Assessment of Cau River water quality assessment using a combination of water quality and pollution indices

Cao Truong Son, Nguyen Thị Huong Giang, Trieu Phuong Thao, Nguyen Hai Nui, Nguyen Thanh Lam and Vo Huu Cong

ABSTRACT

This research aims at using a combined water quality index (WQI) and pollution index (PI) to assess and characterize river water quality of Cau River which is one of the longest rivers in the north of Vietnam. Five different water quality and water pollution indices were used including the Water Quality Index (WQI), Comprehensive Pollution Index (CPI), Organic Pollution Index (OPI), Eutrophication Index (EI), and Trace Metal Pollution Index (TPI). The combined water pollution indices show more serious pollution towards the river downstream. In particular, CPI and OPI reveal a high risk of eutrophication. Cluster analysis was applied to classify water monitoring points into different quality groups in order to provide a better understanding of the water status in the river. This study indicates that a combined water quality analysis could be an option for decision making water use purposes while its single index shows the current situation of water quality.

Key words | Cau River, polluted index, water quality, water quality index

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INTRODUCTION

Water is a vital commodity, both to sustain life and for the global economy. However, the quality of global water has rapidly declined for decades due to the impact of both natural and anthropogenic factors (Vadde *et al.* 2018). Assessing water quality for different water use purposes, such as domestic use, irrigation, conservation and industrial usage, are an important strategy for food safety and human health. Water quality evaluation aims to identify the sources of water pollution and develop a strategy for sustainable water source management, maintaining and promoting human health and other social and economic growth (Carroll *et al.* 2006). Surface water quality indexes have been developed and introduced worldwide by researchers with various applications of the Nation Sanitation Foundation Water Quality Index (NSFWQI) (Carroll *et al.* 2006), the Water Quality Index (WQI) (Gupta *et al.* 2003; Chaturvedi & Bassin 2009; Rocha *et al.* 2015; Sener *et al.* 2017), the Comprehensive Pollution Index (CPI) (Matta *et al.* 2017), the Organic Pollution Index (OPI) (Mezbour *et al.* 2018), the Trace Metal Pollution Index (TPI) (Reza & Singh 2010), the Eutrophication Index (EI) (Liu *et al.* 2011) based on the the database of water monitoring parameters. In Vietnam, research on water quality assessment mostly focuses on comparing the concentration of pollutant to the national surface water quality standard (MONRE 2015). The WQI has been used for 10 years (VEA 2011), however, a combination of WQI with other water pollution indices was not applied widely for water quality assessment research.

Vietnam has abundant water resources with up to 2,360 rivers being over 10 km in length. There are 16 river basins in the whole country with an area larger than 2,500 km^2. The average annual surface flow of Vietnam's river basin ranges from 830 to 840 cubic meters per year and the annual rainfall is around 1,940 mm. Despite the abandance of natural water sources, Vietnam is still considered as a

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water shortage country due to three main causes. About 72% of the river basins are distributed outside the country, which accounts for 63% of the total national water source (equal to 520–525 billion cubic meter) and the volume of water coming from inside the country area only is 37%, around 310–315 billion cubic meters (MONRE 2006). Vietnam water resources are distributed unequally throughout geographical location and seasons. The Cuu Long River delta basin has the largest water proportion at 60%, the Hong and Thai Binh rivers have nearly a fifth of the national water volume at 16%, and less than a quarter of the total water volume belongs to other rivers. Vietnam also has seasonal precipitation in which the rainfall is concentrated mostly in the summer season and the other seasons have less than a third of the total rainfall. Therefore, many areas suffer drought for several months, especially in the winter (MONRE 2012). The other reason is water pollution. The water quality in Vietnam recently has been declining significantly under the pressure of population and economic growth.

Currently, the average water consumption is 9,560 cubic meter per capita annually. It is slightly lower than the middle water consumption country according to the average level of the International Water Resource Agency (IWRA). However, Vietnam accounts for a half (ca. 4,000 cubic meters) while other sources come from neighboring countries (MONRE 2012). The Vietnamese government has implemented various national water monitoring programs to protect the water environment. From 2008 to 2018, the general water monitoring programs of ten main river basins were established and implemented. In this study, we use a monitoring database in Cau River basin (from 2008 to 2018) to calculate the quality index and pollution index. The results of this study provide clear scientific evidence to regulate the situation of water quality of this river. The case of Cau River water evaluation could propose a solution for the Vietnamese government in applying water quality indices to managing and monitoring water sources in the future.

RESEARCH METHODOLOGY

Study area

Cau River is the longest river branch of the Thai Binh River system at 288 km and its basin area covers 6,030 km^2 (Figure 1). The Cau River flows through four provinces including Bac Kan, Thai Nguyen, Bac Ninh and Bac Giang before being discharged into the Thai Binh River to the sea. The river's width changes following the flood season and drought season from 100 to 50 m, respectively. The river's bed is larger and the slope reduces to 0.05%. The downstream river is located in two provinces, Bac Giang and Bac Ninh, with an average elevation of 10–20 m (MONRE 2006).

According to the Center for Environmental Monitoring of Vietnam (CEM) water monitoring report (2018), there are 63 pollution sources discharging into Cau River which are scattered along four provinces: Bac Kan, Thai Nguyen, Bac Giang and Bac Ninh. The upper part is located in Bac Kan Province, and the population density is low at 65.65 persons per square kilometer. This area has ten pollution sources mostly related to agriculture production and residential activities. The middle part of the river flows through Thai Nguyen province, and it has a high population density as well as heavy industrial activities. CEM's water monitoring program at Cau River Basin has identified 16 sources of pollution in this area. The downstream of the river crosses two provinces, Bac Giang and Bac Ninh. These are populated places with diverse economies: agriculture, industrial and craft villages. The total waste water discharge into the river is estimated at 138.192 cubic meters per year (Table 1). The location of these pollution sources is the foundation for the establishment of water monitoring points.

Water sampling

Monitoring locations

A total of 22 monitoring points were selected for sampling of which six points are located in Bac Kan province, seven points in Thai Nguyen Province and the remainder belong to Bac Giang and Bac Ninh Provinces. A description of water sampling location is summarized in Table 2.

Monitoring parameters

Water monitoring statistics of 22 points in the period of 2008–2018 from CEM was collected. Each water

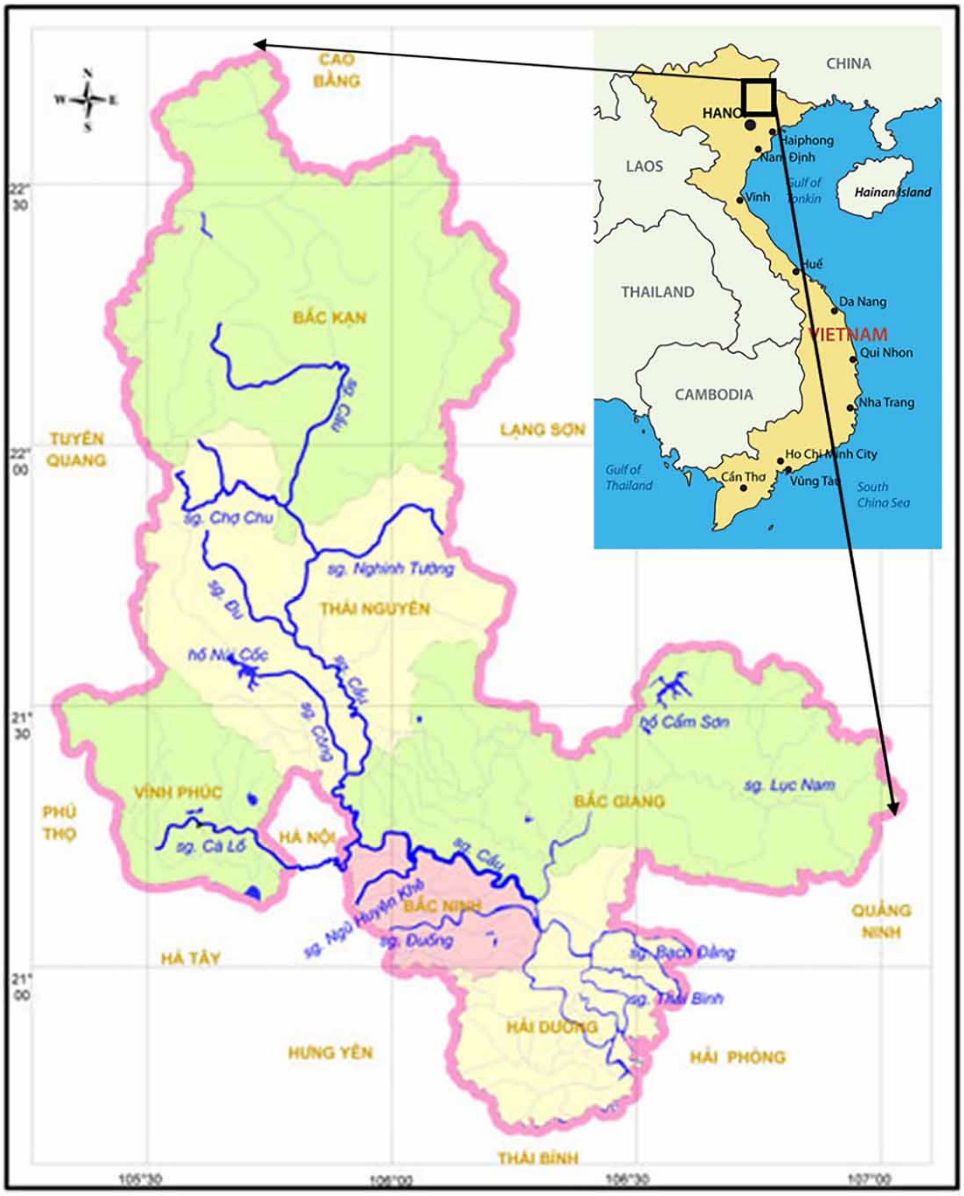

Figure 1 | Cau River watershed in Vietnam.

Table 1 | Characteristics of pollution sources of Cau River

		Population		**Main waste sources**		
Area of Cau River	**Province**	**Number (1,000 people)**	**Density (person/km^2)**	**Quantity (source)**	**Volume (m^3/year)**	**Waste sources**
Upstream	Bac Kan	319	65.65	10	449	Residential area, agricultural production
Midstream	Thai Nguyen	1,364	382.84	16	37,671	Residential area, mining area, agricultural production, industrial zone
Downstream	Bac Giang	1,715	448.13	17	73,339	Residential area, craft villages, agricultural production, industrial zone
	Bac Ninh	1,446	1,756.77	20	26,733	
Entire river		4,844	663.35	63	138,192	

Table 2 | Description of sampling location in Cau River, Vietnam

Sampling location			Locations	
No.	**Name**	**Description of location and land use types**	**Longtitude**	**Latitude**
1	Pha Bridge (Bac Kan)	The starting point of Cau River. Wastewater from agriculture production area	105°51′53.62″	22°9′15.59″
2	Moi Market (Bac Kan)	Urban wastewater from Bac Kan City	105°48′34.03″	21°51′26.17″
3	Gieng Waterfall (Bac Kan)	Urban wastewater from Bac Kan City	105°52′26.67″	22°3′39.52″
4	Na Ban (Bac Kan)	Residential and agricultural wastewater	106°34′17.8″	21°59′06.7″
5	Duong Phong (Bac Kan)	Residential and agricultural wastewater	106°25′43.5″	22°05′56.7″
6	Van Lang (Bac Kan)	Residential and agricultural wastewater	105°50′19.77″	21°48′5.33″
7	Son Cam (Thai Nguyên)	Agricultural wastewater	105°48′.81″	21°37′37.22″
8	Gia Bay Bridge (Thai Nguyen)	Urban wastewater from Thai Nguyen City Industrial wastewater	105°50′.49″	21°35′51.64″
9	May Bridge (Thai Nguyen)	Urban wastewater from Thai Nguyen City Industrial wastewater	105°55′.16″	21°28′41.94″
10	Hoa Binh (Thai Nguyen)	Residential and agricultural wastewater	105°49′45.41″	21°45′25.67″
11	Hoang Van Thu (Thai Nguyên)	Industrial wastewater from Hoang Van Thu Paper Joint Stock Company	105°49′37.47″	21°36′38.35″
12	Tra Vuon Bridge (Thái Nguyên)	Wastewater from Thai Nguyen Iron and Steel Joint Stock Corporation	105°53′38.04″	21°33′52.95″
13	Tan Phu (Thai Nguyên)	Residential and agricultural wastewater	106°39′07.5″	21°21′17.7″
14	Phuc Loc Phuong (Bac Ninh)	Residential and agricultural wastewater	105°56′11.37″	21°14′81″
15	Van Phuc (Bac Ninh)	Residential and agricultural wastewater	106°2′.90″	21°12′22.23″
16	Hoa Long (Bac Ninh)	Residential and agricultural wastewater	106°2′.62″	21°12′56.60″
17	Thi Cau Bridge (Bac Ninh)	Urban wastewater from Bac Ninh City	106°6′.04″	21°12′0.28″
18	Thong Ha (Bac Ninh)	Residential and agricultural wastewater	106°13′6.58″	21°21′4.21″
19	Hien Luong (Bac Ninh)	Wastewater from Que Vo Industrial Park	106°21′6.76″	21° 15′38.9″
20	Vat Bridge (Bac Giang)	Residential and agricultural wastewater	105°53′45.97″	21° 18′55.09″
21	Yen Dung (Bac Giang)	Residential, industrial and agricultural wastewater	106°17′30.87″	21° 07′42.31″
22	Huong Lam (Bac Giang)	Residential and industrial wastewater	105°55′31.72″	21°15′44.41″

sample analysis contains 16 parameters which are described in Table 3. The pH, WT, turbidity and dissolved oxygen (DO) were analyzed by a portable pH meter, WT meter, turbidity meter and DO meter (D–50 Series, Horiba, Co. Ltd), respectively. Ammonium, nitrate, nitrite and phosphates ion concentrations were determined using a spectrophotometer (UV/VIS–EVOLUTION, Model EV0300PC). Heavy metal concentrations were determined using atomic absorption spectrophotometer (AAS) (EPA method). Coliform was analyzed by counting methods (ISO 10304-1:2007).

Water quality and water pollution indices

Water quality index (WQI)

The Vietnam Environmental Agency (VEA) recommended the WQI as a suitable water index for overall evaluation of water quality for multiple usage purposes. In order to compute WQI, according to VEA's guidance, nine parameters are required: pH, DO, biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammonium, phosphate, total suspended solids (TSS), turbidity and coliform

Table 3 | Surface water parameters in the study

No	Parameters	Symbols	Units	Analytical methods
1	pH	pH	–	ISO 10523:2008
2	Water temperature	WT	°C	
3	Total suspended solid	TSS	mg/L	SMEWW 2540B:2012
4	Turbidity	–	NTU	
5	Dissolved oxygen	DO	mg/L	ISO 5814:1990
6	Biochemical oxygen demand	BOD	mg/L	SMEWW 5210B:2012
7	Chemical oxygen demand	COD	mg/L	SMEWW 5220C:2012
8	Ammonium	NH_4^+	mg/L	ISO 7150-1:1984
9	Nitrate	NO_3^-	mg/L	SMEWW 4500-NO_3^-.F:2012
10	Nitrite	NO_2^-	mg/L	SMEWW 4500.NO_2^-.B:2012
11	Phosphate	PO_4^{3-}	mg/L	ISO 10304-1:2007
12	Coliform	–	MNP/100 mL	ISO 9308-2:1990(E)
13	Iron	Fe	mg/L	EPA method 6020A
14	Zinc	Zn	mg/L	EPA method 200.8
15	Copper	Cu	mg/L	EPA method 6010.B
16	Cadmium	Cd	mg/L	EPA method 200.8

ISO, International Standardization Organization; SMEWW, Standard Method for Examination of Water and Wastewater; EPA, Environmental Protection Agency of the United States.

(VEA 2011). The water quality index is represented as follows:

$$WQI = \frac{WQI_{pH}}{100}\left[\frac{1}{5}\sum_{a=1}^{5} WQI_a \times \frac{1}{2}\sum_{b=1}^{2} WQI_b \times WQI_c\right]^{1/3}$$

where WQI_a represents the chemical parameters (DO, BOD, COD, amonium and phosphates); WQI_b represents the physical parameters (TSS and turbidity); WQI_c represents the biological parameter of coliform; WQI_{pH} represents the pH.

Based on the calculated score of WQI, water quality is classified into five categories:

1. Level 1: WQI score obtained from 0 to 25: Water is extremely polluted, emergency treatment is required before reuse.
2. Level 2: WQI score obtained from 26 to 50: water quality is suitable for transportation and equivalent purposes.
3. Level 3: WQI score obtained from 51 to 75: water quality is suitable for irrigation and equivalent purposes.
4. Level 4: WQI score obtained from 76 to 90: water quality is suitable for domestic usage.
5. Level 5: WQI score obtained from 91 to 100: water quality is suitable for domestic water supply.

Comprehensive pollution index (CPI)

The CPI is used to access the level of pollution in a specific watershed by using monitoring statistics (Liu & Zhu 1999). The formula to calculate CPI is presented as follows:

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

where CPI = Comprehensive Polluted Index; n = number of monitoring parameters; PI_i = the pollution index number i.

PI_i is calculated according to the following equation:

$$PI_i = \frac{Ci}{Si}$$

where Ci = measured concentration of parameter number in water; Si = permitted limitation of parameter number according to environmental standard.

CPI is classified into five categories:

1. Category 1: CPI from 0 to 0.20 (clean);
2. Category 2: CPI from 0.21 to 0.40 (sub clean);
3. Category 3: CPI from 0.41 to 1.00 (slightly polluted);
4. Category 4: CPI from 1.01–2.00 (medium polluted);
5. Category 5: CPI≥2.01 (heavily polluted).

In this study, we calculate CPI by using 12 water parameters: COD, BOD, TSS, amonium, phosphates, nitrate, nitrite, coliform, Fe, Cu, Zn and Cd. These parameters were analyzed in the Cau River water monitoring program.

Organic pollution index (OPI)

OPI is used to evaluate the polluted level of a watershed based on four parameters: COD, DO, concentration of dissolved inorganic nitrogen (DIN), and dissolved inorganic phosphate (DIP). The organic pollution index (OPI) is represented in the following equation:

$$\mathrm{OPI} = \frac{\mathrm{COD}}{\mathrm{CODs}} + \frac{\mathrm{DIN}}{\mathrm{DINs}} + \frac{\mathrm{DIP}}{\mathrm{DIPs}} + \frac{\mathrm{DO}}{\mathrm{DOs}}$$

where, according to the environmental standard, CODs, DOs, DINs and DIPs are the limited concentrations of COD and DO; DINs is total limited concentration of nitrate, nitrite and ammonium; and DIPs is the limited concentration of phosphate. OPI is classified into four categories: excellent (OPI <0); good (OPI 0–1); polluted (1–4), extremely polluted (4–5).

Eutrophication index (EI)

EI clarify the eutrophication of the watershed based on three indicators: COD, DIN and DIP (Liu *et al.* 2011). The equation to calculate EI is presented as follows:

$$\mathrm{EI} = \frac{\mathrm{COD} \times \mathrm{DIP} \times \mathrm{DIN}}{4500} \times 10^6$$

where COD = the concentration of chemical oxygen demand; DIN = the concentration of dissolved inorganic nitrogen; DIP = the concentration of dissolved inorganic phosphate.

DIN concentration is calculated by the total concentration volume of nitrate, nitrite, and ammonium, whereas the DIP is calculated by the concentration of phosphate in water. The EI is classified into two categories:

1. EI < 0: Zero eutrophication
2. EI > 0: Eutrophication

Trace metal pollution index (TPI)

TPI is used to evaluate the trace heavy metals in the water (Reza & Singh 2010). TPI is calculated according to the following equations:

$$\mathrm{Q_i} = \frac{\mathrm{TI}}{\mathrm{Xi}} \quad (1)$$

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

$$\mathrm{W_i} = \frac{\mathrm{K}}{\mathrm{Xi}} \quad (3)$$

$$\mathrm{TPI} = \sum_{i=1}^{n} \mathrm{QiWi}/\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{Wi}$$

where k = proportionality constant; Xi = the limited concentration of trace metal number I according to the environmental standard; Wi = the mass ratio of trace heavy metal number i; Qi = the quality index of heavy metal number i; Ti = the concentration of heavy metal number i; n = total number of monitoring heavy metal.

The TPI value is categorized into two groups:

1. Group 1: $0 < \mathrm{TPI} \leq 1$ – none pollution
2. Group 2: TPI > 1 – pollution

In this study, TPI is calculated based on the average concentration of four trace heavy metals: Fe, Cu, Zn and Cd. These are four monitoring indicators in the general water monitoring program of Vietnam.

Data analysis

T-test analysis was used to evaluate the significant difference of water indices between the rainy season and the dry season in Cau River. ANOVA was used to identify the significant difference between upstream, midstream and downstream. Cluster analysis was applied to evaluate the

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water quality and pollution level between monitoring points. The points which have similar polluted levels were gathered into one group. The results of cluster analysis could assist managers to conduct better water monitoring and management plans.

RESULTS AND DISCUSSION

Water quality in Cau River

The average values of ten consecutive years of water quality show that TSS and COD exceed the regulated level indicated in Vietnam National Standards QCVN08:2015/BTMT, column A1 – standard for domestic water usage (Table 4) (MONRE 2015). The TSS concentration was double the permission level, ranging from 49.46 to 54.52 mg/L compared to 20 mg/L of regulated value. The COD concentration was also higher ranging from 11.63 to 13.62 mg/L. Other parameters met the regulated levels. The table also shows the changes of water quality in the dry season and the rainy season. In comparison, parameters of TSS, DO and NH_4^+ in the rainy season were higher than in the dry season, contrary to other parameters. This result was a consequence of the pollutants diluting due to the increase of river water volume in the monsoon season (MONRE 2006).

Table 5 presents the correlated relationship between monitoring parameters. The analysis shows the strong relations between physical and chemical parameters, especially the chemical parameters such as BOD, COD, NH_4^+, NO_2^- and NO_3^-. The correlations were more significant in the dry season compared to the rainy reason. In a similar study, Jahin *et al.* (2020) employed multivariate analysis to develop an irrigation water quality index for suface water in Kafr El-Sheikh Governorate and found that the elements in waster have similar dynamics.

The water quality index

For overall quality assessment, data from 22 sampling points was calculated (Table 6). The average WQI scores were 67.52 and 69.67 in the dry and rainy season, respectively, indicating sufficient quality for irrigation supply. The WQI

Table 4 | Variation of water quality of Cau River between the rainy season and the dry season

Parameters	Units	Dry season	Rainy season	QCVN08:A1
pH	–	7.59 ± 0.20	7.44 ± 0.28	6.0–8.5
Water temperature	°C	25.49 ± 1.21	26.57 ± 0.84	–
Total suspended solid	mg/L	49.46 ± 21.59	54.52 ± 24.53	20
Turbidity	NTU	76.23 ± 51.27	77.84 ± 34.03	–
Dissolved oxygen	mg/L	6.11 ± 0.56	6.26 ± 0.55	≥6
Biochemical oxygen demand	mg/L	3.93 ± 1.50	3.53 ± 1.32	4
Chemical oxygen demand	mg/L	13.62 ± 4.05	11.63 ± 3.51	10
Ammonium	mg/L	0.26 ± 0.10	0.27 ± 0.13	0.3
Nitrate	mg/L	0.85 ± 0.23	0.71 ± 0.17	2
Nitrite	mg/L	0.06 ± 0.04	0.055 ± 0.041	0.05
Phosphate	mg/L	0.07 ± 0.02	0.061 ± 0.012	0.1
Coliform	MNP/100 mL	1,583 ± 1,069.94	1,139.87 ± 615.95	2,500
Iron	mg/L	1.84 ± 0.72	1.483 ± 0.429	0.5
Zinc	mg/L	0.1042 ± 0.116	0.101 ± 0.005	0.5
Copper	mg/L	0.2012 ± 0.0027	0.200 ± 0.000	0.1
Cadmium	mg/L	0.0020 ± 0.00	0.0020 ± 0.00	0.005

QCVN08:A1 = Vietnamese national technical regulation for surface water quality.

Table 5 | Correlation matrix of water parameters in Cau River between the dry season and the rainy season

	WT	pH	Turbidity	DO	COD	BOD	TSS	PO_4^{3-}	NH_4^+	Coliform	NO_3^-	NO_2^-	Fe	Cu	Zn	Cd
a) Dry season																
WT	1															
pH	–0.690	1														
Turbity	0.117	0.361	1													
DO	–0.921	0.649	–0.212	1												
COD	0.795	–0.645	0.174	–0.873	1											
BOD	0.713	–0.549	0.220	–0.799	0.963	1										
TSS	0.293	0.228	0.859	–0.332	0.320	0.419	1									
PO_4^{3-}	–0.109	–0.082	–0.015	0.060	0.082	0.159	–0.072	1								
NH_4^+	0.607	–0.426	0.028	–0.703	0.752	0.773	0.174	0.344	1							
Colifrom	0.438	–0.234	0.045	–0.624	0.625	0.639	0.134	0.172	0.859	1						
NO_3^-	0.925	–0.662	–0.005	–0.815	0.648	0.517	0.112	–0.108	0.540	0.349	1					
NO_2^-	0.930	–0.690	0.016	–0.822	0.754	0.670	0.184	0.046	0.673	0.427	0.920	1				
Fe	0.641	–0.168	0.529	–0.591	0.529	0.559	0.711	0.093	0.375	0.133	0.581	0.608	1			
Cu	0.472	–0.435	–0.035	–0.353	0.440	0.433	0.167	–0.053	0.193	0.157	0.391	0.486	0.130	1		
Zn	0.028	0.245	–0.043	–0.093	–0.032	–0.088	–0.034	–0.145	0.308	0.522	0.167	0.098	–0.053	–0.144	1	
Cd	–0.168	0.581	0.754	0.139	–0.233	–0.160	0.743	–0.262	–0.291	–0.238	–0.263	–0.292	0.289	–0.146	–0.119	1
b) Rainy season																
WT	1															
pH	0.132	1														
Turbity	–0.072	–0.007	1													
DO	–0.742	0.381	–0.253	1												
COD	0.505	–0.027	0.511	–0.650	1											
BOD	0.445	–0.043	0.588	–0.581	0.895	1										
TSS	–0.593	0.271	0.481	0.531	–0.027	0.133	1									
PO_4^{3-}	0.213	–0.052	0.559	–0.367	0.554	0.660	0.297	1								
NH_4^+	0.333	–0.187	0.137	–0.312	0.407	0.413	–0.041	0.738	1							
Coliform	0.247	0.180	–0.145	0.038	–0.060	–0.099	–0.299	–0.248	–0.068	1						
NO_3^-	0.623	–0.124	0.495	–0.837	0.784	0.708	–0.185	0.571	0.362	–0.182	1					
NO_2^-	0.561	–0.102	0.597	–0.763	0.825	0.801	–0.028	0.618	0.362	–0.224	0926	1				
Fe	–0.195	0.055	0.815	0.001	0.347	0.398	0.631	0.650	0.343	–0.296	0.340	0.428	1			
Cu	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0000	1		
Zn	0.136	0.059	0.208	–0.077	0.262	0.390	0.074	0.316	0.091	0.009	0.278	0.335	0.220	0.0000	1	
Cd	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.0000	0.000	1

Table 6 | Water quality indexes of Cau River

Season		WQI score ($n = 22$) Entire river	Upstream	Midstream	Downstream	*P* value
Dry season	Average	67.52	83.31	61.10	61.85	0.018**
	SD	16.96	7.49	21.22	11.04	
Rainy season	Average	69.67	66.36	81.23	62.89	0.000005***
	SD	9.89	5.17	5.16	5.70	
Season difference	*P* value	0.598	0.001***	0.031**	0.805	

SD (standard deviation); (*), (**), (***) indicates level of significance at *P*-value is 0.1; 0.05 and 0.01.

decreased from upstream to downstream indicating an accumulation of pollutants from discharge sources. Figure 2 shows that WQIs of Cau River were fairly stable in the rainy season and generally satisfied the quality for irrigation and similar purposes according to WQI's classification. However, the water quality in the dry season highly fluctuated due to geographical locations and the impacts of pollution sources. In the upper and lower part of the river, the WQI scores were mostly higher than the rainy season. Monitoring point number 5 nearly achieved the quality for domestic usage. This was a consequence of the steep river bed and the increase of turbidity in the monsoon period. Monitoring point number 10 was considered as extremely polluted. Water quality at other points in the river were categorized as suitable for transportation. The results show that the water quality index could be used effectively for water supply purposes. Similar research has been comprehensively conducted in many countries such as Egypt (Jahin *et al.* 2020), Sarayduzu Dam Lake, Turkey (Kükrer & Mutlu 2019), Amazonia Rivers, Brazil (Medeiros *et al.* 2017), and the Ganga River, India (Tripsthi & Singal 2019).

Water pollution indices

The results of water pollution indices calculation in both the dry and rainy season are summarized in Table 7.

Comprehensive pollution index (CPI)

The CPI data show the value of the entire river with no significant difference between dry and rainy seasons. In the dry season, the CPI of Cau River ranged from 0.50 to 1.57 with an average value of 1.08. According to the CPI's classification, this river was slightly and medium polluted. In the rainy season, the CPI of Cau River reached 0.66–1.37 with

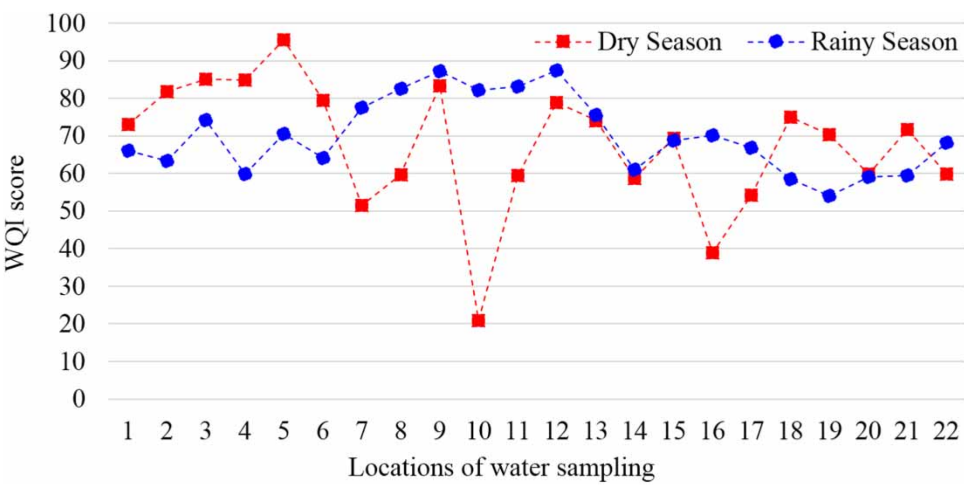

Figure 2 | WQI scores of 22 water monitoring points in Cau River.

Table 7 | Water pollution indices between the dry season and rainy season of Cau River

Index	Value	Entire river		Upstream		Midstream		Downstream	
		Dry season	Rainy season	Dry season	Rainy season	Dry season	Rainy season	Dry season	Rainy season
CPI	Min–Max	0.50–1.57	0.66–1.37	0.50–0.81	0.91–1.06	0.93–1.30	0.66–0.84	1.02–1.57	0.95–1.37
	Ave ± SD	1.08 ± 0.32	0.96 ± 0.21	0.67 ± 0.12***	0.97 ± 0.07***	1.10 ± 0.12	0.73 ± 0.06	1.32 ± 0.34*	1.14 ± 0.17*
OPI	Min–Max	0.42–2.91	0.51–2.32	0.42–1.51	0.51–0.76	0.70–1.92	0.60–1.04	1.72–2.91	1.46–2.32
	Ave ± SD	1.55 ± 0.65*	1.18 ± 0.60*	0.92 ± 0.38	0.63 ± 0.08	1.35 ± 0.40***	0.79 ± 0.16***	2.12 ± 0.14	1.83 ± 0.30
EI	Min–Max	56.47–587.86	72.69–603.07	56.47–242.54	72.69–97.82	86.35–402.63	73.22–139.09	260.34–587.86	202.45–603.07
	Ave ± SD	268 ± 156.27*	188 ± 139.81*	128.57 ± 66.61	85.54 ± 10.31	224.49 ± 117.81**	101.64 ± 24.60**	394.79 ± 128.82	322.84 ± 126.24
TPI	Min–Max	0.39–0.49	0.39–0.42	0.39–0.40	0.40–0.42	0.40–0.44	0.39–0.40	0.40–0.49	0.40–0.42
	Ave ± SD	0.41 ± 0.02	0.40 ± 0.01	0.39 ± 0.003***	0.41 ± 0.01***	0.41 ± 0.02**	0.40 ± 0.003**	0.42 ± 0.03	0.41 ± 0.01

CPI, Comprehensive Pollution Index; OPI, Organic Pollution Index; EI, Eutrophication Index; TPI, Trace Heavy Metal Index. (*), (**), (***) = significant difference at 0.1, 0.05 and 0.01 levels.

an average score at 0.96 and its quality was classified as the same level as the dry season.

Although the water quality of each water monitoring point tended to be better during the monsoon period, this difference was not statistically significant. However, the CPIs were different among the monitoring points upstream, midstream and downstream. The midstream had lower CPIs during the monsoon period in comparison to the dry season. We used the ANOVA test to analyze the significant difference levels of CPI in three parts of the river and the t-test to analyze the significant difference between the two seasons of the year. The results showed that the difference of CPI in three parts of the river was not statistically significant.

Organic pollution index (OPI)

Similar to the CPI, the OPI in the dry season was higher than the rainy season (1.55 compared to 1.18). This result was significant with $\alpha = 0.1$ ($P = 0.0538$). The OPIs of Cau River could be classified into two groups: Good ($0 < \mathrm{OPI} < 1$) and Polluted ($1 < \mathrm{OPI} < 4$). Regarding spatial location, the OPI of the upstream was 0.92 and 0.63 in the dry and rainy season respectively. These scores were in the good quality category ($0 < \mathrm{OPI} < 1$). However, this difference was not statically significant. In the midstream of the river, the OPI was substantially higher in the rainy season (1.35 compared to 0.79 in the dry season) and this difference was statistically significant with $\alpha = 0.01$ ($P = 0.007559$). The average OPI of the downstream in the dry season was 2.12, which was equal to the extremely polluted level, much higher than the OPI in the rainy season (1.83). However, the difference of OPI between the two seasons was not significant. Similar to the results of the CIP analysis, the OPI of the upstream had the highest quality and the downstream had the worst quality (Figure 3). However, the difference of OPI among three geographical areas was not significant.

Eutrophication index (EI)

The EI of the entire river was obtained in the range of about 100–400 for both dry and rainy seasons. This indicates that the river was at high risk of eutrophication. However, the EI in the dry season was much higher than the rainy season

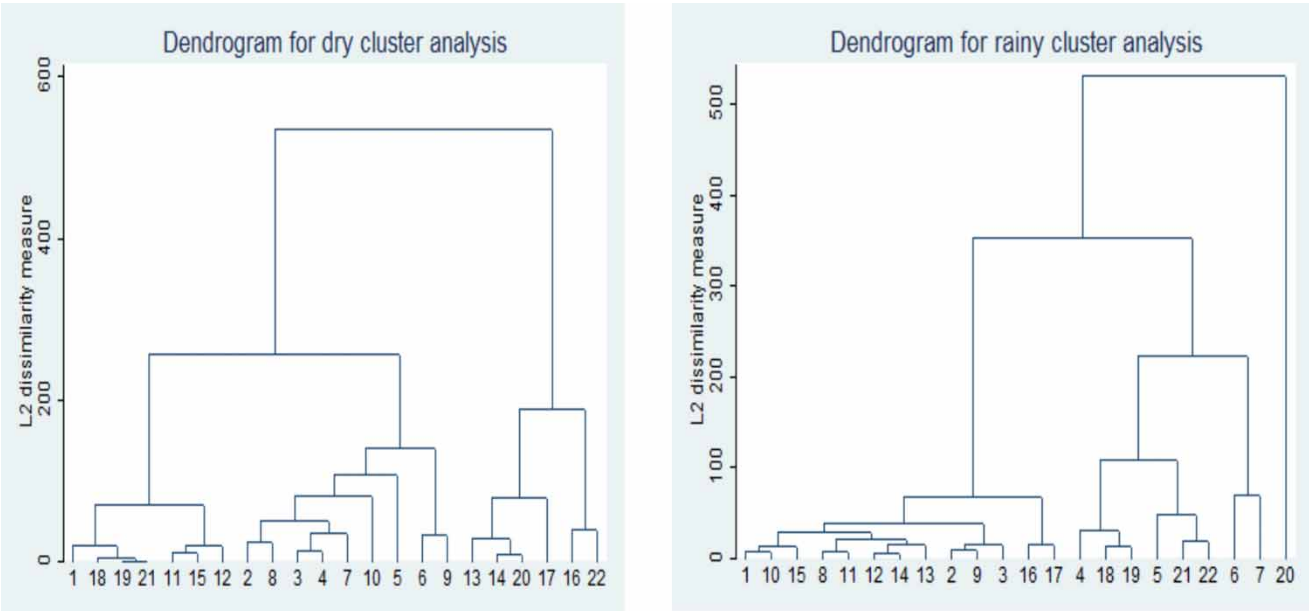

Figure 3 | Cluster analysis water monitoring points in Cau River.

and this difference was statistically significant with $\alpha = 0.1$ ($P = 0.07977$). According to geographical location, the EI of all monitoring points was higher than zero and increased from upstream to downstream of the river. There were significantly different average values of EI in both the dry season and the rainy season with $\alpha = 0.01$ ($P = 0.001376$) and $\alpha = 0.001$ ($P = 0.000101$) respectively. Specifically, the EI of the upstream was 128.57 and 85.54; the midstream was 224.49 and 101.64; downstream was 394.79 and 322.84 in the dry season and rainy season respectively. The EI in the dry season was always higher compared to the rainy season. However, this difference was only significant at midstream with $\alpha = 0.05$ ($P = 0.019287$).

Trace heavy metal index (TPI)

In contrast to other pollution indices, the TPIs of Cau River were low which clarified that this river was not polluted by trace heavy metals according to the TPI's classification. The rainy season also had higher TPI compared to the dry season, although this difference was not significant.

The TPI also slightly differed according to geographical locations. It was highest at the downstream and reduced in the upper part of the river. The difference of TPI in the upstream and downstream between the dry and rainy season was significant at $\alpha = 0.01$ ($P = 0.006916$) and $\alpha = 0.05$ ($P = 0.026554$). However, the average values of TPI at upstream, midstream and downstream monitoring points were not significantly different. The results of water pollution indices calculation determined that the level of pollution increased from the upper part to lower part of the river, specifically the CPI, OPI and EI, but not the TPI. The pollution level also tended to be higher in the dry season compared to the rainy season. This environmental status could be explained by the low density of pollution sources in the upstream. The midstream and downstream received more pressure from agricultural and industrial activities and populous areas. In addition, the accumulation of pollutants due to water flow in the downstream also contributed to higher concentrations of pollutants in this part of the river. The better water quality in the rainy season was a consequence of the increase of water volume which led to a higher dilution capacity. All trends of water pollution indices were reflected and are similar to the results of WQI calculations.

Water quality indices and water pollution indices among monitoring points

Cluster analysis was used in order to classify the monitoring points which have similar water quality characteristics. The

Table 8 | Clustering water monitoring points between dry season and rainy season

Season	Cluster	WQI	CPI	OPI	EI	TPI	Water monitoring location
Dry season	1	70.90	1.06	1.71	278.97	0.40042	1, 12, 15, 18, 19, 21
	2	68.49	0.83	0.82	102.26	0.40785	2, 3, 4, 5, 7, 8, 10
	3	81.40	0.87	1.23	180.57	0.40117	6, 9
	4	61.74	1.40	2.18	431.06	0.43054	13, 14, 17, 20
	5	49.37	1.55	2.64	571.01	0.40978	16, 22
Rainy season	1	74.37	0.84	0.72	94.21	0.40047	1, 2, 3, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17
	2	65.57	1.01	1.51	218.30	0.40398	4, 18, 19
	3	65.60	1.08	1.91	289.60	0.40531	5, 21, 22
	4	56.72	1.30	1.97	389.37	0.41489	6, 7
	5	59.07	1.36	2.31	603.07	0.41223	20

WQI, Water quality index; CPI, Comprehensive Pollution Index; OPI, Organic Pollution Index; EI, Eutrophication Index; TPI, Trace Heavy Metal Index.

computation categorized 22 points into five groups as summarized in Table 8.

According to Table 8, cluster analysis shows the order of water quality of which group 1 represents highest quality and group 5 the lowest. Representing the entire river, the polluted points (belonging to groups 4 and 5) accounted for around 13% (3 of 21 points in total). Nevertheless, in the dry season, the number of polluted points in groups 4 and 5 was double and the number in group 1 significantly reduced to six monitoring points. The results of cluster analysis stated that the water quality in monsoon time of Cau River was better compared to the dry season.

Grouping water monitoring points with similar characteristics could assist managers in making decisions related to water use planning for different purposes, such as domestic water supply, aquaculture cultivation, irrigation, or other purposes. Furthermore, the results of water quality clustering also support managers in designing water quality monitoring systems, especially addressing high attention to the serious pollution points. These benefits provide meaningful foundations for sustainable water source management.

CONCLUSION

This study has suggested a possible combination of quality and pollution indices based on monitoring environmental parameters for river quality assessment. At the current state, the water quality meets the requirements of Vietnam National Environmental Standard QCVN08-(A1 category), the standard for domestic water supply. TSS and COD concentrations are higher than the regulation for domestic water supply. The average concentration of pollutants was lower in the dry season, excluding TSS, DO and NH_4^+. The results of WQI analysis indicate that the water of Cau River achieved the standard for irrigation purposes in both the dry season and rainy season. However, further study on bearing capacity of the river will be needed for water supply purposes.

The water quality indices varied depending on location and monitoring time. In the dry season, the water quality of the upstream was better than other parts of the river, followed by the midstream and downstream respectively.

Pollution Indices calculation indicates that the Cau River is polluted in different geographical conditions. Many locations of the river are contaminated by organic pollution with OIP > 1. The river water was at high risk of eutrophication as EI was above zero. The TPI of Cau River is in the safety level. All pollution indices in the Cau River tend to increase from upstream to midstream, then downstream. Cluster analysis grouped the water monitoring points into five groups with the quality reducing gradually from the first group to the fifth group. The classification of clustering analysis provided meaningful support for water pollution monitoring and appropriate solutions for the treatment of water for water supply.

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