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Impact of Rice Intensification and Urbanization on Surface Water Quality in An Giang Using a Statistical Approach

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Abstract: A few studies have evaluated the impact of land use land cover (LULC) change on surface water quality in the Vietnamese Mekong Delta (VMD), one of the most productive agricultural deltas in the world. This study aims to evaluate water quality parameters inside full- and semi-dike systems and outside of the dike system during the wet and dry season in An Giang Province. Multivariable statistical analysis and weighted arithmetic water quality index (WAWQI) were used to analyze 40 water samples in each seasons. The results show that the mean concentrations of conductivity (EC), phosphate (PO_4^{3-}), ammonium (NH_4^+), chemical oxygen demand (COD), and potassium (K^+) failed to meet the World Health Organization (WHO) and Vietnamese standards for both seasons. The NO_2^- concentration inside triple and double rice cropping systems during the dry season exceeds the permissible limit of the Vietnamese standard. The high concentration of COD, NH_4^+ were found in the urban area and the main river (Bassac River). The WAWQI showed that 97.5 and 95.0% of water samples fall into the bad and unsuitable, respectively, for drinking categories. The main reason behind this is direct discharge of untreated wastewater from the rice intensification and urban sewerage lines. The finding of this study is critically important for decision-makers to design different mitigation or adaptation measures for water resource management in lieu of rapid global changes in a timely manner in An Giang and the VMD.

Keywords: triple-rice cropping system; full-dike; surface water quality; WAWQI; An Giang Province; the Vietnamese Mekong Delta

1. Introduction

Deltas around the world have played a vital role in food security and economic development. However, the rapid exploitation of natural resources and changes in land use land cover (LULC) have also caused severe environmental degradation, such as water quality deterioration in many deltas in recent years [1–4]. The heavy metal concentrations and high bacterial pathogens due to industrial, agricultural activities, poor sanitation, and hygiene were found in the Middle Nile Delta, Egypt [5]. Several studies have also reported irregulated urban expansion and animal husbandry and its impact on water quality deterioration in Irrawaddy delta, Myanmar [6,7]. Consequently, when this

polluted water flows into the city during monsoon, it causes several waterborne diseases such as cholera, gastroenteritis, skin diseases [6,8,9]. Surface water pollution from organic pollutants, microbial contamination, pesticides, metals, etc. is revealed in the Mekong Delta Basin, in both the Cambodian (Phnom Penh) and Vietnamese (Chau Doc, Tan Chau, and Can Tho) part [10–15].

The well-known trans-boundary river of the Mekong River Basin (MRB) in the Asian region has a natural area of 795,000 km^2 and mean annual discharge of 14,500m^3/s [16–18]. The glaciers in the Himalaya mountains is the source of the international Mekong River, which flows to China, Myanmar, Thailand, Laos, Cambodia, Vietnam, and finally to the Pacific Ocean [18]. Therefore, the lower Mekong Delta in Vietnam, located in the downstream of the MRB and accounting for 8% of the entire basin, has dominant diurnal tidal seawater entering twice a day. Changes in water quality and quantity in the upstream region would directly affect the health of proximally 242 million people (2018 data) [19] who live in the lower Mekong river [18,20]. The upper region of the VMD receives from 60% to 80% discharge from outside of the VMD, in which the only location of An Giang Province lies between the two main rivers of Mekong and Bassac. Therefore, the covered lands of An Giang are of fertile soil due to the abundance of water resources and fluvial sedimentation from the Mekong River. Consequently, An Giang has large agricultural areas with dominant rice production [21], but this province has also faced substantial damage by natural flooding phenomena annually from August to November due to the monsoon season in the Asian region [21–23].

The full- and semi-dike systems in An Giang were rapidly built since the 1990s to prevent flooding and to grow rice both for food security and economic development [22,24,25]. The full-dike system and the hydraulic infrastructure were developed to protect the triple-rice cropping system as well as the urban cities [21,25]. Local farmers can grow two or three rice crops per year inside the dike systems instead of single rice crops per year as in the past [21]. Although the dike systems can protect residential areas and increase income for the local farmers, the most critical disadvantage of this system is the surface water quality deterioration [21,22,25]. Water quality degradation may be derived from both natural conditions like rock–water interaction, ion exchange, groundwater–surface water interaction, evapotranspiration, and human activities such as a discharge of untreated wastewater from a point or nonpoint source in natural water bodies [16,21,26].

Water demand for agriculture and aquaculture alone consumes a significant portion of total available water, resulting in high waste discharged from agriculture [27]. Although few studies have reported the impact of land use on stream water quality [21,28,29], studies focusing on different types of dike development for agricultural intensification and its impacts on water quality remain scarce. Henceforth, the objective of this study is to assess the physicochemical properties of the surface water in An Giang Province using the multivariate statistical analysis approach and the weighted arithmetic water quality index (WAWQI). The primary focus of this study is to evaluate the impact of dike development on surface water quality compared to other remaining areas in An Giang. The hypothesis of this study is that the water quality inside the full-dike systems was worse than the outside ones, and water quality in the dry season was worse than that of the wet season.

2. Methodology

2.1. Study Area

An Giang Province (10°12′ N to 10°57′ N and 104°46′ to 105°35′) is located in the most upper part of the VMD and borders with Cambodia in the northwest (104 km long). An Giang is a home to over 2.4 million people (2019) [30], and the total area of 3536 km^2, 70% of which is for agricultural production. There are two distinct seasons: dry and wet (monsoon) in the region. The wet season occurs between May and November annually in which the high rainfall usually occurs at the end of the wet season from October to November (Figure 1). Although total annual rainfall in An Giang is low compared with the average rainfall of the VMD, the rainfall occurs nearly at the same time with the flooding season leading risk at deep inundation. Thus, An Giang has to build a large area of the dike

systems (Figure 2) to increase agricultural production and to protect crops during the flooding season (July to November). Multi-dike protection systems have been built to protect residential areas from flooding, and have mainly supported agricultural intensification since the early 1990s. In addition, hydropower plants were built along the Mekong River, and its branches have led to a change in the water regime (Figure 1). During 1991 and 2015, the average discharge was decreased in the wet season and increased in the dry season. The primary soil type is alluvial soil, accounting for 44.5% of all 37 different soil types present in the province. About 72% of the area is alluvial soil or land receiving huge sediment supply and is suitable for many kinds of crops. The dike systems and hydropower plants have reduced the amount of alluvial soil to be added to the region annually [31,32].
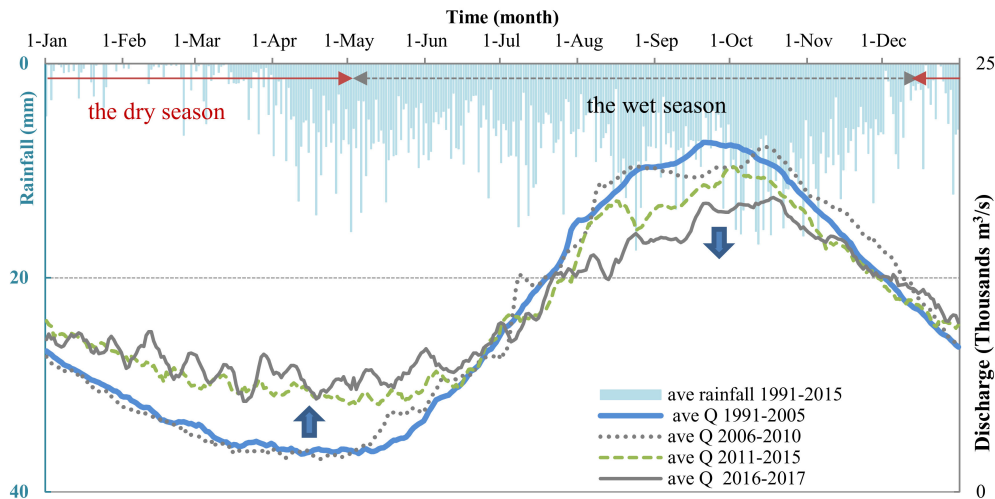
Figure 1. Average hourly discharge (Q) from 2006 to 2017 and average daily rainfall from 1991 to 2015 at Tan Chau Station in An Giang. The discharge imposes a decreasing trend in the wet season and an increasing trend in the dry season. All data were collected from the Southern Regional Hydro-meteorological Center (SRHMC) in Vietnam [33].
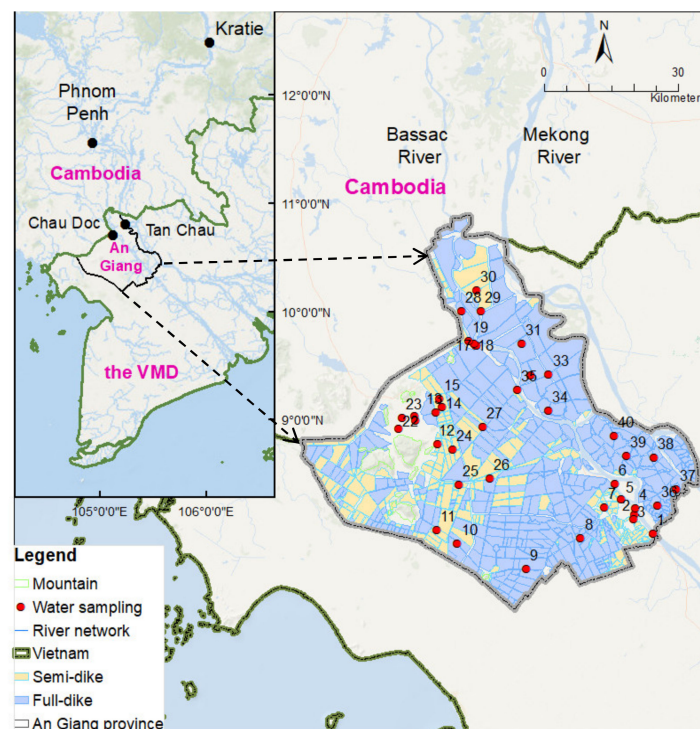
Figure 2. Study area and water sampling sites in An Giang, the Mekong Delta in Vietnam.

2.2. Collection of Water Samples and Analytical Methods

Surface water quality samples were collected and analyzed in the wet and the dry seasons inside the full- and semi-dike systems and outside of the dike system (on the main river and single rice cropping system), as shown in Figure 3. Analyzed data were processed using statistical tools and used to calculate water quality indicators. Finally, the obtained result is discussed to observe spatio-temporal water quality classification and the impact of the dike system on water quality parameters.
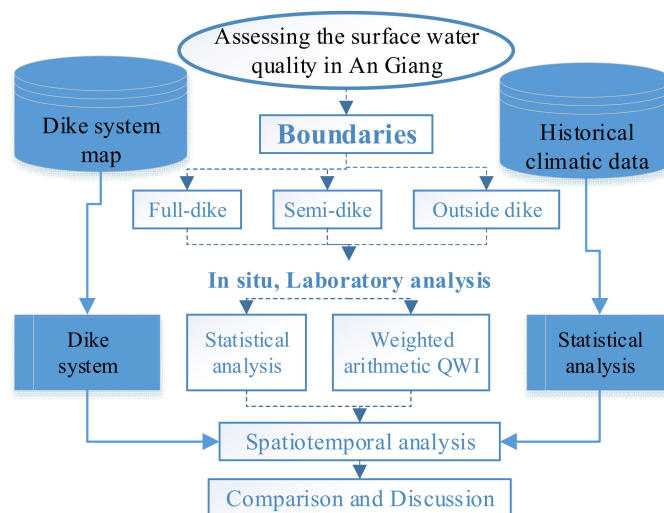

Figure 3. Flowchart for study methodology.

Each season, 40 surface water samples were taken from inside the full- and semi-dike systems, and outside the dike system in An Giang (Figure 3). Sampling was done both for the dry season (22–28 April 2018) and the wet season (6–13 October 2018). Water sample locations were taken by geotagged photos, which were marked in the global positioning system (GPS). The stratified random sampling technique was conducted to select the sampling sites: Cluster 1 includes ten samples outside of the dike system (6 in the main rivers and 4 in single-rice cropping system), Cluster 2 includes ten samples inside the semi-dike system (3 in the forest and 7 in the double-rice cropping system), and Cluster 3 includes 20 samples inside the full-dike system (6 in the urban area and 14 in triple-rice cropping system). After collection, water samples were brought to the laboratory in an ice chest and stored below 4 °C. The collected samples were analyzed for twelve water quality parameters: pH, EC, chloride (Cl^-), nitrite (NO_2^-), nitrate (NO_3^-), NH_4^+, COD, PO_4^{3-}, sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and K^+. The HORIBA multi-parameter meter (Kyoto, Japan) with a precision of 1% and a handheld meter (Oaklom; Tokyo, Japan) was used for in situ analysis of the physical parameters such as pH, Cl^-, EC, and some chemical parameters of NO_2^-, NO_3^-, NH_4^+, COD and PO_4^3 were measured using pack test$^-$. Anions were analyzed by DIONEX ICS-90 ion chromatography with an error percentage of <2%, while cations were analyzed by a Shimadzu mass spectrometer with a precision of <1% using duplicates. The historical meteorological data were collected from the Southern Regional Hydro-meteorological Center (SRHMC) [33].

2.3. Statistical Analyses

2.3.1. Multivariate Statistical Analysis

Multivariate statistical analysis was completed to obtain a better understanding of the processes governing water quality [34–40]. First, we conducted correlation and discriminant analysis (DA) [41] to find out the significant relationship among parameters and discriminant among clusters in terms of water quality characteristics. Second, we used box plots to show differences among different clusters in the dry and wet seasons. Finally, we used the WAWQI method to classify the water quality for

human use. XLSTAT Software version 2018 (Addinosoft SARL, Paris, France) and the inverse distance weighting (IDW) interpolation were used to make different plots and display the results [42–45].

We conducted Spearman rank–order to evaluate the relationship among parameters at each season since most of the dataset had a non-normal distribution. Spearman rank–order consumption does not require any distribution test, such as a person correlation with a normal distribution [46,47]. Moreover, Spearman rank–order is used to identify the correlation between related parameters by producing the significance of the data, as reported in previous studies [45,48].

In this study, we use the DA technique to determine the most significant parameters among 40 samples sites as well as between the dry and wet seasons. The DA was also found in various studies [48,49]. The standard DA, forward stepwise, and backward stepwise were applied, which was previously documented [21,48,50]. The forward stepwise adds a parameter in each step, starting from the most significant fit improvement until no change was found. In the case of backward stepwise, each parameter is excluded step-by-step, starting from the least significant fit improvement until no significant changes [51,52]. After standard DA, the backward stepwise model helped to clarify which parameters are the most important. In this standard model, step-by-step, variables were removed from the beginning of the less significant until no significant changes in removal criteria are achieved [48,51].

2.3.2. Weighted Arithmetic Water Quality Index (WAWQI) Model

The WAWQI is an index number that represents the overall quality of water and is a standard tool for the classification of water pollution (Figure 4). The WAWQI can be identified as a reflection of the composite influence of multivariable quality parameters [53]. Thus, WAWQI becomes an important indicator for the assessment and management of water resources. Here, all the selected water quality parameters are aggregated into an overall index, which is the most effective tool to express water quality [54].
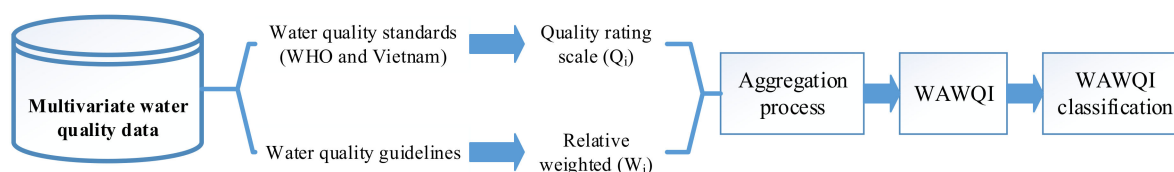
Figure 4. Flowchart of the weighted arithmetic water quality index (WAWQI) model.

In this study, we chose the Horton method to calculate the WAWQI [21,35,54]. The standard for the drinking water was based on the permissible standard for drinking water set by WHO guidelines [55]. These all variables were turned into sub-indices such as quality rating (q_i) and unit weights (W_i). The sub-indices were expressed on a single scale, and water quality was classified. The WAWQI was estimated using Equation (1) [56]:

$$\text{WAWQI}_i = \frac{\sum_{i=1}^{n} Q_i \times W_i}{\sum_{i=1}^{n} W_i} \tag{1}$$

where,

WAWQI is weighted arithmetic water quality index;
Q_i is a quality rating of nth parameters, $Q_i = [(V_i - V_{di})/(S_i - V_{di})] \times 100$ in which V_i is estimated value of nth parameters based on sample location, V_d is ideal value in pure water for n^{th} parameters (pH = 7.0 and other parameters is 0); S_i is permissible limits of nth parameters;
W_i is the unit weight of nth parameters, $W_i = K/S_i$, in which K is proportionality constant, $K = 1/\sum_{i=1}^{n}(1/S_i)$.

Based on the ranges of WAWQI value, the corresponding status of water quality and their possible drinking use are summarized in Table 1.

Table 1. Water quality classification for human consumption using the weighted arithmetic water quality index (WAWQI) [55].

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

3. Results

3.1. Statistical Assessment Using Correlation

The results of correlations matrices among 12 water quality parameters in the dry and wet season are shown in Tables 2 and 3, respectively. The parameters showing weak correlation coefficients with others in both seasons in An Giang have been affected by multiple sources such as agriculture, urbanization, and industry [13,21,57]. In the dry season, COD had a strong statistically significant correlation with Mg^{2+} (0.61) and EC (0.61) and a moderately positive relation with PO_4^{3-} (0.49) and NH_4^+ (0.461). In contrast, in the rainy season, COD had no correlation with PO_4^{3-} and Mg^{2+} parameters, excluding EC, pH, and NH_4^+, with which it showed weak correlations. PO_4^{3-} had a weak correlation with EC and NH_4^+ in both seasons and had a very weak relationship with the only NO_2^- in the wet season. On the other hand, NO_3^- had a strong correlation with NO_2^-, while NO_3^- did not correlate to others in both seasons. During flooding, a large amount of water flowing from the upper Mekong River discharges into An Giang with high COD concentration, supported by previous observation [13].

Interestingly, the characteristics of physical parameters in the dry season are strongly correlated than those in the wet season. Physical parameters such as EC and pH had a negative correlation in the wet season and had almost no correlation in the dry season. In the dry season, EC correlated with COD, NH_4^+, and PO_4^{3-} while pH only correlated with NO_2^-. In the wet season, pH and EC had a moderate correlation with COD and NH_4^+. Besides, EC correlated with PO_4^{3-} and pH correlated with Mg^{2+} in the wet season. The EC parameter qualitatively reflects the status of inorganic pollution [58]. The significantly high relation between EC and NH_4^+ for both seasons signifies the excess of breakdown/decomposition of organic matters, animal, and human waste. Nitrogen fixation is an indicator of anthropogenic input, excess of fertilizer application in the agricultural fields. During the wet season, pH and EC are negatively correlated, indicating a lower prevalence of cations and anions when water becomes alkaline. The strong correlation between EC and COD for both seasons indicates high organic pollutants, while the moderate association with PO_4^{3-} implies anthropogenic input. A strong association between NO_2^- and NO_3^- suggest the same source of origin, likely an agricultural runoff with high fertilizer input.

3.2. Spatial Assessment of Water Quality Using DA

The analysis technique of DA method was used to determine how many discriminant water quality parameters between the two seasons. The DA result shows a temporal comparison of the three discriminant significant parameters: pH, Cl^-, and Ca^{2+} between the dry and wet seasons (Figure 5). The pH, Cl^-, and Ca^{2+} showed different behaviors between the two seasons. The pH measures acidity in water or represents the negative logarithm of the hydrogen-ion activity [59,60]. The pH value beyond 6.5 to 8.5 range represents its contamination or pollution [61]. On the other hand, pH has a significant association with dissolved oxygen (DO) in freshwater. Therefore, the breakdown of organic matter exceeds synthesis activities caused oxygen consumption to increase. In this study, the pH 7.42 ± 0.63 (dry season) and 6.97 ± 1.06 (wet season) were neither highly alkaline nor highly acidic. In the dry

season, the water is slightly alkaline, while the water is slightly acidic in the wet season. This result also confirms that the fluctuations in the value of water quality parameters in the dry season are greater than those in the wet season. On the other hand, the concentrations of Cl^- and Ca^{2+} were also relatively higher for the dry season than that of the wet season. Relatively low river discharge and higher evapotranspiration cause this seasonal difference in the concentration. Even though Cl^- occurs naturally in water, the larger value of Cl^- level can increase the corrosiveness of water, and in combination with sodium, it creates a salty taste.

**Table 2.** Correlation matrices in the dry season using Spearman rank–order.

Variables	PH	EC	Cl^-	NO_2^-	NO_3^-	NH_4^+	COD	PO_4^{3-}	Na^+	Ca^{2+}	Mg^{2+}	K^+
PH	1											
EC	0.050	1										
Cl^-	0.022	0.109	1									
NO_2^-	**0.413**	−0.079	−0.040	1								
NO_3^-	0.250	−0.163	−0.241	**0.775**	1							
NH_4^+	0.022	**0.570**	**0.319**	0.075	−0.006	1						
COD	−0.161	**0.605**	0.306	−0.114	−0.278	**0.461**	1					
PO_4^{3-}	0.200	**0.475**	**0.387**	−0.228	−0.296	**0.478**	**0.488**	1				
Na^+	0.120	0.229	0.032	0.213	−0.009	0.275	0.303	0.014	1			
Ca^{2+}	0.131	0.086	−0.290	0.171	0.029	0.046	−0.049	−0.119	**0.336**	1		
Mg^{2+}	−0.279	**0.380**	0.119	−0.146	−0.133	**0.317**	**0.607**	0.250	**0.394**	0.155	1	
K^+	−0.042	0.194	−0.012	−0.080	−0.075	0.275	0.311	0.111	**0.477**	−0.049	**0.562**	1

Values in bold are different from 0 with a significance level at alpha = 0.05. Concentrations of conductivity (EC), phosphate (PO_4^{3-}), ammonium (NH_4^+), chemical oxygen demand (COD), nitrite (NO_2^-); nitrate (NO_3^-).

Table 3. Correlation matrices in the wet season using Spearman rank–order.

Variables	PH	EC	Cl^-	NO_2^-	NO_3^-	NH_4^+	COD	PO_4^{3-}	Na^+	Ca^{2+}	Mg^{2+}	K^+
PH	1											
EC	**−0.509**	1										
Cl^-	0.176	−0.115	1									
NO_2^-	0.127	−0.042	0.005	1								
NO_3^-	0.143	−0.162	0.216	**0.627**	1							
NH_4^+	**−0.424**	**0.710**	0.077	0.116	0.003	1						
COD	**−0.444**	**0.490**	−0.107	0.005	−0.248	**0.427**	1					
PO_4^{3-}	0.125	**0.404**	0.134	**0.351**	0.223	**0.314**	0.067	1				
Na^+	−0.150	0.179	−0.146	−0.106	0.014	0.038	0.110	0.078	1			
Ca^{2+}	−0.307	0.085	0.133	−0.037	0.094	0.204	0.012	−0.109	0.094	1		
Mg^{2+}	**−0.313**	0.308	−0.263	−0.119	−0.130	0.095	0.178	−0.013	**0.338**	**0.434**	1	
K^+	−0.157	0.178	−0.028	0.180	0.107	0.224	0.111	0.111	**0.410**	0.301	**0.381**	1

Values in bold are different from 0 with a significance level at alpha = 0.05.
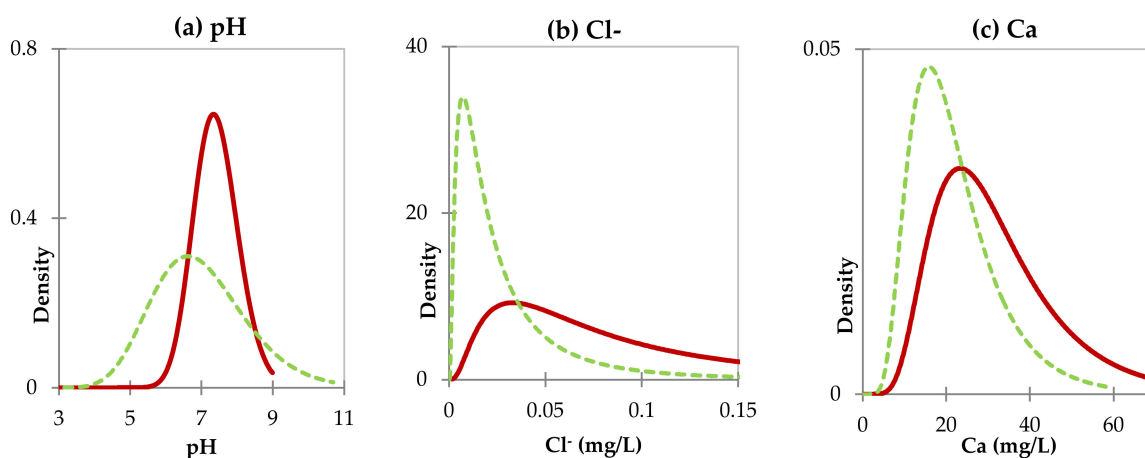
Figure 5. Log-normal probability distribution of (**a**) pH, (**b**) Cl^-, and (**c**) Ca^{2+} during the dry (red line) and wet seasons (green line).

The DA approach was also applied to identify the contribution of the most important parameters of water quality seasonal variations, especially concerning the contribution of the variables in discriminating in space. Therefore, the DA approach is used to determine the discriminant among clusters in the dry and wet seasons (Tables 4 and 5). The significant parameters among clusters are the concentrations of NO_2^-, NO_3^-, and pH in the dry season and Cl^- and Mg^{2+} in the wet season.

Table 4. Unidimensional lambda test of the quality of water parameter equality in the dry season.

Variable	Backward Model			Forward Model		
	Lambda	F	*p*-Value	Lambda	F	*p*-Value
NO_2^-	0.600 ***	8.002	0.000	0.600 ***	8.002	0.000
NO_3^-	0.817 **	2.688	0.006	0.817 **	2.688	0.006
NH_4^+	0.748	4.037	0.014			
COD						
Cl^-						
PO_4^{3-}						
PH	0.609 ***	7.720	0.000	0.609 ***	7.720	0.000
EC						
Na^+	0.805	2.913	0.048			
Ca^{2+}						
Mg^{2+}						
K^+						

Note: Significance levels are denoted as follows: ** $p < 0.01$, *** $p < 0.001$.

Table 5. Unidimensional lambda test of the quality of water parameter equality in the wet season.

| Variable	Backward Model			Forward Model		
	Lambda	F	*p*-Value	Lambda	F	*p*-Value
NO_2^-	0.729 **	4.468	0.009			
NO_3^-				0.712 **	4.858	0.006
NH_4^+						
COD						
Cl^-	0.699 **	5.159	0.005	0.699 **	5.159	0.005
PO_4^{3-}						
PH						
EC						
Na^+						
Ca^{2+}						
Mg^{2+}	0.768 **	3.626	0.002	0.768 **	3.626	0.002
K^+						

Note: Significance levels are denoted as follows: ** $p < 0.01$.

The discriminant of water pollutant level among different clusters (Cluster 3: inside the full-dike system, Cluster 2: inside the semi-dike system, and Cluster 1: outside of the dike system) was evaluated. The discriminant among clusters for selected parameters in both seasons was displayed by using box and whisker plots (Figures 6 and 7). For the dry season, concentrations of pH, NO_3^-, NO_2^- were high in Cluster 3 in comparison with Clusters 1 and 2. Meanwhile, in the wet season, the highest concentration of Mg^{2+} was found in Cluster 2, followed by Cluster 3 and Cluster 1. The concentration of Cl^- was found higher in Cluster 3 than that in Clusters 1 and 2 in the wet season.
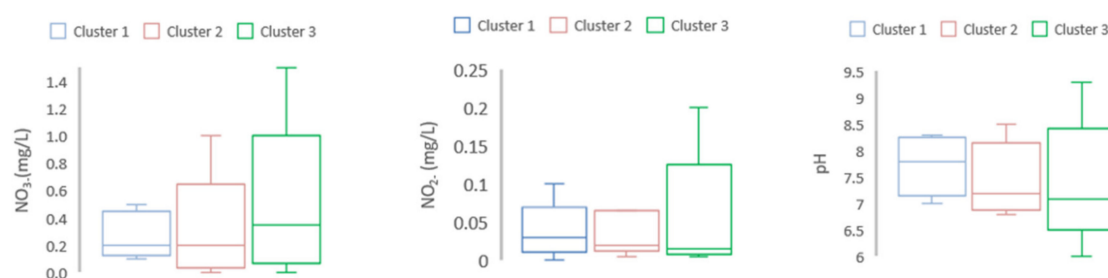
Figure 6. Water quality variables among three Clusters in the dry season. NO_3^-, NO_2^-, and pH were found higher in Cluster 3 than those in Clusters 1 and 2.
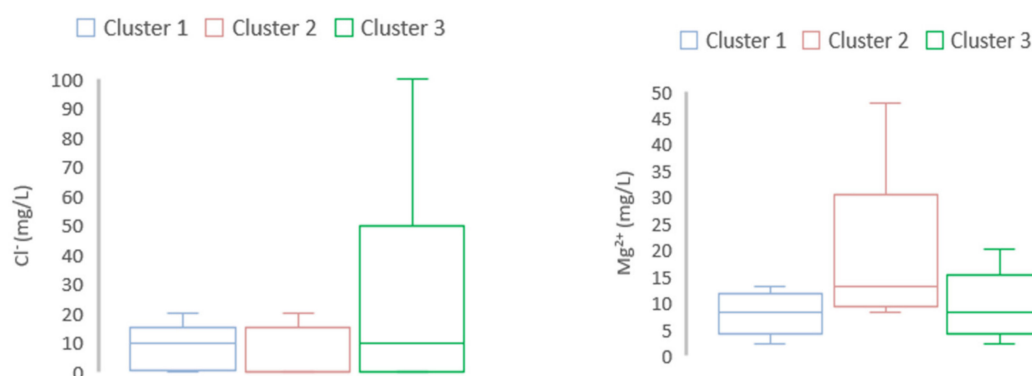
Figure 7. Water quality variables among the three clusters in the wet season. Mg^{2+} was high in Cluster 2 while Cl^- was high in Cluster 3.

3.3. Water Quality Classification Using WAWQI

Table 6 shows the range, mean, and standard deviation values of parameters, some of which were found to exceed the permissible standard for drinking water set by WHO and Vietnam national standard for both seasons. The higher values of these water quality parameters would lead to an increase in WAWQI. Overall, EC, NO_2^-, NH_4^+, COD, PO_4^{3-}, and K^+ were above the permissible standard set by WHO and Vietnamese standards. The EC is a measure of current carrying capacity due to the electrical current being carried by ions in a solution [62]; thus, as the concentration of dissolved salts increases, conductivity value also increases. On the other hand, EC is also used to determine the suitability of water for irrigation and firefighting [61]. Both NO_3^- and NO_2^- are nitrogen-containing compounds that generally indicate contamination from a pasture, decomposed vegetation, agricultural fertilizers, sewage, and rock–water interaction. NO_3^- is the essential nutrients in an ecosystem. Generally, water polluted by organic matter exhibits higher values of nitrate. In this study, the mean concentration of nitrate was 0.34 mg/L in the dry season and 0.5 mg/L in the wet season. Nitrate in all sample sites was below permissible standards.

The Cl^- mean values are 90 mg/L in the dry season and 20 mg/L in the wet season. The concentration of Cl^- in surface water may come from human activities, namely, agricultural runoff and wastewater sources [61,63]. In this study, the high concentration of Cl^- is also considered to be an indication of pollution due to the high organic waste from irrigation drainage, septic tank effluent, animal feed, and landfill leachates [59,60]. This also indicates poor governance and infrastructure to manage wastewater coming from both agricultural fields and urbanized areas.

The WAWQI of the present investigation from 40 sampling sites in both seasons were calculated. The WAWQI calculated from sampling Number 2 in the dry season is shown in Table 7 as an example.

Table 6. Standards for drinking water and relative weight of parameters.

Parameters	Unit	Dry Season			Wet Season			S_i	V_{di}	$(1/S_i)$	K	W_i
		Range	Mean	SD	Range	Mean	SD					
PH		6–9.3	7.37	0.63	3.1–9.3	6.92	1.06	8.5 *	7	0.118	0.0292	0.0034
EC	S.cm^{-1}	150–990	359	186.68	90–1160	340	221	300 *	0	0.003	0.0292	0.0001
Cl$^-$	mg/L	0–200	90	60	0–100	20	30	200 *	0	0.005	0.0292	0.0001
NO$_2$$^-$	mg/L	0–0.9	0.06	0.15	0–0.25	0.04	0.05	0.05 **	0	20	0.0292	0.5848
NO$_3$$^-$	mg/L	0–0.5	0.34	0.48	0–2	0.50	0.52	2 **	0	0.5	0.0292	0.0146
NH$_4$$^+$	mg/L	0.1–10	1.53	2.91	0.05–12	1.10	2.27	0.3 **	0	3.33	0.0292	0.0975
COD	mg/L	4–100	23.75	18.89	7–100	25.53	19.34	10 **	0	0.1	0.0292	0.0029
PO$_4$$^{3-}$	mg/L	0.05–5	0.64	1.09	0.08–4	0.59	0.87	0.1 **	0	10	0.0292	0.2924
Na$^+$	mg/L	6.1–1610	71.80	251.6	0.56–55.5	17.48	13.56	200 *	0	0.005	0.0292	0.0001
Ca^{2+}	mg/L	5.6–65.4	32.21	13.13	5.6–467.4	22.37	10.43	75 *	0	0.013	0.0292	0.0004
Mg^{2+}	mg/L	1.5–34.7	13.11	5.35	2.2–47.7	10.55	7.08	50 *	0	0.02	0.0292	0.0006
K$^+$	mg/L	1.4–43.6	15.84	11.4	2.5–129	13.39	22	10 *	0	0.1	0.0292	0.0029

Permissible limits for drinking * WHO and ** Vietnamese standard. Measured values (V_i), standard values of water quality parameters (S_i), corresponding ideal values (V_{di}), Q_i is a quality rating of n-th parameters, and unit weights (W_i) for sampling.

Table 7. Weighted arithmetic water quality index (WAWQI) calculation for sampling Number 2 as an example in the dry season.

Parameters	Unit	V_i	S_i	V_{di}	Q_i	$(1/S_i)$	K	W_i	$Q_i \times W_i$
PH		8.3	8.5	7	86.7	0.12	0.0292	0.0034	0.30
EC	S.cm^{-1}	240	300	0	80	0.00	0.0292	0.0001	0.01
Cl$^-$	mg/L	0.1	200	0	0.05	0.01	0.0292	0.0001	0.00
NO$_2$$^-$	mg/L	0.04	0.05	0	80	20	0.0292	0.5848	46.79
NO$_3$$^-$	mg/L	0.4	2	0	20	0.50	0.0292	0.0146	0.29
NH$_4$$^+$	mg/L	0.1	0.3	0	33.3	3.33	0.0292	0.0975	3.25
COD	mg/L	4	10	0	40	0.10	0.0292	0.0029	0.12
PO$_4$$^{3-}$	mg/L	0.05	0.1	0	50	10	0.0292	0.2924	14.62
Na$^+$	mg/L	12	200	0	5.8	0.01	0.0292	0.0001	0.00
Ca^{2+}	mg/L	29	75	0	38.2	0.01	0.0292	0.0004	0.01
Mg^{2+}	mg/L	10	50	0	20.8	0.02	0.0292	0.0006	0.01
K$^+$	mg/L	6	10	0	59.4	0.10	0.0292	0.0029	0.17
	Sum					34.20		1	66

Measured values (V_i), standard values of water quality parameters (S_i), corresponding ideal values (V_{di}), Q_i is a quality rating of n-th parameters, and unit weights (W_i) for sampling.

The WAWQI is commonly used for the detection and evaluation of overall water pollution since it can reflect the influence of different quality parameters on the quality of water. The application of WAWQI is a useful method in assessing the suitability of water for various beneficial uses. The WAWQI was analyzed for two seasons, as shown in Appendix A. From the WAWQI of the dry season samples, 70% of the total water samples was unsuitable for drinking, 10% was very bad, 17.7% was bad, and only 2.5% was good. The water quality of the wet season showed that 60% of the total water samples was unsuitable for drinking, 10% was very bad, 20% was bad, and 10% was good. In general, the surface water quality was better in the wet season than in the dry season.

Besides, the WAWQI of both the wet and dry seasons was mapped to show the spatial distribution of WAWQI using the IDW method (Figure 8). The bad conditions of water quality (high values of

WAWQI) were located in the rice intensification areas. Some bad water quality could be found at tributaries of the Bassac River. It might be caused by water discharged from intensive rice crop areas, tourism and urban areas. In the area surrounded by the Mekong and Bassac Rivers in the northeast, the water quality is found to be better. It may be because the proper operation of the sluice-gates system and the alternatives of intensive rice crops (instead of 3 crops/year, it had shifted to 8 crops for every 3-years, and 5 crops for every 2-years by now). Being surrounded by the two large rivers is also advantageous in that the exchange of inside and outside dike systems may lead to a reduction in pollution by dilution.
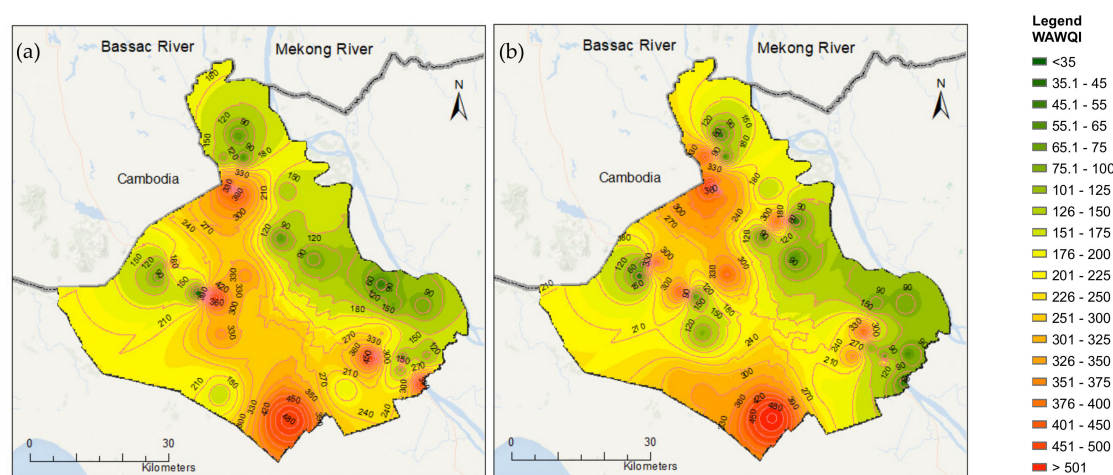
Figure 8. Spatial distribution of weighted arithmetic water quality index (WAWQI) in the (**a**) dry and (**b**) wet seasons using inverse distance weighting (IDW) interpolation.

Overall, the WAWQI values in the wet season are more scattered among the different sites compared to that of the dry season. For example, extreme high WAWQI were found in the northwest and the southwest of An Giang, while the southeast of An Giang was found with good water quality. Regions with high WAWQI were mainly found in the triple-rice system, and the urban area inside the full-dike system was linked with high concentrations of EC, NH_4^+, COD, NO_2^-, and PO_4^{3-}. Contrastingly, locations with low WAWQI mainly represent orchards located inside the full-dike system. The heavy rain in the wet season can dilute pollutant concentrations. Therefore, water quality in this region in the wet season is better than the dry season. The "hotspot" of water quality in the south most of An Giang province is found in both dry and wet seasons. This can be explained by the full triple rice cropping system inside the full-dike system in this location being linked with high concentrations of EC, COD, NO_2^-, and PO_4^{3-}.

4. Discussion

Water is a precious resource for various activities in An Giang. However, due to a rapid rate of increase in rice intensification, urbanization, and tourist area, the water quality has decreased dramatically. This issue was found in various studies in the VMD in recent years [15,21]. The clarification of the seasonal change in water quality was important to evaluate the temporal variations of surface water pollution.

The results show that the concentration of NH_4^+, COD, PO_4^{3-}, and K^+ was relatively higher compared to the World Health Organization (WHO) and the Vietnamese standard for both seasons. Figures 9 and 10 show the concentrations of COD and PO_4^{3-} at the stations of Tan Chau and Chau Doc, respectively, which is close to the Cambodian border. The concentrations of COD showed an increasing trend from 1985 to 2011 at Tan Chau and in 2013 at Chau Doc station. Although COD concentration from 1996 to 2010 in Cambodia was higher than those in Vietnam, most of the COD values were below the permissible standard of Vietnam. From 2015 to 2017, COD has exceeded the Vietnamese standard

for domestic use. Linear progress analysis shows the R^2 values at 0.47 and 0.39 for Tan Chau and Chau Doc stations, respectively. The PO_4^{3-} concentrations from 1995 to 2005 (Figure 10) in the Cambodia side were below the standard of Vietnam, while those concentrations in the Vietnam part fluctuated seasonally and were higher than the permissible standard of Vietnam for several years.
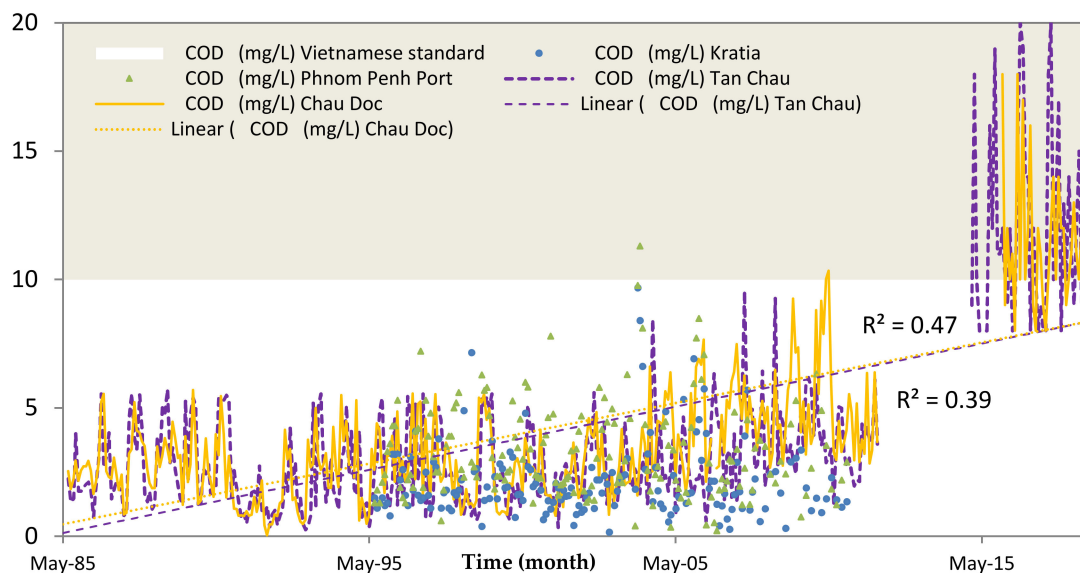
Figure 9. Temporal concentrations of chemical oxygen demand (COD) in the Vietnamese side (Tan Chau and Chau Doc stations) from 1985 to 2017 and in the Cambodia side (Phnom Penh Port and Kratie) from 1995 to 2010.
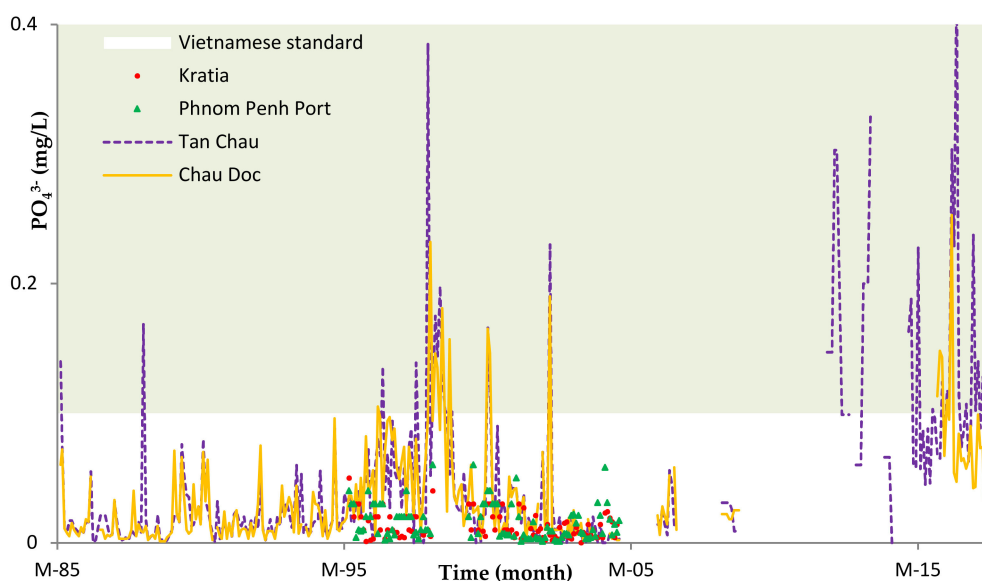
Figure 10. Temporal concentrations of PO_4^{3-} in the Vietnamese side (Tan Chau and Chau Doc stations) from 1985 to 2017 and in the Cambodia side (Phnom Penh Port and Kratie) from 1995 to 2005.

The results of this study show that pH, Cl^-, and calcium were significant discriminant parameters between the two seasons. Cl^- was chosen as an important indicator parameter since its values represent the degree of organic pollution, as mentioned above. The concentration of Cl^- in the dry season was found extremely higher than that in the wets season.

The classification of water quality in this study clearly shows that the status of water bodies in the study area is eutrophic, and it is unsuitable for drinking. It is also observed that most of the pollution loads relatively high in the dry season compared to those in the wet season except NH_4^+ and COD.

Anthropogenic pollutant load is relatively high, as indicated by a higher concentration of PO_4^{3-}, NO_2^- and NO_3^-. These results support the hypothesis that considered water quality deterioration in the dry season.

Furthermore, high concentrations of NO_3^-, NO_2^- and pH in water samples of Cluster 3 inside the full-dike system in the dry season were detected. Meanwhile, high Cl^- and Mg^{2+} were found in water samples of Cluster 3 and Cluster 2, respectively. Minh et al. [21] also found high nitrite and nitrate inside the full-dike system where the triple rice cropping system was dominant in An Giang. The high mean concentration of 90 mg/L in the dry season for Cl^- inside the full-dike system was identified for the influence of wastewater surrounding the urban area and rice fields. Rivers typically have concentrations of Cl^- less than 50 mg/L [64]. The high level of Cl^- may have a negative impact on an ecosystem [64]. This may be an indicator of sewage pollution, which may be from a water softener or sewage contamination discharge from city, located inside the full-dike system. In summary, it also supports the hypothesis that water quality inside the full-dike system is worse than that of outside ones.

The WAWQI for 40 samples ranges from 34 to 1847 in the dry season and from 40 to 1584 in the wet season. Although the range of WAWQI, as well as the minimum values in the dry season, was lower than those in the wet season, the good water quality index of 10% of the location in the wet season was higher than 2.5% of the location in the dry season. The high value of WAWQI at these stations has been found to be mainly due to the higher levels of EC, NH_4^+, and COD. Spatial distribution of water quality using WAWQI values helped to identify factors and processes responsible for water quality evolution.

5. Conclusions

Overall, this study provides an approach for assessing surface water pollutant levels. Water quality in An Giang in the dry and wet seasons has deteriorated tremendously due to urban wastewater discharge and rice intensification in the past 30 years. During the flood season, water from the Upper Mekong River carries high concentrations of pollutants into An Giang. We found high NO_3^-, NO_2^-, Cl^- concentrations inside the full-dike system, while high concentrations of COD and NH_4^+ were found in the urban area and the main river (Bassac River). Most of the water quality samples in both dry and wet seasons were bad or unsuitable for drinking. Thus, the water in An Giang Province should be treated before supplying for drinking water or domestic use. Water quality observation stations along the border should be strengthened to provide a better understanding of the primary pollutant sources that have influenced the surface water quality during the flood season in An Giang as well as the entire VMD.

Appendix A

Table A1. The weighted arithmetic water quality index (WAWQI) at 40 sampling sites in the dry and wet season in 2018.

Sampling Site	Dry Season		Wet Season	
	WAWQI	Water Classification	WAWQI	Water Classification
1	443	Unsuitable for drinking	51	Bad
2	66	Bad	65	Bad
3	241	Unsuitable for drinking	361	Unsuitable for drinking
4	123	Unsuitable for drinking	208	Unsuitable for drinking
5	64	Bad	66	Bad
6	222	Unsuitable for drinking	205	Unsuitable for drinking
7	101	Unsuitable for drinking	124	Unsuitable for drinking
8	198	Unsuitable for drinking	98	Very Bad
9	1847	Unsuitable for drinking	1489	Unsuitable for drinking
10	448	Unsuitable for drinking	239	Unsuitable for drinking
11	1813	Unsuitable for drinking	1584	Unsuitable for drinking
12	187	Unsuitable for drinking	198	Unsuitable for drinking
13	561	Unsuitable for drinking	487	Unsuitable for drinking
14	159	Unsuitable for drinking	312	Unsuitable for drinking
15	339	Unsuitable for drinking	361	Unsuitable for drinking
16	111	Unsuitable for drinking	368	Unsuitable for drinking
17	131	Unsuitable for drinking	151	Unsuitable for drinking
18	131	Unsuitable for drinking	349	Unsuitable for drinking
19	161	Unsuitable for drinking	43	Good
20	81	Very Bad	63	Bad
21	111	Unsuitable for drinking	61	Bad
22	63	Bad	143	Unsuitable for drinking
23	76	Very Bad	75	Bad
24	73	Bad	76	Very Bad
25	52	Bad	107	Unsuitable for drinking
26	595	Unsuitable for drinking	307	Unsuitable for drinking
27	217	Unsuitable for drinking	281	Unsuitable for drinking
28	34	Good	369	Unsuitable for drinking
29	736	Unsuitable for drinking	66	Bad
30	334	Unsuitable for drinking	97	Very Bad
31	334	Unsuitable for drinking	310	Unsuitable for drinking
32	61	Bad	62	Bad
33	67	Bad	48	Good
34	94	Very Bad	77	Very Bad
35	319	Unsuitable for drinking	139	Unsuitable for drinking

Table A1. *Cont.*

Sampling Site	Dry Season		Wet Season	
	WAWQI	**Water Classification**	**WAWQI**	**Water Classification**
36	1075	Unsuitable for drinking	177	Unsuitable for drinking
37	277	Unsuitable for drinking	369	Unsuitable for drinking
38	185	Unsuitable for drinking	274	Unsuitable for drinking
39	78	Very Bad	40	Good
40	102	Unsuitable for drinking	49	Good

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