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THE INFLUENCES OF SEASONAL MONSOONS UPON PHOSPHORUS, CHLOROPHYLL-A AND PHYSICAL CHARACTERISTIC OF THE KELANTAN WATERS

(Kesan Monsun Bermusim ke atas Fosforus, Klorofil-a dan Ciri-ciri Fizikal di Perairan Kelantan)

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Abstract

The influences of seasonal monsoons on the variability of phosphorus (phosphate (PO_4^{3-}), dissolved organic phosphorus (DOP), total particulate phosphorus (TPP)), chlorophyll-a, and physical characteristics in the water columns of Kelantan Waters were investigated based on the datasets collected by three cruises during the southwest monsoon (SWM), inter-monsoon (IM), and northeast monsoon (NEM) seasons. Concentrations of PO_4^{3-} were determined using a discrete analyzer and standard colorimetric techniques. DOP and TPP were measured using an indirect method that involved a UV digestion system. This system utilizes UV light to oxidize organic phosphorus and total phosphorus compounds into PO_4^{3-}, thereby making them measurable. Surface and vertical profiles were investigated and showed that almost all parameters measured showed significant differences ($p < 0.05$) among seasons. The seasonal trends in the surface and vertical distributions of PO_4^{3-}, DOP, and chlorophyll-a concentrations were found to have peaked during the NEM, followed by the SWM and IM periods. The combination factors of heavy rainfalls, large river discharges, and stronger wind-induced processes during the NEM created conditions conducive for the enhancement of PO_4^{3-}, DOP, and chlorophyll-a concentrations in the study area. Principal Component Analysis (PCA) demonstrated a strong correlation between chlorophyll-a and PO_4^{3-}, suggesting that PO_4^{3-} supply was the dominant source for phytoplankton biomass (chl-a) survival during our sampling period. This study has provided valuable information about phosphorus dynamics in the Kelantan Waters, establishing a baseline for future studies.

Keywords: intermonsoon, northeast monsoon, phosphate, dissolved organic phosphorus, South China Sea

Abstrak

Pengaruh musim monsun ke atas kepelbagaian fosforus (fosfat (PO_4^{3-}), organik terlarut fosforus (DOP), jumlah partikulat fosforus (TPP)), klorofil-a, dan ciri fizikal dalam turus air di perairan Kelantan telah dikaji berdasarkan dataset yang dikumpul oleh tiga pelayaran semasa monsun barat daya (SWM), peralihan-monsun (IM), dan monsun timur laut (NEM). Kepekatan PO_4^{3-} ditentukan menggunakan pengnalisis automatik diskret dan kaedah kolorimetrik piawai. DOP dan TPP diukur menggunakan kaedah tidak langsung yang melibatkan sistem pencernaan UV. Sistem ini menggunakan cahaya UV untuk mengoksida fosforus organik dan sebatian jumlah fosforus menjadi PO_4^{3-}, menjadikannya boleh diukur. Profil permukaan dan menegak telah dikaji, dan menunjukkan hampir semua parameter yang diukur adalah berbeza secara signifikan ($p < 0.05$) di antara musim. Kami dapati trend musim dalam taburan permukaan air dan menegak kepekatan PO_4^{3-}, DOP, dan klorofil-a mencapai puncaknya semasa monsun timur laut, diikuti oleh monsun barat daya dan tempoh perlihan-monsun. Gabungan faktor hujan lebat, sungai besar, dan proses yang diperkuatkan oleh angin semasa monsun timur laut mencipta keadaan yang menyokong peningkatan konsentrasi PO_4^{3-}, DOP, dan klorofil-a di kawasan kajian. Analisis komponen utama (PCA) menunjukkan korelasi kuat antara klorofil-a dan PO_4^{3-}, menunjukkan bahawa bekalan PO_4^{3-} adalah sumber dominan untuk fitoplankton (chl-a) biojisim semasa tempoh penyempelan kami. Kajian ini memberikan maklumat berharga mengenai dinamik fosforus di perairan Kelantran and sebagai garis asas untuk kajian masa depan.

Kata kunci: monsun peralihan, monsun timur laut, fosfat, fosforus organik terlarut, Laut China Selatan

Introduction

Phosphorus (P) is long-recognized as an essential nutrient for life, required by all living organisms for growth, energy transport, and membrane synthesis [1, 2]. Phosphorus is present in oceans as inorganic phosphate (i.e., orthophosphate (PO_4^{3-}) and condensed phosphate) and organic phosphate in both dissolved and particulate forms (i.e., dissolved organic phosphorus (DOP) and particulate phosphorus (PP) [3, 4]. Microbial organisms can access a variety of P sources to satisfy nutritional P demands and preferentially utilize orthophosphate, as it can be directly consumed and assimilated, whereas DOP generally requires more energy for conversion into PO_4^{3-} before its metabolic assimilation [5, 6]. However, PO_4^{3-} is present in low concentrations, which is potentially limiting for microbial organisms in the oligotrophic oceans (tropical and subtropical) [1, 7]. These oligotrophic oceans are subject to smaller variations of seasonal temperature than temperate waters and are permanently underlain by a strong thermocline, which is considered the least variable and the least productive in the oceans' surface waters [8]. Microbes actively utilize DOP as an alternative P source when PO_4^{3-} is depleted in the ocean [7, 9-12]. DOP is a complex mixture of organic compounds in the ocean, and is predominantly mediated by phytoplankton through cell excretion, exudation, death, and autolysis [11], and can also be derived from organic compounds discharged from industrial, agricultural, and domestic sewage [12]. The recycling and utilization of DOP play a significant role in primary productivity, which may support approximately 90% of gross primary productivity [13, 14]. Meanwhile, most of the P is transported to the ocean by mainly being attached to the particles phase as total particulate phosphorus (TPP) through riverine input [15, 16], where TPP includes clay and silt-associated organic and inorganic P [9]. Additionally, living microorganisms attached in TPP (98%) are higher than that in particulate C (60%) and N (49%), and thereby result in low TPP in particular detrital sedimentary fractions as evidence of preferential utilization of P [7]. Thus, P availability in the ocean has significantly impacted primary productivity.

The Kelantan waters are located in the east coast of Peninsular Malaysia (ECPM), and lie in the southern region of the South China Sea, bordering the Gulf of Thailand. Kelantan Waters form a system that has a high variability of hydrographical factors predominantly based on its monsoon season. Four different monsoon seasons affect this region, i.e., the northeast (Nov–Feb), southwest (May–Aug), and two transitional shorter inter-monsoon (Mar–Apr and Sep-Oct) periods, which can be distinguished based on their wind flow [17, 18]. The northeast monsoon (NEM) is associated with the strong north-easterly winds that generate a strong southward current along the ECPM, and usually bring heavier rainy seasons and rough seas over this region [17, 19]. Meanwhile, the southwest monsoon (SWM) season generates weaker south-westerly winds and drives northward currents along ECPM, and typically receives minimum rainfall and drier weather regions [17, 19]. The prevailing SWM winds with the north-south orientation of the coastline induce offshore Ekman transport, thus being favourable for upwelling along the ECPM, and unfortunately, less favourable in Kelantan Waters [20,21]. The two inter-monsoons (IM) are referred to as the first IM period (March-April) and the second IM period (Sept-Oct), and have unique features of wind direction and surface current, which are characteristics similar to SWM and NEM accordingly, but are relatively slow and driven by limited mixing [17, 22].

The selected parameters of phosphorus (PO_4^{3-}, DOP, and TPP), chlorophyll-a, and physical characteristics (salinity and temperature) are interlinked, forming a complex web of relationships that govern nutrient dynamics and ecosystem health. PO_4^{3-}, DOP, and TPP collectively provide a comprehensive view of phosphorus cycling, where PO_4^{3-} concentration in the water column directly affects the nutrient availability for phytoplankton biomass (Chl-a), establishing a fundamental link between phosphate levels and overall ecosystem productivity. Furthermore, DOP, represented as an organic form of phosphorus, is intricately linked to nutrient dynamics, and DOP measurement provides insights into the bioavailability of phosphorus, impacting microbial and algal communities. It is also important to measure TPP concentrations, which are associated with suspended particles and sediments, reflecting the interactions between nutrients and the physical environment. Moreover, chl-a serves as a proxy for primary productivity. The relationship between chl-a levels and nutrient concentrations, especially phosphate, is crucial for understanding the impact of nutrient availability on algal biomass and the overall ecosystem health in the study area. Meanwhile, salinity and temperature contribute to the physical context that influences nutrient distribution and biological processes in the water column. The existing knowledge regarding nutrient distribution in Kelantan Waters, particularly in terms of vertical distribution, remains notably scarce.

While previous studies have explored phosphorus (P) nutrient distribution in Peninsular Malaysia Waters during the southwest monsoon (SWM) [21, 23, 24], northeast monsoon (NEM) [23], and inter-monsoon (IM) [25], the focus on nutrient distribution within Kelantan Waters, especially in the vertical profiling in the water column, is still limited. Recognizing this critical gap, our study has aimed to comprehensively investigate the spatial distribution of P-based nutrients (PO_4^{3-}, DOP, and TPP), chlorophyll-a, and the physical characteristics (temperature and salinity) across both, the surface and vertical profiles in Kelantan Waters. In addition, this research has also sought to evaluate the temporal patterns of nutrient variations in response to the three monsoon seasons (IM, SWM, and NEM), and identify the key environmental factors governing these patterns. By addressing this research gap, our study contributes essential insights crucial for the effective and robust monitoring of nutrient dynamics in the Kelantan Waters. The interplay between all parameters measured would help researchers and environmental managers grasp the intricate relationships within the water column.

Materials and Methods

Study area and sampling activity

The study area of Kelantan Waters is located between 102° to 105° E longitude (Figure 1), which lies within the shallow continental shelf with less than 100 m in water depth. This study was part of the cruise expedition "HICOE 2017". Three cruises to the Kelantan Waters aboard the RV Discovery occurred from 1-2 April, 4-8 July, and 16-18 November 2017, respectively. A total of 7 sampling stations were sampled, which were in the transect that is oriented perpendicular to the coast of Kelantan and is about 260 km towards the offshore region (Figure 1). The sampling area is influenced by anthropogenic activities from its adjacent city of Kota Bharu, mainly discharged through the Kelantan River [21, 23]. Seawater samples were collected in Niskin bottles attached to a CTD (Conductivity-Temperature-Depth, Sea-Bird) probe frame. At each sampling station, surface water samples (~ 0.5 m) were collected for surface distribution, while water samples for vertical profiling were taken at 5, 10, 20, 30, 45, and 60 m depths, respectively. The seawater samples for PO_4^{3-}, DOP, and chlorophyll-a analyses were vacuum filtered onboard, through pre-combusted (5 hours at 450ºC) and pre-weighed GF/F filters (0.7 µm pore-size, Whatman). The filtrate samples were transferred into acid-washed polyethylene bottles and immediately kept frozen at –20 °C to reduce all the activities and metabolism of the organisms in the water. Meanwhile, unfiltered samples were used for TPP determination. Chlorophyll-a filters were folded in half twice, and placed in a 15 mL centrifuge tube wrapped in aluminium foil to protect the phytoplankton from light. Both the filtrate samples and the chlorophyll-a filters were immediately stored at –20 °C until laboratory analyses.

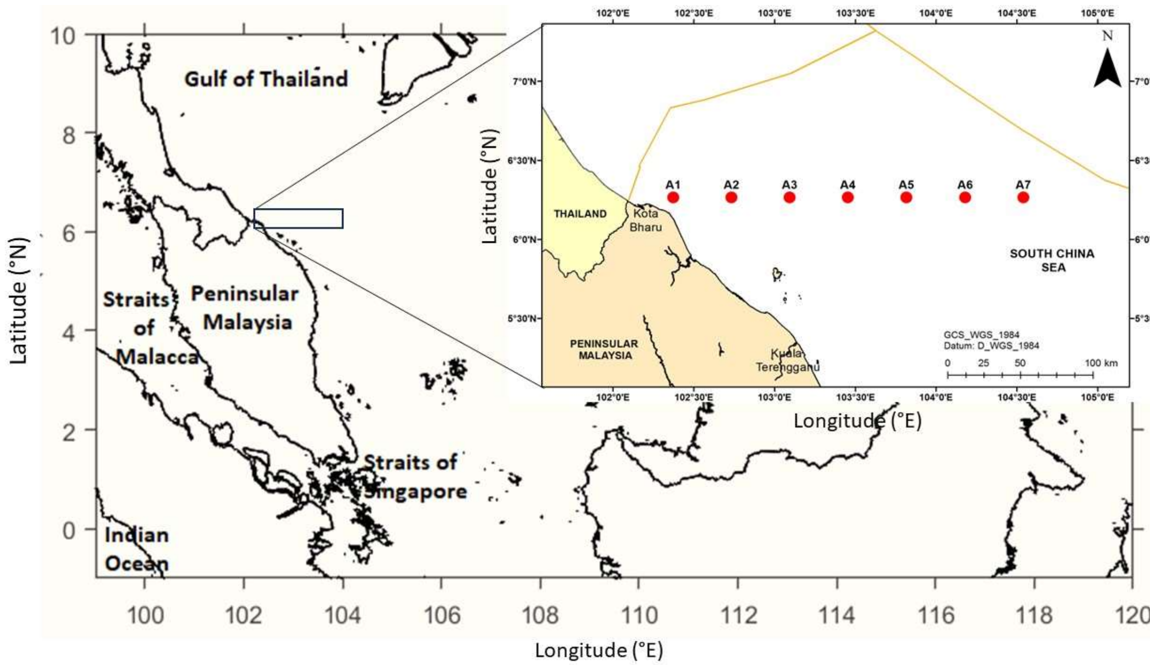

Figure 1. Map of the study area. Transect and stations are shown in the inset

Physical measurement

The physical data measurements began with temperature and salinity using a CTD sensor, and were displayed on a computer screen in the labs onboard. The sea surface current data were retrieved from the global ocean model, and the HYbrid Coordinate Ocean Model (HYCOM) global reanalysis (https://www.hycom.org/). The monthly means near-surface currents (u and v components of the current, unit: m/s) averaging over the top 10 m were used to investigate the influence of monsoons on the seasonal ocean circulation of the Kelantan Waters.

Laboratory analysis

In the laboratory, PO_4^{3-} samples were analysed based on standard colorimetric methods [26] using a SmartChem 200 discrete autoanalyzer (AMS Alliance), and were detected spectrophotometrically as a coloured complex. Basically, a water sample reacts with molybdate under acidic conditions (pH < 2) to form phosphomolybdic acid; the formed heteropolyacid is then reduced by ascorbic acid to produce a blue colour complex and detected at 880 nm using a SmartChem 200 discrete autoanalyzer. The determination of DOP relies upon the measurement of total dissolved phosphorus (TDP) and PO_4^{3-}, where DOP is calculated by subtracting PO_4^{3-} from TDP (DOP= TDP - PO_4^{3-}). TDP was first converted to measurable PO_4^{3-} by UV oxidation techniques using a Metrohm 909 UV digestion system, without the addition of any reaction initiators, catalysts, or oxidants. This process breaks down complex organic phosphorus forms, simplifying their quantification through analytical methods for inorganic phosphate PO_4^{3-}, which was subsequently measured using the same method as used for PO_4^{3-} determination above. This UV oxidation method is sufficient to oxidise 60–70% of DOP in the sample to PO_4^{3-} [27]. The unfiltered waters were used to determine the concentrations of TPP. The concentration of TPP measurement depends on the analyses of total phosphorus, TDP, and PO_4^{3-} (TPP = TP – TDP). TP was measured by converting all P forms to PO_4^{3-}, and the same method as used for TDP determination was applied. The Chl-a was determined using a UV-VIS spectrophotometer (Shimadzu 1201) after chlorophyll pigment was extracted from filters under subdued light in 90% (v/v) acetone and refrigerated at ~4 °C for 24 h [28].

Quality control (QC) measures were applied to ascertain the precision and accuracy of phosphorus determination in this study, aligning with the EPA standard method [26]. These measures encompassed the analysis of duplicate samples, examination of blanks (utilizing deionized water treated as a sample), and the analysis of standard additions. Precision was evaluated through duplicate samples by estimating the standard deviation based on the results of a set of duplicate samples. The accuracy of measurements was assessed through the analysis of standards with known concentrations, reported as a percentage error. The percentage error was calculated using the following equation:

$$\text{Percentage error} = ((\text{measured concentration} - \text{actual concentration}) / \text{actual concentration}) \times 100 \quad (1)$$

Samples with error > 10% were reanalysed. The midrange standard concentrations and blanks were analysed periodically and simultaneously with the samples run at the beginning, intermediately and at the end of the run to confirm that instrument performance. The analyses yielded satisfactory results, with a percent measurement error staying consistently at less than 5%. Triplicates of every sample were analysed, and the concentrations of PO_4^{3-}, DOP, and TPP used here were the average of two measurements, and the overall analytical precision was within ± 2%. The detection limit was determined by calculating three times the standard deviations (DL=3SDb) of the blank measurement. The detection limit for phosphorus-based nutrients was found to be 0.05 µM P (n = 20).

Estimation of river nutrient input

Nutrient input from the Kelantan rivers, which were directly discharged to the study area, was estimated and calculated according to the following equation [23]

$$F = c \times f \quad (2)$$

where c is the nutrient concentration and f is the river flow. The information presented in this paper was calculated from data collected during the period of January-December 2017. The daily river flows in the Kelantan River are gauged and recorded by the Malaysian Department of Irrigation and Drainage (DID) and summed as monthly totals. Riverine nutrient concentrations were acquired from the Malaysian Department of Environment (DOE) for the Kelantan River estuary station, with sampling done at every two-three months of 2017. Unfortunately, load data is unavailable for the northeast monsoon season.

Statistical analysis

Statistical analyses were implemented by using the Xlstat 2019 (Addinsoft, France) software. We opted to apply a non-parametric test since most data distribution deviates from normality through the Shapiro-Wilk test ($p<0.05$, two-tailed). The Kruskal – Wallis with Bonferroni correction was employed as the post hoc analysis (at $p<0.05$), to test the significant differences of all parameters measured between stations (spatial pattern) and between monsoon seasons (temporal pattern). The degrees of potential correlations among the variables were identified through Spearman correlation analysis. The correlation was considered statistically significant when p-value < 0.05, and the strength of correlation was determined in three different classes (strong ($r \geq 0.60$), moderate ($r = 0.30 \leq, 0.59$), weak $r \leq 0.29$). Additionally, the compressed information of many correlated variables was further investigated through principal component analysis (PCA) to identify latent information generated from the spatiotemporal difference variations. In preparation for PCA, all variables were log-transformed to normalise their distributions, and eigenvalues >1 were considered significant principal components. Furthermore, to ensure the appropriateness of the data for PCA, Bartlett's test and Kaiser–Meyer–Olkin (KMO) was conducted. Bartlett's test should have a significance measure of less than 0.05 to indicate significant relationships among variables, and the minimum score of 0.60 was suggested for the KMO value. The high KMO values indicate a PCA with few errors [29].

Results and Discussion

Surface current

The surface current movement is largely controlled by wind, and Kelantan Waters' current circulation pattern is strongly influenced by monsoon winds. Figure 2 shows the sea surface current retrieved from the HYCOM in April, July, and November 2017, respectively, to represent current circulation during (A) IM, (B) SWM, and (C) NEM, respectively. In general, the current direction during IM and NEM is similar, which moves towards the southward direction along Peninsular Malaysia; but both show different current patterns due to the stronger north-easterly winds occurring during NEM compared to IM. The variability of current circulation in the coastal area during IM due to winds is much weaker, which causes slow current movements, and which may be interrupted by tidal currents. Earlier research has proven that features of IM periods in East Coast Peninsular Malaysia include relatively weak winds as it is in prior monsoon seasons [17, 30], affected by local winds from the coast [17]. Strong north-easterly winds during NEM produce a stronger current that contributes to rough seas and brings colder water to Peninsular Malaysia [17, 31], with the current speed reaching up to 1.33 m/s during the sampling period. In contrast, surface currents during SWM showed a reverse direction, with the current circulation pattern flowing in the northward direction along the coast, with a maximum current speed recorded at 0.8 m/s. The prevailing winds during the SWM with the north-south orientation of the coastline are favourable for upwelling along the east coast of Peninsular Malaysia [20, 21]. However, so far, there has been no evidence of upwelling that can reach Kelantan Waters, because, as can be seen, the current movement diverts near 6˚N (Figure 2b) north-eastward towards the Vietnam coast [21, 32]. The variability of surface current circulation is an important factor to understand the oceanic environment. Strong water current causes water column mixing that may supply nutrients into the photic zone and vice versa.

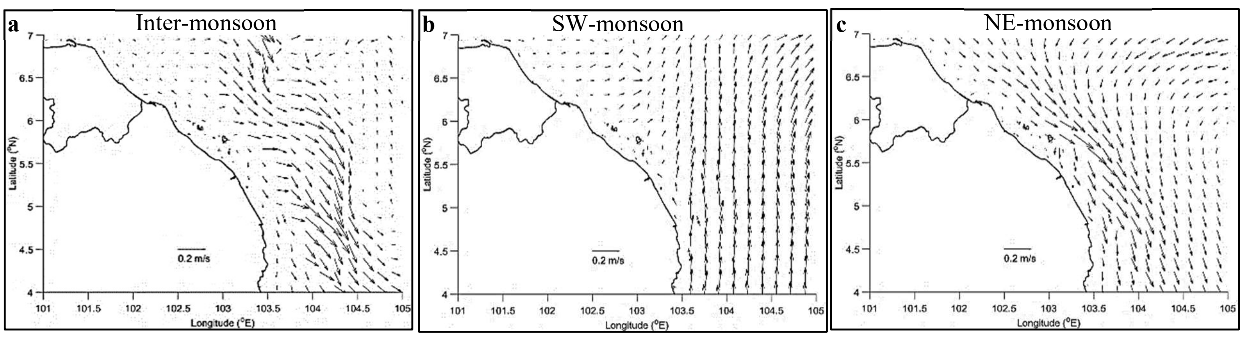

Figure 2. The seasonal variation of the mean surface current from HYCOM (unit: m/s) in Kelantan Waters

Kelantan river nutrient input

Kelantan River Nutrient Input in terms of PO_4^{3-} concentration was estimated based on the F = c x f equation. The results of Kelantan River Nutrient Input in terms of PO_4^{3-} concentration for April (IM) and July (SWM) were found to be 0.09 x 10^6 and 390 x 10^6 g per year, respectively. There were expectations of higher PO_4^{3-} inputs during November (NEM) based on higher rainfall and increased river discharge during NEM. Literature [23] recorded PO_4^{3-} riverine input from the river along the ECPM as 76% of its total annual input to ECPM waters in NEM, compared to SWM, where it was only 24%.

Surface distribution

The surface distribution of temperature, salinity, Chl-a, PO_4^{3-}, DOP, and TPP during three monsoon seasons for the seven stations area are illustrated in Figures 3 (a)-(r). The surface temperature in the study area exhibited relatively warm temperatures with a very slight variation, which was ubiquitous, with the surface temperatures reaching as high as 30 °C for all monsoon seasons. A clear decreasing gradient of surface temperatures toward the offshore region was recorded in the IM (28.26-30.4 °C; 29.13 ± 0.61 °C) (Figure 3a), while an opposite pattern was observed in SWM (29.56-30.7 °C; 30.08 ± 0.34 °C) (Figure 3b), with a few areas having a high temperature. Surface temperature measurements in NEM (Figure 3c) recorded low temperature values reaching 28 °C, especially in the coastal and middle areas (28-30.14 °C; 29.1 ± 0.52 °C). Figures 3d-f shows a surface salinity distribution pattern with low-salinity patches in the coastal area, which increase towards the open ocean. The lowest and the highest salinity values of 28.18 psu and more than 34.16 psu were recorded during IM (31.98 ±2.0 psu), respectively. Meanwhile, the salinity pattern was slightly homogenous in the offshore areas during SWM and NEM, ranging from 29.69 – 33.38 psu (32.58 ± 1.3 psu) and 30.81 – 32.30 psu (31.81 ± 0.5 psu), respectively. The strong low-salinity distribution pattern observed in the coastal areas indicated the influence of freshwater from the adjacent river (Kelantan River) to our sampling area. This observation agrees well with existing studies in ECPM [21, 23, 25]. Overall, surface Kelantan Waters were characterised by relatively low salinity, and the warm temperature was variable between seasons. The Kruskal-Wallis test showed that salinity and temperature distributions were significantly different between seasons (p <0.05), but not significant among the stations (p>0.05).

The Chl-a gives an overview of phytoplankton biomass featuring monsoonal season influence. Surface Chl-a levels were significantly low with concentrations less than 0.2 µg/L, which varied from 0.03 to 0.17 µg/L (0.07 ±0.05 µg/L) during IM (Figure 3g), and 0.03-0.14 µg/L (0.07 ±0.04 µg/L) during SWM (Figure 3h), respectively. Both monsoon seasons were noticed with relatively uniform distribution, with a gradual decrease in Chl-a concentrations from coastal toward offshore stations. Meanwhile, high chlorophyll patches were observed in the coastal area during NEM, with concentrations ranging between 0.05 to 0.57 µg/L (0.14 ±0.2 µg/L). In NEM, particularly, the highest total rainfall (Figure 4) resulted in greater discharges from Kelantan rivers into nearshore areas. These discharges might have carried more domestic sewage from anthropogenic activities into the coastal seawater, leading to the higher nutrient concentrations and Chl-a observed in that season. Similarly, previous study [33] also found peak and extreme Chl-a concentrations (7.74 µg/L) along the coastal area of ECPM during NEM, and indicated that heavy rainfall and strong river discharge were the factors that affected the higher availability of Chl-a. Moreover, other previous studies also reported a similar pattern of Chl-a concentrations higher in coastal areas and lower towards offshore areas in Peninsular Malaysia Waters [21, 23, 34]. Statistically, the Kruskal–Wallis test shows that Chl-a concentrations were significantly different among the studied stations (p <0.05) and during monsoon season (p <0.05).

The concentrations of PO_4^{3-} (Figures 3 j-l) were measured to be low at less than 1 µM, and some were almost undetectable as the lowest concentration was below the detection limit (bdl) (bdl, <0.05 µM). Across the IM, SWM, and NEM, the following range of concentrations were recorded – bdl-0.22 µM (0.17 ± 0.07 µM), bdl-0.32 µM (0.14 ± 0.10µM), and 0.14-0.34 µM (0.29 ± 0.07 µM), respectively. The highest concentrations of DOP also have been estimated during NEM (Figure 3o), with concentrations ranging between 0.17-0.6 µM (0.38 ± 0.14 µM), followed by DOP concentrations during SWM (0.11-0.42 µM; 0.23 ± 0.10 µM) and IM (bdl-0.20 µM; 0.08 ± 0.07 µM). Generally, the DOP distribution patterns show large variations among monsoon seasons, with a uniform distributed pattern during IM (Figure 3m). TPP showed a similar trend with DOP, where a uniform distribution pattern was found in the IM (bdl-0.14 µM; 0.07 ± 0.05 µM) season, but irregular TPP distributions were found during SWM (0.23-0.59 µM;0.36 ± 0.16 µM) and NEM (0.12-0.44 µM; 0.29 ± 0.11 µM). Seasonally, the general trends of surface PO_4^{3-} and DOP show higher concentrations in NEM, probably attributed to the strong monsoonal winds that are associated with strong sea surface currents, resulting in increased nutrient input to the surface waters. The strong monsoon current was able to exchange Kelantan Waters and the adjacent bodies of water, since the surface current direction moves in the southward direction along Peninsular Malaysia, suggesting higher DOP and PO_4^{3-} during NEM, especially in the middle region, which could be transported from the Gulf of Thailand. Previous studies have found that the Gulf of Thailand-derived nutrients dominated the northern area of peninsular Malaysia [21, 23]. However, an unclear surface trend of TPP was observed in this study, with higher TPP during SWM. In terms of spatial distribution, PO_4^{3-}, DOP, and TPP showed a strong concentration onshore-offshore gradient, decreasing seaward. Except for TPP, the highest concentration was recorded at the nearshore station (A1) during NEM. The higher nutrients input during NEM at the nearshore station is in relation to the strong riverine input from Kelantan River due to higher rainfall (900 mm) associated with greater river discharge (665 m^3/s), resulting in more PO_4^{3-} and DOP input to this station. Even so, there were still non-significant differences between stations (Kruskal Wallis $p > 0.05$), which were significant among the monsoons ($p < 0.05$).

The comparison of the data obtained in this study with previous studies in Peninsular Malaysia is useful in providing information on Chl-a and P distributions in Peninsular Malaysia (Table 1). Overall, the Chl-a concentration in this present study is much lower than in the previous study in ECPM [25] and coastal areas in Peninsular [6], but higher than the latest study in ECPM [23]. Surface PO_4^{3-} in this present study (0.14-0.34 µM) was recorded as slightly higher than other ECPM areas i.e., <0.10-0.11 µM [24] and <0.02-0.20 µM [23], but lower than coastal areas around Peninsular Malaysia (0.02-0.84 µM). Meanwhile, DOP concentrations (<0.11-0.60 µM) in this study were within the range previously reported for Peninsular Malaysia, by Lim et al. [6] (<0.01-0.61 µM) and Hee et al. [23] (<0.1-0.7 µM). However, as far as we know, no previous research has investigated TPP in Peninsular Malaysia Waters.

Depth-profile Distribution

The vertical profiles of temperature, salinity, and concentration of Chl-a, PO_4^{3-}, DOP, and TPP during all monsoon seasons are visualised in the contour plot, Figure 4. In IM, the temperature ranged from 26.32 - 30.04 °C, with an average of 28.24 ± 1.18 ºC, and salinity values were spread between 28.18-34.29 psu (33.11 ± 1.29 psu). The temperature (Figure 4a) and salinity (Figure 4d) profiles show similar stratification as observed at depths of 10-20 m, and there are significant differences between the depths ($p < 0.05$). The temperature and salinity profiles during SWM were already discussed in our previous work [21]. Briefly, the isotherm of 29.5 °C (Figure 4b) and isohaline of 32.5 psu (Figure 4e) was shoaled until 10 m in the region of 103 °E and bent downward towards the coast. This well-stratified water column was due to the Kelantan River plume and strong solar radiation during both IM and SWM. Both seasons of IM and SWM show a similar distribution pattern of warm temperatures and low salinities at ~10 m above the layer. This pattern indicated the typical features of riverine discharge that are influenced by the nearest adjacent river, i.e., the Kelantan River's direct input into the study area. The river outflow restricted the movement of water underneath from reaching the surface layer. Similar features were also observed in ECPM by [25], where these were studied during IM and SWM, and [20], during SWM. Moreover, weak water column mixing is mainly due to large surface water heating on the surface and weak surface current, which also explains why the underneath water did not reach the surface. In contrast, well-mixed water columns during NEM for temperature and slightly mixed for salinity, varied from 28.51- 30.14 °C (29.08 ± 0.26 ºC) and 30.81-33.10 psu (32.34 ± 0.5 psu), respectively. Temperature is vertically homogeneous with a mean of 29 °C occupied by all water columns (Fig. 4C), and offshore water of > 40 m depth showing a colder temperature (28.51°C). Thus, the temperature did not show any significant difference against the depth ($p > 0.05$). However, significant differences were observed in different depths ($p < 0.05$) for salinity, where salinity is more saline at the bottom layer, especially in offshore water (33.10 psu). The well-mixed water column was expected as a result of the large river discharge and strong water current, which increased the vertical mixing from the bottom to reach the surface layer. Although this study did not emphasise vertical water current, the river discharge and rainfall data obtained from the DID reveal that there was an increased rainfall amount associated with strong river discharge during November 2017 (NEM) as compared to April (IM) and July (SWM) 2017 (Figure 4). This is in agreement with previous studies in ECPM [17, 23], where NEM tends to have well-mixed water columns due to higher freshwater influence and strong wind speeds associated with the strong vertical current. The Kruskal-Wallis test results indicate significant differences among the monsoonal seasons regarding temperature and salinity ($p < 0.05$). Seasonally, the vertical profile of Chl-a varied remarkably from the surface to the bottom, where Chl-a concentration showed a similar pattern with high concentration in the bottom and low concentration in the surface layers. Chl-a concentration varied from 0.02 to 0.73 µg/L (0.16±0.18 µg/L) during IM, with a weak trend of Chl-a movement towards the surface. Meanwhile, Chl-a concentration was recorded as 0.01 to 0.60 µg/L

(0.16±0.16 µg/L) during SWM, and 0.02 to 0.75 µg/L (0.22±0.17 µg/L) during NEM, respectively. The Chl-a variability shown in NEM slightly fluctuates and is higher in the middle of the water column. The strong vertical mixing mechanism induced by strong winds during NEM led to the re-suspension of bottom sediment and facilitates the release of nutrients. Consequently, this has supported increased phytoplankton biomass, reflected in higher Chl- a. concentration toward middle water. Previously, [35] revealed the occurrence of higher Chl-a concentration at the bottom water of the shallow region attributed to resuspension and turbulent water mixing, which modify the vertical dispersion rates of phytoplankton and the upward flux of nutrients and further promote the phytoplankton growth. Moreover, [36] also found higher Chl-a concentration at the bottom water due to the occurrence of turbulent vertical mixing that resulted in more efficient transport of nutrients from bottom to the water column and subsequently increased phytoplankton abundance and the chlorophyll-a content. Additionally, when there are low nutrients available in the surface water, phytoplankton tends to survive in bottom water without light limitations, especially in shallow water, due to the sediments releasing an abundant amount of nutrients [37]. Thus, in agreement with this study, where limited surface P availability in the surface water (except for PO_4^{3-} in NEM) and water depth was less than 60 m, phytoplankton (Chl-a) tended to grow in bottom layers. The Kruskal-Wallis test showed significantly different ($p < 0.05$) Chl-a levels among the monsoon seasons.

Table 1. The variability of the surface concentrations ranges of Chl-a, PO_4^{3-}, DOP, and TPP measured in different areas of Peninsular Malaysia

Location	**Chl-a (µg/L)**	**PO_4^{3-} (µM)**	**DOP (µM)**	**TPP (µM)**	**Ref.**
Current study	0.02-0.57	0.14-0.34	<0.11-0.60	0.01-0.69	
ECPM	0.068-7.744			-	[33]
ECPM	-	<0.10-0.11		-	[24]
ECPM	<0.01-0.06	<0.02-0.20	<0.1-0.7	-	[23]
Coastal around Peninsular Malaysia	2.77 ± 3.36	0.02-0.84	<0.01-0.61	-	[6]
ECPM	0.076-1.27	0.54-1.68			[25]

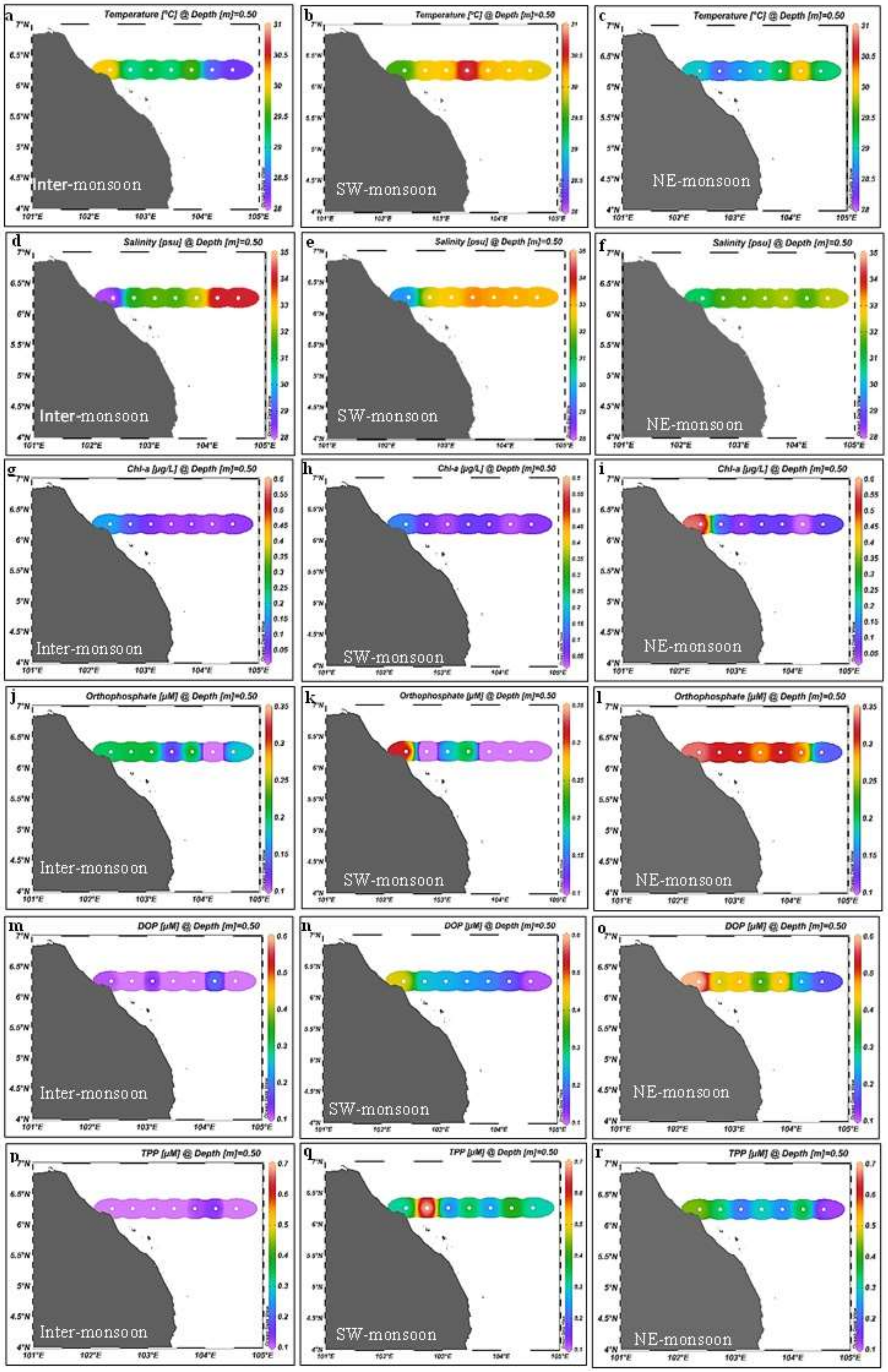

Figure 3. Seasonal variation of the surface physical characteristics, Chl-a, and P-based nutrients in Kelantan Waters

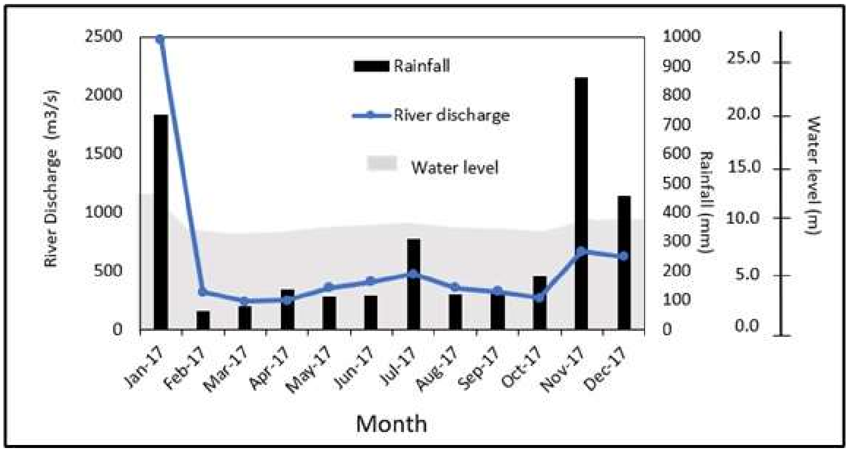

Figure 4. Monthly river discharge and rainfall in Kelantan River

The vertical profile of PO_4^{3-} during IM ranged between bdl to 0.44 µM (0.23 ± 0.09 µM), showing a large fluctuation, and an irregular variation for the entire water column (Figure 5d). Meanwhile, in SWM, PO_4^{3-} was exhausted or near the detection limit in most of the offshore area; nevertheless, higher concentrations were observed in the coastal area (bdl to 0.45 µM; 0.20 ± 0.13 µM). However, the Kruskal-Wallis test indicated that no significant depth change was noted (p >0.05) during both seasons. Conversely, the PO_4^{3-} distribution patterns showed a vertically uniform pattern in NEM (Figure 5F), and recorded concentrations of 0.20-0.45 µM (0.33 ± 0.05 µM), where a significant variability of PO_4^{3-} in the water columns was apparent (p <0.05). Uncommon PO_4^{3-} concentrations were notably higher in the offshore bottom water rather than in the coastal water, possibly due to stronger wind-induced vertical mixing during NEM; hence causing re-suspension of bottom sediments that brings up PO_4^{3-}-rich bottom water to the water column. PO_4^{3-}-rich bottom water is derived from remineralization processes of organic matter and sediment as a buffer to release nutrients to the water column when wind-induced currents disturb the water-sediment interface, especially in the shallow region [38]. However, this situation was not observed in the bottom water of the coastal area, which could be due to the lack of PO_4^{3-} resources in the bottom water, as a consequence of biological uptake or a strong river influence which transported PO_4^{3-} away to the offshore region. Earlier studies indicated that no matter how efficient the re-suspension event, the re-suspending of materials in the bottom also depends on the availability of the resources due to earlier re-suspension and/or benthic predation, which reduces the resources [35].

Overall, all monsoonal seasons have displayed a significant influence on PO_4^{3-} variation in the study area (p < 0.05). DOP was both seasonally and spatially significantly different (p <0.05). Vertically, the DOP distribution exhibited a general pattern of increased concentration with depth for all seasons ranging between 0.18 and 0.76 µM (0.39 ± 0.15 µM) in IM, 0.11 and 0.71 µM (0.41 ± 0.17 µM) in SWM, and 0.17 and 0.79 µM (0.51 ± 0.11 µM) in NEM, respectively. The DOP enrichment in the bottom depends on organic matter export processes, i.e., gravitational settling of living and dead cells or plankton biomass that can be remineralized into DOP. The DOP rapidly cycled and created a balance between local DOP production and utilisation processes occurring in the bottom water, leading to high DOP in the bottom water [39, 2]. However, DOP functioning in the bottom could not be clarified completely in this study, which can be clarified by further studying about P recycling in the future. Seasonally, the higher DOP concentrations have been estimated in the NEM, likely due to higher riverine run-offs induced by higher precipitation. According to [40], it was estimated that 61% of DOP in the Yellow Sea was mainly from riverine input, and [41] found peak DOP concentrations during wet seasons compared to dry seasons due to greater run-offs associated with higher precipitation. Thus, DOP distribution may vary depending on physical and chemical environmental conditions. Vertically, TPP distribution exhibited a similar pattern with DOP, where concentration increased with depth. TPP was present in significant concentrations with depth ($p < 0.05$) for all seasons, and the concentrations ranged from 0.21-0.87 µM (0.54 ± 0.16 µM) during IM, 0.11-0.95 µM (0.46 ± 0.21 µM) during NEM, and 0.21-0.86 µM (0.54 ± 0.18 µM) during SWM, respectively. Monsoonal weather is an important factor that controls the distribution of Chl-a and nutrients measured in this present study, but plays a relatively insignificant ($p > 0.05$) role in TPP distribution.

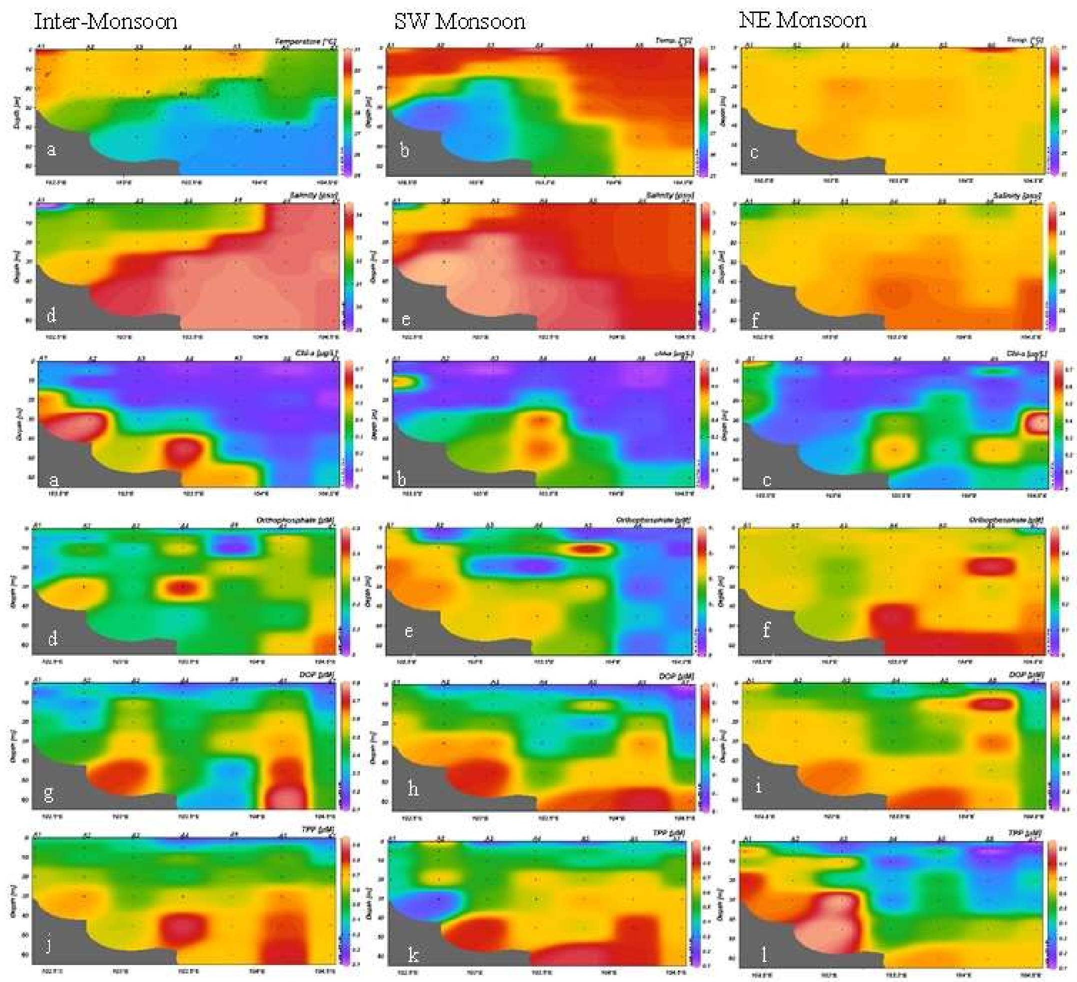

Figure 5. The seasonal cross-sectional profile of physical characteristics, Chl-a and P-based nutrients in Kelantan Waters

Principal component analysis (PCA)

The phosphorus species distribution within the Kelantan Waters is subject to influences not solely attributable to physical determinants but also governed by biological parameters, specifically chlorophyll-a (chl-a). This interplay is potentially modulated by the monsoonal fluctuations prevalent in the Southern South China Sea [21, 23]. The Kaiser-Meyer-Olkin (KMO) correlation coefficient, registering at 0.60, and the statistically significant Bartlett's sphericity test (p <0.001) collectively affirm the adequacy of the dataset for principal component analysis (PCA). The utilization of PCA proves instrumental in discerning the most salient variables in our investigation, facilitating a comprehensive understanding of the dataset while minimizing the loss of original information.

Consequently, PCA is applied to ascertain the potential influence of variables such as temperature, salinity, and Chl-a on the distribution of phosphorus variables throughout the study. The outcome of the PCA analysis reveals the acquisition of Principal Component 1 (PC1, denoted as F1 in Figure 6) for this study, possessing eigenvalues exceeding 1 (2.456) and accounting for 40.9% of the total variance in the dataset. This suggests a substantial explanatory power of the identified factors. The findings further suggest a strong correlation between salinity and Chl-a in determining the variability of phosphorus within the Kelantan Waters

The results of factor loading obtained from the PCA, as presented in Table 2, reveal distinctive contributions of various variables to the overall variability in phosphorus distribution within the Kelantan Waters. Specifically, phosphate exhibits the highest factor loading at 0.853, succeeded by DOP at 0.765, salinity at -0.698, and Chl-a at 0.687. These numerical values elucidate the respective influences of these variables on the observed fluctuations in phosphorus levels in the study area. Figure 6a visually elucidates the interrelationships between phosphorus species and other environmental factors in the Kelantan Waters. Notably, the concentration of phosphate demonstrates an inverse correlation with both salinity and temperature, while Chl-a stands as the singular variable deviating from this observed trend. The identified inverse relationships imply that regions characterized by lower salinity and temperature are prone to exhibit higher concentrations of phosphate. In contrast, the positive correlation between phosphate levels and Chl-a concentrations suggests that elevated phosphate availability contributes to increased phytoplankton biomass, subsequently augmenting Chl-a production. These findings align with prior research [21, 43], underscoring a significant correlation between Chl-a and phosphate, thereby emphasizing the essential role of phosphate in phytoplankton production. Consequently, the availability of phosphate emerges as a pivotal factor influencing Chl-a levels during the studied period.

Principal component analysis (PCA) was applied to delineate the distinctions in phosphorus distribution during the monsoon seasons, as elucidated in Figure 6b. This graphical representation underscores the statistically significant disparities ($p < 0.05$), previously ascertained through the Kruskal–Wallis test. The PCA results manifested as ellipses, characterizing the phosphorus distribution during the NEM, SWM, and IM seasons. Each ellipse encapsulated distinctive features corresponding to the respective monsoon seasons, except A1 during SWM. The discerned differences among the ellipses underscore the pivotal role played by monsoon seasons in shaping the observed variability in phosphorus distribution. Each monsoon season exhibited specific patterns and trends in phosphorus distribution, as delineated by the individual characteristics of the ellipses. Notably, the overlapping ellipses for SWM, IM, and NEM implied shared characteristics in phosphorus distribution during these seasons. This overlapping pattern suggests the persistence of certain factors and conditions, such as nutrient cycling, that influence phosphorus levels across SWM, IM, and NEM, highlighting the interconnected nature of phosphorus dynamics. The larger size of the ellipse for the SWM indicates its predominant influence on the observed phosphorus variability in the study area. This observation underscores the heightened impact of the SWM on shaping the phosphorus dynamics during the study period.

Table 2. Factor loading, eigenvalue, and percent of variance for 6 variables on the first two factor

Variables	**Factor 1**	**Factor 2**
Temperature	-0.173	**0.626**
Salinity	**-0.698**	0.396
Chlorophyll-a	**0.687**	-0.210
PO_4^{3-}	**0.853**	-0.169
DOP	**0.765**	0.441

Variables	Factor 1	Factor 2
TPP	0.392	**0.856**
Eigenvalue	2.456	1.526
Variability (%)	40.94	25.81
Cumulative	40.94	66.75

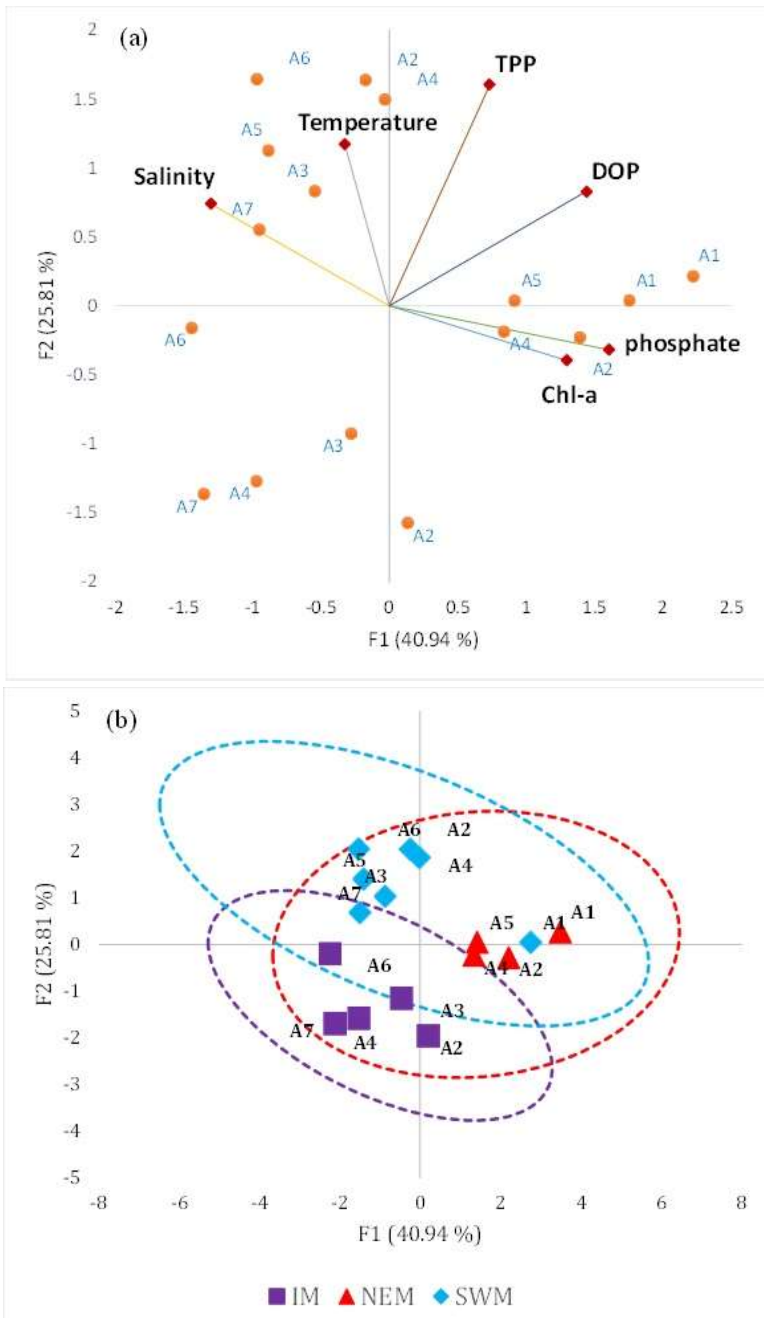

Figure 6. The correlation biplot using PCA of (a) phosphorus concentration and environmental factors and (b) phosphorus abundance

Conclusion

In this study, both surface and vertical distributions of PO_4^{3-}, DOP, TPP, Chl-a, and their physical characteristics in the Kelantan Waters were evaluated. Surface distributions of the most distinguished parameters demonstrated higher concentrations in the coastal waters compared to the offshore region, which indicates the influence of freshwater from the adjacent river of Kelantan River to our studied area. Supporting the warmer water with low salinity in the coastal area has proved the features of riverine discharge from the Kelantan River into the ocean. The influence of Kelantan riverine input is localized to the nearshore station (≤20 km), where further offshore areas may be influenced by the Gulf of Thailand-derived water. Offshore areas have their own ecological dynamics and biological processes, including nutrient cycling and phytoplankton activity, which can influence phosphorus levels. Vertical profiling showed higher concentrations of P-based nutrients and Chl-a in the deeper layer as compared to the surface layer, potentially derived from biological activities of remineralization processes and sediment as a buffer to release nutrients to the water column when wind-induced currents disturb the water-sediment interface. A direct link between the monsoon wind forcing with nutrients and Chl-a was noticed. Based on PCA, Chl-a strongly correlated with phosphate, which suggested that phosphate supply was the dominant source during our sampling. The monsoon weather pattern significantly acts as a key factor in controlling all the variables measured in Kelantan Waters, with SWM having a dominant influence on the variability observed in the study. Even though the obtained data are limited to one transect, the information provided an oceanographically meaningful spatial and temporal pattern of field data during all three monsoon seasons, which is vital for this study area, where a very limited amount of field data is available.

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