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Comparative assessment of water quality classification techniques in the largest north-western river of Cambodia (Sangker River-Tonle Sap Basin)

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ABSTRACT

The lack of adequate and good water quality is one of the serious issues that most developing countries are facing, yet environmental monitoring programs are not efficiently protecting ecosystem health. Here, we aimed to assess the suitability of different water quality assessment frameworks in order to define the most suitable method, especially for data-scarce environments, to quantify river ecosystem health. The study was conducted in the largest north-western river of Cambodia, the Sangker River in the Tonle Sap Lake (TSL) basin (UNESCO Biosphere Reserve). Five water quality assessment methods were selected for the study: Basic & Single Prati indices, Mekong River Commission water quality index (MRC-WQI), French water quality assessment system (SEQ-EAU) and US Environmental Protection Agency (US-EPA) framework. Overall, a physico-chemical gradient of water quality was observed along the river course. The river head was defined by high levels of dissolved oxygen (DO), low nutrients and chloride, while the middle course was marked by a gradual decrease of DO and increased concentration of nutrients up to the TSL floodplains. This degradation was explained by multiple impacts from human activities, e.g. domestic wastes, livestock, crop farming, causing simultaneous eutrophication and oxygen depletion along the river course. Despite those multiple pressures, the Sangker river health status was scored as fairly good reflecting the current situation of the river. So far, we found a convergence of the five water quality assessment methods; however, SEQ-EAU and Basic Prati seemed to be less suitable for tropical river health assessment. The study defined the US-EPA assessment method as the most suitable technique to quantify the Sangker river health. This method could potentially be used to monitor river ecosystem health in data-scarce environments. This would help overcome environmental monitoring challenges in developing countries faced by rapid global environmental changes.

1. Introduction

Water is a crucial natural resource globally used for social and economic development (agriculture, industry, recreation, irrigation, etc.) to support the daily life of people (Garrick et al., 2017). Keeping in balance both quality and quantity of water for multipurpose uses is indeed a critical question for the scientific community and for policy makers (Assouline et al., 2015; Gunda et al., 2019; Wade et al., 2021). Water quality has become one of the key environmental concerns due to the important loss of biodiversity and water pollution driven by human activities (industrialization, urbanization, agricultural intensification and fragmentation) (Mujere and Moyce, 2018; Rahman et al., 2021; Teng et al., 2011; Vörösmarty et al., 2010). Meanwhile, many studies revealed the significant negative impacts of the combined climatic and non-climatic factors on the quality of freshwater ecosystems, particularly in the Oriental region (Mekong River Basin) (Hughes, 2017; Vörösmarty et al., 2010); where high density of people and high levels of fragmentation were observed (Grill et al., 2015). Therefore an important question pertains to the sustainable use of water resources both in terms of quantity and quality in the near future while the climate is changing and catastrophic events (floods and drought) occur more frequently (An, 2014; Duran-Encalada et al., 2017; Gunda et al., 2019). This vulnerability is even more important in the less developed countries of Cambodia, Laos and Vietnam, where adaptative capacity is low and economic development has been prioritized over environmental protection (Yusuf and Francisco, 2009).

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Facing these challenges, environmental monitoring programs are crucial to maintain good ecosystem health and to keep in balance both the quality and quantity of water resources. Moreover, environmental monitoring is crucial to manage, minimize and mitigate harmful human impacts on natural environments and to protect the health of human beings and their livelihood (O'Brien et al., 2016). Many approaches have been proposed to monitor environment quality and freshwater ecosystem health, e.g. water quality index (WQI), ecological indices based on different bio-indicator taxa such as fish, invertebrate and algae (O'Brien et al., 2016). Indeed, it is widely accepted that water quality index (WQI) assessment framework is one of the better known and most effective tools for river ecosystem health assessment. However, there remains a debate in both the scientific community and environmental managers on the implementation of water quality index (WQI) to assess freshwater ecosystem health status, particularly the selection of water quality indicators, weighting systems of parameters/indicators and aggregation of sub-indices to measure water quality status (Gupta and Gupta, 2021; Uddin et al., 2021). So far, there is no consensus nor a universal agreement on the number of parameters and weighting systems to be used for river ecosystem health assessment and monitoring; the WQI was developed based on a specific case of river or lake and purpose of (Kirschke et al., 2020).

Furthermore, environmental monitoring is costly, it is the primary reason behind the scarcity of environmental monitoring programs in developing regions (Tang et al., 2022). Many developing countries are facing financial constraints, technical capacity challenges and governance issues resulting in the lack of monitoring programs in those countries (Kirschke et al., 2020). So far, no clear and affordable water quality assessment frameworks at local or regional scales have allowed authorities and stakeholders to perform monitoring. Accordingly, few environmental monitoring programs have been established in the region, particularly in developing countries such as Cambodia (Famiyeh

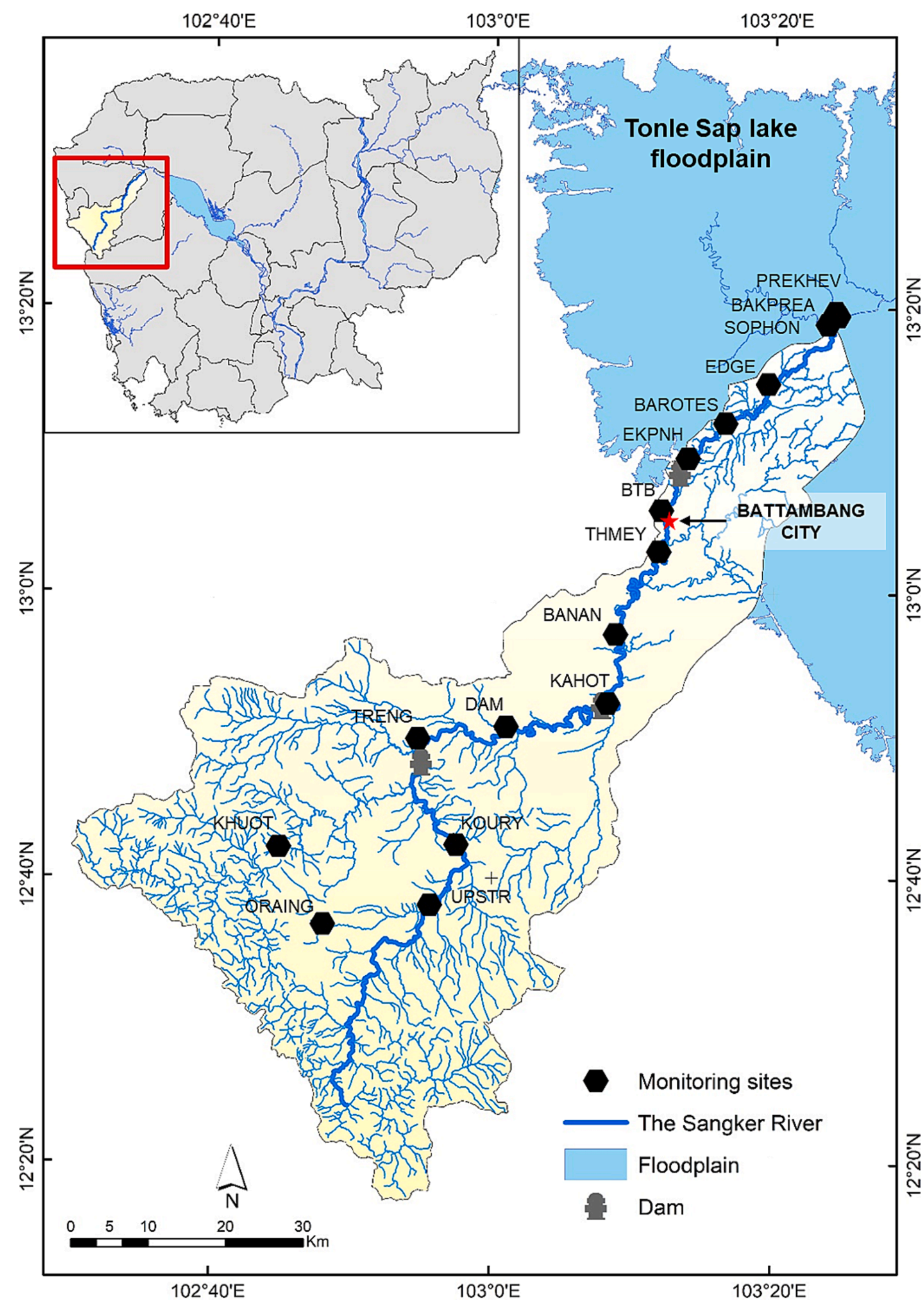

Fig. 1. Map of the Sangker River catchment (Tonle Sap Basin) with the geographical location of the sixteen water quality monitoring sites (black polygons).

et al., 2018). So far, only the long-term water quality monitoring program of the Mekong River Commission (MRC) was introduced in 1995 within the Lower Mekong River Basin (LMB); this program was primarily conducted along the Mekong mainstream and some important tributaries within the LMB. In 2008, based on its long-term water quality monitoring dataset, the MRC developed the water quality assessment framework using the water quality index (WQI) to assess water quality status in the LMB in order to protect biodiversity and human health in response to environmental degradation in the region (MRC, 2008). Likewise, several water quality assessment frameworks from Europe and the USA were adapted and used in the Mekong region, e.g., the French water quality assessment framework (SEQ-EAU), Prati indices and US-Environmental Protection Agency water quality assessment framework (US-EPA). However, these assessment techniques were often criticized and inappropriate due to their assessment criteria (i.e. threshold value of physico-chemical parameters) that seemed to be too strict or too loose to score the water quality of tropical river systems (Chea et al., 2016; Ismail, 2011; Prati et al., 1971; Sor et al., 2021).

Cambodia is the conjunction of two extraordinary hydrological systems, i.e. the Tonle Sap Lake and the Mekong River, but very few studies on water quality, biodiversity and ecosystem health on its river networks are available in the literature besides the TSL and the Mekong river systems. A great focus was given to TSL, while the dynamic of the lake depends on the lake itself but also on its eleven tributaries with more than 40% of its water comes from its tributaries (Uk et al., 2018). Located in the north-western Cambodia, the Sangker river is one of the largest tributaries of the TSL basin and plays a crucial role for biodiversity and people's livelihood in TLS basin (Fig. 1). It is known as a rich agricultural basin and home for more than 200 freshwater birds (i.e. Prek Toal Ramsar Site). Over the last two decades, a lot of scientific studies and research programs have been conducted in order to figure out the effect of climate change on water balance, flood and drought, contamination of heavy metals (micro-plastic, arsenic) in underground and drinking water (Babel and Dork, 2021; Chheang et al., 2021; Ich et al., 2022; Phan et al., 2013). However, patterns of water quality or ecosystem health assessment in the Cambodian river network, i.e. the Sangker River catchment, remain untouched. So far, there was no clear guideline on ecosystem health assessment beside the Sub-Decree on Water Pollution Control in 1999 (RGC, 1999). This sub-decree documented the list of 25 physico-parameters with their allowable concentration ranges, while no frameworks nor guidelines to assess water quality were described. But monitoring 25 parameters is very costly in the economic context of Cambodia, or in other developing countries in Africa and Asia as reported from the global perspective of water quality experts and Chinese water quality monitoring experience over the last 20 years of practice (Kirschke et al., 2020; Tang et al., 2022).

A recent study on the agricultural vulnerability within the Sangker river catchment raise concerns about the negative effects of climate change, soil degradation and water quality potentially negatively affecting agricultural production (Heng et al., 2013). As a consequence, eutrophication and biodiversity loss (e.g. fish deaths) were frequently reported by local authorities and appeared more often in the news. It is indeed a critical concern nowadays for local authorities and people living in the Sangker river catchment who directly rely on the river ecosystem services for their livelihoods. Unfortunately, very little scientific documentation or research on water quality and biodiversity of the Sangker river were found in the literature leaving a shadow behind the sustainable uses of the river basin ecosystem services. Therefore, a holistic description of water quality patterns as well as a comprehensive ecological health assessment are needed to ensure the sustainable development and livelihood of people within the Sangker river catchment as well as in the Tonle Sap basin.

Facing rapid environmental changes, freshwater ecosystems are vulnerable and there are profound uncertainties regarding the management and assessment of freshwater ecosystem health, particularly in the developing world (Angeler et al., 2014). Ideally, a simplified and affordable water quality assessment framework should be developed to fill the gaps and overcome challenges on environmental monitoring. Currently, there is no consensus on which assessment method to choose within the LMB or in Cambodia to determine the health of ecosystems in the face of rapid global environmental changes. Recent studies have reported a sharp decline of water quality in many locations within the LMB over the last three decades, particularly in the Mekong delta and Tonle Sap Lake (TSL) basin in Cambodia, signaling the need for closely monitoring the quality of ecosystem health (Chea et al., 2016; Kumar et al., 2020; Sor et al., 2021; Sutadian et al., 2015). The question is what is the most appropriate water quality assessment framework to quantify river ecosystem health in the Cambodian river networks? Given the fact that, the country is facing many challenges such as limited technical capacity or financial constraints (Kirschke et al., 2020). So far, many water quality assessment frameworks have been developed to simplify assessments and monitoring procedure, e.g. the use of fewer water quality indicators, simplified data collection procedure, lower laboratory analysis costs. Indeed, the latest developments of simplified assessment frameworks have moved further away from socio-economic analysis based framework (Zessner et al., 2017) to water quality index (WQI) (Alilou et al., 2018) and modeling (Uddin et al., 2021) and the use of IoT (internet of things) for water quality management and monitoring in freshwater ecosystems (Jan et al., 2021).

The current paper aims to assess the suitability of different water quality assessment methods and to define the most suitable technique to quantify the ecosystem health status of the largest north-western Tonle Sap basin's tributary, the Sangker River. Specifically, the study describes the spatial distribution of water quality patterns along the Sangker river course based on primary physico-chemical parameters; then performs a holistic comparative assessment of different water quality assessment frameworks to quantify their suitability for tropical river ecosystem health assessment. The study then provides suggestions on water quality assessment frameworks and their potential use in data-scarce environments or areas with restricted resources such as the Sangker river catchment in TLS basin. So far, the current work is the first study of water quality pattern in the largest north-western river of Cambodia. More importantly, the outcome from the current work could be an initiative for a low cost and sustainable way to ensure river ecosystem health assessment and monitoring in the developing world, where resources are restricted and environment monitoring is needed. The lessons learned from the current work could be a model for river ecosystem health assessment in other Cambodian hydrological networks and help to build a foundation for further developments of biomonitoring tools in tropical freshwater ecosystems and locally adapted tools that can be used by local governments, stakeholders and practitioners to support river basin management plans in the face of global change (Tan et al., 2015; Wang et al., 2023).

2. Materials and methods

2.1. Study area: The Sangker river

Flowing from the west to the east of Cambodia, the Sangker river is one of the most important tributaries of the Tonle Sap Lake (TSL) basin. The river possesses an immense socio-economical, ecological and cultural value for people living in north-western Cambodia. The river basin drains a huge north-western region of the TSL basin with a total land area of 6 051 km^2 (*ca.*10% of the TSL basin catchment area) (Oeurng et al., 2019). The land-use in the watershed is dominated by agricultural crops at the head of the basin; while by the middle of the basin, where Battambang city is located (Fig. 1) it is replaced by a wide range of land-uses such as paddy fields, industrial and urban areas. Finally, the river flows into the floodplain of the TSL after a flowing distance of 200 km from the source (Fig. 1). As part of the TSL basin, the river exhibits the same tropical monsoon climate as the lake with two distinct seasons, i.e. wet (May-October) and dry (April-November) seasons. Recent basin development over the last decades such as the construction of cascade dams (e.g. Sek Sak, Kahot, Taorn dams), deforestation, expansion of agricultural land and rapid growth of urban areas are simultaneously affecting the biodiversity and ecological health of the river (Sourn et al., 2022). Thus, water quality monitoring is essential to protect the river health and livelihoods of people living in the Sangker river catchment. Sixteen water quality monitoring sites were selected for the study; the majority of sites were located along the Sangker mainstream and only few sites were located in the tributaries (Fig. 1). The selection of monitoring sites was based on geographical conditions and environmental gradients, i.e. mountainous area, upland and floodplains, to ensure that these studied sites were representative to assess the water quality within the whole river catchment.

2.2. Water quality data collection

Water quality sampling campaigns were conducted annually from November 2018 to November 2021 within the Sangker river catchment (Tonle Sap basin) under the framework of the Tonle Sap research project entitled "Preservation of Tonle Sap lake ecosystem function and productivity facing the global change" funded by the French National Research Institute for Sustainable Development (IRD). The project aims to develop decision support tools for sustainable uses of ecosystem services in the Tonle Sap lake basin. Specifically, in the Sangker river catchment, the project aims to develop and implement monitoring tools for a long-term survey. Sampling campaigns started in November 2018 to collect both physico-chemistry and diatoms. November is the most favorable period for both physico-chemical and biological samplings since it is the end of the rainy season (no significant effect from the rainfall/erosion). The 2018 sampling campaign was our reference sampling campaign, while we explored for the first time the entire Sangker river catchment to understand the overall ecosystem health status and to identify the strategic monitoring sites based on the typology of the river. Then, with the exception of the year 2020 (due to the COVID19 pandemic outbreak), two more consecutive sampling campaigns were performed in November 2019 and 2021.

In total, for each campaign at the sixteen sampling sites (Fig.1), twenty-three physico-chemical parameters were measured either *in-situ* or analyzed in the laboratory. The detailed description of physico-chemical parameters, units and laboratory standard measurement are provided in the Table 1. In this study, eleven physico-chemical parameters were selected for the analyses based on their importance in describing the water quality patterns and their relevance for the water quality assessment framework; the selected parameters are listed on the first eleven rows of the Table 1. Indeed, water temperature (WT), dissolved oxygen (DO), oxygen saturation (OS), electrical conductivity (EC) and pH were measured *in-situ* using a multi-parameter probe (WTW Multi 3420 Set G), while the turbidity (Turb) was measured with a portable turbidity meter (HANNA-HI937030). Other chemical parameters, such as nutrients (total nitrogen (TN), nitrate (NO_3^-), orthophosphate (PO_4^{3-}) and various cations and anions were analyzed in the laboratory in accordance with ISO standard methods (listed in the Table 1). *In situ*, two 100 ml plastic containers were collected at each site; one container was used to sample raw water and the other one was used to store the filtered water (filtration through a 1.2 µm microglass fiber filter). The filters were stored and used to quantify total suspended solids (TSS).

2.3. Statistical analyses

Firstly, the data were averaged and prepared in Excel table before being processed. To describe water quality patterns, physico-chemical parameters were standardized to be dimensionless. Then, the principal component analysis (PCA) was performed on the physico-chemical table to assess the co-variance of all physico-chemical parameters and their relationships to the monitoring sites. PCA is one of the well-known variable reduction techniques to explore and visualize the data set in a multi-dimensional space (Dray and Dufour, 2007). The four most important parameters, i.e. DO, COD, Cl^- and NO_3^-, were plotted in bubble diagrams as a function of their concentration in mgL^{-1} using ArcGis 10.5 in order to describe the spatial variation of the water quality along the Sangker river.

Secondly, five water quality assessment frameworks, i.e. US-EPA (United States for Environmental Protection), MRC-WQI (Mekong River Commission-Water quality index), SEQ-EAU (Système d'evaluation de la qualite de l'eau des cours d'eau), Basic Prati & Single Prati indices, were selected and used to assess the water quality status of the Sangker river catchment. These assessment methods were selected on the basis of their quality and suitability for quantifying ecological health of freshwater ecosystems from a primary set of physico-chemical parameters. Numerous studies have shown the potential application of these assessment methods in different environments both in temperate and tropical river systems (Chea et al., 2016; Ismaïl et al., 2016; MRC, 2007; Prati et al., 1971; Sor et al., 2021). Indeed, the US-EPA water quality assessment framework is recognized worldwide, while many case studies from different geographic regions (America, Africa, Asia) reported its potential and appropriateness. Partly, the development of the environmental quality concept in the European Water Framework Directive was derived from the US-EPA Red Book reflecting its international recognition as a holistic assessment framework (Vighi et al., 2006). Comparatively, under the World Health Organization (WHO) water quality standards, the assessment guideline for recreational water quality could be an option; nevertheless, this guideline was rather narrative and its implementation would require more technical

Table 1
List of physico-chemical parameters monitored in the Sangker River catchment (Tonle Sap Basin, Cambodia), their measurement units and their average concentrations with reference to the corresponding standardized methods. The first eleven physico-chemical parameters correspond to those selected for the study.

Parameters	Units	Observed concentration		Standard
		Mean	SD	
Ammonium (NH_4^+)	mgL^{-1}	0.03	0.03	ISO 14911:1998
Chemical oxygen demand (COD)	mgL^{-1}	406.57	483.80	ISO 15705:2002
Chloride (Cl^-)	mgL^{-1}	8.09	4.13	ISO 10304–1:1995
Dissolved oxygen (DO)	mgL^{-1}	5.95	2.53	Standard method WTW Multi 3420 Set G
Electrical Conductivity (EC)	μScm^{-1}	180.36	68.43	Standard method WTW Multi 3420 Set G
Nitrate (NO_3^-)	mgL^{-1}	0.27	0.59	ISO 10304–1:1995
Orthophosphate (PO_4^{3-})	mgL^{-1}	0.02	0.05	ISO 15681–1:2003
Oxygen saturation (OS)	%	75.63	32.15	Standard method WTW Multi 3420 Set G
Potential hydrogen (pH)	–	7.47	0.37	Standard method WTW Multi 3420 Set G
Total suspended solid (TSS)	mgL^{-1}	27.14	27.89	Standard method WTW Multi 3420 Set G
Water temperature (WT)	°C	28.23	2.16	Standard method WTW Multi 3420 Set G
Florine (F^-)	mgL^{-1}	0.27	0.22	ISO 10304–1:1995
Bromine (Br^-)	mgL^{-1}	0.01	0.02	ISO 10304–1:1995
Sulphate (SO_4^{2-})	mgL^{-1}	0.57	0.49	ISO 10304–1:1995
Sodium (Na^+)	mgL^{-1}	12.71	4.18	ISO 14911:1998
Potassium (K^+)	mgL^{-1}	1.67	0.99	ISO 14911:1998
Magnesium (Mg^{2+})	mgL^{-1}	8.51	4.18	ISO 14911:1998
Calcium (Ca^{2+})	mgL^{-1}	17.10	6.64	ISO 14911:1998
Silicon dioxide (SiO_2)	mgL^{-1}	21.91	10.80	Standard method NF-T-90-007
Total nitrogen (TN)	mgL^{-1}	0.82	0.98	Standard method NF EN 12260
Iron (Fe^{3+})	mgL^{-1}	30.12	51.72	ISO 14911:1998
Nitrite (NO_2^-)	mgL^{-1}	0.01	0.01	ISO 10304–1:1995
Turbidity (Turb)	NTU	25.32	26.27	ISO 7027–1:2016

knowledge (WHO, 2021). Consequently, studies carried out in developing countries have focused more on WHO drinking water quality than on its guidelines for recreational water.

The detailed description of each water quality assessment method and its scoring procedure are described in the section 2.4. below. Last but not least, to study the relationship between the five water quality assessment methods, a multiple correspondence analysis (MCA) was performed to determine their similarity on the basis of water quality classes, i.e. very good, good, moderate or poor, obtained from each assessment method. Indeed, MCA is an extension of a simple correspondence analysis (CA) and used to study and visualize the association of many qualitative or categorical data in a multidimensional space. It is a counterpart of PCA for qualitative data (Husson et al., 2017). The water quality assessment methods best suited to the Sangker river catchment were defined from the MCA factorial map generated during the analysis. All multivariate analyses were performed using packages ("ade4") and ("FactoMineR") in R program (R Core Team, 2022).

2.4. Water quality assessment methods & its scoring procedure

In Cambodia, there is no specific guideline for assessing the freshwater ecosystem health is available. Yet, in 1999 the Sub-Decree on Water Pollution Control was developed by the Royal Government of Cambodia (RGC) known as the public water quality standard used to assess the water quality of rivers, lakes and hydrosystems in urban area (Dahee, 2016). However, the document contained only the range of admissible concentration of 25 physico-chemical parameters required to assess the quality of surface water. In addition to that, assessing 25 parameters is costly; thus, water quality or environmental monitoring programs have been restricted and remain very limited on a national scale.

Here, we introduced five well-known water quality assessment methods widely used in temperate and tropical regions. Our purpose was to identify the most suitable water quality assessment method based on a few sets of physico-chemical parameters. Accordingly, the number of physico-chemical parameters used varied from one parameter based method (Single Prati index) to eleven parameters (SEQ-EAU method). To set up sustainable environmental or water quality monitoring programs in developing countries with limited resources, while freshwater ecosystems are degraded because of rapid economic development activities, remains highly challenging. Indeed, environmental monitoring is costly and required technical capacities for sampling data on the field and to analyze parameters at the laboratory. For that reason, the development of a low cost and a simpler assessment procedure would help to tackle challenges. Thus, to rely on a few set of physico-chemical parameters to monitor the water quality would be very beneficial and relevant in developing countries where funds are restricted and would make methods more suited for long-term monitoring programs. Detailed descriptions and scoring procedures for each method are given as follows:

2.4.1. United States environmental protection Agency (US-EPA)

The US-EPA's guideline was developed under the Water Clean Act of 1972 and known as the foundation of water quality-based pollution control program to protect the human health and aquatic life. The guidelines consist of many criteria with specific uses (i.e., aquatic life, human, recreation, reuse and irrigation) and are potentially applicable to any kinds of water bodies (e.g., cold, cool and warm water) (US-EPA, 1986). In the US-EPA, four parameters, i.e. dissolved oxygen (DO), total phosphorus (TP), total ammonia (TA) and chloride (Cl^-), are used to classify the water quality for the protection of aquatic life. In this study, the TP was computed based on the orthophosphate (PO_4^{3-}) using the following equation TP = PO_4^{3-}(mgL^{-1} as PO_4) × 0.3262 (WRC, 2020); while the concentration of total ammonia (TA) was approximately replaced by the concentration of ammonium (NH_4^+) since the concentration of ammonia (NH_3^-) in the Sangker river accounted in a very low percentage within the observed ranges of pH (7–8). Besides, the concentration of NH_4^+ was also quite low; thus, the addition of NH_3^- would not change the concentration of TA. In other word, NH_3^- concentration can be negligible.

In regard to the scoring system for water quality classification, a simple scoring procedure was applied. If the observed value of the physico-chemical parameter in the studied site was lower than the threshold value indicated in each guideline as shown Table 2 then the site was scored 1 point, vice versa 0. Thus, the maximum score was the sum of the scores of the four assessed parameters (4 points) and accounted for 100% of quality. Consequently, if the assessed site was scored below 50%, it was classified as "poor" quality, while the site was classified as "moderate" if it received the score between 50% to 69%. Subsequently, the sites with "good" quality must be scored between 70% to 89%, while the "very good" quality sites were graded only if the site received more than 90% of total scores.

2.4.2. Mekong river Commission's water quality index (MRC-WQI)

The MRC-WQI was developed by the Mekong River Commission (MRC) in 2008 based on the long-term time series data obtained from the water quality monitoring program within the Lower Mekong River Basin (LMB). The MRC-WQI was used to monitor and quantify the water quality health status along the Mekong mainstream and some important tributaries within the LMB for the protection of aquatic life and human health (MRC, 2008). In the MRC-WQI framework, six physico-chemical parameters, i.e. pH, dissolved oxygen (DO), ammonia (NH_3^-), electrical conductivity (EC), nitrate (NO_3^-), and total phosphorus (TP) were used to compute the water quality index (WQI) for the protection of aquatic life following the equation:

$$WQI = \frac{\sum_{i=1}^{n} Pi}{M} \times 10 \tag{1}$$

where n is a number of samples, P is the number of scores per sample day, M is the maximum possible score for the measured parameters.

In the MRC-WQI, the assessed parameters were weighted based on their importance for aquatic life. Nitrates and total phosphorus were given the score of 1 if they meet the criteria, while the rest of parameters were given the score of 2 if they meet the criteria during the computation (Eq. 1) (Table 2). Accordingly, the water quality was classified as "very good" if the WQI was scored between 9 and 10, as "good" if it was scored between 8 and 9, as "moderate" if it was scored between 7 and 8 and as "poor" quality if the WQI was scored lower than 7.

2.4.3. Prati water quality classification (Single Prati & Basic Prati indices)

The Prati water quality classification or index was developed by the European Union in 1971 and composed of three sub-classifications or indices, i.e. Single Prati index, Basic Prati index, and Full Prati index (Prati et al., 1971). Only single Prati and basic Prati indices were included in this study while the full Prati required other parameters beyond our observation, e.g. Biochemical Oxygen Demand (BOD5) and Alkyl Benzene Sulphonates (ABS). The Single Prati index was computed based on only one key parameter, i.e. oxygen saturation (OS), considered as the predominant parameter for aquatic life (Prati et al., 1971). Whereas, the basic Prati index were computed based on three important physico-chemical parameters, i.e. OS, NH_4^+ and COD. The formula uses to compute both indices were shown in Table 2. Indeed, the Prati indices suggested 5 classes of water ranging from very heavily polluted (Xprati ≤ 8), heavily polluted (4 ≤ Xprati < 8), polluted (2 ≤ Xprati <4), acceptable (1 ≤ Xprati <2) and good quality (0 ≤ Xprati <1). Thus, to be consistent with other assessment methods selected for the study, the classes of the water quality were grouped into 4 classes as follows: very heavily and heavily polluted were assigned to poor quality, polluted and acceptable water were assigned to moderate and good qualities, and finally good water was assigned to very good quality.

Table 2
Criteria of water quality classification with the maximum allowable concentration (MAC) values used in the study.

Parameters	MAC values	Parameters	MAC values
1). US-EPA	***2). MRC-WQI***		
Dissolve Oxygen (DO)	>5 mgL^{-1}	pH	6.0—9.0
Total Phosphorus (TP)	< 50 μgL^{-1}	Dissolved oxygen (DO)	> 5 mgL^{-1}
Total Ammonia (TA)	< 20 μgL^{-1}	Total phosphorus (TP)	< 0.13 mgL^{-1}
Chloride (Cl^-)	< 250 mgL^{-1}	Total ammonia (TA)	< 0.2 mgL^{-1}
		Nitrate (NO_3^-)	< 0.7 mgL^{-1}
		Electrical Conductivity (EC)	< 700 μScm^{-1}
3). SEQ-EAU water quality assessment			
Criteria & parameters	**MAC values & classes** *(Class: Very good [VG], Good [G], Moderate [M], Poor [P])*		
Organic matter	VG [8– 6], G [6 – 4], M [4 – 3], P [3 – 0] VG [5– 0], G [7 – 5], M [12 – 7], P [12 – 10]		
- Dissolve oxygen (DO) (mgL^{-1})	VG [0.5– 0], G [1.5 – 0.5], M [2.8 – 1.5], P [4 – 2.8]		
- Chemical oxygen demand (COD) (mgL^{-1})			
- Ammonium (NH_4^+) (mgL^{-1})			
Nutrient matters	VG [0.03 – 0], G [0.3 – 0.03], M [0.5 – 0.3], P [1 – 0.5] VG [2– 0], G [10 – 2], M [25 – 10], P [50 – 25]		
- Nitrite (NO_2) (mgL^{-1})	VG [0.1– 0], G [0.5 – 0.1], M [1 – 0.5], P [2 – 1]		
- Nitrate (NO_3^-) (mgL^{-1})	VG [0.05– 0], G [0.2 – 0.05], M [0.5 – 0.2], P [1 – 0.5]		
- orthophosphate (PO_4^{3-}) (mgL^{-1})			
- Total Phosphorus (TP) (mgL^{-1})			
Suspended matter	VG [5– 0], G [25 – 5], M [38 – 25], P [50 – 38]		
Total suspended solid (TSS) (mgL^{-1})			
Temperature	VG [21.5– 0], G [23.5 – 21.5], M [25 – 23.5], P [25 – 28]		
Water temperature (WT) (°C)			
Mineralization	VG [2500– 0], G [3500 – 3000], M [4000 – 3500], P [4000 – 3500]		
Electrical conductivity (EC) (μS/cm)			
Acidification	VG [8.2– 6.5], G [8.5 – 6.0], M [9.0 – 5.5], P [10 – 4.5]		
pH			
4). Prati index classification			
Parameters	*Observed value*	*Equations*	
Oxygen saturation (OS)	OS $\geq$ 100%	$Y_{OS} = 0.08 \times (OS - 100)$	
	50% $\leq$ OS $\leq$100%	$Y_{OS} = 0.08 \times (100 - OS)$	
	OS$<$ 50%	$Y_{OS} = 4.2 - 0.437\left(\frac{100-OS}{5}\right) + 0.042\left(\frac{100-OS}{5}\right)^2$	
pH	$7 \leq Y_{pH} < 9$	$Y_{pH} = \left(Y_{pH}-7\right)^2$	
	$5 \leq Y_{pH} < 7$	$Y_{pH} = 2\left(7-Y_{pH}\right)$	
Ammonium (NH_4^+)	NH_4^+(mgL^{-1})	$Y^+_{NH4} = 2^{2.1\log_{10}\left(12\times NH_4^+\right)}$	
Chemical oxygen demand (COD)	COD (mgL^{-1})	$Y_{COD} = \frac{1}{10} \times (COD)$	
Chloride (Cl^-)	$Y^-_{Cl} < 50$ (mgL^{-1})	$Y_{Cl} = 1.57\left(\frac{Y_{Cl}}{50}\right) + 0.57\left(\frac{Y_{Cl}}{50}\right)^2$	

2.4.4. French water quality assessment system (SEQ-EAU)

The French water quality assessment system, or SEQ-Eau, is a tool for characterizing the physico-chemical status of freshwater systems developed in the early 2000 and used by the local authorities for both surface and underground waters in France (SEQ-EAU, 2003). The SEQ-EAU assessment method comprises of many criteria and is potentially able to assess both warm and cold waters for different kinds of purposes (e.g. protection of aquatic life, irrigation, wastewater, etc.). In our study, eleven physico-chemical parameters such as dissolved oxygen (DO), chemical oxygen demand (COD), ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), orthophosphate (PO_4^{3-}), total phosphorus (TP), total suspended solid (TSS), water temperature (WT), electrical conductivity (EC) and pH were used for the assessment. In SEQ-EAU, five classes of water quality were categorized based on their threshold values (Table 2). Thus, if the observed value of the parameter at each monitoring site met the criteria/threshold value, it was scored based on the percentage in Table 2. In SEQ-EAU, five classes of water quality were defined ranking from "very poor" to "very good" quality. In our case study, we combined poor and very poor as one class (i.e. poor quality) to be consistent with other assessment methods. Thus, the maximum scores were 880 points and accounted for 100% of the quality. If the assessed site received a score lower than 50%, it was classified as "poor" quality. The site was classified as "moderate" if it received a score between 50% to 69%. Subsequently, the sites with "good" quality must be scored between 70% to 89%; while the site was classified as "very good" quality if it received 90% of total score.

3. Results

3.1. Spatial variation of water quality along the Sangker river

The pattern of water quality within the Sangker river catchment was described by the spatial variation of the important physico-chemical parameters obtained from the principal component analysis (PCA). Four axes of PCA were kept to describe the water quality patterns of Sangker river catchment and accounted for 87% of total variances (Fig. 2). Overall, we found a positive correlation between pH and DO on the first axe of PCA, while a very good association between EC and Cl^- was observed on the second axe of PCA (Fig. 2a). Besides, a negative association between NH_4^+ and COD was observed on the third axe of PCA and a positive correlation between nitrates (NO_3^-) and orthophosphate (PO_4^{3-}) was depicted on the fourth axe of PCA (Fig. 2b). However, the contribution of both NH_4^+ and PO_4^{3-} to the variation of water quality in the Sangker River were less important than the physico-chemical parameters mentioned above, e.g. DO, COD, pH (Fig. 2b).

The upstream–downstream gradient of water quality was captured by the variation of PCA factorial scores along the first three axes of PCA (Table S1, Fig. S1). Consequently, the pattern of water quality varied greatly from upstream to downstream. The first axe of PCA (Axis 1) showed a clear trend of oxygen depletion related to an increase in organic load from upstream to downstream (Fig. 2a, Fig. S1). The upstream sites exhibited negative PCA scores defining high level of DO, while downstream sites were associated with positive PCA scores reflecting low levels of DO. The second axe of PCA (Axis 2) showed a pollution pattern induced by chloride (Cl^-), where negative PCA scores were associated with high concentration of Cl^- in downstream sites and vice-versa. The third axe of PCA (Axis 3) exhibited an organic pollution pattern caused by an increase of chemical oxygen demand (COD) from upstream to downstream, where positive PCA scores were associated with high levels of COD and vice-versa (Fig. 2b, Fig. S1).

Precisely, the head of river basin was characterized by high levels of DO, pH, while their values declined gradually when arriving into the TSL floodplain. The profile of DO changed significantly between upstream and downstream, while it exhibited high value at upstream sites (7 mgL^{-1} to 9 mgL^{-1}), e.g. ORAING, UPSTR, and KOURY, and low values in the TSL floodplain (1.76 mgL^{-1} to 3.83 mgL^{-1}) (Fig. 3a, Fig. S1). Similarly, the value of pH was high at upstream sites (7.60 to 8.15) and gradually decreased at downstream sites (6.70 to 7.60). We found a contrast profile of EC and chloride (Cl^-) concentration to the above element, where low values of EC and Cl^- were exhibited in most of the

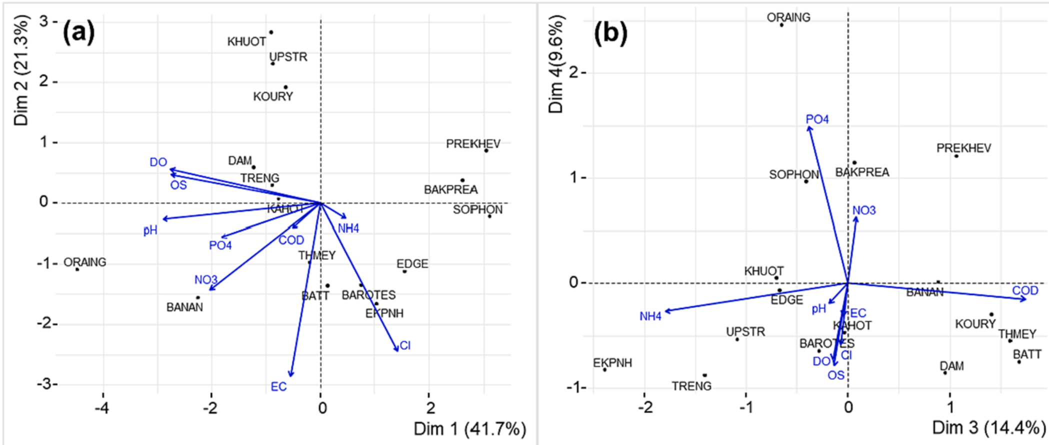

Fig. 2. Principal component analysis (PCA) biplot showing the relationships between selected physico-chemical parameters (blue arrows) and monitoring sites (black dots) and the upstream–downstream gradient of water quality along the Sangker River catchment. (a) The 1st and 2nd axes of PCA exhibited oxygen and electrical conductivity gradients and (b) the 3rd and 4th axes of PCA revealed nutrient gradients (Table S1 and Fig. S1).

upstream sites; their concentration reached maximum (240 μScm^{-1}) in the middle stream (e.g. BTB, THMEY, EKPHN) and reduced slightly while entering the TLS floodplain (Fig. 3b, Fig. S1).

However, no clear pattern was observed for orthophosphate (PO_4^{3-}) and nitrate (NO_3^-). Actually, important value of orthophosphate was shown at the most upstream sites (e.g. ORAING, UPSTR, and KOURY) associated with the impact from agricultural activities (e.g. chemical fertilizers); its concentration reduced significantly from the middle-stream, where a lower exposure to agricultural activities is observed. Additionally, nitrate (NO_3^-) seemed to increase from upstream to downstream as the result of the organic pollutant accumulation driven by human activities. Basically, high concentration of NO_3^- was shown at the downstream sites below the Battambang city, e.g. EKPNH and BAROTES, (Fig. 3c, Fig. S1). Similarly, a decreased profile of COD concentration was revealed along the Sangker river, while important concentration of COD was exposed in two sites in the middle stream of Sangker (i.e., THMEY, BTB) (Fig. 3d, Fig. S1). This could result from direct domestic waste injections of riparian villages/cities into the river.

3.2. Comparative assessment of water quality assessment methods

Multiple correspondence analysis (MCA) factorial map showed a positive relationship between the five water quality assessment methods based on the similarity of water quality classes defined by each method. The first two axes of MCA accounted for 60.52% of total variances, while an important variation between the studied methods was observed on the first axe of MCA, e.g. Basic Prati *vs*. US-EPA (Fig. 4a). Indeed, the Basic Prati was quite different from MRC-WQI, while we found the similarity between MRC-WQI, Single-Prati and US-EPA assessment methods. Overall, the distribution of the five assessment methods on the MCA map suggested a convergence of the classification of water quality in the Sangker river. This result clearly indicates the adaptability and the relevance of these five assessment methods to assess the water quality of the Sangker river catchment and by extension to the entire Cambodian river network. Though, some techniques were quite strict to score the water quality resulting in many sites of poor quality (e.g. Basic-Prati, Single Prati) and vice-versa (e.g. SEQ-EAU).

3.3. Water quality status in the Sangker river catchment

Overall, the water quality classification with the five assessment methods showed that the water quality of the Sangker river varied from “very good” to “poor”. Basically, based on the US-EPA assessment method, 50% of sites were assessed as “very good”, 25% and 25% of sites were scored as “good” and “moderate” respectively, while no site was assessed as “poor” quality (Fig. 4b). In contrast, the Basic Prati classified all sites to “poor” quality (Fig. 4b). The MRC-WQI assessment method classified the monitoring sites into two classes of quality ranking from “very good” to “good”. Specifically, 75% of sites were scored as “very good”, while 25% of sites were scored as “good”. Similarly, with the Single-Prati classification, 50% of sites were classified as “very good”, while 12.5%, 12.5% and 25% of sites were rated as “good”, “moderate” and “poor” quality respectively (Fig. 4b). Last, the French water quality assessment method (SEQ-EAU) determined only two classes of water quality; 94% of sites were scored as “good” and only 6% was scored as “moderate” quality (Fig. 4b). Therefore, considering the average scores of the classification with these five methods, the water quality varied greatly from upstream to downstream with 35% of sites rated as “very good”, 31% as “good”, 9% as “moderate”, while 25% of sites were rated as “poor”. These classifications showed the current ecological health status of the Sangker river catchment facing multiple environmental pressures.

4. Discussion

4.1. Spatial variation of water quality in the Sangker river catchment

Multiple pressures from human activities associated with the complexity of river landscape impact water quality and its river basin’s ecosystem services (Sourn et al., 2022). Consequently, the water quality changed greatly from upstream to downstream of the Sangker river (Table S1, Fig. S1). The water quality pattern was described by four key physico-chemical parameters (i.e. DO, COD, Cl^-, and NO_3^-), which are essential factors for the protection of aquatic life and ecosystem health (Chea et al., 2016). Basically, the high level of DO and low nutrient concentration at the head of the Sangker river basin was explained by its topography and land-uses (mountainous areas with forest cover) associated with a low level of human disturbances. The quality of water declined gradually along the river gradient, particularly in the middle part of the river. This pattern is quite common in tropical river systems (Chea et al., 2016; Ibrahim et al., 2021; Necker et al., 2019; Yadav et al., 2019) and reflects the river continuum concept (RCC) (Vannote et al., 1980). The increased nutrient content, especially the nitrates (NO_3^-) in the middle part of the Sangker river, was explained by the accumulation of agricultural waste and domestic pollution from the riparian cities. Consequently, the concentration of nutrients accumulated up to the TLS floodplain in the opposite trend to DO concentration suggests the impact of organic pollution derived from human activities and the transition from lotic (river) to lentic ecosystems (Tonle Sap floodplain) (Alvarez-Mieles et al., 2013; Necker et al., 2019).

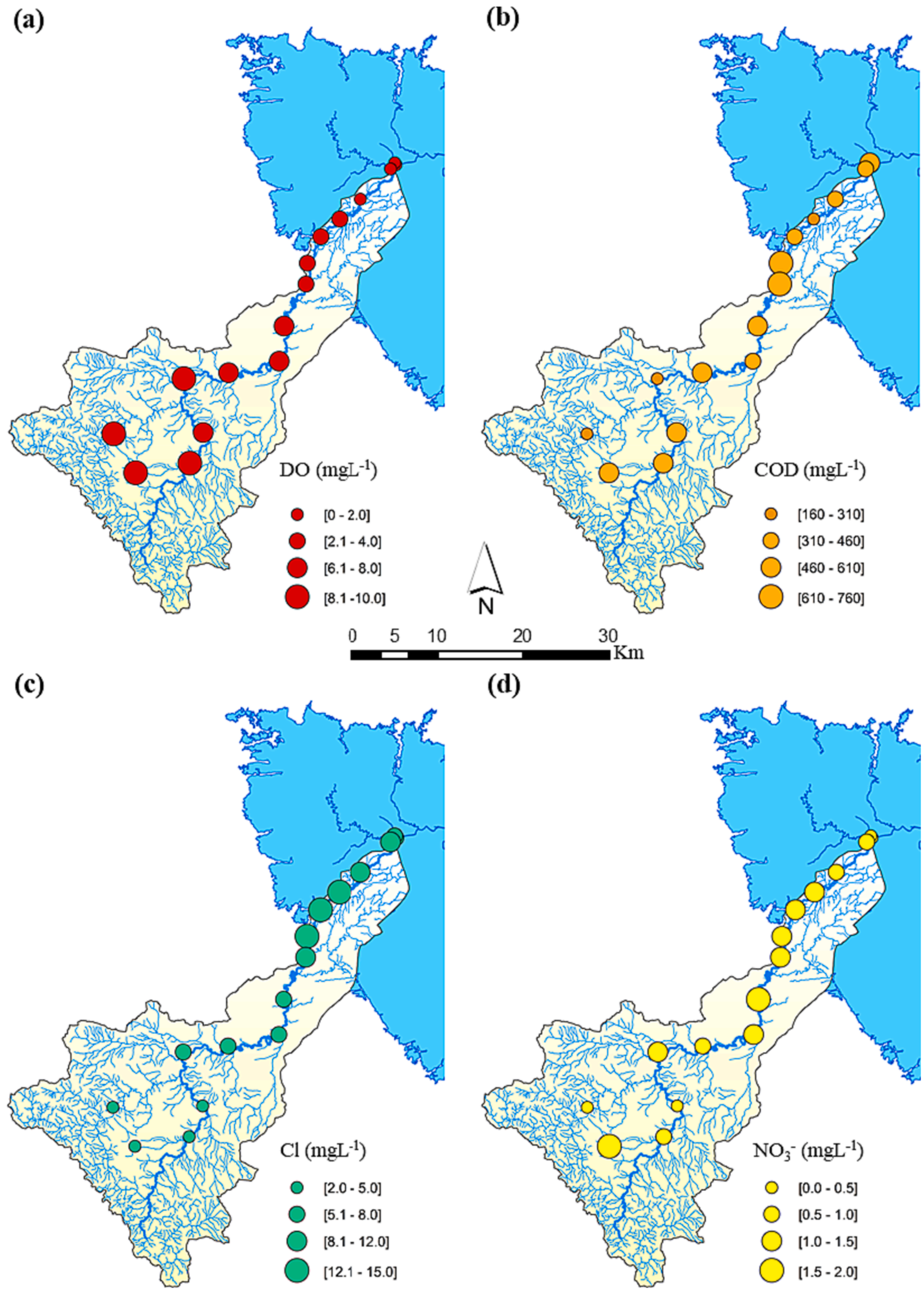

Fig. 3. Spatial variation of water quality along the environmental gradient in the Sangker river catchment (Tonle Sap Lake Basin, Cambodia). The patterns of water quality were described by the variation of averaged concentration between 2018 to 2021 of the four primary physicochemical parameters: (a) dissolved oxygen (DO), (b) chemical oxygen demand (COD), (c) chloride (Cl^-), and (d) nitrate (NO_3^-).

Additionally, these observed patterns were consistent with many studies in the Mekong region; for instance, from the Sai Gon river in southern Vietnam, the DO concentration was very high upstream of the river (6.1 mgL^{-1}) and concentrations dropped by 50% (from 6.1 mgL^{-1} to 3.2 mgL^{-1}) at the downstream of the river due to domestic pollution and direct injection of sewage from the Ho Chi Minh city (Pham, 2020; Pham and Nguyen, 2018). Besides, similar patterns of oxygen depletion along the river gradient were revealed in many tropical river systems, e. g. Mekong river, Mun river, Tha Chin river, Chao Praya river in Thailand (Chea et al., 2016; Molle et al., 1999; Muttamara and Sales, 1994; Yadav et al., 2019). Indeed, the sharp decline of DO and the increase of nutrients (COD, NO_3^-) in the Sangker river was primarily caused by organic pollution from the riparian cities and economic activities (e.g. livestock, agricultural crops, small-medium enterprises). This situation was worse during the low water period, when eutrophication occurred frequently along the river, particularly in the middle part of the Sangker river below Battambang city (e.g. BTB, EKPNH, BAROTES, EDGE, SOPHON, BAKPREA, and PREAKHEV). In the middle part of the Sangker river, an abrupt shift of COD concentration (from 160 mgL^{-1} to 750 mgL^{-1}) was observed. This was explained by the high level of accumulation of domestic and agricultural wastes in the middle stream, where high density of population was exhibited (Heng et al., 2013; Sourn et al., 2022). As an example, in the Melana river in Malaysia, the concentration of COD was reported to increase twice due to the organic disposal and domestic wastes (Arman et al., 2013). Consequently, eutrophication is very harmful to aquatic life and ecological health of Sangker river.

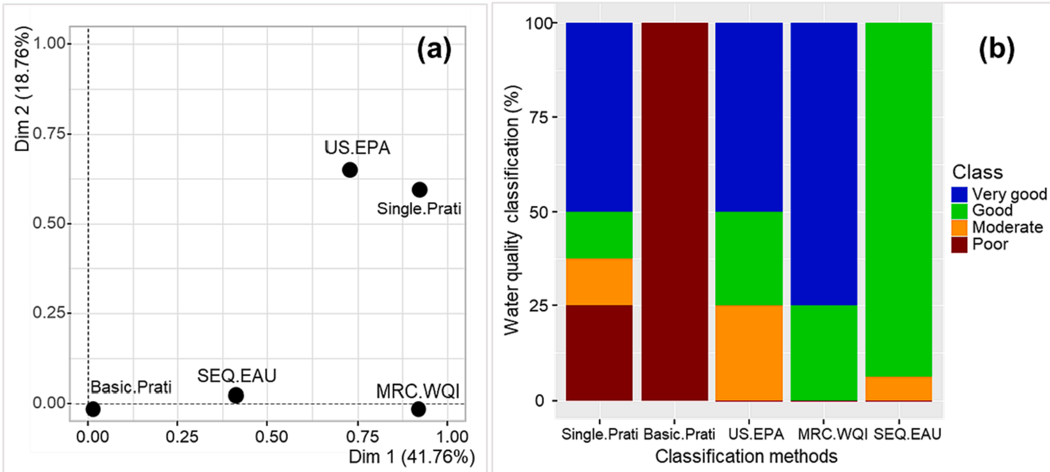

Fig. 4. Comparison of water quality assessment methods in the Sangker river catchment (Tonle Sap basin) using the physico-chemical parameters of surface water. (a) Multi-correspondence analysis (MCA) factorial map showing the association between the five water quality assessment methods (Basic Prati, MRC-WQI, SEQ-EAU, Single Prati and US-EPA) and (b) Stacked bar chart presenting the percentage of water quality by class ("very good", "good", "moderate" and "poor"). US-EPA denoted the United States for Environmental Protection Agency (US-EPA) assessment method, while MRC-WQI indicated the Mekong River Commission water quality index assessment framework and SEQ-EAU referred to the French water quality assessment method (Système d'Évaluation de la Qualité de l'eau).

Furthermore, the concentration of chloride (Cl^-) increased simultaneously with nutrient as the result of livestock and agricultural fertilizers (Al-Khateeb, 2017; Kelly et al., 2012). The increase of Cl^- was associated with the increase of COD concentration since these two parameters were positively correlated. This positive relationship was also revealed in the Gombak river basin in Malaysia, where the concentration of Cl^- increased from 1.00 mgL^{-1} to 102.22 mgL^{-1} as a result of the Kuala Lumpur city's waste (Ismail, 2011). Indeed, in the Sangker river catchment, the concentration of Cl^- was less harmful (2.76 mgL^{-1} to 13.22 mgL^{-1}) compared to other tropical river systems. Besides, the organic pollution and eutrophication observed in the Sangker river are fairly common water issues in freshwater ecosystems. Consequently, the current concentration of DO, NO_3^-, COD and Cl^- were at tipping points and could potentially affect ecological health of aquatic organism (e.g. fish, invertebrates, mollusks) and the livelihood of the communities living by the river catchment if we do not take appropriate measures. This situation could be worse in the future since the climate is changing, and the population is growing, associated with important levels of fragmentation within the river catchment (Heathwaite, 2010; Whitehead et al., 2009).

4.2. Comparative assessment of water quality assessment methods

Our study revealed a positive convergence of the five water quality assessment methods on the classification of water quality in the Sangker river catchment, while the US-EPA method was found to be the most appropriate assessment method for the Sangker river. Indeed, the proposed assessment methods above were quite comprehensive and complementary to quantify the water quality in freshwater ecosystems. However, we still found differences in water quality classes defined by the proposed assessment techniques. This could be explained by their relevance and adaptability to assess the quality of surface waters in mesotrophic ecosystems as the Sangker river and Tonle Sap lake. Consequently, some assessment methods were quite loose to score the quality of water resulting in too many "good" sites (e.g. SEQ-EAU), while others were too strict resulting in too many "poor" quality sites (e.g. Basic Prati index). This variation could be explained by the criteria of the assessment methods and its appropriateness in mesotrophic tropical ecosystems since most of the proposed assessment techniques originated outside of Cambodia (Tyagi et al., 2020).

Indeed, Basic Prati index used only three parameters oxygen saturation (OS), NH_4^+ and COD with a low COD threshold value (5 mgL^{-1}) compared to the reality of COD concentration in tropical river systems (Arman et al., 2013). Thus, this mismatch resulted in bad classifications in most of the monitoring sites within the river catchment. In contrast, the SEQ-EAU provided a good water classification. This method contains too many parameters and their threshold values determined from temperate freshwater ecosystems are not fitted to track changes of water quality in tropical hydrosystems such as the Sangker river (MRC, 2007; SEQ-EAU, 2003). As a result, these above-mentioned assessment methods (i.e. SEQ-EAU, Prati indices) do not appear to be sufficiently discriminating, as shown by the overrepresentation of a single quality class (e.g. the SEQ-EAU contained 94% of good sites while the Basic Prati contained 100% of sites with poor quality). In consequence, these above classifications did not truly reflect the reality of water conditions in the Sangker river catchment.

On the other hand, both the US-EPA and the MRC-WQI methods provided more suitable classification reflecting the water quality gradient of the Sangker river catchment. Most upstream sites were graded as very good, the quality was progressively reduced in the middle part to the downstream river into the TLS floodplain. From the recent work of Chea et al. (2016) in the LMB, the authors used the US-EPA method to assess the water quality for the protection of aquatic life in the LMB and showed its suitability for the mesotrophic system as TSL basin (Chea et al., 2016; Sor et al., 2021). Interestingly, our study suggested that the US-EPA assessment technique was suitable not only to assess the water quality for large rivers as the Mekong, but it could provide an accurate assessment for medium size rivers as the Sangker. The MRC-WQI was well known for the water quality assessment in the LMB, particularly for the protection of aquatic life based on the six important physico-chemical parameters. Indeed, it was not surprised that MRC-WQI method provided an acceptable assessment since the method was developed in the Mekong region; thus, it must be relevant to quantify the ecological health of tropical river systems including the Sangker river (MRC, 2016, 2008).

Surprisingly, the Single Prati index provided a correct classification of water quality in the Sangker river even though the method relied on a single physico-chemical parameter (oxygen saturation). This suggests that oxygen saturation is the predominant water parameter in the Sangker river basin. However, water quality assessment framework should be multifaceted to capture accurately the pollution from different sources (Dwivedi and Shikha, 2016; Singh and Gupta, 2017). Consequently, relying on a single parameter is tricky to track pollution from multiple sources. This method could be suitable for one-shot quality assessments; however, it is questionable whether it could provide an accurate long term assessment when the river becomes exposed to extreme multiple environmental pressures.

Therefore, the US-EPA and MRC-WQI methods were suitable to assess the water quality in the Sangker river, as well as in the Tonle Sap basin. Beyond an accurate assessment, both assessment methods contained an ideal number of assessed parameters (4 to 6 parameters) that is convenient for long-term environmental monitoring in developing countries such as Cambodia. Furthermore, the US-EPA and MRC-WQI assessment techniques could be interchangeable and potentially used to assess the ecosystem health within the Cambodian river networks.

The current study provided new insights on the water quality assessment framework within data-scarce environments; especially, in developing countries such as Cambodia where long term water quality monitoring is missing. In the developing world, assessment and monitoring of water quality face many challenges, i.e. financial, institutional and technical capacity challenges, as reported recently in a review on the assessment of the capacity challenge on water quality monitoring in the world (Kirschke et al., 2020). In order to address these challenges, the current work proposed a framework with less indicators and simplified assessment procedures to monitor river ecosystem health for the protection of aquatic life. This contributes to reduce costs associated with data collection and laboratory analysis and an easier access to local authorities to handle the tasks without requiring advanced expertise. Indeed, there is always a big discussion and disagreement on the use of water quality index (WQI) to assess or monitor river ecosystem health such as the selection of parameters and weighting systems. So far, there is no consensus on a “universal” WQI for assessing water quality or river health (Kachroud et al., 2019). Consequently, the implementation of WQI requires more data (e.g. time-series data and more parameters), technical expertise and costly laboratory analysis which are major challenges for developing countries like Cambodia. The present work has therefore proposed a monitoring framework that is inexpensive, quick and easy to implement, accessible and relevant for developing countries where temporal and spatial scales of environmental monitoring are lacking and needed, e.g. Cambodia, Laos, Vietnam. Based on the comparative analysis of different water quality assessment frameworks, the US-EPA framework was highly recommended for river ecosystem health in Cambodia and the Mekong region. Indeed, this framework proposed only four primary physico-chemical parameters that is low cost and can be quickly implemented on the field. For these reasons, the proposed framework could potentially be used by local authorities and stakeholders to fill the gaps on environmental monitoring of freshwater ecosystems in Cambodia. Furthermore, the current framework was the baseline reference condition of the Sangker river ecosystem health, which can be further developed into ecological indices incorporating biological components of rivers (e.g. invertebrates, benthic diatoms) and transformed into interactive map tools for river ecosystem monitoring and management with wider accessibility and use in the future.

5. Conclusions

Facing multiple environmental pressures resulting from rapid economic development activities (e.g. urbanization, industrialization, agricultural intensification), the overall ecological health status of the Sangker river catchment remains fairly good. Organic pollution and eutrophication seem to be major issues for the decline in water quality within the catchment; particularly, in the middle course and the TLS floodplains. This can be an alarming signal for environmental managers and local actors to take appropriate action in response to these issues. Accordingly, river ecosystem health monitoring is an important measure to ensure the sustainable use of its ecosystem services and people’s livelihoods. Nevertheless, ecosystem health monitoring is frequently a challenging issue in most developing countries with restricted resources to maintain regular monitoring; thus, monitoring programs were sparse in those countries. Consequently, the outcome of the current study could a be a milestone to address river ecosystem health monitoring’s challenge by proposing a low cost and quick water quality assessment framework, potentially used in data-scarce environments or adapted to developing countries with limited resources. Specifically, the US-EPA assessment framework was defined as the most suitable technique to quantify ecosystem health of the Sangker river catchment and was highly recommended in data-scarce environments or locations with financial and technical capacity constraints. Moreover, the current study provided a baseline reference of the Sangker river catchment condition that is needed for further development of ecological indices, i.e. diatom based tools that can be used for assessing ecosystem health status of other tributaries around TSL systems. In addition to that, the current river health assessment framework can be further used as a decision support tool by local authorities, researchers, environmental managers and practitioners to perform regular monitoring and river basin management planning. Last but not least, the lessons learned from the current work could promote an initiative to develop inexpensive and sustainable tools for environmental monitoring programs in Cambodia and other developing countries in Asia or Africa, where monitoring programs are needed to maintain river ecosystem health facing human pressures and climate change.

CRediT authorship contribution statement

Socheat Chrea: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft. **Loïc Tudesque:** Conceptualization, Investigation, Resources, Writing – review & editing, Supervision. **Ratha Chea:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.110759.

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