Assessment of Eutrophication in Middle-Lower Chao Phraya River (2020–2022)

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ABSTRACT

This study investigated eutrophication in the Chao Phraya River from 2020 to 2022, focusing on ten monitoring stations between Ayutthaya and Samut Prakan. Distinct seasonal dynamics associated with the monsoon were observed. During the wet season (May-November), agricultural and urban runoff elevated BOD, suspended solids, and nutrient concentrations. In contrast, during the dry season (December-April), reduced freshwater discharge intensified salinity intrusion. Hypoxic conditions, with dissolved oxygen (DO) frequently dropping below 2 mg·L^{-1} near the river mouth. Nutrient enrichment-particularly dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP)-was strongly associated with phytoplankton blooms, especially near the salinity front where chlorophyll-*a* concentrations peaked. Nutrient levels increased downstream, driven by untreated discharges from urban, agricultural, and industrial sources. Wastewater nitrification increased nitrate levels, while nitrate overall comprised 41.36% of the total DIN. Peaks in phosphate and total dissolved phosphorus (TDP) followed agricultural runoff, notably in November 2020. Principal component analysis (PCA) revealed clear spatial distinction between middle and lower river stations, with the lower section characterized by elevated nitrogen, phosphorus, and chlorophyll-*a* concentrations. The AARL-PC Score (a trophic state index) supported these findings, showing consistently high trophic scores in downstream stations indicative of eutrophic conditions, particularly during June and July 2020. Overall, the results indicate a worsening ecological condition compared to historical records and highlight the urgent need for integrated pollution control and sustainable river basin management to protect this tropical urban river.

Keywords: Chao Phraya River, Eutrophication, Hypoxia, Nutrient enrichment, Water quality

INTRODUCTION

Rivers in densely populated regions across the globe are increasingly affected by nutrient enrichment and organic pollution, which lead to water quality degradation, eutrophication, and ecological imbalance. Urbanized rivers such as the Mississippi River in the United States (Turner and Rabalais, 2003), the Pearl River in China (Ke *et al*., 2022), and the Ganges River in India (Mishra *et al*., 2025) have all shown progressive deterioration due to untreated wastewater discharges, agricultural runoff, and altered hydrological regimes. These rivers contribute significantly to coastal eutrophication, algal blooms, and seasonal hypoxia, posing serious risks to aquatic ecosystems and human livelihoods.

The Chao Phraya River, the main river of Thailand, exhibits similar concerns. It supports extensive agricultural, industrial, and urban activities as it flows through the central plains into the Gulf of Thailand, with its middle and lower reaches passing through major cities such as Ayutthaya, Pathum Thani, Bangkok, and Samut Prakan. Land use is predominantly agricultural (over 50%), mostly rice fields, followed by residential areas and built-up

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Received 31 May 2025 / Accepted 31 October 2025

areas (30–40%) (Ligaray *et al*., 2015; Visessri and Ekkawatpanit, 2020). Rapid urban expansion, insufficient wastewater infrastructure, and intensified agricultural inputs have turned the river into a major recipient of domestic, municipal, and industrial effluents (PCD, 2022). Both point and non-point sources, such as untreated sewage, aquaculture effluents, and urban or agricultural runoff, have been identified as key contributors to pollution in the basin (Avakul and Jutagate, 2012).

Over the past decades, there has been a notable decline in the ecological condition of the Chao Phraya River. Between 2020 and 2022, the Pollution Control Department reported that more than 50% of the monitoring stations along the lower river failed to meet national standards for dissolved oxygen (DO<2 $mg \cdot L^{-1}$), while biochemical oxygen demand (BOD) frequently exceeded 4 $mg \cdot L^{-1}$ (PCD, 2023). Ammonia concentrations also surpassed the Type 3 (agricultural use) and Type 4 (industrial use) surface water standards (0.5 $mg\ N \cdot L^{-1}$) in 76% of samples collected in the lower reaches. Total phosphorus concentrations in the Bangkok section of the Chao Phraya River from 2012–2024 ranged from 0.2 to 0.4 $mg \cdot L^{-1}$, showing an increasing trend (WQMO, 2025). Elevated levels of nutrients, particularly nitrogen and phosphorus, have been linked to frequent algal blooms and widespread oxygen depletion. These symptoms of eutrophication are most severe in the lower reaches, where tidal intrusion, low freshwater discharge, and limited wastewater treatment contribute to pollutant accumulation (Singkran *et al*., 2019).

The Chao Phraya River, together with the Bang Pakong, Tha Chin, and Mae Klong Rivers, serves as a major source of nutrients and organic matter flowing into the inner Gulf of Thailand. Studies indicate that freshwater inputs from these rivers deliver large nutrient loads to coastal waters, contributing to coastal eutrophication and seasonal hypoxia (Cheevaporn and Menasveta, 2003; PCD, 2021a). During the wet season, enhanced river discharge transports greater nutrient loads, which are closely linked to coastal algal (red tide) blooms and bottom-water hypoxia. Data on red tide events in Thailand from 2014 to 2024 show an increasing trend, with over 378 recorded cases, most occurring during the southwest monsoon (PCD, 2025). Key water quality indicators such as DO, BOD, and nutrient concentrations frequently exceed environmental standards, affecting not only riverine ecosystems but also coastal and marine resources in the inner Gulf.

Given the increasing anthropogenic inputs, the water quality of the Chao Phraya River needs urgent and comprehensive investigation. Previous studies have primarily focused on long-term trends using secondary data collected by government agencies, but detailed analyses of seasonal and intra-annual variations remain limited. Few studies have examined the physicochemical processes driving eutrophication or applied standardized methods to evaluate the river's trophic status. This study addresses these gaps by conducting high-frequency, continuous field monitoring and analyzing multiple key parameters. Its objectives are to: (1) describe the spatial and temporal variations of major water quality indicators in the middle and lower Chao Phraya River from 2020 to 2022; (2) identify physicochemical relationships and seasonal patterns linked to eutrophication; and (3) assess trophic levels using the Applied Algae Research Laboratory Physical and Chemical Properties Score (AARL-PC Score). By combining multi-year field observations with regional comparisons, this study enhances understanding of riverine degradation in tropical urban watersheds and supports science-based strategies to mitigate water quality decline and reduce impacts on coastal ecosystems.

MATERIALS AND METHODS

This study was conducted in the middle and lower sections of the Chao Phraya River, extending from Ayutthaya Province to Samut Prakan Province (Figure 1a), as designated by the Pollution Control Department (PCD, 1994). A total of ten monitoring stations were selected, spaced approximately 6–13 km apart (Figure 1b and Table 1). Water sampling was carried out ten times between June 2020 and July 2022, including eight surveys during the wet season and two during the dry season (Table 2), thereby capturing the contrasting hydrological and water quality conditions associated with the monsoon cycle.

Table 1. Locations of water-sampling stations along the Chao Phraya River.

Stations	Longitude	Latitude	Location	Provinces	River sections
CP2	100° 33' 55.49"	14° 17' 49.16"	Prodsat Temple	Ayutthaya	The middle Chao Phraya River
CP3	100° 33' 30.77"	14° 11' 42.59"	Bangkrasan Subdistrict Municipality	Ayutthaya	
CP4	100° 32' 26.50"	14° 06' 54.96"	Bot Temple (Samkhok)	Ayutthaya	
CP5	100° 32' 06.73"	14° 01' 14.48"	Pathum Thani Town Municipality	Pathum Thani	
CP7	100° 29' 40.88"	13° 54' 55.46"	Bo Temple	Nonthaburi	
CP9	100° 31' 02.46"	13° 48' 45.87"	Soi Thong Temple	Bangkok	The lower Chao Phraya River
CP13	100° 30' 45.15"	13° 43' 02.54"	Yannawa Temple	Bangkok	
CP16	100° 35' 12.12"	13° 40' 55.26"	Bang Namphueng Noi Temple	Samut Prakan	
CP18	100° 32' 56.17"	13° 37' 04.66"	Port opposite Bang Fai Temple	Samut Prakan	
CP19	100° 34' 26.39"	13° 34' 06.86"	SEFFDEC	Samut Prakan	

Table 2. Sampling dates and corresponding seasons.

Date	Season
5 June 2020	Wet
19 July 2020	Wet
18 October 2020	Wet
27 November 2020	Wet
5 March 2021	Dry
3 September 2021	Wet
22 October 2021	Wet
11 March 2022	Dry
19 May 2022	Wet
8 July 2022	Wet

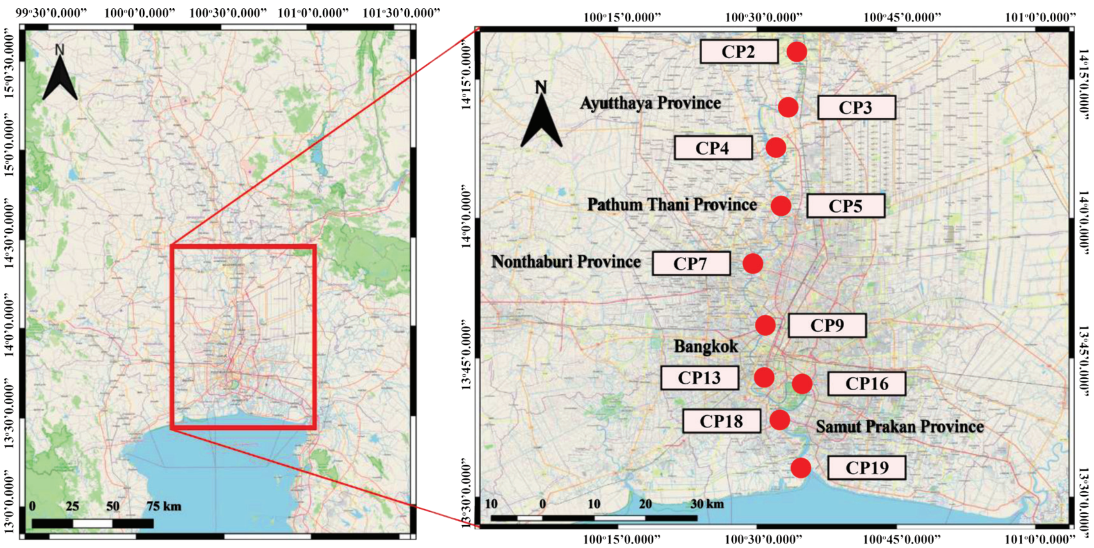

Figure 1. Overview map of the lower Chao Phraya River region (a) and detailed map showing the sampling stations along the river (b).

At each station, in situ measurements of water quality parameters were taken using a YSI Pro 2030 multiparameter water quality meter and an STD/CTD SD 204 sensor to measure temperature, salinity, and dissolved oxygen (DO). The pH was measured using a Horiba PD 110 pH meter. Water samples were collected approximately 1 meter below the surface using a Van Dorn water sampler. Each collected sample was divided into three portions. One portion was analyzed immediately for dissolved oxygen (DO) using the azide-modified Winkler titration method (Strickland and Parsons, 1972). Another portion was set aside for 5-day biochemical oxygen demand (BOD) test using the azide-modification method (APHA, 1998). The remaining portion was filtered through GF/C filters for chlorophyll-*a* (Chl-*a*) and total suspended solids (TSS) analyses. Filters for Chl-*a* were wrapped in aluminum foil and frozen at -20 °C to prevent pigment loss. The filtrate for dissolved-nutrient analysis was kept at 4 °C in the dark to slow microbial activity and chemical alteration until laboratory analysis. Nutrient analyses included measurements of ammonia (NH_3+NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), silicate (SiO_4), and orthophosphate (PO_4^{3-}), using colorimetric methods (Strickland and Parsons, 1972; Grasshoff *et al*., 1999). Total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP) were determined using persulfate oxidation methods, while dissolved organic nitrogen (DON) and dissolved organic phosphorus (DOP) concentrations were calculated by subtracting the corresponding inorganic fractions (DIN and DIP) from total dissolved nutrients. All analytical methods used for water quality assessments in this study, along with their corresponding references, are summarized in Table 3.

Statistical analysis

Statistical analysis was performed using R software version 4.5.0 (R Core Team, 2024). The trophic level of the river water was assessed by applying the method known as the Applied Algae Research Laboratory Physical and Chemical Properties Score (AARL-PC Score) according to Lorraine and Vollenweider (1981), Wetzel (2001), and Peerapornpisal *et al*. (2004). The AARL-PC score is designed to classify water bodies based

Table 3. Methods for analyzing dissolved oxygen, biological oxygen demand, suspended sediment, Chlorophyll-*a*, and nutrients.

Water parameter	Analysis methods
Dissolved oxygen (mg·L^{-1})	Azide modification (Strickland and Parsons, 1972)
Total suspended solids (mg·L^{-1})	GF/F filter (APHA, 1992)
Biological oxygen demand (mg·L^{-1})	5-day BOD test, Azide-modification methods (APHA, 1998)
Chlorophyll-*a* (µg·L^{-1})	Spectrophotometric (Strickland and Parsons, 1972)
Ammonia (µg N·L^{-1})	Phenol-hypochoride (Grasshoff *et al*., 1999)
Nitrite (µg N·L^{-1})	Diazotization (Strickland and Parsons, 1972)
Nitrate (µg N·L^{-1})	Cadmium reduction + diazotization (Strickland and Parsons, 1972)
Dissolved inorganic nitrogen (µg N·L^{-1})	Ammonia + Nitrite + Nitrate
Total dissolved nitrogen (µg N·L^{-1})	Persulphate oxidation (Grasshoff *et al*., 1999) + cadmium reduction + diazotization (Strickland and Parsons, 1972)
Dissolved organic nitrogen (µg N·L^{-1})	Total dissolved nitrogen - dissolved inorganic nitrogen
Orthophosphate (µg P·L^{-1})	Ascorbic acid (Strickland and Parsons, 1972)
Total dissolved phosphorus (µg P·L^{-1})	Acid persulphate oxidation (Grasshoff *et al*., 1999) + ascorbic acid (Strickland and Parsons, 1972)
Dissolved organic phosphorus (µg P·L^{-1})	Total dissolved phosphorus - orthophosphate
Silicate (µg Si·L^{-1})	Silicomolydate (Strickland and Parsons, 1972)

on their nutrient status, ranging from low-nutrient (oligotrophic) to very high-nutrient (hypereutrophic) conditions. This method has been widely applied to evaluate the trophic status of major rivers in Thailand, including the Ping, Tha Chin, Chi, Kwai, Tapee, and Chanthaburi Rivers (Leelahakriengkrai and Peerapornpisal, 2011). Water quality parameters associated with eutrophication, including DO, BOD, nitrate, ammonia, phosphate, chlorophyll-*a*, and conductivity, were originally included in the calculation. However, conductivity was excluded from the present analysis because the study area is an estuary influenced by seawater, where conductivity may not be a suitable indicator for comparison. Excluding conductivity (one parameter) lowered the total score. We recalculated scores without conductivity and compared them with the original results and with a one-parameter–adjusted scale, following Leelahakriengkrai and Peerapornpisal (2011). Although absolute scores decreased, trophic classifications remained largely consistent. This finding indicates that excluding conductivity effectively minimizes salinity-driven bias while preserving the integrity of trophic status assessment.

In the first step, each water quality parameter was converted into a score ranging from 0.1 to 1.0 as shown in Table 4. These scores were then summed and used to determine the trophic status based on the criteria for the six water-quality parameters shown in Table 5.

Table 4. Water quality parameter scores and trophic status based on the AARL-PC score.

	Water quality parameters					
Score	**DO ($mg \cdot L^{-1}$)**	**BOD ($mg \cdot L^{-1}$)**	**NO_3^- ($mg\ N \cdot L^{-1}$)**	**NH_3+NH_4^+ ($mg\ N \cdot L^{-1}$)**	**PO_4^{3-} ($mg\ P \cdot L^{-1}$)**	**Chl-*a* ($\mu g \cdot L^{-1}$)**
0.1	>9	<0.2	<0.1	<0.01	<0.01	<1
0.2	8.0–8.9	0.2–0.5	0.1–0.2	0.01–0.03	0.01–0.05	1–2
0.3	7.0–7.9	0.6–1.5	0.3–0.4	0.04–0.06	0.06–0.1	2.1–5
0.4	6.0–6.9	1.6–3	0.5–0.8	0.07–0.1	0.11–0.15	5.1–15
0.5	5.0–5.9	3.1–5	0.9–1.5	0.11–0.3	0.16–0.25	15.1–25
0.6	4.0–4.9	5.1–8	1.6–3	0.31–0.5	0.26–0.35	25.1–50
0.7	3.0–3.9	8.1–15	3.1–10	0.51–0.70	0.36–0.5	51–100
0.8	2.0–2.9	15.1–30	10.1–20	0.71–1	0.51–1.25	101–200
0.9	1.0–1.9	30.1–50	20.1–40	1.1–3	1.26–2.5	200.1–400
1.0	<1	>50	>40	>3	>2.5	>400

Source: Leelahakriengkrai and Peerapornpisal (2011)

Table 5. Trophic status based on the AARL-PC score.

AARL-PC Score	
Score	**Trophic status**
<0.8	Hypooligotrophic
0.9–1.6	Oligotrophic
1.7–2.4	Oligo–mesotrophic
2.5–3.2	Mesotrophic
3.3–4.0	Meso–eutrophic
4.1–4.8	Eutrophic
>4.9	Hypereutrophic

Source: Peerapornpisal et al. (2004); Leelahakriengkrai and Peerapornpisal (2011)

RESULTS AND DISCUSSION

Based on long-term monthly average rainfall data from meteorological stations within the Chao Phraya River Basin (Figure 2), the seasons can be divided into two main periods: the wet season (May–November) and the dry season (December–April). Rainfall in the wet season begins to increase in May, with an average of 115.41 mm, and continues to rise steadily, reaching its highest peak in September (257.29 mm). November remains classified as part of the wet season because, although rainfall decreases, river discharge is still high during this month. Rainfall decreases sharply in the dry season, with the lowest monthly average in December (10.30 mm), and remains low until April.

During 2020–2022, rainfall generally exceeded the long-term average, with a particularly notable peak in September 2022, when it was nearly twice as high as the average (Figure 2). Among the three years, 2022 recorded the highest monthly rainfall in most months, followed by 2021 and 2020. Such variations in precipitation likely affected river discharge and water quality conditions during the study period.

The study of physical and biological water quality in the Chao Phraya River revealed that monthly water temperature was generally lower in the upper part of the study area and higher near the river mouth. The maximum temperature (32.5 °C) was recorded in June 2020 at Station CP7 (middle part of the study area) and again in July 2020 at Station CP19 (lower part). In contrast, the lowest temperature (27.60 °C) was observed in October 2020 at Station CP18 (lower part).

Salinity showed a similar spatial gradient, with lower values observed upstream and higher values near the river mouth. The maximum salinity (22.30 ppt) occurred in March 2021 at Station CP19 (lower part) during a period of pronounced saltwater intrusion that extended as far upstream as Station CP7 (middle part). Conversely, minimal salinity values (0.10–0.20 ppt) were recorded throughout the river in October 2021, indicating a complete absence of seawater intrusion during that period.

The pH values were relatively uniform along the river but tended to be slightly higher in the upper reaches. The highest pH (8.05) was observed in October 2021, while the lowest (7.03) was recorded in October 2020.

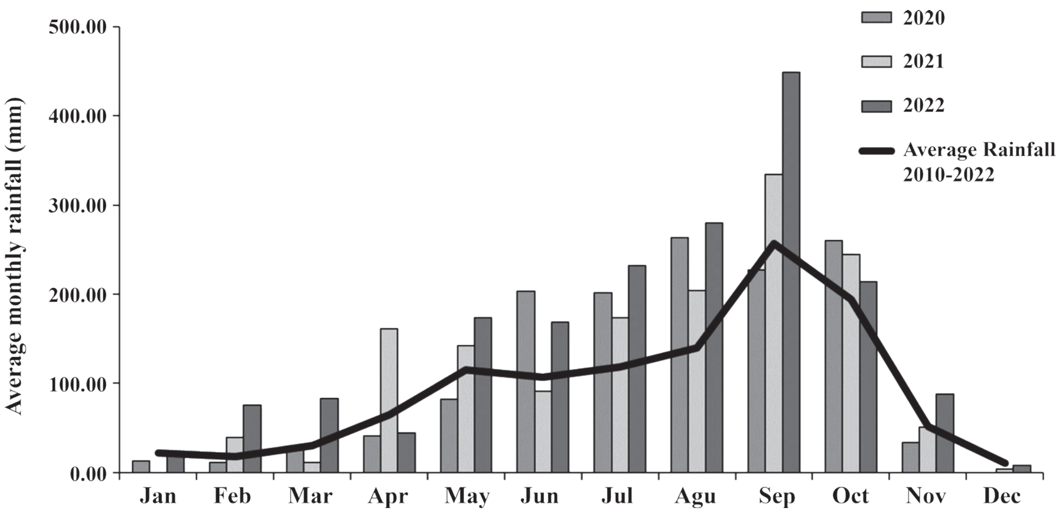

Figure 2. Monthly average rainfall (bar chart) in the Chao Phraya River Basin during 2020–2022, together with the long-term average monthly rainfall (black line) based on data from meteorological stations (TMD, 2022a).

Dissolved oxygen (DO) concentrations were generally higher in the upstream section and decreased toward the river mouth. Critically low DO levels (as low as 0.40 mg·L^{-1}) were detected at the river mouth during October 2020, September 2021, and May 2022. This pattern contrasted sharply with November 2020, when the highest DO concentration (5.80 mg·L^{-1}) was recorded at the same location (Figure 3).

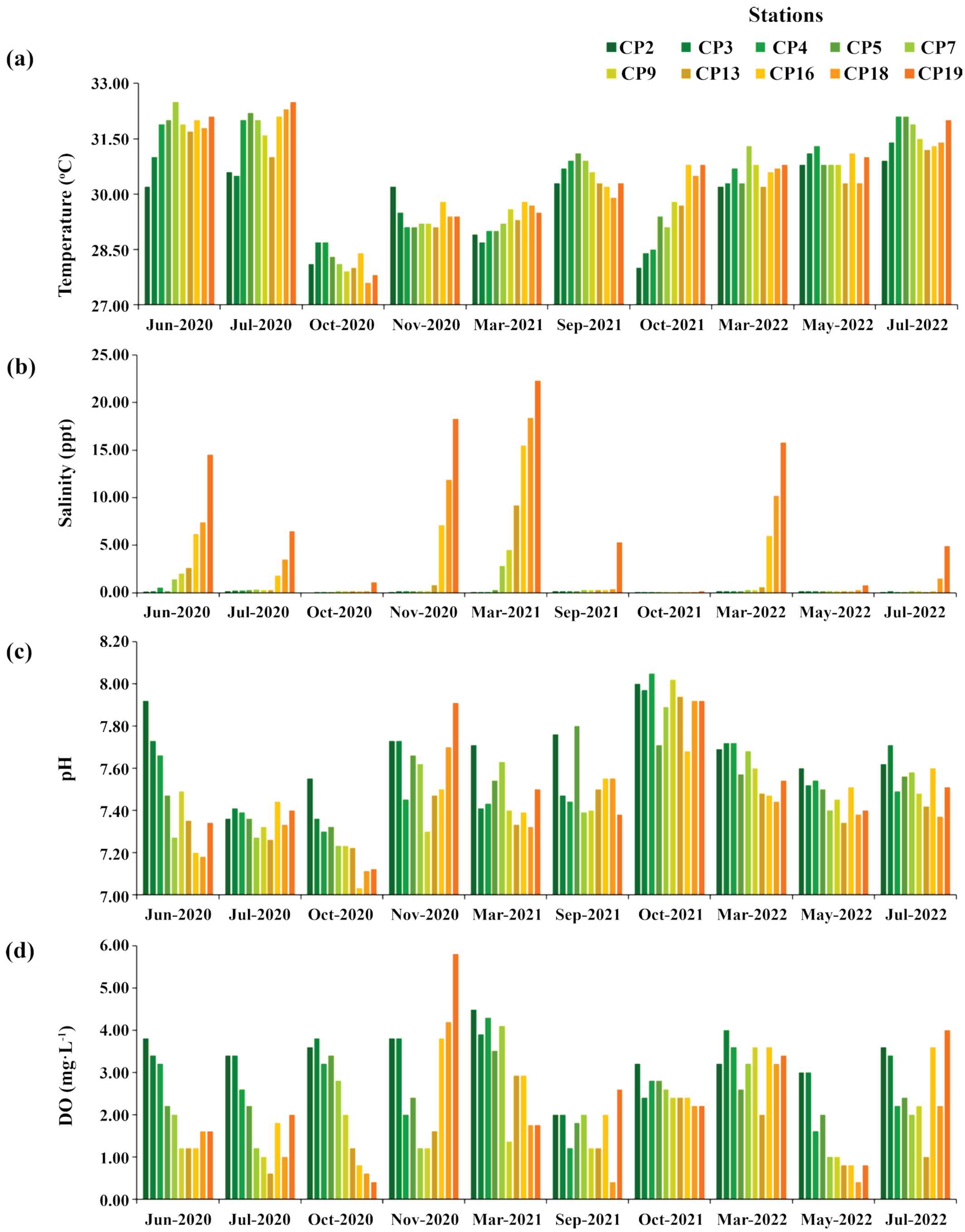

Figure 3. Monthly variation in water quality parameters: (a) temperature, (b) salinity, (c) pH, and (d) dissolved oxygen (DO) in the Chao Phraya River.

Chlorophyll-*a*, biochemical oxygen demand (BOD), and total suspended solids (TSS) were generally lower upstream and increased toward the middle to lower sections of the study area, near the estuarine zone. Chlorophyll-*a* concentrations peaked at 133.60 µg·L^{-1} in July 2020 and dropped to their lowest levels (0.32 µg·L^{-1}) in October and November 2020. BOD was lowest at Station CP4 (upper part) in November 2020 (0.60 mg·L^{-1}) and highest at Station CP9 (middle part) in June 2020 (10.68 mg·L^{-1}). Similarly, TSS concentrations peaked at 331.00 mg·L^{-1} in June 2020 and declined to a minimum of 3.60 mg·L^{-1} in November 2020 (Figure 4).

The analysis of nutrient concentrations revealed considerable variation in silicate levels, although values remained relatively consistent along the river. Notably, silicate concentrations were higher in the upper reaches, decreased in the central section, and rose slightly again near the river mouth. The highest silicate concentration (8,232.23 µg Si·L^{-1}) was observed at the middle part of the study area in November 2020 at Station CP5, while the lowest (297.31 µg Si·L^{-1}) occurred in March 2021 at Stations CP7 and CP9.

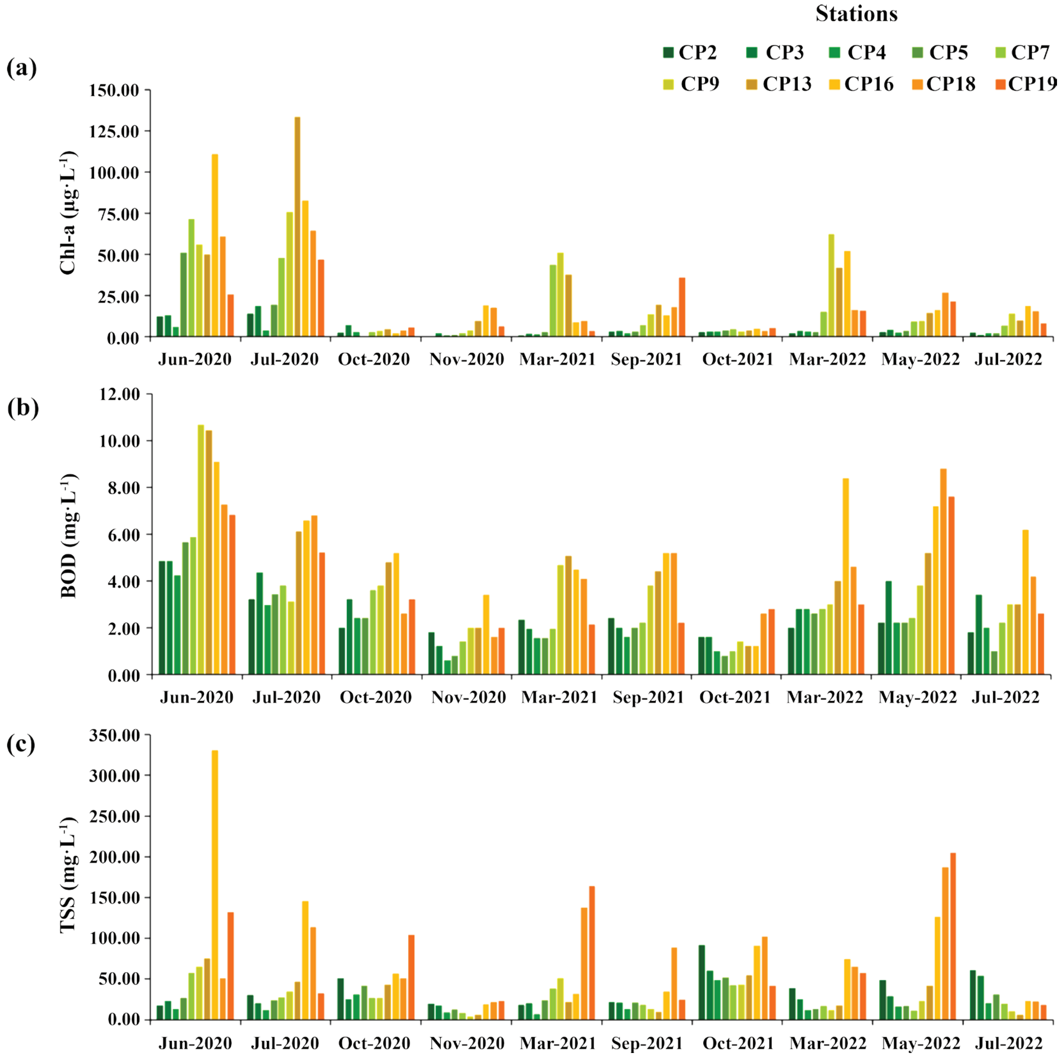

Figure 4. Monthly variations in water quality parameters: (a) chlorophyll-*a* (Chl-*a*), (b) biological oxygen demand (BOD), and (c) total suspended solids (TSS) in the Chao Phraya River.

Orthophosphate and total dissolved phosphorus (TDP) levels were generally low in the upstream area but increased downstream, particularly near the river mouth. Exceptions occurred in November 2020 and March 2021, when unusually high concentrations were detected in the central section at Station CP9 (middle part). The highest dissolved phosphorus concentrations (10,358.83 µg $P \cdot L^{-1}$) were recorded in November 2020, while the lowest orthophosphate and TDP values (32.41 µg $P \cdot L^{-1}$ and 34.04 µg $P \cdot L^{-1}$, respectively) were found in June 2020. Dissolved organic phosphorus (DOP) concentrations were lower than those of orthophosphate and TDP but were generally highest near the river mouth, peaking at 119.68 µg $P \cdot L^{-1}$ in March 2021 at Station CP19 (lower part). DOP was undetectable in November 2020 (Figure 5).

For nitrogen-related nutrients, most compounds showed increasing concentrations from the central to the lower part of the study area. However, nitrate displayed a distinct pattern, with lower concentrations in both the upper and lower sections and elevated levels in the central area. The highest ammonia concentration (2,700.98 µg $N \cdot L^{-1}$) was detected in November 2020 at Station CP16 (lower part), while the lowest (20.91 µg $N \cdot L^{-1}$) occurred in March 2022. Nitrite and nitrate concentrations peaked in March 2021 at Station CP16 (1,541.42 µg $N \cdot L^{-1}$) (lower part) and Station CP9 (2,706.99 µg $N \cdot L^{-1}$) (middle part), respectively. The lowest nitrite concentration (2.34 µg $N \cdot L^{-1}$) occurred in October 2020, and the lowest nitrate concentration (158.22 µg $N \cdot L^{-1}$) was recorded in November 2020.

Total dissolved nitrogen (TDN) and dissolved organic nitrogen (DON) were highest at Station CP16 (lower part) in November 2020, reaching 15,974.82 µg $N \cdot L^{-1}$ and 14,140.70 µg $N \cdot L^{-1}$, respectively. The lowest TDN concentration (297.38 µg $N \cdot L^{-1}$) was recorded in October 2021, and DON was undetectable during the same month (Figure 6).

Statistical analysis revealed significant seasonal variations in water quality parameters. Temperature, DO, TSS, silicate, orthophosphate, ammonia, TDN, TDP, DON, and DOP were significantly higher ($p<0.05$) during the wet season (May–November) than in the dry season (December–April), reflecting increased inputs from runoff. Conversely, salinity, pH, DO, chlorophyll-*a*, nitrite, and nitrate were significantly higher ($p<0.05$) in the dry season, likely due to reduced river discharge and seawater intrusion.

Spearman's rank correlations at a 95% confidence level were conducted to evaluate the relationships among physical, chemical, and biological water quality parameters during 2020–2022 (Figure 7). The results revealed several distinct patterns. Salinity, chlorophyll-a, BOD, nitrite, and nitrate exhibited significant positive correlations with temperature, indicating that warmer conditions were associated with higher concentrations of these parameters. In contrast, DO, silicate, and DON did not exhibit positive relationships with temperature, suggesting different responses to thermal variation.

Further analysis demonstrated that chlorophyll-*a*, BOD, and salinity were positively correlated with orthophosphate, ammonia, nitrite, nitrate, TDN, and TDP, suggesting that nutrient enrichment enhances both organic matter decomposition and phytoplankton growth. Conversely, these parameters were negatively correlated with pH and DO, implying that areas with intense biological activity and nutrient loading experienced reduced oxygen levels and slight acidification.

Silicate was negatively correlated with temperature, salinity, chlorophyll-*a*, biochemical oxygen demand, nitrite, and nitrate, indicating that conditions promoting biological productivity may simultaneously deplete silicate concentrations, possibly due to diatom uptake. Meanwhile, TSS was positively correlated with chlorophyll-*a*, BOD, ammonia, and nitrite, but negatively correlated with DO, suggesting that areas with higher particulate loads tended to experience greater oxygen depletion.

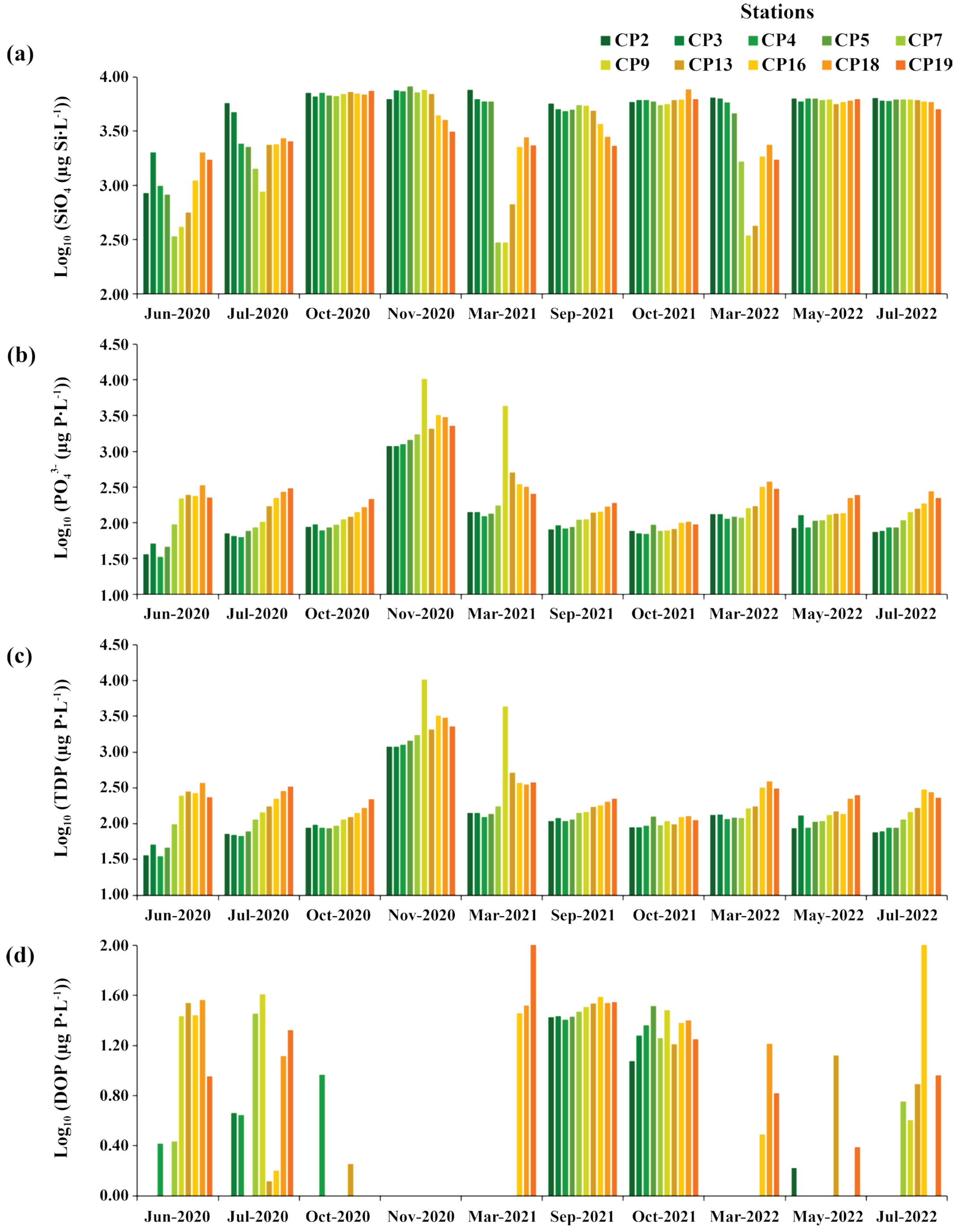

Figure 5. Monthly variations in water quality parameters: (a) silicate (SiO_4), (b) orthophosphate (PO_4^{3-}), (c) total dissolved phosphorus (TDP), and (d) dissolved organic phosphorus (DOP) in the Chao Phraya River.

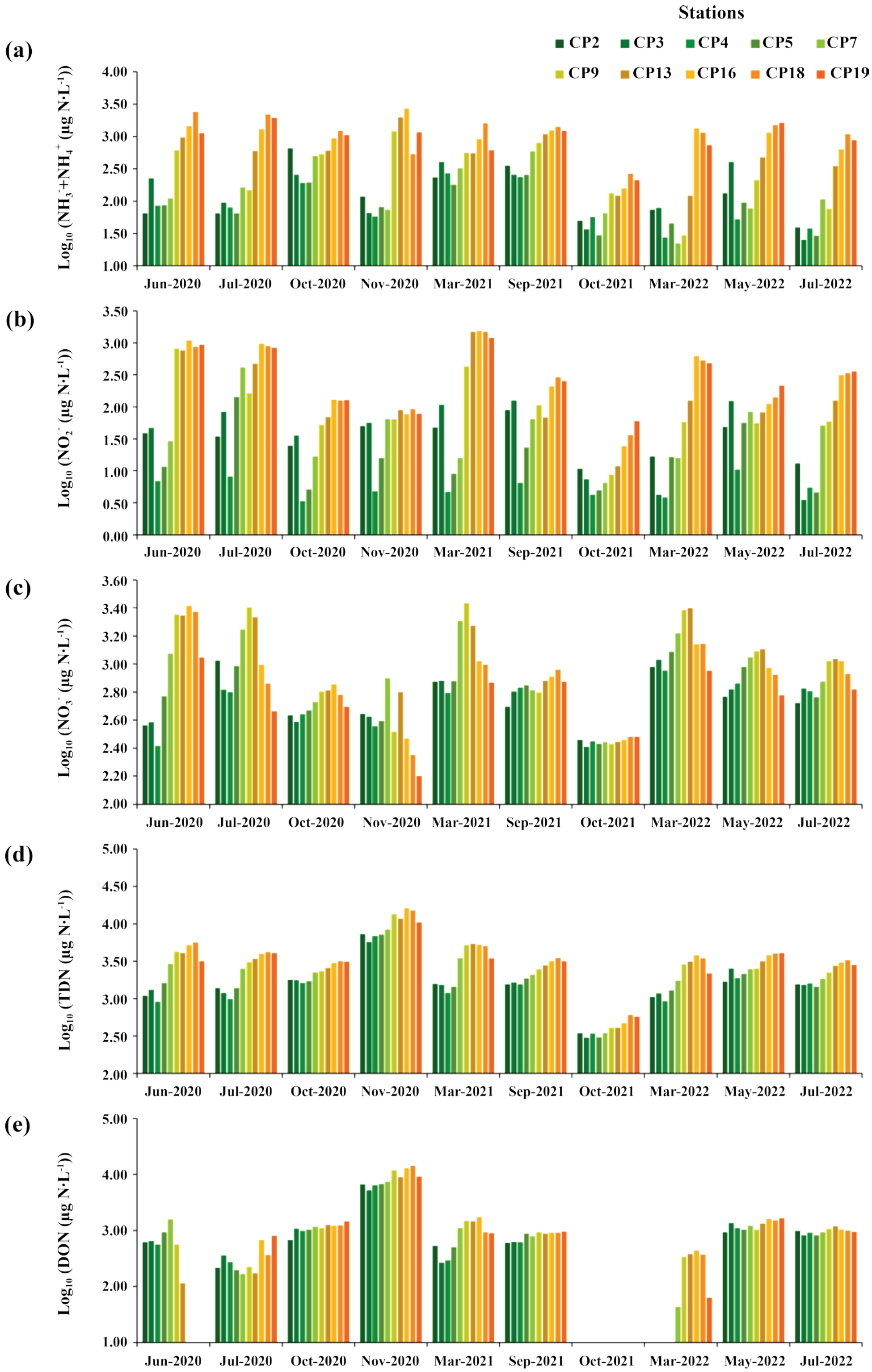

Figure 6. Monthly variations in water quality parameters: (a) ammonia (NH_3^-), (b) nitrite (NO_2^-), (c) nitrate (NO_3^-), (d) total dissolved nitrogen (TDN), and (e) dissolved organic nitrogen (DON) in the Chao Phraya River.

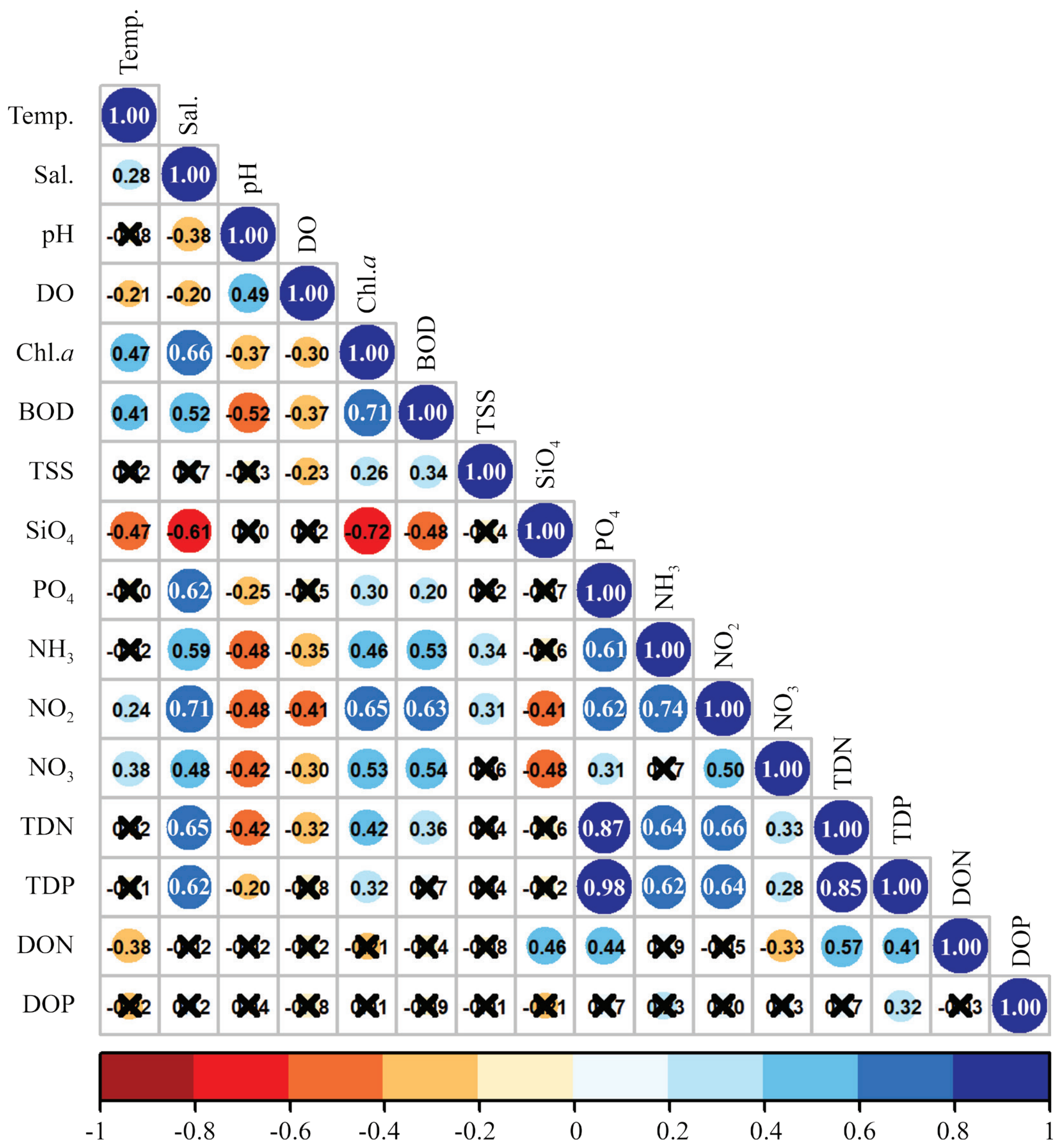

Figure 7. Spearman's rank correlation matrix of physical, biological, and chemical water quality parameters in the Chao Phraya River during 2020–2022.

Note: Correlation coefficients (r) are shown in the matrix. Values marked with "×" are not statistically significant ($p \geq 0.05$), while unmarked values indicate significant correlations ($p < 0.05$).

The proportion of dissolved inorganic nitrogen (DIN; comprising ammonia, nitrite, and nitrate) relative to dissolved organic nitrogen (DON) was analyzed (Figure 8). The results revealed temporal variations in the DIN:DON ratios, with DIN generally representing the dominant nitrogen form across most observed months. Elevated DIN contributions were observed in June 2020 (70.44: 29.56), July 2020 (84.81:15.19), October 2020 (50.59:49.41), March 2021 (72.54:27.46), September 2021 (64.40:35.60), October 2021 (100:0), and March 2022 (94.86:5.14). Conversely, more balanced ratios were recorded in May 2022 (53.42: 46.58) and July 2022 (53.07:46.93). These patterns suggest a predominance of DIN during specific periods, potentially influenced by seasonal runoff and anthropogenic inputs such as municipal and agricultural wastewater.

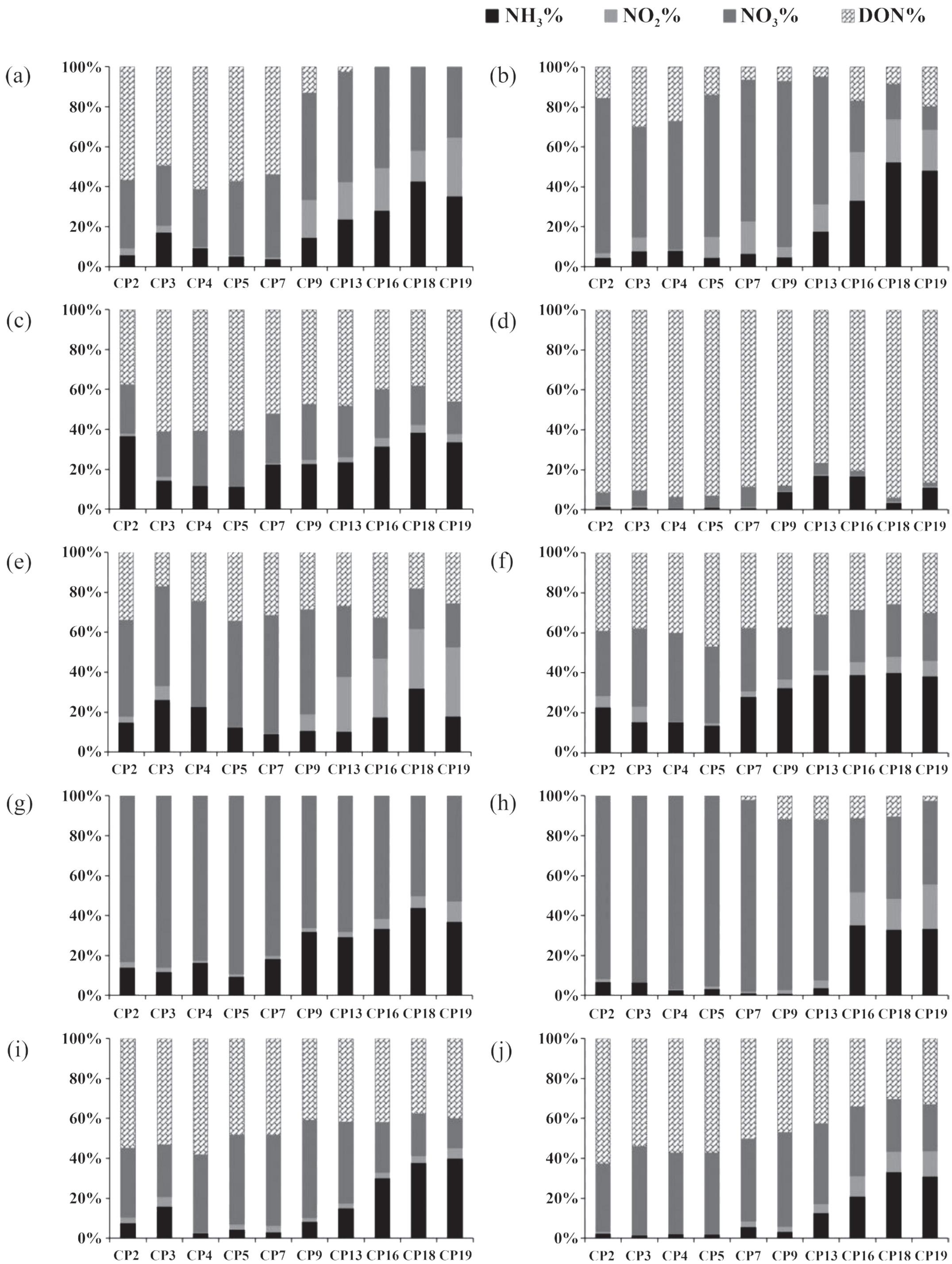

Figure 8. Monthly variation in the proportion of dissolved inorganic nitrogen (DIN) and dissolved organic nitrogen (DON) in the Chao Phraya River. Panels (a) to (j) represent individual observation periods: (a) Jun–2020, (b) Jul–2020, (c) Oct–2020, (d) Nov–2020, (e) Mar–2021, (f) Sep–2021, (g) Oct–2021, (h) Mar–2022, (i) May–2022, and (j) Jul–2022.

On average, DIN contributed approximately 65.56% of the total dissolved nitrogen pool, while DON contributed 34.44%. Within the DIN fraction, ammonia, nitrite, and nitrate comprised 17.97%, 6.26%, and 41.36%, respectively. A notable exception was observed in November 2020, when DON exceeded DIN across all stations, with an approximate ratio of 88.48% DON to 11.52% DIN.

For phosphorus, the proportion of dissolved inorganic phosphorus (DIP; orthophosphate) relative to dissolved organic phosphorus (DOP) consistently showed DIP dominance throughout the study period (Figure 9). In November 2020, the DIP:DOP ratio reached 100:0, indicating that only inorganic phosphorus was detected in the river. DOP was primarily present near the river mouth and was detected throughout the river during September and October 2021.

Water quality analysis revealed distinct monthly and seasonal variations in temperature. In 2020, the highest temperatures were recorded during the summer months of June and July, while the lowest occurred in October. Notably, the average annual temperature in Thailand in 2020 was approximately 28 °C–ranking as the second highest in 70 years, surpassed only by 2019. In contrast, October 2020 experienced slightly cooler conditions, with temperatures 0.2 °C below the climatological average (TMD, 2022b).

Salinity also showed marked seasonal variability. The highest values were observed in March 2021, coinciding with the dry season when limited rainfall and reduced river discharge allowed seawater to intrude further upstream. Comparison of salinity between March 2021 and March 2022 showed lower values in March 2022, attributed to greater rainfall and freshwater inflow relative to the previous year.

The pH values observed in the Chao Phraya River exhibited relatively little variation among months. Spatially, pH tended to be higher in the upper reaches of the study area, likely reflecting the influence of freshwater inflows, and lower toward the river mouth. This spatial pattern closely mirrored that of DO, which showed higher concentrations upstream and lower levels from the midstream area toward the estuary. The lowest DO concentrations (0.4 $mg \cdot L^{-1}$) were recorded in October 2020, September 2021, and May 2022.

In contrast, BOD displayed an opposite trend, generally low in the upper river but increasing downstream, particularly from the middle section to the river mouth. This pattern may be explained by the presence of a salinity front, where freshwater from upstream mixed with intruding seawater, creating conditions conducive to rapid microbial decomposition. These zones are also home to densely populated urban areas, including Nonthaburi, Bangkok, and Samut Prakan Provinces. The heavy discharge of untreated or inadequately treated wastewater in these areas often exceeds the river's natural assimilation capacity (PCD, 2020; 2021a), leading to elevated BOD levels while simultaneously depressing both pH and DO values.

Chlorophyll-*a* concentrations were generally highest near the salinity front. Elevated levels were particularly evident in June and July 2020, likely associated with the first rainfall events of the season, which delivered substantial inputs of nitrogen and phosphorus into the river system. This period also featured alternating rain and intense sunlight, conditions highly favorable for the rapid proliferation of algae and phytoplankton, the principal producers of chlorophyll-*a*. In contrast, chlorophyll-*a* concentrations were markedly low in October 2020 and October 2021, with consistently reduced values recorded along the entire river. These decreases may be attributed to overcast weather, high river discharge, decreased temperatures, and increased flow velocity, factors that together reduce the environmental stability needed for phytoplankton accumulation. Statistical analysis further revealed that high chlorophyll-*a* levels were positively correlated with increased BOD and elevated concentrations of dissolved inorganic nutrients, including ammonia, nitrite, nitrate, and phosphate, suggesting that nutrient enrichment plays a key role in phytoplankton productivity.

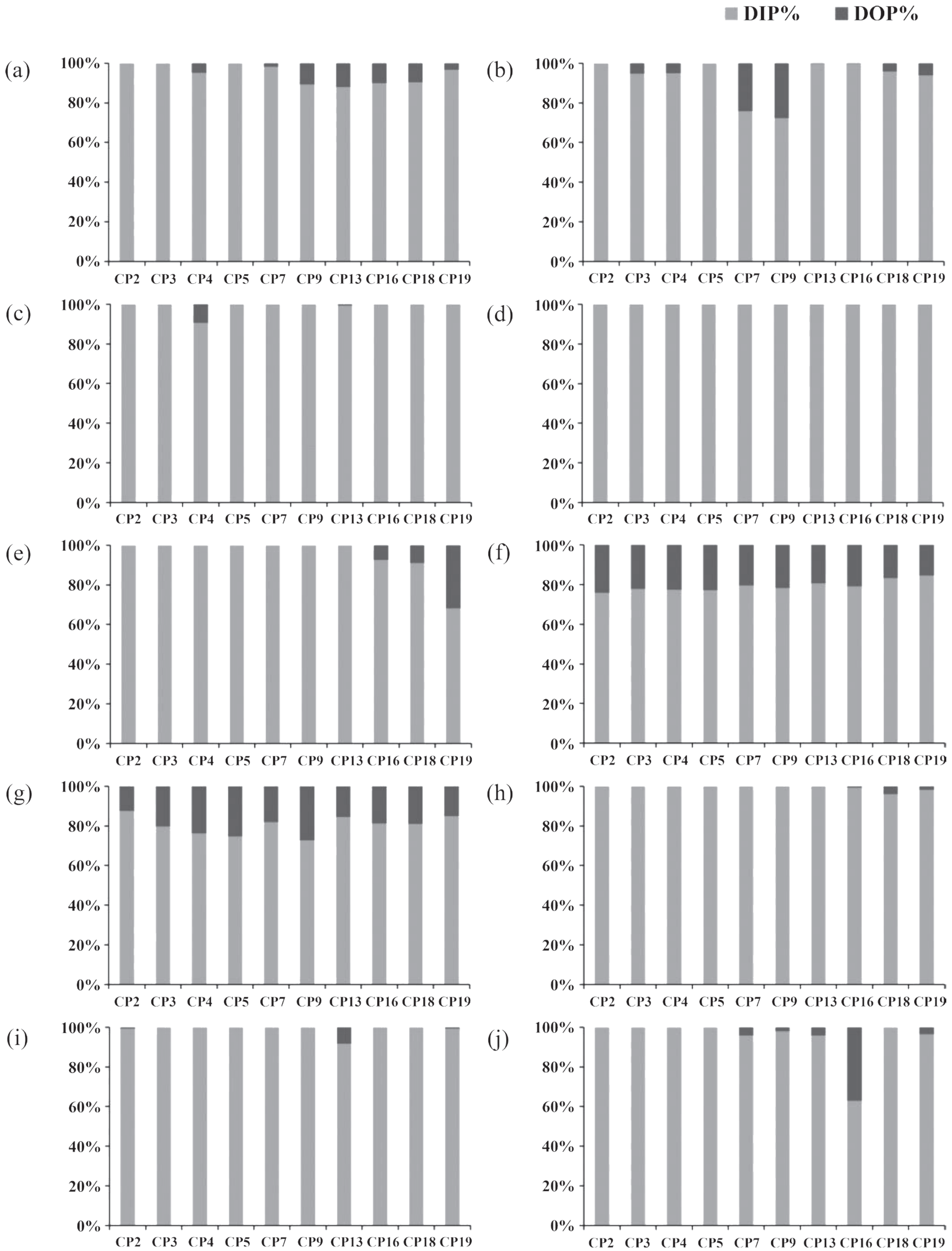

Figure 9. Monthly variation in the proportion of dissolved inorganic phosphorus (DIP) and dissolved organic phosphorus (DOP) in the Chao Phraya River. Panels (a) to (j) represent individual observation period: (a) Jun–2020, (b) Jul–2020, (c) Oct–2020, (d) Nov–2020, (e) Mar–2021, (f) Sep–2021, (g) Oct–2021, (h) Mar–2022, (i) May–2022, and (j) Jul–2022.

TSS concentrations were highest near the river mouth, particularly at Stations CP16, CP18, and CP19. TSS showed strong positive correlations with chlorophyll-*a* and BOD, but no apparent relationship with salinity. This lack of correlation likely reflects the composition of TSS, which includes planktonic particles–biological components not directly affected by salinity. The estuarine zone and is subject to dynamic physical processes such as tidal mixing, sediment resuspension, and estuarine circulation. These factors likely contribute to the uneven distribution of particulates and the decoupling of TSS concentrations from salinity gradients at the river mouth.

Silicate concentrations exhibited a distinct seasonal pattern, increasing toward the end of the year (wet season) and decreasing in the early months (dry season), in accordance with Thailand's monsoonal climate. Spatially, silicate levels were generally consistent along the river but followed a subtle pattern, higher in the upper reaches, lower in the midsection, and slightly higher again near the river mouth. This variability may be associated with regional geological characteristics or biogeochemical processes at the freshwater–seawater interface. Notably, in June 2020, July 2020, March 2021, and March 2022, silicate concentrations declined in the midsection, precisely where chlorophyll-*a* levels were elevated. This inverse relationship suggests enhanced diatom growth, as these phytoplankton require silicate to form their frustules. Their rapid proliferation likely caused localized silicate depletion in those zones.

The spatial distribution of phosphorus nutrients revealed that concentrations of orthophosphate and TDP were generally low in the upstream areas and gradually increased downstream toward the river mouth. This pattern suggests that the primary sources of phosphorus are concentrated in the lower reaches of the river and/or that accumulation occurs as water flows seaward. However, exceptions were observed in November 2020 and March 2021, during which markedly elevated concentrations of both orthophosphate and TDP were detected in the midstream area, particularly at Station CP9. This anomaly is likely linked to domestic wastewater discharge, as the area encompasses parts of Bangkok–a highly urbanized and densely populated city known to contribute significant phosphorus loads (Wang *et al*., 2021).

Runoff from agricultural areas using phosphorus-based fertilizers represents another important source. In November 2020, both orthophosphate and TDP levels peaked across all sampling periods, while DOP was not detected. This may be attributed to large-scale water releases from agricultural zones, which typically occur after 2–3 months of water retention (Phuboonkong, 2023). The organic phosphorus derived from decomposed plant and organism remains undergoes microbial mineralization, a process in which microorganisms convert DOP into DIP before it enters the river (Condron *et al*., 2005). Consequently, the elevated phosphate levels observed during this period likely resulted from both direct fertilizer input and microbial decomposition.

Throughout the study, DOP concentrations remained lower than those of orthophosphate and TDP. Nonetheless, DOP levels tended to increase near the estuarine zone, possibly indicating the accumulation of organic material from anthropogenic activities or intensified biological processes occurring in the freshwater–seawater mixing zone.

The study of nitrogen-based nutrients revealed a clear spatial pattern, with concentrations of ammonia, nitrite, TDN, and DON increasing significantly from the midstream region toward the river mouth. This trend strongly indicates the presence of major nitrogen sources in the lower Chao Phraya River, likely stemming from agricultural runoff, domestic sewage, and industrial discharges, which may become more concentrated as water flows into the Gulf of Thailand. In Bangkok, an estimated 2.1 million cubic meters of wastewater is generated daily, but only about 881,003 cubic meters (41.76%) are treated effectively. Consequently, approximately 1.23 million cubic meters–or 58.24%–of untreated wastewater is discharged directly into natural water bodies (Rocket Media Lab, 2022). This results in a significant gap between generated and treated wastewater volumes (PCD, 2023), which directly contributes to elevated nitrogen levels in the river.

Nitrate was notably elevated in the midstream section. This could be linked to the nitrification processes occurring in centralized wastewater treatment systems, where ammonia is biologically oxidized to nitrate under aerobic conditions. This nitrate-rich effluent is then discharged into the river (Noophan *et al*., 2009). However, nitrate concentrations declined near the river mouth, possibly due to dilution by seawater or denitrification occurring under anoxic conditions. The exceptionally high levels of DON observed in November 2020 may have resulted from the release of agricultural drainage water in the rice field containing organic nitrogen compounds into the Chao Phraya River during that period (Phuboonkong, 2023). The low levels of DOP observed were due to the faster decomposition of DOP to DIP compared to DON to DIN (Agedah *et al*., 2009; Thompson and Cotner, 2018), leading to high DON (low DIN) but low DOP (high DIP) in the river during this period.

Salinity differences of $\geq$ 5 ppt between stations indicated the presence of distinct salinity fronts, which were associated with significantly higher concentrations of nutrients, particularly nitrogen and phosphorus, compared to adjacent areas. This threshold was defined based on field observations, where abrupt shifts in salinity coincided with strong gradients in turbidity and nutrient levels, marking a clear transition between freshwater and seawater mixing zones. These nutrient enrichments are largely influenced by anthropogenic inputs, such as wastewater and runoff, as well as natural biogeochemical processes. The elevated nutrient concentrations in these zones stimulate algal and phytoplankton growth, as reflected by the higher chlorophyll-*a* values. This, in turn, enhances the microbial decomposition of organic matter, leading to increased BOD. The release of nutrients during decomposition further reinforces primary productivity, establishing a positive feedback loop. Meanwhile, the decomposition process consumes oxygen and lowers pH, contributing to the observed negative correlations of DO and pH with salinity.

Silicate, on the other hand, exhibited negative correlations with temperature, chlorophyll-*a*, and salinity. Typically, silicate concentrations are higher during the wet season due to terrestrial inputs from river runoff.

According to the Pollution Control Department (PCD, 1994), the middle section of the Chao Phraya River is designated as a Type 3 surface water resource, intended for agricultural use. The corresponding water quality standards specify that DO should not fall below 4 $mg \cdot L^{-1}$, BOD should not exceed 2 $mg \cdot L^{-1}$, ammonia should not exceed 0.5 mg $N \cdot L^{-1}$, and nitrate should not exceed 5 mg $N \cdot L^{-1}$. Meanwhile, the lower Chao Phraya River is classified as a Type 4 surface water resource, intended for industrial use, with more relaxed standards: dissolved oxygen not less than 2 $mg \cdot L^{-1}$, biochemical oxygen demand not more than 4 $mg \cdot L^{-1}$, ammonia not more than 0.5 mg $N \cdot L^{-1}$, and nitrate not more than 5 mg $N \cdot L^{-1}$.

Based on the findings of this study, water quality in both river sections failed to comply with the designated standards. In the middle section, noncompliance rates were as follows: DO (92%), BOD (54%), ammonia (6%), and nitrate (0%). In the lower section, DO failed to meet standards in 54% of samples, BOD in 58%, ammonia in 76%, while nitrate remained within the standard in all samples (0% noncompliance). These results are consistent with national water quality reports from 2020 to 2022 (PCD, 2021b; 2022; 2023).

Principal component analysis (PCA) was used to examine spatiotemporal patterns of water quality variation in the Chao Phraya River. The results were presented in a PCA biplot showing the first and second principal components (PC1 and PC2) at a 95% confidence level (Figure 10). The analysis revealed a consistent distribution pattern of water quality during both the dry and wet seasons. According to the classification by the Pollution Control Department (PCD, 1994), the sampling stations could be grouped into two main clusters. The middle Chao Phraya River stations (CP2, CP3, CP4, CP5, and CP7) were located on the right side of the plot and were influenced primarily by DO, pH, and silicate. In contrast, the lower Chao Phraya River stations (CP9, CP13, CP16, CP18, and CP19) were distributed on the left side of the plot and were strongly associated with higher concentrations of nitrogen and phosphorus nutrients, as well as chlorophyll-*a*. This distribution reflects a clear difference in water quality between the middle and lower parts of the river. The lower section showed higher nutrient accumulation, indicating an increased risk of eutrophication, while the middle section generally had better water quality.

The heat map based on the Average Annual River Load–Principal Component (AARL-PC) Score illustrates the trophic status of the Chao Phraya River at ten stations from June 2020 to July 2022 (Figure 11). Stations in the middle

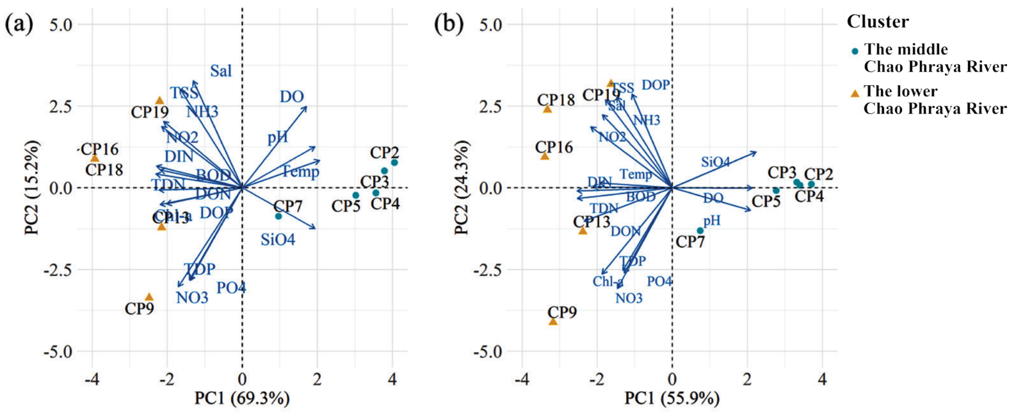

Figure 10. Principal component analysis (PCA) biplots of water quality parameters in the Chao Phraya River during the wet (a) and dry (b) seasons. Symbols and colors represent two river sections (Middle vs Lower Reach).

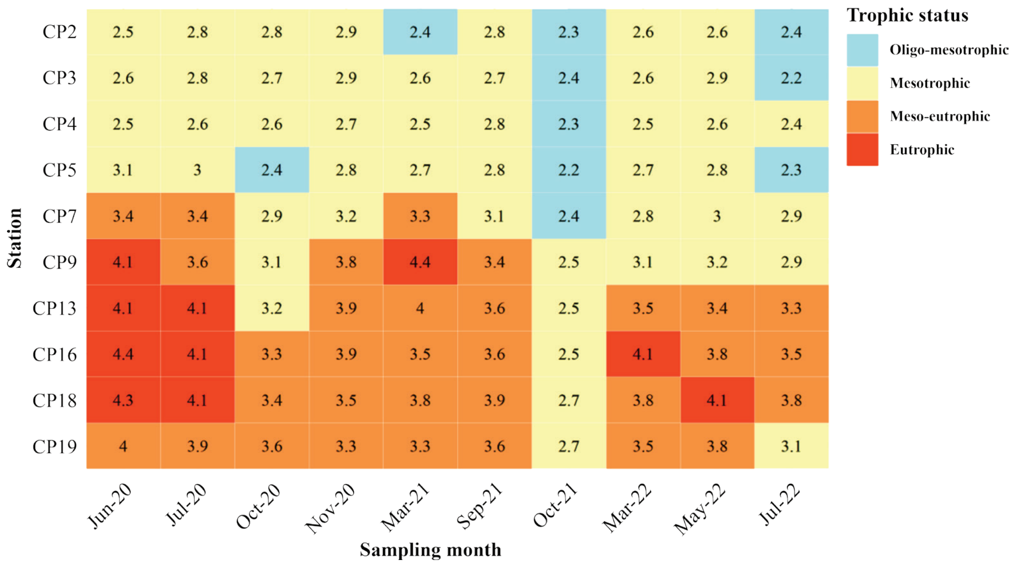

Figure 11. Heat map illustrates the spatial variation of trophic status in the Chao Phraya River, derived from the AARL-PC Score index. The classification indicates relative nutrient enrichment levels across sampling stations during the study period.

section (CP2–CP7) consistently showed low scores (<3.0), indicating better water quality with low to moderate nutrient levels. In contrast, stations in the lower section (CP9–CP19) showed higher scores, particularly at CP13 to CP18, where values frequently exceed 4.0, reflecting pronounced nutrient enrichment and potential eutrophic conditions.

The highest scores were recorded in March and May 2021, suggesting peak eutrophication events in the lower estuarine zone. Conversely, scores in October 2021 decreased markedly across most stations, particularly in the lower river, indicating a temporary improvement in water quality, likely due to dilution from increased freshwater inflow during the peak wet season. By contrast, the higher scores during the dry season correspond to reduced river flow, which diminishes flushing capacity and prolongs residence time, leading to nutrient accumulation in the lower Chao Phraya River.

This spatial and temporal pattern aligns closely with the PCA results, which also revealed that lower-river stations were strongly associated with elevated nitrogen, phosphorus, and chlorophyll-*a* concentrations, whereas middle-river stations correlated with higher DO, pH, and silicate. Collectively, these findings highlight a distinct spatial disparity in trophic status between the middle and lower river sections, with the lower reach being more vulnerable to nutrient accumulation and eutrophication pressure.

According to Uthaipan *et al*. (2025), water quality in the Chao Phraya River has steadily declined. The main drivers are socioeconomic pressures, urban expansion, rising population density, and industrial growth, which have contributed to increasing nitrogen, phosphorus, BOD, and coliform bacteria levels, alongside declining DO, particularly in the lower river. While hydrological factors such as rainfall and flow affect dilution and transport, their influence appears secondary to anthropogenic pressures. Previous studies similarly reported that the lower section consistently exhibited the poorest conditions, characterized by low DO and elevated BOD and ammonia. The midstream section generally showed slightly better water quality than the lower reach (Avakul and Jutagate, 2012). Similarly, Singkran *et al*. (2019) reported an increasing DO gradient from downstream to upstream, while BOD, ammonia, and total dissolved phosphorus concentrations decreased along the same transect–findings that are consistent with the present study.

When comparing the results of this study (2020–2022) with previous surface water quality assessments in the midstream and downstream sections of the Chao Phraya River (Table 6), a clear deterioration in water quality is evident. The decline in DO concentrations reflects increasing oxygen deficiency, particularly in the lower river, which may have significant ecological implications. Concurrent increases in BOD and total dissolved phosphorus indicate a rise in organic matter and phosphorus pollution, consistent with intensified human activities in the catchment. Although nitrate and ammonia levels were slightly lower than those reported in earlier studies, the overall pattern highlights growing anthropogenic pressures and continued nutrient loading.

The deterioration observed in the Chao Phraya River reflects broader global patterns of eutrophication and hypoxia in coastal and estuarine systems. The continual discharge of nutrient-rich effluents, particularly nitrogen and phosphorus compounds, not only degrades riverine water quality but also threatens downstream coastal ecosystems, including the Gulf of Thailand. International studies have demonstrated that coastal eutrophication leads to persistent hypoxia, disrupting ecosystem functioning, diminish biodiversity, and undermining fisheries and aquaculture productivity. Hence, the ongoing decline in DO in the lower Chao Phraya River represents more than a localized issue: it forms part of a land-to-sea continuum of anthropogenic impact. Without timely intervention, such conditions are likely to increase the frequency and severity of hypoxic events in the Gulf of Thailand, triggering cascading socio-ecological consequences.

Table 6. Comparison of mean (±SD) water quality parameters between historical datasets (1990–2017 and 1991–2008) and the present study (2020–2022) for the middle and lower sections of the Chao Phraya River.

Parameter ($mg \cdot L^{-1}$)	River section	1990–2017[1]		1991–2008[2]	2020–2022 (this Study)		
		Wet season	Dry season	Overall	Wet season	Dry season	Overall
DO	Middle	4.4±1.23	4.2±1.23	2.9±1.20	2.6±0.81	3.7±0.58	2.8±0.88
	Lower	2.0±1.33	1.8±1.35	1.2±0.60	1.8±1.18	2.7±0.85	1.9±1.17
BOD	Middle	1.5±1.84	1.6±1.77	1.9±0.90	2.6±1.35	2.2±0.50	2.5±1.23
	Lower	3.5±1.71	3.7±1.85	4.3±1.50	4.6±2.53	4.4±1.69	4.6±2.37
$NH_3+NH_4^+$	Middle	-	-	1.4±3.70	0.2±0.15	0.2±0.14	0.2±0.15
	Lower	-	-	2.3±2.90	1.0±0.66	0.8±0.50	0.9±0.63
NO_3^-	Middle	0.9±1.69	0.9±1.64	-	0.6±0.30	1.1±0.45	0.7±0.38
	Lower	1.4±1.71	1.4±1.69	-	0.9±0.67	1.6±0.73	1.1±0.73
TP	Middle	0.1±0.15	0.1±0.27	-	0.3±0.43	0.1±0.02	0.2±0.39
	Lower	0.2±0.19	0.2±0.17	-	0.7±1.74	0.7±1.28	0.7±1.65

Source: [1]Singkran *et al*., 2019; [2]Avakul and Jutagate, 2012
Note: Wet season (May–November), Dry season (December–April)

Consequently, improving river water quality through integrated watershed management and targeted nutrient-reduction strategies is essential for mitigating degradation across both freshwater and coastal ecosystems (Dai *et al*., 2023). Long-term monitoring and the application of ecosystem-based management approaches will be critical to sustain the ecological integrity of the Chao Phraya River and safeguard the productivity of the connected marine environment.

The Chao Phraya River, often referred to as the lifeline of Thailand, continues to experience water quality deterioration driven by rapid urbanization and industrial expansion. Elevated BOD and nutrient concentrations in the lower river raise serious concerns about eutrophication and subsequent hypoxic conditions, as DO levels frequently fell below 2 $mg \cdot L^{-1}$. These conditions are comparable to those observed in other large tropical river systems. For instance, the Ganges River in India has shown gradual improvement under the Namami Gange Program, which expanded wastewater treatment capacity, strengthened monitoring systems, and enforced stricter regulations on industrial effluents (Chaurasia *et al*., 2024). Likewise, in the Mekong River Basin, transboundary cooperation and the implementation of enhanced monitoring frameworks have improved scientific understanding of nutrient fluxes and supported the development of targeted pollution control strategies (Sor *et al*., 2021).

Therefore, comprehensive and effective water quality management and wastewater treatment systems in Thailand should be expanded from the current 41.76% treatment coverage to full basin-wide implementation. Such actions are essential to mitigate potential hypoxia in the Chao Phraya River and reduce eutrophication severity in the Inner Gulf of Thailand, which receives the river's discharge.

CONCLUSIONS

Between 2020 and 2022, the Chao Phraya River exhibited recurring hypoxic conditions, with DO frequently below 2 $mg \cdot L^{-1}$, particularly in the lower reaches. Nutrient enrichment, especially from dissolved nitrogen and phosphorus compounds, was closely linked to phytoplankton blooms, as reflected by elevated chlorophyll-*a* concentrations near the salinity front. Nitrate contributed approximately 41.36% of total dissolved nitrogen, suggesting active nitrification within wastewater systems. A sharp increase in DIP in November 2020 likely following agricultural drainage.

PCA revealed a clear spatial separation between midstream and downstream stations, with eutrophic conditions concentrated in the lower river. This finding was corroborated by the AARL-PC Score, which consistently showed high trophic levels in downstream areas, particularly in June and July 2020.

Collectively, these findings highlight progressive nutrient-driven degradation in the Chao Phraya River and emphasize the urgent need for long-term, integrated pollution control and catchment -scale management strategies to restore and sustain water quality across the entire river basin.

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to the students and faculty members of the Oceanography Group, Department of Aquatic Science, Faculty of Science, Burapha University, for their kind support in providing field equipment, chemical supplies, and laboratory facilities for water sample analysis. We also extend our appreciation to the Thai Meteorological Department for providing rainfall data used in this study. This research was partially supported by the Graduate School of Burapha University under the Thesis Grant for Graduate Students, Fiscal Year 2023, and JSPS KAKENHI Grant Number 22KK0167.

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