Mekong River Commission
For Sustainable Development

2019 LOWER MEKONG WATER QUALITY MONITORING REPORT

August 2022

Mekong River Commission

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The MRC is funded by contributions from its Member Countries and Development Partners, including Australia, the European Union, Finland, Flanders/Belgium, France, Germany, Japan, Luxembourg, the Netherlands, New Zealand, Sweden, Switzerland, and the United States of America.

First published (2010)

Title: 2018 Lower Mekong water quality report
DOI: 10.52107/mrc.aqrsav

Keywords: water quality/human health/Lower Mekong River Basin/Mekong River Commission/ Spatiotemporal trends

For bibliographic purposes, this volume may be cited as:
Mekong River Commission. (2022). *2019 Lower Mekong water quality report*. Vientiane: MRC Secretariat. https://doi.org/10.52107/mrc.aqrsav

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CITATION

Mekong River Commission. (2022). *2019 Lower Mekong water quality report*. Vientiane: MRC Secretariat. https://doi.org/10.52107/mrc.aqrsav

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ABBREVIATIONS AND ACRONYMS

BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
DO	Dissolved oxygen
EC	Electrical conductivity
HH	Guidelines for the Protection of Human Health
ISO	International Organization for Standardization
LMB	Lower Mekong Basin
MCs	Member Countries
MRC	Mekong River Commission
MRCS	Mekong River Commission Secretariat
NH_4N	Ammonium
NMC	National Mekong Committee
NMCS	National Mekong Committee Secretariat
NO_{3-2}	Nitrate-nitrite
PWQ	Procedures for Water Quality
QA/QC	Quality assurance/quality control
SMK	Seasonal Mann-Kendall
TGWQ	Technical Guidelines for the Implementation of the Procedures for Water Quality
TOTN	Total nitrogen
TOTP	Total phosphorus
TSS	Total suspended solids
UMB	Upper Mekong Basin
WQGA	MRC Water Quality Guidelines for the Protection of Aquatic Life
WQGH	MRC Water Quality Guidelines for the Protection of Human Health
WQI	Water Quality Index
WQI_{ag}	Water Quality Index for Agricultural Use
WQI_{al}	Water Quality Index for the Protection of Aquatic Life
WQI_{hh}	Water Quality Index for the Protection of Human Health
WQMN	Water Quality Monitoring Network

EXECUTIVE SUMMARY

The Mekong River Commission (MRC) Water Quality Monitoring Network (WQMN), which was established in 1985, has provided a continuous time series of water quality data on the Mekong River and its tributaries. The routine water quality monitoring under the WQMN is one of the MRC key environmental monitoring activities and is being carried out to support the implementation of the Procedures for Water Quality (PWQ) and its Technical Guidelines). The actual monitoring of water quality is being implemented by the designated laboratories of the Member Countries (MCs) (Cambodia, Lao PDR, Thailand, and Viet Nam) with technical support from the Environmental Management Division of the MRC Secretariat (MRCS).

In 2019, routine water quality monitoring of the Mekong River and its tributaries was conducted at 48 stations, of which 17 were located along the Mekong mainstream and 31 in key tributaries of the Mekong River, including five stations along the Bassac River. At each station, 19 water quality parameters were monitored, of which 13 were considered routine and were monitored monthly. The other six parameters (i.e. major anions and cations) were also monitored monthly but only between April and October.

This report contains the assessment of the status and trends of water quality at 30 stations across the Lower Mekong Basin (LMB). In addition to the assessment of water quality at all 17 mainstream and 5 Bassac stations, this report also includes the results of water quality analyses at 8 selected tributary stations covering 7 tributaries of the Mekong River, namely the Mae Kok River, Nam Ou River, Houay Mak Hiao, Nam Mun River, Se San River, Sre Pok River, and Tonle Sap River.

The analyses of the status and trends of water quality at these 30 stations were carried out using a combination of statistical techniques and the MRC Water Quality Indices (WQI). Water quality data collected in 2019 was first compared with the MRC Water Quality Guidelines for the Protection of Human Health (WQGH) and for the Protection of Aquatic Life (WQGA) to identify any non-compliance. Annual spatial and temporal analyses of key water quality parameters were carried out to determine how their instream concentrations change over space and time. These key parameters include pH, electrical conductivity (EC), total suspended solids (TSS), nitrate-nitrite (NO_{3-2}), ammonium (NH_4N), total nitrogen (TOTN), total phosphorus (TOTP), dissolved oxygen (DO), chemical oxygen demand (COD), and biochemical oxygen demand (BOD). Potential transboundary water quality issues were also examined by comparing water quality conditions of stations strategically located immediately upstream and downstream of national boundaries of the MCs. Statistical analysis techniques such as seasonal Mann-Kendall, independent t-test, and/or the one-way analysis of variance (ANOVA) was carried out to determine whether levels of spatial and temporal changes were statistically significant. Pearson's correlation analysis was used to establish relationships among key water quality parameters. These relationships along with results of prior research within the LMB and other parts of the world were used to explain the status and trends of key water quality parameters detected in 2019. To assess the suitability of the water quality of Mekong River and its tributaries for various purposes, the MRC WQI was used which allowed possible the quantification of water quality conditions for the purposes of protecting human health and aquatic life and of various agricultural uses.

Results of the analyses of 2019 water quality monitoring data at the 30 stations included in this report showed that water quality of the Mekong River and its tributaries was still of good quality when compared to the WQGH and the WQGA. In 2019, water quality was slightly impaired at a few stations including those located in the Mekong Delta. At these stations, elevated levels of NO_{32}, NH_4N, TOTN, TOTP and/or COD were detected. Consequently, slight reductions in DO levels were also detected at these stations. Of special concern are the DO levels at Chau Doc, where 100% of monitoring occasions in 2019 showed DO concentrations lower than the target value of WQGH (6 mg/L). Prolonged reduction of instream DO levels can cause stress or even death to aquatic animals, and therefore should continue to be monitored to ensure the timely detection of any water quality issues.

Compared to historical records, significant changes in TSS, TOTP and COD levels were detected. In the case of TSS, temporal analysis of TSS data from 1985 to 2019 revealed that TSS levels in the Mekong River had decreased significantly since 1985. The average TSS concentration in the Mekong River in 1985 was about 388 mg/L, whereas in 2019, the average concentration for TSS was recorded at about 46.8 mg/L, representing a net reduction of about 88%. Compared to 2018, where mean TSS concentration was recorded at 84.9 mg/L, the 2019 shows a reduction of about 45%. Conversely, COD levels increased during the same timeframe: the mean COD concentration increased from 1.60 mg/L in 1985 to 1.97 mg/L in 2019. While COD levels were largely still within the target value of the WQGH (5 mg/L), the results of the one-way ANOVA and Seasonal Mann-Kendall (SMK) analyses revealed the change to be statistically significant, with p-values less than 0.01 for both annual mean comparison (one-way ANOVA) and temporal trend analyses (SMK).

Despite the few non-compliances recorded in 2019, the assessment of water quality using the MRC Water Quality Indices (WQI) confirmed that water quality of the Mekong River and its tributaries was still of 'acceptable/good' condition for the protection of aquatic life, with water quality at 14 and 13 stations rated as 'excellent' and 'good', respectively. In addition to these 27 stations, 3 located in the Mekong Delta including Chau Doc were rated as 'moderate' for the protection of aquatic life due to the slight impairment associated with DO, $NO_{3\text{-}2}$, and TOTP. The impairments, however, did not affect the water quality for the protection of human health. In 2019, water quality at 22 stations was rated 'excellent' for the protection of human health, while at the remaining eight stations, it was rated as 'good'. Compared to the previous year (2018), 2019 water quality for the protection of human health improved at seven stations with rating for Water Quality Index for the Protection of Human Health (WQI_{hh}) improved from 'good' to 'excellent'. The improvement was due to the reduction in COD levels in 2019, where only 1.5% of the monitoring occasions exceeded the target values of the WQGH (5 mg/L).

Historically, the water quality of the Mekong River and its tributaries has always been rated as either 'good' or 'excellent' for the protection of aquatic life. The only exception were stations located in the Mekong Delta where annual water quality for the protection of aquatic life was rated as either 'moderate' or 'good' since 2008 due to the elevated TOTP levels and slightly impaired DO levels. Similarly, ratings for water quality for the protection of human health fluctuated between ‘good’ and ‘excellent’ since 2008 with only a few stations rated ‘moderate’ in 2009, 2010, and 2014.

With only one EC concentration that exceeded 70 mS/m (Vientiane in November 2019, 91 mS/m), water quality of the Mekong River and its tributaries had no restriction for general and paddy rice irrigation. From 2008 to 2019, water quality ratings for agricultural use had not changed with the only exception being in 2016 at My Tho, where a slight restriction was detected for general irrigation due to elevated EC levels.

In term of transboundary river pollution, while analyses of water quality data at Pakse/Stung Treng, Kaorm Samnor/Tan Chau, and Koh Thom/Chau Doc reveal significant differences in levels of NO_{3-2}, TOTN, and COD, with p-values less than 0.01, the levels were still well below their respective target values of WQGH and the WQGA. However, the combined levels of these pollutants appear to have affected DO levels, particularly at Chau Doc, and should be further closely monitored to ensure timely detection of further change so that any potential effects on human health and aquatic life are detected and addressed in a timely manner

The maintenance of ‘acceptable/good’ water quality of the Mekong River is key to achieving the objective of the PWQ. While the water quality of the Mekong River and its tributaries is still suitable for the protection of human health, aquatic life and agricultural uses, levels of some water quality parameters have changed significantly compared to their historical records. Increased economic development, urbanization, and climate variability can further exacerbate these changes, as well as introduce emerging pollutants not previously seen in the river. Therefore, ensuring the relevancy of the WQMN in responding to these emerging threats is crucial for the continued maintenance of ‘good/acceptable’ water quality of the Mekong River.

1. INTRODUCTION

1.1 Background

Ranked as 12th longest at about 4,880 km and 8th in terms of mean annual discharge at its mouth at about 14,500 m^3/s (MRC, 2019b), the Mekong River is one of the world's largest rivers. Originating in the Himalayas, the Mekong River flows southward through China, Myanmar, Lao PDR, Thailand, Cambodia and Viet Nam. With a total catchment area of 810,000 km^2, the Mekong River Basin can be divided into the Upper Mekong Basin (UMB), which comprises an area in China where the Mekong is known as the Lancang River and makes up 23.2% of the total Mekong Basin (186,356 km^2), and the LMB, which comprises an area downstream of the Chinese border with Lao PDR.

The LMB is functionally subdivided into four broad physiographic regions described by topography, drainage patterns and the geomorphology of river channels. These are the Northern Highlands, the Khorat Plateau, the Tonle Sap Basin and the Delta. With a total catchment area of about 623,644 km^2, the LMB covers a large part of northeast Thailand, almost the entire countries of Lao PDR and Cambodia, and the southern tip of Viet Nam (MRC, 2019b).

According to the 2018 State of the Basin Report (MRC, 2019b), the Lower Mekong River is home to around 70 million people, of whom about 85% live in rural areas where many practises subsistence farming, with supplemental fish catch for livelihoods and food security. The Mekong River is also one of the most biodiverse rivers in the world with estimated 1,148 fish species (MRC, 2019b). The river's annual flood pulse continues to support a rich natural fishery and an extensive and unique wetland environment. This makes the rich ecology of the Basin extraordinarily important in terms of its contribution to livelihoods and sustainable development. Hence, water quality monitoring is an integral part of detecting changes in the Mekong riverine environment and for maintaining good/acceptable water quality to promote the sustainable development of the LMB.

1.2 Water Quality Monitoring Network and the Procedures for Water Quality

1.2.1 Water Quality Monitoring Network

Recognising that sustainable development of water resources of the LMB will not be possible without effective management of water quality, the MCs agreed to establish the Water Quality Monitoring Network (WQMN) in 1985 with the specific objectives of monitoring the status and detecting changes in the water quality of the Mekong River, and ensuring preventive and remedial actions are taken if any changes are detected. Between 1985 and 1992, the WQMN comprised of stations in Lao PDR, Thailand and Viet Nam. Cambodia later joined the WQMN in 1993 when it started to routinely monitor water quality within its national boundary.

Since its inception, the WQMN has provided valuable information on the condition of the river water quality, which is integral to the 70 million people who live in the basin and continue to depend on the resources and values provided by the Mekong River ecosystems. As many as 90 water quality stations were monitored as part of the WQMN across the LMB. The peak sampling year was recorded in 2005, when 90 stations were monitored. In 2006, the MRC led by the Environment Programme, conducted a full assessment of water quality monitoring activities in the Mekong River under the WQMN. One of the outcomes of the assessment was the need to reduce the cost of the monitoring while at the same time increase its relevancy and suitability in detecting changes associated with the basin rapid economic development and population growth. An agreement was reached for the Network to include only primary stations while the secondary stations would be monitored by individual MCs. Primary stations are those that are located in the mainstream and key tributaries of the Mekong River. Since 2006, 48 stations have been classified as 'primary stations' and were designed to detect changes and capture pressures and threats to Mekong water quality. A number of these stations were also strategically selected to detect transboundary water quality problems. In 2019, these stations continued to be monitored by the MCs as part of the WQMN. Seventeen of these 48 stations were located along the Mekong mainstream and the remaining stations (31) were located in the tributaries of the Mekong River. Annex A of this report provides a list of all 48 stations monitored in 2019 and Annex B spatially illustrates their locations across the LMB.

In 2019, 19 water quality parameters were monitored by the WQMN monthly, but during its peak years, between 1995 and 2004, up to 23 water quality parameters were monitored. These parameters comprise physical, chemical, and bacteriological parameters, and have been determined as critical for assessing the effects of development on the quality of the Mekong River water.

The WQMN is one of the MRC's core river basin management function activities that will be decentralized to the MCs for full implementation. Following decentralization, MCs through their designated water quality laboratories will be required to finance and undertake the monitoring, sampling, and analysis of the water quality of the Mekong River and its tributaries. At the national level, each MC has designated a national water quality laboratory to undertake the monitoring, sampling, and analysis of Mekong water quality. The designated laboratories are responsible for undertaking routine monitoring and measurement of 19 water quality parameters (Table 2.3). They are also responsible for analysing, assessing, sharing, and reporting water quality data on an annual basis. Their specific duties are to:

- conduct routine monthly water quality monitoring of the Mekong River and its tributaries as defined in their Terms of Reference (ToR);
- participate in the annual MRC quality assurance/quality control (QA/QC) auditing which includes proficiency testing (PT) and internal auditing to ensure consistency and integrity of the recorded data;
- manage water quality data in accordance with the agreed format and submit the data to the MRCS for validation and sharing through the MRC data portal;
- produce and publish annual water quality data assessment report, outlining the results of water quality monitoring, analysis and assessment.

At the regional level, the MRCS is responsible for providing technical support for the monitoring of water quality and to ensure the integrity and compatibility of data recorded at the national level. The MRCS also acts as a central hub for maintaining regional water quality data and provides a platform for data exchange in accordance with the MRC Procedures for Data and Information Exchange and Sharing (PDIES) and its Technical Guidelines. In addition, the MRCS conducts regional data quality assurance, and quality control and analysis, and prepares regional annual reports on water quality monitoring of the LMB.

1.2.2 Procedures for Water Quality

Routine water quality monitoring under the WQMN has become an integral part of sustainable water resources development in the LMB with the establishment of the 1995 Mekong Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin, which led to the adoption of the Procedures for Water Quality (PWQ) in 2011. With its objective being '*to establish a cooperative framework for the maintenance of acceptable/good water quality to promote the sustainable development of the LMB*', the PWQ provides systematic guidelines for the MCs to individually and/or jointly manage water quality and respond to any water quality incident that would constitute an emergency within their respective national boundaries and in the Mekong River.

To support the implementation of the PWQ, MCs have jointly developed and adopted the Technical Guidelines for the Implementation of the Procedures for Water Quality (TGWQ), which consisting of two main parts focusing on the management of water quality (Part I) and framework for responding to water quality emergency incident (Part II). Since its adoption, the implementation of Part I of the TGWQ has been through the implementation of the WQMN. With the first part of the TGWQ provides systematic guidelines for the management of water quality for the protection of human health (Chapter 1) and the protection of aquatic life (Chapter 2), MCs have integrated these guidelines into the routine activities of the WQMN, including the adoption of methods for field sampling, laboratory analysis, and data assessment that ensure the comparability of the monitoring data.

1.3 Objectives

The routine water quality monitoring under the WQMN has become one of the key environmental monitoring activities implemented under the MRC Environmental Management Division. Its importance is captured in the MRC Basin Development Strategy for 2021–2030, where two major outputs are expected on an annual basis – annual water quality data and an annual water quality and data assessment report. This report has been prepared in response to these required outputs. It provides the consolidated results from the water quality monitoring activities of the MCs, focusing on the compliance of water quality data with target values established in the TGWQ for the protection of human health and aquatic life. As such, the main objectives of this report are to:

- provide the status of water quality in the Mekong River in 2019 by assessing water quality monitoring data monitored by the WQMN laboratories in 2019 and compare them with target values established in the TGWQ;
- identify any spatial changes observed in the Mekong River water quality in 2019;

- identify annual temporal changes observed in the water quality of the Mekong River at the basin scale over three decades (1985–2019);
- identify and discuss any transboundary water quality issue observed in 2019;
- assess the influences of seasonality on water quality across the LMB;
- assess the status and temporal trends at selected tributary stations to identify their potential influences on the Mekong River water quality;
- provide recommendations for future monitoring and continuous improvement of the water quality monitoring activities.

2. MATERIALS AND METHODS

2.1 Monitoring Locations and Frequency

Forty-eight stations were monitored by the WQMN in 2019. A breakdown of the number of stations in each MC is presented in Table 2.1. As shown in the table, of the 48 stations monitored in 2019, 11 stations are located in Lao PDR, eight in Thailand, 19 in Cambodia and 10 in Viet Nam. Overall, routine water quality is monitored across the LMB at 17 mainstream stations, five Bassac stations, and 26 tributary stations. Annex A provides a full list of the stations monitored in 2019 with Annex B showing their spatial location across the LMB.

This report contains the analyses of water quality conditions including status and trends at all 17 mainstream stations as well as five Bassac stations and six tributary stations. For this report, these stations will be referred to as number 1 to 30, as listed and illustrated in Table 2.2 and Figure 2.1, respectively.

For consistency, the MCs have agreed to carry out monthly sampling and monitoring of water quality between the 13th and 18th day of each month.

Table 2.1. A summary of 2019 water quality monitoring stations

Countries	No. of Stations	No. on the Mekong River	No. on tributaries		Monitoring Frequency
			No. on the Bassac River	Other Tributaries	
Lao PDR	11	5	0	6	Monthly
Thailand	8	3	0	5	Monthly
Cambodia	19	6	3	10	Monthly
Viet Nam	10	3	2	5	Monthly
Total	48	17	5	26	Monthly

Table 2.2. A list of water quality stations included in the 2019 Lower Mekong Water Quality Monitoring Report

No.	Station ID	Name of station	River	Types of river	Country	Latitude	Longitude
1	H010500	Houa Khong	Mekong River	Mainstream	Lao PDR	21.54710	101.15980
2	H010501	Chaing Sean	Mekong River	Mainstream	Thailand	20.2674	100.0908
3	H011200	Luang Prabang	Mekong River	Mainstream	Lao PDR	19.93880	101.30380
4	H011901	Vientiane	Mekong River	Mainstream	Lao PDR	17.96920	102.55060
5	H013101	Nakhon Phanom	Mekong River	Mainstream	Thailand	17.4250	104.7744
6	H013900	Savannakhet	Mekong River	Mainstream	Lao PDR	16.55830	104.75220
7	H013401	Khong Chaim	Mekong River	Mainstream	Lao PDR	15.3255	105.4937
8	H013801	Pakse	Mekong River	Mainstream	Thailand	16.92830	104.68830
9	H014501	Stung Treng	Mekong River	Mainstream	Cambodia	13.54500	106.01639
10	H014901	Kratie	Mekong River	Mainstream	Cambodia	12.47000	106.02000
11	H019802	Kampong Cham	Mekong River	Mainstream	Cambodia	11.99418	105.46891

12	H019801	Chrouy Changvar	Mekong River	Mainstream	Cambodia	11.58605	104.94065
13	H019806	Neak Loung	Mekong River	Mainstream	Cambodia	11.25797	105.27928
14	H019807	Kaorm Samnor	Mekong River	Mainstream	Cambodia	11.06792	105.20855
15	H019803	Tan Chau	Mekong River	Mainstream	Viet Nam	10.90360	105.52060
16	H019804	My Thuan	Mekong River	Mainstream	Viet Nam	10.80440	105.24250
17	H019805	My Tho	Mekong River	Mainstream	Viet Nam	10.60390	104.94360
18	H033401	Takhmao	Bassac River	Tributary	Cambodia	11.47853	104.95303
19	H033402	Koh Khel	Bassac River	Tributary	Cambodia	11.26762	105.02922
20	H033403	Koh Thom	Bassac River	Tributary	Cambodia	11.10536	105.06778
21	H039801	Chau Doc	Bassac River	Tributary	Viet Nam	10.82530	105.33670
22	H039803	Can Tho	Bassac River	Tributary	Viet Nam	10.70640	105.12720
23	H100101	Ban Hatkham	Nam Ou River	Tributary	Lao PDR	20.08500	102.25220
24	H050104	Chaing Rai	Mae Kok River	Tributary	Thailand	19.9208	99.8461
25	H910108	Houay Mak Hiao	Houay Mak Hiao	Tributary	Lao PDR	17.99990	102.90820
26	H380128	Mun (Khong Chiam)	Nam Mun River	Tributary	Thailand	15.3036	105.4888
27	H440202	Pleicu	Se San River	Tributary	Viet Nam	14.22760	107.82920
28	H450101	Lumphat	Sre Pok River	Tributary	Cambodia	13.54944	106.52833
29	H451303	Ban Don	Sre Pok River	Tributary	Viet Nam	12.89800	107.78240
30	H020102	Prek Kdam	Tonle Sap River	Tributary	Cambodia	11.81533	104.80723

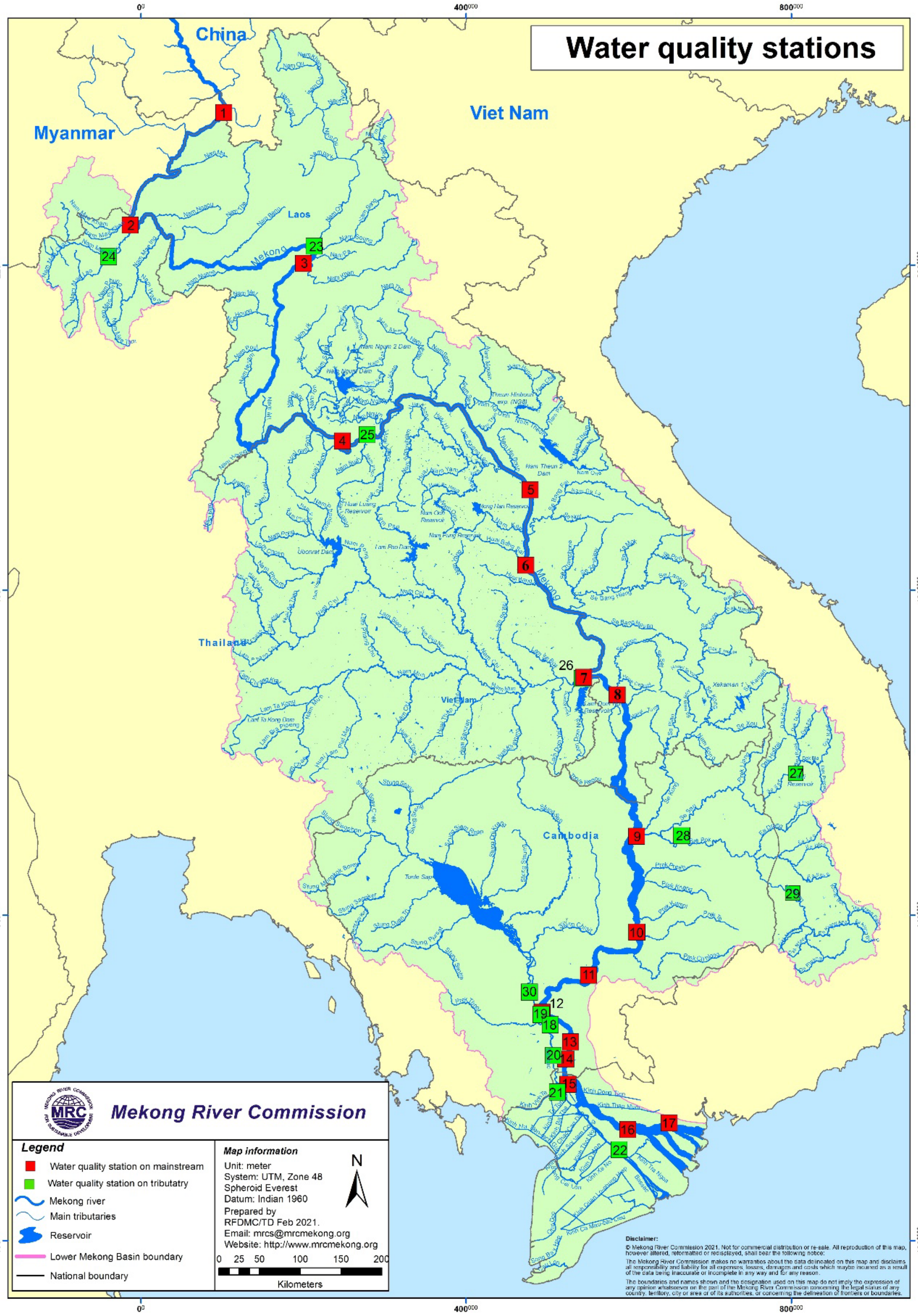


Figure 2.1. Spatial location of water quality stations included in the 2019 Lower Mekong Water Quality Monitoring Report

2.2 Sampling Techniques

In an effort to standardise the sampling techniques, in 2019 MRC continued to work with the designated WQMN laboratories of the MCs to identify appropriate sampling techniques for collecting water samples. Through consultations, it was agreed that water sampling, sample preservation, sample transportation and storage would be carried out in accordance with methods listed in the TGWQ, which have been prepared in accordance with the 23rd edition of the Standard Methods for the Examination of Water and Wastewater (Baird, 2017) or with national standards complying with the requirements of method validation of ISO/IEC 17025-2005.

Specifically, the designated laboratories are required to:

- collect water samples using the simple surface grab technique at the middle of the stream where free flowing water is observable;
- collect water samples at about 30 to 50 cm under the surface of the stream;
- if in-situ measurement is not possible, immediately preserve samples collected with proper preservative agents (i.e. sulphuric acid for nutrients measurement) and store them in a cooler to prevent further breakdown of chemicals and biological contents;
- analyse all water samples within the recommended holding time.

All designated laboratories of the WQGH are required to adhere to the MRC QA/QC procedures outlined in the TGWQ, which were developed in accordance with ISO/IEC 17025-2005 and personnel safety procedures when collecting water samples and measuring water quality parameters.

2.3 Laboratory Analytical Methods

Since its inception in 1985, the WQMN has provided data on water quality in the Mekong River and its selected tributaries by measuring a number of different water quality parameters. At its peak, the Network provided measurements of 23 water quality parameters. However, in 2019, 19 water quality parameters were measured by the WQGH (Table 2.3). Of the 19 parameters measured in 2019, 12 are routine water quality parameters that are required to be measured for each sampling month. It is required that the other 7, major anions and major cations, be analysed for each sample taken between May and October.

In addition to providing a list of parameters measured by the WQGH, Table 2.3 provides a list of recommended analytical methods used for measuring water quality parameters, as mentioned in Section 2.2.

Table 2.3. Water quality parameters and their corresponding analytical methods

Analytical parameter	WQGH recommended analytical methods[1]	Frequencies
Temperature	2550-Temp/SM	Monthly
pH	4500-H^+/SM	Monthly
Electrical conductivity	2510-EC/SM	Monthly
Alkalinity/acidity	2320-A/SM	Monthly (May–October)
Dissolved oxygen (DO)	4500-O/SM	Monthly
Chemical oxygen demand (COD)	Permanganate oxidation	Monthly
Total phosphorous (T-P)	4500-P/SM	Monthly
Total nitrogen (T-N)	4500-N/SM	Monthly
Ammonium (NH_4-N)	4500-NH_4/SM	Monthly
Total nitrite and nitrate (NO_{2-3}-N)	4500-NO_{2-3}/SM	Monthly
Faecal coliform	9221-Faecal coliform group/SM	Monthly
Total suspended solids	2540-D-TSS-SM	Monthly
Calcium (Ca)	3500-Ca-B/SM	Monthly (May–October)
Magnesium (Mg)	3500-Mg-B/SM	Monthly (May–October)
Sodium (Na)	3500-Na-B/SM	Monthly (May–October)
Potassium (K)	3500-K-B/SM	Monthly (May–October)
Sulphate (SO_4)	4500- SO_4–E/SM	Monthly (May–October)
Chloride (Cl)	4500-Cl/SM	Monthly (May–October)
BOD_5	5210-BOD_5/SM	Monthly

2.4 Data Analysis

2.4.1 Status and Trends

The overall status of the Mekong water quality in 2019 was examined by applying descriptive statistics such annual maximum, mean and minimum to summarize data series of key water quality parameters collected in 2019 along the Mekong River. Descriptive statistics are commonly used to analyse and compare various aspects of water quality data (Ai et al., 2015; Gu et al., 2019; He et al., 2009; Johnson et al., 2009), because they provide quick snapshots of data series that are generally large and not evenly distributed in nature (Fisher & Marshall, 2009; Lee, 2020). These values were compared to the MRC Water Quality Guidelines for the Protection of Human Health (Chapter 1 of the TGWQ) and for the Protection of Aquatic Life (Chapter 2 of the TGWQ) to identify any exceeded values that need special attention.

Variations of key water quality parameters were assessed spatially and temporally. Spatial variation was carried out for 2019 to examine the differences in levels of key water quality parameters along the Mekong and Bassac Rivers. Pearson correlation analyses (Franzese &

[1] MCs can use their national methods for the analyses of water quality parameters as long as the methods have been validated to produce scientifically comparable results with the methods recommended by the WQGH.

Iuliano, 2019) were performed to establish relationships between these parameters and to help explained the variation observed.

Temporal analyses of water quality data from the 1985–2019 period were carried out for key parameters using a combination of box-and-whisker plots, seasonal Mann-Kendall trend test (SMK) and one-way ANOVA mean comparison analysis (Hutson, 2003). Known as a non-parametric method, SMK has the advantage of being capable of handling environmental monitoring data series similar to those found in the water quality data series and has been used to detect trends for data series that exhibit seasonality, missing data points and non-normal distribution (Fu & Wang, 2012; Ly et al., 2020).

In addition to these statistical analyses, box-and-whisker plots were used to help support the characterisation of water quality data, for both spatial and temporal analyses. Box-and-whisker plots are often used to analyse variation and central tendency of data. It is an effective statistical tool that can be used to explore a dataset and show key statistics associated with it. In particular, when using box-and-whisker plots the following key statistical information can be drawn (Fu & Wang, 2012):

- median value of the dataset;
- upper quartile and lower quartile or the median of all data above and below the median, respectively;
- upper and lower extremes, or the maximum and minimum values of the dataset (excluding outliers), respectively.

2.4.2 Transboundary Water Quality

Transboundary water quality was assessed for six stations located at or near national borders of the MCs. Water quality data comparison and assessment were made for Pakse versus Stung Treng; Kaorm Samnor versus Tan Chau; and Koh Thom versus Chau Doc. Comparisons were made for two stations using key pollutant monitoring data in 2019 for the stations closest upstream and downstream of the national border. Box-and-whisker plots, using the statistical software package SPSS 23, were used to characterize water quality data. Any observed differences between the upstream and downstream stations were tested using an independent t-test, to determine whether the differences observed are statistically significant.

2.4.3 Water Quality Indices

Another way to assess water quality in the Mekong River is through the use of the MRC Water Quality Indices, which combine the results of several parameters into one overall value describing the water quality. In 2013, the MCs adopted three water quality indices, taking into account requirements under the TGWQ and available water quality guidelines of the MCs. These indices are:

- The Water Quality Index for the Protection of Aquatic Life (WQI_{al});
- The Water Quality Index for the Protection of Human Health (WQI_{hh});

- The Water Quality Index for Agricultural Use (WQI_{ag}), which is divided into two categories: general irrigation and paddy rice.

2.4.3.1 The Water Quality Index for the Protection of Aquatic Life

The Water Quality Index for the Protection of Aquatic Life is calculated using **Equation 2.1**. The index has been developed as an open-ended index, which would allow more parameters to be added once data becomes available (Campbell, 2014). In this annual water quality report, only six parameters are included. These parameters, together with their target values, are listed in Table 2.4. The classification system for the Water Quality Index for the Protection of Aquatic Life is summarized in Table 2.5.

$$WQI_{al} = \frac{\sum_{i=1}^{n} p_i}{M} \qquad \textbf{Equation 2.1}$$

Where:

- 'p_i' is the points scored on sample day i. If each parameter listed in Table 2.4 meets its respective target value in Table 2.4, one point is scored; otherwise, the score is zero;
- 'n' is the number of samples from the station in the year;
- 'M' is the maximum possible score for the measured parameters in the year.

Table 2.4. Parameters used for calculating the rating score of the Water Quality Index for the Protection of Aquatic Life, together with their target values

Parameters	Target values
pH	6–9 (inclusive)
EC (mS/m)	<150
NH_3 (mg/L)	≤0.1
DO (mg/L)	≥5
$NO_{2\text{-}3}$ – N (mg/L)	≤0.5
TOTP (mg/L)	≤0.13

Table 2.5. Rating systems for the Water Quality Index for the Protection of Aquatic Life

Rating score	Class
9.5 ≤ WQI ≤10	A: High Quality
8 ≤ WQI < 9.5	B: Good Quality
6.5 ≤ WQI < 8	C: Moderate Quality
4.5 ≤ WQI < 6.5	D: Poor Quality
WQI < 4.5	E: Very Poor Quality

2.4.3.2 Water Quality Index for the Protection of Human Health

With the finalization of Chapter 1, Guidelines for the Protection of Human Health (HH) of the TGWQ, the MCs agreed to include the HH in the analysis of the water quality of the Mekong River. To assist in communicating water quality information concerning the protection of human health, water quality indices and classification systems were developed, focusing on human health acceptability and human health risk.

The Human Health Acceptability Index utilizes parameters of indirect impact, as identified by the HH, while the Human Health Risk Index utilizes direct impact parameters. The rating score for both indices can be calculated using **Equation 2.2**, which is based on the Canadian Water Quality Index (Khan et al., 2005). It should be noted that since the monitoring of direct impact parameters has not commenced, MCs have agreed to adopt only the human health acceptability index. The list of the approved parameters to be included in the calculation of the rating score for the human health acceptability index together with their target values are listed in Table 2.6. The classification system for the (WQI_{hh}) – Human Acceptability Index is summarized in Table 2.7.

$$WQI_{hh} = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right)$$ **Equation 2.2**

Where F_1 is the percentage of parameters that exceed the guidelines and can be calculated by **Equation 2.3**.

$$F_1 = \left(\frac{\#\ of\ failed\ parameters}{Total\ \#\ of\ parameters} \right)$$ **Equation 2.3**

F_2 is the percentage of individual tests for each parameter that exceeded the guideline and can be calculated by **Equation 2.4**.

$$F_2 = \left(\frac{\#\ of\ failed\ tests}{Total\ \#\ of\ tests} \right)$$ **Equation 2.4**

F_3 is the extent to which the failed test exceeds the target value and can be calculated using **Equation 2.5.**

$$F_3 = \left(\frac{nse}{0.01 nse + 0.01} \right)$$ **Equation 2.5**

where nse is the sum of excursions and can be calculated using **Equation 2.6**.

$$nse = \left(\frac{\sum excursion}{Total\ \#\ of\ tests} \right)$$ **Equation 2.6**

The excursion is calculated by **Equation 2.7**.

$$excursion = \left(\frac{failed\ test\ value}{guideline\ value} \right) - 1$$ **Equation 2.7**

Table 2.6. Parameters used for calculating the rating score of the Water Quality Index for the Protection of Human Health together with their target values

Parameters	Target values
pH	6–9 (inclusive)
EC (mS/m)	≤150
NH_3 (mg/L)	≤0.5
DO (mg/L)	≥4
$NO_{2\text{-}3} - N$ (mg/L)	≤5
COD (mg/L)	≤5
BOD* (mg/L)	≤4

Note: *Due to the required holding time for BOD, MCs have agreed to only monitor BOD at stations where samples can be analysed within the required holding time of less than 48 hours. Therefore, BOD was only included for the stations where data is available.

Table 2.7. Rating systems for the Water Quality Index for the Protection of Human Health

Rating Score	Class	Description
95 ≤ WQI ≤100	A: Excellent Quality	All measurements are almost always within objectives
80 ≤ WQI < 95	B: Good Quality	Conditions rarely depart from desirable levels
65 ≤ WQI < 80	C: Moderate Quality	Conditions sometimes depart from desirable levels
45 ≤ WQI < 65	D: Poor Quality	Conditions often depart from desirable levels
WQI < 45	E: Very Poor Quality	Conditions usually depart from desirable levels

2.4.3.3 WATER QUALITY INDEX FOR AGRICULTURAL USE

Another index adopted by the MCs as a means for communicating water quality monitoring information to the public is the WQI_{ag}, which focuses on water quality for general irrigation and paddy rice. The indices for general irrigation and paddy rice are calculated based on the MRC water quality guidelines for salinity (EC). The EC guidelines, together with the degree of consequence for the indices for general irrigation and paddy rice are outlined in Table 2.8.

Table 2.8. Electrical conductivity guidelines and degrees of consequence for Water Quality Index for Agricultural Use – general irrigation and paddy rice

Irrigation raw water	Unit	Degree of consequence*		
		None (A)	Some (B)	Severe (C)
Electrical conductivity				
General irrigation	mS/m	<70	70–300	>300
Paddy rice	mS/m	<200	200–480	>480

Note: * None = 100% yield; Some = 50–90% yield; Severe = <50% yield.

2.5 Quality Assurance/Quality Control

Recognizing the need to improve the quality, precision and accuracy of the water quality data, all designated laboratories of the WQGH were requested to participate in the implementation of a quality assurance and quality control (QA/QC) test for water sampling, preservation, transportation and analysis from 2004. The goal of the implementation of the QA/QC procedures is to ensure that the designated laboratories carry out their routine water quality monitoring activities in accordance with the TGWQ and international standard ISO/IEC 17025-2005. To date, of the four designated laboratories of the WQGH, the laboratory in Lao PDR and Viet Nam have received ISO/IEC 17025-2005 certification. The certifications were given by the Bureau of Accreditation, Directorate for Standards and Quality of Viet Nam.

Other designated laboratories, while not being ISO/IEC 17025-2005 certified, have rigorously implemented the WQGH QA/QC in sampling and laboratory work or national QA/QC procedures that meet the requirements of the ISO/IEC 17025-2005. The MRC QA/QC procedure requires the designated laboratories to:

- be well prepared for each sampling event, by having a sampling plan with clear sampling objectives, and ensure that sampling teams are equipped with appropriate sampling and safety equipment, and preservative chemical reagents;
- apply quality control during sampling, which consists of taking duplicate samples and field blanks for certain parameters;
- analyse all water samples within recommended holding times;
- conduct routine maintenance and calibration of all measurement equipment;
- conduct data analysis using control chart and reliability score testing using ion balance test;
- archive raw data and any important pieces of information relating to the results of the analysis in order to make it possible to trace all data and reconfirm the results of the analysis.

3. RESULTS

3.1 Status of the Mekong and Bassac Water Quality

With the adoption of the Procedures for Water Quality (Section 1.2.2), water quality monitoring under the WQGH has become an integral part of its implementation. To confirm whether the water quality of the Mekong River is still 'good/acceptable', target values for key water quality parameters were established with the aim of protecting human health and aquatic life, and assessing the suitability of the river water for agricultural uses. For this report, water quality data from the 2019 routine WQMN were compared against the target values established in Chapter 1 (WQGH) and Chapter 2 (WQGA) of the TGWQ.

Using commonly applied descriptive statistical analysis (Section 2.4.1), the maximum, mean and minimum values of key water quality parameters were determined for stations located in the Mekong River (Table 3.1), Bassac River (Table 3.2), and selected tributaries (Annex C). As with other types of environmental monitoring time series data, water quality time series data of the Mekong River is lengthy and influenced by numerous factors including seasonality. Summarizing the data using descriptive statistics allows for a quick assessment of whether the water quality of the river is still of 'good/acceptable' quality compared to the established target values (Fu & Wang, 2012; von Sperling et al., 2020).

Tables 3.1 and 3.2 provide the results of descriptive statistical analyses for 10 key water quality parameters monitored under the WQMN in the Mekong and Bassac Rivers, respectively. Although the minimum DO and maximum COD and BOD values violated either the target values of WQGH or the WQGA, water quality of the Mekong and Bassac River can still be considered to be 'good/acceptable' quality and to still meet the requirements of the PWQ. In the Mekong River, the highest COD concentration (5.87 mg/L) was recorded at Nakhone Phanom (5) in July 2019. This value is slightly higher than the target values of the WQGH of 5 mg/L. Nevertheless, COD only exceeded the WQGH on three monitoring occasions, representing less than 1.5% of the total data.

In 2019, the highest concentration of BOD was recorded at Chiang Sean (2), at 4.69 mg/L in September 2019. The value is slightly higher than the target values for both the WQGH (4 mg/L) and the WQGA (3 mg/L). Similar to COD, BOD concentrations exceeded the target values during two monitoring missions, with the other exceedance recorded at My Thuan (16) in November 2019 (3.38 mg/L).

In terms of DO, slight impairment in levels against its target value or the protection of aquatic life was recorded at Tan Chau (15), My Thuan (16) and My Tho (17), with the lowest DO concentration recorded at My Thuan (16) in November 2019. Of the 12 monitoring occasions carried out at My Thuan (16), 42% showed DO concentrations of less than 5 mg/L (WQGA). However, only about 10% of all the monitoring campaigns carried out in 2019 showed non-compliance with the WQGH.

In addition to the COD, BOD, and DO, all but one EC concentration measured in 2019 were less than the lower range of the target values of 70 mS/m. The only exception was the maximum concentration (91 mS/m), measured at Vientiane (4) in November 2019. These exceedances, however, should not be considered impairment because historical EC concentrations in the Mekong River were generally low and rarely exceeded 30 mS/m, including the levels measured in the Mekong Delta during low tide. With 99.5% of EC data lower than 70 mS/m, the waters of the Mekong and Bassac River continued to be suitable for general and paddy rice irrigation in 2019 (Table 2.8). In comparison, the maximum EC value (841 mS/m) was recorded during the high tide in April 1998 at My Tho (17).

Between 1985 and 2018, the highest concentration of COD (65 mg/L) was recorded at Houa Khong (1) in July 2014. This maximum concentration was well above the WQGH of 5 mg/L. During the same period, pH levels also violated the target ranges of the WQGH and the WQGA (6–9), with the highest value recorded at 9.94 and the lowest value at 3.78. The lowest recorded DO concentration was recorded in March 2004 at Tan Chau (15), where DO was as low as 2.26 mg/L.

Similar to those observed in Mekong River, the same four key water quality parameters (COD, BOD, DO, and EC) monitored in the Bassac River were recorded to have values exceeding target values of either the WQGH or the WQGA (Table 3.2). In the Bassac River, about 7% of the COD values were higher than the target value of the WQGH (5 mg/L), with the highest concentration recorded at Takhmao (18) in February 2019 (7.51 mg/L). Similarly, about 7% of the BOD recorded values exceeded the target value of WQGA (3 mg/L). The highest BOD concentration (5.87 mg/L) was also recorded at Takhmao (19) in February 2019.

The recorded exceedance in BOD and COD levels appear to have influenced DO levels of the Bassac River, especially at Chau Doc (21) and Can Tho (22). At Chau Doc (21), 50% of the DO concentration was lower than the target value of WQGA (5 mg/L), with the minimum DO concentration recorded at 4.08 mg/L (March 2019). Similarly, 42% of DO concentration at Can Tho (22) was lower than the same target value of WQGA. At Chau Doc, 100% of DO concentration recorded in 2019 were lower than the target value of the WQGH (6 mg/L), indicating impairment for both the protection of human health and aquatic life. In comparison, only 8% of DO values recorded from 1985 to 2018 were less than 5 mg/L.

With the maximum concentration of 26 mS/m, all EC values recorded in the Bassac River in 2019 were below the lower limit of the target values for the WQGH (70–150 mS/m). With historical EC concentrations in the Bassac River rarely exceeding 20 mS/m during low tide, the values of EC recorded in 2019 should not be considered impairment. Similar to Mekong River, the water of Bassac River continued to be suitable for both general and paddy rice irrigation during low tide.

Table 3.1. Comparison of water quality data in the Mekong River between 1985-2018 and 2019

Parameters	Unit	Water Quality Guidelines		1985–2018				2019			
		Protection of Human Health (WQGH)	Protection of Aquatic Life (WQGA)	Max.	Mean	Min.	Stdev	Max.	Mean	Min.	Stdev
pH	–	6–9	6–9	9.94	7.48	3.78	0.51	8.94	7.45	6.03	0.51
TSS	mg/L	–	–	5716.00	144.28	0.10	251.38	255.50	46.79	2.29	50.32
EC	mS/m	70–150	–	841.00	20.60	1.20	26.65	91.00	23.21	6.94	8.99
NO_{3-2}	mg/L	5	5	1.42	0.25	0.00	0.17	0.98	0.29	0.01	0.19
NH_4N	mg/L	–	–	2.99	0.05	0.00	0.10	0.71	0.05	0.00	0.07
TOTN	mg/L	–	–	4.89	0.58	0.00	0.39	1.53	0.52	0.17	0.29
TOTP	mg/L	–	–	2.20	0.10	0.00	0.12	0.45	0.09	0.01	0.09
DO	mg/L	≥ 6	> 5	13.85	7.20	2.25	1.10	9.82	7.01	4.52	1.05
COD	mg/L	5	–	65.00	2.26	0.00	1.96	5.87	2.00	0.07	1.25
BOD_5	mg/L	4	3	4.50	1.19	0.00	1.07	4.69	1.15	0.10	0.82

Note: The yellow highlights indicate non-compliance with the WQGH or the WQGA.

Table 3.2. Comparison of water quality data in the Bassac River between 1985-2018 and 2019

Parameters	Unit	Water Quality Guidelines		1985–2018				2019			
		Protection of Human Health (WQGH)	Protection of Aquatic Life (WQGA)	Max.	Mean	Min.	Stdev.	Max.	Mean	Min.	Stdev.
pH	-	6–9	6–9	9.36	7.18	3.80	0.39	8.19	7.24	6.57	0.33
TSS	mg/L	–	–	636.00	68.22	0.10	73.80	211.00	39.19	4.88	40.80
EC	mS/m	70–150	–	63.70	13.38	1.30	4.61	26.00	17.22	6.64	4.95
NO_{3-2}	mg/L	5	5	1.99	0.26	0.00	0.20	0.98	0.36	0.09	0.22
NH_4N	mg/L	–	–	3.04	0.07	0.00	0.13	0.65	0.09	0.00	0.12
TOTN	mg/L	–	–	4.03	0.73	0.03	0.43	1.43	0.64	0.22	0.31
TOTP	mg/L	–	–	1.78	0.13	0.00	0.12	0.45	0.17	0.01	0.11
DO	mg/L	≥ 6	> 5	12.25	6.38	1.79	1.06	7.81	6.19	4.08	1.03
COD	mg/L	5	–	13.06	3.09	0.04	1.68	7.51	3.28	1.21	1.38
BOD_5	mg/L	4	3	4.66	1.83	0.03	1.12	5.87	1.93	0.46	1.11

Note: The yellow highlights indicate non-compliance with the WQGH or the WQGA.

3.2 Trends of Key Water Quality Parameters

Water quality data from the WQMN have allowed to establish relationship between key water quality parameters (Table 3.3). These relationships are important to understand the instream behaviours of key water quality parameters (Ly et al., 2020). For example, NO_{3-2} levels in the Mekong appear to be positively correlated with TOTN, NH_4N, TOTP and COD while negatively correlated with DO, EC, TSS, and pH (Table 3.3). The results of the Pearson's correlation analyses revealed that the positive relationships between NO_{3-2} and TOTN, TOTP, and COD were significant at 0.01 level. Similarly, the negative relationships between NO_{3-2} and DO and pH were revealed to be statistically significant at 0.01 level. Hence, as TOTN, COD, TOTP levels increased, so did the levels of NO_{3-2}. Conversely, the decrease in NO3-2 levels were due to the increased in pH and DO levels. Table 3.3 also revealed that while there appear to be relationships between NO_{3-2} and TSS (negative), EC (negative), and NH_4N (positive), the results of the Pearson's correlation analyses indicated that they were not statistically significant, with p-values greater than 0.05 (two-tailed).

Table 3.3 Relationships among key water quality parameters in the Mekong River as monitored by the WQMN from 1985 to 2019

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

** Correlation is significant at the 0.05 level (2-tailed)*

TSS (mg/L)	*0.034*							
EC (mS/m	0.015	- 0.421**						
NO_{3-2} (mg/L)	- 0.259**	- 0.048	- 0.047					
NH_4N (mg/L)	- 0.021	0.004	- 0.026	0.025				
TOTN (mg/L)	- 0.032	0.089	- 0.097	0.400**	0.749**			
TOTP (mg/L)	- 0.137**	0.067	- 0.071	0.189**	0.155**	0.125		
DO (mg/L)	0.381**	0.074	0.005	- 0.295**	- 0.053	- 0.067	- 0.252**	
COD (mg/L)	- 0.181**	0.030	- 0.160**	0.218**	0.139**	0.144	0.361**	- 0.322**
Water Quality Parameters	**pH**	**TSS (mg/L)**	**EC (mS/m)**	**NO_{3-2} (mg/L)**	**NH_4N (mg/L)**	**TOTN (mg/L)**	**TOTP (mg/L)**	**DO (mg/L)**

3.2.1 pH

In aquatic ecosystems, pH can affect many chemical and biological processes. This is because pH affects the solubility and availability of nutrients and heavy metals in water (Swenson & Baldwin, 1965). At extremely low pH, some toxic compounds and elements from sediments may be released into the water where they can be taken up by aquatic animals or plants, and ultimately by humans through direct contact and/or human consumption of aquatic animals or plants (USEPA, 2012a). Additionally, changes in pH can also influence the availability of trace elements, iron and nutrients, such as phosphate and ammonia in water (USEPA, 2012a).

Recognizing the importance of pH on the Mekong riverine environment, the MCs agreed to establish the technical water quality guidelines for pH levels in the Mekong River and its tributaries to protect human health and aquatic life, with the overall goal of achieving the MRC water quality objective, i.e. to maintain acceptable/good water quality to promote the sustainable development of the Mekong River Basin. As such, pH is one of the key water quality parameters monitored by the MRC Water Quality Monitoring Network. In 2019, MCs continued to monitor pH levels at all 48 water quality monitoring stations including those in the Mekong (17 stations) and Bassac (5 stations) Rivers.

Compared to the target values of WQGH and WQGA, the results of 2019 monitoring revealed that all pH values measured along the Mekong and Bassac Rivers were within the upper and lower target values of the WQGH (6–9) and the WQGA (6–9) (Tables 3.1 and 3.2). In comparison, 1.5% of pH values measured along the Mekong and Bassac Rivers in 2018 were either lower or higher than the recommended target range of 6 to 9. In 2019, the pH values recorded in the Mekong ranged from 6.03 to 8.94, with a mean value of 7.45. This value is similar to the average values recorded between 1985 and 2018 (pH of 7.4). In the Bassac River, pH ranged from 6.57 to 8.19 in 2019, with an average value of 7.24, which is slightly higher than the average pH value recorded from 1985 to 2018 (an average pH value of 7.18).

In the Mekong riverine system, pH levels tend to be highest in the upper part of the basin: about 90% of historical data (1985 to 2019) recorded between Houa Khong (1) and Pakse (8) water quality monitoring stations were greater than 7. The alkaline levels suggest that water quality in this section of the river is mainly influenced by the natural environment where dissolved salts and carbonates, as well as mineral composition from surrounding soil are introduced through surface and groundwater interaction dynamics (Lintern et al., 2018; Sophocleous, 2002). As the Mekong River flows southward, pH levels become less alkaline, with about 75% of pH historical data recorded between Stung Treng (9) and Chouy Changvar (12) greater than 7. Further downstream in a more densely populated Mekong Delta region, the proportion of pH data that was greater than 7 reduced to about 70%. The analyses of pH levels during the wet and dry seasons further show that the Mekong River water was more alkaline during the dry season with about 86% of the historical data being above 7, whereas during the wet season, surface runoff carrying inland pollution and human-induced wastes and wastewater caused the river water to be more acidic. The negative relationships between pH and COD, NO_{3-2}, TOTN, and TOTP, as illustrated in Table 3.3, further confirmed that as instream concentrations of COD and nutrients increased, pH levels decreased.

In 2019, The spatial variations of pH levels in the Mekong and Bassac Rivers appear to follow annual historical trends where pH levels were highest on average in the upper part of the basin and lowest in the Mekong Delta region (Figure 3.1). The only exception were the levels recorded at Luang Prabang (3), which were highly variable compared to other stations, with pH ranging from 6.05 to 8.07. Seasonality appears to have also influenced the pH levels in 2019, with about 90% of data above 7.0 during the dry season; however, this decreased to about 67% during the wet season.

Temporal variations of pH are shown in Figure 3.2, where its levels appear to have decreased since 1985, a reflection of increase development and population in the basin (Ai et al., 2015; Huang et al., 2015). In 1985, the average pH level in the Mekong River was 7.78, compared to 7.24 in 2019. The results of the one-way ANOVA analyses of mean annual pH levels from 1985 to 2019 revealed that observed temporal changes were statistically significant, with a p-value of less than 0.01.

Among the many factors that affect the pH levels of a river system, as discussed above, the anthropogenic and natural environment influences of the Mekong River water quality are expected to continue during both the wet and dry seasons. The reduction in water levels in the dry season due to instream disturbances, water abstraction, or climate variability, for example, could reduce the natural capacity of the river to dilute wastewater entering the river from industrial, agriculture and urban areas. This could result in a reduction of dry season pH levels and further increased the acidity of the river water during the wet season with laden nutrients surface runoff. The reduction in dry season water levels have already caused increased levels of chlorophyll and cyanobacteria in some sections of the Mekong River (MRC, 2019a).

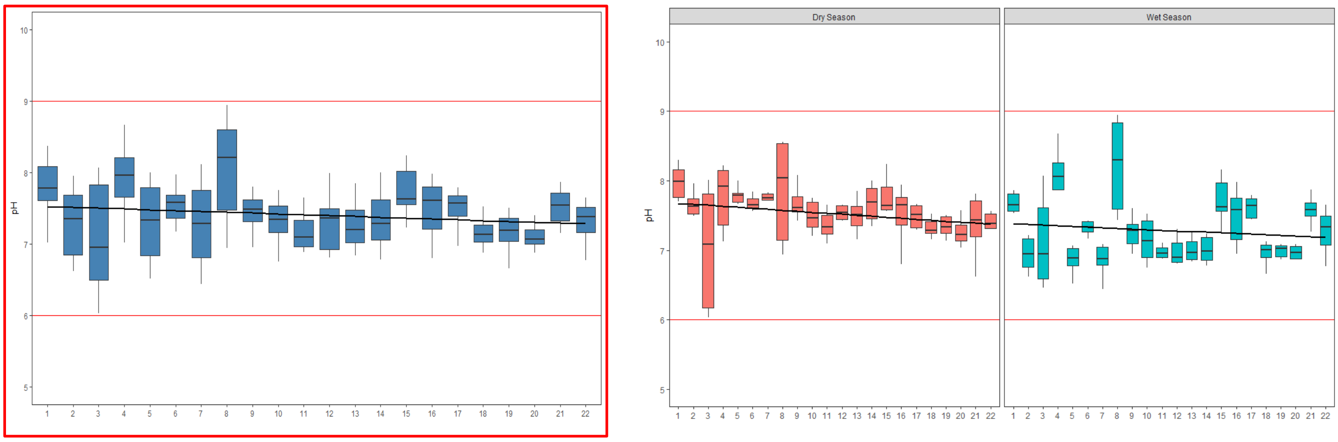


Figure 3.1. Spatial variation in pH levels along the Mekong River (Stations: 1-17) and Bassac River (Stations: 18-22) as observed in 2019

Note: The horizontal lines at 6.0 and 9.0 represent lower and upper pH limits of the MRC WQGA and WQGH

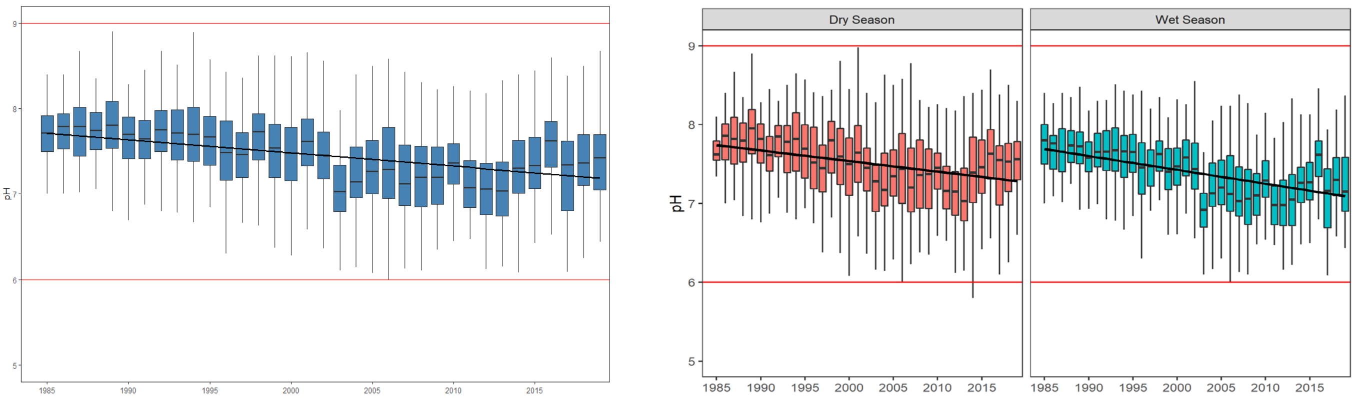


Figure 3.2. Temporal variation in pH levels in the Mekong River from 1985 - 2019

Note: The horizontal lines at 6.0 and 9.0 represent lower and upper pH limits of the MRC WQGA and WQGH

3.2.2 Electrical Conductivity

Electrical conductivity (EC) is another useful water quality indicator monitored by the WQGH. It provides a valuable baseline that has been used to identify any emerging effects of development on water quality in the Mekong River. It is also the most important parameter in determine the suitability of the Mekong River water for irrigation uses (Gholami & Srikantaswamy, 2009). In the LMB, the EC guidelines, together with the degree of consequence for general irrigation and paddy rice, are listed in Table 2.8.

Under normal circumstance and in areas that are not affected by salinity intrusion, the Mekong and Bassac Rivers, similar to other water bodies, have constant ranges of conductivity, and therefore, any sudden and significant change in EC can be an indicator of water pollution (Pal et al., 2015; USEPA, 2014a). Similar to other water quality indicators, EC levels in a river are influenced by both natural and human-induced factors (USEPA, 2014a). Under natural conditions, EC is influenced by the amount of dissolved inorganic solids from surrounding soils and geology (Ohtani, 2013). Therefore, significant changes of EC levels in the river could indicate increased pollution levels, even if its physical characteristics (i.e. colour, smell, clarity, etc.) remain the same. Wetzel (2001b) states that pollution from agricultural runoff or sewage leaks can increase EC levels, whereas a spill of organic compound such as oil can reduce EC levels.

The Mekong and Bassac Rivers are naturally low-salinity rivers with EC values rarely exceeding 50 mS/m when monitored during low tide. In 2019, EC levels of both the Mekong and the Bassac Rivers continued to be low, with average values of 23.21 and 17.22 mS/m, respectively. Other than the maximum EC value of 91 mS/m recorded in Vientiane (4) in November, all EC levels fell outside the recommended range of the WQGH of 70–150 mS/m, and were lower than the non-impairment target values for both general irrigation (< 70 mS/m) and paddy rice (< 200 mS/m). Statistically, the maximum EC value of 91 mS/m can be considered an outlier and may have been influenced by either instream disturbance and/or monitoring error during the monitoring. The next highest EC value was recorded at 57.40 mS/m, which is in line with maximum levels generally detected historically in the river during low tide.

Spatially EC levels in the Mekong River in 2019 were slightly higher in the upper part of the basin than in the lower and Delta regions (Figure 3.3). On average, the EC value for stations located between Houa Khong (1) and Pakse (8) was around 28 mS/m. In comparison, the average EC value for stations located between Stung Treng (9) and Chrouy Changvar (12) was 19 mS/m. The value further reduced to 17 mS/m for stations located in the Mekong Delta – both on the Mekong (13–17) and Bassac Rivers (18–22). Since the average wet season (22 mS/m) and dry season (25 mS/m) concentrations were at similar levels, the EC of the Mekong and Bassac was not influenced by seasonality in 2019. Without the maximum EC value of 91 mS/m, the range of EC values for the wet season (7.0–57.4 mS/m) and the dry season (12.6–52.1 mS/m) would have also been similar.

On a temporal scale, high EC levels were observed in the Delta (Viet Nam's stations) during high tide due to the backwater effects of sea water, with a maximum value of 841.0 mS/m recorded. This maximum value was recorded at My Tho (17) in April 1998. With the exception of the values recorded during high tide, annual EC levels have not changed since the inception of the WQMN (Figure 3.4). The Mekong and Bassac Rivers can be generally characterized as rivers with low conductivity values, with average historical values from 1985 to 2018 of about 20.6 and 13.4 mS/m, respectively (Tables 3.1 and 3.2).[2] In 2019, mean EC values for the Mekong (23.21 mS/m) and Bassac Rivers (17.22 mS/m) were slightly higher than their historical counterparts (Table 3.2).

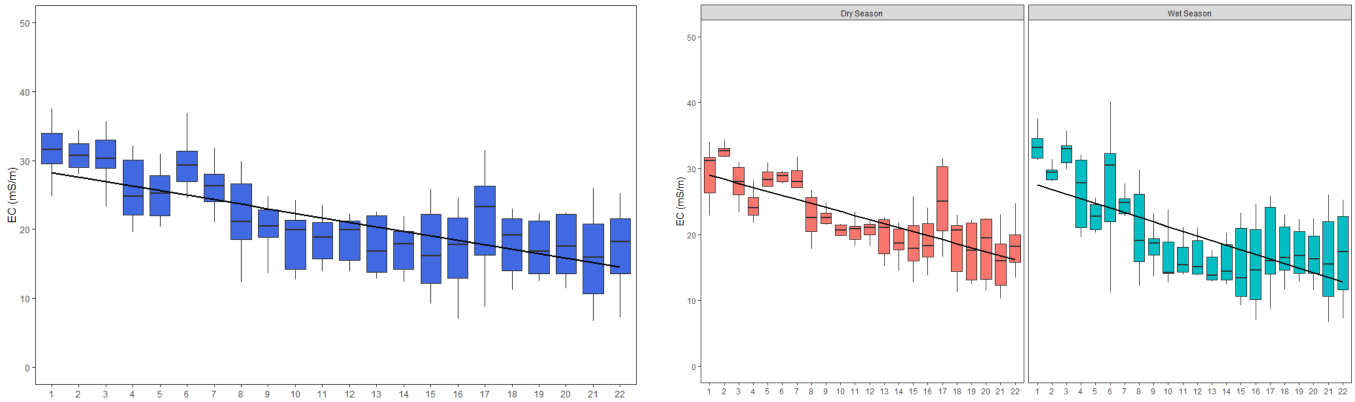


Figure 3.3. Spatial variation in Electrical Conductivity levels along the Mekong River (1-17) and Bassac River (18-22) as observed in 2019

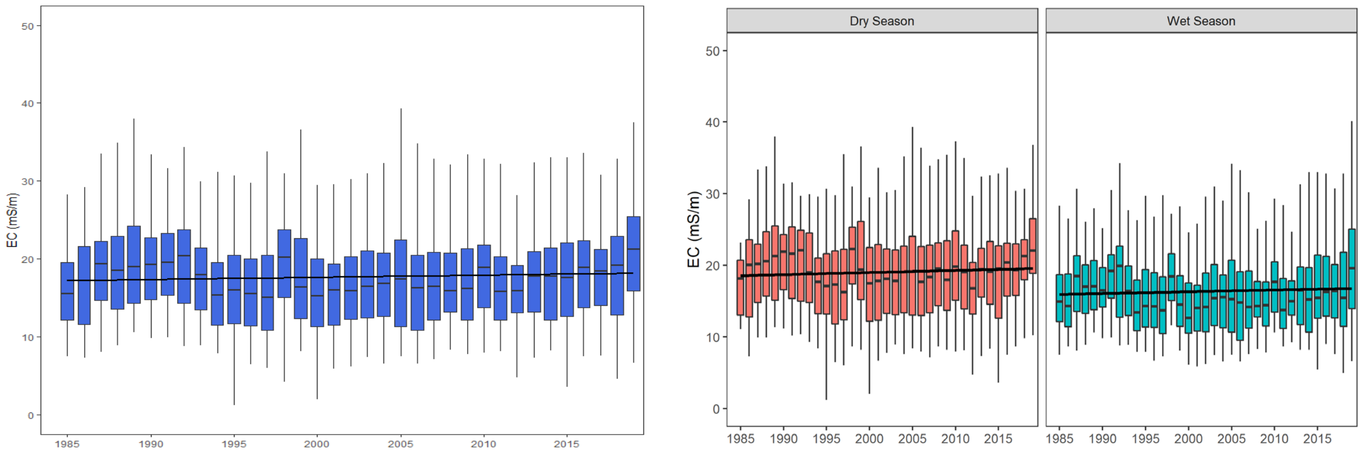


Figure 3.4. Temporal variation in Electrical Conductivity levels in the Mekong River as observed from 1985 to 2019

3.2.3 Total Suspended Solids

In the Mekong River, total suspended solids (TSS) are influenced by both natural and anthropogenic factors. Natural factors including vegetation composition and coverage, topography, and climate variability have been shown to influence the variability levels of instream TSS concentration of the Mekong River (Chaplot et al., 2007; Lacombe et al., 2018; Ly et al., 2020; Suif et al., 2016). Studies have also shown that human-induced activities such

[2] These average values are based on measurements taken during low tide. EC values for stations located in the Delta can generally reach up to more than 5,000 mS/m during high tide.

as urbanization and damming of the Mekong River and its tributaries have resulted in the reduction of instream TSS levels (Fu et al., 2008; Hecht et al., 2019; Kummu & Varis, 2007; Ly et al., 2020). The method used by the WQGH to sample TSS does not reflect the sediment concentration in the whole water column,[3] but currently provides an indication of long-term trends in suspended solids contents in the Mekong River.

In 2019, the TSS concentrations observed along the Mekong River continued to be highly variable, with values ranging from 2.3 to 255.5 mg/L. The average TSS concentration was about 46.8 mg/L (Table 3.1). TSS concentrations along the Bassac River, in contrast, were less variable compared to the range observed along the Mekong River. Along the Bassac River, TSS concentrations ranged from about 4.9 to 211.0 mg/L, with an average value of 39.2 mg/L (Table 3.2).

Historically, the highest TSS levels were observed in the upper part of the basin, where the topography of the region is dominated by mountainous ranges and fast flowing instream water, resulting in highly variable TSS levels. For example, between 1985 and 2018, TSS concentrations at Chiang Sean (2) ranged from 1.6 mg/L (September 2000) during the dry season to as high as 2,372 mg/L (August 1991) during the wet season. Similarly, the highest ever recorded TSS concentration during the same period was also recorded in the upper section of the River in Vientiane (4) at 5,716 mg/L in July 1988.

In 2019, instream dynamics of TSS appear to have deviated from the norms, with levels of TSS recorded at stations in the upper part of the basin lower and less variable than in stations located in the middle part of the basin (Figure 3.5). In 2019, TSS levels at Chiang Sean (2) ranged from 16.4 mg/L to a merely 147.42 mg/L, while at Vientiane (4), TSS concentrations were ranged from 8 mg/L to 54.66 mg/L. In comparison, levels at Kampong Charm (11) ranged from 8.5 mg/L to 255.5 mg/L. In fact, maximum TSS concentration was recorded at Kampong Charm (255.5 mg/L) in 2019, which was the first time that the annual maximum TSS concentration was not recorded in the upper part of the basin. It should be noted that in 2018, the highest TSS concentration was recorded in Luang Prabang (3), at 518 mg/L.

For both the Mekong and Bassac Rivers, the lowest TSS concentrations were observed during the dry season (November to April). In general, the Lower Mekong River receives very little to no rainfall during the dry season, which causes the dry season TSS concentrations to be lower than those generally observed during the wet season. Along the Mekong River, the average dry season TSS concentration of 2019 was recorded at about 21.2 mg/L. The highest dry season concentration for TSS was recorded at 131.25 mg/L at Chiang Sean Water Quality Monitoring Station, in January 2019, while the lowest concentration was recorded at 2.29 mg/L at Stung Treng Water Quality Monitoring Station in December 2019.

During the wet season 2019, the average concentration for the Mekong River was recorded at about 72.4 mg/L, a reduction of 48% compared to 2018 (138 mg/L). The lowest wet season TSS concentration was recorded in Vientiane in May 2019 (8.0 mg/L), while the highest concentration was recorded at Kampong Charm (11) in September 2019.

[3] Water samples are taken approximately 30 cm below the water surface.

Since the TSS levels deviated from the norms in 2019, it is important to continue to monitor whether this trend is an outlier or if it is becoming the norm with increased hydropower development, land use/land cover changes, urbanization, and climate variability. It should also be noted that the results of the Pearson's correlation analyses revealed a negative relationship between TSS and $NO_{3\text{-}2}$, and positive relationships between TSS and NH_4N, TOTN, and TOTP. These relationships, however, were not statistically significant, indicating that the reduction in TSS levels did not significantly affect the levels of instream nutrients. This is likely because instream nutrients were introduced locally and not transported across the river system with TSS.

The temporal analysis of data from 1985 to 2019 suggests that TSS levels in the Mekong River decreased significantly since 1985 (Figure 3.6). The average TSS concentration in the Mekong River in 1985 was about 388 mg/L, whereas in 2019, the average concentration for TSS was about 46.8 mg/L, i.e. a net reduction of about 88%. Compared to 2018, where mean TSS concentration was 84.9 mg/L, the 2019 figure shows a reduction of about 45%.

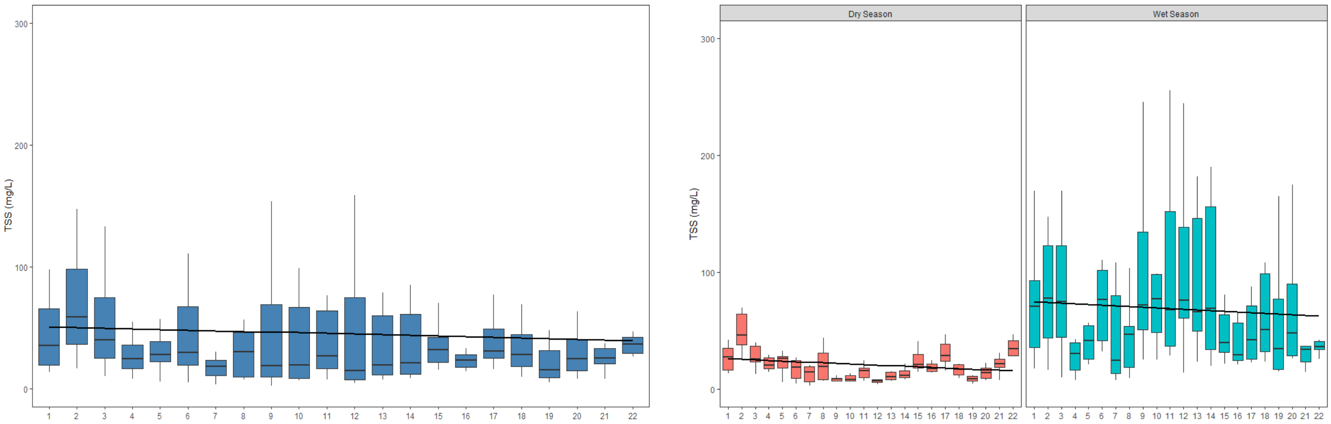


Figure 3.5. Spatial variation in TSS concentrations along the Mekong River (1-17) and Bassac River (18-22) as observed in 2019

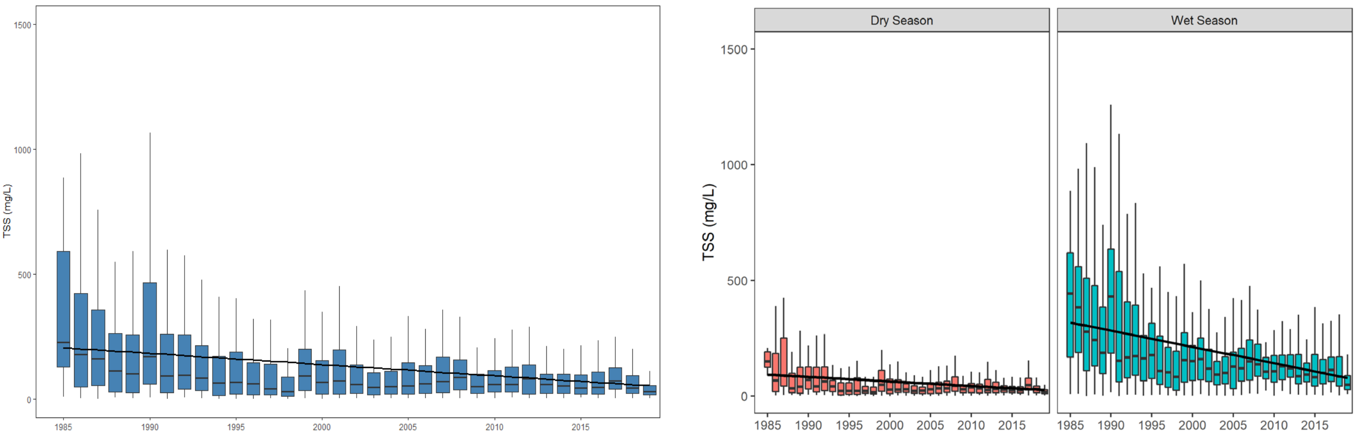


Figure 3.6. Temporal variation in TSS concentrations along the Mekong River as observed from 1985 to 2019

3.2.4 Nutrients

The WQGH-designated laboratories continued to monitor concentrations of nitrate-nitrite (NO_{3-2}), ammonium (NH_4), total nitrogen (TOTN), and total phosphorus (TOTP) as part of nutrients monitoring in 2019. Results of the Pearson's correlation analyses (Table 3.3) revealed that these parameters have strong positive relationships, indicating that an increase in levels of one will lead to an increase in levels of all.

Concentrations of nutrients at all mainstream stations in the Mekong and Bassac Rivers remained well below the WQGH and WQGA (Table 3.1).

3.2.4.1 Nitrogen

The spatial analysis of water quality data (Figure 3.7) shows that in 2019 NO_{3-2} concentrations were highly variable at a number of stations, including Vientiane (4) and Pakse (8) which are located in the upper and middle parts of the river, respectively, and My Thuan (16), My Tho (17), Chau Doc (21), and Can Tho (22), which are located in the Mekong Delta. Among the 17 stations located along the Mekong River, the maximum NO_{3-2} concentration (0.98 mg/L) was recorded at Vientiane (4) in December 2019 while the minimum concentration (0.01 mg/L) was recorded at Kratie in November 2019. Along the Bassac River, NO_{3-2} concentration ranged from 0.09 to 0.98 mg/L, with the highest concentration detected at Can Tho (22) during the wet season (July 2019) and the lowest at Takhmao (18) during the dry season (October 2019). The maximum NO_{3-2} concentrations at both the Mekong and Bassac Rivers were still well within the target values of 5 mg/L for WQGH and WQGA (Tables 3.1 and 3.2).

Figure 3.7 further revealed that NO_{3-2} levels in the Mekong River were not affected by seasonality, since concentrations recorded during the dry and wet seasons were at similar ranges. During the dry season, NO_{32} concentrations ranged from 0.01 to 0.98 mg/L, while during the wet season, they range from 0.09 to 0.89 mg/L. Along the Bassac River, the wet season NO_{3-2} levels were similar to those observed in the Mekong River with concentrations ranged from 0.09 to 0.98 mg/L. During the dry season, NO_{3-2} levels became less variable with concentrations ranged from 0.2 to 0.7 mg/L.

Temporal analysis of NO_{3-2} concentrations from 1985 to 2018 reveals that NO_{3-2} levels in the Mekong River remained relatively constant (Figure 3.8). For the Mekong River, NO_{3-2} concentrations in 2019 (average value of 0.29 mg/L) were similar to those recorded from 1985 to 2018 (average value of 0.25 mg/L). The values are well below the target values for both WQGH and WQGA of 5 mg/L.

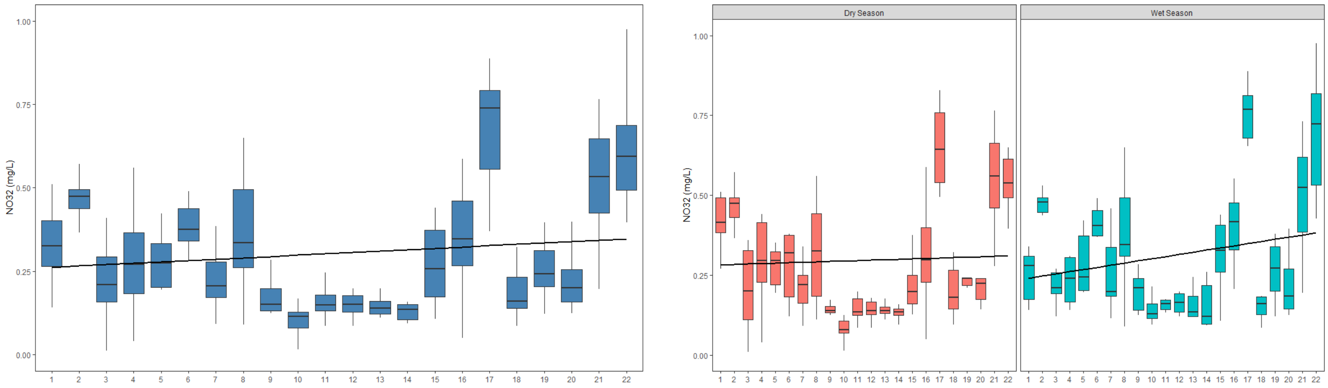


Figure 3.7. Spatial variation in nitrate-nitrite concentrations in the Mekong River (1-17) and Bassac River (18-22) in 2019

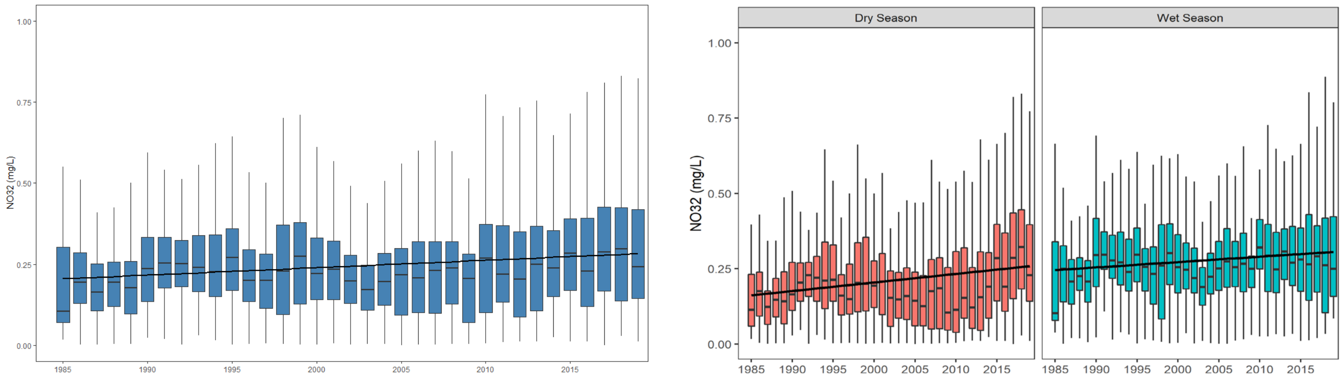


Figure 3.8. Temporal variation in nitrate-nitrite concentrations in the Mekong River as observed from 1985 to 2019

Spatial analysis of NH_4N levels (Figure 3.9) shows that NH_4N concentrations at stations in the lower part of the basin were highly variable compared to those measured at stations located in the upper part of the basin. In 2019, the highest ammonium concentration was measured at Kampong Cham (11) (0.71 mg/L) in January 2019, and Takhmao (18) (0.65 mg/L) in December 2019, for the Mekong and Bassac Rivers, respectively. At Kampong Cham and Takhamao, the average NH_4N concentrations were estimated at around 0.15 and 0.18 mg/L, respectively.

Unlike the levels observed for NO_{3-2}, NH_4N levels appear to have been influenced by seasonality, with the highest and more variable levels being recorded during the dry season. In 2019, dry season concentrations for NH_4N ranged from 0.0 to –0.71 mg/L for the Mekong River, and 0.0 mg/L to 0.65 mg/L for the Bassac River. In contrast, wet season concentrations ranged from 0.0 mg/L to 0.34 mg/L, and 0.0 to 0.58 mg/L, respectively.

Temporal analysis of data from 1985 to 2019 for the Mekong River reveals that overall ammonium concentrations increased slightly (Figure 3.10), from about 0.03 mg/L in 1985 to 0.05 mg/L in 2019. Analysis results of the one-way ANOVA and SMK revealed that the increase was not statistically significant, with p-values for both analyses greater than 0.05.

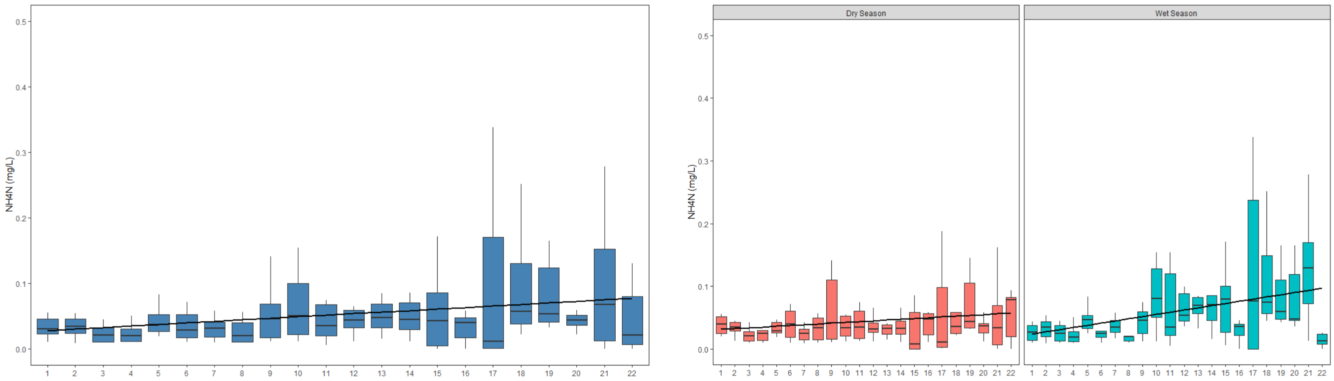


Figure 3.9. Spatial variation in ammonium concentrations in the Mekong River (1-17) and Bassac River (18-22) in 2019

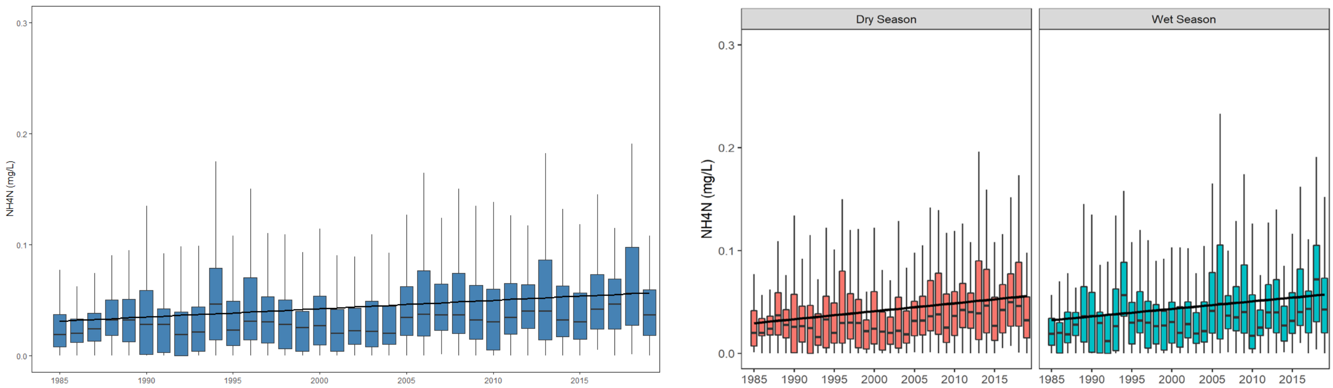


Figure 3.10. Temporal variation in ammonium concentrations in the Mekong River as observed from 1985 to 2019

In the Mekong and Bassac River, instream TOTN levels appear to mostly be influenced by NO_{3-2} levels, with both spatial and temporal TOTN trends (Figures 3.11 and 3.12 closely resembling those of NO3-2 (Figures 3.7 and 3.8). On a spatial scale, TOTN levels were highest in the upper and Delta parts of the LMB, with concentrations at Houa Khong (1) ranging from 0.58 to 1.52 mg/L. In the Delta, concentrations at My Tho (17) ranged from 0.90 mg/L to 1.53 mg/L, while at Can Tho (22), concentrations ranged from 0.62 mg/L to 1.27 mg/L. In the middle section of the Mekong River, TOTN concentrations were lowest and less variable, with levels less than 0.5 mg/L. The minimum TOTN concentration (0.17 mg/L) was recorded along this section of the river (Kratie (10) – in March and May 2019.

Variations in the spatial scale of TOTN appear to be influenced by seasonality, with overall levels decreased as the river flowed from the upper section to the Delta during the dry season (Figure 3.11). This indicates the increased natural capacity of the river to dilute nutrients pollution as discharge increased and accumulated from tributaries inflow. In contrast, wet season spatial variation exhibits the opposite of that observed during the dry season, with TOTN levels increased as the river flowed to the Delta. This was likely due to increased nutrients-laden surface runoff introduced into the river as land use/land cover (LUCL) changes from a mostly forest-dominated to an agricultural-dominated area (Bonometto et al., 2019; Ly et al., 2020).

At a temporal scale (Figure 3.12), TOTN levels in the Mekong River remained relatively constant compared to the historical record, with the 2019 average concentration of 0.52 mg/L. In comparison, the average concentration of TOTN from 1986 to 2018 was 0.58 mg/L. In the Bassac River, the temporal trend of instream TOTN appeared to be decreasing, with the 2019 average concentration recorded at 0.62 mg/L, compared to the 1986–2018 average concentration recorded at 0.73 mg/L.

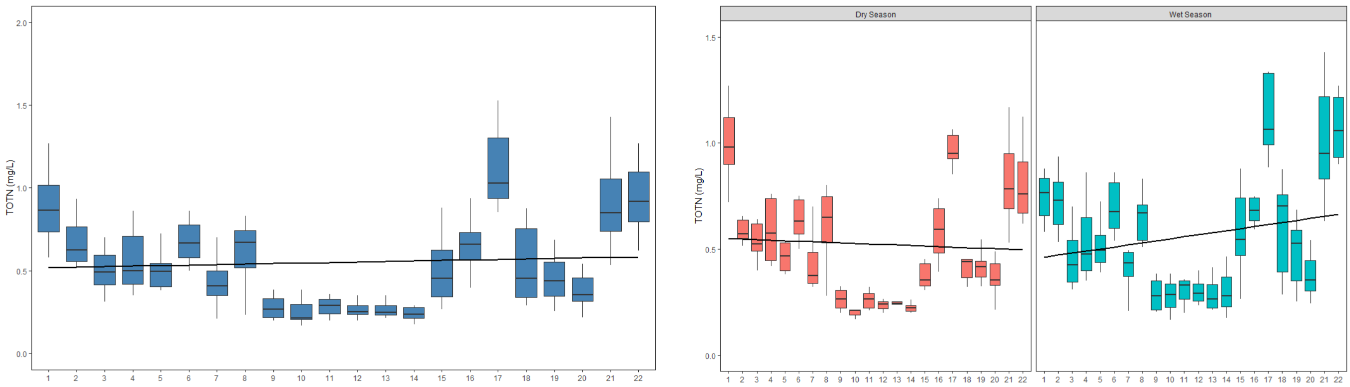


Figure 3.11. Spatial variation in TOTN concentrations in the Mekong River (1-17) and Bassac River (18-22) in 2019

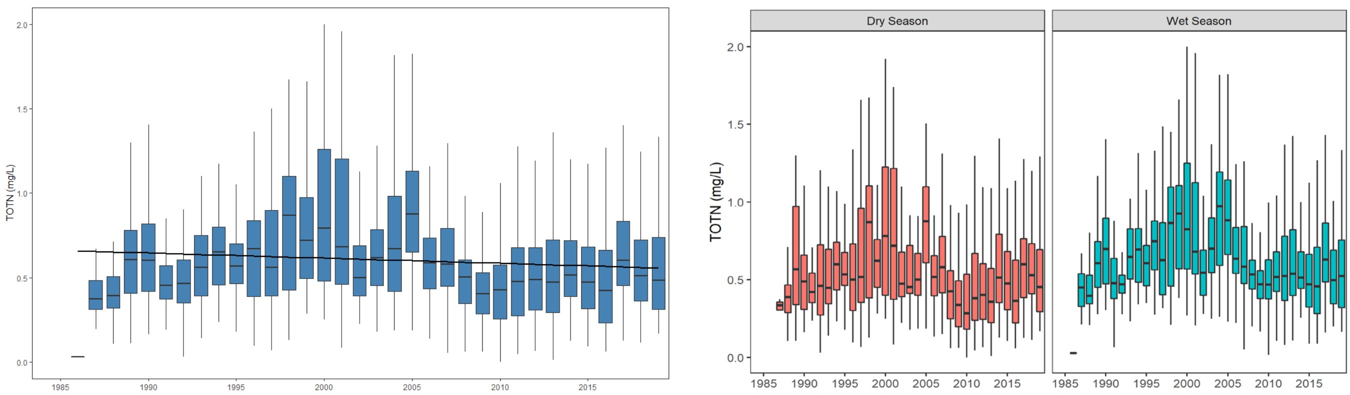


Figure 3.12. Temporal variation in TOTN concentrations in the Mekong River as observed from 1985 to 2019

3.2.4.2 Phosphorus

Like other water quality parameters monitored under the WQMN, instream phosphorus levels can be influenced by both natural processes during rock and soil weathering, which release phosphate ions and mineralize phosphate compounds that form phosphorus during instream processes (USEPA, 2012b). In addition, instream phosphorus can be introduced through surface runoff from agricultural areas and human discharges of organic waste and industrial effluents (Liu et al., 2018). Although phosphorus is an essential nutrient for aquatic plants and animals, an increase in instream levels can cause water quality problems, including accelerated algae blooms and reduced DO levels essential for aquatic fauna (USEPA, 2012b). Therefore, continued monitoring of phosphorus levels in water can facilitate early detection of water quality issues including the blue-green water colour phenomenon recently observed along certain sections of the Mekong River and potential water quality hotspots associated with human-induced activities.

In 2019, total phosphorus concentrations were highly variable among stations located in the Mekong and Bassac Rivers (Figure 3.13). On a spatial scale, TOTP levels were lowest in the upper section of the river, with the average concentration of 0.05 mg/L for stations located between Houa Khong (1) and Pakse (8). Of all TOTP data recorded at these stations, only one data point (0.14 mg/L at Nakhon Phanom in June 2019) exceeded the target value (0.13 mg/L) used for calculating WQI_{al} (Table 2.4).

As the river meanders southward reaching Stung Treng (9), TOTP levels became more variable, with concentrations ranging from 0.01 to 0.35 mg/L at Stung Treng (9). With the highest concentration recorded during the wet season (0.35 mg/L in September and 0.25 mg/L in October), elevated levels of instream TOTP at Stung Treng were likely due to surface runoff carrying organic wastes and phosphate compounds into the river. From Stung Treng (9) to the Mekong Delta, the average TOTP concentration was 0.13 mg/L, with a maximum concentration of 0.45 mg/L recorded at My Thuan (16) in September 2019. Between Stung Treng (9) and My Tho (17), the last monitoring station in the Mekong River before discharging to the East Sea (also known as the South China Sea), about 40% of TOTP data exceeded the target value (0.13 mg/L) used for the calculation of the WQI_{al} (Table 2.4).

Along the Bassac River, the highest concentration of TOTP was recorded at Takhmao (18) in September 2019 (0.45 mg/L). At Takhmao (18), about 92% of the TOTP data exceeded the target value (0.13 mg/L) used for the calculation of the WQI_{al} (Table 2.4). The instream TOTP levels in Takhmao may have been influenced by organic wastewater inputs that are rich with detergents and human and animal wastes. Compared to the Mekong River, TOTP levels in the Bassac River slightly increased, with the average concentration recorded at 0.17 mg/L, compared to 0.05 mg/L for the entire Mekong River, or 0.12 mg/L for the Mekong section from Neak Loung (13) to My Tho (17). Of all TOTP data collected at the five stations along the Bassac River, 50% exceeded the WQI_{al} target value of 0.13 mg/L.

Further examination of Figure 3.13 reveals that TOTP levels were highly variable during the wet season, with concentrations ranging from 0.01 to 0.45 mg/L in the Mekong River, whereas the wet season concentrations along the Bassac River ranged from 0.06 to 0.45 mg/L. In comparison, dry season concentrations in the Mekong and Bassac Rivers ranged from 0.01 to 0.25 mg/L, and 0.01 to 0.37 mg/L, respectively.

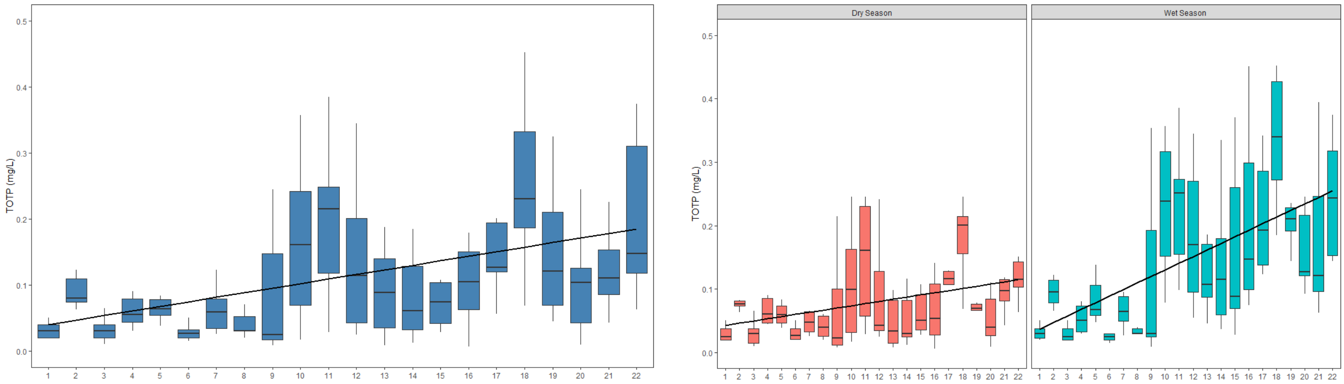


Figure 3.13. Spatial variation in total phosphorus concentrations in the Mekong River (1-17) and Bassac River (18-22) in 2019

Between 1985 and 2019, the overall TOTP concentrations in the Mekong River increased slightly, from a mean concentration of about 0.06 mg/L in 1985 to about 0.09 mg/L in 2019 (Figure 3.14 and Table 3.1). The results of increased human activities, such as agricultural runoff and municipal wastewater discharge in the lower part of the basin, were the likely reasons for the trend, as can be seen in the significant increase of levels during the wet season. It should be noted, however, that the average concentration of TOTP in 2019 remained the same as in 2018 (0.09 mg/L).

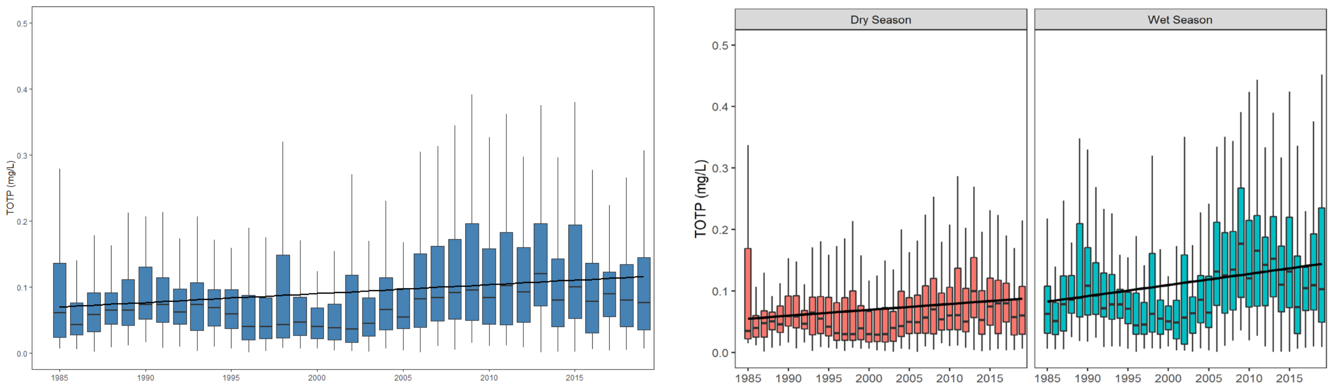


Figure 3.14. Temporal variation in total phosphorus concentrations in the Mekong River as observed from 1985 to 2019

3.2.5 Dissolved Oxygen

DO is one of the key water quality parameters that has been monitored routinely by the WQMN since 1985. To maintain acceptable/good water quality, which is the main aim of PWQ, an adequate concentration of DO is necessary. This is because DO is essential to the respiratory metabolism of aquatic organism. In a river system, the distribution dynamics of DO are governed by atmospheric oxygen inputs, photosynthesis, and oxygen depletion from chemical and biotic oxidations (Wetzel, 2001a). Prolonged reduction of DO levels in water bodies can lead to fish kill, and can affect other water quality indicators, including biochemical and aesthetic indicators, such as odour, clarity and taste (Ly et al., 2020; Paule-Mercado et al., 2017).

Recognizing that DO is an integral component for determining the water quality of the Mekong River, the MCs have jointly established target values WQGH (≥ 6mg/L) and WQGA (> 5 mg/L). These target values have been used as guidelines for determining the suitability of the Mekong River and its tributaries water for the protection of human health and aquatic life.

In 2019, DO continued to be monitored at all 48 water quality stations across the LMB. Figure 3.15 shows the spatial patters of DO in the Mekong River (1–17) and the Bassac River (18–22) where a distinct oscillatory pattern can be observed. In the upper and middle parts of the LMB, DO levels fluctuated from stations to stations starting at Houa Khong (1) to Stung Treng (9). At Houa Khong (1), DO levels were less variable ranging from 6.4 to 8.7 mg/L with an average concentration of 6.8 mg/L. As the river reached Chiang Sean (2), DO levels slightly increased and became more variable with concentrations ranging from 6.6 to 8.9 mg/L and an average value of about 7.9 mg/L. At Luang Prabang (3), DO level slightly decreased with an average concentration of 6.7 mg/L, and concentrations ranging from 6.1 to 8 mg/L. The oscillatory pattern in DO levels continued until the river reached Stung Treng (9), where the levels gradually decreased to the levels recorded at Kraorm Samnor (14). At Kraorm Samnor (14), the average DO concentration was 7.2 mg/L. Once the River entered the Viet Nam section of the Mekong D DO levels decreased significantly, where a combined 81% and 28% of DO data from Tan Chau (15), My Thuan (16) and My Tho (17) fell below the target values of WQGH (6 mg/L) and WQGA (5 mg/L), respectively. In 2019, the minimum DO concentration of 4.52 mg/L was recorded at My Thuan (16) in November 2019. On the southern side of the Mekong Delta where the Bassac River flows, similar patterns were detected, with DO concentrations for Takhmao (18), Koh Khel (19), and Koh Thom (20) ranging from 5.5 to 7.8 mg/L. However, once the river entered Viet Nam, DO levels decreased with a combined 83% and 46% of the data fell below the target value of WQGH (6 mg/L) and WQGA (5 mg/L), respectively. In the Bassac River, the lowest DO concentration was recorded at Chau Doc in March 2019 (4.08 mg/L). At Chau Doc (21), 50% of the DO data were non-compliant with WQGA. When compared to the target value of WQGH, 100% of the data were non-compliant.

A number of natural and human-induced factors may have influenced the DO patterns observed in 2019. In the upper part of the basin, both climate and topography may have influenced the river DO levels, as surface water DO is known to be influenced by both temperature and fast moving water (Michaud, 1991). Figure 3.15 further reveals that in the upper section, DO levels were highest during the dry season months including in December and January, where water temperature is cooler and can hold more DO. In addition, the topography of the upper part of the basin is dominated by steep mountain ranges, causing the water to move rapidly and turbulently through the river channel, which causes atmospheric oxygen to be easily mixed in the water column. In contrast, the Delta section of the river is characterized by flat flood plains and warmer temperature, which made difficult for atmospheric oxygen to be introduced and held in the water column. Furthermore, as the river flowed in the Delta, instream pollutants also accumulated, depleting DO in the river through chemical and biotic oxidation processes (Wetzel, 2001a).

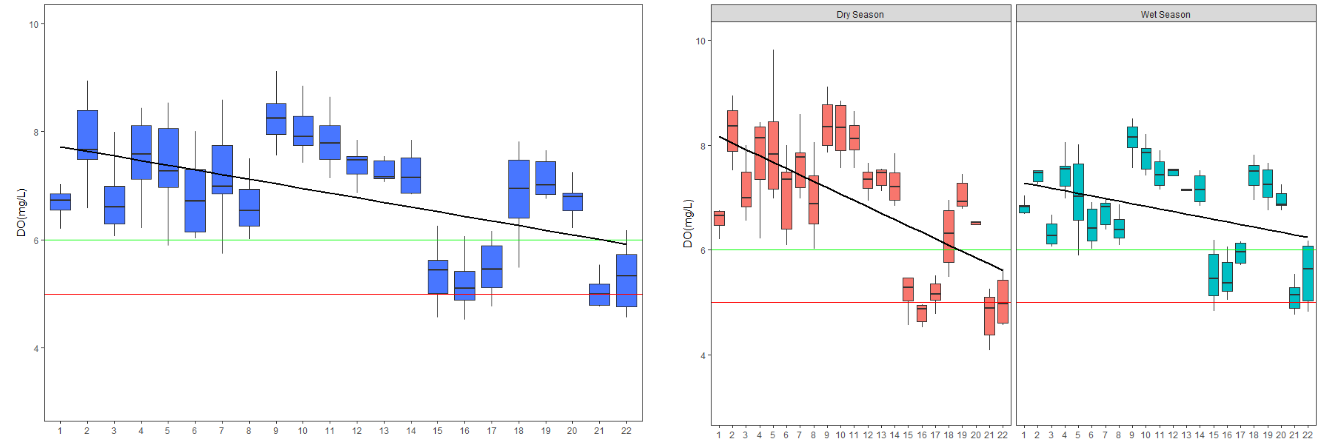


Figure 3.15. Spatial variation in dissolved oxygen (mg/L) at 22 stations along the Mekong (1-17) and Bassac (18-22) Rivers in 2019

Note: The horizontal lines at 5.0 and 6.0 represent DO target values for WQGH and WQGA, respectively.

A temporal analysis of DO in the Mekong River from 1985 to 2019 (Figure 3.16) reveals that DO concentrations in the mainstream decreased during the period. From 1985 to 2018, the average DO level was recorded at about 7.2 mg/L. This value decreased to about 7.0 mg/L in 2019. The reduction appears to be related to the increased levels of COD, NO_{3-2}, NH_4N, TOTN and TOTP, with significant relationships detected with NO_{3-2}, NH_4N, and COD (Table 3.3).

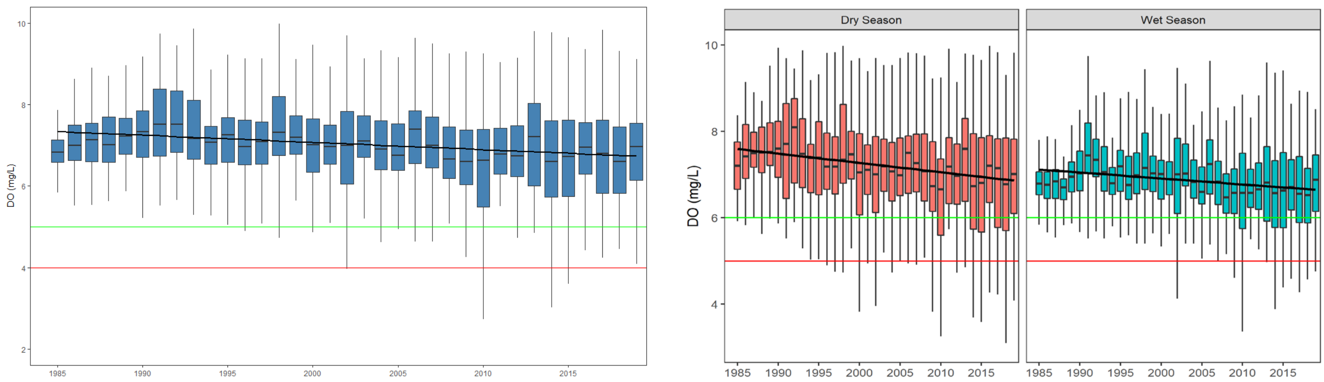


Figure 3.16. Temporal variation in dissolved oxygen (mg/L) in the Mekong River as recorded from 1985 to 2019

Note: The horizontal lines at 5.0 and 6.0 represent DO target values for WQGH and WQGA, respectively.

3.2.6 Chemical Oxygen Demand

COD and BOD (Section 3.2.7) have been widely used to measure the amount of organic and inorganic pollutants in water systems including surface water (Lee et al., 2016). Under the WQGH, COD is used as a proxy for measuring organic pollution from industrial, human, and animal wastes. As such, the main purpose for monitoring COD is to assess the effects of human activities on the Mekong River water quality. As listed in Table 2.3, potassium permanganate is used to chemically oxidize organic material in water samples under the conditions of heat and strong acid. In 2019, the maximum COD concentration in the Mekong River was recorded at 5.87 mg/L at Nakhon Phanom (5) in July 2019. In comparison, the highest concentration of COD recorded was at Khong Chiam (6.48 mg/L) in July 2018. Both 2018 and 2019 were slightly higher than the target value of the WQGH (5mg/L). Along the Bassac River, highest COD concentration was recorded at Takhmao (18) in February 2019 (7.51 mg/L). On average, the COD levels were highest in the Mekong Delta part of the river. Levels at stations in this part of the river are also highly variable compared to those at the stations located in the middle and upper sections of the river (Figure 3.17). In Takhmao (18), for example, COD concentrations were highly variable in 2019, ranging from 1.25 to 7.51 mg/L, with the average concentration of about 3.5 mg/L. In comparison, at Nakhon Phanom (5), where the highest 2019 COD concentration was recorded, levels ranged from 1.39 to 5.87 mg/L, with the average COD concentration of 2.70 mg/L. Except for the maximum concentration recorded at Nakhon Phanom, no other COD concentration measured at stations located along the Mekong River (1–17) in 2019 exceeded the WQGH's target value of 5 mg/L. In contrast, about 18% of COD data recorded at stations along the Bassac River exceeded the target value of the WQGH.

Figure 3.17 shows that instream COD concentrations in the Bassac River tend to elevate and be more variable during the dry season where the river water levels were low, indicating a reduced natural capacity of the river to adequately dilute human-induced wastewater entering the river in the region (Chea et al., 2016; Ly et al., 2020; Phung et al., 2015).

From 1985 to 2019, COD levels in the Mekong River increased slightly, and the mean COD concentrations increased from about 1.6 mg/L in 1985 to about 2.0 mg/L in 2019. However, these values are still well within the target value of the WQGH (5 mg/L). Figure 3.18 reveals that COD concentrations in the Mekong River increased significantly from 1985 to 2018, with the results of the one-way ANOVA analyses showing that annual mean COD concentrations were different, at a p-value of less than 0.01. In addition, the result of the SMK analysis applied on individual COD concentrations also revealed that the increased trends from 1985 to 2019 were statistically significant, with p-values less than 0.01. In comparison, the mean COD concentration of the 17 Mekong Stations was estimated at around 1.6 mg/L in 1985, while the mean COD concentration for the same stations was about 2.3 mg/L in 2017 and 2.47 mg/L in 2018. From 1985 to 2019, the highest COD levels, on average, were recorded in 2010, with the average concentration of 3.20 mg/L and levels ranged from 0.21 mg/L to 15.03 mg/L. During the same timeframe, the lowest COD levels, on average, were recorded in 1991, with mean a COD concentration of 1.54 mg/L and levels ranging from 0.10 mg/L to 5.00 mg/L.

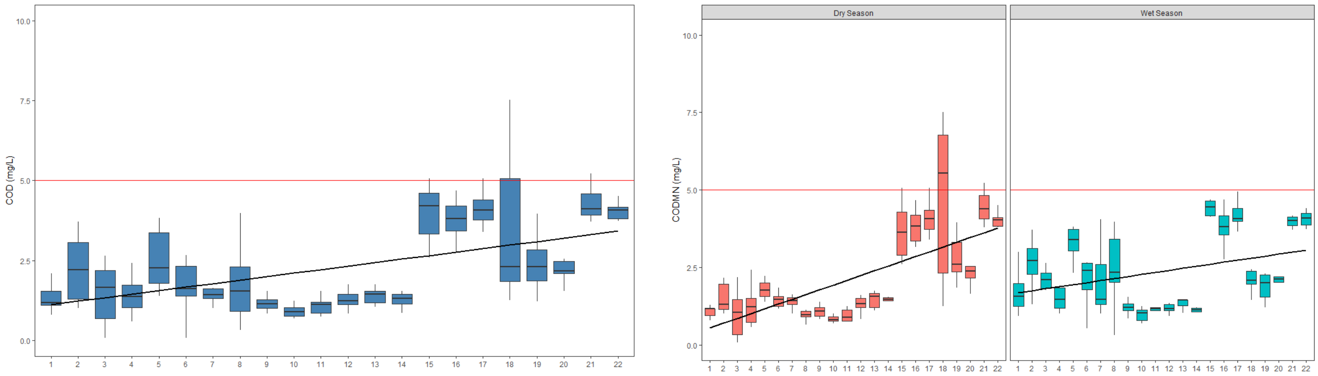


Figure 3.17. Spatial variation in COD (mg/L) at 22 stations along the Mekong (1-17) and Bassac (18-22) Rivers in 2018

Note: The horizontal lines at 5.0 represent the COD target value of the WQGH.

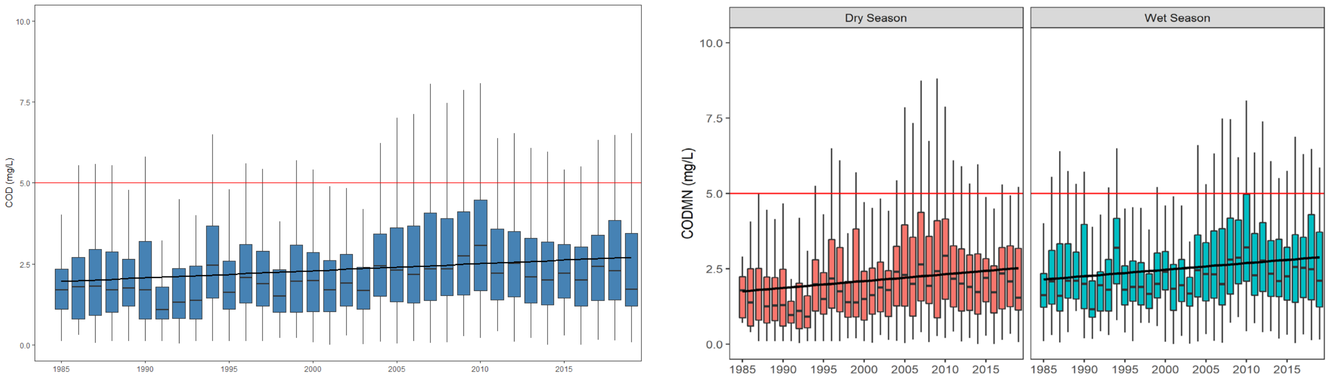


Figure 3.18. Temporal variation in COD (mg/L) in the Mekong River as recorded from 2000 to 2018

Note: The horizontal lines at 5.0 represent the COD target value of the WQGH.

3.2.7 Biochemical Oxygen Demand

In addition to COD (Section 3.2.6), BOD is used for the measurement of the amount of organic and inorganic pollutants in water systems including surface water (Lee et al., 2016). Under the WQMN, BOD is used to determine the relative oxygen requirements by aerobic biological organisms to break down organic pollution. Once collected, samples for BOD analysis can be significantly deteriorated during storage and transportation resulting in readings that may not be representative of the actual conditions of the river (Jouanneau et al., 2014; Pasco et al., 2000). Baird (2017) recommended a maximum holding of 24 hours for water samples to be analysed for BOD. Due to the required holding time and accessibility to certain monitoring stations, BOD measurements were only able to be carried out at 14 stations along the Mekong and Bassac Rivers in 2019. The results of the monitoring (Figure 3.19) shows that spatial trend of BOD followed that of COD (Figure 3.17), with levels slightly high in the Delta region.

Similar to levels recorded for COD, the highest and most variable BOD concentrations were recorded in Takhmao (19). At this station, BOD ranged from 0.78 to 5.87 mg/L, with the average value of 2.47 mg/L. Overall, 33% of the data recorded at Takhmao (18) exceeded the target values for the WQGA (3 mg/L). With the main sources of BOD include domestic and industrial waste effluents (USEPA, 2012b), it is possible that BOD together with COD and TOTP levels at Takhmao (19) were influenced by human-induced activities.

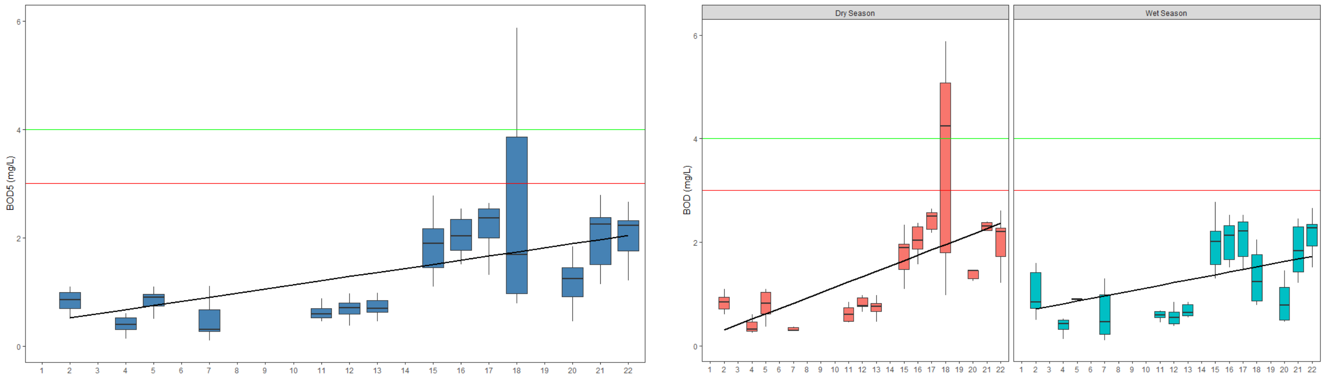


Figure 3.19. Spatial variation in BOD (mg/L) at stations along the Mekong and Bassac Rivers in 2019

Note: The horizontal lines at 3.0 and 4.0 mg/L represent BOD target values of the WQGH and WQGA, respectively.

3.3 Transboundary Water Quality

In its Technical Paper No. 19 "*An assessment of water quality in the Lower Mekong Basin*" (MRC, 2008), five main transboundary areas along the Mekong River were identified for assessing transboundary water quality in the Mekong and Bassac Rivers:

1. **People's Republic of China/Lao PDR** – A water quality monitoring station was established in Houa Khong in 2004 to monitor the boundary between the UMB and the LMB;
2. **Lao PDR/Myanmar** – There is no water quality station in this part of the river since it is remote and sparsely populated;
3. **Thailand/Lao PDR** – There are a number of monitoring stations along this stretch of the Mekong River, including those located in the vicinity of urban areas such as Vientiane, Nakhon Phanom, and Savannakhet. However, none of the stations can be referred to as transboundary stations since they receive run-off from both countries and water is normally sampled in the middle of the river;
4. **Lao PDR/Cambodia** – While not located directly at the border of the two countries, in the past, Pakse and Stung Treng monitoring stations were considered transboundary stations. Data from these stations have been used to assess transboundary effects on water quality;
5. **Cambodia/Viet Nam** – Both the Mekong and the Bassac Rivers have stations that can be used to capture transboundary effects on water quality. On the Mekong side, Kaorm Samnor station in Cambodia and Tan Chau in Viet Nam are located not far from the Cambodian/Vietnamese border. Similarly, Koh Thom station in Cambodia and Chau Doc station in Viet Nam, which are located on the Bassac River, can be considered transboundary stations due to their proximity to the Cambodian/Vietnamese border.

3.3.1 Pakse vs. Stung Treng

Water quality was compared at Pakse and Stung Treng Stations to examine potential transboundary water quality issues in the Mekong River between Lao PDR and Cambodia. For this purpose, six key parameters were selected based on the availability of data to support the assessment. These parameters are NO_{3-2}, NH_4N, TOTN, TOTP, COD, and DO.

Figure 3.20 provides a summary of the comparison of 2019 water quality between the two stations. As can been seen in the figure, slightly higher concentrations of NH_4N were recorded in Stung Treng (9) compared to Pakse (8). The average values of NH_4N at Pakse and Stung Treng were M = 0.03 mg/L (Std. = 0.02) and M = 0.05 mg/L (Std. = 0.04), respectively. However, the result of an independent t-test carried out for Pakse and Stung Treng revealed that the difference was not statistically significant. Therefore, it can be concluded that there is no transboundary water quality issue associated with NH4N.

Likewise, independent t-tests were carried out to determine whether the differences observed in mean concentrations of NO_{3-2}, TOTN, TOTP, COD, and DO at the two stations were statistically significant. The results of an independent t-test reveal that the differences in mean concentrations of NO_{3-2}, TOTN and DO at Pakse were significant, with p-values of less than 0.01 for all three parameters. However, the average values of NO_{3-2} and TOTN at Pakse were higher than those at Stung Treng. The average values of NO_{3-2} at Pakse and Stung Treng were M = 0.35 mg/L (Std. = 0.18) and M = 0.17 mg/L (Std. = 0.08), respectively; for TOTN, these figures were M = 0.61 mg/L (Std. = 0.19) and M = 0.28 mg/L (Std. = 0.07), respectively. These figures indicate that, likely, there was no transboundary water quality issue of nitrogen in both stations in 2019. This is further supported by the generally higher DO concentrations recorded at Stung Treng, with M = 8.26 mg/L (Std. = 0.45), compared to the lower levels recorded upstream at Pakse (M = 6.69 mg/L, Std. = 0.61).

With the average values of 1.15 mg/L (Std. = 0.22) and 1.78 mg/L (Std. = 1.18) recorded at Stung Treng and Pakse, respectively, independent t-test revealed that the difference in mean concentrations at these two stations was not statistically significant.

The average concentration of phosphorous at Stung Treng was about 0.09 mg/L (Std. = 0.12) compared to 0.04 mg/L (Std. = 0.02) recorded at Pakse. The average values were slightly different at the two stations but not statistically significant, with an independent t-test p-value of 0.16.

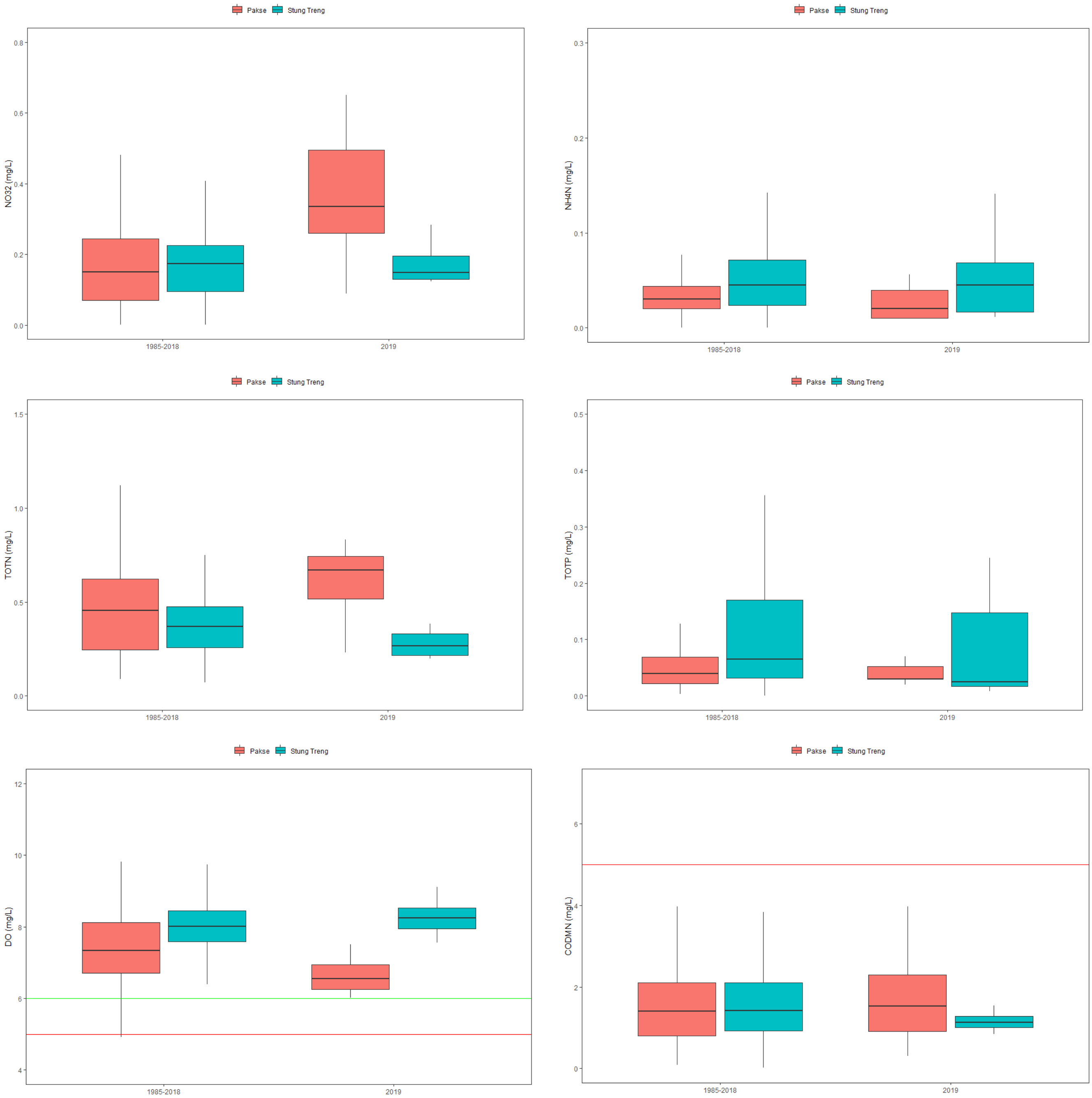


Figure 3.20. Comparisons of 2018 water quality data at Pakse and Stung Treng

3.3.2 Kaorm Samnor vs. Tan Chau

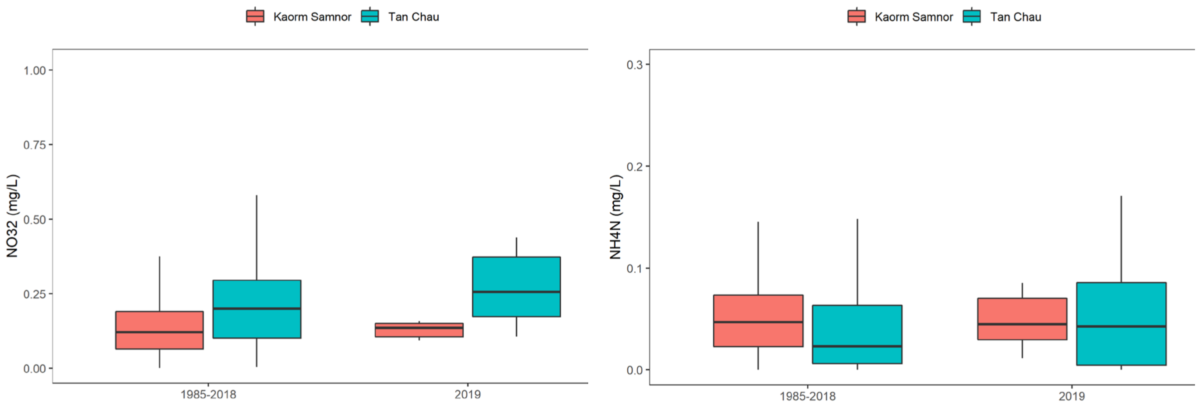
Kaorm Samnor and Tan Chau monitoring stations are located on the Mekong River, with Kaorm Samnor on the Cambodian side and Tan Chau on the Vietnamese side. To assess potential transboundary water quality issues at these two stations, a number of key water quality parameters were compared, including NO_{3-2}, NH_4N, TOTN, TOTP, COD, and DO. The outcomes of these analyses are illustrated in Figure 3.21.

In general, water quality in the Mekong River in 2019 was more degraded in Tan Chau than in Kaorm Samnor, with regard to NO_{3-2}, TOTN and COD. For instance, in 2019, generally higher levels of these parameters were observed at Tan Chau than at Kaorm Samnor, which indicated a possible transboundary water quality issue. Statistically, independent t-tests revealed that there were significant differences in levels of NO_{3-2}, TOTN, and COD at these two stations, with p-values of less than 0.01. In 2019, maximum NO_{3-2} concentrations at Kaorm Samnor (0.26 mg/L) and Tan Chau (0.44 mg/L) did not exceed the target values for WQGH (5 mg/L) and WQGA (5 mg/L), indicating that the water quality of the Mekong River at these stations was still 'good' for the protection of human health and aquatic life when taking into consideration the levels of NO_{3-2}.

In contrast, the maximum COD concentration at Tan Chau (5.06 mg/L) exceeded the target value of WQGH (5 mg/L). The concentration was the only record to have exceeded the target value. Nonetheless, COD levels in Tan Chau have steadily increased since it was first monitored in 1985, with an average concentration of M = 2.10 mg/L (Std. = 0.98). In comparison, in 2019, the average COD concentration at Tan Chau was 3.97 mg/L, which significantly different from that of the 1985, as confirmed by the result of the one-way ANOVA analysis with a p-value of less than 0.01. Therefore, it is important to continue to monitor the levels of COD at Tan Chau to ensure that any prolonged exceedance of COD concentrations is detected in a timely manner.

With DO appearing to be negatively correlated with NO_{3-2}, total N, and COD (Table 3.3), the levels of DO at these two stations were in direct contrast to NO_{3-2}, total N, and COD – higher in Kaorm Samnor (Figure 3.21). The mean concentrations of DO were M = 7.21 mg/L (Std = 0.33) at Kaorm Samnor, and M = 5.4 mg/L (Std = 0.54) at Tan Chau, with a p-value less than 0.01.

In contrast, an independent t-test showed that there was no significant difference between the mean concentration of NH_4N (p-value of 0.82) and the mean concentration of total phosphorus (p-value of 0.46). The mean concentrations of NH_4N were M = 0.06 mg/ (Std = 0.04) at Kaorm Samnor, and M = 0.05 mg/L (Std = 0.05) at Tan Chau. Similarly, the mean concentrations of TOTP were M = 0.10 mg/L (Std = 0.09) at Kaorm Samnor, and M = 0.11 mg/L (Std = 0.11) at Tan Chau.



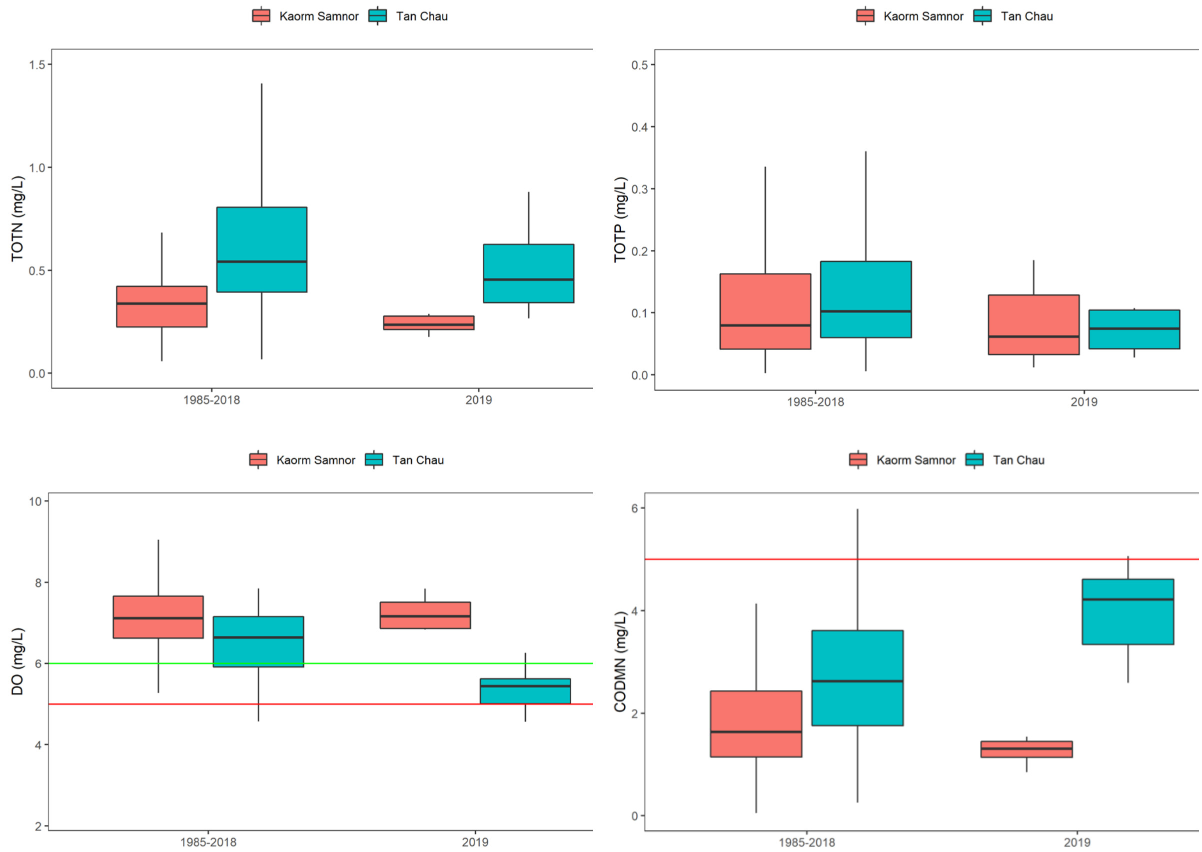


Figure 3.21. Comparisons of water quality data at Kaorm Samnor and Tan Chau

3.3.3 Koh Thom vs. Chau Doc

Similar analyses were carried out for Koh Thom (on the Cambodian side of the river) and Chau Doc (on the Vietnamese side of the river) water quality monitoring stations on the Bassac River to assess potential transboundary water quality issues. Figure 3.22 illustrates comparisons of the concentrations of NO_{3-2}, NH_4H, TOTN, TOTP, DO, and COD recorded at Koh Thom and Chau Doc monitoring stations in 2019.

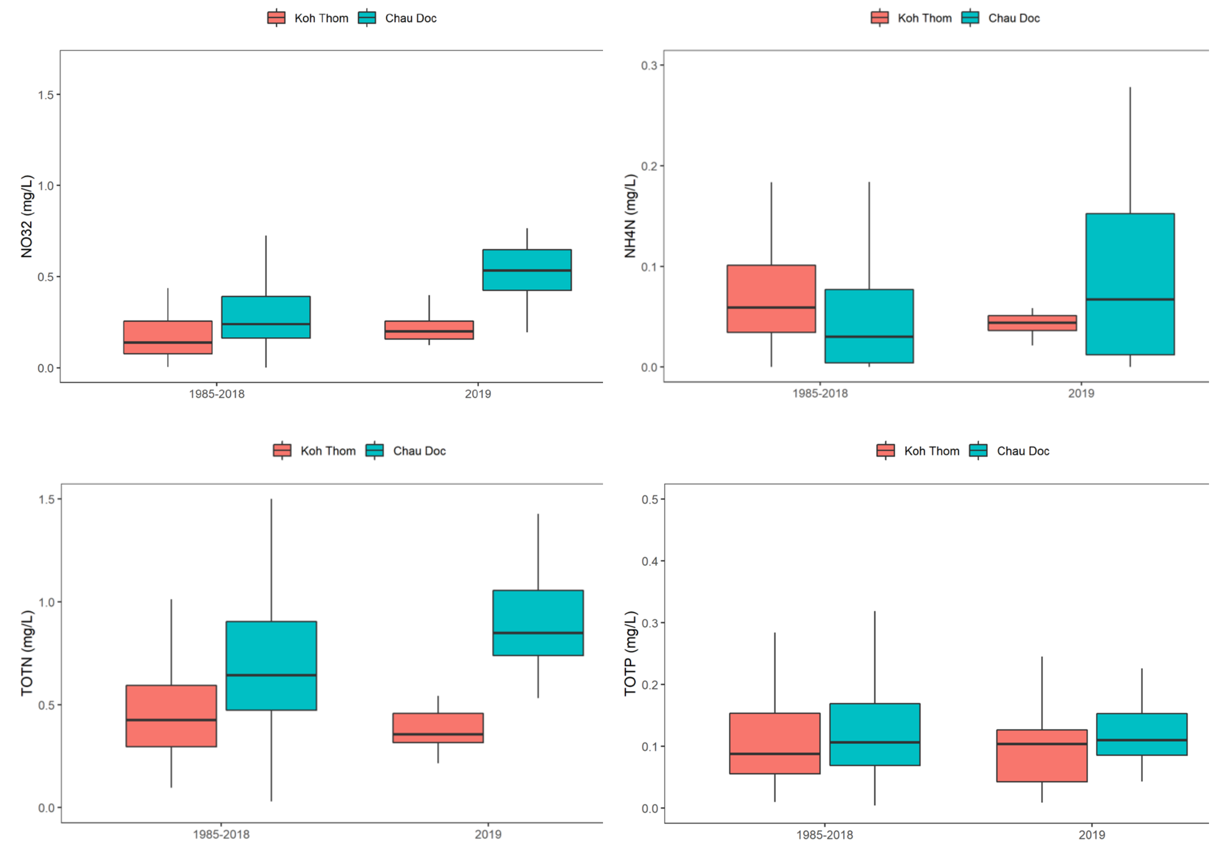
In terms of pollutant levels, Figure 3.22 shows that concentrations of NO_{3-2}, TOTN, and COD were generally higher in the downstream station (Chau Doc) than the upstream station (Koh Thom) in 2019. This is similar to the conditions detected between Kaorm Samnor and Tan Chau (Section 3.3.2) and may reflect pollution discharges between the two stations with respect to these parameters.

The analysis of individual parameters in 2019 for both stations revealed that the observed differences in the mean concentrations of NO_{3-2}, TOTN, COD, and DO were statistically significant, with a p-value of less than 0.01. Mean NO_{3-2} concentrations for Koh Thom and Chau Doc were estimated at 0.23 mg/L (Std = 0.09) and 0.52 mg/L (Std = 0.18), respectively. However, with the maximum concentrations recorded at less than 1 mg/L for both stations, NO_{3-2} levels at these stations were still well below the target values for the WQGH and the WQGA (5 mg/L).

With regard to TOTN, the result of an independent t-test for both stations revealed that the observed difference in the mean concentrations was statistically significant, with a p-value of less than 0.01. Mean TOTN concentrations for Koh Thom and Chau Doc were estimated at 0.37 mg/L (Std = 0.10) and 0.92 mg/L (Std = 0.27), respectively.

The observed difference in the mean concentrations of COD between Koh Thom (M = 2.23 mg/L, Std = 0.42) and Chau Doc (M = 4.26 mg/L, Std = 0.47) was statistically significant, with a p-value of less than 0.01. However, the maximum COD concentrations at the two stations were still below the target value for the WQGH (5 mg/L), indicating that COD did not contribute to any impairment of water quality of the Mekong River with regards to the protection of human health.

In 2019, DO concentrations at Chau Doc were generally lower than those recorded at Koh Thom. A comparison of mean DO concentrations between the two stations revealed that the difference is statistically significant, with a p-value less than 0.01. Mean DO concentrations for Koh Thom and Chau Doc were estimated at 6.74 mg/L (Std = 0.30) and 4.93 mg/L (Std = 0.4), respectively. Since 100% of DO values monitored in Chau Doc were lower than 6 mg/L (target value for WQGH), there is a potential concern with regard to the suitability of the river water at the station of human use. In addition, 50% of the DO data at this station were lower than the target value of WQGA (5 mg/L), indicating water quality impairment with respect to the protection of aquatic life with possible transboundary implications. Therefore, DO levels at Chau Doc should be closely monitored to ensure that non-compliance with the target values of both the WQGH and the WQGA will be detected.



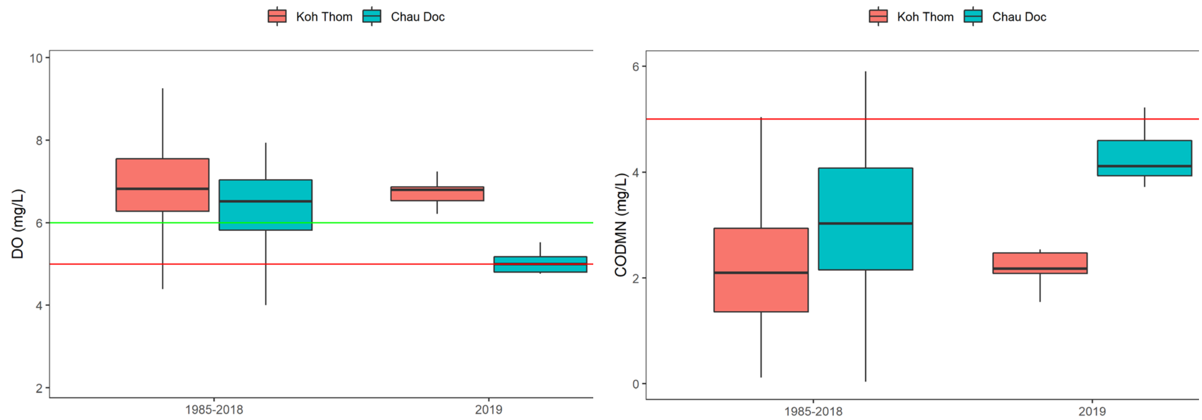


Figure 3.22. Comparisons of water quality data at Koh Thom and Chau Doc

3.4 Water Quality Indices

3.4.1 The Water Quality Index for the Protection of Aquatic Life

In 2019, water quality of the Mekong and Bassac Rivers ranged from ‘moderate’ to ‘excellent’ for the protection of aquatic life (Table 3.4). In 2019, 12 stations were rated as ‘excellent’ for the protection of aquatic life, an increase of 175% from the previous year. In 2018, only four stations were rated as ‘excellent’ for the protection of aquatic life. These were Luang Prabang (3), Vientiane (4), Khong Chiam (7) and Stung Treng (9). In 2019, the rating of water quality for the protection of aquatic life remained ‘excellent’ for these four stations. Additionally, ratings at Houa Khong (1), Chiang Sean (2), Nakhone Phanom (5), Savannakhet (6), Pakse (8), Neak Loung (13), Kraorm Samnor (14) and Koh Thom (20) improved from ‘good’ in 2018 to ‘excellent’ in 2019. The increased ratings were due the reduction in TOTP and NO_{3-2} levels at these stations. For example, at Kraorm Samnor (20), the proportion of sampling occasions that showed TOTP exceeding its target value of 0.13 mg/L (Table 2.4) decreased from 41% in 2018 to 25% in 2019.

In addition to the 12 stations rated as ‘excellent’ for the protection of aquatic life, 7 stations were rated ‘good’: Kratie (10), Kampong Charm (11), Chrouy Changvar (12), Tan Chau (15), My Thuan (16), Takhmao (18), and Koh Khel (19). The ratings at these stations in 2019 were the same as in 2018.

In contrast, in two stations, My Tho (17) and Can Tho (22), there were slight impairments of water quality for the protection of aquatic life; WQI_{al} ratings decreased from ‘good’ in 2018 to ‘moderate’ in 2019. Together with Chau Doc (21), whose water quality also rated as ‘moderate’ in 2018, these three stations were the only ones in which water quality was rated ‘moderate’ for the protection of aquatic life in 2019. At My Tho (17), the main factors that caused the lowering of WQI_{al} ratings from ‘good’ to ‘moderate’ were NO_{3-2} and TOTP. In 2019, sampling showed an exceedance of 83% and 42% for NO_{3-2} and TOTP, respectively, against only 42% and 33% for NO_{3-2} and TOTP, respectively, in 2018. Similarly, at Can Tho (22) the sampling showed exceedance in 2019 were 67% for both NO_{3-2} and TOTP. In 2018, 50% of sampling occasions showed NO_{3-2} concentrations that exceeded the target value for WQI_{al} (Table 2.4), while no exceedance was recorded for TOTP.

From 2008 to 2019, annual ratings for WQI_{al} remained relatively at the same levels, fluctuating between 'good' and 'excellent' for stations located in the upper and middle parts of the Mekong River (1–14). Except for 2017, where WQI_{al} at Tan Chau was rated 'excellent', annual ratings for the protection of aquatic life at both Tan Chau (15) and My Thuan (16) had been consistent ('good'). At My Tho (17), the annual WQI_{al} ratings was mostly 'moderate' from 2008 to 2019, with the only exception being in 2012 and 2018, where water quality was rated 'good' for the protection of aquatic life, and in 2016, where water quality was rated 'poor' for the protection of aquatic life. In the Cambodia's section of the Bassac River, despite the increase of TOTP levels at some stations in 2019 (Section 3.2.4.2) water quality remained 'good' for the protection of aquatic life.

Table 3.4. Water quality class of the Mekong River (1-17) and Bassac River (18-22) for the protection of aquatic life 2008-2019

No.	Station names	Countries	Class											
			2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
1	Houa Khong	Lao PDR	A	A	A	A	B	B	B	B	B	B	B	A
2	Chiang Saen	Thailand	A	B	B	A	B	B	A	B	B	B	B	A
3	Luang Prabang	Lao PDR	A	A	B	A	A	B	B	B	A	B	A	A
4	Vientiane	Lao PDR	A	A	A	A	A	B	B	A	A	A	A	A
5	Nakhon Phanom	Thailand	B	A	B	A	B	B	A	A	B	B	B	A
6	Savannakhet	Lao PDR	A	A	A	A	A	B	B	B	A	A	B	A
7	Khong Chiam	Thailand	B	A	A	A	A	B	A	A	A	B	A	A
8	Pakse	Lao PDR	A	A	A	A	A	B	B	B	A	A	B	A
9	Stung Trieng	Cambodia	B	B	B	B	B	B	B	B	B	A	A	A
10	Kratie	Cambodia	B	B	B	B	B	B	B	B	A	B	B	B
11	Kampong Cham	Cambodia	B	B	B	B	B	B	A	B	A	A	B	B
12	Chrouy Changvar	Cambodia	B	B	B	B	B	B	B	B	A	A	B	B
13	Neak Loung	Cambodia	B	B	B	B	B	B	B	B	A	A	B	A
14	Kaorm Samnor	Cambodia	B	B	B	B	B	B	B	B	A	A	B	A
15	Tan Chau	Viet Nam	B	B	B	B	B	B	B	B	B	A	B	B
16	My Thuan	Viet Nam	B	B	B	B	B	B	B	B	B	B	B	B
17	My Tho	Viet Nam	C	C	C	C	B	C	C	C	D	C	B	C
18	Takhmao	Cambodia	B	B	B	B	B	B	B	B	B	B	B	B
19	Koh Khel	Cambodia	B	B	B	B	B	B	B	B	B	B	B	B
20	Koh Thom	Cambodia	B	B	B	B	B	B	A	B	B	B	B	A
21	Chau Doc	Viet Nam	B	B	B	B	B	B	B	B	B	B	C	C
22	Can Tho	Viet Nam	B	C	C	C	C	C	B	B	B	B	B	C

A – High **B – Good** **C – Moderate** **D – Poor** **E – Very Poor**

3.4.2 Water Quality Index for the Protection of Human Health

The analysis of the 2019 water quality data using the Water Quality Index for Human Health Acceptability (WQI_{hh}) reveals that the water quality of the Mekong and Bassac Rivers for the protection of human health is still of good quality, with all stations rated as either ‘good’ or ‘excellent’ (Table 3.5).

Of the 22 stations located in the Mekong and Bassac Rivers, 18 were rated as ‘excellent’ for the protection of human health in 2018, while the other 4 were rated as ‘good’. Among the 18 stations rated as ‘excellent’, 15 were located along the Mekong River, while 3 were located in the Bassac River. The remaining 4 stations, which were rated as ‘good’ for the protection of human health, were Nakhone Phanom (5) and Tan Chau (15) in the Mekong River, and Takhmao (18) and Chau Doc (21) in the Bassac River.

With respect to the protection of human health, water quality of the Mekong and Bassac Rivers improved slightly in 2019 compared to 2018, where 7 stations rated were higher than in the previous year (Table 3.5): i.e. Houa Khong (1), Chiang Sean (2), Luang Prabang (3), Khong Chiam (7), My Thuan (16), My Tho (17), and Can Tho (22). The improvement was due to the reduction in COD levels; only 1.5% of the monitoring missions showed an exceedance of the target values of 5 mg/L (Table 2.6). In comparison, about 6% of monitoring occasions showed COD concentrations greater than 5 mg/L in 2018.

Historically, water quality of the Mekong and Bassac Rivers has been acceptable for human health with ratings of mostly 'good' or 'excellent'. The only exceptions were recorded in 2009 (Tan Chau, My Tho, and Chau Doc), 2010 (My Thuan, My Tho, Chau Doc, and Can Tho) and 2014 (Houa Khong, Savannakhet, and Takhmao), when a few stations were rated as 'moderate' (Table 3.5).

Table 3.5. Water quality class of the Mekong River (1-17) and Bassac River (18-22) for the protection of human health 2008-2019

No.	Station Names	Countries	Class											
			2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
1	Houa Khong	Lao PDR	A	A	B	A	B	B	C	A	A	A	B	A
2	Chiang Saen	Thailand	B	B	B	A	B	B	B	B	B	B	B	A
3	Luang Prabang	Lao PDR	A	A	B	A	B	A	B	B	B	A	B	A
4	Vientiane	Lao PDR	A	A	B	A	B	B	B	B	B	A	A	A
5	Nakhon Phanom	Thailand	B	B	B	B	B	B	B	B	B	B	B	B
6	Savannakhet	Lao PDR	A	A	A	A	B	B	C	B	B	A	A	A
7	Khong Chiam	Thailand	B	B	B	A	B	B	B	B	B	B	B	A
8	Pakse	Lao PDR	B	A	A	A	A	B	A	B	B	A	A	A
9	Stung Trieng	Cambodia	B	A	A	A	A	A	A	A	A	A	A	A
10	Kratie	Cambodia	B	A	A	A	A	A	A	A	A	A	A	A
11	Kampong Cham	Cambodia	B	A	A	A	A	A	A	B	A	A	A	A
12	Chrouy Changvar	Cambodia	B	A	A	A	A	A	A	A	A	A	A	A
13	Neak Loung	Cambodia	B	A	A	A	A	A	A	B	A	A	A	A
14	Kaorm Samnor	Cambodia	B	A	A	A	B	A	A	B	A	A	A	A
15	Tan Chau	Viet Nam	B	C	B	B	A	A	A	A	A	A	B	B
16	My Thuan	Viet Nam	B	B	C	A	A	B	A	A	A	B	B	A
17	My Tho	Viet Nam	B	C	C	B	B	B	B	A	B	B	B	A
18	Takhmao	Cambodia	B	A	A	A	A	B	C	A	B	A	B	B
19	Koh Khel	Cambodia	A	A	B	A	B	B	A	B	A	A	A	A
20	Koh Thom	Cambodia	B	A	A	A	B	B	A	A	A	A	A	A
21	Chau Doc	Viet Nam	B	C	C	B	B	A	A	A	A	B	B	B
22	Can Tho	Viet Nam	B	B	C	B	A	A	A	A	A	A	B	A

A – High	**B – Good**	**C – Moderate**	**D – Poor**	**E – Very Poor**

3.4.3 Water Quality Index for Agricultural Use

The level of water quality impairment for agricultural use was assessed using the MRC Water Quality Indices for Agricultural Use. While two indices were adopted by the MRC to assess the level of impairment of water quality for general irrigation and paddy rice irrigation, all indices for agricultural use can be assessed against threshold values for EC (Table 2.8).

An analysis of EC data from 2019 revealed that with the exception of the maximum value of 91 mS/m recorded in Vientiane (4) in November (Section 3.1), all EC values fell within the guideline value for the Water Quality Index for General Irrigation Use of 70 mS/m. With only one value exceeding the target value for general irrigation restriction (70 mS/m), water quality of the Mekong and Bassac Rivers was rated 'no restriction' for both generation irrigation and paddy rice irrigation. However, it should be noted that the monitoring and measurement of EC under the WQGH since 2005 have been carried out during the low tide only in the Mekong Delta (Section 3.2.2). Therefore, care should be taken to ensure that water for general and paddy rice irrigation in the Mekong Delta be used during low tide with continuous monitoring of salinity levels to ensure the maintenance of the 'no restriction' use of the Mekong and Bassac River water.

From 2008 to 2019, water quality of the Mekong and Bassac Rivers remained suitable for both general and paddy rice irrigation purposes, with the annual Water Quality Index for Agricultural Use ($WQI_{ag)}$ ratings of mostly 'no restriction'. The only exception was in 2016 at My Tho (17), which may have been affected by prolonged seawater intrusion (Table 3.6).

Table 3.6. Water quality class of the Mekong River (1-17) and Bassac River (18-22) for agricultural use for 2008-2019

No.	Station Names	Countries	Class											
			2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
1	Houa Khong	Lao PDR	A	A	A	A	A	A	A	A	A	A	A	A
2	Chiang Saen	Thailand	A	A	A	A	A	A	A	A	A	A	A	A
3	Luang Prabang	Lao PDR	A	A	A	A	A	A	A	A	A	A	A	A
4	Vientiane	Lao PDR	A	A	A	A	A	A	A	A	A	A	A	A
5	Nakhon Phanom	Thailand	A	A	A	A	A	A	A	A	A	A	A	A
6	Savannakhet	Lao PDR	A	A	A	A	A	A	A	A	A	A	A	A
7	Khong Chiam	Thailand	A	A	A	A	A	A	A	A	A	A	A	A
8	Pakse	Lao PDR	A	A	A	A	A	A	A	A	A	A	A	A
9	Stung Trieng	Cambodia	A	A	A	A	A	A	A	A	A	A	A	A
10	Kratie	Cambodia	A	A	A	A	A	A	A	A	A	A	A	A
11	Kampong Cham	Cambodia	A	A	A	A	A	A	A	A	A	A	A	A
12	Chrouy Changvar	Cambodia	A	A	A	A	A	A	A	A	A	A	A	A
13	Neak Loung	Cambodia	A	A	A	A	A	A	A	A	A	A	A	A
14	Kaorm Samnor	Cambodia	A	A	A	A	A	A	A	A	A	A	A	A
15	Tan Chau	Viet Nam	A	A	A	A	A	A	A	A	A	A	A	A
16	My Thuan	Viet Nam	A	A	A	A	A	A	A	A	A	A	A	A
17	My Tho	Viet Nam	A	A	A	A	A	A	A	A	B	A	A	A
18	Takhmao	Cambodia	A	A	A	A	A	A	A	A	A	A	A	A
19	Koh Khel	Cambodia	A	A	A	A	A	A	A	A	A	A	A	A
20	Koh Thom	Cambodia	A	A	A	A	A	A	A	A	A	A	A	A
21	Chau Doc	Viet Nam	A	A	A	A	A	A	A	A	A	A	A	A
22	Can Tho	Viet Nam	A	A	A	A	A	A	A	A	A	A	A	A

A – No Restriction
B – Some Restriction
C – Severe Restriction

3.5 Water Quality of Selected Tributaries

3.5.1 Status of Water Quality

In 2019, the WQGH carried out water quality monitoring of 26 tributaries across the LMB (Annexes A and B). In addition to reporting the water quality status and trends of the Mekong and Bassac Rivers, this report also provides an assessment of water quality at 8 tributary stations[4] covering 7 tributaries of the Mekong River located in the upper, middle, and lower section of the LMB. These 7 tributaries (Figure 2.1 and Table 2.1) and their corresponding eight water quality monitoring stations are as follows:

[4] Due to the time constraint in the preparation of this report, only the status and trends of water quality at 6 tributaries are included in this report.

- Nam Ou River monitored at **Ban Hat Kham Water Quality Monitoring Station (23)** in Lao PDR;
- Mae Kok River monitored at **Chiang Rai Water Quality Monitoring Station (24)** in Thailand;
- Houay Mak Hiao monitored at **Houay Mak Hia Monitoring Station (25)** in Lao PDR;
- Mun River monitored at **Mun-Khong Chiam Monitoring Station (26)** in Thailand;
- Se San River monitored at **Pleicu Water Quality Monitoring Station (27)** in Viet Nam and **Lumphat Water Quality Monitoring Station (28)** in Cambodia;
- Sre Pok River monitored at **Ban Don Water Quality Monitoring Station (29)** in Viet Nam;
- Tonle Sap River monitored at **Prek Kdam Water Quality Monitoring Station (30)** in Cambodia.

The 2019 water quality status of these tributaries in terms of pH, TSS, EC, NO_{3-2}, NH_4N, TOTP, DO, and COD are summarized in Sections 3.5.1.1 and 3.5.1.6.

3.5.1.1 pH

In 2019, pH levels at all 8 selected tributary stations were well within the target ranges (6–9) of the WQGH and WQGA. Collectively, the lowest pH concentration was recorded at Houay Mak Hiao in September 2021 (pH of 6.01). Spatial comparison of pH levels across the 8 stations (Figure 3.23a) revealed that pH levels did not vary from station to station. Similar to the levels recorded in the mainstream, pH levels were slightly alkaline, with about 74% of the data recorded as higher than pH 7. Except for Houay Mak Hiao (25), pH at these tributaries did not vary greatly between dry and wet seasons. At Houay Mak Hiao (25), wet season pH levels may have been influenced by anthropogenic factors, such as nutrient and sewage runoff during rainfall event (Khatri & Tyagi, 2015).

Compared to historical data (1985–2018) (Figure 3.23c), pH levels of Mae Kok and Nam Ou rivers slightly decreased in 2019, as monitored at Ban Hat Kham (23) and Chiang Rai (24). Both tributaries are in the upper part of the basin. At Chiang Rai (24), average pH levels decreased from about 7.5 in 1985 to about 7.2 in 2019, whereas at Ban Hat Kham (24), average pH levels also decreased from about 7.7 to 7.3. However, the changes at the two stations were not statistically significant, with p-values of the one-way ANOVA test greater than 0.05.

In other tributaries, pH levels increased in 2019 when compared to historical data with Pleicu (27) recorded the highest increase, from about 6.8 during period of 2004–2018 to about 7.24 in 2019. The increase between the two-time periods was statistically significant, with a p-value of less than 0.01.

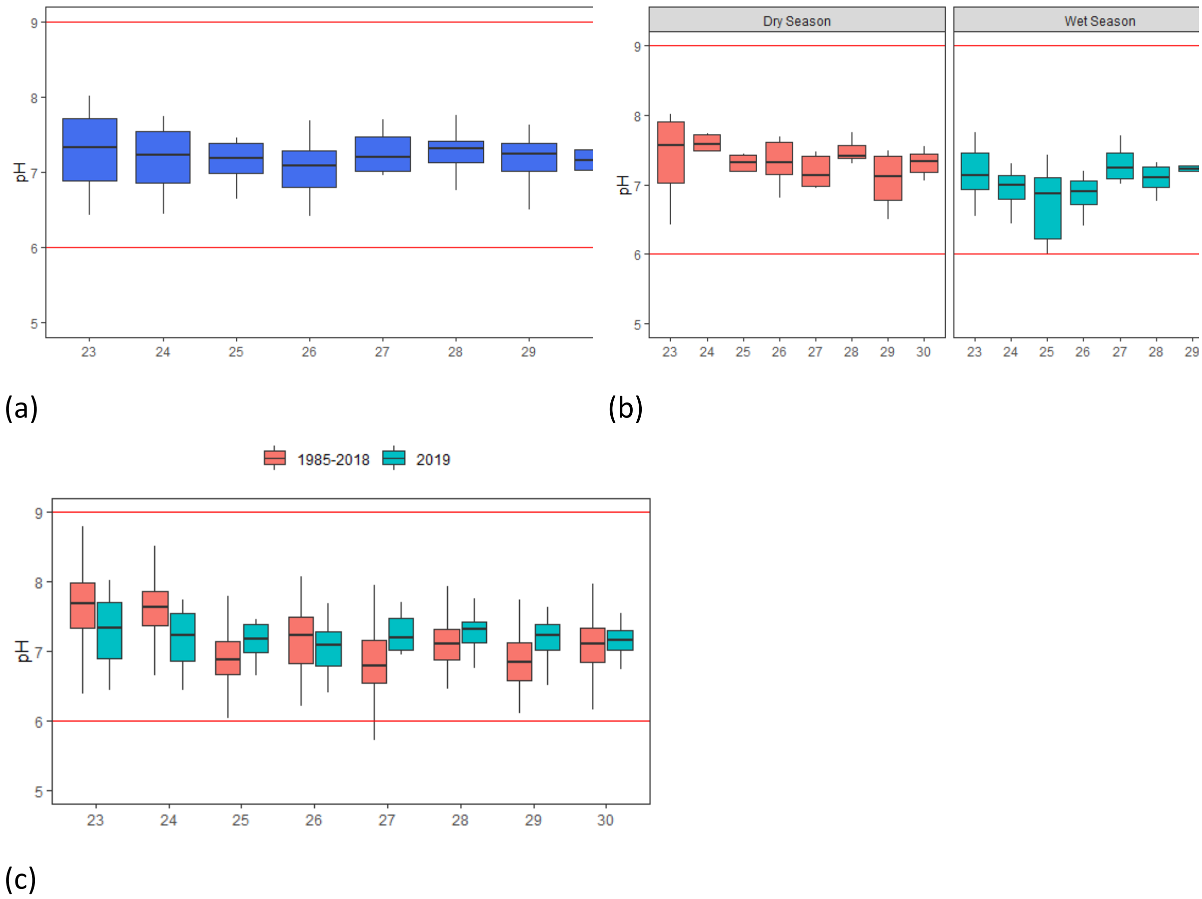


Figure 3.23. Spatial and temporal distribution of pH levels in key tributaries of the Mekong River in 2019

3.5.1.2 Total Suspended Solids

TSS levels in these tributaries vary greatly from station to station. Levels were slightly variable at Chiang Rai (24), Houay Mark Hiao (25), Ban Don (29), and Prek Kdam (29): Prek Kdam recorded the largest TSS range (22 mg/L to 187 mg/L). At Mun (Khong Chiam) (26) and Pleicu (27), monthly TSS levels were relatively constant throughout 2019, with TSS levels, ranging from 1.8 mg/L to 69.3 mg/L, and 9 mg/L to 30 mg/L, respectively. with the datasets that were less variable compared to those of other stations, TSS levels at both Mun (Khong Chiam) (26) and Pleicu (27) were not significantly influenced by season factors, but may have been influenced by factors such as a high proportion of plant cover and human-induced alteration of the river channel, which have been proven to suppress instream TSS levels (Kummu & Varis, 2007; Ly et al., 2020). In contrast, TSS levels at Ban Hat Kham (23) Chiang Rai (24), Houay Mak Hiao (25), and Prek Kdam (30) were influenced by seasonal factors, i.e. high wet season concentrations but low concentrations during the dry season. The patterns at these stations mirrored those recorded in the Mekong mainstream, in particular along the stations located in the upper part of the basin, whose topography is dominated by mountainous terrains and steep slopes that are susceptible to erosion and soil detachment during the wet season (Chaplot & Poesen, 2012; Ly et al., 2020; Ribolzi et al., 2017; Suif et al., 2016).

Compared to historical data, TSS levels became less variable in 2019. Historically, the highest TSS concentrations at stations Ban Hat Kham (23) and Chiang Rai (24) were over 2,000 mg/L.

In 2019, the highest concentration recorded among the six tributary stations assessed as part of this study was 243.8 mg/L at Chiang Rai (24) in August 2019. The changes in instream TSS levels in these tributaries may have been influenced by human alteration of stream channel preventing tributaries from transporting sediment into the Mekong River. Prior studies of the Mekong sediment flux have linked the reduction of instream sediment levels to hydropower operations (Kummu et al., 2010; Lu & Siew, 2006; Ly et al., 2020).

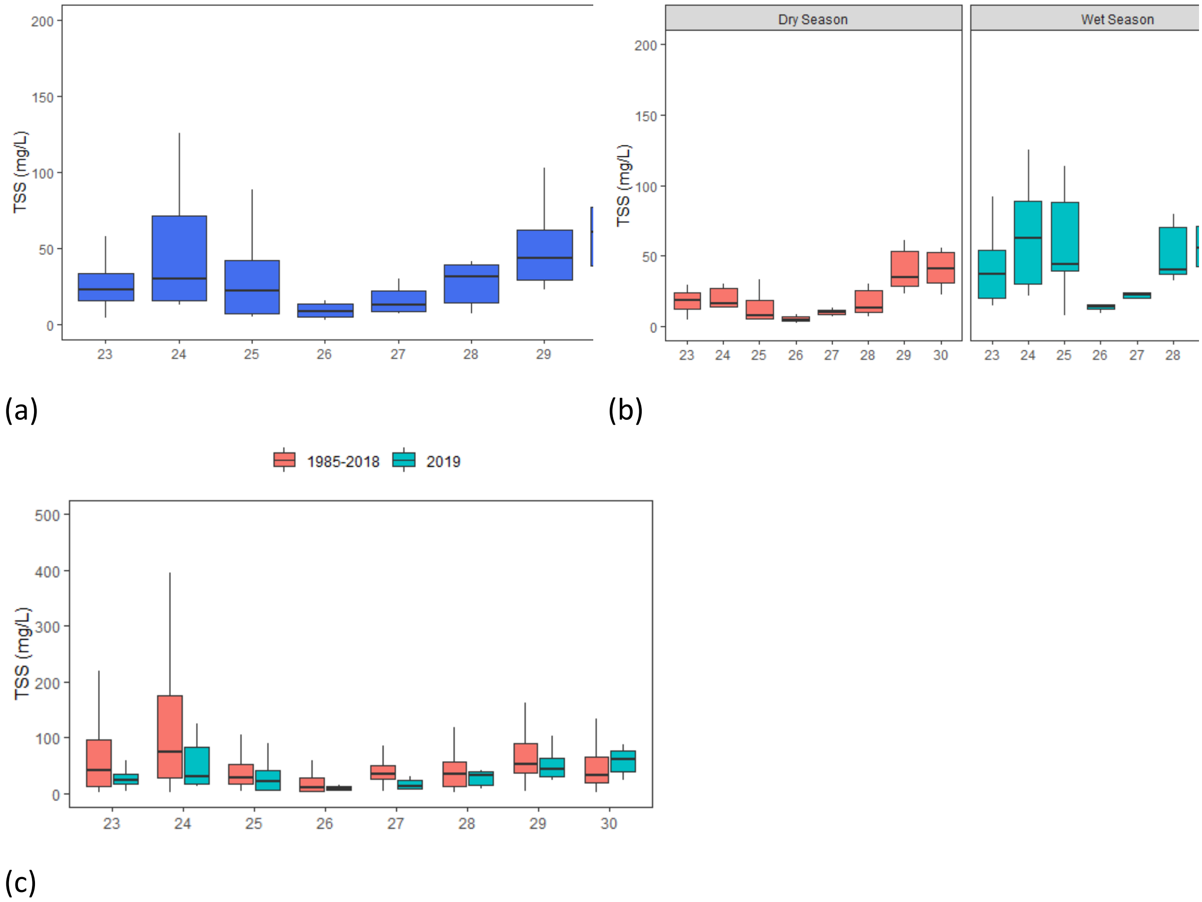
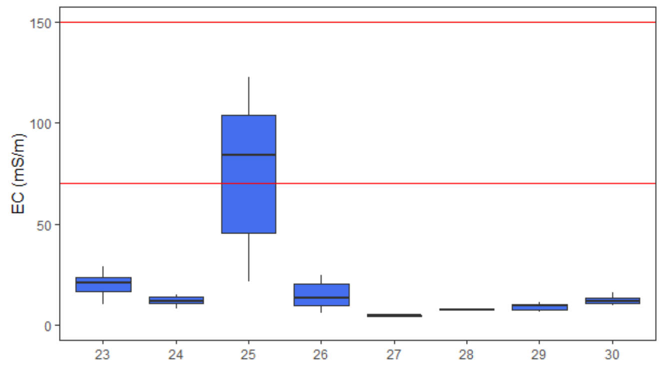


Figure 3.24. Spatial and temporal distribution of TSS levels in key tributaries of the Mekong River in 2019

3.5.1.3 Electrical Conductivity

With the exception of levels recorded at Houay Mak Hiao (25), EC levels in the tributaries were similar to the levels recorded in the Mekong mainstream, rarely exceeding 30 mS/m during both the wet and dry season (Figures 3.25a and 3.25b). This further provides evidence that the Mekong River and its tributaries generally have low EC levels. Therefore, levels beyond the normal condition are likely influenced by anthropogenic factors, including industrial and domestic effluents that increase the presence of inorganic dissolved solids of both positive ions (i.e. Ca^{2+}, Na^{+}, Mg^{2+}, etc.) and negative ions (i.e. SO_4^{2-}, PO_4^{2-}, Cl^{-}, etc.) (USEPA, 2014a). This may have been the case for the levels observed at Houay Mak Hiao (25), a tributary of the Mekong River that transports effluents and runoff from Vientiane urban area through Thaluang Marsh before discharging into the Mekong River (Kyophilavong, 2008; Mackenzie & Simpson, 2009; Olsson, 2010). At Houay Mak Hiao (25), the maximum EC concentration was recorded at 182 mS/m in July 2019. This value is higher than the upper target value of the

WQGH (i.e. 150 mS/m) (Table 3.1). The high EC levels at Houay Mak Hiao were e consistent with the high levels of other water quality parameters including NO_{3-2} (Section 3.5.1.4).



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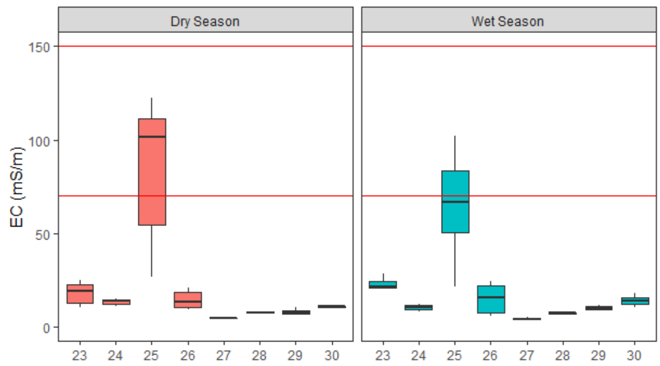

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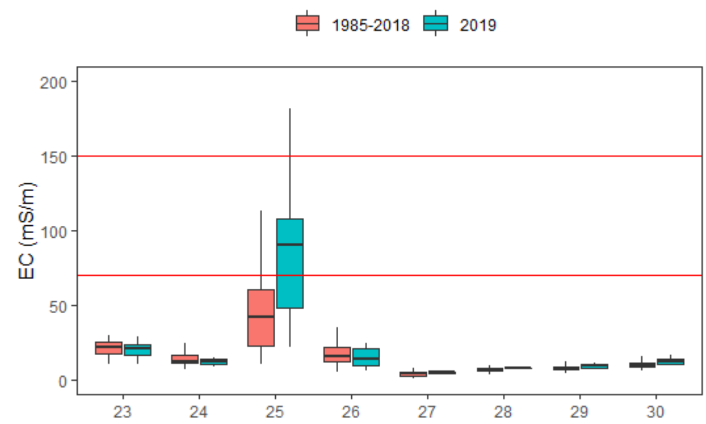

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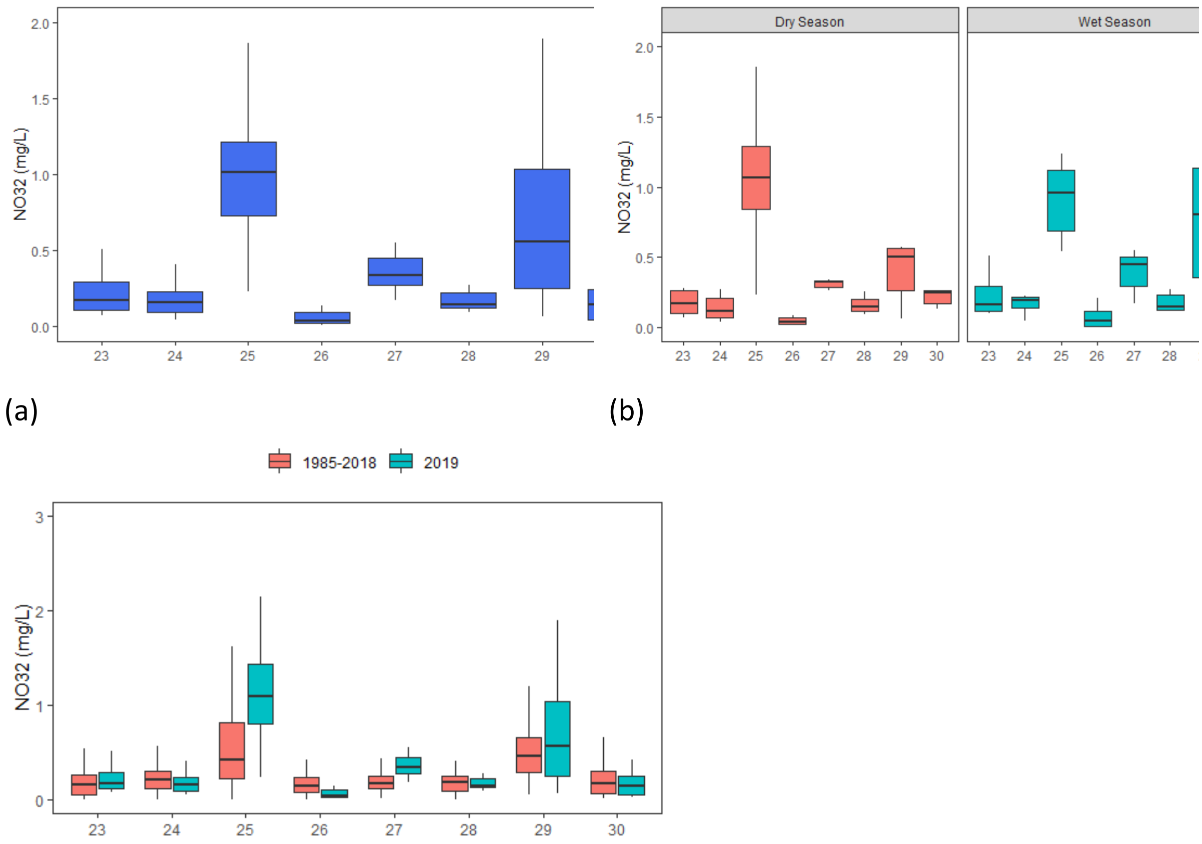
Figure 3.25. Spatial and temporal distribution of EC levels in key tributaries of the Mekong River, 2019

3.5.1.4 Nutrients

NO_{3-2} levels at the eight tributary stations included in this report were highly variable, with levels at Ban Hat Kham (23), Chiang Rai (24), Mun (Khong Chiam) (26), Pleicu (27), Lumphat (28), and Prek Kdam (30) remained relatively low (Figure 3.26a). The maximum NO_{3-2} concentration recorded at these stations in 2019 was 0.65 mg/L at Ban Hat Kham (24) in December, while the minimum concentration was 0.01 mg/L recorded at Mun (Khong Chiam) (26) in July. At Houay Mak Hiao (25) and Ban Don (29), levels were highly variable, ranging from 0.23 mg/L to 2.65 mg/L for Houay Mak Hiao (25), and 0.07 mg/L to 1.89 mg/L for Ban Don (29). At Houay Mak Hiao (25), NO_{3-2} did not differ significantly during the wet (M = 1.12 mg/L, Std. = 0.57) and dry (M = 1.32 mg/L, Std. = 0.84) seasons, with t-test p-value for wet and dry season 2019 greater than 0.05. This indicates NO_{3-2} levels at this station were not influenced by the seasonal factor and that elevated levels may have been associated with direct urban effluents. In contrast, wet season NO_{3-2} levels (M = 0.84 mg/L, Std. = 0.65) at Ban Don (29) were statistically higher than those of the dry season (M = 0.58 mg/L, Std. = 0.41), with the t-test p-value between two seasons calculated at less than 0.01. This indicates the

NO_{3-2} levels at Ban Don were influenced by runoff from agricultural areas during the wet season.

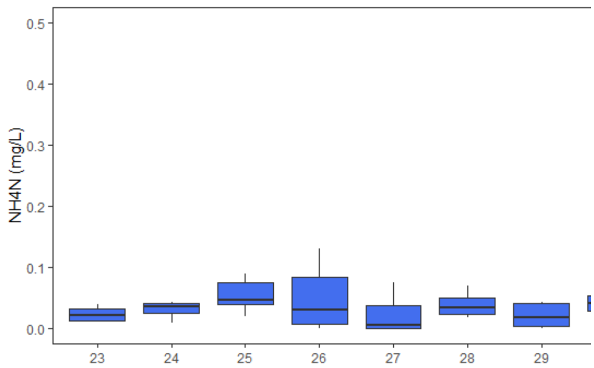
On a temporal scale (Figure 3.26c), the 2019 NO_{3-2} levels appear to be similar to those recorded historically, with the only exception being at Houay Mak Hiao (25) and Ban Don (29), where levels had increased slightly. At Houay Mak Hiao (25), NO_{3-2} levels increased from an average of 0.81 mg/L historically to 1.22 mg/L in 2019. The result of one-way ANOVA analysis revealed that the difference was statistically significant, with a p-value less than 0.05. The increased NO_{3-2} levels at Houay Mak Hiao were likely due to an increase in urban areas and population in Vientiane, which in turn likely resulted in increased domestic and urban effluents being discharged into Houay Mak Hiao. Previous studies have shown significant correlation between urban area and instream nitrate levels (Poor & McDonnell, 2007; Poudel et al., 2010), including studies surrounding Vientiane urban areas (Ly et al., 2020; Okamoto et al., 2014). The increased levels at Ban Don (29) were likely associated with the intensive agriculture production in the region where the fertile soils and cooler climate were found to be suitable for coffee plantation (D'Haeze et al., 2017), resulting in the conversion of forest areas for other purposes including agriculture (Hung et al., 2020). However, studies have shown that runoff from agricultural areas can increase instream NO_{3-2} levels (Liu et al., 2018; Ly et al., 2020; Oeurng et al., 2016).



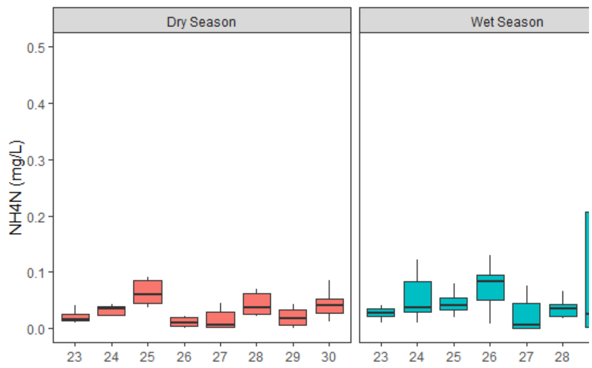
(c)

Figure 3.25. Spatial and temporal distribution of NO_{3-2} levels in key tributaries of the Mekong River in 2019

NH4N levels were relatively low across the eight tributary stations (Figure 3.27a), with the exception of levels recorded at Ban Don (29) during the wet season (Figure 3.27b). Similar to NO_{3-2}, sources of instream NH_4N include runoff from agricultural areas, domestic and industrial wastewater discharge, and runoff from animal manure storage areas (USEPA, 2014b). NH4N levels at Ban Don (29) in 2019 appear to mirror those of NO_{3-2} (Figure 3.26) and are highly variable during the wet season, with concentrations ranging from 0.01 to 0.50 mg/L. Similar to NO_{3-2}, instream NH_4N concentrations at Ban Don (29) were likely influenced by runoff from agricultural areas.



(a)



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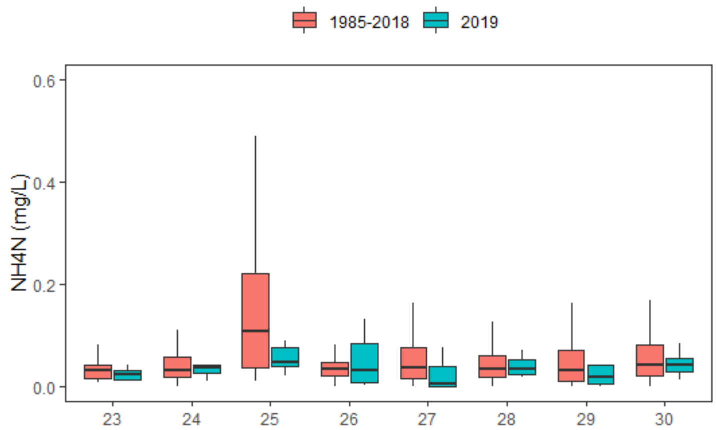

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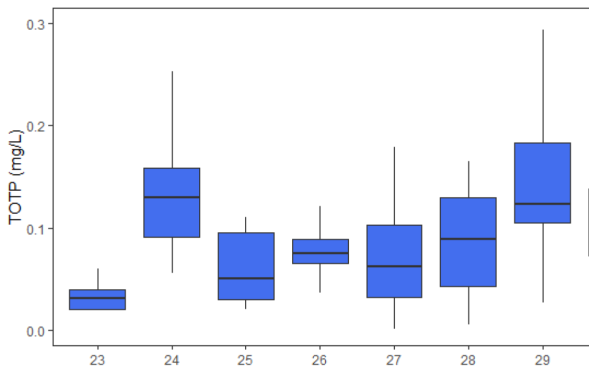
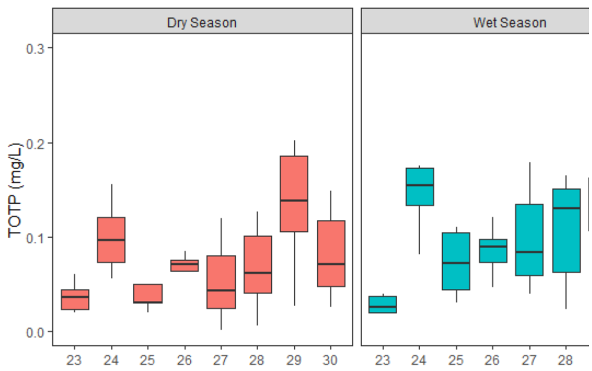
Figure 3.26. Spatial and temporal distribution of NH4N levels in key tributaries of the Mekong River in 2019

In 2019, TOTP levels did not vary greatly from station to station (Figure 3.28a) with average concentrations ranging from 0.03 mg/L at Ban Hat Kham (24) to 0.14 mg/L at Ban Don (29). The highest concentration recorded in 2019 was 1.01 mg/L at Houay Mak Hiao (25) in December, while the lowest was recorded at Lumphat (28), at 0.01 mg/L in January. The analysis of TOTP at the seasonal time scale (Figure 3.28b) revealed that instream TOTP concentrations at these tributary stations were not influenced by seasonal factors. The results of the t-test analyses performed at all stations further support that the mean differences of wet and dry season at these stations were not statistically significant, with p-values greater than 0.05. Hence, TOTP at these stations was likely influenced by both natural processes and human activities (Abell et al., 2011; Vaccari, 2009). Under natural processes, weathering of rock and soil containing inorganic phosphate and mineralization of organic phosphate to inorganic phosphorus have been linked to the fluctuation of instream TOTP (Bünemann et al., 2007; Maavara et al., 2015; Prentice et al., 2019; Stewart & Tiessen, 1987). Effluents and from urban and agricultural areas have also been linked to the fluctuation of TOTP (Arheimer & Lidén, 2000; Gu et al., 2019; Jarvie et al., 2006; Powers et al., 2016).

Compared to the historical records (Figure 3.28c), TOTP increased slightly at Houay Mak Hiao (25) and Ban Don (29) while remaining relatively constant for the remaining tributary stations. At Houay Mak Hiao (25), the average TOTP concentration increased to 0.15 mg/L in 2019 compared to the historical average of 0.12 mg/L. Similarly, the average TOTP concentration at Ban Don (29) increased to 0.14 mg/L compared to the historical average of 0.12 mg/L. The results of one-way ANOVA analyses at both stations, however, revealed that the increases were not statistically significant, with p-values greater than 0.05.



(a)



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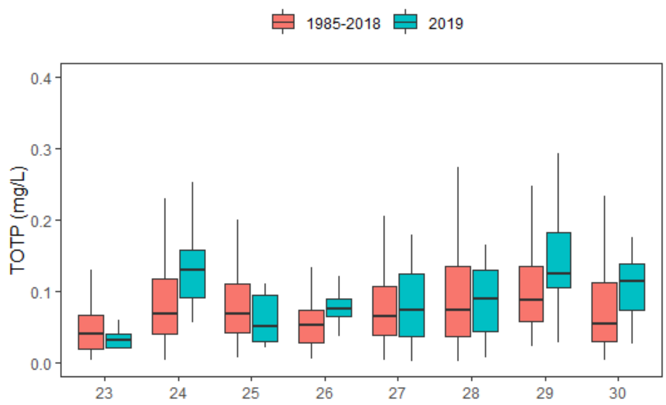


(c)

Figure 3.27. Spatial and temporal distribution of TOTP levels in key tributaries of the Mekong River in 2019

3.5.1.5 Dissolved Oxygen

In 2019, DO levels varied from station to station, yet Chiang Rai (24) and Lumphat (28) recorded all DO concentrations greater than the target value of WQGH (6 mg/L) (Figure 3.29a). Among the eight tributary stations, the lowest DO concentration was recorded at Mun (Khong

Chiam) (26) at 4.4 mg/L in July 2019 and the highest concentration (8.7 mg/L) was recorded at Chiang Rai (24) in December 2019. Despite high nutrients levels (Section 3.5.1.4), DO at Houay Mak Hiao (25) continued to be suitable for the protection of aquatic life, with DO concentrations ranging from 5.5 to 7.4 mg/L, which were higher than the target value of WQGA (5 mg/L). The results indicate that the water at Houay Mak Hiao was well aerated in 2019 despite high levels of nutrients.

At Ban Don (29), another tributary station with high levels of nutrients (Section3.5.1.4), about 20% of the DO data fell below the target value of WQGA (5 mg/L). However, based on 2019 data, Pleicu (27) had the most DO impaired station, where none of the concentrations reached the target value of WQGH (6 mg/L). In addition, 42% of the DO data recorded at Pleicu (27) were below the target value of WQGA (5 mg/L). The impairment of DO at Pleicu (27) did not appear to be related to nutrient levels, since concentrations for $NO_{3\text{-}2}$, NH_4N, and TOTP were relatively low in 2019 (Section 3.5.1.4). In addition, the analyses of 2019 COD data (Section 3.5.1.6) also reveal relatively low COD levels at Pleicu (27) (Figure 3.30).

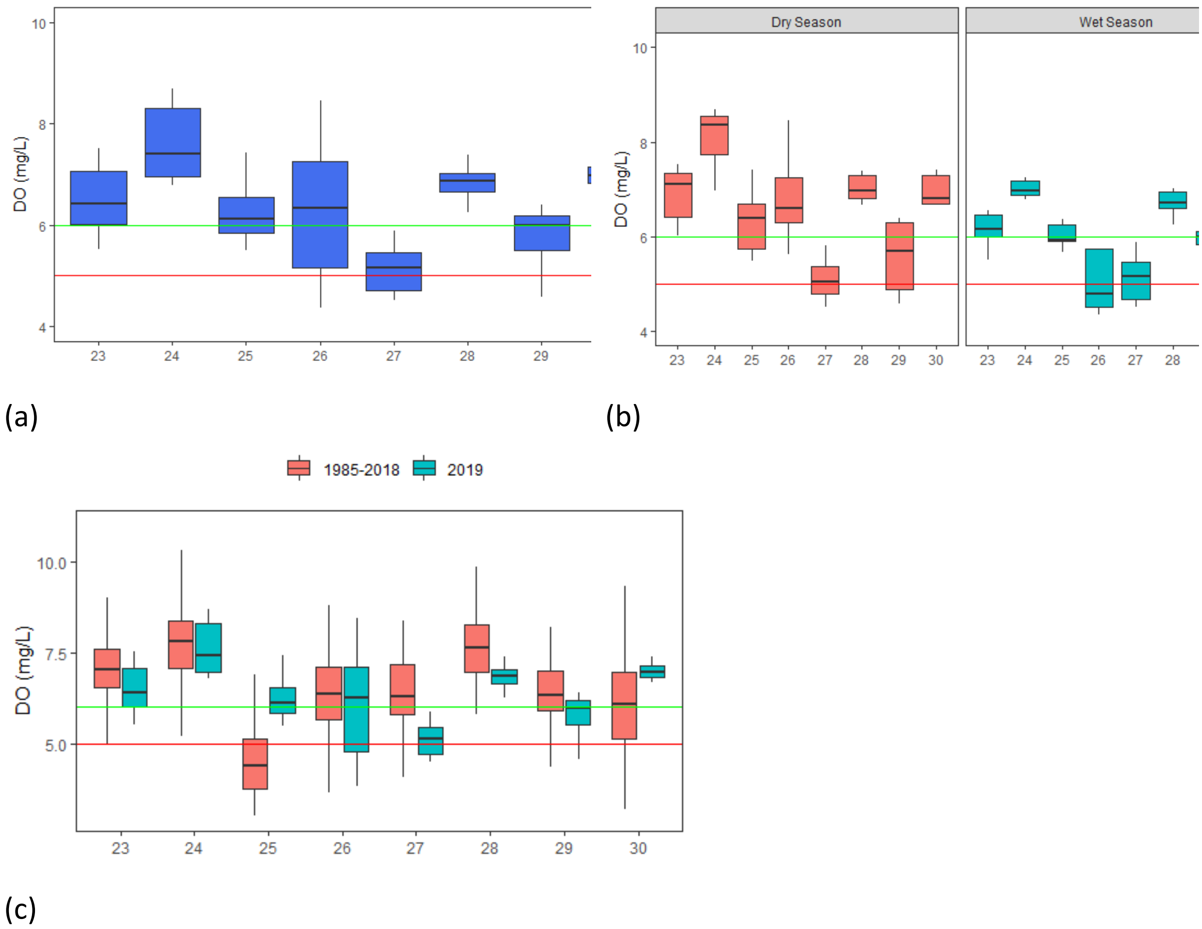


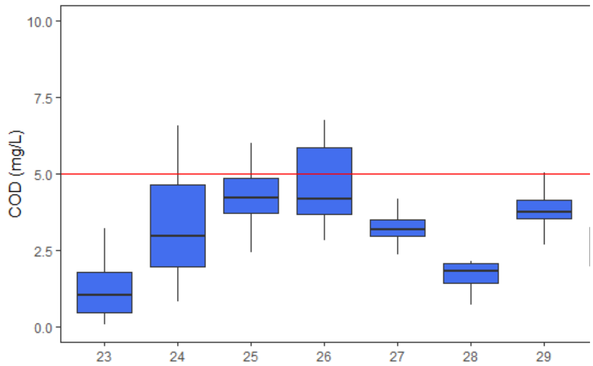
Figure 3.28. Spatial and temporal distribution of DO levels in key tributaries of the Mekong River in 2019

Compared to historical records (Figure 3.29c), DO levels improved at Houay Mak Hiao (25) and Prek Kdam (30) but were slightly impaired at Ban Hat Kham (23), Pleicu (27), Lumphat (28), and Ban Don (29). DO levels at Chiang Rai (24) and Mun (Khong Chiam) (26) appear to be similar to their respective historical levels. One-way ANOVA analyses revealed that the change in DO levels at Pleicu (27) was statistically significant, with levels of p-value of less than 0.01.

3.5.1.6 Chemical Oxygen Demands

Similar to DO levels, 2019 COD levels (Figure 3.30a) also varied from station to station, with concentrations ranging from 0.8 mg/L to 9.7 mg/L for Chiang Rai (24), but from 0.1 to 3.2 mg/L for Ban Hat Kham (23). Among the six tributary stations, three recorded COD values greater than the target value of the WQGH (5 mg/L): Chiang Rai (24) with a maximum COD concentration of 9.7 mg/L; Houay Mak Hiao (25) with a maximum COD concentration of 7.2 mg/L; and Mun (Khong Chiam) (26) with a maximum COD concentration of 6.9 mg/L. At Mun (Khong Chiam) (26), about 33% of the data exceeded the target value of the WQGH (5 mg/L).

On a temporal scale (Figure 3.30c), in 2019, COD levels slightly increased at Pleicu (27) and Ban Don (29): the average COD concentrations at Pleicu (27) increased to 3.2 mg/L in 2019 compared to the historical value of 2.5 mg/L, and the average COD concentration at Ban Don increased slightly to 3.7 mg/L compared to the historical value of 3.1 mg/L. These increases, however, were not statistically significant, with one-way ANOVA p-values calculated for both stations at greater than 0.05.



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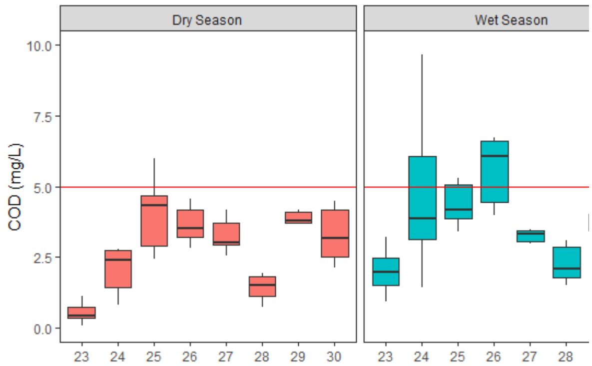

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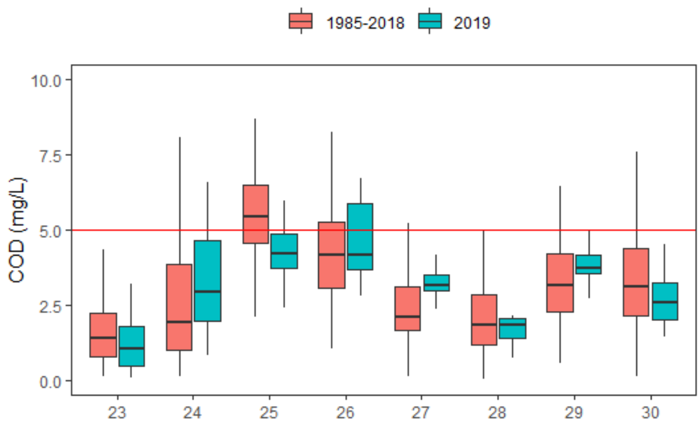

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Figure 3.29. Spatial and temporal distribution of COD levels in key tributaries of the Mekong River in 2019

3.5.2 Water Quality Indices

Despite high levels of nutrients at some tributary stations, the water quality at these stations was still suitable for the protection of human health, aquatic life, and agricultural use. The analyses of the 2019 water quality data using the Water Quality Index for Human Health (WQI_{hh}), reveal that at the eight tributary stations, the water quality for the protection of human health is still 'good'; all stations rated as either 'good' or 'excellent' (Table 3.7). In 2019, water quality for the protection of human health was rated as 'excellent' at Ban Hat Kham (23), Pleicu (27), Lumphat (28), and Prek Kdam (30). The remaining stations (Chiang Rai (24), Houay Mak Hiao (25), and Mun (Khong Chiam) (26)) were rated as having water of 'good' quality for the protection of human health. High NO_{3-2} and COD were the main causes preventing the water quality at these stations from achieving an 'excellent' rating.

At these eight tributary stations, water quality was also still of good quality for the protection of aquatic life, with Ban Hat Kham (23) and Lumphat (28) rated as 'excellent' for the protection of aquatic life. The water quality at the remaining six tributary stations was rated as 'good' for the protection of aquatic life.

With the exception of the slightly high EC levels at Houy Mak Hiao (25), EC levels at the tributary stations were relatively low, with no concentration exceeded 70 mS/m. Consequently, there was no restriction on water quality at the eight tributary stations for general irrigation and paddy rice irrigation in 2019 (Table 3.7).

Table 3.7. Status of water quality of the Mekong tributaries for the protection of human health, the protection of aquatic life, and agricultural use in 2019

Station No.	Station name	River name	2019		
			WQI_{hh}	WQI_{al}	WQI_{ag}
23	Ban Hat Kham	Nam Ou River	A	A	A
24	Chiang Rai	Mae Kok River	B	B	A
25	Houay Mak Hiao	Houay Mak Hiao	B	B	A
26	Mun (Khong Chiam)	Nam Mun River	B	B	A
27	Pleicu	Se San River	A	B	A
28	Lumphat	Se San River	A	A	A
29	Prek Kdam	Tonle Sap River	A	B	A
30	Ban Don	Sre Pok River	B	B	A

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

This report provides an overall assessment of water quality of the Mekong River and its selected tributaries in the 2019, using key water quality parameters monitored under the WQGH and listed in Chapters 1 and 2 of the TGWQ as proxies for water quality. The analyses of water quality data collected from 30 water quality monitoring stations were carried out for this report. Of these 30 stations, 17 were located along Mekong River, 5 along Bassac River, and 8 in the selected tributaries of the Mekong River. It can be concluded based on the results of statistical analyses of water quality data and the results of the analyses of water quality indices that water quality at the 30 stations included in this report was of good quality as of 2019, with only a small number of COD and DO measurements not in compliance with the WQGH and WQGA**.** As a result, water quality of the Mekong River and its tributaries continued to be suitable for the protection of human health and aquatic life in 2019. With low EC levels, the water of the Mekong River and its tributaries also continued to be suitable for both general irrigation and paddy rice irrigation purposes.

While water quality of the Mekong River and its tributaries was still rated 'good', the levels of individual water quality parameters were higher than the WQGH, WQGA, and historical levels. Spatial analyses of water quality at the 30 stations reveal that levels of NO_{3-2}, NH4N, TOTP, and COD varied from station to station across the basin but tend to increase in levels as the river flow from the upper part of the basin to the Delta. For example, levels of TOTP were observed to be highest at stations downstream of urban and agricultural areas, including My Thuan (16) in the Mekong River, and Takhmao (18) and Can Tho (22) in the Bassac River. In the LMB, these parameters have been determined to strongly and negatively correlated with instream DO levels. Consequently, reduced DO levels were detected at many stations located in the Mekong Delta including Tan Chau (15), My Thuan (16), My Tho (17), Chau Doc (21), and Can Tho (22). Of a slight concern are the DO levels at Chau Doc, which were not in compliance with the WQGH for all sampling occasions, thus causing the rating of water quality index for the protection of aquatic life to be 'moderate' in 2019. Together with Chau Doc (21), water quality at My Thuan (16) and My Tho (17) also rated 'moderate' for the protection of aquatic life 2019. At My Thuan (16), impairment of DO was the main cause for the 'moderate' rating; 42% of DO data were lower than the target value of WQGA (5 mg/L). In contrast, water quality at My Tho (17) for the protection of aquatic life was influenced by high nutrient levels, with 83% NO_{3-2} data and 42% TOTP exceeding their respective target values for WQI_{al} (0.5 mg/L for NO_{3-2} and 0.13 mg/L for TOTP). In addition to these three stations, the water quality of the Mekong River and its tributaries continued to be rated as either 'good' or 'excellent' for the protection of aquatic life in 2019. Of the 30 stations included in this report, 14 were rated 'excellent' and 13 were rated 'good' for the protection of aquatic life.

The high levels of nutrients and COD did not affect water quality of the Mekong River and its tributaries for the protection of human health. In 2019, water quality at 22 stations (15 mainstream, 3 Bassac, and 4 selected tributary stations) was rated 'excellent' for the protection of human health, while water quality of the remaining 8 stations (2 mainstream, 2 Bassac, and 4 selected tributary stations) was rated 'good' for the protection of human health.

On a temporal scale, slightly high levels of nutrients and COD were detected at many stations in 2019. However, their levels continued to be mostly in compliance with the target values of the WQGA and WQGH. Despite the slight increase in levels, both water quality for the protection of human and aquatic have remained largely at similar levels for all stations since 2008. Historically, the water quality of the Mekong River and its tributaries has always been rated as either ‘good’ or ‘excellent’ for the protection of aquatic life, with the only exception being a station located in the Mekong Delta, where annual water quality for the protection of aquatic life was rated as either ‘moderate’ or ‘good’ since 2008. Similarly, ratings for water quality for the protection of human health have fluctuated between ‘good’ and ‘excellent’ since 2008, with only a few stations rated ‘moderate’ in 2009, 2010, and 2014.

With only a few EC concentrations exceeding 70 mS/m, the water quality of the Mekong River and its tributaries had no restrictions for general and paddy rice irrigation. From 2008 to 2019, water quality ratings for agricultural use had not changed with the only exception in 2016 at My Tho, where a slight restriction was detected for general irrigation. Continuous caution should be exercised when using the Mekong and Bassac River water for irrigation in the Delta area, since salinity intrusion during the high tide could lead to high EC concentrations making the water unsuitable for irrigation (Le et al., 2007). This problem could be further exacerbated if the low tide flows are reduced (Trung et al., 2018).

In terms of transboundary river pollution, the analyses of water quality at Pakse (8)/Stung Treng (9) revealed no potential transboundary water quality pollution between the two stations in 2019, with levels of NO_{3-2}, TOTN, TOTP, and COD lower in Stung Treng (9) than in Pakse (8). In contrast, NH4N and DO levels were higher in Stung Treng (9) than in Pakse (8). However, the difference in NH4N levels between the two stations was not statistically significant with an independent t-test p-value greater than 0.05.

Between Kaorm Samnor (14)/Tan Chau (15), instream levels of NO_{3-2}, TOTN and COD were found to be higher at the downstream station (Tan Chau (15), which could indicate a potential transboundary water quality issue. Results of independent t-test analyses of these parameters revealed the differences in levels at the two stations to be statistically significant (p-value of less than 0.01 for all three parameters). In contrast, DO levels were found be lower at Tan Chau (15) with the difference in DO levels determined to be statistically significant (p-value less than 0.01). While there is a possibility of transboundary water quality issues between these two stations, levels of NO_{3-2}, COD, TOTP, TOTN, NH4N, and DO are still largely in compliance with the available target values of the WQGH and the WQGA.

The analyses of 2019 water quality data at Koh Thom (20)/Chau Doc (21) also revealed significant differences in levels of NO_{3-2}, TOTN, and COD between the two stations, with p-values less than 0.01. However, the levels of these parameters were still well below the WQGH and the WQGA in 2019. The combined levels of these parameters, however, appeared to have affected DO levels, particularly at Chau Doc (21), where 100% of the data were not in compliance with the WQGA (mg/L) and 42% were not in compliance with the WQGH (6 mg/L). Water quality at these six transboundary stations should be closely monitored to ensure the timely detection of further changes so that any potential effects on human health and aquatic life are detected and addressed in a timely manner.

4.2 Recommendations

MCs' efforts in maintaining 'acceptable/good' water quality of the Mekong River and its tributaries require that water quality complies with the TGWQ. In addition to the 19 parameters monitored in 2019, Chapters 1 and 2 of the TGWQ lists several additional water quality parameters that need to be monitored in the near future. These indicators have been added, taking into consideration emerging threats to water quality, including population growth, intensive agriculture and aquaculture, navigation, hydropower and industrialization. These threats can often lead to increased inputs of chemicals and debris that can ultimately affect the aquatic ecosystems and human health. The monitoring of these parameters will require concerted efforts at both the national and regional levels to improve the capacity of the line agencies responsible for water quality monitoring. In addition, concerted efforts will also be required to develop cost-effective monitoring methodology to ensure its long-term and sustainable implementation.

In recent years, specific monitoring programmes have been carried out to complement activities of the WQMN, including the Joint Environmental Monitoring Programme for Water Quality (JEM WQ) to monitor the potential effects of hydropower development on water quality, the Riverine Plastic Debris Monitoring and Assessment, and the Multi-Media Monitoring and Assessment of the Mekong Riverine. The lessons learned from the implementation of these specific water quality monitoring activities, together with the anticipated increase in development in the LMB, have renewed the focus and raised question on the relevance of the current WQMN in terms of its objectives, spatial coverage compared to other existing environmental monitoring programmes, monitoring frequency for the timely detection of emerging threats, and the relevance of data to support the assessment of basin-wide development. As part the MRC Core River Monitoring Network, the WQMN will be reviewed to ensure its complementary with the MCs and MRC's other environmental monitoring activities.

Considering the status of water quality as highlighted in the report, the upcoming review of the MRC Core River Monitoring Network, and the anticipated increase in development and population growth, the following are recommended for the sustainable implementation of the routine water quality monitoring under the WQGH:

- Closely monitor nutrients and DO levels in the mainstream stations including those highlighted in this report as of concern in order to ensure the timely detection of further changes so that any potential effects on human health and aquatic life can be detected and addressed in a timely manner;
- Develop and pilot detailed methodology for long-term and cost-effective monitoring of macro and micro riverine plastic debris in the LMB;
- Improve and update the water quality monitoring facilities, knowledge, and skills for the national laboratories by providing training programmes on various aspects of water quality monitoring and data assessment. This will be based on a long-term capacity-building plan to be developed by consultations with the MCs;

- Advocate for the timely submission of water quality monitoring data and reports in order to support the timely assessment of basin-wide water quality status and trends, and the timely preparation of basin-wide water quality reports;
- Advocate for, and support the MCs, in the timely identification and sharing of information on any water quality incident that may constitute an emergency through the finalization of Chapter 4 of the TGWQ and its implementation plan;
- Through a review of the MRC Core Monitoring Network, explore feasible solutions for improving water quality monitoring in remote areas (e.g. close to the Lao PDR–Myanmar border and possibly, the Lao PDR–China border), including the feasibility of monitoring through a high frequency water quality monitoring system;
- Explore the feasibility of monitoring additional water quality parameters listed in Chapters 1 and 2 of the TGWQ, including heavy metals and persistent and non-persistent organic substances;
- Strengthen the capacity of the MCs to monitor water quality associated with development, including by installing and operating high frequency water quality monitoring systems downstream of hydropower dams, as recommended by JEM;
- Continue to support QA/QC for water quality monitoring and highlight its importance, through the provision of training, validation of data, development and maintenance of monitoring standard operating procedures, and proficiency testing;
- Assist national designated laboratories in achieving ISO/IEC 17025 certification, which will enable them to demonstrate that they operate competently and generate valid results, thereby promoting confidence in the monitoring results nationally, regionally and globally.

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ANNEX A: 2019 WATER QUALITY MONITORING STATIONS ARRANGED FROM UPSTREAM TO DOWNSTREAM AS PER THE LATITUDE OF THE STATION

Station ID	Name of station	River	Types of River	Country	Latitude	Longitude
H010500	Houa Khong	Mekong River	Mainstream	Lao PDR	21.54710	101.15980
H010501	Chiang Sean	Mekong River	Mainstream	Thailand	20.26740	100.09080
H100101	Ban Hatkham	Nam Ou River	Tributary	Lao PDR	20.08500	102.25220
H011200	Luang Prabang	Mekong River	Mainstream	Lao PDR	19.93880	101.30380
H050104	Chiang Rai	Mae Kok River	Tributary	Thailand	19.92080	99.84610
H230103	Ban Hai	Nam Ngum River	Tributary	Lao PDR	18.17920	103.05650
H910108	Houay Mak Hiao	Houay Mak Hiao Stream	Tributary	Lao PDR	17.99990	102.90820
H011901	Vientiane	Mekong River	Mainstream	Lao PDR	17.96920	102.55060
H290103	Ban Chai Buri	Song Khram River	Tributary	Thailand	17.64380	104.46160
H013101	Nakhon Phanom	Mekong River	Mainstream	Thailand	17.42500	104.77440
H320101	Se Bangfai	Se Bangfai River	Tributary	Lao PDR	17.08000	104.98470
H013900	Pakse	Mekong River	Mainstream	Lao PDR	16.92830	104.68830
H310102	Na Kae	Nam Kam River	Tributary	Thailand	16.95720	104.50410
H013401	Savannakhet	Mekong River	Mainstream	Lao PDR	16.55830	104.75220
H350101	Ban Kengdone	Se Banghieng River	Tributary	Lao PDR	16.18360	105.31670
H380128	Mun (Kong Chiam)	Nam Mun River	Tributary	Thailand	15.30360	105.48880
H013801	Khong Chaim	Mekong River	Mainstream	Thailand	15.32550	105.49370
H380104	Ubon	Nam Mun River	Tributary	Thailand	15.24300	104.95470
H390105	Sedone bridge	Se Done River	Tributary	Lao PDR	15.07160	105.48420
H430102	Siempang	Sekong River	Tributary	Cambodia	14.11917	106.39330
H440103	Angdoung Meas	Se San River	Tributary	Cambodia	14.04694	107.10694

Station ID	Name of station	River	Types of River	Country	Latitude	Longitude
H440102	Phum Pi	Se San River	Tributary	Cambodia	13.79138	107.44861
H450101	Lumphat	Srepork River	Tributary	Cambodia	13.54944	106.52833
H014501	Stung Treng	Mekong River	Mainstream	Cambodia	13.54500	106.01639
H020107	Backprea	Sang Keo River	Tributary	Cambodia	13.30861	103.39917
H020108	Phnom Krom	Tonle Sap Lake	Mainstream	Cambodia	13.29389	103.81722
H020106	Kampong Luong	Tonle Sap Lake	Tributary	Cambodia	12.60075	104.22112
H014901	Kratie	Mekong River	Mainstream	Cambodia	12.47000	106.02000
H020103	Kampong Chnang	Tonle Sap River	Tributary	Cambodia	12.26942	104.68215
H019802	Kampong Cham	Mekong River	Mainstream	Cambodia	11.99418	105.46891
H020102	Prek Kdam	Tonle Sap River	Tributary	Cambodia	11.81533	104.80723
H020101	Phnom Penh Port	Tonle Sap River	Tributary	Cambodia	11.58672	104.92315
H019801	Chrouy Changvar	Mekong River	Mainstream	Cambodia	11.58605	104.94065
H033401	Takhmao	Bassac River	Tributary	Cambodia	11.47853	104.95303
H033402	Koh Khel	Bassac River	Tributary	Cambodia	11.26762	105.02922
H019806	Neak Loung	Mekong River	Mainstream	Cambodia	11.25797	105.27928
H033403	Koh Thom	Bassac River	Tributary	Cambodia	11.10536	105.06778
H019807	Kaorm Samnor	Mekong River	Mainstream	Cambodia	11.06792	105.20855
H019803	Tan Chau	Mekong River	Mainstream	Viet Nam	10.90360	105.52060
H039801	Chau Doc	Bassac River	Tributary	Viet Nam	10.82530	105.33670
H988316	Tinh Bien	Vinh Te Canal	Tributary	Viet Nam	10.82530	105.33670
H019804	My Thuan	Mekong River	Mainstream	Viet Nam	10.80440	105.24250
H039803	Can Tho	Bassac River	Tributary	Viet Nam	10.70640	105.12720
H019805	My Tho	Mekong River	Mainstream	Viet Nam	10.60390	104.94360
H451303	Ban Don	Sre Pok River	Tributary	Viet Nam	10.52060	105.84580
H440202	Pleicu	Se San River	Tributary	Viet Nam	10.43610	105.05530

Station ID	Name of station	River	Types of River	Country	Latitude	Longitude
H988115	Thong Binh	Thong Binh Canal	Tributary	Viet Nam	10.34310	106.35060
H988114	Tu Thuong	Tu Thuong Canal	Tributary	Viet Nam	10.27250	105.91000

ANNEX B: MAP OF WATER QUALITY MONITORING STATIONS AS MONITORED IN 2019

APPENDIX C: DESCRIPTIVE STATISTIC OF KEY WATER QUALITY INDICATORS OF THE MEKONG TRIBUTARIES

				Historical				2019			
Stations	**Parameters**	**Unit**		**Max**	**Mean**	**Min**	**Std.**	**Max**	**Mean**	**Min**	**Std.**
Ban Hatkham	TEMP	°C		31.2	25.2	18.0	2.7	28.6	26.9	25.5	1.0
	pH	-	6–9	9.4	7.6	4.6	0.6	8.0	7.3	6.4	0.5
	TSS	mg/L	–	2,080.0	111.8	1.0	246.2	92.3	30.1	4.5	24.4
	EC	mS/m	70–150	38.1	21.3	10.5	4.6	28.7	19.8	10.2	5.9
	NO_{3-2}	mg/L	5	1.85	0.18	0.00	0.20	0.65	0.23	0.07	0.18
	NH4N	mg/L	–	0.91	0.04	0.01	0.07	0.04	0.02	0.01	0.01
	TOTN	mg/L	–	1.90	0.51	0.06	0.39	1.16	0.62	0.32	0.28
	TOTP	mg/L	–	0.98	0.06	0.00	0.10	0.06	0.03	0.02	0.01
	DO	mg/L	5 or 6	10.3	7.1	4.6	0.9	7.5	6.5	5.5	0.6
	COD	mg/L	5	16.0	1.9	0.1	1.9	3.2	1.3	0.1	1.0
Chiang Rai	TEMP	°C		33.0	25.0	17.7	3.1	30.2	25.9	20.9	3.3
	pH	-	6–9	8.9	7.6	6.2	0.4	7.7	7.2	6.4	0.4
	TSS	mg/L	–	9,364.0	161.1	1.0	473.0	243.8	61.7	12.8	68.0
	EC	mS/m	70–150	224.5	14.5	1.9	10.6	15.0	11.8	8.1	2.3
	NO_{3-2}	mg/L	5	1.0	0.2	0.0	0.2	0.4	0.2	0.0	0.1
	NH4N	mg/L	–	0.6	0.0	0.0	0.1	0.1	0.0	0.0	0.0
	TOTN	mg/L	–	2.3	0.5	0.1	0.3	0.9	0.5	0.4	0.1
	TOTP	mg/L	–	0.6	0.1	0.0	0.1	0.3	0.1	0.1	0.1
	DO	mg/L	5 or 6	10.3	7.8	5.0	0.9	8.7	7.6	6.8	0.7
	COD	mg/L	5	13.5	3.0	0.1	2.8	9.7	3.6	0.8	2.5
Pleicu	TEMP	°C		30.1	26.1	19.7	2.2	25.8	24.8	23.1	0.6
	pH	-	6–9	8.0	6.8	5.7	0.4	7.7	7.2	7.0	0.3
	TSS	mg/L	–	288.0	42.5	2.5	32.5	30.0	15.5	7.0	7.7

	EC	mS/m	70–150	8.9	3.7	1.0	1.7	5.4	4.5	3.7	0.6
	NO_{3-2}	mg/L	5	0.6	0.2	0.0	0.1	0.6	0.4	0.2	0.1
	NH4N	mg/L	–	0.6	0.1	0.0	0.1	0.1	0.0	0.0	0.0
	TOTN	mg/L	–	1.4	0.5	0.2	0.2	0.8	0.5	0.3	0.2
	TOTP	mg/L	–	0.3	0.1	0.0	0.1	0.4	0.1	0.0	0.1
	DO	mg/L	5 or 6	10.1	6.4	2.9	1.1	5.9	5.1	4.5	0.5
	COD	mg/L	5	14.7	2.5	0.1	1.6	4.2	3.2	2.4	0.5
Mun at Khong Chiam	TEMP	°C		34.0	29.2	21.0	2.4	33.0	29.4	25.0	2.3
	pH	-	6–9	8.1	7.2	6.2	0.4	7.4	7.2	6.9	0.1
	TSS	mg/L	–	101.0	18.7	0.8	18.5	69.3	12.7	1.8	19.4
	EC	mS/m	70–150	34.9	16.9	5.0	6.6	26.9	16.3	6.1	6.6
	NO_{3-2}	mg/L	5	0.5	0.2	0.0	0.1	0.3	0.1	0.0	0.1
	NH4N	mg/L	–	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	TOTN	mg/L	–	1.7	0.5	0.0	0.3	0.8	0.4	0.1	0.2
	TOTP	mg/L	–	0.2	0.1	0.0	0.0	0.1	0.1	0.0	0.0
	DO	mg/L	5 or 6	8.8	6.3	2.4	1.2	7.7	6.5	4.4	0.9
	COD	mg/L	5	12.1	4.4	1.0	1.8	6.9	4.1	2.5	1.5
Houay Mak Hiao	TEMP	°C		32.9	27.8	15.0	3.2	31.9	28.8	25.2	2.2
	pH	-	6–9	8.2	6.9	5.5	0.4	8.2	7.1	6.0	0.6
	TSS	mg/L	–	253.0	42.1	4.0	45.7	1269.5	137.0	4.8	358.3
	EC	mS/m	70–150	113.1	44.8	9.9	26.8	182.0	84.4	21.4	46.1
	NO_{3-2}	mg/L	5	7.20	0.81	0.00	1.04	2.65	1.22	0.23	0.69
	NH4N	mg/L	–	2.88	0.35	0.01	0.57	0.09	0.05	0.02	0.02
	TOTN	mg/L	–	16.00	2.15	0.13	2.07	4.72	3.04	0.82	1.22
	TOTP	mg/L	–	2.01	0.12	0.01	0.21	1.01	0.15	0.02	0.28
	DO	mg/L	5 or 6	8.3	3.8	0.6	1.6	7.4	6.2	5.5	0.6
	COD	mg/L	5	19.0	5.9	0.4	2.3	7.2	4.4	2.4	1.4
Prek Kdam	TEMP	°C		33.2	29.8	25.5	1.6	31.0	29.4	26.0	1.5
	pH	-	6–9	8.7	7.1	5.7	0.4	7.6	7.2	6.7	0.2

	TSS	mg/L	–	484.0	50.3	1.0	53.5	187.5	72.5	22.4	51.7
	EC	mS/m	70–150	20.6	10.2	5.5	2.9	18.0	12.6	9.8	2.6
	NO_{3-2}	mg/L	5	3.21	0.23	0.00	0.31	0.41	0.16	0.02	0.12
	NH4N	mg/L	–	1.00	0.07	0.00	0.08	0.18	0.05	0.01	0.05
	TOTN	mg/L	–	2.31	0.47	0.05	0.36	0.57	0.30	0.20	0.11
	TOTP	mg/L	–	0.81	0.09	0.00	0.09	0.27	0.11	0.03	0.06
	DO	mg/L	5 or 6	10.2	6.0	1.0	1.3	65.7	11.8	5.5	17.0
	COD	mg/L	5	9.8	3.4	0.1	1.8	4.5	2.7	1.4	1.0
Ban Don	TEMP	°C		31.2	24.9	19.8	2.7	27.5	26.2	24.1	1.0
	pH	-	6–9	7.7	7.3	6.7	0.2	7.6	7.2	6.5	0.3
	TSS	mg/L	–	566.0	62.6	2.5	75.4	103.0	49.4	23.0	23.8
	EC	mS/m	70–150	12.9	6.5	4.8	1.1	11.4	8.8	6.4	1.8
	NO_{3-2}	mg/L	5	2.23	0.40	0.08	0.37	1.89	0.68	0.07	0.55
	NH4N	mg/L	–	0.55	0.04	0.00	0.03	0.50	0.08	0.00	0.15
	TOTN	mg/L	–	2.28	0.90	0.35	0.44	2.10	1.02	0.23	0.59
	TOTP	mg/L	–	0.57	0.12	0.03	0.08	0.29	0.14	0.03	0.07
	DO	mg/L	5 or 6	9.5	7.6	6.6	0.5	6.4	5.8	4.6	0.6
	COD	mg/L	5	10.7	3.1	0.8	2.2	5.0	3.7	2.2	0.7
Lumphat	TEMP	°C		34.0	28.2	21.0	2.0	31.0	29.0	25.0	1.8
	pH	-	6–9	8.0	7.1	5.6	0.4	7.8	7.3	6.8	0.3
	TSS	mg/L	–	166.0	40.2	0.7	33.2	135.0	38.8	7.3	36.1
	EC	mS/m	70–150	16.2	6.4	3.1	1.8	8.2	7.6	7.0	0.3
	NO_{3-2}	mg/L	5	1.28	0.19	0.00	0.15	0.27	0.17	0.09	0.06
	NH4N	mg/L	–	0.48	0.05	0.00	0.07	0.07	0.04	0.02	0.02
	TOTN	mg/L	–	2.26	0.37	0.05	0.27	0.37	0.29	0.23	0.05
	TOTP	mg/L	–	0.48	0.10	0.00	0.08	0.17	0.09	0.01	0.05
	DO	mg/L	5 or 6	10.9	7.7	4.8	1.0	7.4	6.9	6.2	0.3
	COD	mg/L	5	11.8	2.3	0.0	1.8	4.7	2.0	0.7	1.1

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