a multi-objective decision-making method, and has been widely used in the assessment and management of water quality in developing countries [7,13–15].

To date, no studies have been conducted to assess the impacts of natural and anthropogenic factors on the hydrological regimes and water quality in the nature reserves of Vietnam. Considering the above-mentioned information gap and necessity, this study aimed to assess the impacts of infrastructure development in the LNHNR and its surrounding areas using an integrated hybrid approach of hydrochemical analysis, WAWQI development, and household surveys.

2. Materials and Methods

Current analysis of water quality parameters was undertaken as representative of the current situation post dike and sluice construction. However, as no past data on water quality parameter were available previous to construction, household surveys were conducted to understand the situation before the construction and operation of engineered solutions and to quantify differences.

2.1. Materials

2.1.1. Apparatus and Chemicals

GPS navigation device, thermometer, pH meter, multiparameter probe, turbidity meter, HCl (0.05 M).

2.1.2. Study Area

The Lung Ngoc Hoang Nature Reserve (LNHNR), Mua Xuan Agriculture Center (MXAC), and My Phuoc melaleuca forest (MPMF) were chosen as three case study areas. They can be seen in Figure 1.

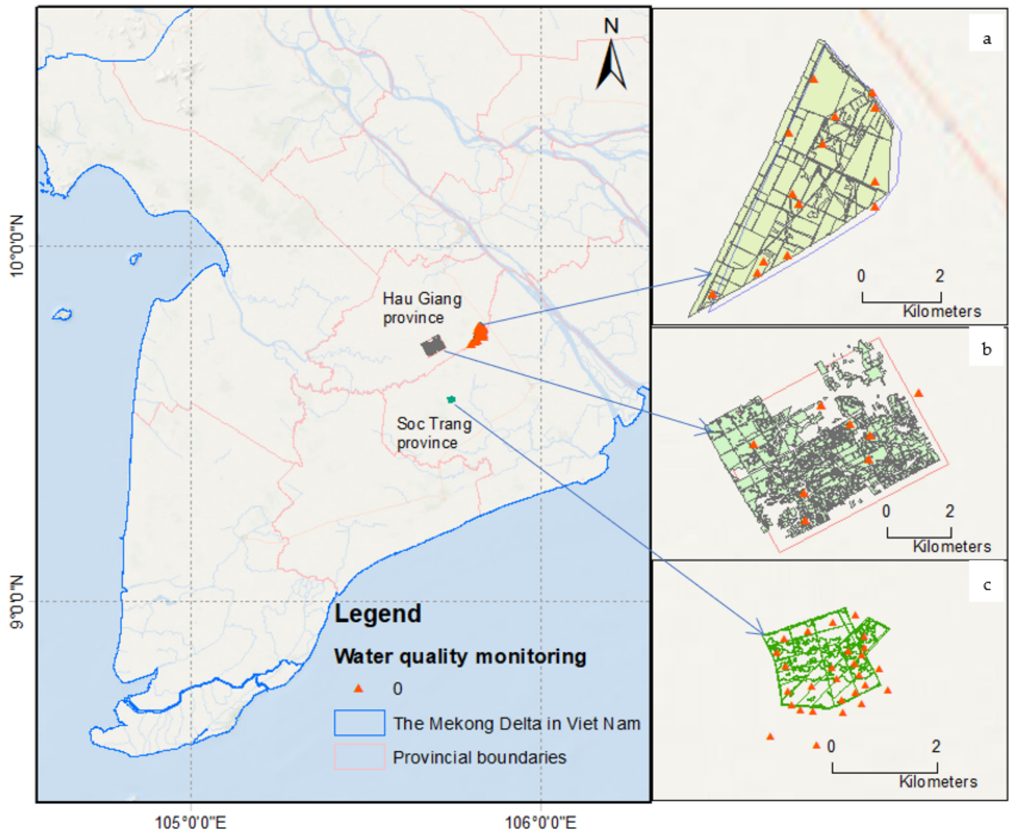


Figure 1. Location map of the studied wetland areas of MXAC (**a**), LNHNR (**b**), and My Phuoc Maleuleca Forest (MPMF) (**c**).

The Lung Ngoc Hoang Nature Reserve (LNHNR) is a species habitat protection area with a total area of approximately 3000 ha, in which functional subdivisions include: a Strict Protection Zone (1000 ha), Ecological Restoration Zone (1000 ha), and Administrative Service Subdivision (400 ha). The LNHNR is a low-lying area located southwest of the Hau River that borders the Lai Hieu, Quan Lo, Xang Bo, and Xeo Xu canal systems. The MXAC has a total natural area of 1500 ha and is located in Tan Phuoc Hung Commune, Phung Hiep District, Hau Giang province. The MXAC's hydrological regime is primarily influenced by the Quan Lo and Soc Trang canals. The MPMF is alluvial land located along the My Thanh River in My Phuoc commune, My Tu district, Soc Trang Province. The MPMF is located on a low plain with an elevation of only 0.2 m AMSL. The climate of the MPMF is mild in the sub-equatorial monsoon tropical region, and has an average temperature of 27 °C and total rainfall of 1100 mm. Due to the influence of tides, the water in the MPMF is typically salinized to a high degree during the dry season (from December to April).

2.2. Methodology

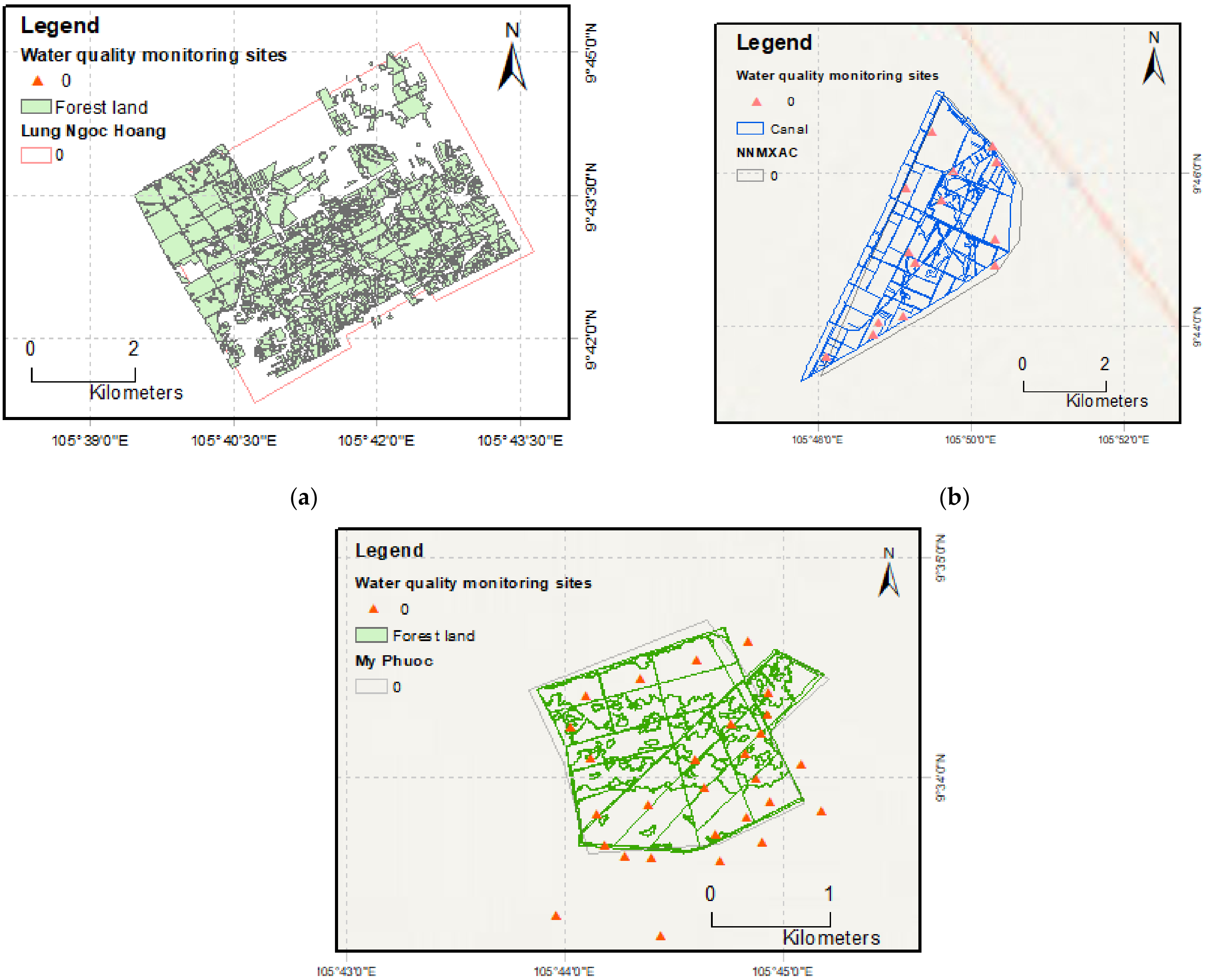
2.2.1. Water Sampling

Water samples were collected from 8, 14, and 28 different points from the LNHNR, MXAC, and MPMF respectively, distributed randomly across the NRs' canal systems (Figure 1).

Prior to the sampling, 1000 mL capacity plastic bottles were soaked overnight in a solution of HCl (0.05 M), washed thoroughly the next day, and rinsed several times with distilled water before being sun-dried. Each water sample was collected at a depth of 20–30 cm in the canal from random and homogenous locations. Samples were collected twice/year, i.e., during the wet and dry seasons of the year 2016 (at LNHNR, MXAC) and 2018 (at MPMF). On-site measurements of temperature, DO, pH, and electrical conductivity were carried out using multi-probe meters [16–18]. The turbidity was determined via three sub-samples of 10 mL (the maximum capacity of the turbidimeter model Tub-430) within glass containers of different sizes and calculating the average of the three subsamples [19]. All samples that were not measured on-site were stored at 4 °C under laboratory conditions and analyzed within 24 h for parameters [20].

2.2.2. Data Collection

Random water sampling was done from various canal system locations and habitat types in the areas shown in Figures 2 and 3. Table 1 additionally displays information about surface water sampling locations including their coordinates.



(a) (b)

(c)

Figure 2. Water sampling locations at (**a**) Lung Ngoc Hoang Natural Reserve; (**b**) Mua Xuan Agriculture Center; (**c**) My Phuoc melaleuca forest.

Figure 3. Location sampling at MPMF. (**a**) Melaleuca habitat, (**b**) wetland, (**c**) Nypa fruticans habitat, (**d**) canal habitat, (**e**) buffer zone.

Primary data was collected from direct interviews through semi-structured questionnaires. In total, in the LNHNR, MXAC and MPMF 120, 105, and 200 households were interviewed, respectively). The targeted households were in hamlets adjacent to melaleuca forests. Other interviewees were from diverse fields, including local stakeholders such as authorities, forestry staff, and management staff of the NRs. Households participating in the interviews were randomly selected without classification of household economic conditions and occupations, and were divided into 6 groups: (1) rice-growers; (2) growers of other crops and breeders of livestock (or a combination); (3) inhabitants of the melaleuca forest; (4) non-agricultural service workers in agricultural product processing, trade, machinery repair, etc.; (5) staff with stable salary/jobs (local governance staff); and (6) irregular employees receiving daily wages. Comparison of before and after the construction of irrigation infrastructure was done to assess the impact of irrigation construction on livelihoods, water quality, and quality of irrigation construction. As a result, the study employed a closed-question structure to classify the impacts of dyke and sluice gates on livelihoods (based on the annual average income). The following terminologies were used to quantify the impact. (a) "Good" means that the interviewee's family income increased compared to that before the irrigation construction; (b) "Not good/not bad" means that the interviewee's family's income did not change before and after irrigation construction; and (c) "Bad" means the interviewee's family income further reduced compared to that before the construction of irrigation infrastructure; (d) "Clean" means water quality improved post-installation of irrigation infrastructures compared to that pre-installment; (e) "Pollution" means water quality deteriorated a bit after the installation; (f) "More pollution" means water quality deteriorated a lot after the infrastructure's installation. Finally, in terms of the current water quality in the canal system, five different options, viz., "Very good", "Good", "Permissible", "Not good", and "No opinion" represented the different levels of consumers' satisfaction.

Table 1. Sample Location Specifications with Global Positioning System (GPS) coordinates. Seasonal samples were collected in 2016 and 2018.

Sample ID *	Sampling Site	Sample ID *	Sampling Site
	Locational Features		**Locational Features**
L1	Level 2 canal (TKII canal, plot 88)	P1	Canal habitat
L2	Sub-branch canal (plot 85)	P2	*Nypa fruticans* habitat
L3	Sub-branch canal (plot 27)	P3	Canal habitat
L4	Sub-branch canal (plot 5, plot 32)	P4	Control canal in buffer zone
L5	Level 2 canal (plot 1, plot 7)	P5	Control canal in buffer zone surrounded by the trees and *Acacia auriculiformis*
L6	Sub-branch canal (plot 45)	P6	Canal habitat surrounded by tropical hornwort, *Ipomoea aquatic*, *Eichhornia crassipes*
L7	Level 1 canal (Hau Giang 3 canal, plot 48)	P7	*Nypa fruticans* habitat
L8	Level 1 canal (Phung Hiep canal)	P8	Canal habitat
T1	Melaleuca habitat	P9	Canal habitat
T2	Melaleuca habitat	P10	Wetland habitat
T3	Melaleuca habitat	P11	Melaleuca habitat
T4	Melaleuca habitat	P12	Melaleuca habitat
T5	Melaleuca habitat	P13	Melaleuca habitat with floating membrane surrounded by *Melaleuca*, *Nypoideae*
T6	Melaleuca habitat	P14	Melaleuca habitat surrounded by tropical hornwort, *Annona glabra*, *Melaleuca*, *Nypoideae*
T7	Melaleuca habitat	P15	Canal habitat with *Eichhornia crassipes*
T8	Melaleuca habitat	P16	Canal habitat with *Eichhornia crassipes*
T9	Melaleuca habitat	P17	Canal habitat
T10	Paddy habitat	P18	Canal habitat with *Eichhornia crassipes*
T11	Paddy habitat	P19	Canal habitat with membrane and *Eichhornia crassipes*
T12	Sugarcane habitat	P20	*Nypa fruticans* habitat
T13	Sugarcane habitat	P21	*Nypa fruticans* habitat
T14	Sugarcane habitat	P22	Canal habitat surrounded by *Eichhornia crassipes*, *Stenochlaena palustris Annona glabra*

Table 1. *Cont.*

Sample ID *	Sampling Site	Sample ID *	Sampling Site
	Locational Features		Locational Features
-	-	P23	Canal habitat, surrounded by *Pistia stratiotes L*, *Stenochlaena palustris Annona glabra*, *Neptunia oleracea*
-	-	P24	Canal habitat with *Eichhornia crassipes Annona glabra*,
-	-	P25	Canal habitat with *Annona glabra*, *Stenochlaena palustris*, *Eichhornia crassipes*
-	-	P26	Level 1 canal
-	-	P27	*Nypa fruticans* habitat with tropical hornwort, *Eichhornia crassipes*, *Pistia stratiotes L*,
-	-	P28	Canal habitat with *Eichhornia crassipes*, tropical hornwort

L: Lung Ngoc Hoang Natural Reserve; T: Mua Xuan Agriculture Center; P: My Phuoc melaleuca forest; Sample ID * is used in the subsequent tables.

2.3. Data Analysis

2.3.1. Descriptive Statistics Method

The collected surface water quality data from the LNHNR, MXAC, and MPMF were processed using Microsoft Excel software using descriptive statistics and WQI. Water quality parameters including temperature, pH, electrical conductivity (EC), and dissolved oxygen (DO) were measured directly on-site using handheld devices. Samples for chemical oxygen demand (COD), biological oxygen demand (BOD), total suspended solids (TSS), nitrogen nitrate (NO_3^- -N), and ammonium orthophosphate (PO_4^{3-} -P) were collected, properly stored, and transported to the laboratory for the analysis using standard methods.

2.3.2. Water Quality Assessment

The index classifies water quality according to the degree of water purity by using the most commonly measured water quality variables; WQI was calculated to evaluate the suitability of water quality. Scientific communities have employed this approach extensively in water-related research works [2,21–29]. According to theory, WAWQI was calculated via the weightage of water quality parameters by the Equations (1)–(3) [2,7,22–31]; the rating of water quality according to WAWQI is given in Table 2 [29]:

$$Q_i = \left[\frac{(V_i - V_{di})}{(S_i - V_{di})}\right] \times 100 \quad (1)$$

$$W_i = \frac{K}{S_i} = \frac{\frac{1}{\sum_{i=1}^{n} 1/S_i}}{S_i} \quad (2)$$

$$WAWQI_i = \frac{\sum_{i=1}^{n} Q_i \times W_i}{\sum_{i=1}^{n} W_i} \quad (3)$$

where V_i is the estimated value of ith parameter, V_{di} is the ideal value of ith parameter in pure water (pH = 7 and all other parameters equal to zero), S_i is the permissive standard of ith parameter, W_i is the weightage of ith parameter and K is a proportionality constant.

The WAWQI has the following merits: 1. it incorporates data from multiple water quality parameters into a mathematical equation that quantitively rates the health of a water body; 2. it also requires fewer parameters in comparison to all water quality parameters for particular uses; 3. it is useful for the communication of overall water quality information to concerned citizens and policy makers alike; 4. it reflects the composite influence of different parameters, i.e., those that are important in the assessment and management of water quality; 5. it describes the suitability of both surface and groundwater sources for human consumption.

Table 2. Classification of Weighted Arithmetic Water Quality Index.

Range of WAWQI	Classification of Water Quality
<25	Excellent
26–50	Good
51–75	Poor
76–100	Very poor
>100	Unsuitable for drinking

The weighted arithmetic water quality index (WAWQI) was used as a standard indicator for classifying water quality status (Table 3).

Table 3. Water parameters for WAWQI calculation [30]. (QCVN 08-MT:2015/BTNMT, Column A1-Ministry of Natural Resources and Environment-Vietnam Environment Directorate).

No	Parameters	Standard (S_i)	Units
1	pH	8.5	
2	EC	300 **	μS/cm
3	COD	10	mg/L
4	PO_4^{3-}	0.1	mg/L
5	BOD_5	4	mg/L
6	DO	6	mg/L
7	NO_3^-	2	mg/L
8	NH_4^+	0.3	mg/L
9	TSS	20	mg/L
10	Fe	0.5	Mg/L

** ICMR (1975) [31–33].

3. Results and Discussions

3.1. Hydrological Regime in LNHNR

Figures 4 and 5 show the change in the infrastructure distribution and the flow directions in the LNHNR for the years 2015 and 2020, respectively. It can be seen that increased infrastructure in the year 2020, such as bridges, sluices, and pumping stations, were built for regulating, exchanging, and supplying water to the LNHNR. The construction of infrastructure was considered to have a positive impact on the surrounding community by 48.39% of interviewee respondents (Figure 6). However, 6.45% disagreed, mentioning that sluices were closed to store water for the fire protection work in the dry season, resulting in a lack of water for farming and aquaculture. Moreover, the lack of water also affected the quality of water sources in the LNHNR, which was evaluated sensorily by people living in the LNHNR as summarized in Figure 7. This is because the closed sluices in the dry season could restrict the flow out to the LNHNR, resulting in no exchange of water inside and outside the LNHNR, affecting both the quality and quantity of the water. Additionally, the biological decomposition of plants contributed to a decrease in the water quality, causing a black color at the end of the dry season.

The hydrological regime in the LNHNR is influenced by the diurnal and semi-diurnal tides of the West Sea and East Seas. The Cai Con and Cai Lon-Cai Be rivers in the East and West Sea, respectively, as well as well-planned canals, provide adequate water to the LNHNR. Figure 8 presents the current status of the canal system based on the assessments of people living in the LNHNR, in which 61% of respondents rated it good or very good, while 26% rated it permissible and 10% rated it not good.

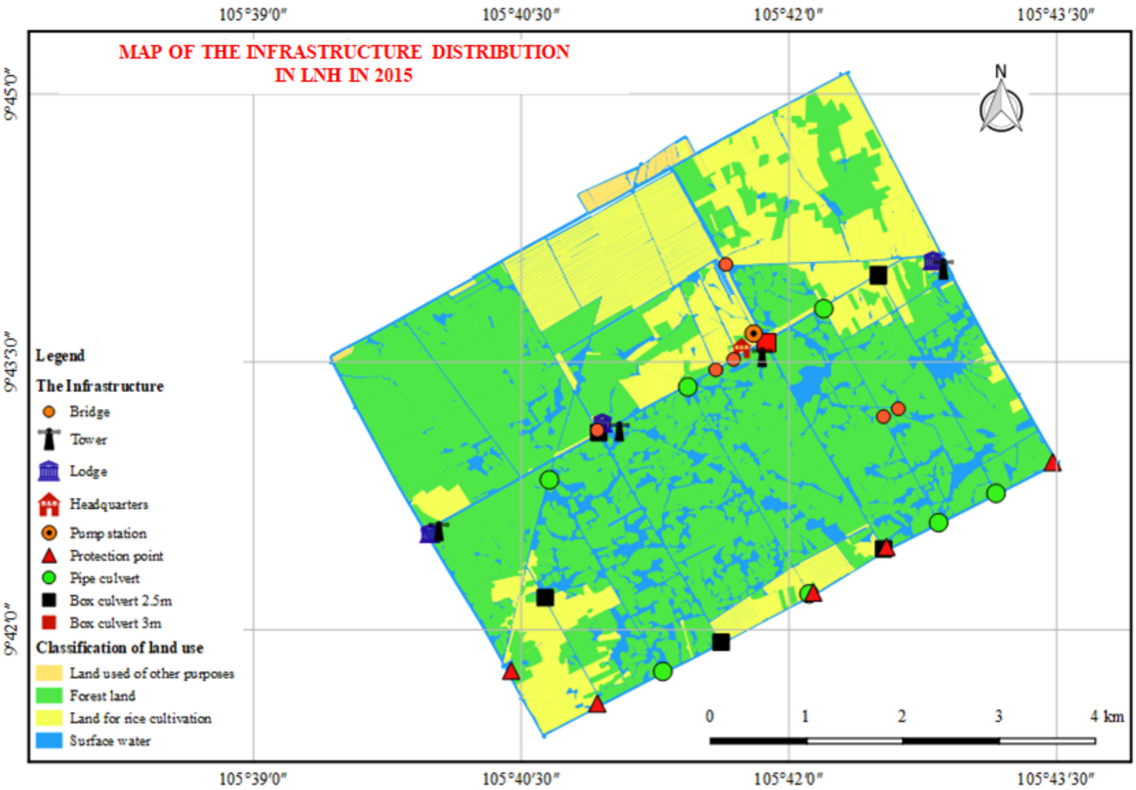


Figure 4. Infrastructure distribution in LNHNR in 2015.

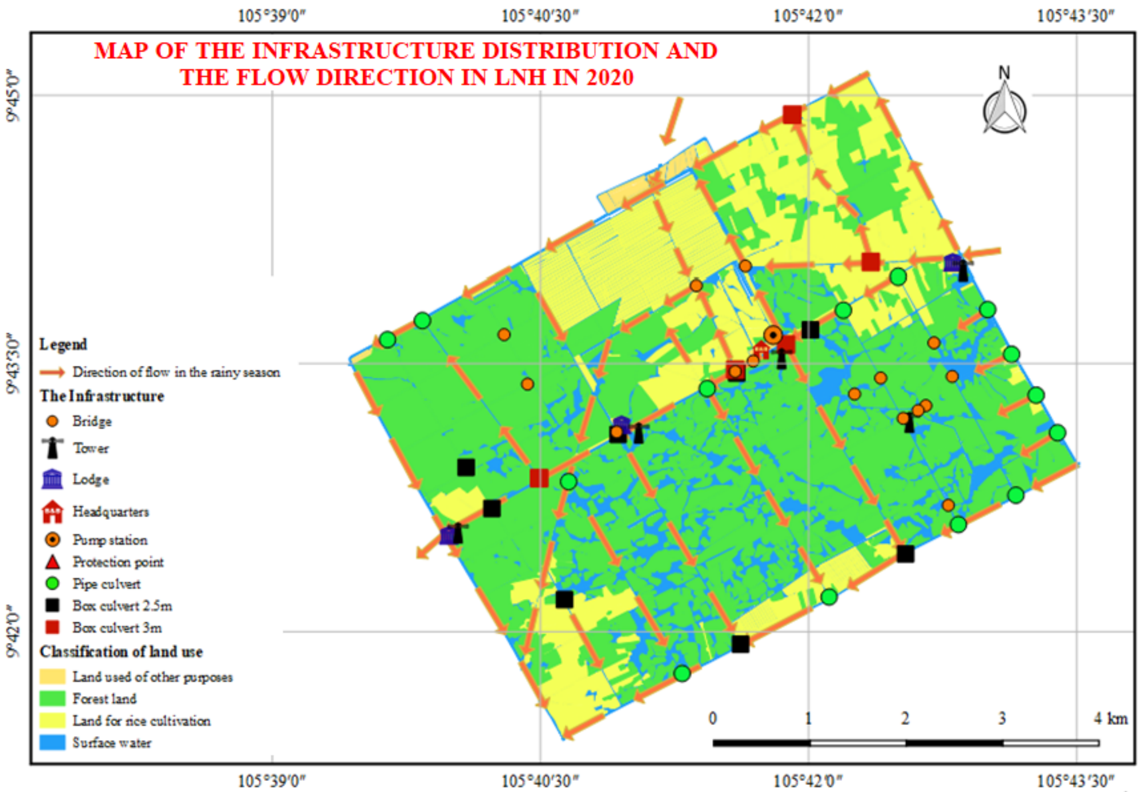


Figure 5. Map of the infrastructure distribution and the flow directions in LNHNR in 2020.

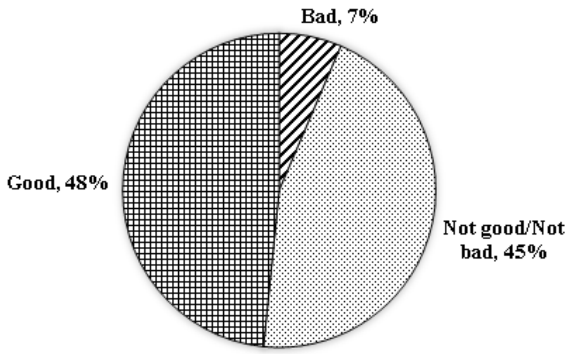


Figure 6. Interview results of the assessment of the impact of construction projects on people's livelihoods in the surrounding community.

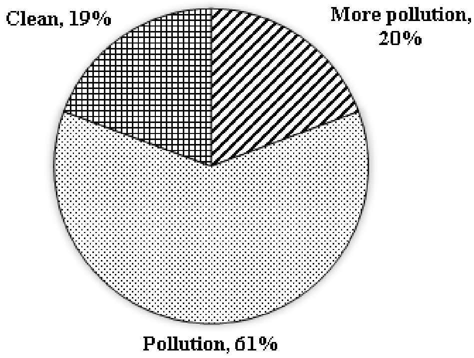


Figure 7. Sensory assessment of water quality in the study area quality in LNHNR.

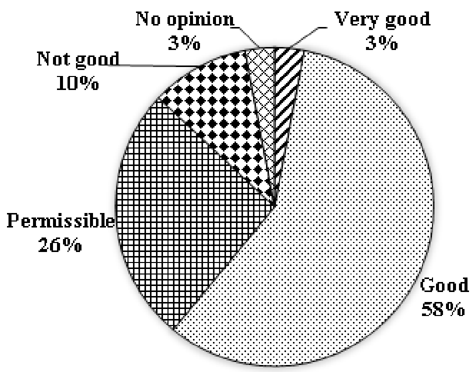


Figure 8. Interview results on the quality of irrigation systems in LNHNR.

3.2. Weighted Arithmetic Water Quality Index

According to the calculations, the WAWQI value in 2016 showed a discrepancy between ranks. Water quality index readings at locations ranged from 58 (L3) to 201 (L6) during the wet season, and from 107 (L4 point) to 375 (L1 point) during the dry season (Tables 4 and 5 and Figure 9).

During the dry season, the WAWQI water quality levels highlight an extremely polluted status (WAWQI $\geq$ 100). By contrast, the WAWQI values in the rainy season ranged from 58, 73, to 95, corresponding to light and moderate pollution levels, respectively. Although the remaining values remain at heavy pollution levels, their values are still lower than those in the dry season. The water quality index in L3, L4, and L5 sample locations were lower than those in other locations, because those sites are located in the core zone of the melaleuca forest, far from residential areas. In the dry season, the WAWQI index in L1 and L8 was above 300, owing to high phosphate P-PO_4^{3-} (0.39 mg/L and 0.36 mg/L) concentrations of 3.5–4 times the standard (0.1 mg/L). This can be explained by the fact that point L1 was a small canal area where the flow was close to stagnant, leaving plant residues, whereas position L8 was in a densely populated area where the surface water contained a lot of phosphate from household waste. Most of the indicators at the survey sites were below the acceptable national standards, such as a high EC (264.67–323 $S.cm^{-1}$), the DO indicator below standard (≥6.0 mg/L), the COD indicator at only one qualified position (L7), the BOD_5 indicator exceeding the standard by 1.09–2.93 times, and the $P\text{-}PO_4^{3-}$ indicator exceeding the standard by 1.1–3.9 times. The results clearly show that the NRs' surface water quality was polluted throughout both the wet and dry seasons.

Table 4. Calculation of the WAWQI for the LNHNR in the 2016 Wet Season.

Sample ID *	EC	pH	COD	PO_4^{3-}	BOD_5	DO	WAWQI
	μS/cm		mg/L				
QCVN 08-MT:2015/BTNMT (Column A1)	**300 ****	**6.5–8.5**	**10**	**0.1**	**4**	**6**	
L1	276	6.94	11.28	0.18	4.85	4.73	178
L2	278	7.02	12.73	0.12	5.48	3.25	116
L3	274	7.03	16.78	0.05	7.22	3.83	58
L4	291	6.96	19.17	0.07	8.24	3.09	73
L5	272	6.94	23.20	0.09	9.98	3.65	95
L6	297	6.80	22.40	0.20	9.63	4.11	201
L7	265	7.16	7.74	0.11	3.33	4.79	105
Descriptive Statistics							
Maximum	297	7.16	23.20	0.20	9.98	4.79	201
Minimum	265	6.80	7.74	0.05	3.33	3.09	58
Mean	279	6.97	15.98	0.12	6.87	4.00	123
SD	10	0.09	5.08	0.05	2.19	0.61	48

* Sample ID is mentioned in Table 2 with specific locations; ** ICMR (1975); SD = standard deviation.

Table 5. Calculation of the WAWQI for the LNHNR in the 2016 Dry Season.

Sample ID *	EC	pH	COD	PO_4^{3-}	BOD_5	DO	WAWQI
	μS/cm		mg/L				
QCVN 08-MT:2015/BTNMT (Column A1)	**300 ****	**6.5–8.5**	**10**	**0.1**	**4**	**6**	
L1	306.80	7.17	10.17	0.39	4.37	4.33	375
L2	301.40	7.19	14.43	0.24	6.21	2.67	236
L3	275.73	7.16	18.07	0.16	7.77	2.72	156
L4	309.00	7.01	14.60	0.11	6.28	3.11	107
L5	284.43	7.20	27.27	0.17	11.72	5.38	168
L6	316.10	7.17	15.87	0.16	6.82	4.70	160
L7	323.00	7.14	8.83	0.21	3.80	4.84	202
Descriptive Statistics							
Maximum	323.00	7.20	27.27	0.39	11.72	5.38	375
Minimum	275.73	7.01	8.83	0.11	3.80	2.67	107
Mean	301.50	7.15	15.63	0.23	6.72	4.03	219
SD	14.79	0.06	5.24	0.10	2.25	0.98	89

* Sample ID is mentioned in Table 2 with specific locations; ** ICMR (1975); SD = standard deviation.

Tables 6 and 7 and Figure 10 show the calculation of WAWQI values in the MXAC. It should be noted that the WAWQI values ranged from 134 (T11) to 7344 (T10) in the dry season to roughly 82 (T11) to 272 (T13) in the wet season.

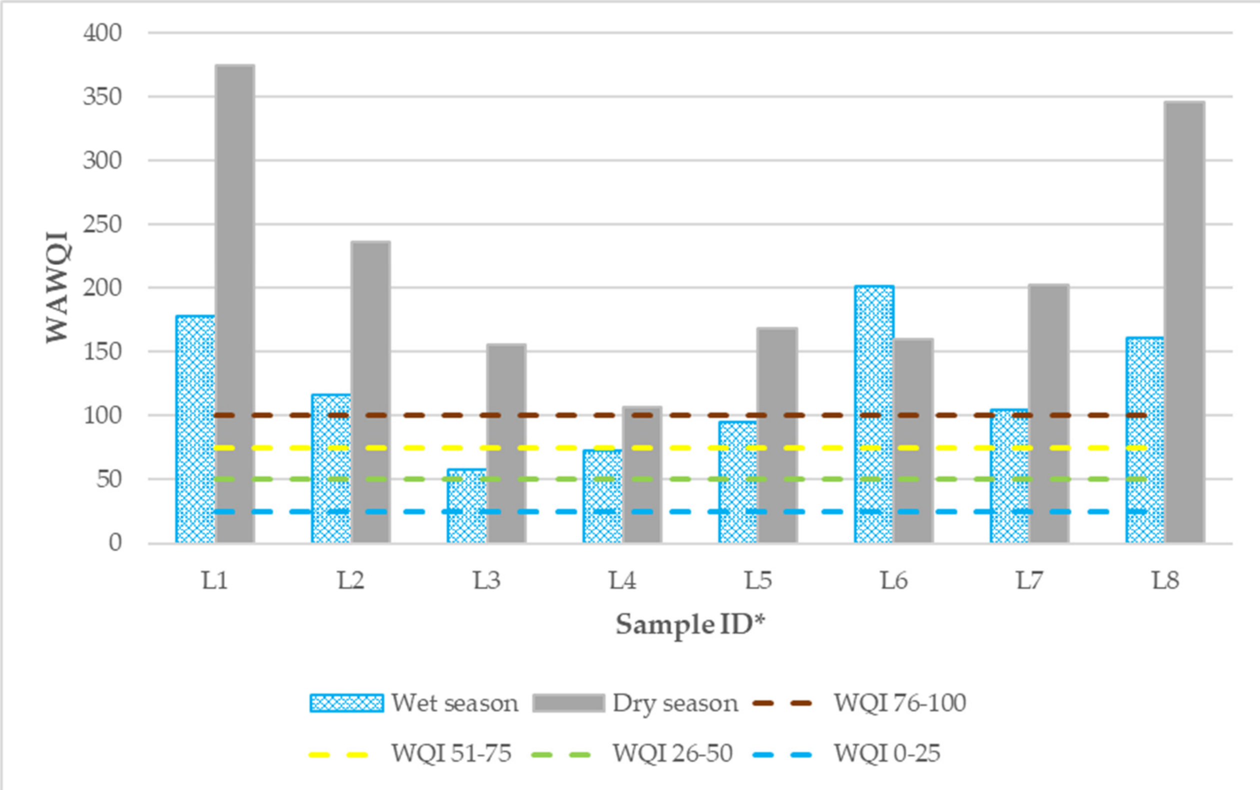


Figure 9. WAWQI in LNHNR by season in 2016. * Sample ID is mentioned in Table 2 with specific location.

Table 6. Calculation of WAWQI for the MXAC in the 2016 Dry Season.

Sample ID *	EC	pH	COD	PO_4^{3-}	NH_4^+	Fe	BOD_5	DO	WAWQI
	µS/cm		mg/L						
QCVN 08-T:2015/BTNMT (Column A1)	**300 ****	**6.5–8.5**	**10**	**0.1**	**0.3**	**0.5**	**4**	**6**	
T1	530	6.83	42.7	0.41	0.70	1.49	26.70	2.50	357
T2	315	7.13	32.0	0.33	0.30	0.64	26.20	2.60	257
T3	545	6.83	64.0	0.36	0.60	1.47	22.20	2.70	318
T4	406	6.84	58.7	0.33	0.30	1.46	26.20	1.33	280
T5	216	6.90	48.0	0.29	0.20	1.10	25.30	2.02	237
T6	248	6.80	42.7	9.01	0.10	0.89	27.60	1.92	5686
T7	272	6.84	42.7	0.17	ND	0.52	20.4	3.44	166
T8	258	6.97	42.7	0.56	0.1	0.73	13.8	1.73	386
T9	454	6.61	170.7	0.25	ND	3.27	148	1.5	390
T10	282	6.81	58.7	0.4	0.2	1	29.8	1.3	306
T11	423	6.91	58.7	0.45	ND	1.09	22.2	1.3	408
T12	488	6.94	64	0.31	ND	0.71	28.9	1.6	289
T13	253	6.92	42.7	9.2	ND	1.47	25.3	2	7344
T14	242	7.34	64	0.14	0.2	0.83	17.8	7.5	134
Descriptive Statistics									
Maximum	545	7.34	170.7	9.2	0.7	3.27	148	7.5	7344
Minimum	216	6.61	32	0.14	0.10	0.52	13.8	1.3	134
Mean	352.29	6.91	59.45	1.59	0.30	1.19	32.89	2.39	1183
SD	112.92	0.16	32.43	3.07	0.20	0.66	32.21	1.54	2201

* Sample ID is mentioned in Table 2 with specific locations; ** ICMR (1962); SD = standard deviation; ND: not detected.

Table 7. Calculation of WAWQI from Data from the MXAC in the 2016 Wet Season.

Sample ID *	EC	pH	COD	PO_4^{3-}	NH_4^+	Fe	BOD_5	DO	WAWQI
	μS/cm				mg/L				
QCVN 08-T:2015/BTNMT (Column A1)	300 **	6.5–8.5	10	0.1	0.3	0.5	4	6	
T1	195	6.26	5.2	0.25	0.00	1.12	4.00	3.10	187
T2	191	6.24	3.8	0.17	0.00	1.24	1.90	3.30	140
T3	203	6.22	4.1	0.15	0.00	0.55	2.40	3.50	110
T4	223	6.26	3.7	0.19	0.00	1.00	1.60	1.90	146
T5	579	5.71	5.5	0.04	0.00	1.60	5.20	2.70	68
T6	380	6.15	6.8	0.07	0.00	0.87	5.90	2.30	70
T7	560	5.91	7	0.03	ND	1.14	5.6	1.6	65
T8	278	6.35	7.4	0.13	ND	0.87	5	2.7	135
T9	553	5.65	7.8	0.04	ND	2.11	5	1.6	103
T10	292	6.11	4.7	0.18	ND	1.49	2.5	2	193
T11	243	6.31	4	0.22	ND	1.4	2.2	1.6	221
T12	584	6.44	17	0.17	ND	0.6	6.5	2.1	160
T13	212	6.15	4.2	0.18	ND	1.07	2.4	2.9	179
T14	432	6.3	5.1	0.09	ND	0.19	4.9	5.5	81
Descriptive Statistics									
Maximum	584	6.44	17	0.25	0	2.11	6.5	5.5	221
Minimum	191	5.65	3.7	0.03	0	0.19	1.6	1.6	65
Mean	351.79	6.15	6.16	0.14	0	1.09	3.94	2.63	133
SD	152.64	0.23	3.29	0.07	0	0.46	1.63	1.01	49

* Sample ID is mentioned in Table 2 with samples' specific location; ** ICMR (1962); SD = standard deviation; ND: not detected.

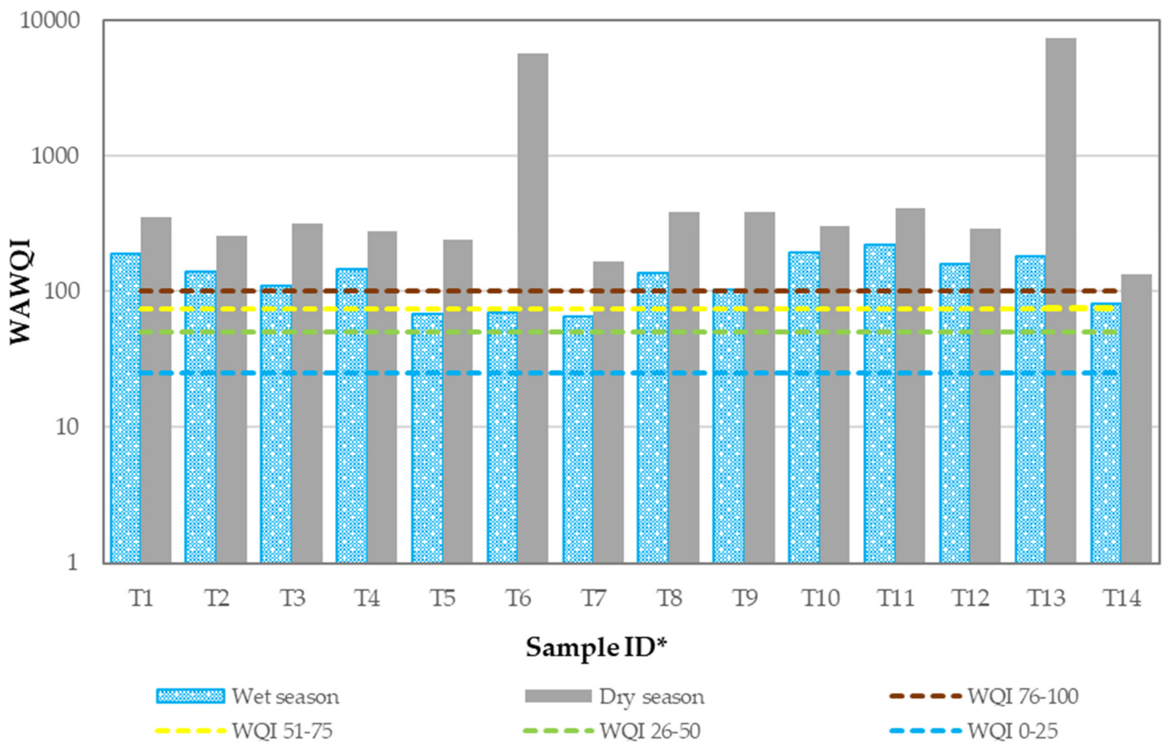


Figure 10. WAWQI at the MXAC by season in 2016. * Sample ID is mentioned in Table 2 with specific location.

The WAWQI values at all sampling points indicate heavy pollution (WAWQI $\geq$ 100) during the dry season. During the wet season, the WAWQI values at locations T5, T6, and T7 were 68, 70, and 65, respectively, indicating light pollution levels, whereas location T14 had an average pollution level of 81. The rest of the locations were taken as extremely polluted, showing WAWQI values ranging from 103–221, but still less so than during the dry season. There were very high WAWQI values above 5000 at sites T6 and T13 due to a very high concentration of phosphorus P-$PO_4^{3\times}$ (9.01 and 9.2 mg/L), which is more than 90 times higher than the standard (0.1 milligrams per liter). The T6 site can be explained as an aqueous environment. The majority of the locations were polluted due to a number of unsatisfactory criteria, including a high EC (191–584 S.cm^{-1}), low DO content (≥6 mg/L) with only one site at the standard position (7.5 mg/L), COD levels exceeding the standard by 1.7–17 times, the BOD_5 criterion exceeding the standard by 1.23–37 times, and the P-PO_4^{3-} criterion exceeding the standard by 1.3–92 times. As a result, the results of the WAWQI analyses in the heavy pollution classification range are reliable.

The WAWQI values at the MPMF are shown in Tables 8 and 9 and Figure 11, which range from 60 (P17) to 252 (P13) in the dry season and around 404 (P1) to 193 (P24) in the wet season.

Table 8. Calculation of WAWQI for data at MPMF in Dry season 2018.

Sample ID *	EC	pH	COD	PO_4^{3-}	NH_4^+	NO_3^-	TSS	BOD_5	DO	WAWQI
	µS/cm		mg/L							
QCVN 08-T:2015/BTNMT (Column A1)	**300 ****	**6.5–8.5**	**10**	**0.1**	**0.3**	**0.5**	**20**	**4**	**6**	
P1	1950	6.8	18	0.1	0.2	3.145	8.40	2.48	4.2	96
P2	460	6.8	18.5	0.09	0.1	2.168	7.90	2.32	4.28	79
P3	1990	6.5	16.5	0.08	0.3	2.517	6.40	1.49	4.19	88
P4	2100	6.6	18	0.13	0.1	2.13	11.40	2.69	5.1	108
P5	2150	6.3	19.5	0.1	0.1	1.21	3.50	0.67	5.44	82
P6	318	6.01	90	0.09	0.25	2.38	12.40	3.48	2.34	98
P7	341	6.33	110	0.15	0.2	3.808	18.80	4.40	3.02	142
P8	322	6.9	95	0.1	0.3	3.618	10.20	2.08	2.47	111
P9	330	4.57	111	0.08	0.1	3.5	17.60	4.24	3.22	84
P10	338	6.51	100	0.09	0.09	2.987	11.20	2.51	1.74	87
P11	329	5.21	116	0.09	0.15	3.018	8.90	1.87	2.9	91
P12	330	6.35	90	0.085	0.5	3.331	18.50	4.53	2.12	118
P13	334	6.53	90	0.3	0.3	3.025	22.30	5.44	1.52	252
P14	333	6.12	110	0.1	0.1	3.103	24.10	5.52	1.18	101
P15	322	6.83	18.5	0.05	0.45	3.003	8.20	1.71	3.48	80
P16	316	7.01	19	0.15	0.4	2.725	14.60	3.44	4.24	148
P17	331	6.85	18.5	0.06	0.1	2.015	12.30	2.53	4.23	60
P18	334	6.89	20.5	0.085	0.15	2.12	8.70	2.12	5.43	80
P19	379	6.78	19.5	0.25	0.22	3.04	12.40	2.88	4.85	202
P20	350	6.5	19.5	0.09	0.38	3.415	24.60	8.64	4.56	110
P21	347	6.68	18.5	0.1	0.1	3.221	26.20	8.64	4.37	96
P22	336	6.01	105.2	0.026	0.47	2.015	6.0	4.24	2.65	68
P23	332	6.41	108.9	0.026	0.45	2.201	5.0	3.44	1.62	67
P24	335	6.51	113.6	0.026	0.51	2.613	8.0	4.24	1.67	74
P25	334	6.6	113.6	0.021	0.40	2.915	12.5	2.53	1.82	65
P26	335	6.65	120.3	0.036	0.46	3.025	17.5	2.12	1.97	82
P27	338	6.9	119.3	0.021	0.53	3.08	10.5	2.08	3.9	75
P28	326	7.06	111.0	0.060	0.24	3.209	0.5	2.32	1.83	75
Descriptive Statistics										
Maximum	2150	7	120	0.3	0.53	3.81	26.2	8.64	5.44	252
Minimum	316	4.57	16.5	0.02	0.09	1.21	0.5	0.67	1.18	60
Mean	583.57	6.47	68.87	0.09	0.27	2.80	12.45	3.38	3.23	101
SD	598.98	0.52	44.1	0.06	0.15	0.58	6.47	1.86	1.30	41

* Sample ID is mentioned in Table 2 with specific locations; ** ICMR (1975); SD = standard deviation.

Table 9. Calculation of WAWQI for data at MPMF in Wet season 2018.

Sample ID *	EC	pH	COD	PO_4^{3-}	NH_4^+	NO_3^-	TSS	BOD_5	DO	WAWQI
	μS/cm		mg/L							
QCVN 08-T:2015/BTNMT (Column A1)	300 **	6.5–8.5	10	0.1	0.3	0.5		4	6	
P1	1640	6.94	75	0.010	0.189	2.985	14	5.91	1.75	40
P2	1467	5.38	90	0.015	0.671	2.776	44	3.55	0.79	93
P3	1275	5.87	90	0.040	0.450	2.615	27	2.85	0.67	86
P4	1611	5.76	80	0.020	0.328	1.942	36	3.01	3.36	64
P5	1382	6.18	82	0.025	0.247	2.005	19	3.31	0.54	55
P6	1195	6.67	77	0.045	0.484	2.635	102	3.97	0.79	124
P7	619	6.54	105	0.080	0.284	4.492	7	4.05	0.32	97
P8	756	6.79	80	0.075	0.069	4.443	11	3.73	0.68	77
P9	615	7.28	95	0.085	0.162	4.411	5	3.95	2.01	89
P10	884	6.56	90	0.165	0.113	4.395	99	5.23	1.73	181
P11	747	6.75	115	0.080	0.069	4.234	12	4.27	0.65	83
P12	706	6.59	105	0.065	0.216	4.217	7	6.29	0.45	81
P13	755	6.56	85	0.105	0.112	4.201	12	6.29	0.56	101
P14	638	6.54	87	0.125	0.139	4.573	10	4.40	0.73	117
P15	1514	6.94	77	0.055	0.199	4.406	6	5.65	1.76	71
P16	1471	6.85	80	0.040	0.186	4.125	6	7.09	1.54	59
P17	1308	6.23	90	0.030	0.168	4.337	30	3.73	1.49	62
P18	1179	5.33	80	0.020	0.215	3.987	55	4.96	1.87	67
P19	1357	6	80	0.040	0.129	4.014	27	3.36	1.31	63
P20	1478	5.77	90	0.045	0.324	4.403	97	5.81	2.73	113
P21	717	6.54	110	0.105	0.096	4.783	11	2.83	1.27	102
P22	1221	6.45	95	0.060	0.200	2.748	18	2.40	0.7	77
P23	1378	6.14	85	0.030	0.012	2.416	30	3.55	0.94	46
P24	1414	6.02	85	0.030	1.883	3.675	34	3.68	0.58	193
P25	1406	6.01	90	0.035	0.474	3.669	33	3.87	0.4	89
P26	1439	5.94	90	0.030	0.457	4.107	37	4.59	0.5	86
P27	1432	5.64	70	0.035	1.514	4.321	42	6.48	0.71	172
P28	1386	6.63	85	0.055	0.15	4.272	16	5.65	1.67	71
Descriptive Statistics										
Maximum	1640	7.28	115	0.17	1.88	4.78	102	7.09	3.36	193
Minimum	615	5.33	70	0.01	0.012	1.94	5	2.4	0.32	40
Mean	1178.21	6.32	87.96	0.06	0.34	3.76	30.25	4.45	1.16	91
SD	337.24	0.48	10.43	0.04	0.41	0.84	27.29	1.25	0.73	37

* Sample ID is mentioned in Table 2 with specific locations; ** ICMR (1975); SD = standard deviation.

During the dry season, 25% (7 locations) of WAWQI water quality values were in the moderately polluted range, 43% (12 locations) were in the average pollution range, and 32% (9 locations) were in the seriously polluted range (≥100). In the dry season, the greatest WAWQI values were found at positions P13 and P19, which were caused by a low dissolved oxygen index below the acceptable threshold and a relatively high concentration of phosphorus P-PO_4^{3-} (0.3 and 0.25 mg/L, respectively) three times that of the norm (0.1 mg/L). This can be explained by the presence of several plant remains in the P13 and P19 locations, which had decomposed or were in the process of decomposition. The water quality was better in the wet season, with 7% (2 sites) having an acceptable quality; equal numbers containing light and medium pollution, accounting for 32% of the total number (9 sites for each); and 28% (8 sites) being severely contaminated. In the wet season, the WAWQI was highest at positions P24, P27, and P10, which was due to low DO contents below the standard level by 8.5 to 10.3 times, very high EC indicator values of 1414 and 1432 $S.cm^{-1}$, and high N-NH_4^+ contents at 1883 and 1514 mg/L at P24 and P27, respectively.

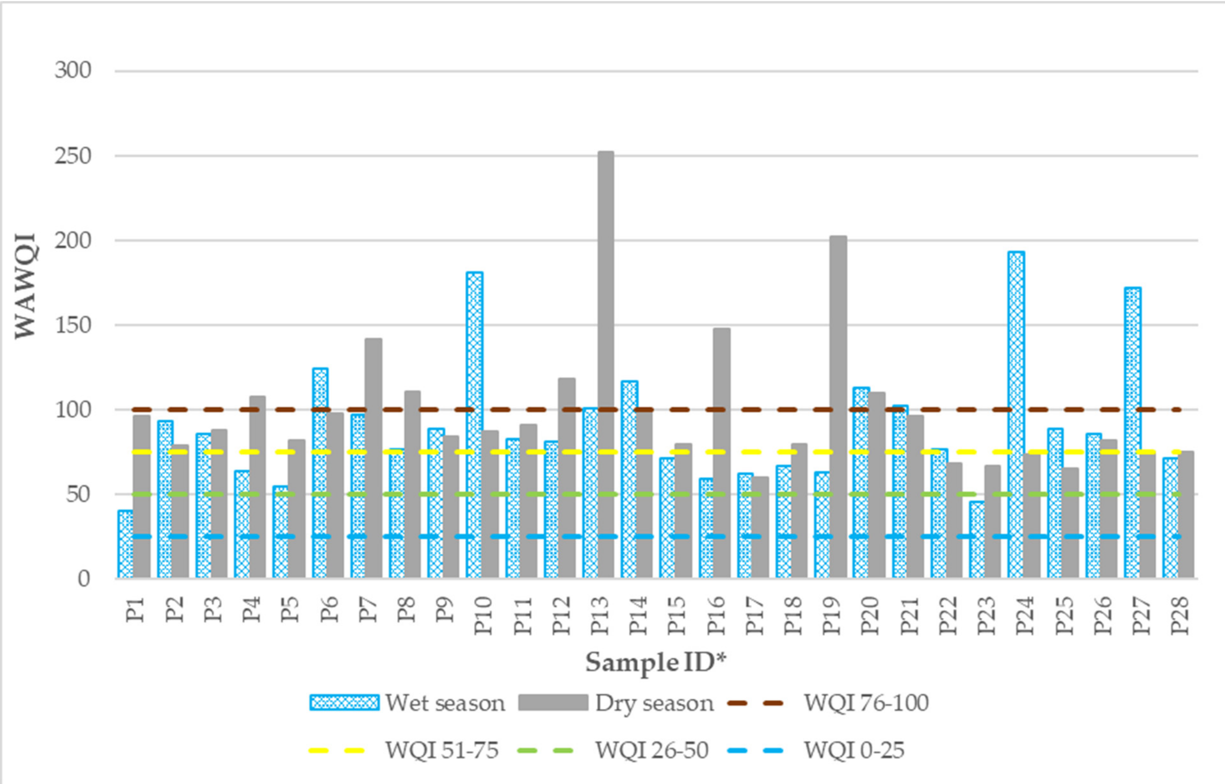


Figure 11. WAWQI at MPMF by season in 2018. * Sample ID is mentioned in Table 2 with specific location.

The percentages of water quality levels according to the WAWQI in the wet and dry seasons in the NRs can be seen in Figure 12. During the dry season, the WAWQI in the LNHNR and MXAC was clearly in the heavy pollution category (100). During the wet season, the water quality improved slightly; 25% of sites contained slight pollution, and 12.5% and 62.5% contained heavy pollution in the LNHNR, while pollution and heavy pollution levels in the MXAC were 21.4%, 14.3%, and 64.3%, respectively. The main reason is that the concentrations of parameters such as EC, COD, BOD_5, and $P\text{-}PO_4^{3-}$ were higher than the standard. Due to the low concentrations of EC and COD, the WAWQI at the MPMF (Figure 10e) in the dry season was in 25% of sites at little pollution, 43% at moderate pollution, and 32% at heavy pollution levels. Similarly, during the wet season, pollution in the MPMF decreased progressively, with 7%, 32%, 32%, and 29% having good, slight pollution, pollution, and heavy pollution levels, respectively. The reason for this is the dilution effect of rainfall on pollution concentrations.

Spatially and temporally, the aforementioned assessments are generally consistent. Spatially, the high population densities in the LNHNR and MXAC might lead to increased water exploitation and retention for the purpose of living, resulting in substantial water quality impacts during the dry season. The MPMF, on the other hand, contained only a melaleuca forest with no inhabitants, hence the water quality was better. The flow velocity did not differ between the dry and wet seasons. The flow velocity in canals is normally very low, because sluice systems are normally closed except in rare cases where the flow rate may increase due to the sluice opening. The water level inside the dyke system was always kept at a sufficient level in rivers and canals to help prevent forest fires. As a result, during the wet season, some of the water from the on-site rain and upstream runoff reached the protected areas, necessitating the use of the sluice gate system to drain this excess water. As a result, the water was diluted, resulting in a water quality improvement compared to the water quality in the dry season.

Based on the results of the annual average, the WQI values at the LNHNR, MXAC, and MPFM were 171, 658, and 96, respectively, which means that the surface water quality in the three NRs was very bad and could not be used for domestic use. In this case, it should be noted that the annual average in the MXAC was 3.8–6.9 times higher than that in the other study areas. In addition, the WAWQI results also reveal that the WQI tended to be higher in the dry season at all three sites.

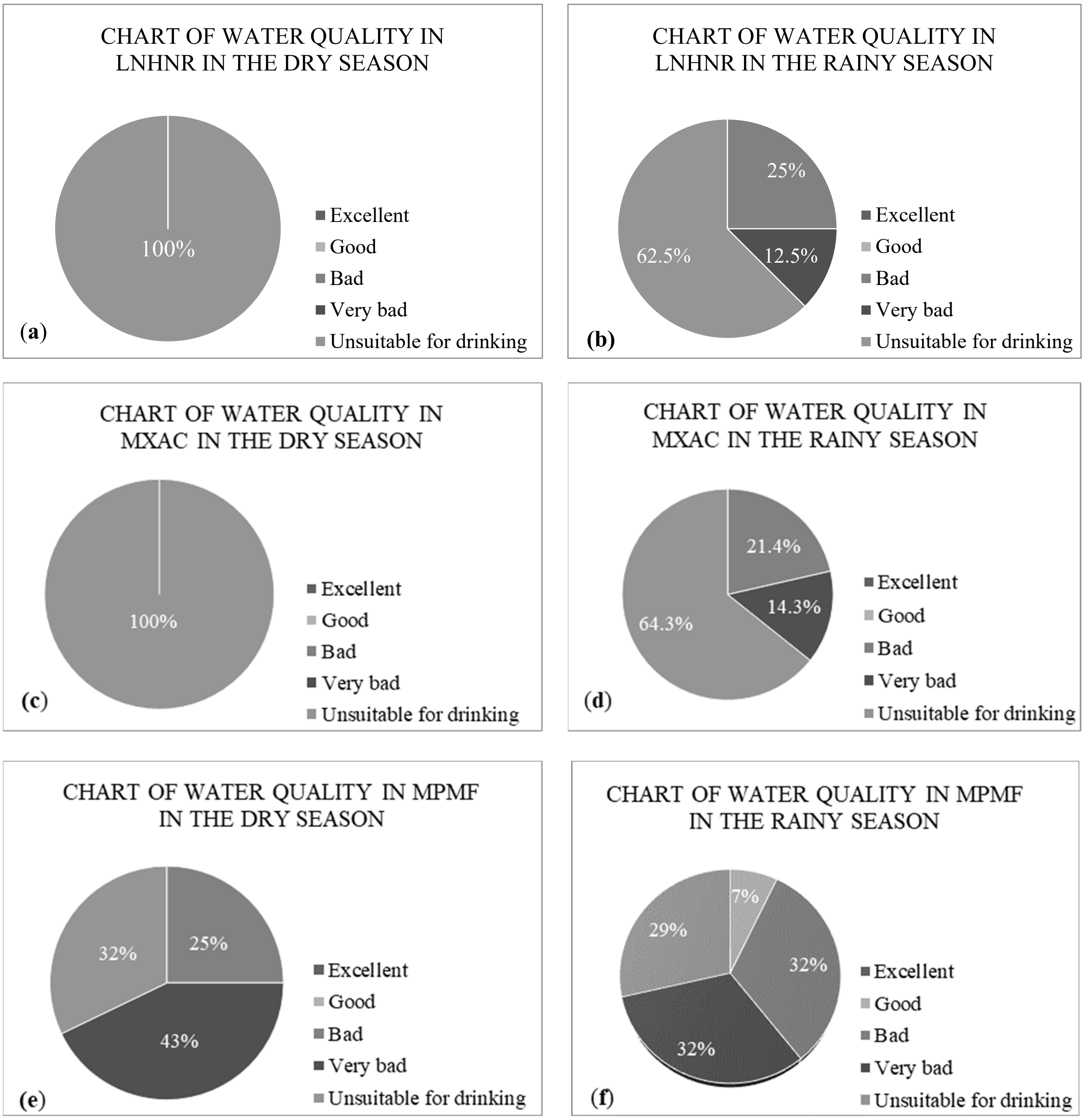


Figure 12. Water quality classification based on WAWQI values. (**a**,**b**) Water quality at LNHNR in dry and wet seasons; (**c**,**d**) Water quality at MXAC in dry and wet seasons; (**e**,**f**) Water quality at MPMF in dry and wet seasons.

Due to organic pollution waste from falling leaves and trunks, the water quality had deteriorated (the surface water became black), which was seen at all three studied NRs. PO_4^{3-} concentrations at T6 and T13 were found to be 90–92 times higher than QCVN 08-MT:2015/BTNMT [32] during the dry season of 2016. As a result, the WQI calculation results ranged between 5686 and 7433. Poor water circulation and low water flow conditions resulted in high phosphate levels, reducing the self-purifying ability of the channels. Agricultural practices, specifically rice and sugarcane cultivation in the

TTNNMX, were responsible for the high phosphate levels. Furthermore, the DO contents in the NRs were significantly lower than the standard 08:2015/BTNMT (column A1) used for aquatic animal conservation. It should be noted that the levels of organic pollution were found to be higher in the study area than those found in the intensive rice [2,3,33–35], aquaculture [36,37], and fruit areas [34] in the VMD.

In summary, this study provides an overall assessment of the impact of different infrastructural developments on NRs and the effects on their ecosystem services, especially regulation. It also provides scientific evidence for designing robust management plans. This kind of study is of great importance, especially in the context of urban landscape where green spaces, namely, public parks, forests, green open spaces, etc., contribute to human well-being (recreation, meditation, community bonding, etc.), as well as environmental management (water quality improvement, air quality improvement, regulation of microclimate, etc.) [38–41].

4. Conclusions

The water quantity was circulated throughout the wet season, but flow directions were problematic due to the geography, which included several intersecting canals. During the dry season, the sluices were closed, which prevented water exchange in and out of the LNHNR and resulted in somewhat stagnant water dynamics with no distinct flow direction. Furthermore, the construction of infrastructure has had a significant impact on the hydrological regime and degradation of the water quality due to water retention for firefighting and livelihood provision for the inhabitants.

Although the water budget conditions have improved for forest fire prevention, they have had an impact on the water quality in the reserves and surrounding areas. The irrigation infrastructure can benefit trade and fire prevention purposes, changes the natural hydrological conditions, and pollutes the, water which has an impact on the livelihoods and quality of life of some households outside of the NRs. The hard construction works may also have a negative impact on biodiversity conservation. As a result, finding a solution that combines hard and soft works may minimize the impact of construction on the long-term development on NRs in the Mekong Delta of Vietnam.

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