Seasonal Fluxes of Dissolved Nutrients and Suspended Solids at the Tha Chin River Mouth, Thailand (2023–2024)

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ABSTRACT

Eutrophication in the inner Gulf of Thailand is strongly influenced by nutrient discharges from multiple river systems, with the Tha Chin River being one of the major sources. This study assessed concentrations and land–sea fluxes of dissolved nutrients and total suspended solids (TSS) at the river mouth from 2022 to 2023 across wet, dry, and transitional seasons of the Tha Chin River. Sampling was conducted every 25 h over full tidal cycles. Dissolved oxygen levels remained critically low throughout the period, ranging from 0.66 to 2.87 $mg \cdot L^{-1}$. TSS peaked in the transitional season (497.41±347.44 $mg \cdot L^{-1}$) and was lowest during the wet season (38.64±43.93 $mg \cdot L^{-1}$). Ammonia (612.91–1,291.49 µg $N \cdot L^{-1}$) and DIP (165.34–265.42 µg $P \cdot L^{-1}$) reached hypertrophic levels, with nitrogen identified as the limiting nutrient based on the Redfield ratio. Water fluxes peaked in the wet season (61.26×10^6 $m^3 \cdot d^{-1}$), over five times higher than in the dry season. The Tha Chin River delivered substantial nutrient loads: ammonia fluxes were 38.42 t $N \cdot d^{-1}$ (wet), 20.20 t $N \cdot d^{-1}$ (dry), and 36.70 t $N \cdot d^{-1}$ (transitional). DIP fluxes were 10.43, 4.04, and 4.78 t $P \cdot d^{-1}$, respectively. TSS flux was highest during the transitional season (4,749.77 $t \cdot d^{-1}$) and lowest in the dry season (1,571.86 $t \cdot d^{-1}$). Normalized to watershed area, the Tha Chin River yielded higher net DIN and DIP loads than other major Thai rivers. These findings underscore the river's key role in eutrophication and red tide formation in the inner Gulf, emphasizing the urgent need for effective watershed and nutrient management to mitigate coastal ecosystem degradation.

Keywords: Eutrophication, Nutrients fluxes, Suspended solids fluxes, Tha Chin River

INTRODUCTION

Eutrophication occurs when water bodies receive excessive nutrient inputs (Akinnawo, 2023). This nutrient surplus trigger rapid phytoplankton growth, leading to blooms. As the blooms decay, microbial decomposition consumes oxygen, further depleting oxygen levels and contributing to hypoxia. Both nutrient enrichment and oxygen loss harm aquatic life and disrupt ecosystem balance. Globally, eutrophication has become more frequent and sever, with well-documented cases in the Chesapeake Bay (Zimmerman and Canuel, 2000), the Baltic Sea (Rönnberg and Bonsdorff, 2004), and the Zhujiang River Estuary (Zhang *et al.*, 2022), all primarily linked to anthropogenic nutrient inputs. The inner Gulf of Thailand is similarly affected, with major nutrient contributions from rivers. Among them, the Tha Chin River plays a significant role, carrying high nutrient loads and exhibiting persistently low dissolved oxygen levels (Thaipichitburapa *et al.*, 2010). This makes it a major source of nutrients that exacerbate eutrophication in the inner Gulf of Thailand (Meksumpun, 2021).

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The Tha Chin River, one of four main rivers feeding the inner Gulf of Thailand (Jaritkhuan *et al*., 2010), stretches approximately 325 km. It branches off the Chao Phraya River in Chai Nat Province and flows through Suphan Buri Province and Nakhon Pathom Province before reaching the inner Gulf of Thailand in Samut Sakhon Province (Figure 1). Its 13,492 km^2 basin (Thaipichitburapa *et al*., 2010) supports agriculture, industry, aquaculture, and residential use (HAII, 2018). Land use is dominated by agriculture (76.39%), followed by residential/industrial (9.06%), and forests (8.84%) areas (HAII, 2018). Both natural processes and human activities contribute to nutrient accumulation, especially in downstream areas, often exceeding water quality standards and causing hypoxia (Meksumpun and Meksumpun, 2008).

River flux studies track the movement and direction of substances to determine whether they flow seaward or landward (Meesub *et al*., 2021). These studies are essential for understanding nutrient inputs to coastal waters and their role in eutrophication. For example, the Jiulong River Estuary showed increased dissolved inorganic nitrogen (DIN) and inorganic phosphorus (DIP) fluxes linked to land use and fertilizer input between 2006 to 2012 (Wu *et al*., 2017). Similarly, nutrient fluxes from the Yangtze River to the East China Sea varied seasonally with discharge and were influenced by fertilizer use, correlating with red tide occurrence (Yang *et al*., 2023). The Mississippi River Basin also exemplifies how nutrient runoff, primarily from agriculture, causes hypoxia in the Gulf of Mexico (Rabalais *et al*., 2014). These global examples emphasize the influence of human activity on nutrient transport and its impact on coastal ecosystems.

The most recent study of nutrient fluxes in the Tha Chin River was conducted in 2008 (Thaipichitburapa *et al*., 2010). In light of environmental changes since then, an updated assessment is needed. This study investigates seasonal fluxes of dissolved nutrients, including ammonia (NH_3+NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), total dissolved nitrogen (TDN), total dissolved phosphorus (TDP), and dissolved inorganic silicate (DISi), and total suspended solids (TSS) at the river mouth across wet, dry, and transitional seasons. Our findings provide insights into seasonal nutrient dynamics and fluxes entering the inner Gulf of Thailand which are essential for pollution sources and their potential link to red tide events in the region.

MATERIALS AND METHODS

The flux measurement station is located at the mouth of the Tha Chin River, between latitude 13°31'8.56"N–13°31'17.24"N and longitude 100°16'1.59"E–100°16'17.28"E (Figure 1). Sampling and data collection were conducted during three periods: 28–29 October 2022 (wet season), 17–18 February 2023 (dry season), and 3–4 July 2023 (transition period). Each measurement session employed an Acoustic Doppler Current Profiler (ADCP) mounted on a floating buoy, which was towed across the river by a small boat traveling at approximately 1.5 $m\cdot s^{-1}$ to measure water flux. Measurements were repeated twice every 2.5 h over a 25–h period to capture a full tidal cycle. Simultaneously, water samples were collected using 2–L water samplers at two depths: 1 m below the surface (surface) and 1 m above the riverbed (bottom). These samples were analyzed for dissolved oxygen (DO), total suspended solids (TSS), total dissolved nitrogen and phosphorus, and dissolved inorganic compounds including ammonia, nitrite, nitrate, phosphate, and silicate (as summarized in Table 1). Temperature and salinity were measured mid-channel using a multi-parameter water quality instrument (YSI 6920) and pH was recorded with a Horiba PD 110 pH meter. Statistical analyses, including the Kruskal-Wallis test and Spearman correlation coefficients, were applied at a 95% confidence level ($p<0.05$), as the data did not meet the assumption of a normal distribution.

The fluxes of dissolved nutrients and total suspended solids (F) were calculated by multiplying the water flux (Q) by the concentration (C) of dissolved nutrients and suspended solids (Equation 1). Water flux was determined by multiplying the cross-sectional area of the river by the velocity of water flow. The total measurement

Table 1. Analytical methods used for water quality parameter measurements.

Parameter	Unit	Methods
Dissolved oxygen (DO)	mg·L^{-1}	Azide modification of the Winkler Method (Strickland and Parsons, 1972)
Biochemical oxygen demand (BOD)	mg·L^{-1}	5-day BOD test, Azide-modification of the Winkler Method (Strickland and Parsons, 1972)
Total suspended solids (TSS)	mg·L^{-1}	GF/F Filter (APHA, 1992)
Ammonia (NH_3+NH_4^+)	µg N·L^{-1}	Phenol-hypochlorite (Grasshoff *et al*., 1999)
Nitrite (NO_2^-)	µg N·L^{-1}	Diazotization (Strickland and Parsons, 1972)
Nitrate (NO_3^-)	µg N·L^{-1}	Cadmium reduction+Diazotization (Strickland and Parsons, 1972)
Dissolved inorganic nitrogen (DIN)	µg N·L^{-1}	Ammonia+Nitrite+Nitrate
Total dissolved nitrogen (TDN)	µg N·L^{-1}	Persulphate oxidation+Cadmium reduction+ Diazotization (Grasshoff *et al*., 1999)
Dissolved inorganic phosphate (DIP, PO_4^-)	µg P·L^{-1}	Ascorbic acid (Strickland and Parsons, 1972)
Total dissolved phosphorus (TDP)	µg P·L^{-1}	Acid persulphate oxidation+Ascorbic acid (Grasshoff *et al*., 1999)
Dissolved inorganic silicate (DISi)	µg Si·L^{-1}	Silicomolypdate (Strickland and Parsons, 1972)

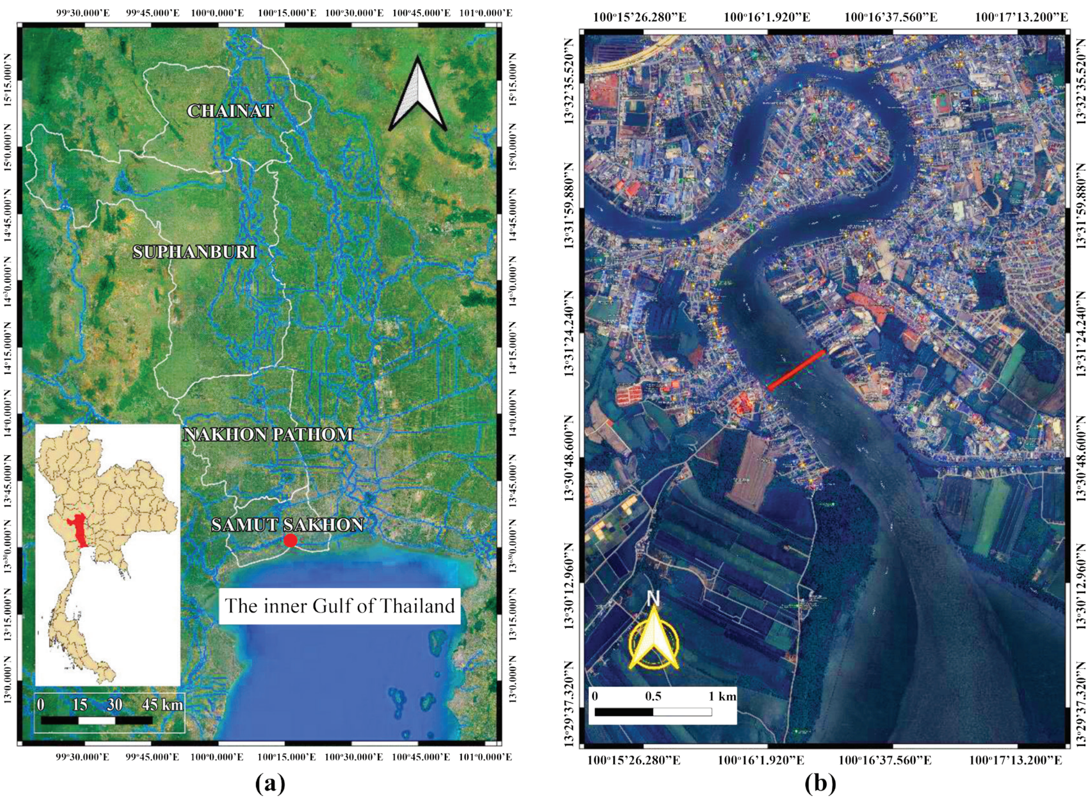

Figure 1. Location of the flux measurement station at the mouth of the Tha Chin River, indicated by the red dot (a) and the red line (b).

duration (T) was 25 h. Subscripts 's' and 'b' denote the surface and the bottom water layers, respectively. Values obtained from each layer were combined prior to calculating the time-averaged net flux over the tidal cycle. This calculation is expressed in Equation 1 (adapted from Kjerfve and McKellar 1980; Dyer, 1973).

$$F = \frac{1}{T}\int_{t=0}^{T}(Q_sC_s+Q_bC_b)dt \quad \text{(Equation 1)}$$

RESULTS AND DISCUSSION

Water quality parameters, including dissolved oxygen (DO), biochemical oxygen demand (BOD), temperature, salinity, pH, and total suspended solids (TSS) (Figure 2), revealed significant seasonal variations ($p<0.05$) across all variables. DO levels remained consistently below 4 mg·L^{-1} throughout the study, with the lowest values observed during the wet season in October (0.66±0.45 mg·L^{-1}) and the highest during the transition period in July (2.87±1.51 mg·L^{-1}). BOD was lowest in July (1.96±1.10 mg·L^{-1}) and peaked during the dry season in February (4.23±1.17 mg·L^{-1}). Temperature varied seasonally, with lower values during the dry season (February) (27.34±0.52 °C) and higher values during the transition period (July) (32.37±0.62 °C).

Salinity followed a similar trend, being lowest in the wet season (3.48±4.34 psu) and highest in the transition period (20.07±7.10 psu). Stratification of the water column was noted during periods of low salinity, likely driven by increased freshwater discharge from the river. pH values ranged from 6.92 to 7.69, with the lowest average during the wet season (7.28±0.13) and the highest during the dry season (7.46±0.18). TSS concentrations were lowest in the wet season

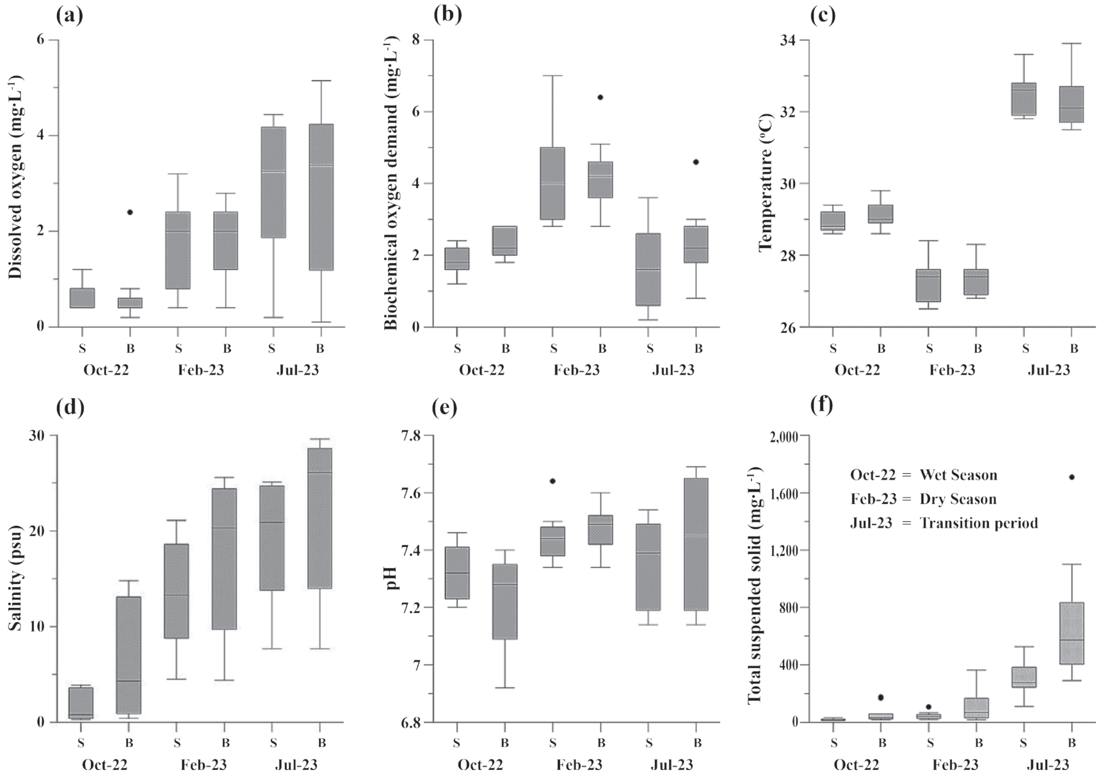

Figure 2. General water quality parameters at the sea surface (S) and sea bottom (B) during a tidal cycle at the mouth of the Tha Chin River: (a) dissolved oxygen (DO), (b) biochemical oxygen demand (BOD), (c) temperature, (d) salinity, (e) pH, and (f) total suspended solids (TSS).

(38.64±43.93 mg·L^{-1}) but increased sharply in the transition period (497.41±347.44 mg·L^{-1}), with higher concentrations generally recorded near the bottom of the water column. In summary, the results indicate clear seasonal patterns in water quality at the mouth of the Tha Chin River, reflecting the dynamic interplay between river discharge and marine influences.

Salinity and pH were lower during the wet season due to increased freshwater runoff. In contrast, the dry season saw stronger seawater influence, resulting in elevated salinity and pH (Kan-atireklarp *et al*., 2015; Yuenyong *et al*., 2019; 2023). During the wet season, salinity was higher at the bottom than at the surface, as seawater intrudes beneath the freshwater layer. In contrast, during the dry season and the transition period, salinity levels were similar between surface and bottom waters, suggesting that low river discharge and dominant tidal forces created a well-mixed estuarine system.

In both the dry season and the transition period, DO levels remained below 4 mg·L^{-1}. This reduction is largely attributed to the discharge of high-strength wastewater from domestic, agricultural, and industrial sources in the Tha Chin River basin, which introduces substantial inorganic and organic nutrient loads into the river. Additionally, the accumulation and subsequent decomposition of organic matter in bottom sediments consume oxygen, further lowering DO levels (Meksumpun, 2021). DO levels declined even further during the wet season, falling below 2 mg·L^{-1}. This sharp decrease is likely due to flooding in agricultural areas, which accelerates organic matter decomposition and intensifies oxygen depletion (Thaipichitburapa *et al*., 2010; Zhu *et al*., 2011). While rising tides can bring seawater with relatively higher DO into the river mouth, levels still remained below Thailand's Surface Water Quality Standards Type 4 waters (DO>2.0 mg·L^{-1}) (PCD, 2020). These results align with observations from 2008 during the same period (Thaipichitburapa *et al*., 2010).

Suspended solids showed a positive correlation with salinity and were generally higher at the bottom. The elevated concentrations during the transition period may be influenced by coastal sediment transport driven by tidal intrusion (Buranapratheprat *et al*., 2013) and the resuspension of sediments due to tidal erosion (Buranapratheprat *et al*., 2023). In contrast, suspended solid concentrations were lower during the wet season, possibly due to low turbidity and stronger runoff transporting particles further from the river mouth.

The seasonal variation in dissolved nutrient concentrations (Figure 3) was significant ($p<0.05$) for most parameters, except for total dissolved phosphorus (TDP). In the dry season, nitrogen-based nutrients such as ammonia, nitrite, and dissolved inorganic nitrogen (DIN) reached their peak concentrations, with averages of 1,291.49±424.15 µg N·L^{-1}, 45.49±30.32 µg N·L^{-1}, and 1,461.60± 462.86 µg N·L^{-1}, respectively. In contrast, the wet season showed a higher level of nitrate and TDN, at 227.78±44.41 µg N·L^{-1} and 3,450.86±335.50 µg N·L^{-1}, respectively. Ammonia levels dropped sharply in the wet season (612.91±122.34 µg N·L^{-1}), while the transition period marked the lowest concentrations of nitrite (10.56±6.57 µg N·L^{-1}), nitrate (15.88±6.96 µg N·L^{-1}), and DIN (682.18± 481.18 µg N·L^{-1}).

DIP and TDP reached their peak during the dry season, averaging 265.42±86.96 µg P·L^{-1} and 266.13±88.25 µg P·L^{-1}, respectively. These values declined in the wet season to 165.34±25.81 µg P·L^{-1} and 199.86±21.79 µg P·L^{-1}. Meanwhile, dissolved inorganic silicate (DISi) was highest in the wet season (5,154.98±878.61 µg Si·L^{-1}) and lowest during the transition period (2,640.93±122.87 µg Si·L^{-1}). The high DIN and DIP concentrations in the dry season reflect continuous nutrient release from local sources. Reduced river discharge in February 2023 (Figure 6a) likely contributed to nutrient accumulation (Uttayarnmanee *et al*., 2019).

In the transition period, increased runoff diluted certain nutrients, such as ammonia, nitrite, nitrate, and DIN, leading to temporary reductions in their concentrations. However, TDN surged during the wet season, driven by prolonged flooding in the Tha Chin Basin. Agricultural activities in upstream area, particularly rice paddies and crop fields, contributes to organic nitrogen loading through the decomposition of plant residues (Berman and Bronk, 2003), resulting in high TDN levels (HAII, 2012).

The nitrogen-to-phosphorus (N:P) mole ratio remained similarly high during the wet and dry season (12) but drop during the transition period (8) (Figure 4). According to Redfield (1958), an N:P ratio above 16 indicates phosphorus limitation, while a ratio below 16 suggests nitrogen limitation for phytoplankton growth. In this study, all observed N:P ratios were below 16, indicating nitrogen-limited conditions throughout the year.

A comparison with the Bang Pakong River (Yuenyong *et al*., 2019) indicates that the

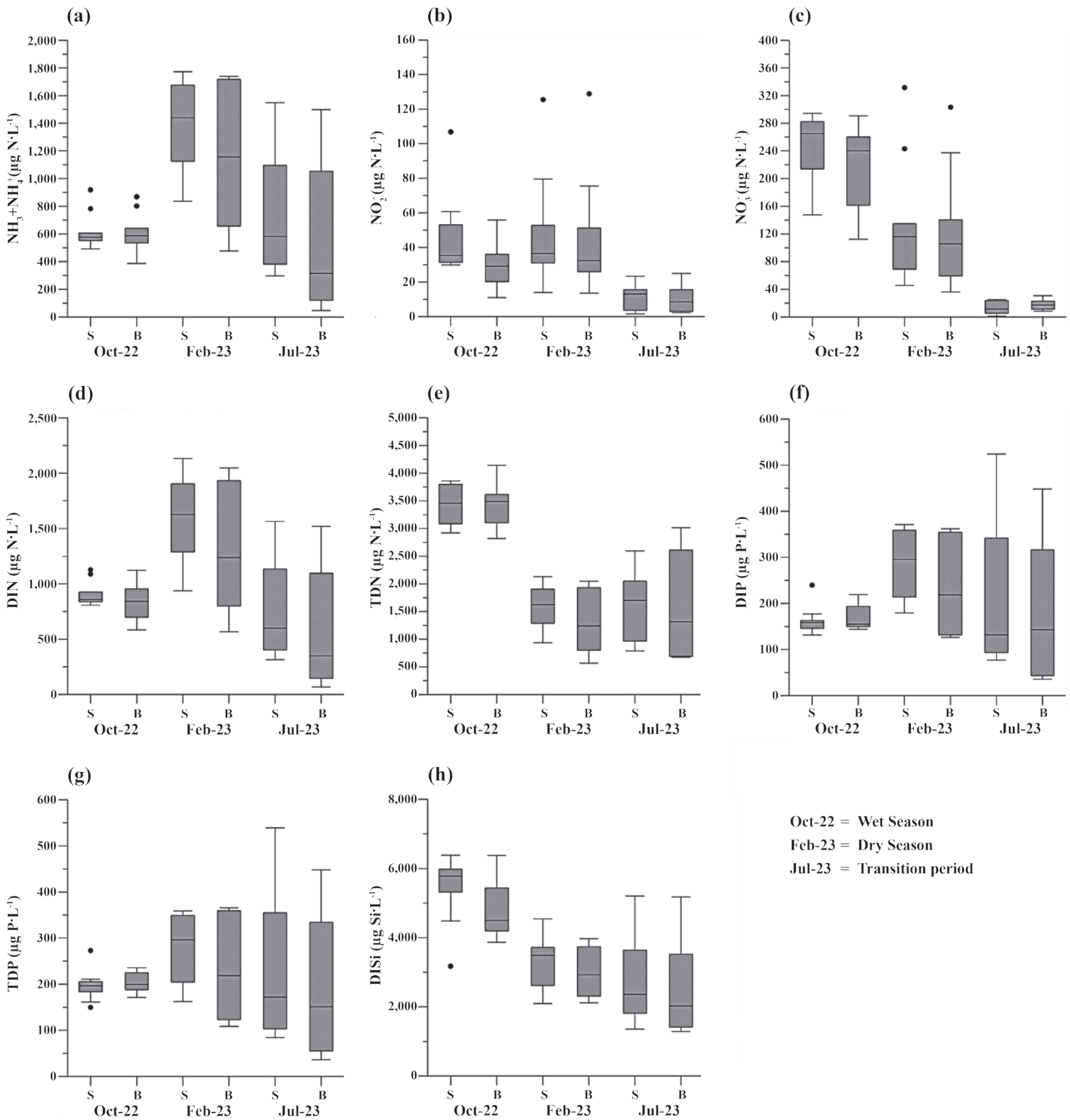

Figure 3. Concentrations of dissolved nutrients at the sea surface (S) and sea bottom (B) during a tidal cycle at the mouth of the Tha Chin River: (a) ammonia, (b) nitrite, (c) nitrate, (d) dissolved inorganic nitrogen (DIN), (e) total dissolved nitrogen (TDN), (f) dissolved inorganic phosphate (DIP), (g) total dissolved phosphorus (TDP), and (h) dissolved inorganic silicate (DISi).

Tha Chin River consistently exhibits lower N:P ratios. In nitrogen-limited environments, certain phytoplankton species, such as *Noctiluca*, which can utilize alternative nitrogen sources (Pithakpol *et al*., 2000), may gain a competitive advantage and proliferate. This aligns with frequent *Noctiluca* bloom events observed at the Tha Chin River estuary (Chuenniyom *et al*., 2012).

Despite the nitrogen limitation, ammonia concentrations consistently exceeded the Type 4 surface water quality standard of 500 µg N·L^{-1} (PCD, 2020) across all seasons, ranging from 612.91 µg N·L^{-1} in the wet season to 1,291.49 µg N·L^{-1} in the dry season, or 1.2 to 2.6 times above the allowable limit. When compared with the Bang Pakong River (Yuenyong *et al*., 2019), ammonia levels in the Tha Chin River were considerably higher, 1.4 to 2.8 times greater during the wet season and 5.1 to 11.8 times higher in the dry season. These elevated ammonia levels indicate severe nutrient pollution in the Tha Chin River and pose significant ecological risks.

DIP concentrations averaged 165.34 µg P·L^{-1} in the wet season, 265.42 µg P·L^{-1} in the dry season, and 200.38 µg P·L^{-1} during the transition period. All values significantly exceeded the Type 1 seawater quality standard of 15 µg P·L^{-1} (PCD, 2021), by approximately 11.0 to 17.7 times. DIP levels in the Tha Chin River were also substantially higher than in the Bang Pakong River (Yuenyong *et al*., 2019) by about 2.5–5.3 times in the wet season and 7.8–10.7 times in the dry season.

DISi concentrations also increased during high runoff period, consistent with leaching processes reported by Kan-atireklarp *et al*. (2015). The Tha Chin River consistently surpassed hypereutrophic thresholds defined by Smith et al. (1999), which are >400 µg·L^{-1} for TDN and >40 µg·L^{-1} for TDP. In this study, TDN exceeded the threshold by 8.63 times in the wet season, 3.65 times in the dry season, and 3.90 times during the transition period. TDP also exceeded the threshold by 5.00, 6.51, and 5.25 times during the wet, dry, and transition period, respectively.

The relationship between nutrient concentrations and salinity (Figure 5) shows a negative correlation, dissolved nutrient concentrations decreased as salinity increased, suggesting that

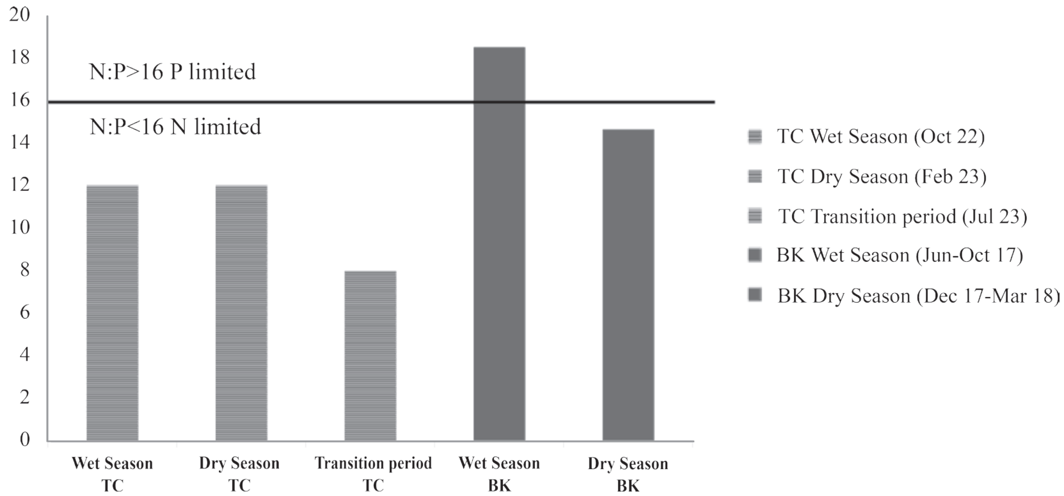

Figure 4. Comparison of N:P Mole Ratio between the Tha Chin River (TC) and the Bang Pakong River (BK) across different seasons. The horizontal line at N:P = 16 represents the Redfield ratio, indicating the threshold between nitrogen limitation (N:P<16) and phosphorus limitation (N:P > 16). Data include the wet season (October 2022), dry season (February 2023), and transition period (July 2023) for the Tha Chin River, and previously reported wet and dry seasons for the Bang Pakong River (June–October 2017 and December 2017–March 2018, respectively).

terrestrial runoff is the primary nutrient sources at the Tha Chin River mouth. A particularly strong correlation was observed between ammonia and DIN ($r = 0.94$), indicating that ammonia constitutes a major portion of DIN. This may be attributed to low dissolved oxygen (DO) levels, which inhibit nitrification, thereby preventing the conversion of ammonia into nitrite or nitrate (Cui *et al.*, 2020). Additionally, the dissimilatory nitrate reduction to ammonium (DNRA) pathway may be active. In this process, bacteria under low-DO conditions use nitrate for anaerobic respiration, reducing into ammonia (Zhao *et al.*, 2022; Cheng *et al.*, 2016). However, as this interpretation is based solely on chemical data, further microbiological and genetic studies are needed to confirm these mechanisms.

A linear regression model (Table 2) was used to describe the association between dissolved nutrient fluxes (represented by F in the equations) and water discharge. Coefficients of determination (r^2) exceeding 0.83, especially for FDIN and FDIP, indicate that river water, particularly from domestic and industrial sources (Thaipichitburapa *et al.*, 2010) is the dominant contributor of nutrient inputs.

Water movement toward the sea varied noticeably across the three seasons, as shown in Figure 6. The highest net water flux was observed during the wet season, 61.26×10^6 $m^3 \cdot d^{-1}$. This value dropped substantially during the transition period to 13.59×10^6 $m^3 \cdot d^{-1}$ in the transition period and further decreased in the dry season to 10.28×10^6 $m^3 \cdot d^{-1}$.

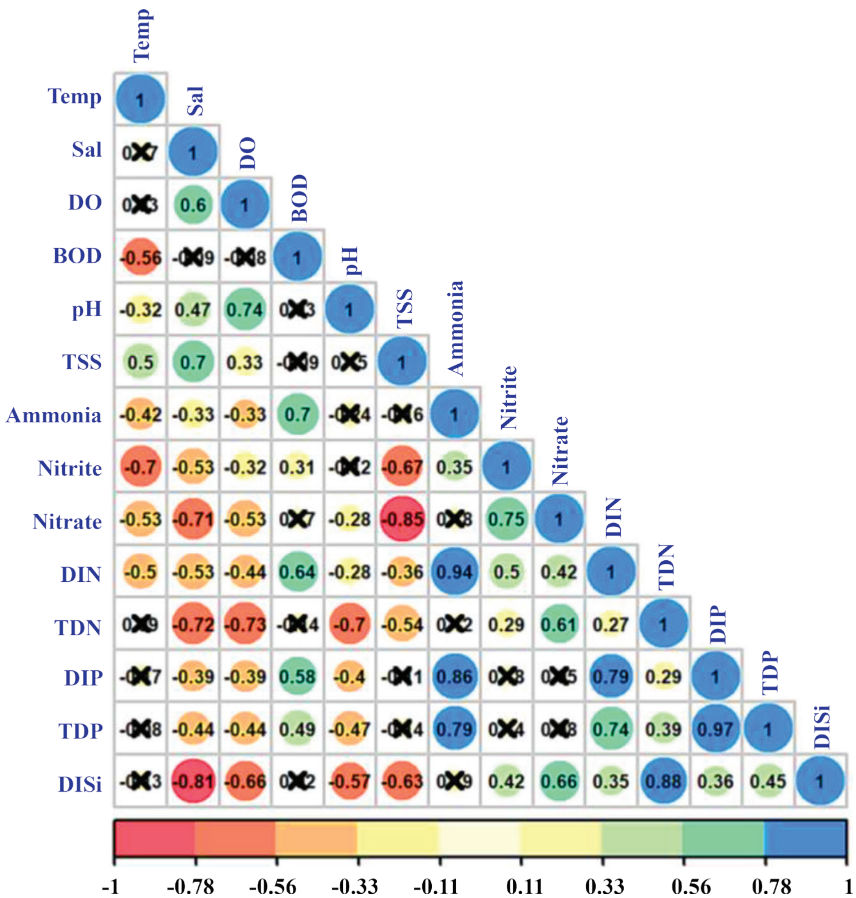

Figure 5. Correlation coefficient (r) illustrating the relationships between physical and chemical water qualities at the Tha Chin River Mouth in a tidal cycle from all observations during 2022–2023.

Note: r values marked with “×” are non-significant ($p \geq 0.05$, 2-tailed) and ones without marks are significant ($p < 0.05$, 2-tailed); Abbreviations as shown in Figure 2 and 3.

Interestingly, the transition period recorded the highest flux of total suspended solids (TSS) at 4,749.77 t·d^{-1}, which exceeded both the wet season (2,260.50 t·d^{-1}) and the dry season (1,571.86 t·d^{-1}). Notably, during the dry season, the direction of TSS flux reversed, with movement from the sea into the river, driven by tidal currents during high tide (Figure 6b). This indicates that the TSS primarily originated from the resuspension of bottom sediments in the coastal area, subsequently transported landward by incoming tides.

Net fluxes of nitrogenous nutrients followed a seasonal trend, peaking in the wet season, declining during the transition period, and reaching their lowest during the dry season. During the wet season, the highest seaward fluxes were observed for ammonia (38.42 t N·d^{-1}), nitrite (3.51 t N·d^{-1}), nitrate (14.37 t N·d^{-1}), DIN (58.94 t N·d^{-1}), and TDN (207.29 t N·d^{-1}), driven by strong river discharge (Figure 6). In the transition period, although slightly decreased, nutrient fluxes remained considerable: ammonia (36.70 t N·d^{-1}), nitrite (0.03 t N·d^{-1}), nitrate (0.57 t N·d^{-1}), DIN (37.29 t N·d^{-1}), and TDN (45.05 t N·d^{-1}), all continuing in the seaward direction. By contrast, the dry season exhibited the lowest nutrient fluxes: ammonia (20.20 t N·d^{-1}), nitrate (0.28 t N·d^{-1}), DIN (20.32 t N·d^{-1}), and TDN (20.32 t N·d^{-1}), with all still flowing seaward, except for nitrite, which reversed direction and moved at 0.16 t N·d^{-1}.

The seasonal variation in net fluxes of phosphorus and silicate nutrients mirrored the pattern observed for nitrogen. Peaked fluxes were recorded during the wet season: DIP (10.43 t P·d^{-1}), TDP (12.80 t P·d^{-1}), and DISi (322.37 t Si·d^{-1}). These were followed by moderate fluxes in the transition period: DIP (4.78 t P·d^{-1}), TDP (4.78 t P·d^{-1}), and DISi (47.39 t Si·d^{-1}). The lowest fluxes occurred in the dry season: DIP (4.04 t P·d^{-1}), TDP (3.71 t P·d^{-1}), and DISi (22.18 t Si·d^{-1}). Importantly, the net movement of all these nutrients remained consistently seaward throughout the study period (Figure 6h–6j).

Increased water flux during periods of heavy rainfall enhances the leaching of nutrients and suspended solid from land into the river. This effect is particularly evident in the elevated TSS concentrations near the bottom, which exceed those at the surface, as shown in Figure 2. When compared to other rivers in Thailand (Figure 7), the Tha Chin River exhibited higher net material fluxes than both the Trat River (Meesub *et al*., 2021) and the Prasae River (Buranapratheprat *et al*., 2013) during both wet and dry seasons. The high nutrient loads carried during the wet season are transported to the estuarine and inner Gulf of Thailand, potentially contributing to red tide events. This is consistent with observations that red tide outbreaks frequently during the wet season (Thaipichitburapa *et al*., 2010; Chuenniyom *et al*., 2012).

Although the Tha Chin River has a lower net water flux, especially during the wet season (Figure 7), it shows higher DIN and DIP fluxes compared to the Bang Pakong River. This indicates a higher level of nutrient contamination in the Tha Chin River. Notably, the nutrient fluxes observed in this study are significantly lower than those reported in a previous investigation conducted in the same area in 2007 (Thaipichitburapa *et al*., 2010). In the 2007 study, the wet season discharge volume reached 230.34×10^{6} m^{3}·d^{-1}, which greatly exceeds the 61×10^{6} m^{3}·d^{-1} recorded in the present study. Since nutrient flux is calculated as the product of nutrient concentration and discharge volume, the higher discharge in 2007 resulted in much larger nutrient fluxes. The differences in water flux between studies may be attributed to variations in measurement methods or natural fluctuations in hydrological and climatic conditions between the two study periods.

The Tha Chin River also exhibits higher net DIN and DIP fluxes per unit watershed area than other rivers in Thailand (Figure 8). This is largely due to extensive land use: approximately 76% of the Tha Chin River Basin is used for agriculture (HAII, 2018), particularly in upstream areas, contributing to nutrient runoff despite the river's noted high self-remediation capacity (Thaipichitburapa *et al*., 2010). In downstream region, the presence of dense residential areas, industrial facilities, and an estimated 157,000 livestock farms further contributes to nutrient loading. The discharge of untreated wastewater from these sources elevates nutrient concentrations and reduces dissolved

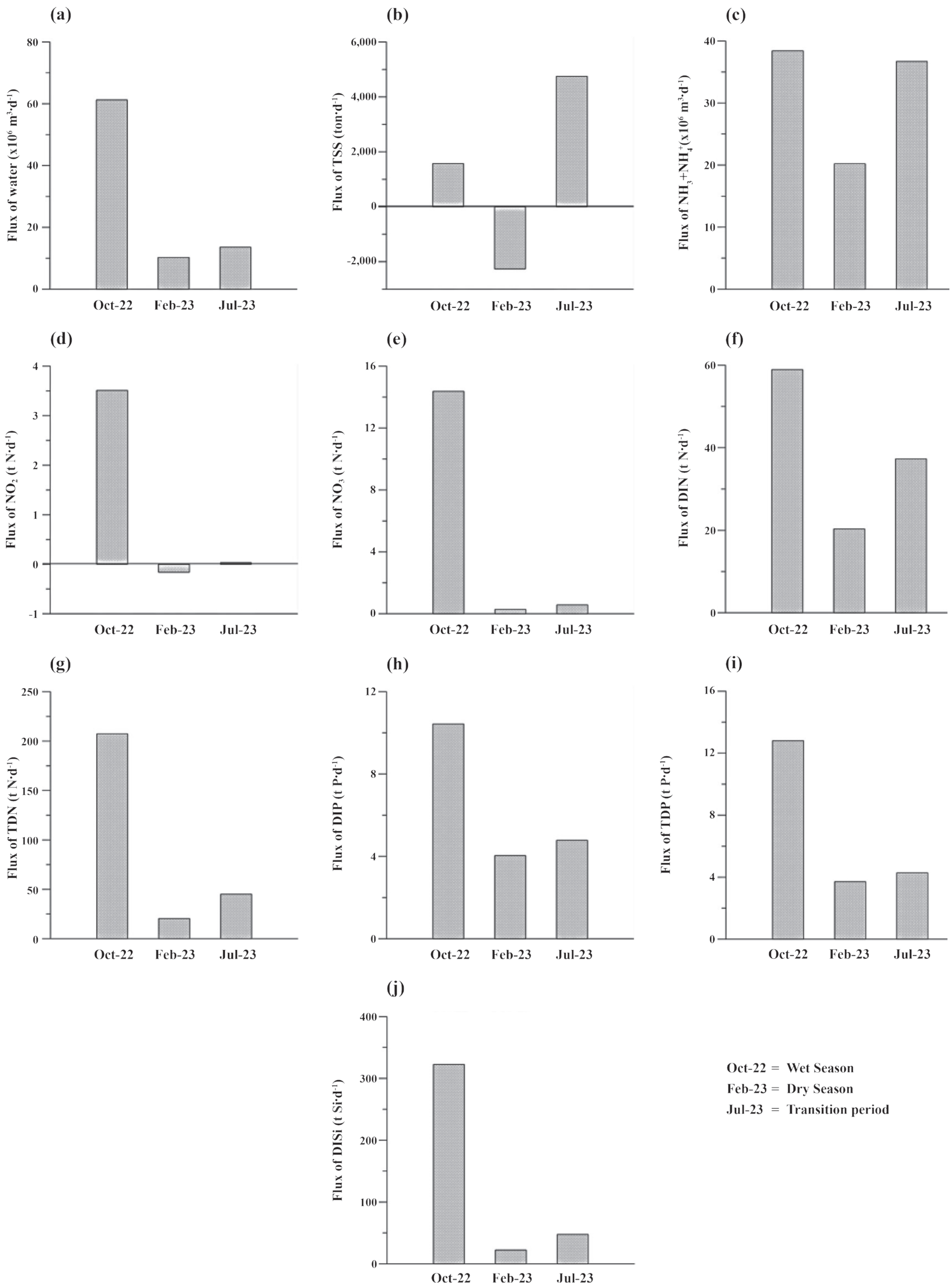

Figure 6. Net fluxes of (a) water, (b) total suspended solids (TSS), (c) ammonia, (d) nitrite, (f) nitrate, (g) total dissolved nitrogen (TDN), (h) dissolved inorganic phosphate (DIP), (i) total dissolved phosphorus (TDP), and (j) dissolved inorganic silicate (DISi) across three seasons.

Note: Positive values indicate flow from the river to the sea; negative values indicate flow from the sea to the river.

Table 2. Regression analysis between water discharge (D) at Tha Chin River and nutrient fluxes (F)

Regression Analysis	Regression equation	r^2
FTDN with discharge	FTDN = 23.7+2.369 D	0.86
FTDP with discharge	FTDP = -0.01+0.2445 D	0.91
FDIN with discharge	FDIN = 9.11+1.0482 D	0.83
FDIP with discharge	FDIP = 0.00+0.2261 D	0.86
FDIN with FDIP	FDIN = 9.55+4.567 FDIP	0.93

Note: D = Discharge; F = Fluxes; r^2 = coefficient of determination

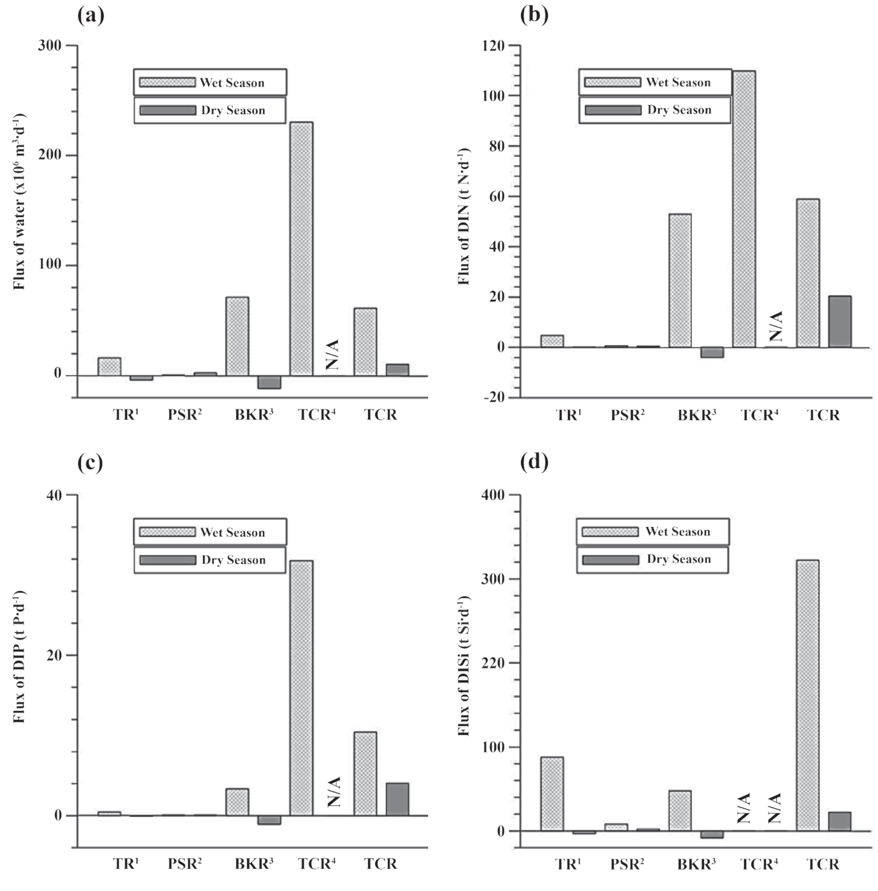

Figure 7. Comparison of net fluxes of (a) water, (b) dissolved inorganic nitrogen (DIN), (c) dissolved inorganic phosphorus (DIP), and (d) dissolved inorganic silicate (DISi) between the Tha Chin River (TCR) and other rivers in Thailand: Trat River (TR), Prasae River (PSR), and Bang Pakong River (BKR). N/A = not detected.

Note: Positive values indicate flow from the river to the sea; negative values indicate flow from the sea to the river.

oxygen levels, thereby degrading the aquatic ecosystem (Meksumpun and Meksumpun, 2008; Chuenniyom *et al*., 2012; DLD, 2022).

A key distinction between the Tha Chin and Bang Pakong Rivers lies in the composition of DIN. In the Bang Pakong River, nitrates accounted for approximately 66% of DIN during the wet season, whereas in the Tha Chin River, ammonia was the dominant form, comprising 68% of DIN in the wet season and increasing to as much as 99% in the dry season (Figure 9). This contrast reflects differences in land use within the two basins. The Bang Pakong River basin (10,707 km^2) is 66% agricultural (Yuenyong *et al*., 2023) and contains 16% forest cover, while the Tha Chin River basin is approximately 2,700 km^2 larger and has 10% more land allocated to agriculture, with less forest area. Additionally, higher dissolved oxygen levels at the mouth of the Bang Pakong River facilitate the nitrification process, enabling more efficient conversion of ammonia to nitrate (Yuenyong *et al*., 2019).

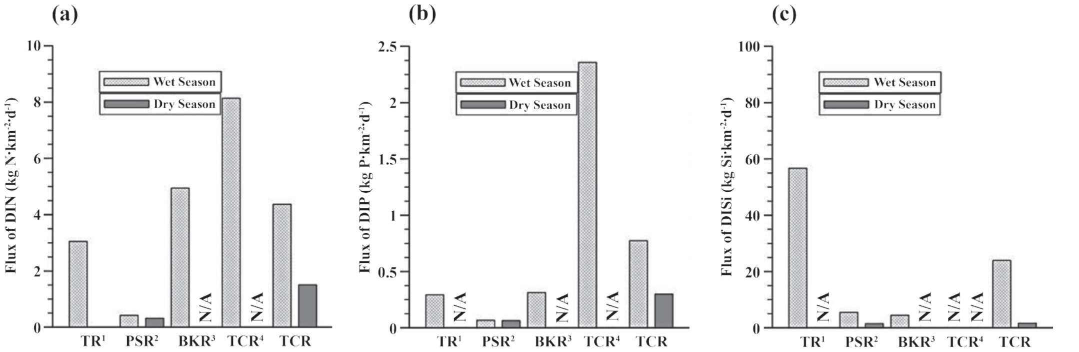

Figure 8. Comparison of fluxes per unit watershed area for (a) dissolved inorganic nitrogen (DIN), (b) dissolved inorganic phosphorus (DIP), and (c) dissolved inorganic silicate (DISi) between the Tha Chin River (TCR) and other rivers in Thailand: Trat River (TR), Prasae River (PSR), Bang Pakong River (BKR).

Note: [1]Meesub *et al*. (2021); [2]Buranapratheprat *et al*. (2013); [3]Yuenyong *et al*. (2023); [4]Thaipichitburapa *et al*. (2010)

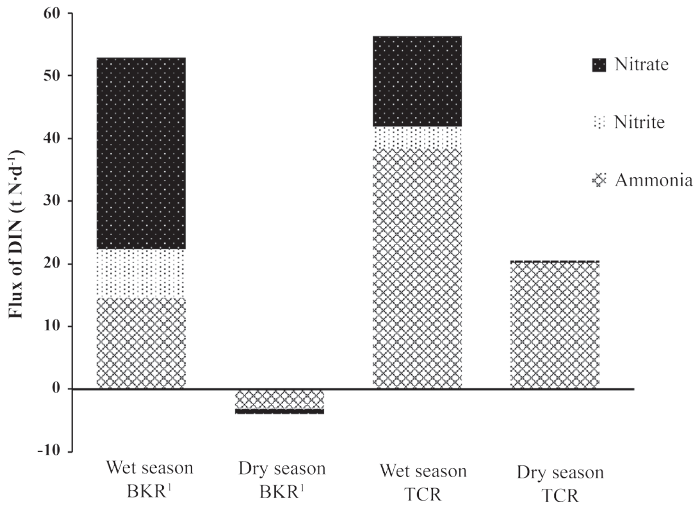

Figure 9. Comparison of the proportion of net fluxes of dissolved inorganic nitrogen (DIN) components between the Tha Chin River (TCR) and the Bang Pakong River (BKR) during wet and dry seasons.

Note: BKR = Bang Pakong River; TCR = Tha Chin River; Positive values indicate flow from the river to the sea; negative values indicate flow from the sea to the river

Source: [1]Yuenyong *et al*. (2023)

CONCLUSIONS

A 2022–2023 study of the Tha Chin River revealed that seasonal variation significantly influenced water quality. DO levels remained critically low throughout the study period (0.66–2.87 mg·L^{-1}), with some observations dropping to 0.0 mg·L^{-1}. Concentrations of ammonia, nitrate, and DIP exceeded national water quality standards, with DIP consistently surpassing Type 1 seawater limits by 11–17.7 times (165.34–265.42 µg P·L^{-1}). Both TDN and TDP levels indicated persistent hypertrophic conditions, highlighting the impact of anthropogenic pollution.

The net fluxes of water, nutrients, and suspended solids generally moved seaward toward the inner Gulf of Thailand, except for TSS and nitrite during the dry season. Nutrient fluxes peaked during the wet season. Among Thai rivers, the Tha Chin River discharged particularly large amounts of ammonia and DIP into the Gulf. Ammonia fluxes reached 38.42 t N·d^{-1} in the wet season, 20.20 t N·d^{-1} in the dry season, and 36.70 t N·d^{-1} during the transition period. Corresponding DIP fluxes were 10.43 t P·d^{-1} in the wet season, 4.04 t P·d^{-1} in the dry season, and 4.78 t P·d^{-1} during the transition period. These elevated fluxes exceed those from most other rivers in the region, underscoring the Tha Chin River's major contribution to nutrient loading in the inner Gulf and its likely role in supporting red tide events.

Future research should focus on elucidating the direct relationship between nutrient fluxes, eutrophication, and harmful algal blooms in the inner Gulf of Thailand. These findings highlight the urgent need for watershed-scale nutrient management strategies, including the enforcement of stricter discharge regulations. Policymakers are encouraged to adopt evidence-based approaches to mitigate nutrient pollution, support long-term water quality monitoring programs, and implement sustainable coastal resource management practices.

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