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Identifying Key Influences on Surface Water Quality in Freshwater Areas of the Vietnamese Mekong Delta from 2018 to 2020

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Abstract: Urbanization, industrialization, and the loss of freshwater resources are leading to an increased awareness of the importance of surface water quality worldwide. Limited ground water resources, prolonged drouths, and flooding are creating pressure on the availability of freshwater sources in the Vietnamese Mekong Delta. However, the surface water quality in this region is measured mainly at the provincial level, without reference to the water quality of adjacent regions. In order to identify and understand the key factors that contribute significantly to the quality of surface water, it is necessary to consider the delta region as a holistic system and to systematically investigate the influence of different land uses on water quality. In this study, surface water quality was evaluated during the dry season, when flow is low and water exchange is limited. For this purpose, the temporal variation in the surface water quality of 12 water quality parameters at 132 monitoring stations was analyzed according to their surrounding type of land use. To further investigate the impact on low-hierarchy canals, a correlation analysis between the river and canal class hierarchy and all investigated water quality parameters was performed. The results show that surface water quality suffers particularly in the case of a low dissolved oxygen (DO) content, with a measured minimum of 0.48 mg/L, and in cases of organic pollution in the form of total suspended solids, biochemical oxygen demand, and chemical oxygen demand, with values up to 146 mg/L, 75.0 mg/L, and 41.0 mg/L, respectively. As the main factors influencing surface water pollution, freshwater aquaculture and industrial activities were identified. This could have a relevant impact on future sustainable land use planning.

Keywords: surface water quality; land use; Vietnamese Mekong Delta; fresh water; dry season; correlation analysis; principal component analysis

Citation: Wehrheim, C.; Lübken, M.; Stolpe, H.; Wichern, M. Identifying Key Influences on Surface Water Quality in Freshwater Areas of the Vietnamese Mekong Delta from 2018 to 2020. *Water* **2023**, *15*, 1295. https://doi.org/10.3390/w15071295

Academic Editors: Chihhao Fan and Sheng-Wei Wang

Received: 15 February 2023
Revised: 19 March 2023
Accepted: 22 March 2023
Published: 25 March 2023

1. Introduction

Surface water quality is gaining increasing attention due to the coupling of the two time-relevant issues of increasing water demand and increasing water scarcity. In particular, in countries with strong economic growth and a high population density, sustainable water resource planning has become a major challenge. With around 21% of the total population and an area of 39,000 km^2, the Vietnamese Mekong Delta (VMD) is one of the most densely populated regions in Vietnam and the most important "rice bowl" in the country. The share of the country's economic output is almost one-third and is largely composed of the proceeds of agriculture [1]. Among the production of rice, vegetables, and fruits, and the overall increasing industrial production, the VMD is a major contributor of aquaculture production for national demand, with increasing international exports within recent decades [2]. Since the green revolution in the 1980s, the transition from traditional to intensified systems, intensified agricultural production with up to three times the annual rice cultivation, and (hyper-) intensive shrimp farming have become increasingly prevalent [3].

However, surface water quality can be strongly affected by changes in land use [4]. While intensified aquaculture activity releases millions of m^3 of wastewater each year, including high amounts of biodegradable organic matter, nitrogen, phosphorous, pathogens, and sludge, agriculture is responsible for high loads of nitrogen, phosphorous, and potassium, as well as pesticide residues, including insecticides, herbicides, fungicides, and other pest control substances [1,5,6]. According to Nguyen 2017, the amount of imported plant protection products increased by more than 100% from 1990 to 2004, since the change from traditional to continuous rice cropping requires a higher usage of fertilizer and pesticides [3]. In addition, urbanization and a prospected increase in population intensify the number of diffuse entries of pollutants into the water bodies that result from urban and rural settlements and contain high amounts of organic pollutants and pathogens. While the Vietnamese Government had specific targets for 2005 that included the equipment of 50% of rural households with sanitary latrines and the connection of 30% of husbandries and 10% of cottage villages with treatment facilities, centralized municipal wastewater treatment is still a rarity, with reported connection rates for urban households of 10% in 2013 and 52% in 2019 [7–9]. However, in addition to diffuse inputs, point discharges have a major impact on surface water quality. Food and seafood processing industries are often responsible for surface water pollution in the VMD, since their untreated wastewater contains high amounts of suspended solids, organic matter, nitrogen, phosphorous, and bacteria [10]. Not all industrial parks and export processing zones that were put into operation within the project area have centralized wastewater treatment plants [8,11]. Therefore, regions with a high population density and strong industrial activity are affected by a severe degradation of water quality due to strong pollution and stagnation [12–14].

Hence, in contrast to their numerous advantages, delta systems are highly vulnerable considering climate-change-induced scenarios (such as increased flooding and prolonged droughts, acid sulphate soils and acid water movements, and a shortage of freshwater sources), as well as severe pollution resulting from industrial, agricultural, and aquaculture activities and discharges from urban and rural living [15]. Studies in the upper parts of the VMD have shown that there is a strong correlation between land use and surface water quality [13,16–20]. The type of land use plays an important role in the understanding of water quality degradation and its prevention. However, the influence of different land use types on surface water has not been studied in a large-scale freshwater area in this region and could make an important contribution to future sustainable water and land use planning. IT-supported tools, such as geographic information systems (GISs), can make an essential contribution to investigations such as this. On the one hand, an extensive comparison of the water quality of entire regions and, on the other hand, a detailed method for examining local conditions are possible [21]. The use of GIS has therefore become an important and powerful tool in regional water and land use planning [22]. Furthermore, the application of statistical methods, such as a principal component analysis (PCA), allows for a deeper investigation of the variance of the measured data in order to identify pollution sources and to determine the significant parameters of water pollution. Recent studies show that PCA is a suitable method to investigate water quality measurement data and improve the monitoring system [13,19,23]. Therefore, this study analyzes (i) the surface water quality of managed freshwater areas in the southern VMD on a large-scale to differentiate between local peculiarities and regional commonalities, (ii) time-dependent changes in surface water quality and land use, (iii) the correlation of water quality and river class hierarchy, and (iv) the potential aggregation of investigated pollution parameters for adjusted monitoring options.

2. Materials and Methods

2.1. The Study Area

The study area is located in the southern part of the VMD and includes all mainland provinces south of the Hau River. The prevailing tropical monsoon climate results in constantly high temperatures and seasonal rainfall, creating a dry season (November–April) and a rainy (May–October) season. During the rainy season, large parts of the area are flooded [24,25]. Highly fertile alluvial soils make agricultural activity prevalent in this region. Irrigation canals in the VMD are classified into categories, depending on their size. Therefore, the complex deltaic river and the canal system consists of nearly 15,000 km of main and primary canals (I) that are 20–45 m in width, about 27,000 km of secondary canals (II) that are 8–10 m in width, and 50,000 tertiary canals (III) that are 2–5 m in width [15]. In accordance with the different flow regimes, the water quality can change strongly between these categories. In addition to seasonal and tidal changes in the flow system, the use of more than 21,500 sluice gates, around 880 culverts, and over 1000 large- and medium-sized electric pumps enables adequate water management, including the subdivision of the area into fresh and saline or brackish water areas. For a better understanding of the waterways, the area is further divided into subregions I–X, depending on the predominant water management. While subregions I–V and IX are almost solely freshwater-fed, subregions VII and X are mainly saltwater-influenced during the dry season. The subregions VI and VIII are divided into a freshwater area and a saline/brackish water area.

2.2. Data Collection and Pre-Processing

For the water quality analysis, data were collected from provincial Departments of Natural Resources and Environment (DONREs) for all seven provinces within the project area: An Giang, Bac Lieu, Ca Mau, Can Tho, Hau Giang, Kien Giang, and Soc Trang. Because land use and regional water quality can change within a year depending on the season, the data included annual sampling at the end of the dry season (March and April) for three consecutive years from 2018 to 2020. Therefore, the same land use and hydrologic conditions could be assumed. Water quality sampling and measurements are specified in the Vietnamese national standards (TCVNs). The threshold values for surface water quality parameters are specified within the Vietnamese national regulations (QCVNs). The data were analyzed for 132 representative freshwater monitoring stations. The observed parameters included temperature (T), pH, dissolved oxygen (DO), total suspended solids (TSS), chemical oxygen demand (COD), biochemical oxygen demand after five days (BOD_5), ammonium–nitrogen (NH_4-N), nitrate–nitrogen (NO_3-N), nitrite–nitrogen (NO_2-N), ortho-phosphate (PO_4-P), total iron (Fe_{total}), and total coliform bacteria (TC). For data validation, the data set was statistically analyzed for extreme values and outliers that could be considered unrepresentative of the homogeneity of the data set. Statistically significant high values measured for TSS ($\geq$150 mg/L), COD ($\geq$80 mg/L), and BOD_5 ($\geq$50 mg/L) were therefore considered outliers. Since no similarly high values were found throughout the study period, these measurements were not considered representative and were removed from the data set to avoid biasing the analysis [26]. Fresh and saline water zones were classified according to the land use and further information on surface water bodies during the dry season.

For the land-use-based analysis, the monitoring stations were classified according to their main surrounding land use type. Therefore, land use characteristics within the project area were investigated according to their relevance and impact on the quality of the water body examined based on its size and vicinity to the respective monitoring station. Then, the monitoring stations were further classified into 6 main categories according to their land use type and additional information about the monitoring station: agriculture, aquaculture, national park, residential land, industrial land, and constructed land (see Figure 1). Due to the interweaving of urban populations and industrial activity, the category of constructed land represents monitoring stations in areas affected by both types of land use. Hence, each monitoring station was assigned an additional attribute depending on the predominant land use with a maximum distance between the monitoring station and the land use type of 50 m. To verify this spatial allocation, a manual visual analysis was performed for all monitoring stations afterwards. All monitoring stations that could not be exactly classified according to their land use system, e.g., due to their location being in transitional zones, were removed from the data set to avoid inaccuracies in the analysis. Data for the land use types were received from the Ministry of Natural Resources and Environment (MONRE).

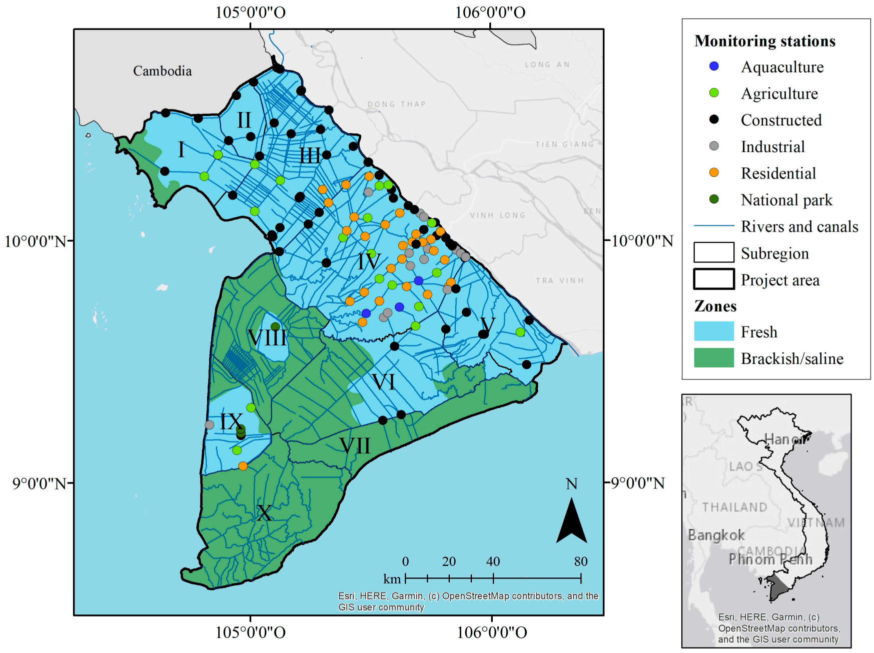

Figure 1. Freshwater monitoring stations within the project area and subregions (I–X) during dry season.

2.3. Methods of Water Quality Assessment

2.3.1. Analysis of Surface Water Quality and Surrounding Land Use

To identify the key influences on the surface water quality within the project region, the pre-processed data were analyzed temporally and regarding the surrounding main land use type. Therefore, the general characteristics of land use types were examined in terms of their calculated area fraction and corresponding relevance to the project area, as well as the statistical characteristics of the surface water quality in the project area. The median monitoring values for each parameter were analyzed according to their exceedance level of national limit values. The underlying values are defined within the Vietnamese technical regulation on water quality (QCVN08-MT-2015/BTNMT).

To further identify the major indicators that contribute to the corresponding water quality, each water quality parameter was analyzed individually according to its assigned land use characteristic for each year of investigation. Therefore, the influence of the main land use types on the investigated water quality parameters could be identified, and the temporal features could be emphasized.

2.3.2. Correlation Analysis

To evaluate the importance of river and canal size in relation to the water quality parameters, a correlation analysis was performed between all studied parameters and the river and canal hierarchy (primary, secondary, and tertiary). For this, the data were tested according to the criteria of Kolmogorov–Smirnov and Shapiro–Wilk. Due to the asymmetric distribution of the data, a non-parametric correlation analysis, the Spearman rank order according to Daniel (1990), was performed [27].

2.3.3. Principal Component Analysis

A principal component analysis (PCA) was carried out for all stations. This analysis method is particularly useful for large data sets to easily identify anomalies and correlations by means of a dimensional reduction with the minimal loss of information. A detailed description of the procedure of the PCA is given in Text S1, Supplementary Material [23,28,29].

Statistical and spatial analyses were performed by using IBM SPSS Statistics (version 28.0.1.1) and ArcGIS (version 10.7), respectively. Data for Ca Mau Province in 2019 were not available during the dry season and could not be evaluated within this study. An overview of the steps of this study can be found in Figure S1, Supplementary Material.

3. Results and Discussion

3.1. Analysis of Surface Water Quality and Surrounding Land Use

The main dominant land use type within the project area is agriculture, including that of rice and other freshwater crops, which account for approx. 84% of the total land use area (see Table 1). Paddy rice yields continued to increase, averaging 0.03 t/ha from 2018 to 2020 [30]. The land use types of residential land, national park, freshwater aquaculture, and constructed land have a much smaller proportion of the total land size, with values of 6.6%, 3.8%, 3.7%, and 2.2%, respectively. However, with a population density of about 460 inhabitants/km^2, an average annual index of industrial production of 107.9%, and an increasing production of aquaculture shrimp and fish of 113.2%, these land uses contribute heavily to the national GDP and have a major impact on water quality in their surroundings through the production and release of wastewater [31,32].

Table 1. Investigated land use types of freshwater land use within the project area of the VMD.

Type of Land Use	Area (ha)	Percent of Total (%)	Monitoring Stations
agriculture	1,057,050	83.6	18
freshwater aquaculture	46,970	3.7	3
forest (national park)	48,290	3.8	5
residential land	83,310	6.6	28
constructed land	28,290	2.2	61
industrial land	n.a.	n.a.	17
total	1,263,910	99.9	132

Note: n.a. = data not available.

The water quality analysis of all freshwater samples from 2018 to 2020 and the corresponding exceedance or undercutting intensity of the calculated median values regarding the national water quality standards are shown in Table 2. This Vietnamese standard is the national technical regulation on surface water quality, which specifies the limit values of water quality parameters in surface water bodies. Measured values are thereby classified into category A or B to assess and control the water quality of inland surface water sources and subsequently represent the proposed applicability of water use (A = domestic use; B = agricultural use or other purposes with low water quality requirements).

Given the tropical climate, the median temperature value lies around 29.2 °C, with a variability of ±1.2 °C, which represents values similar to those in the investigations of Ozaki et al. (2014) and Giao et al. (2022) [12,20]. Temperature is one of the defining parameters for aquatic species and has a relevant influence on chemical and biological processes, as well as the oxygen saturation in the water column. Even though An Giang and Can Tho share a provincial border, the temperature discrepancy here is the highest, with average water temperatures of 30.0 °C and 28.3° C, respectively.

Table 2. General water quality of freshwater samples of investigated monitoring stations with minimum, maximum, and median values as well as the exceedance or undercutting intensity of limit values according to the Vietnamese regulation on surface water quality (QCVN08-MT-2015/BTNMT).

						QCVN08-MT-2015/BTNMT			
Parameter	**Unit**	**n**	**Min**	**Max**	**Median (±STD)**	**A (Domestic)**	**B (Agriculture)**	**Median Exceedance/ Undercut A**	**Median Exceedance/ Undercut B**
T	°C	362	26.9	32.3	29.2 (±1.20)	-	-	-	-
pH	-	374	5.36	8.65	7.16 (±0.40)	6–8.5	5.5–9	0.0%	0.0%
DO	mg/L	336	0.48	7.62	4.46 (±1.00)	≥5	≥4	11%	0.0%
TSS	mg/L	374	10.0	146.0	48.4 (±28.0)	30	50	61.3%	0.0%
COD	mg/L	374	5.22	75.0	17.0 (±9.28)	15	30	13.3%	0.0%
BOD_5	mg/L	374	2.30	41.0	9.00 (±5.74)	6	15	50.0%	0.0%
NH_4-N	mg/L	374	bdl [1]	2.11	0.19 (±0.25)	0.3	0.9	0.0%	0.0%
NO_3-N	mg/L	362	bdl [1]	1.95	0.30 (±0.42)	5	10	0.0%	0.0%
NO_2-N	mg/L	305	bdl [1]	1.10	0.04 (±0.21)	0.05	0.05	0.0%	0.0%
PO_4-P	mg/L	374	bdl [1]	3.03	0.09 (±0.18)	0.2	0.3	0.0%	0.0%
Fe_{total}	mg/L	311	0.03	12.3	0.53 (±0.99)	1.0	1.5	0.0%	0.0%
TC	MPN [2]/100 mL	367	275	2.4×10^5	5.4×10^3 ($\pm 2.1 \times 10^4$)	5000	7500	8.0%	0.0%

Note: [1] bdl = beneath detection limit. [2] MPN = most probable number.

Regarding pH, a median value of 7.16 was calculated, which meets the requirements of national standards A and B and is slightly lower than the value of 7.43 in Can Tho city in March 2020 measured by Giao et al. (2020) [20]. In particular, at high temperatures, pH plays an essential role in the dissociation equilibrium between ammonium ion and ammonia. Ammonia is considered to be toxic to fish at low concentrations. According to Huff et al. (2013), the chronic criteria magnitude (CCC), which gives the thirty-day average concentration for invertebrate sensitivity at the measured pH and T within the study area, should not exceed 0.69 mg NH_3/L [33]. However, since elevated levels of pH have an even stronger influence on the occurrence of NH_3 than temperature and since the monitored pH values remained at relatively moderate values, the proportion of total ammonia that existed as un-ionized ammonia can be estimated to be between 0.007 and 0.024. Despite the low CCC, the presence of NH_3 should not be neglected, even at low concentrations of ammonium.

The DO content in the water shows generally low values, with values ranging from 0.48 mg/L to 7.62 mg/L and a median of 4.46 mg/L; this corresponds to the value of 4.6 mg/L measured by Wilbers et al. (2014) in secondary rivers and canals [13]. Even though the minimum and maximum values are far apart, the standard deviation indicates a rather small range of variation with ±1.00 mg/L. The median value is not only 0.54 mg/L below the requirements for the national standard on domestic water supply (A) but is furthermore below the water quality criteria according to international recommendations [34]. A low oxygen content in the water may originate from elevated levels of pollutants and will further affect the oxidation of biodegradable materials, such as nutrients and organic matter.

The TSS shows a relatively strong fluctuation, with values up to 146 mg/L and a general median of 48.4 mg/L, which exceeds national quality standard A by more than 60%. While natural water bodies contain suspended matter that increase turbidity, exceptionally high values are often coupled with strong organic or inorganic pollution and can further be a carrier for microbial contamination [35,36]. Corresponding to the TSS, BOD_5 and COD show relatively high values, with calculated medians of 9.00 mg/L and 17.0 mg/L, respectively. Even though both medians exceed the quality standard for domestic water use (A) and additionally confirm the assumption of high organic pollution in the freshwater zones of the VMD, these values are lower than those measured in previous studies of around 22 mg/L [13,18].

Nutrients represented by NH_4-N, NO_3-N, and NO_2-N show values from below the detection limit (bdl) up to maximum values that partly exceed those of the national thresholds by several times. Individual measurements of NO_2-N show exceptionally high values up to 1.10 mg/L. This indicates incomplete nitrification due to elevated temperatures and a proportionally high activity of anoxic microorganisms due to the absence of oxygen, which results in the biochemical reduction of nitrate by denitrification. However, the calculated median values of NH_4-N, NO_3-N, and NO_2-N are within the limit values of the Vietnamese regulations, with values of 0.19 mg/L, 0.30 mg/L, and 0.04 mg/L, respectively. The strong deviation of the median values indicates a spatial discrepancy in the results of the nitrogen measurements within the samples. While water that is influenced by human activity can have nitrate concentrations from 1 mg/L to 5 mg/L, natural concentrations in surface water are mainly found to be around 0.1 mg/L [26]. Even though the NH_4-N and NO_3-N levels are similar to the levels in the VMD measured by Stärz (2012), a tendency towards higher levels was observed [37]. Considering the large agricultural areas in the project area, the phosphorus levels could be considered relatively high. However, the calculated median value is 0.09 mg/L, which meets the national requirements for domestic and agricultural purposes.

Investigations on iron show median values of around 0.53 mg/L and relatively high results for individual measurements, with values up to 12.3 mg/L. The median values, however, are within QCVNs A and B. The microbial analysis of total coliform bacteria shows an exceedance of the water quality requirements for domestic purposes (QCVN A) of 8%. However, the measured maximum levels are two $\log_{10}$-steps higher than the median, which indicates a strong inhomogeneity of the data set or a high sensitivity of the data collection, storage, and sampling.

Due to fluctuations in surface water quality between rainy and dry seasons, different values are to be expected during the rainy season. Even though surface water quality is generally worse during the dry season considering the reduced water exchange, the results from previous studies have shown that measured values of turbidity, TSS, and iron were even higher during the rainy season than during the dry season [13,18].

In order to specifically investigate pollution potentials, the following section examines the individual parameters in terms of the surrounding land use type.

3.1.1. Dissolved Oxygen

The boxplot analysis of the quality measurements of the water and its surrounding land use (see Figure 2) shows that the DO values are comparatively low regarding the national standards for surface water according to QCVN classification A for almost all main land use types. Furthermore, the results of this analysis point out that there is a clear trend towards lower DO levels from 2018 to 2020 in the water quality samples for almost all land use types. The only land use type where the trend is not degrading is within national park areas, where the DO levels seem to increase from below to above QCVN quality criteria B, but, still, they remain the lowest at levels around 2.33 mg/L. The highest DO contents are observed at monitoring stations within industrial, constructed, and residential land areas. However, considering the decreasing tendency, agriculture- and aquaculture-affected areas seem to be the strongest affected areas in the case of low oxygen values since the values were already beneath the QCVN criteria A with a decreasing tendency.

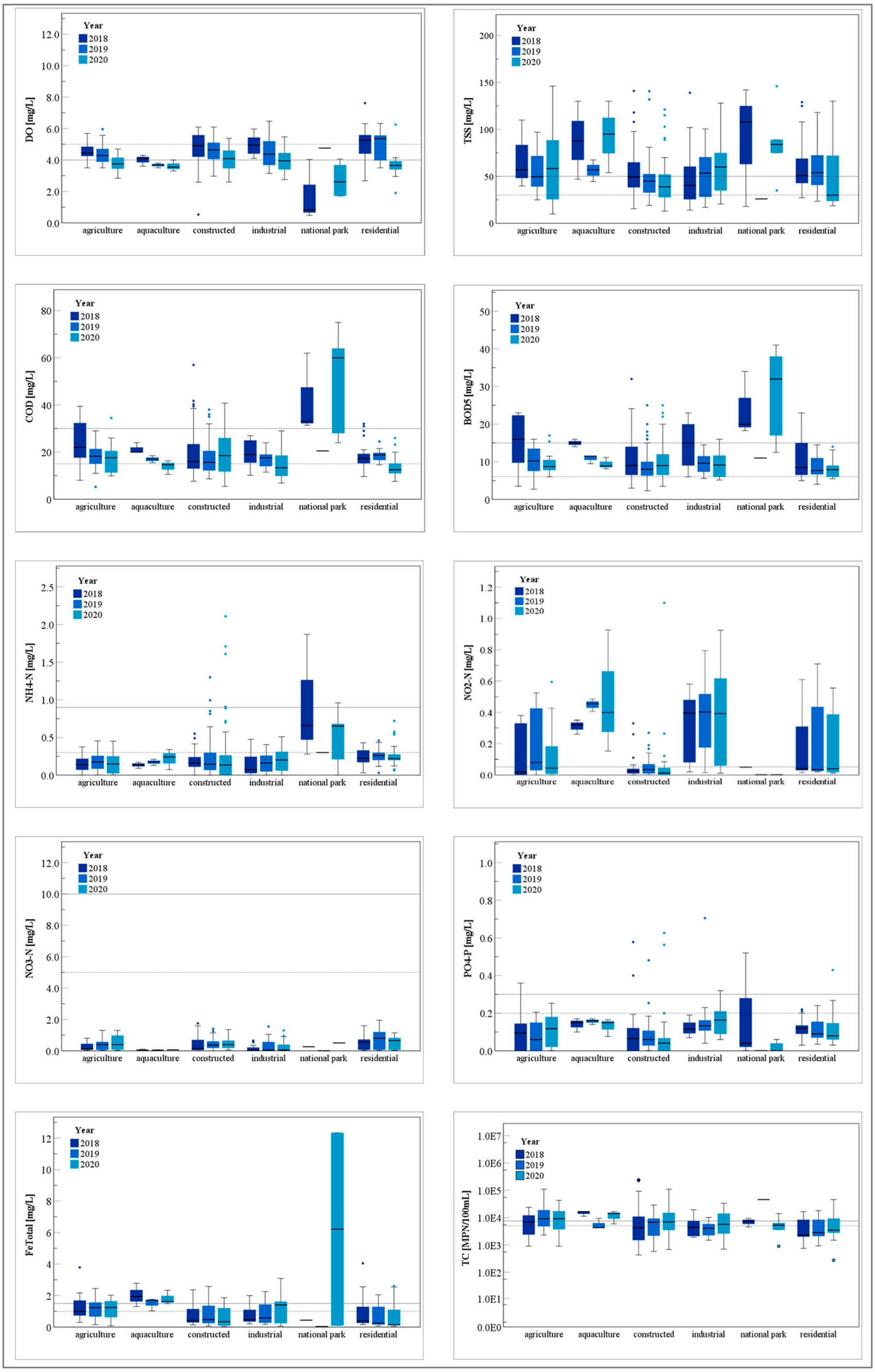

Figure 2. Surface water quality in freshwater monitoring stations at the end of dry season from 2018 to 2020 for main land use types (QCVN A = dashed, QCVN B = line; boxplots showing min, max values with upper (Q3) and lower quartile (Q1) boundaries, median values, and extreme values).

The main contributors to the overall degrading DO content in the water may be the intensification of agriculture and aquaculture farming and the increasing industrial activity, since the released wastewater of the aforementioned land use types often includes highly oxidizable material. Additionally, overall increasing air and water temperatures, which were observed within the project area, affect local water temperatures and result in higher microbial activity and the decreased solubility of oxygen in water. Hence, during the time of the investigation, the average water temperature increased from 29.1 °C to 29.7 °C.

3.1.2. Total Suspended Solids

Regarding the suspended matter within the project area, a strong variation between the samples from meeting the national criteria to exceeding them several times was observed in all investigated land use types. However, a clear trend of increasing TSS was observed in industrial-dominated areas, while the values in residential and constructed areas decreased during the observation period. The suspended matter in agricultural areas remained high, with median values above those in quality standard QCVN B. The highest TSS contents were generally observed in aquaculture-dominated areas and national park land areas, with values up to 95 mg/L and 108 mg/L, respectively, with an overall increasing tendency. In recent years, several investigations have observed that TSS exceeded the national limits in several provinces within the VMD [19,20,38]. However, the boxplot analysis of TSS water quality samples displays a large inhomogeneity of the water samples, which could be due to hydrologic conditions (e.g., flow velocity) or meteorologic events (e.g., rain).

3.1.3. Chemical Oxygen Demand and Biochemical Oxygen Demand

COD measurements are generally low, except in national park areas, where the measured values exceed the national standards several times. However, the median values in agricultural, constructed, and residential land areas remain predominantly constant around the lower boundary of the QCVN standards (B); from 2018 to 2020, the values in aquaculture and industrial land areas tend to decrease from 22.0 mg/L to 13.4 mg/L and from 19.0 mg/L to 13.4 mg/L, respectively. The decreasing values in aquaculture and industrial areas contrast with the statistically increasing activity and the previously observed increasing TSS values in these areas. Given the otherwise strong similarity between the behavior of the measured values of TSS and COD, a correlated increase in values would be expected here. The reasons for this could be an improved self-purification performance of the water body due to temperature increases, improved discharge values, or generally reduced COD loading at these monitoring sites. Since BOD_5 represents the biodegradable compounds within COD, the results regarding BOD_5 show a distribution similar to that of COD, which is an indicator of biodegradable and non-biodegradable organic pollution. Hence, the surface water quality in national park areas seems to suffer from strong organic pollution. This is strengthened by the low DO content since organic pollution is a contributor to low oxygen values. In addition, the managed freshwater areas around national parks in subregion VIII and in subregion IX create stagnation zones that lead to a deterioration in water quality via the intensified agglomeration of pollutants, low flow zones, and limited water exchange.

3.1.4. Nutrients

The NH_4-N levels are relatively low for all land use types, except in national park areas, where the median values are high, and the variability is strong. Therefore, the low-flow areas of the managed freshwater zones in subregion VIII and subregion IX seem to suffer particularly from nitrogen-containing discharge (such as domestic wastewater or agricultural run-off). Extreme values in both constructed land and residential areas may represent fractions of residential land that are included in constructed areas. While the median values of NH_4-N remain relatively constant over the years for nearly all land use types, aquaculture and industrial areas show slight increases from 0.12 mg/L to 0.19 mg/L and from 0.08 mg/L to 0.20 mg/L, respectively.

The results of the NO_3-N analysis show overall low values. Aquaculture and national park areas are distributed along the detection limit, while agricultural, constructed, residential, and industrial land areas show measurable values. In contrast, the NO_2-N values are excessively high in nearly all land use types, especially in aquaculture- and industrial-dominated areas, with average values of 0.33 mg/L to 0.39 mg/L, respectively.

Regarding the analysis of phosphate, a clear correlation between the elevated levels of PO_4-P and aquaculture and industrial areas with average values of 0.15 mg/L and 0.14 mg/L, respectively, can be observed. High values in the national park areas in 2018 suggest strong phosphorous pollution within these areas. However, this is not further observed in the following years, where the values remain below the threshold values. Extreme values above the national thresholds are specifically observed in constructed land areas, representing the high industrial and urban activity. Hence, freshwater aquaculture and (sea-) food processing industries seem to have a relevant effect on the nutrient levels of the surrounding water quality. In particular, pangasius fish farming and processing have been reported to contain, among other pollutants, high amounts of nitrogen and phosphorous [6]. Aquaculture, industry, and urban/rural settlements are common sources of phosphate [2,36]. However, regarding the intense application of fertilizer in agricultural areas, the monitored phosphorous values remain relatively low, with the median values below both national thresholds' limits.

3.1.5. Iron

The measurements of Fe_{total} showed elevated levels in aquaculture-affected and national park areas. While the measurement in national park areas seemed to be generally low, with one peak in 2020, measurements in aquaculture areas remained comparatively high, with values around the upper QCVN quality standard of around 2.0 mg/L. The median values in industrial areas increased from 2018 to 2020, while the values in residential land areas continuously decreased during the time of the investigation. Extreme values were measured in agricultural and residential land areas, with values up to 4.05 mg/L. Elevated levels of iron can be caused by several reasons, such as inhibited iron oxidation due to oxygen limitations, iron-based pollution, or soil leaching from acid sulfate soils [39].

3.1.6. Microbiology

The analysis of TC, as the most probable number (MPN), found overall high values for each land use type with an increasing tendency; in particular, from 2018 to 2020 in constructed and residential land areas, an increase in median values was observed from 4.3×10^3 MPN/100 mL to 7.0×10^3 MPN/100 mL and from 2.3×10^3 MPN/100 mL to 3.5×10^3 MPN/100 mL, respectively. The overall highest median TC contents were observed in agriculture-dominated areas with a value of 9.2×10^3 MPN/100 mL, in aquaculture land with a value of 1.7×10^4 MPN/100 mL, and in national park land with a value of 4.6×10^4 MPN/100 mL. Outbreaks of diseases in aquaculture ponds are common due to high stocking densities and often insufficient water exchange, which has also been reported in the VMD [40]. However, the strong variance in the TC measurements could be an indicator of measurement uncertainty.

3.2. Correlation Analysis of River and Canal Hierarchy and Water Quality

Correlating the water quality parameters with the river and canal hierarchy resulted in a significant but weak correlation between the hierarchy level and NH_4-N (0.30) and NO_3-N (0.20) (see Table 3). With a decreasing river and canal hierarchy from I to III, the amount of measured ammonium–nitrogen content within the samples increased from 0.16 mg/L in the water samples of category I to 0.25 mg/L in category II and to 0.27 mg/L in the samples of category III. The higher the river and canal category, the lower the flow velocity and the size of the river body. Secondary and tertiary canals are especially densely populated, and the agricultural activity is high. Since households within rural areas are unlikely to be connected to a sewer system, domestic wastewater is discharged directly or via the seepage of septic tanks into water bodies [7,9,41]. Therefore, these canals suffer particularly from sever domestic and agricultural pollution. Correlating the results of the investigated secondary canals in Can Tho and Hau Giang provinces underline the high relevance of water quality measurements in rivers and canals of a lower hierarchy order and, furthermore, warn against the untreated use of secondary canal water due to the high level of pollution and the increased potential for health risks [13].

Table 3. Correlation coefficients of river and canal hierarchy and nitrogen content.

	River and Canal Hierarchy (1,2,3)	**NH_4-N (mg/L)**	**NO_3-N (mg/L)**
river and canal hierarchy (1,2,3)	1.00	0.30 **	0.20 **
NH_4-N (mg/L)	0.30 **	1.00	0.21 **
NO_3-N (mg/L)	0.20 **	0.21 **	1.00

Note: ** Correlation is significant at the 0.01 level (2-tailed).

3.3. Principal Component Analysis of Investigated Water Quality Parameters

The principal component analysis was performed to detect local particularities and to evaluate the main factors that explain organic pollution, turbidity, nutrients, and microbial pollution. Four new components with an eigenvalue > 1 (see Text S1, Supplementary Material) that form 79.3% of the total variance of the samples were distinguished. The rotated component matrix (see Text S1, Supplementary Material) showed that cluster 1 is strongly defined by COD, BOD_5, and TSS and, therefore, represents samples with high suspended solid contents that mainly comprise biodegradable organic loading (see Table 4). According to the land use and surface water quality analysis in Section 3.1., this may represent organic pollution that was found especially in national park areas in subregion VIII and subregion IX, where areas with low-flow velocities are predominant and organic particles settle slowly due to their low density [33].

Table 4. Rotated component matrix with the resulting 4 components representing biodegradable organic loading (1), highly oxidizable components (2), nutrients (3), and microbial pollution (4).

Component	**1**	**2**	**3**	**4**
DO	−0.04	−0.80	−0.10	−0.14
TSS	0.59	0.44	0.39	0.13
COD	0.98	−0.03	0.07	−0.03
BOD_5	0.99	−0.01	0.05	−0.05
NH_4-N	0.10	−0.06	0.93	0.13
NO_2-N	−0.08	0.80	0.02	−0.29
PO_4-P	0.18	0.39	0.57	−0.49
Fe_{Total}	0.08	0.79	−0.04	0.22
Coliform	0.00	0.16	0.10	0.85

Note: a Rotation converged in 5 iterations.

The variables of component 2 comprise the loadings of highly oxidizable components (NO_2-N and Fe_{total}) and DO, showing a negative correlation between DO and NO_2-N and Fe_{total}. The highly oxidizing characteristics of the reduced substance nitrite and iron seem to have the strongest influence on the low DO values of the investigated samples for the assessed water quality parameters. Component 2, therefore, could be summarized as the group of "strongly oxidizing pollution". According to the water quality and land use correlation analysis in Figure 2, this group is predominantly found around aquaculture-, industrial-, and residential-dominated areas, since the NO_2-N concentrations in these areas had the highest and the lowest DO values.

Component 3 is defined by high loadings of nutrients represented by NH_4-N and PO_4-P, and, therefore, it is representative of nutritious pollution around agricultural and residential land areas. In contrast to all other components, component 4 is represented by only one parameter: TC. Therefore, this parameter group stands alone and can be understood as microbial pollution.

An overview of the three components that represent organic pollution, nutrient pollution, and highly oxidizing pollution regarding their variance in a three-dimensional space is shown in Figure 3. This clearly shows the spatial similarity of the new components. While TSS, BOD, and COD are found in the right corner of the plot near the maximum value of component 1, the parameters of component 2, NO_2-N, Fe_{total}, and DO, are distributed at the top and bottom of the component plot. The nutrients (NH_4-N and PO_4-P), however, are found at the very front. Since COD and BOD_5 have a similar weighting in component 1, reducing the frequency of the measurements in which both parameters are measured should be considered. The results of the correlation analysis between land use and water quality show a strong correlation between both parameters for all main land use types. Therefore, the costs of the investigation could be reduced, or, alternatively, more site-specific parameters could be included in the regular monitoring program. Since the VMD represents a densely populated river and canal system with high agricultural, aquaculture, and industrial activities, several studies have already shown an increased abundance of antibiotic and pesticide residues and organochloride compounds, as well as an increasing prevalence of antibiotic-resistant bacteria within the water system [42,43].

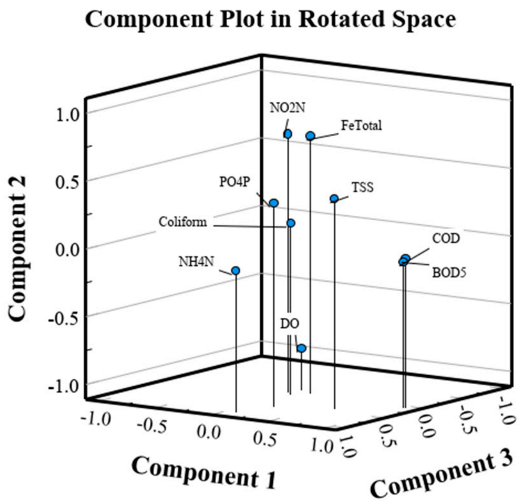

Figure 3. Plotted eigenvalues of components 1–3.

4. Conclusions

The results of this study show that the quality of the surface water in the project area suffers from a low oxygen content and high organic pollution. The large-scale analysis showed that, in contrast to previous studies, this is not only a local problem but rather one that affects the surface water quality of the freshwater areas of the Mekong Delta on a wide scale. Furthermore, the results of the temporal analysis show constantly decreasing oxygen contents, and, thus, not only do they confirm the observation of a far-reaching trend, but they also indicate an urgent need for action.

The correlation analysis of the surface water quality and its surrounding land use pointed out that the water quality has suffered particularly in aquaculture- and industrial-affected areas. Both land use types, especially aquaculture activity, seem to have a strong contribution to elevated levels of TSS, NO_2-N, and PO_4-P, and this results in limited DO concentrations. Furthermore, it could be observed that the monitoring stations in national parks suffer from organic pollution in the case of BOD, COD, and low DO contents. Since these monitoring stations are located within managed freshwater zones, the limited water exchange and flow velocities inhibit the settling, transport, and degradation of pollution sources and, therefore, suffer from elevated levels of organic contaminants. Regarding the importance of these designated areas, more attention should be paid to water exchange, as well as the entry of pollution, due to the increased significance in low-flow areas.

The correlation analysis of river and canals class hierarchy showed that smaller rivers and canals suffer more from elevated levels of nitrogen than larger canals. Since these water bodies are often used for irrigation purposes or for water supply for rural water demand, more investigations should be conducted considering rivers and canals of lower hierarchies. This could be essential not only for the prevailing water quality but also for the health of the human population living there.

The results of this study further show that the investigated parameters can be classified into four main pollution groups: organic pollution, nutrient pollution, pollution by highly oxidizing substances, and microbial pollution. Subsequently, the water quality parameters could be reduced within these groups. This would allow for more cost-effective monitoring and enable the inclusion of more site-specific and highly relevant parameters, such as antibiotic and pesticide residues, organochlorine compounds, or antibiotic-resistant bacteria.

The significance of these results is limited to the statistical investigations and the accuracy of the measurement data in this study. Since the data inhomogeneity limited the explicit assignment of the individual parameters to the respective land use and water body categories, further investigations should be carried out in relation to the hydrodynamic conditions in the study area.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/w15071295/s1. Text S1: Principal component analysis. Figure S1: Flow diagram.

Author Contributions: Conceptualization, C.W.; methodology, C.W.; software, C.W.; validation, C.W.; formal analysis, C.W.; investigation, C.W.; resources, H.S.; data curation, C.W.; writing—original draft preparation, C.W.; writing—review and editing, M.L., H.S. and M.W.; visualization, C.W.; supervision, M.L., H.S. and M.W.; project administration, M.L., H.S. and M.W.; funding acquisition, H.S. and M.W. All authors have read and agreed to the published version of the manuscript.

Funding: This study was part of the project ViWaT—Mekong—Planning, which was funded by the Federal Ministry of Education and Research (BMBF), funding number: 02WCL1474I), Bonn, Germany. The publication was funded by the DFG Open Access Publication Funds of the Ruhr-Universität Bochum.

Data Availability Statement: Data sharing (analysis data and geocoordinates) is not applicable to this article.

Acknowledgments: The authors would like to acknowledge the support by the DFG Open Access Publication Funds of the Ruhr-Universität Bochum. The authors would further like to thank the BMBF for the funding of the ViWaT—Mekong—Planning project, which allowed this study to be conducted.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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