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Spatial and Temporal Analysis of Surface Water Pollution Indices Using Statistical Methods

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Abstract

This study was conducted to evaluate surface water quality using pollution indices including the organic pollution index (OPI), comprehensive pollution index (CPI), and water quality index (WQI), cluster analysis (CA), with the support of one-way analysis of variance (One-way ANOVA), and principal component analysis (PCA). Water quality data at 42 locations, with 22 water quality parameters including temperature, pH, turbidity, salinity, chloride, total dissolved solids, electrical conductivity, sulfate, dissolved oxygen, total suspended solids, biological oxygen demand, chemical oxygen demand, nitrite, nitrate, ammonium, orthophosphate, coliform, E. coli, arsenic, cadmium, lead, and copper, were used for the evaluation. The results showed that all the pollution indices fluctuated spatially and temporally. The OPI index ranged from slight organic pollution to heavy organic pollution, and the OPI values in February and April were higher than those in other months. OPI values were classified as moderate with 54.76% of the locations and heavily polluted with 45.24%. Assessment based on the CPI revealed that 16.7% and 83.3% of locations were classified as moderately contaminated and heavily contaminated, respectively. The WQI classified 45% of the locations as poor and 55% of the locations as having average water quality. In particular, the water quality in August, October, and December was better than that in other months. PCA results showed that eight polluting sources were responsible for 77.1% of the water quality variation. The main surface water polluting sources could be natural sources (riverbank erosion, rainwater runoff), wastewater (domestic, agricultural, and industrial), water discharge from the national park, and livestock areas. Local environmental management agencies need to have appropriate solutions to improve water quality. Future research should focus on the contribution sources to surface water degradation.

Keywords: Dong Thap; Organic Matters; Surface Water Quality; Water Bodies; Water Pollution Index.

1. Introduction

Dong Thap is one of the thirteen provinces of the Vietnamese Mekong Delta. Dong Thap's terrain is relatively flat, with a typical height of 1-2 meters above sea level. The terrain is divided into two large regions: the northern region of the Tien River and the southern region of the Tien River. Dong Thap is located in a tropical climate zone; the climate is divided into two distinct seasons, namely the rainy and dry seasons. In particular, the rainy season usually starts from May to November, and the dry season starts from December to April of the following year [1]. The average rainfall is from 1,170 to 1,520 mm, concentrated in the rainy season, accounting for 90–95% of the yearly rainfall. The climatic characteristics in Dong Thap province are relatively favorable for comprehensive agricultural development [1]. The soil in Dong Thap province can be divided into four main soil groups including alluvial soil (which accounts for 59.06%), and sandy soil (which accounts for 0.04%). Forest resources in Dong Thap are small-scale, which has Melaleuca forest area of less

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than 10,000 hectares [1]. In terms of economics, which includes agriculture, forestry, and fisheries, industry and construction, trade, and services, play a crucial role in the economy of Dong Thap province. In recent years, Dong Thap province's economy has continuously grown [1].

Social and economic development often results in environmental issues, especially water quality degradation [2–6]. Water sources are the recipients of pollutants from the air, including solid waste, domestic wastewater, production wastewater, and industrial wastewater [3, 7-10]. Besides, water use in agricultural production and rainwater runoff are also the main causes of impacts on water quality [9-11]. Therefore, water quality monitoring plays a vital role in protecting water resources and maintaining development activities [9, 12, 13]. Typically, physical, chemical, and biological parameters are monitored [9, 13, 14]. The monitoring location is selected mainly based on the impact source affecting water quality [9, 12]. In Vietnam, monitoring data are evaluated using Vietnamese standards and the water quality index [12, 15]. In the world, surface water quality is evaluated using various pollution indices, such as the comprehensive pollution index (CPI), organic pollution index (OPI), and water quality index (WQI) [16, 17]. Calculating the water pollution indices plays a crucial role in water quality assessment because it is calculated from several parameters, representing the characteristics of the water source [9, 15, 18, 19]. Moreover, the composite index is easy to use, providing information to the community to reflect water quality, thereby improving water quality management and usage planning [9, 15, 19, 20]. Statistical analyses such as one-way analysis of variance (one-way ANOVA), cluster analysis (CA), and principal component analysis (PCA) were also combined and widely applied in strongly supporting surface water quality evaluation [9, 21, 22]. These analytical methods could assist water scientists in identifying similarity or dissimilarity, potential polluting sources, and key variables influencing surface water quality in the study areas.

In Dong Thap province, there has been research on surface water quality using Vietnamese standards and the water quality index [23]. Water quality grouping based on water quality parameters has also been performed [23]. However, surface water quality assessment using several surface water pollution indices, such as the comprehensive pollution index (CPI), organic pollution index (OPI), and water quality index (WQI), with the support of statistical analysis, is still limited. This study was conducted to evaluate surface water quality simultaneously using the OPI, CPI, and WQI indices. In addition, the cluster analysis method is used to group water quality based on these indices. Potential sources affecting surface water quality indicators were analyzed using principal component analysis. The research results provide additional information for selecting water quality assessment indices suitable for monitoring surface water quality in Dong Thap province.

2. Material and Methods

2.1. Description of the Sampling Locations

Dong Thap province belongs to the Mekong Delta region including two parts located on the North and South banks of the Tien River, the North borders Pray Veng province (Cambodia), the South borders Vinh Long province and Can Tho city, the West borders An Giang province, the East borders Long An province and Tien Giang province [1]. The fields of agriculture, industry, and services are crucial aspects of the economic development of Dong Thap province. In recent years, Dong Thap province's economic development has continued to progress well [1]. Economic development can impact water quality. Therefore, monitoring activities at rivers and canals in Dong Thap province were carried out (Figure 1). Forty-two water samples (D1-D42) were collected from the Department of Natural Resources and Environment of Dong Thap province, Vietnam in 2022. The water quality parameters included temperature (°C), pH, turbidity (Turb, NTU), salinity (Sal, ‰), chloride (Cl⁻, mg/L), total dissolved solids (TDS), electrical conductivity (EC, mS/cm), sulfate (SO₄²⁻, mg/L), dissolved oxygen (DO, mg/L), nitrite (NO₂⁻-N, mg/L), nitrate (NO₃⁻-N, mg/L), ammonium (NH₄⁺-N, mg/L), orthophosphate (PO₄³⁻-P, mg/L), coliform (MPN/100mL), *E. coli* (MPN/100mL), arsenic (As, mg/L), cadmium (Cd, mg/L), lead (Pb, mg/L) and copper (Cu, mg/L) [1]. The sampling months were in February, April, June, August, October and December. Sampling, storage, and analysis methods were conducted according to the standard methods [24].

2.2. Calculation of the Water Quality Pollution Indices

The Organic Pollution Index (OPI) was calculated using Equation 1 [19].

$$OPI = \frac{COD}{COD_s} + \frac{DIN}{DIN_s} + \frac{DIP}{DIP_s} - \frac{DO}{DO_s}$$
(1)

In which DIN included NH_4^+ -N, NO_3^- -N, NO_2^- -N; DIP included P-PO₄³⁻; COD, DIN, DIP and DO were the actual measured values in surface water; the values of COD_s, DIN_s, DIP_s and DO_s were obtained from the national technical regulations on surface water quality (QCVN 08-MT:2015/BTNMT column A1) [14].



Figure 1. Maps of the sampling locations

Comprehensive Pollution Index (CPI) was calculated by Equation 2 [19], in which n is the number of parameters (DO, Cl⁻, TSS, COD, BOD, NO₃⁻-N, NO₂⁻-N, NH₄⁺-N, P-PO₄^{3⁻}, coliform, *E. coli*, As, Cd, Pb and Cu); C_i and S_i were the actual measured concentrations and the limit values of parameters in QCVN 08-MT:2015/BTNMT column A1, respectively [14].

$$CPI = \frac{1}{n} \sum_{i=1}^{n} PI_i$$

$$PI_i = \frac{C_i}{S_i}$$
(2)
(3)

The water quality index (WQI) was calculated using temperature, pH, DO, COD, BOD, $NO_3^{-}N$, $NO_2^{-}N$, $NH_4^{+}-N$, P-PO₄^{3⁻}, coliform, *E. coli*, As, Cd, Pb, Cu followed the technical guidance on calculating and announcing Vietnam water quality index (Decision No. 1460/QD-TCMT) [15]. The OPI calculation was used to apply the weight of the parameter group in the WQI calculation. Specifically, according to Decision No. 1460/QD-TCMT [15], if the water body is organically polluted, the parameter group (*i.e.*, DO, COD, BOD, $NO_3^{-}-N$, $NH_4^{+}-N$ and $P-PO_4^{3^-}$) and microbiological group (coliform and *E. coli*) will have weights of 2 and 1, respectively. The values of OPI, CPI and WQI classify surface water quality as shown in Table 1.

Table 1. Classifications of surface water quality using OPI, CPI and WQI

Values of OPI	Water quality	Values of CPI	Water quality	Values of WQI	Water quality
OPI < 0	Excellent	0 - 0.2	Excellent	91 - 100	Excellent
$0 \leq \mathrm{OPI} < 1$	Good	0.21 - 0.4	Good	76 - 90	Good
$1 \leq \mathrm{OPI} < 2$	Initially polluted	0.41 - 1	Slightly polluted	51 - 75	Moderate
$2 \leq \mathrm{OPI} < 3$	Slightly polluted	1.01 - 2	Moderately polluted	26 - 50	Poor
$3 \leq \mathrm{OPI} < 4$	Moderately polluted	> 2.01	Heavily polluted	10 - 25	Very poor
OPI > 4	Heavily polluted			< 10	Heavily polluted

2.3. Statistical Analyses

The average differences in water quality indices according to the months of the year and sampling locations were evaluated using the analysis of variance (one-way ANOVA). The cluster analysis (CA) and Principal component analysis (PCA) were used to group water quality indices at the sampling stations and to identify main sources impacting surface water quality in the study areas, respectively. After CA analysis, one-way ANOVA analysis was applied to test for statistically significant differences between clusters. SPSS software (Version 20, IBM, Armonk, NY, USA) and Primer software (Version 5, Primer-E Ltd, Plymouth, UK) were used for one-way ANOVA and CA, PCA analyses, respectively.



Figure 2. Flowchart of the study

3. Results and Discussion

3.1. Spatial and Temporal Variation of Organic Pollution Index

The spatial variation of the organic pollution index is presented in Figure 3. Figure 3 illustrates that the OPI index changed according to the sampling locations, meaning that the OPI index was affected by economic and social activities. In other words, the OPI index depends on the type of waste discharged into the water source in the study area. The organic pollution index at 42 sampling locations ranged from 2.2±0.8 to 16.7±16.6, indicating water quality from slight organic pollution to heavy organic pollution. Specifically, slight and moderate organic pollution accounted for 21.4% (9 out of 42 locations) and 23.8% (10 out of 42 locations), whereas heavy accounted for 54.8% (23 out of 42 locations). Locations with the lowest organic pollution index included the D2 location (a branch of the Tien River), and locations with the highest organic pollution index included locations D14-D16 (related to Tram Chim National Park, where stagnant water is exchanged with the river). The results showed that polluted water from Tram Chim National Park had a great impact, significantly increasing the organic matter concentration in surface water. Other sources of impact, such as wastewater from agriculture and waste from market areas, had an impact on organic matters in surface water, but not as much as the impact from wastewater from Tram Chim National Park. The research by Hong & Nguyen (2023) [25] also showed that the water flowing from the Lung Ngoc Hoang Nature Reserve was black, mainly due to the presence of organic matter, supporting the findings of the current study. Previous studies showed that water affected by human activities (markets, agriculture, industry, etc.) also contained levels of organic substances exceeding allowable limits [25–30]. Former studies also showed that the OPI index fluctuated spatially related to the influence of wastewater discharge [30-33]. The presence of organic matter in surface water makes the water smelly, causing increasing costs in the water supply treatment process [34, 35]. Furthermore, the presence of organic matter could lead to the formation of compounds harmful to human health during the use of surface water as a domestic water supply [35–37]. The results of this study provide useful information for the water supply sector. For instance, surface water with a low OPI value should be used as intake water for the treatment process.



Figure 3. Spatial variation of OPI

Figure 4 shows that the organic pollution index in the study area was subjected to temporal variation. The OPI index ranged from 2.9 ± 4.4 to 9.1 ± 4.5 , showing that surface water ranged from slight organic pollution to heavy organic pollution. Organic pollution in surface water in the study area was found to be the lowest in August (moderately polluted), October (moderately polluted), and December (slightly polluted), and it had the highest organic pollution index in February and April (heavily polluted). The results showed that the organic pollution index in the dry season (February and April) was significantly higher than that in other months in 2022. This could be explained by the lower water flow in the river in the dry season, leading to higher pollution. OPI values in the water bodies in Can Tho city showed that surface water was organically polluted all year round, with apparent seasonal fluctuations, in which organic pollution was the highest in March and the lowest in September [38]. The OPI values in surface water were seasonally varied because organic matter in surface water fluctuated over time [33, 39, 40]. However, it was found that the organic pollution in this study was significantly higher than that reported in the water bodies in the previous studies [31, 33, 40].



Figure 4. Seasonal variation of OPI

Clustering surface water quality using OPI values formed four groups (Figure 5). Group IV had the highest average OPI value of 16.47, including three positions D14–D16. Group II had an average OPI value of 3.36 with 23 locations (Table 2). Group III had four positions (D8, D12, D27, and D28), while Group I had 12 positions with an average OPI value of 5.97. The results indicated that surface water in the study area had organic pollution at a moderate level (23 locations, accounting for 54.76%) and a heavy level (19 locations, accounting for 45.24%). Organic pollution in the water bodies of Dong Thap province tended to be more severe than organic pollution in the water bodies of Can Tho city (OPI < 4) [38]. Previous research also showed that 44.66% of water samples in the Damodar River were heavy organic pollution [30]. The result of the current study was comparable with other studies; this could mean that surface water quality tends to be polluted by organic matters.



Figure 5. Clustering surface water quality using OPI

	Fable 2.	Characteristics	of OPI in	the identified	clusters
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Cluster	Sites in clusters	Number of sites	%	OPI _{average}	Water quality
Ι	D1, D6, D7, D10, D11, D13, D17, D18, D19, D29, D32, D37	12	28.57	5.97	Heavily polluted
Π	D2, D3, D4, D5, D9, D20, D21, D22, D23, D24, D25, D26, D30, D31, D33, D34, D35, D36, D38, D39, D40, D41, D42	23	54.76	3.36	Moderately polluted
III	D8, D12, D27, D28	4	9.53	9.13	Heavily polluted
IV	D14, D15, D16	3	7.14	16.47	Heavily polluted

3.2. Spatial and Temporal Variation of Comprehensive Pollution Index

CPI values in water bodies in the study area showed slight spatial variation. However, there are significant water quality fluctuations at locations D11, D23, and D29; heavy metals and *E. coli* were the causes of this fluctuation, which means that water quality is significantly affected by waste sources depending on the time of year. CPI values varied from 1.77–9.18, with values less than 2 at positions D4–D7, D34, and D41–D42. The research results showed that CPI values classified water quality at all surveyed locations as moderate to heavily polluted, especially at the D1-D3, D23, and D29 locations (Figure 6). There was about 16.7% moderate pollution and 83.3% heavy pollution. This finding is similar to the previous studies, which showed that CPI fluctuates over space [38].



Figure 6. Spatial variation of CPI

The average comprehensive pollution index in the study area ranged from 2.4 to 6.2 (Figure 7). The CPI value showed that the surface water quality of Dong Thap province was heavily polluted. The parameters that were the leading

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causes of seriously polluted water quality include TSS, coliform, and *E. coli*. The highest CPI value was found in August, and the lowest value was found in April, June, October, and December. The unusual fluctuation in August was mainly caused by outlier sites such as D1-D3 and D14-D16 (Tram Chim National Park). The results of this study confirmed that the comprehensive pollution index also fluctuated depending on the month. Former research by Giao et al. (2022) [38] in Can Tho city's water bodies showed that the CPI index also fluctuated seasonally, in which the CPI value in December being significantly higher than those in March, June, and September. The current study recorded the opposite of Giao et al. (2022) [38], which had the lowest value in December and the highest value in August. It could be due to the location and activities of the study area, which is adjacent to the flow and influenced by An Giang and Dong Thap provinces. Furthermore, the opening of water exchange culverts and the closing of sluices in the Tram Chim National Park area are carried out from July to August and October to December, respectively [41].





Similar to the organic pollution index, surface water quality based on the CPI index was also divided into four groups (Figure 8). Group I had the highest average CPI value (9.03), including three positions from D1-D3. Then, Group IV had an average CPI value of 4.65, including positions D11, D12, D13, D14, D16, D23, D28, D29, and D30. Group III had 11 positions (Table 3) with an average CPI value of 2.99. Finally, Group II had an average CPI value of 2.15, with 19 positions. Thus, it can be seen that all clusters have heavily polluted water quality. Previous research in Can Tho city's water bodies [38] showed that surface water quality assessed through the CPI index was less polluted than that in water bodies in Dong Thap province. In Can Tho City's water bodies, the CPI classified water quality as moderate to heavily polluted, of which only nearly 8% of locations had severe pollution levels [38]. Hoque and Islam (2024) [30] reported that 73.39% of water samples in the Damodar River (India) had a low CPI, indicating slight pollution. However, Kuma et al. (2023) [32] reported that the water quality of the Chambal River was rising due to pollution from artificial activities since the CPI values were in the unsafe ranges.



Figure 8. Clustering surface water quality using CPI

Cluster	Sites in clusters	Number of sites	Percentage (%)	CPIaverage	Water quality
Ι	D1, D2, D3	3	7.14	9.03	Heavily polluted
П	D4, D5, D6, D7, D8, D9, D18, D19, D24, D26, D32, D33, D34, D37, D38, D39, D40, D41, D42	19	45.24	2.15	Heavily polluted
III	D10, D15, D17, D20, D21, D22, D25, D27, D31, D35, D36	11	26.19	2.99	Heavily polluted
IV	D11, D12, D13, D14, D16, D23, D28, D29, D30	9	21.43	4.65	Heavily polluted

Table 3. Characteristics of CPI in the identified clusters

3.3. Spatial and Temporal Variation of Water Quality Index

The average WQI values in the study area ranged from 33 ± 6 to 66 ± 19 , classifying water quality from poor to moderate (Figure 9). The locations with the lowest WQI values were at D14 (Tram Chim National Park), D27 (affected by the market area), and the highest were at D2, D4-D6 (locations on the So Thuong River, Trung Uong Canal, and all rivers connected to the Tien River). The research results showed that, besides causing organic pollution to water sources, water from the national park greatly impacted the overall water quality of the area. Therefore, Tram Chim National Park can be considered a pollutant-generating area that needs to be monitored.



Figure 9. Spatial variation of WQI

The seasonal change in the water quality index is presented in Figure 10. The research results showed that WQI values ranged from 43.1 ± 14.2 to 65.5 ± 15.5 , corresponding to poor to moderate water quality. The best water quality was found in June, and the lowest water quality was found in February. The months with poor water quality include February and April, while June, August, October, and December had average water quality. The temporal fluctuation of the WQI index has also been reported in previous studies [28, 38, 42]. For example, in Can Tho city's water bodies, water quality in March and September was classified from average to very good; water quality in December was graded from poor to very good [38]. A former study reported the seasonal variation of WQI values, in which water quality in the summer season was from moderate to good, while water quality was from poor to good in the monsoon and winter seasons [43]. Nguyen et al. (2022) [44] reported that surface water quality in a coastal province of Vietnam was widely varied by season. About 65% of the sampling locations were classified as having very poor water quality. The categories of excellent, good, moderate, and poor were only occupied by 4%, 20%, 6%, and 4%, respectively [44].

Water quality grouping based on the WQI index is presented in Figure 11 and Table 4. The grouping results showed the difference between WQI values at 42 research locations divided into four groups. Group IV had an average WQI value of 36 including two positions (D14 and D27). Group III included 17 locations and had an average WQI value of 48. Group II had an average WQI value of 55 with 14 locations. Group I had 9 locations with an average WQI value of 63. The final results showed that water quality was classified into two categories, which were poor (19 locations, accounting for 45%) and moderate (23 locations, accounting for 55%). In Can Tho city's water bodies, the WQI index classified water quality from moderate to excellent, of which 50% of locations had excellent water quality and 47% of locations had good water quality. Only 3% of the locations had moderate water quality [38]. Kuma et al. (2023) [32] revealed that WQI values were not within the safe limits after crossing the Kota Dam (Kota, Rajasthan), indicating the rising levels of pollution due to manufactured activities. Another study found that river water (Surma River, Bangladesh)

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with very poor, poor and good were 12%, 72% and 16%, respectively [28]. Khan et al. (2023) [45] evaluated the quality of water in Jamuna River using six WQI models and all indicated that water quality fell into the lowest category. These studies used different ways of calculating WQI to assess water quality; however, it was common that water quality globally was on the decline, with most being classified as poor to moderate.



Figure 10. Seasonal variation of WQI



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Cluster	Sites in clusters	Number of sites	Percentage (%)	WQI _{average}	Water quality
Ι	D1, D2, D3, D4, D5, D6, D24, D25, D32	9	21.43	63	Moderate
II	D7, D12, D17, D19, D23, D26, D31, D33, D34, D36, D39, D40, D41, D42	14	33.33	55	Moderate
III	D8, D9, D10, D11, D13, D15, D16, D18, D20, D21, D22, D28, D29, D30, D35, D37, D38	17	40.48	48	Poor
IV	D14, D27	2	4.76	36	Poor

3.4. Identifying Polluting Sources and Key Parameters Impacting Surface Water Quality

Principal component analysis results showed that there were at least eight main sources (explaining 77.1% of water quality variation) affecting surface water quality in the study area (Table 5). The results showed that the sources affecting water quality in water bodies of Dong Thap province were very diverse. Former research on surface water quality in Ca

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Mau province showed that there were at least three main sources affecting water quality [46]. Surface water quality in the South of Vietnam was affected by five main factors [47]. Surface water quality in Vinh Long province was explained by four principal sources [48]. Surface water quality in Hau Giang province was explained by three main sources [49]. As can be seen that, surface water quality in Dong Thap province was influenced by more polluting sources than that in other water bodies in the Mekong Delta of Vietnam.

Par/PC	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
pH	-0.307	-0.234	0.003	0.081	-0.171	-0.199	0.006	-0.136
Temp.	0.211	0.121	0.236	-0.105	0.343	-0.309	-0.007	0.211
DO	-0.208	-0.301	0.076	-0.315	-0.076	-0.099	0.110	0.160
EC	-0.019	-0.243	-0.272	0.277	0.012	0.194	0.073	0.083
TDS	-0.007	-0.207	-0.302	0.183	0.320	0.189	0.149	-0.062
Turb.	0.084	-0.337	0.072	-0.123	0.044	-0.391	-0.011	0.268
Sal.	-0.032	0.025	-0.001	0.353	0.363	-0.224	0.396	0.207
Cl ⁻	0.065	-0.393	-0.043	0.430	-0.018	0.057	0.063	0.128
TSS	0.165	-0.325	0.097	-0.273	-0.025	-0.166	0.267	0.069
COD	0.370	-0.016	0.128	0.106	-0.128	0.131	-0.008	0.074
BOD	0.370	-0.007	0.126	0.123	-0.129	0.087	0.010	0.086
$\mathbf{NH_{4}^{+}}$ -N	0.251	-0.189	-0.205	-0.062	0.283	-0.118	0.077	-0.437
NO ₃ ⁻ -N	0.394	-0.014	0.034	0.035	-0.101	-0.100	-0.090	-0.079
NO2 ⁻ -N	0.331	-0.023	0.029	0.141	-0.325	-0.073	-0.039	0.193
PO4 ³⁻ -P	0.333	-0.053	-0.089	-0.031	0.168	0.034	-0.151	-0.375
SO_4^{2-}	0.174	0.028	-0.271	-0.197	-0.296	0.288	0.254	0.191
As	-0.015	-0.011	0.262	-0.179	-0.017	0.381	0.607	-0.080
Cd	0.034	-0.033	-0.032	-0.172	0.432	0.406	-0.342	0.513
Pb	0.161	0.052	-0.426	-0.260	-0.004	-0.178	0.189	0.123
Cu	-0.010	0.431	0.004	0.341	-0.054	-0.182	0.235	0.162
Coliform	0.080	-0.003	0.519	0.010	0.233	0.162	0.135	-0.171
E. coli	-0.057	-0.365	0.281	0.193	-0.145	0.091	-0.174	0.019
Eigenvalues	5.56	3.08	1.97	1.55	1.38	1.26	1.15	1.03
%Var.	25.3	14.0	9.0	7.0	6.3	5.7	5.2	4.7
Cum.%Var.	25.3	39.3	48.2	55.3	61.5	67.3	72.5	77.1

Table 5. Potential sources and parameters influencing surface water quality

In this study, PC1 explained that 25.3% of the surface water variation was related to pH, chemical oxygen demand, biological oxygen demand, nitrate, nitrite and orthophosphate. PC2 was responsible for 14% of water quality variation related to parameters such as dissolved oxygen, turbidity, chloride, total suspended solids, copper and *E. coli*. PC3 was related to total dissolved solids, lead and coliform, explaining 9% of the variation in water quality. DO, salinity, Cl⁻ and Cu in PC4 explained 7% of the water quality variation. PC5 was weakly correlated with temperature, total dissolved solids, salinity, nitrite and cadmium. PC5 explained 6.3% of water quality variation. PC6 was weakly correlated with temperature, turbidity, arsenic and cadmium, while PC7 was weakly correlated with salinity, cadmium and moderately correlated with arsenic. PC8 explained 4.7% of water quality variation, with the critical contribution of N-NH₄⁺, P-PO₄³⁻ and Cd. The parameters (*i.e.*, pH, TSS, BOD, COD, N-NH₄⁺, N-NO₃⁻, Pb, coliform and *E. coli*) were only affected by one source of pollution. However, temperature, dissolved oxygen, total dissolved solids, turbidity, chloride, nitrite, orthophosphate, arsenic and copper were affected by two sources of pollution. In particular, salinity and cadmium parameters were affected by three and four pollution sources. Sulfate was affected by four sources; however, sulfate had a very weak correlation with these sources.

Previous studies reported that pH fluctuations were mainly due to the presence of aquatic plants, nitrification, and industrial wastewater [5, 9, 50, 51]. The variation of DO, BOD and COD concentrations were mainly due to the presence of organic matters [52, 53]. The increase in TSS concentration was mainly due to river bank erosion, resuspension of sediment and stormwater runoff [4, 52]. The presence of nutrients mainly came from domestic wastewater and agricultural wastewater [2, 9, 21, 52]. The presence of coliform and *E. coli* was mainly due to poor hygiene conditions and the discharging of animal and human waste directly into the environment [9, 54]. Heavy metals mainly stem from industrial activities, fertilizers, and pesticides containing heavy metals [9, 21, 55]. In this study, the main sources could be possible including natural sources (riverbank erosion, rainwater runoff), wastewater (domestic, agricultural, industrial), water discharge from the national park and livestock.

4. Conclusion

The results showed that water pollution indices in water bodies in the study areas were spatially and temporally varied. The OPI classified water quality from slight organic pollution to heavy organic pollution, in which OPI values in February and April were higher than in the remaining months. The CPI presented surface water as heavily polluted, with the pollution status in August significantly higher. WQI classified water quality from poor to moderate, with water quality in August, October, and December being better than in other months. In the study area, about 54.76% of the survey locations had moderate organic pollution, and 45.24% had heavy organic pollution. The CPI index showed that 83.3% of locations had heavily polluted water quality. The WQI index categorized water quality into poor (19 locations, accounting for 45%) and moderate (23 locations, accounting for 55%). The principal component analysis identified eight sources responsible for 77.1% of water quality fluctuations. The main sources of water pollution are derived from natural sources (riverbank erosion, rainwater runoff), wastewater (domestic, agricultural, and industrial), the national park, and livestock. The use of various pollution indices could provide useful information for local environmental authorities in surface water quality assessment and management.

5. Declarations

5.1. Author Contributions

L.D.K. and P.Q.N. contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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