

Article

Water Quality Degradation in the Lower Mekong Basin

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Abstract: The Mekong River is one of the world's largest rivers, unparalleled in terms of its biodiversity and ecosystem services. As in other regions, sufficient water quality is required to support diverse organisms, habitats, and ecosystems, but in the Mekong region, water quality has not been well studied. Based on biological and physical-chemical data collected over the last two decades, we evaluated spatial-temporal water quality of the Lower Mekong Basin (LMB) using biotic and abiotic assessment metrics. We found that during the 2000s, water quality in the LMB was unpolluted, with "very good" metrics for tributary rivers and "good" status for mainstem rivers. However, during the last decade, water quality has been degraded in the LMB, particularly near Vientiane City; the Sekong, Sesan, and Srepok (3S) Rivers; the Tonle Sap Lake system; and the Mekong Delta. Water quality degradation likely corresponds to flow alteration, erosion, sediment trapping, and point and non-point wastewater, which have occurred from rapid hydropower development, deforestation, intensive agriculture, plastic pollution, and urbanization. Regular biomonitoring, physical-chemical water quality assessment, transparent data sharing, and basin-wide water quality standards or management are needed to sustain water quality to support biodiversity and ecosystem function in the LMB.

Keywords: water quality monitoring and assessment; macroinvertebrates; water quality index; BMWP score; Prati index; 3S Rivers; Tonle Sap Lake; water pollution



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1. Introduction

Healthy river ecosystems depend on sufficient water quality, which supports native biodiversity and ecosystem services. Without suitable water quality, riverine organisms become stressed, and populations of vulnerable species can decline or, in extreme cases, face extinction [1,2]. Moreover, poor water quality leads to degraded ecosystems, decreased aquatic biodiversity, and declining fisheries [3], resulting in reduced local livelihood opportunities and national economic growth [4].

Water quality can be assessed using biological and physical-chemical metrics. Biotic assessments have been widely applied throughout the world, but are most common in developed countries. Typical metrics include Chandler's Biotic Score [5] and Hilsenhoff's Biotic Index [6] in the United States of America, the Biological Monitoring Working Party (BMWP), Iberian BMWP, Belgian Biotic Index, and Danish Stream Fauna Indices that have

been implemented in Europe [7,8], South America [9,10], and Australia [11]. Similarly, abiotic assessments, which are based on physical-chemical variables, are commonly used to assess water quality across the globe [12–16]. Overall, researchers measure physical-chemical variables in rivers about twice as often as biotic variables [17]. However, the two metrics can be used together to validate each other. A strong agreement between the two provides a more reliable indication of water quality [18,19].

The Mekong River, hereafter referred to as “Mekong”, is one of the most significant rivers in the world in terms of length discharge, economic importance (e.g., fisheries, agriculture, hydroelectricity, trade, navigation, etc.), and biodiversity [20]. The Mekong supports at least 890 fish species (1200 estimated), the majority of which occur in the Lower Mekong Basin (LMB) [21]. The LMB provides an estimated fishery harvest ranging from 1.3 to 2.7 million tonnes per year [22], and supports at least 131 insects, 38 crustaceans, and 32 annelids [23], approximately 146 mollusk taxa [2,24], and over 400 species of other invertebrates (e.g., rotifer) [25]. Many of these species are endemic, and increasing numbers are threatened by human activity [1,2,26]. All of these species are affected by the Mekong River hydrology, and their communities are altered where water quality changes occur [3,27].

The Mekong River has been altered considerably in the last two decades [28]. Although water quality has historically been graded as “good” across most of the basin [29,30], more recent studies have identified degraded water quality at many sites [13,31,32]. For example, sediment loads and total suspended solids have been altered as sediment is trapped behind mainstem and tributary dams [33], and salinization of the Mekong Delta has increased [29]. Some key water quality variables such as total phosphorus, nitrate, ammonium, and total suspended solids have fluctuated above the historical baseline throughout the basin and the Sekong, Sesan, and Srepok (3S) River system, which together form a major tributary to the Mekong. Nitrate and ammonia concentrations have increased at Thai Mun River’s lower reaches where the river meets the Mekong. Changes in water quality are also affected by strong climate variability between the dry and rainy seasons. For example, in the Mun River Basin, the poorest water quality coincides with the flooded season due to high inputs of nutrients, pollutants, and sediment from agricultural and urban sources [34]. Chea et al. [13] found that tributary sites were characterized by eutrophication (e.g., the northern part of the Cambodian Tonle Sap Lake and upstream reaches of the Mun river in Thailand) and high salinity (e.g., the Mekong Delta).

Macroinvertebrate and physical-chemical sampling to assess water quality is scarce in the LMB, particularly at a large spatial scale. Moreover, a scientific comparison of water quality indices through time has never been conducted for the LMB. The only existing study of water quality throughout the basin is from Chea et al. [13], which revealed more water quality degradation in tributaries than mainstem rivers, and from Mekong River Commission (MRC) technical papers, which reported “good” water quality across most of the basin [29,30]. Other water quality studies have been limited to smaller areas of the LMB using either aquatic organisms or physical-chemical parameters, and include Wilbers et al. [35] and Phung et al. [36] in the Mekong Delta, Oeurng and Sok [33] in the 3S rivers, Sor et al. [27] in the upper Cambodian Mekong, Tian et al. [34] in Mun River, and Kudthlang [37] in Chi River.

The overall aim of this study is to analyze spatial and temporal changes of water quality in the LMB using macroinvertebrate presence/absence data for biotic assessment and physical-chemical data for abiotic assessment. Comparing indices between sampling sites in the mainstem Mekong and its tributary rivers is important to understand where suitable water quality and habitat exist. We expect better water quality in the mainstem sites as compared to the tributaries, as revealed by previous studies in the LMB [13]. We investigate the temporal changes in water quality in the 2000s and 2010s, following unprecedented hydropower dam development in the LMB [38]. In response to hydropower dam development and increasing anthropogenic activities, we hypothesize that water quality of the LMB is more degraded in the 2010s as compared to the 2000s period. We

discuss water quality results spatially and temporally to inform sustainable management and dam development in the LMB.

2. Materials and Methods

2.1. Study Area and Hydrology

The LMB extends from the border of Yunnan, China to the Mekong Delta, and includes portions of Laos, Thailand, Cambodia, and Vietnam [20]. The LMB is characterized by fairly flat topography, extensive floodplains, and significant tributaries such as the 3S River and Tonle Sap systems. The LMB has pronounced wet (May–October) and dry (November–April) seasons, creating a prominent flood pulse that is the foundation for extraordinary biodiversity. Average wet season discharge is about 65 km³ at the Chinese border and increases to 350 km³ at the border of Cambodia and Vietnam [20]. Cambodia's Tonle Sap (TS) Lake is the largest floodplain of the LMB. The Mekong and TS Lake are connected via the TS River. In the dry season, the water flows from TS Lake to the Mekong via the TS River when the Mekong water level drops. A reverse flow into TS Lake occurs in the wet season when the Mekong water level rises. This process forms a unique hydrological system with the Mekong and TS system. The regular hydrologic cycle in the LMB historically brought nutrients and sediment to TS Lake and the Mekong Delta.

Large rivers in the LMB have been an important conduit for trade and transportation, and a target location for city development of each country for centuries [39]. In Cambodia, the capital of the country (Phnom Penh) and the capitals of many provinces (e.g., Kampong Cham, Kratie, and Stung Treng) are situated along main rivers. Similarly, the capital of Laos (Vientiane) and provincial cities (e.g., Pakse, Savannakhet, and Luang Prabang) are located along the Mekong's banks. In the Mekong Delta, mainstem segments have been used for city development (e.g., Chau Doc, Cao Lanh, Long Xuyen, Can Tho, etc.). In this regard, the region's main rivers have long been exposed to anthropogenic pressure. On the other hand, upstream LMB tributaries like the 3S Rivers remained relatively natural compared to the mainstem, until the recent hydropower development occurred.

Profound changes are occurring in the LMB, which include intensive agriculture, land use change, forest loss, urbanization (industry, transportation, infrastructure, cities, etc.), and hydropower dam development [32,40]. In the last decade, hydropower dam development has greatly expanded in the LMB mainstem and tributaries [38]. Before the 2000s, only 9 projects \geq 15 megawatts (MW) were commissioned, with a total of 1303 MW installed capacity and 14,531 million cubic meters (Mm³) of reservoir storage (Figure 1). By the end of 2000s, 21 projects were commissioned, with 3617 MW and 15,933 Mm³ of reservoir storage, and by the end of 2010s, 51 projects were commissioned, with an estimated 10,236 MW and 37,921 Mm³ of reservoir storage [38]. Most of the 51 dams that have been commissioned were medium to large size, with installed capacity up to 1285 MW and reservoir storage up to 4700 Mm³ (Figure 1). Most of the dams are located in the 3S River system and in upstream tributaries in Laos. Their operations have caused changes in water quality such as increased nitrate, total phosphorus, and chloride loadings, reduced sediment transport and discharge, and sea water intrusion near the Mekong Delta [31,33].

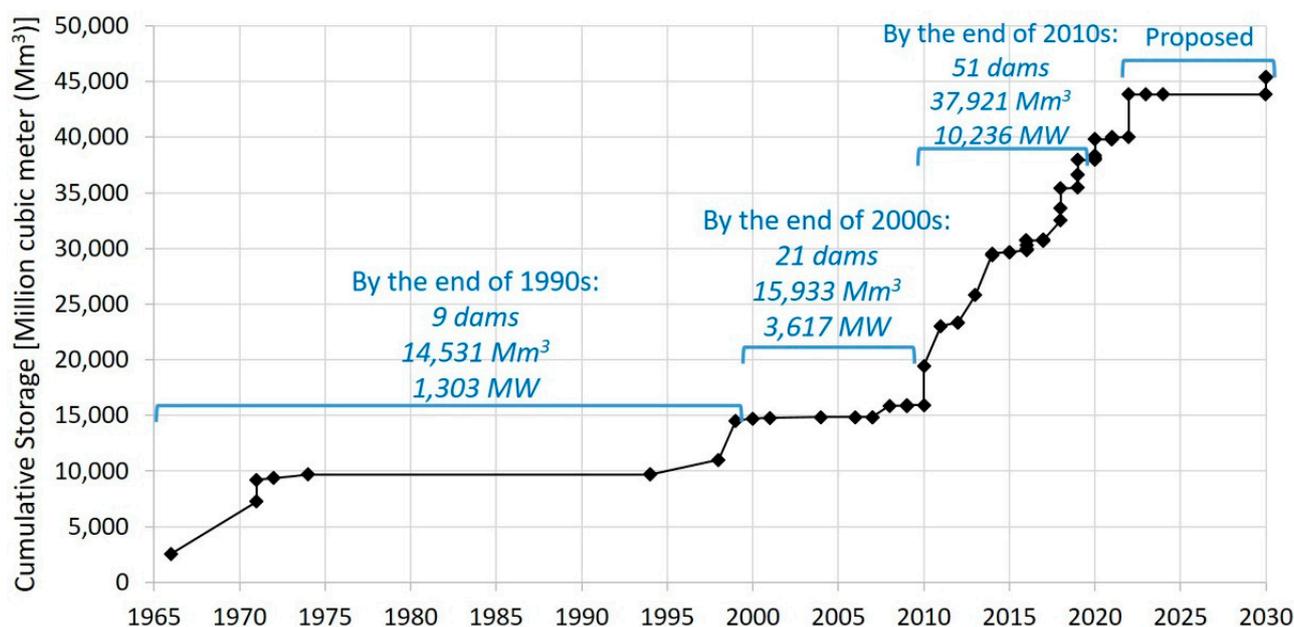


Figure 1. Hydropower dam development and cumulative storage and installed capacity in the Lower Mekong Basin. Data is derived from WLE [38].

2.2. Data Collection and Processing

Macroinvertebrate samples and physical-chemical data were from the Mekong River Commission's (MRC) Biomonitoring Program (60 sites) and Water Quality Monitoring Network (over 130 sites). For this analysis, we used sample sites shared between the two monitoring programs, which provided 47 sample sites for our study.

Benthic and littoral macroinvertebrates from the LMB were sampled once a year in March, the dry season, from 2004 to 2008, to quantify biotic water quality. They were collected separately at the same sites. Benthic invertebrates were collected using a Petersen grab sampler. With the grab, four sub-samples were collected and pooled to give a single sample covering a total area of 0.1 m². For detailed information on benthic invertebrates sampling, see Sor [41] and Sor et al. [23]. Littoral macroinvertebrates were sampled by sweeping with a 475 µm mesh D-frame net (30 cm × 20 cm). Ten sweeps were made to obtain a sample. Each sweep covered a 20 m distance near the shore at a depth no greater than 1.5 m. All invertebrate samples were brought to the laboratory to be sorted, identified to the species level when possible, and counted. Median values of invertebrate counts from the whole period (2004–2008) were used to assess water quality at each sample site. Median counts were used because they are a robust statistical indicator that reduces the effect of noisy data [42]. Data for the biotic-based analysis were available only for the 2000s period.

Physical-chemical water quality data was collected from 1985 to 2017 via the Water Quality Monitoring Network Program. The program began in Laos, Thailand, and Vietnam in 1985, and in Cambodia in 1995 [29]. From the physical-chemical dataset, dissolved oxygen (DO), total phosphorus (TP), total ammonia (TA), chemical oxygen demand (COD), ammonium-N (NH₄⁺-N), and chloride were analyzed in this study. Of those variables, DO, TP, TA, and chloride were used for the water quality assessment based on the Environmental Protection Agency of United States (US-EPA)'s guidelines, while DO, COD, and NH₄⁺-N were used for the water quality assessment based on DO and Basic Prati indices [14]. These variables are considered good indicators for the impact of water quality on aquatic life and ecosystem health [14,29]. Low levels of DO affect aquatic biodiversity, and excess levels of TP, TA, and ammonia can be toxic or lead to eutrophication, and therefore affect human and ecological health [43]. To investigate temporal changes in water quality, we divided the data into two periods. The first dataset contained all samples in

the 2000s during a period with few dams, and the second dataset contained all samples in the 2010s, which was a period of increased dam development with a marked increase in water storage and hydropower operations in the LMB (Figure 1). Median values of water quality variables from each period summarized physical-chemical water quality at each sampled site.

2.3. Water Quality Assessment and Analysis

Biotic water quality was assessed using presence/absence of macroinvertebrate families from each sampling site. The presence/absence data were then used to compute the biotic indices using the Biological Monitoring Working Party for Thailand (BMWP-Thai). This biotic-based assessment is a modification of the original BMWP index for macroinvertebrate assemblages collected from northern Thailand [44]. Macroinvertebrate families were scored from 1 to 10, where a score of 1 signifies the most pollution-tolerant family and 10 signifies the most pollution-sensitive family [44]. Scores assigned to each family were summed for each site.

We assessed biotic water quality in pool and pool-riffle habitats [7] because they were predominant in this basin with relatively flat topography and extensive floodplains. The average score per taxon (ASPT) was calculated by dividing the BMWP score by the number of contributing families. The ASPT score is thus independent of the number of families, and therefore is less sensitive to sampling error or seasonal variability [45]. Water quality was determined from BMWP-Thai and ASPT-Thai indices for each site. Lastly, the Lincoln index was also calculated using averaged BMWP-Thai and ASPT-Thai indices. This index is considered to be less biased when either the BMWP or ASPT indices are distorted. Good agreement among the three indices indicates a reliable classification of water quality status [7]. All of the biotic-based water quality indices range from 1 to 7, where 1 represents very poor water quality and 7 represents excellent water quality [7]. Criteria to assess the biotic water quality are provided in Table 1.

Table 1. Biotic-based water quality assessment criteria based on BMWP-Thai and its corresponding water quality classification [44].

BMWP Score	BMWP Index	ASPT Score	ASPT Index	Lincoln Index	Water Quality Classification
0–9	1	0.0–2.0	1	1.0–1.5	Very Poor
10–24	2	2.1–3.0	2	2.0–2.5	Poor
24–50	3	3.1–3.5	3	3.0–3.5	Fair
51–80	4	3.6–4.0	4	4.0–4.5	Good
81–100	5	4.1–4.4	5	5.0–5.5	Very Good
101–120	6	4.5–4.9	6	≥6.0	Very Good
>120	7	≥5.0	7	-	Very Good

For the abiotic-based water quality assessment, four variables (DO, TP, TA, and chloride) were used following the US-EPA’s guidelines to estimate impact on aquatic life [46], which was developed under the USA’s Clean Water Act of 1972. The US-EPA guidelines can be applied to various water bodies such as warm, cool, and cold water [47], and therefore the guidelines can reasonably be applied to the Mekong [13]. US-EPA guidelines have been used in tropical rivers in Costa Rica [48] and Ghana [49]. For the US-EPA method, a score of 1 is given to each variable if it meets water quality thresholds (Table 2). Using four water quality constituents, a sampling site would be classified as “very good” water quality with a score of 4 when all criteria are met, while a 3 indicates “good” water quality, 2 indicates “fair” water quality, and 0 or 1 indicates “poor” water quality.

Table 2. Variables, thresholds, and scores to assess water quality based on the US-EPA [46].

Variable	Abbreviation	Threshold Value	Score
Dissolved Oxygen	DO	>5 mg/L	1
Total Phosphorus	TP	<50 µg/L	1
Total Ammonia	TA	<20 µg/L	1
Chloride	Cl	<250 mg/L	1

In addition to the US-EPA guidelines, abiotic water quality was also assessed using the DO Prati and Basic Prati indices [14]. Prati indices assess general surface water quality and have been applied in temperate [14] and tropical [15] regions. The DO Prati index was computed based only on DO percent saturation (Table 3) and the Basic Prati index used DO percent saturation, ammonium-N, and chemical oxygen demand (Table 3). The three computed index variables (DO, $\text{NH}_4^+\text{-N}$, and COD) were averaged for the final Basic Prati index (Table 3). Each Prati index was used to assess water quality following the criteria provided in Table 4. To standardize the interpretation of all indices, we used reciprocal forms ($1/\text{computed index}$) for Prati indices, since scores for Prati indices are inverse from BMWP, ASPT, Lincoln, and US-EPA indices.

Table 3. Variables, units, and formulas to compute Prati indices [14].

Variables	Abbreviation	Unit	Observed Value	Index Variable Computation
Dissolved Oxygen	DO	%	DO < 50%	$X_{\text{DO}} = 4.2 - 0.437\left(\frac{100-\text{DO}}{5}\right) + 0.042\left(\frac{100-\text{DO}}{5}\right)^2$
Dissolved Oxygen	DO	%	$50\% \leq \text{DO} < 100\%$	$X_{\text{DO}} = 0.08 \times (100 - \text{DO})$
Dissolved Oxygen	DO	%	DO $\geq 100\%$	$X_{\text{DO}} = 0.08 \times (\text{DO} - 100)$
Ammonium-N	$\text{NH}_4^+\text{-N}$	mg/L	$\text{NH}_4^+\text{-N}$ (mg/L)	$X_{\text{NH}_4^+} = 2^{2.1 \log_{10}(12 \times \text{NH}_4^+)}$
Chemical Oxygen Demand	COD	mg/L	COD (mg/L)	$X_{\text{COD}} = \text{COD} \times \left(\frac{1}{10}\right)$

Table 4. Prati index category and its reciprocal form to assess water quality, adopted from [14].

Prati Index (X_{Prati})	Reciprocal X_{Prati}	Water Quality Assessment
$0 \leq X_{\text{Prati}} < 1$	>1.0	Good Quality
$1 \leq X_{\text{Prati}} < 2$	$1.0 \geq X_{\text{Prati}} > 0.5$	Fair Quality
$2 \leq X_{\text{Prati}} < 4$	$0.5 \geq X_{\text{Prati}} > 0.25$	Polluted Quality
$4 \leq X_{\text{Prati}} < 8$	$0.25 \geq X_{\text{Prati}} > 0.125$	Very Polluted Quality
$8 \leq X_{\text{Prati}}$	$0.125 \geq X_{\text{Prati}}$	Extremely Polluted Quality

2.4. Statistical Analysis

Student's *t*-tests and Wilcoxon tests were used to assess differences in water quality indices in the mainstem versus tributary rivers and through time (2000s versus 2010s). Wilcoxon tests were used when the data were not normally distributed. Statistically significant results had *p*-values < 0.05. All statistical analyses were performed using the R programming language [50].

3. Results

3.1. Macroinvertebrates and Biotic Water Quality

Forty-four macroinvertebrate families were identified and used to compute the biotic-based water quality indices. The family *Chironomidae* was found at 100% of sites sampled. Other common families included *Corixidae*, which was found at 92% of sites, *Palaemonidae*

(86%), *Corduliidae/Libellulidae* (82%), and *Baetidae* (80%). The least common families were *Sphaeriidae*, *Hydrobiidae*, *Corydalidae*, and *Ancylidae*, each of which was found at 2% of the sites sampled. The number of families found at each site ranged from 6 to 31, with an average of 14.9 ± 5.5 standard deviation. An average of 11.8 ± 3.3 and 17.6 ± 5.7 families were collected in the mainstem and tributary sites, respectively. The Wilcoxon test indicated that the numbers of macroinvertebrate families in the mainstem river were significantly less than in tributary rivers ($p < 0.01$).

The BMWP-Thai and ASPT indices ranged from 3 to 7 and 6 to 7, respectively. The Lincoln index ranged from 4.5 to 7. Based on the three indices, no “polluted” sites were observed for the LMB in the 2000s. The BMWP-Thai index revealed 8 sites with “fair” water quality, and 23 and 19 sites with “good” and “very good” water quality, respectively. The ASPT and Lincoln indices resulted in almost all sites having “very good” water quality, except for one site indicating “good” water quality (Figure 2).

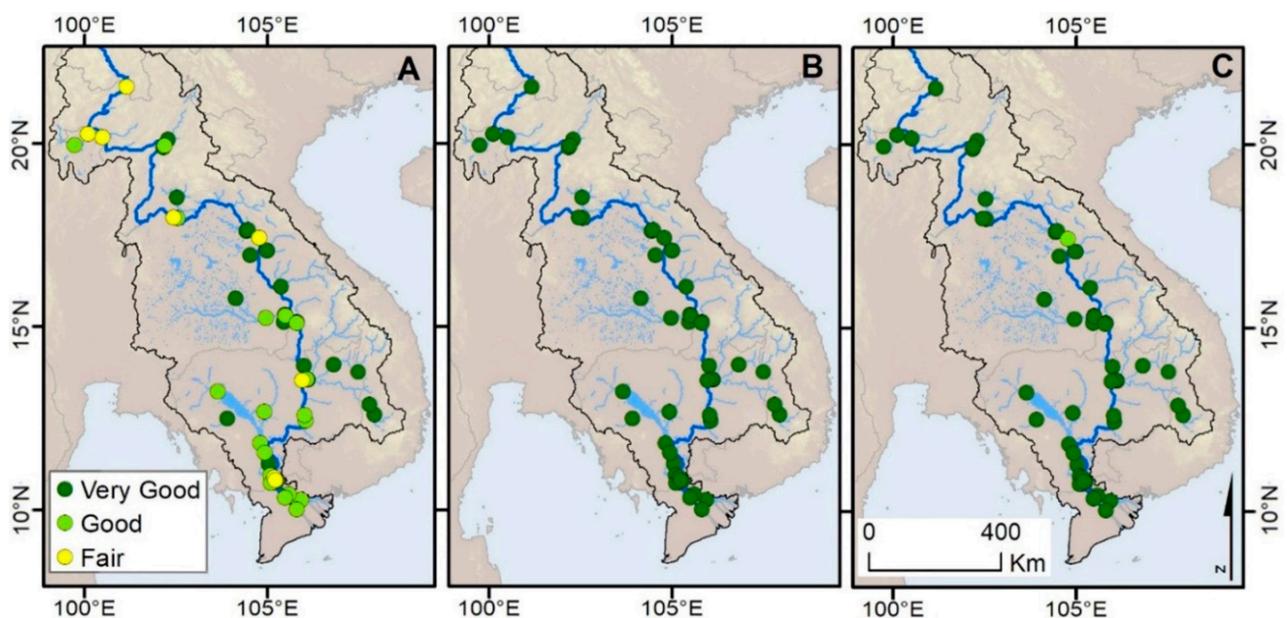


Figure 2. Biotic water quality classification at each sampling site during the 2000s, based on BMWP-Thai (A), ASPT-Thai (B), and Lincoln (C) indices.

3.2. Abiotic Water Quality

The US-EPA scores ranged from 1 to 4, indicating that water quality at the sites ranged from “polluted” to “very good”. The Basic Prati index ranged from 0.29 to 2.11, and 0.08 to 4.12 for the DO Prati index (DO saturation ranged from 49% to 106%). In the 2000s, average scores of the US-EPA and the reciprocal Basic and DO Prati indices were 2.96 ± 0.75 , 1.58 ± 0.66 , and 1.44 ± 2.51 , and their corresponding average scores in the 2010s were 2.60 ± 0.71 , 1.39 ± 0.62 , and 0.94 ± 0.97 . Based on these indices, most of the sites had “fair” to “very good” water quality (Figure 3).

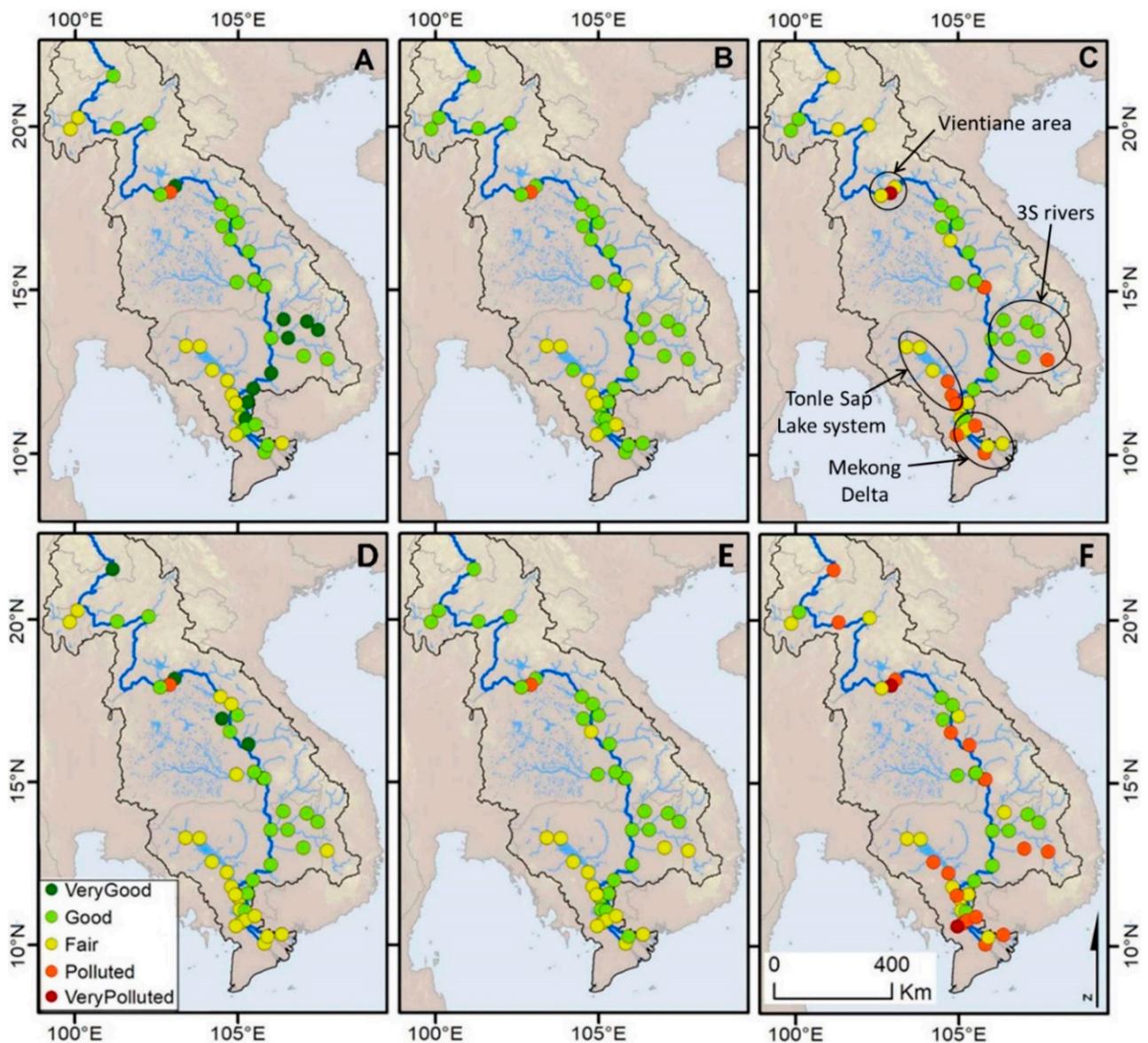


Figure 3. Abiotic water quality classification at each sampling site during the 2000s (A–C) and 2010s (D–F), based on the US-EPA (A,D), Basic Prati (B,E), and DO Prati (C,F) indices.

3.3. Spatial Variation in Water Quality

Most biotic indices indicated water quality differed between the mainstem and tributary sites in the 2000s (Wilcoxon test, $p < 0.01$), except for the ASPT index (Figure 4). The tributary sites had higher index values, and thus better water quality, compared to the mainstem sites. However, abiotic water quality between the mainstem and tributary sites was similar (Wilcoxon test, all $p \geq 0.25$).

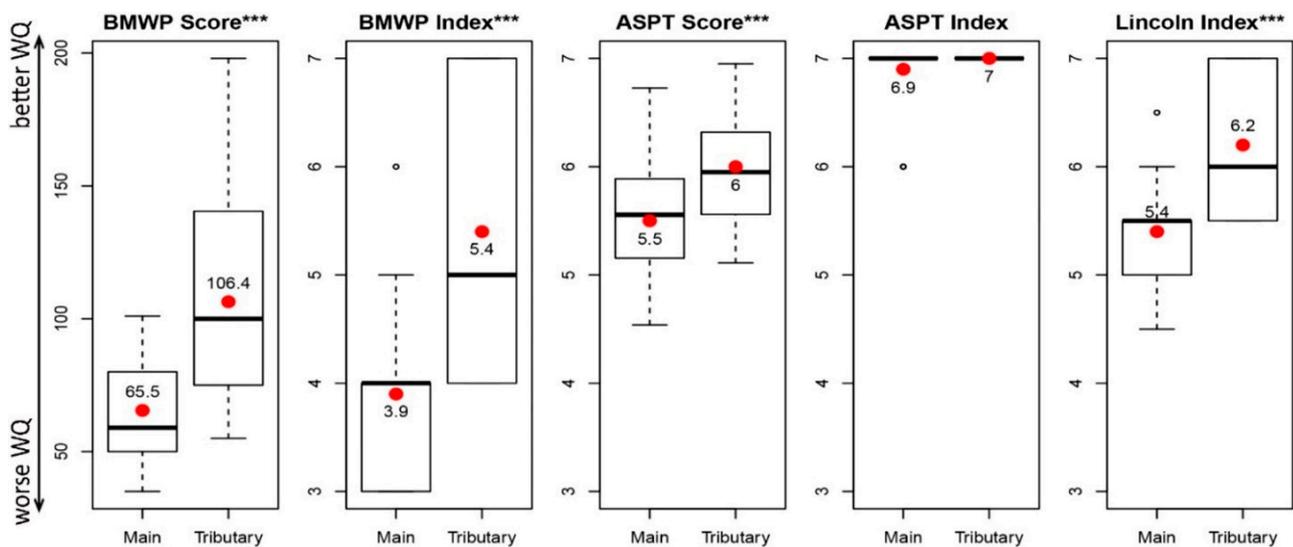


Figure 4. Biotic indices showing water quality between mainstem and tributary sites sampled in 2000s. Red dots indicate the mean values of each corresponding index. WQ: water quality. *** indicate statistically significant differences at $p < 0.001$.

3.4. Temporal Changes in Water Quality

We compared water quality in the 2000s and 2010s before and after considerable hydropower dam development in the basin. Overall, water quality degraded through time, indicating more widespread impairment (Table 5). Wilcoxon tests indicated significant differences for the US-EPA indices through time at all sites and at mainstem sites, but not at tributary sites (Figure 5). There were no significant water quality changes through time with the Prati-Basic or Prati-DO indices.

Table 5. Number (and percentage) of sites by water quality status in the 2000s and 2010s.

WQ Status	US-EPA		Prati-Basic		Prati-DO	
	2000s	2010s	2000s	2010s	2000s	2010s
Very Poor	0	0	0	0	1 (2%)	2 (4%)
Poor	1 (2%)	1 (2%)	1 (2%)	1 (2%)	9 (19%)	17 (36%)
Fair	11 (23%)	22 (47%)	9 (19%)	16 (34%)	17 (36%)	15 (32%)
Good	24 (51%)	19 (40%)	37 (79%)	30 (64%)	20 (43%)	13 (28%)
Very Good	11 (23%)	5 (11%)	na	na	na	na

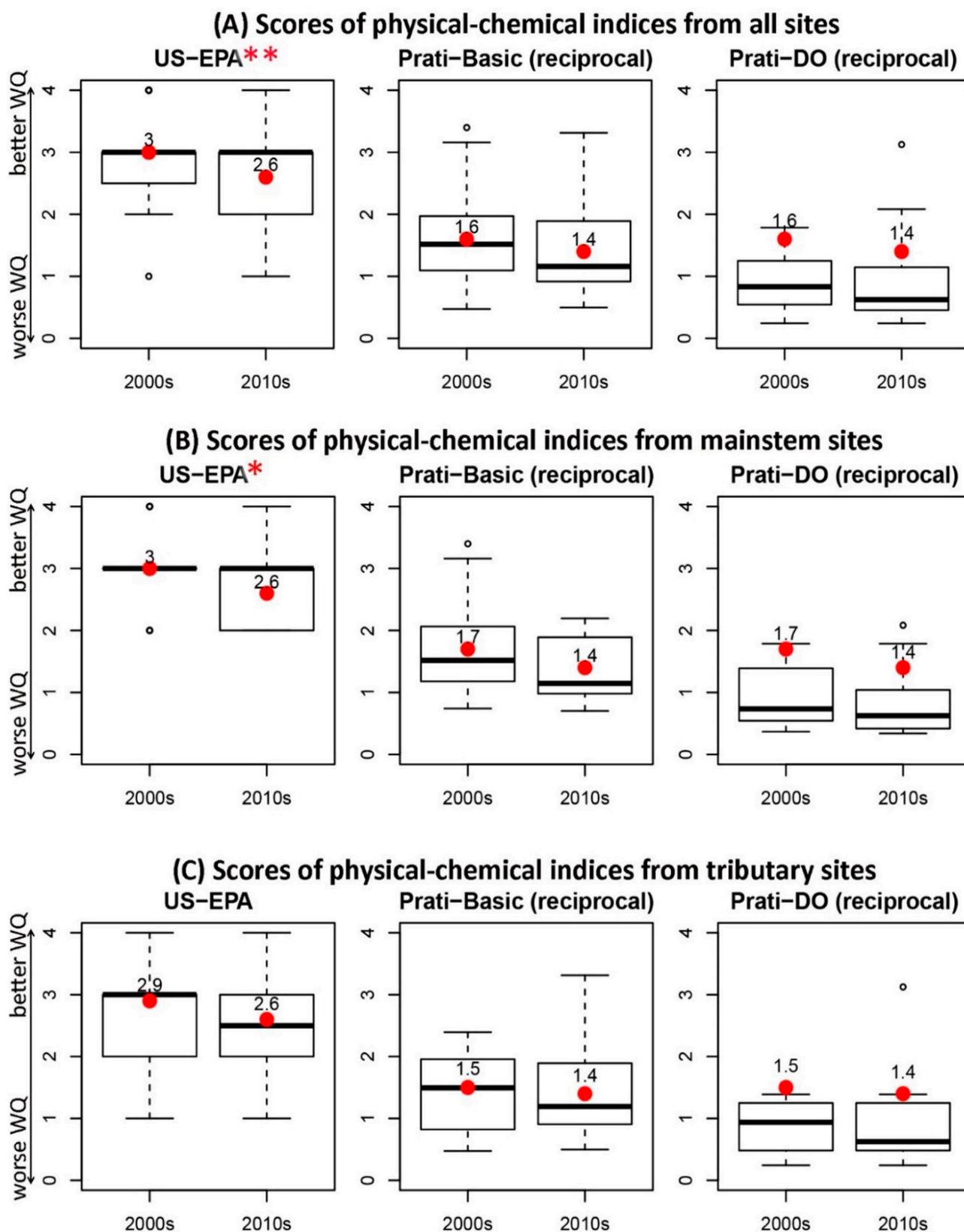


Figure 5. Water quality change from the 2000s to 2010s, based on abiotic indices at all sites (A), mainstem sites (B), and tributary sites (C). * and ** (in red) indicate statistically significant differences at $p < 0.05$, and $p < 0.01$, respectively. Red dots indicate the mean value for each index. WQ: water quality.

4. Discussion

Based on biotic and abiotic assessment indices, water quality of the LMB was generally good in the 2000s, especially when compared to several other major rivers in Asia such as the Chao Phraya in central Thailand [51], the Red River in Vietnam [52], and the Yangtze [53] and Yellow Rivers [54] in China. Moreover, upstream tributary rivers such as the 3S had better water quality and biological diversity, measured as invertebrate family richness and abundance, than mainstem rivers, indicating that in the 2000s, the upstream tributary ecosystems were healthier than those of mainstem rivers. Nevertheless, current water quality across the LMB has generally degraded compared to the 2000s (Table 5). This finding supports the results of Chea et al. [13] that most parts of the LMB are experiencing noticeable water pollution, particularly degrading water quality near Vientiane, in the 3S rivers, Tonle Sap Lake system, and the Mekong Delta (Figure 3).

4.1. Biotic and Abiotic Metrics for Water Quality Assessment Methods

Using both biotic and abiotic metrics to assess water quality and compare them is not widely implemented. Abiotic water quality assessments are less time-consuming, simpler, and provide useful information [12], making them generally preferred in river systems over biotic assessments [17]. This is particularly true in Asia [55]. However, abiotic assessments are threshold-based and restricted to measured constituents (e.g., DO, COD, pH etc.), regardless of other natural and anthropogenic disturbances. On the other hand, biotic assessments indicate both water quality and overall ecosystem health [55]. This suggests that using both biotic and abiotic metrics, as we did, provides a deeper understanding of water quality, and may be useful to inform fisheries or ecosystem management [56,57].

Abiotic indices, particularly those utilizing fewer variables, are more sensitive due to their threshold-based and restricted criteria as discussed above [55,58], compared to biotic indices. In our study, the Prati indices yielded surprisingly different results (Figure 3). The single variable index (DO Prati) indicated more polluted sites than the Basic Prati index, which was based on three variables. This means that the DO Prati index was sensitive to variations in DO saturation, regardless of other variables. Single variable indices, like DO Prati, should be used only when other variables are not available or when water quality improvement depends on that particular variable [14]. Otherwise, the abiotic indices that use more variables provide a better indication of physicochemical-based water quality [12,14].

Biotic indices that use macroinvertebrate and fish taxa have generally been considered as a better indicator of water quality than abiotic indices because the biotic indices are indicative of long-term ecological condition of rivers [58]. However, these indices may not work in the same manner when applied to different regions, due to varied occurrence ranges, life history, and degree of pollution tolerant/sensitive biota [58]. To overcome this, biotic indices should be based on those developed or adopted for specific river basins or from closely related systems [44,59]. In our study, we used the BMWP, ASPT, and Lincoln index that were developed using macroinvertebrate data from the upper part of Chao Phraya River Basin (Mae Ping Basin) in northern Thailand. The eastern part of this basin borders the Mekong, and thus macroinvertebrates in these basins may share similar habitat characteristics, life history, and tolerance ranges [44], and these indices have performed satisfactorily for the Mekong [59].

4.2. Historical Water Quality of the LMB

Historically, the majority of the LMB was characterized as good and very good water quality. Biotic metrics did not indicate any sites with poor or very poor water quality. Abiotic metrics suggested that only one site was polluted based on the US-EPA and Basic Prati indices. Nine sites were classified as polluted based on the DO Prati index, which is dependent only on DO saturation.

More importantly, in the 2000s, tributary rivers were classified as having very good water quality, as reflected by high average scores and index values of the biotic metrics

(average tributary BWMP score = 106.4, average tributary BMWP index = 5.4) compared to the mainstem rivers that were classified as having good water quality (average mainstem BWMP score = 65.5, average mainstem BMWP index = 3.9). Abiotic metrics show that there was no significant change in tributary water quality from the 2000s to the 2010s. This may not be true if one compared the sites sampled close to Yali Dam, a dam built during the 2000s, where water quality was polluted [60]. Our results contradicted Chea et al. [13], who found that mainstem sites were less polluted than tributaries using data from 1985–2010. Their finding is likely from including tributaries in the Mekong Delta and Mun-Chi River Basin where considerable water pollution occurred [61,62] and which outnumbered mainstem sites [13]. Nevertheless, our spatial-temporal analysis suggests that the upstream tributary habitats that we investigated, which did not include tributaries in the Mun-Chi River Basin, historically had better water quality than mainstem rivers and therefore supported higher macroinvertebrate biodiversity. Tributaries are important as a spawning habitat for many LMB fish species. Good water quality in upstream tributaries suggest that pockets of high-quality habitat are likely to persist with dam building and other anthropogenic changes occurring in the LMB.

4.3. Drivers of Temporal Degradation of Water Quality in the LMB

Water quality in the LMB has degraded during the last decade (Figure 3, Figure 5). Although our study did not directly analyze drivers of water quality impairment, deforestation, agricultural expansion, plastic waste, urbanization, and hydropower dam development are likely culprits [32,63–66]. The rapid loss of primary (19%), floodplain (31%), and highland (18%) forests in the LMB have been reported from the 1990s to 2010s [32,63], mirroring similar trends in Indonesia, Brazil, and elsewhere [61,64]. Rapid forest loss induces soil erosion, which transports nutrients, heavy metals, and other chemicals into rivers. This process also leads to a higher sediment load that can result in eutrophication of river systems [65]. Agricultural run-off produces similar effects, increasing sediment, nutrients, pesticide, and fertilizer concentrations. In the LMB, agricultural intensification and expansion have increased noticeably from the 1990s to the 2010s, and therefore an increasing amount of agricultural waste drains to the Mekong [40,62]. Plastics are an emerging contaminant. An estimated 221,700 tons of plastic waste have entered the Tonle Sap Lake system between 2000 and 2020 [66]. Finally, water quality is susceptible to urbanization, which has increased five-fold in the LMB over the last two decades [67], primarily in the 3S river system, around Tonle Sap Lake, and in the Mekong Delta. Urbanization leads to road and infrastructure construction, and resident and industry development, from which industrial and household waste are discharged to the rivers [13,62].

Our temporal water quality findings suggest that dam development is a driver of water pollution. Similar findings have been revealed elsewhere, for example, in Asia [68,69], Africa [70], and Europe [71]. Dams detrimentally affect biodiversity, hydrology, and water quality [3,72]. In the LMB, there has been a rapid increase in hydropower dam development. By the end of the 1990s, nine hydropower dams were commissioned, with ~14,531 Mm³ of reservoir storage and 1303 MW of installed capacity. The number doubled by the end of the 2000s (21 dams, ~15,933 Mm³ and 3617 MW), and increased six-fold by the end of the 2010s (51 dams, ~37,921 Mm³ and 10,236 MW) (Figure 1). Water storage and dam operations impact water quality by trapping sediment and nutrients behind dams, and altering water temperature and dissolved oxygen dynamics [33]. Moreover, regulated upstream flows and sediment trapping drive sea water intrusion into the Mekong Delta [31]. This in turn increases chloride concentration, further degrading water quality [31,36].

Last but not least, regional government decisions to utilize water resources in the Mekong region are often driven by politics and economic interests rather than by genuine environmental concerns. The decisions indeed have strong implications for overall environmental sustainability, including water quality, biodiversity, and the ecosystem as a whole. At the regional level, national interests among MRC member states prevail in the Mekong's water governance. National governments jealously maintain national

sovereignty over their own river reaches, and invoke the discourse of “national interest” to legitimize development of basin resources [73]. For instance, the construction of the Don Sahong hydropower dam on the Mekong mainstream was already completed and the dam has been in operation since early 2020, although Cambodia, Thailand, and Vietnam expressed their concerns over transboundary environmental and socio-economic impacts in their January 2015 official responses to the MRC’s “Procedures for Notification, Prior Consultation, and Agreement” consultation [74]. Such concerns were also voiced by civil societies and local and international non-governmental organizations [75]. Environmental degradation in the Mekong is also exacerbated by poor governance at the national and sub-national levels, which has led to rapid deforestation [32], loss of flooded forest, expansion and intensification of rice farming, unsustainable fishing practices, and floodplain development [76–80]. Water quality regulation that is effective and implementable across regional, national, and subnational scales is needed to prevent further degradation, although this is politically and institutionally challenging.

4.4. Water Quality Degradation Hotspots

We found water degradation hotspots in four areas: near Vientiane City (Laos), in the 3S River Basin, in the Tonle Sap Lake system (including Phnom Penh area), and in the Mekong Delta. Hotspots were clearly indicated by the three abiotic-based water quality assessment metrics (Figure 3). The sites close to Vientiane City have direct discharge of municipal waste [81]. Previous analysis also showed low levels of DO and high concentrations of total ammonia [13]. Hydropower dam development, which brings deforestation and urbanization, has been extensive in the 3S River Basin [1,32]. These changes have led to altered streamflow, sediment loads, and erosion rates that consequently affect water quality. A sharp decline in DO concentrations and increased ammonium and total phosphorus concentrations have been recorded in the Tonle Sap Lake system [13]. Agricultural run-off and household waste from floating villages are sources of pollution [82]. The Mekong Delta’s canals are heavily used by residents whose livelihoods depend on agriculture and aquaculture, which contribute nutrients, fertilizers, and pesticides [62]. We also noted water quality deterioration in the highly populated areas of the Mekong Delta, where pollution occurs from untreated agricultural wastewater and urban sewage [62]. As a result, water quality variables like nitrate and phosphate exceed thresholds designated by the World Health Organization (WHO) and Vietnamese standards [35,62]. Sea water intrusion and rising chloride concentrations also lead to impaired water quality in the Mekong Delta [31].

4.5. Importance of Water Quality for Biodiversity, Sustainable Development, and River Management

The LMB has unparalleled biodiversity, upon which nearly 65 million people depend for food [39]. The unique hydrology of the Mekong is one of the key drivers of ecosystem function and biodiversity [72]. The Mekong supports an estimated 1200 fish species, other fauna and flora such as aquatic insects, mollusks, crustaceans, annelids, and rotifers, and numerous species of aquatic plants [21,23,25,72]. All of these are important resources that contribute to ecosystem function, provide food security, and support local livelihoods.

However, water availability, hydrology, and quality in the Mekong is fundamentally changing. Up to 47 billion m³ of water may be trapped in China’s upstream mainstem dams [83], leading to altered hydrology and water quality, and sometimes water shortages downstream. Reduced streamflow exacerbates water quality impairment and the duration of impairment because water temperature rises, oxygen concentrations fall, and pollutants become more concentrated [84]. The ongoing deterioration of water quality, as demonstrated in our study, can lead to the following effects. (1) Primary production may decrease because suspended solids or turbidity at polluted sites limit photosynthesis, and therefore reduce oxygen levels. (2) Aquatic biodiversity is likely to decline, impacting aquatic vegetation composition, macroinvertebrate communities, and fish assemblages [3,33,84]. Higher levels of nutrients and sediments are preferred by annelids and molluscs [85],

while oxygenated water supports a high diversity of pollution-sensitive insects [23]. (3) Ecosystem function is impaired where pollution occurs. Impaired sites, which already indicate unhealthy systems, can support only pollution-tolerant taxa, and therefore are incapable of supporting many complex and dynamic ecosystem processes, food webs, and ecosystem functions [86,87]. (4) Public health of local people who depend on rivers and aquatic ecosystems is in decline. Polluted sites can become health risks because they are the source of water borne diseases, like *Escherichia coli* and coliform bacteria, which have been recorded from the Mekong Delta [35]. (5) The livelihoods of local people are threatened due to the loss of productivity caused by water pollution, which reduces fisheries resources, food security, and incomes, as has been observed in Tonle Sap Lake [88].

Given recent water quality deterioration and the considerable consequences of poor water quality in one of the world's largest and most productive systems, water quality should be routinely monitored and assessed. Robust biomonitoring should be conducted at least twice per year, in the dry and wet season, and invertebrate identification should be conducted at least to the genus level. MRC may be able to train scientists and build capacity for taxonomical identification and scientific research. Monitoring and assessment can help Mekong riparian countries develop management strategies to maintain water quality, preventing further degradation. Such routine monitoring has already been implemented in small and large river systems such as China's Songhua River [89], the Arkansas River, Catskill Mountain River and other western rivers in the USA [86,90,91], Poland's Kwacza River [92], and South Korea's Chonggyecheon River [93]. In Europe, water quality assessment and restoration are mandatory by the European Union's Water Framework Directive since 2000, and as a result, 90% and 44% of ground- and surface-waters, respectively, have been classified as good water quality as of 2016 [94]. Likewise, LMB countries should prioritize water quality monitoring and assessment, and also train professional staff to complete water quality assessments.

Although water quality monitoring has been conducted in the LMB by the MRC [29,30], the monitoring has not been at fine enough intervals for analyses to aid policy recommendations and prevent water quality degradation. At pollution hotspots, water quality should be more strictly monitored and controlled. For example, runoff and wastewater from industry, agriculture, and households could be collected or treated prior to draining to river systems. Similarly, improved water quality assessment could help detect pollution from non-point sources. Water quality degradation from dams should be considered with hydropower objectives so that environmental costs cost-benefit analyses of dams can be correctly estimated [1,95]. Moreover, transparency in reservoir storage and releases is needed and is starting to be estimated by the Mekong Dam Monitor platform [96]. However, such information should be collected, validated, and shared by each riparian country to ensure accuracy and transparency. Finally, water quality standards that are consistent throughout the LMB would help to regulate water quality among riparian nations. These steps may preserve LMB water quality and minimize sea water intrusion in the Mekong Delta.

5. Conclusions

Based on our biotic and abiotic assessments, we found that water quality in the LMB was historically "good" or "very good" quality. ASPT-Thai and Lincoln biotic indices produced similar results, although the BMWP-Thai index was more sensitive to water quality degradation. Abiotic water quality classification showed that more sites were categorized as "fair", "polluted", or "very polluted" in the 2010s, as compared to the 2000s. US-EPA and Basic Prati indices provided more robust water quality assessment than the DO Prati index, which relied only on DO saturation. Tributary rivers high in the LMB historically had "very good" water quality, and abiotic indices indicate that water quality scores and classification are not significantly different in tributary rivers in the 2000s and 2010s. Although current water quality degradation is not as severe as in other Asian rivers such as the Chao Phraya (central Thailand), Red (Vietnam), Yangtze, or Yellow (China) Rivers, an alarming increase in water pollution has been detected near Vientiane City, and

in the 3S Rivers, the Tonle Sap system, and the Mekong Delta, which should be further monitored and protected to maintain system biodiversity and ecosystem function. Rapid hydropower development, urbanization, deforestation, intensive agriculture, and plastic pollution are likely causes of water quality degradation, although drivers of water quality impairment were not directly studied.

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