MJFAS
Malaysian Journal of Fundamental and Applied Sciences

Hassan *et al.* | Malaysian Journal of Fundamental and Applied Sciences, Vol. 21 (2025) 1784-1795

RESEARCH ARTICLE

Effect of Tidal Events on Water Quality of Sungai Perai Penang, Malaysia

Zaharadeen Hassan Yusuf, Hazzeman Haris*, Akuaka George Obinna

School of Biological Sciences, Universiti Sains Malaysia 11700 Gelugor, Pulau Pinang, Malaysia

Abstract The increasing demand for water in developing countries, driven by economic growth and rising living standards, has led to significant environmental challenges, including the degradation of river water quality. This study was carried out to study the effects of tidal events on the water quality of Sungai Perai Penang, Malaysia. Eight sampling sites were selected for the analysis of some water quality parameters during the neap and spring tides of January, February, April and May 2024. Conductivity (EC), Total dissolved solids (TDS), Salinity (Sal), Dissolved oxygen (DO), Temperature (Temp) and Transparency (TRPC) were measured in situ. Biochemical oxygen demand (BOD), Total suspended solids (TSS), Phosphate (PO_4), Nitrite (NO_2), Ammonia (NH_3), and Chlorophyll-a (Chlrp a) were analysed in the lab using standard methods. The results showed that water quality parameters varied with the following ranges: EC (0.12- 413 µS/cm), TDS (73.23-98,466 mg/l), Sal (0.05 48.87 ppt), pH (6.4 to 7.8), DO (1.83-10.74 mg/l), BOD(0.24-7.14 mg/l), TSS (0.01-0.43 mg/l), PO_4 (0.27-4.41 mg/l), TRPC (0.03-183 m). NO_2 (63.83-109.6 µg/l), NH_3 (0.5-0.74 mg/l), Temp (28.9-31.27ºC), and Chlrp-a (0.26-6.89 µg/l). EC, TDS, Sal, pH, BOD, TSS, PO_4, TRPC, and Chlrp a were higher during spring tide which could be due to increased tidal range and stronger currents causing greater mixing and movement of water. ANOVA results showed that TDS, Salinity, Temperature, and Chlorophyll-a showed significant spatial variation ($p<0.05$), while the other parameters did not vary spatially ($p>0.05$). EC, TSS, PO_4, NO_2, NH_3, pH, TDS, TRPC, and Sal showed significant variation between spring and neap tides (T-test, $p<0.05$). Spring tides are found to have a more pronounced effect on water quality compared to neap tides. This study highlights the combined influence of tidal events, anthropogenic activities, and diurnal cycles on the river's water quality. Understanding these dynamics is crucial for developing effective monitoring and management strategies to mitigate the impacts of pollution and ensure the sustainability of water resources in tidal rivers.

Keywords: Anthropogenic, diurnal cycle, neap tide, spring tide, water quality.

Introduction

The need for water is growing exponentially as developing countries experience economic revolutions and see an increase in living standards. The use of the environment for production and consumption leads to the destruction of the biosphere and water supplies [1]. Urban and industrial land use expansion is associated with less infiltration, higher runoff, and the movement of pollutants from the catchment area to aquatic bodies. This may result in the degradation of water quality in rivers. Human activities related to urban land, such as discharging domestic and industrial sewage, applying fertilizers and pesticides, surface runoff, and other non-point pollution sources, affect the concentration of pollutants in river water [2]. Monitoring water quality is crucial for assessing the condition and makeup of streams, rivers, and lakes at various time intervals, ranging from a single moment to weeks, months, and years. Rivers and streams are the main channels via which freshwater travels on Earth. River water supplies may be impacted by both natural elements and human actions [3].

Tidal rivers experience seawater influx affected by spring tides and neap tides, while freshwater intake comes from neighbouring rivers [4]. The fluctuations in estuarine water levels and turbulences during neap tides and monsoon seasons impact water quality [5]. Neap and spring tides have unique impacts on water quality. During neap tides, which happen a week following a spring tide, saltwater flows beneath

***For correspondence:**
hazzeman@usm.my

Received: 15 July 2024
Accepted: 20 Feb. 2025

freshwater instead of being horizontally divided. This phenomenon can affect the flow of water, salinity levels, and fertiliser distribution, which can affect water quality [6]. Spring tides, occurring when the sun, moon, and Earth are aligned, result in the highest and lowest tides, resulting to a significant mixing of fresh and saltwater [7]. These variations are crucial for resource managers to consider as they affect organisms differently based on salinity levels, ultimately influencing water quality in the ecosystem [6]. In tidal-affected areas, fluctuations in bottom water salinity between high and low tides lead to significant variations in nitrogenous nutrients, dissolved oxygen levels, and organic matter imports. Water quality indicators such as salinity, turbidity, dissolved oxygen, nutrients, and suspended particles are influenced by the changing conditions of tide occurrences in coastal areas [8].

The quality of river water in Malaysia has deteriorated, posing challenges in making it suitable. Malaysian rivers face pollution from both point and non-point sources. Main sources of pollution include sewage treatment plants, agro-industry, manufacturing, sulfur or greywater from commercial and residential establishments, and pig farms [9]. These sources contribute to the deterioration of water quality across numerous rivers and lakes, which are vital for domestic, agricultural, and industrial use. The number of clean rivers in Malaysia has declined significantly over the years. Department of Environment reported a decline from 579 rivers in 2008 to only 477 by 2019, with many rivers now classified as "dead" due to high pollution levels [10]. The recent pollution of Sungai Semenyih and Sungai Selangor has led to supply disruptions to hundreds of thousands of households for several days, which resulted in significant difficulties. In Malaysia, rivers and streams have been subjected to garbage dumps by the general public and businesses. Several water catchments in Malaysia have not been protected and gazetted. Without this, maintenance and protection from exploitation for development cannot be guaranteed. This results in exposure to all kinds of pollutants that result in detrimental effects on the aquatic environment, which ultimately makes water resources unsustainable [11]. It has been reported that urban land use activities in Malaysia pose a greater impact on water quality by altering hydrological processes. Agricultural activities and forest degradation correlated strongly with physical and chemical parameters of water quality. Understanding the relationship between land use and water quality would facilitate the management not only of the main sources of water pollution but also of the processes involved [12].Tidal influence is a key factor that needs to be considered when assessing and managing the water quality issues in the Perai River basin. This study aimed to assess the impact of tides on Perai River surface water by examining water quality parameters during neap and spring tides.

Materials and Methods

Study Area

Sungai Perai is located in the state of Penang, Malaysia. The river is at Latitude: 5° 22' 59.99" N and Longitude: 100° 21' 59.99" E. The Perai River, which spans 45 km and has a surface area of 447.824 km^2, is the longest and biggest river in Penang, Malaysia. The Sungai Perai basin covers an area of 505 square kilometers and includes 5 tributaries. The rivers mentioned include Sg. Kulim, Sg. Jarak, Sg. Kereh, Sg. Pertama/Derhaka, and Sg. Maklom/Tok Sani. [13]. Eight sampling sites were chosen from tributaries that drain downstream of the river around the industrial estate, where the river is exposed to effluents and dumps from surrounding industries, households, farmlands, and restaurants. The sampling sites are described as follows: Site A is closest to the sea with heavy industries, and a cargo containers storage yard, Site B is closer to several scattered factories, and flood control valves are situated at the site, Site C is situated close to a drain from shops and electronics company, Site D is closer to several restaurants, malls, and warehouses, Site E is closer to temples, container repairs, and recreational areas, Site F is situated along a tributary that empties into the river, Site G is situated closer to a drain from households that contain wastes and Site H is receives drains from households and drains from Sungai Sintok.

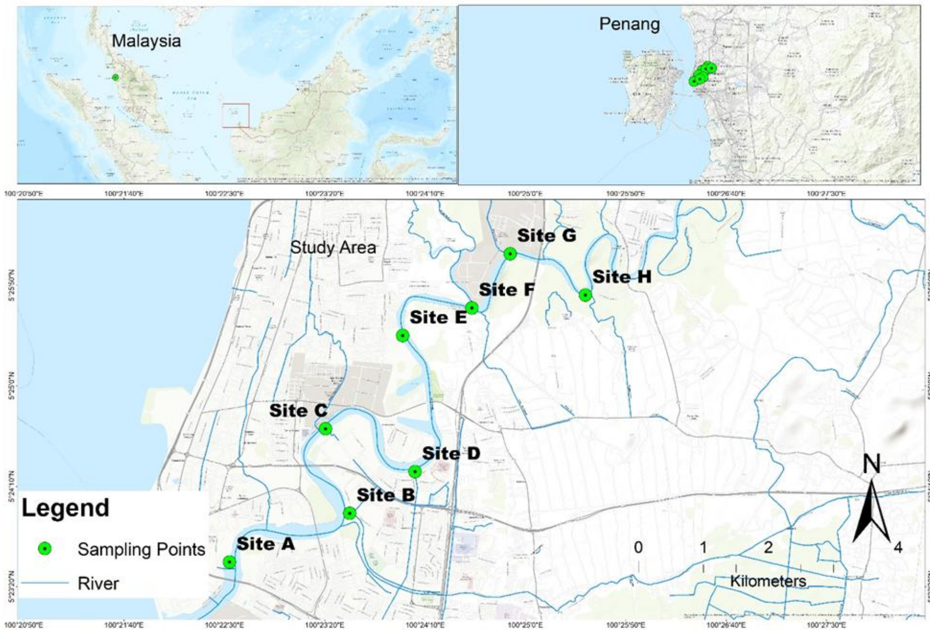


Figure 1. Study area map showing sampling sites

Water Sampling

For safety concerns following a preliminary visit to the river, a boat was used for transportation across the sampling sites. Water samples from the eight sampling sites were collected from the sampling sites twice monthly during the spring and neap tides of January to February and April to May 2024. Water samples were collected in triplicates at each of the sampling sites in a clean 1-liter plastic container. The collected samples were then preserved in a cooler containing ice and transported to the lab for further analysis. The average of the triplicates was used as the result for a parameter at each sampling site.

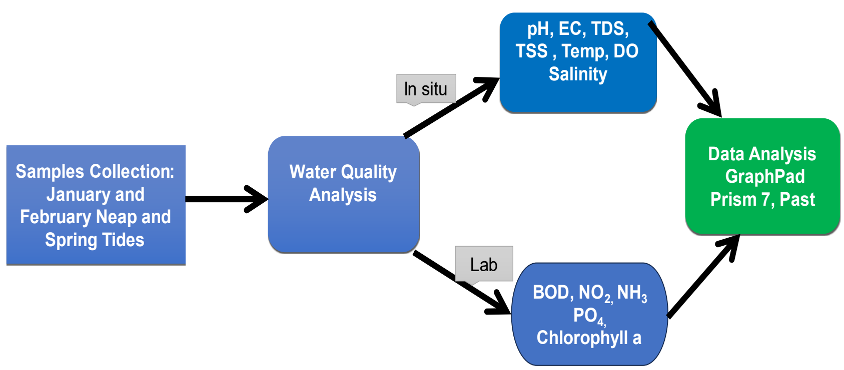


Figure 2. Methodology flowchart

Tests for Physicochemical Parameters

The physicochemical parameters of the rivers, namely; temperature, dissolved oxygen (DO), transparency (TRPC), Salinity (Sal) total dissolved solids (TDS) and electrical conductivity (EC), were analysed using YSI ProQuatro Multiparameter Meter SKU: 606950 United States of America (USA). pH was measured using the LAQUAtwin- pH-33 pH meter by HORIBA Japan. Nitrite (NO_2) Phosphate (PO_4), chlorophyll a (Chlrp a), ammonia (NH_3), total suspended solids (TSS) and Biochemical oxygen (BOD) demand were determined using standard methods described by [14].

Data Analysis

Differences in water quality parameters during spring and neap tides were analysed using T-test. Statistical analysis of one way ANOVA and Tukey post hoc was used to analyse spatial differences in water quality among the sampling sites. Pearson correlation was used to determine the relationships among the water quality parameters. All statistical analyses were done using GraphPad Prism (9.5.1) software.

Results and Discussion

The means of the water quality parameters analyzed during the spring and neap tides at the sampling sites are depicted in Table 1. The analysis results show the impacts of seawater intrusion due to tidal events into the Perai River. Overall, spring tide had much impact on the water quality parameters when compared with neap tide. Spring tides have more significant movement and water level changes compared to neap tides, which have negligible fluctuations [15].Results from ANOVA showed that there is no significant difference (p>0.05) between the spatial variability of EC, TSS, pH, DO, BOD, PO_4, TRPC, NO_2, NH_4, and Temperature. TDS, Salinity, Temperature and Chlorophyll-a showed significant spatial variation (p<0.05) (Table1). Results of the T-test showed that there is no significant difference (p>0.05) in the neap and spring tide concentrations of temperature, BOD, DO, PO_4, NO_2, NH_3, Temp and chlorophyll-a, while EC, TSS, PO_4, NO_2, NH_3, pH, TDS, TRPC, and Sal showed significant variation between spring and neap tides (T-test, p<0.05)

Electrical Conductivity (EC)

EC ranges from 0.12 µS/cm at site G during neap tide to 413 µS/cm during spring tide at site A. The higher EC during spring tide was also reported by [5]. This is due to the high saltwater intrusion from the sea that is associated with spring tides. The high concentration of dissolved sodium and chlorides in the seawater directly increases the conductivity of the river water as these salts dissociate into ions that can conduct electricity. Site A being closest to the sea receives the highest saltwater intrusion and hence recorded high EC which decreases upstream away from the impact of saltwater intrusion [16]. The neap tide data showed that the conductivity variations were like the Total Dissolved Solids (TDS) changes. Various sources, such as wastewater from residential, commercial, and industrial areas, as well as urban and surface run-off, impact the concentration of ions in the water. These sources contribute to ions like bicarbonate ions (HCO^{3-}), carbonate ions (CO^{3-}), sodium ions (Na^+), chloride ions (Cl^-), and others, which are influenced by seawater and affect the river's conductivity [44].

Total Dissolved Solids (TDS)

Water with high TDS is considered saltwater while water with low TDS is considered as freshwater [16]. TDS kept is important to aquatic life by keeping cell density balanced. Cells shrink with high TDS which affects the organism's swimming ability[17] .TDS ranges from 73.23 mg/l at site G in neap tide to 98,466 mg/l during spring tide at site A. The higher TDS recorded during spring tides was similar to the findings of [18] at the Semarak River in Kelantan. The high TDS readings were recorded at site A where there is the mixing of seawater and freshwater is also reported by [16]. The TDS values decline sharply from sites E to H which are located upstream and are minimally impacted by saltwater influx due to tides. High TDS in the saltwater zones of a river and low TDS in the freshwater zones of a river were also reported by the findings of [18].

Salinity

Salinity is a crucial water characteristic that commonly acts as an ecological barrier and a dependable indication in an estuary system [19]. Salinity ranges from 0.05 ppt at G in neap tide to 48.87 ppt during spring tide at site A. Salinity was higher during the spring tide. Site A always records the highest concentration of salinity. This is because site A is the closest to the sea and it receives the highest inflow of sea water. These findings were similarly reported by Fatima *et al.* (2016). Salinity concentrations gradually reduce from A site up to site H which has the lowest salinity concentration. This wide salinity range is attributed to the location of the sampling sites, some are located downstream close to the sea, and some are located upstream where the saltwater influx is limited. These findings are similar to the findings of [5,20,21]. Seawater from the sea enters the estuarine zone and thus raises the salinity of surface water [16]. Strong tidal forces during spring tides facilitate the intrusion of saltwater from the sea into the river, leading to higher mixing of seawater and freshwater. This intrusion can extend further upstream, leading to higher salinity concentrations during the spring tides. In the Sumjin River estuary, the effect of salinity was found to be six times higher during the spring tide compared with the neap tide, due to the overwhelming effect of vertical mixing, resulting in stronger exchange flow during the spring tide [22].

pH

pH values ranged between 6.4 to 7.8. Both the lowest and highest pH values were recorded during spring tides at sites B and C respectively. During spring tides, the pH is higher than during neap tides due to the increased tidal energy pushing fresh water from the river, resulting in a greater cyclical amplitude for pH [23]. The entry of seawater during spring tide generally introduces high amounts of dissolved oxygen and carbonate ions, which foster a more alkaline environment. The pH is increased by this dilution action which reduces the concentration of acidic chemicals in the water[24]. The alkaline nature of seawater might be responsible for the high pH at sites A and B which are located downstream as reported by [25]

Dissolved Oxygen (DO)

The highest and lowest values of DO 1.83-10.74 mg/l were recorded at site E during spring tide and site C during neap tide. The recorded DO values were within the ranges reported by [26] and [20]. Natural diurnal fluctuation in dissolved oxygen which corresponds with the photosynthesis of aquatic organisms may be responsible for the high DO during the neap tides as reported by [27]. The fluctuation in DO levels is most significant during spring tides because of the more intense high tides and lower low tides, leading to increased water flow and increased oxygen mixing between the atmosphere and water. Furthermore, factors including as temperature, salinity, and biological processes like photosynthesis and decomposition play a role in determining DO concentrations in estuarine habitats [28]. The low DO level could be attributed to the high load of organic matter observed during the spring tide and when the demand for the oxygen needed to oxidize organic matter surpasses the amount of oxygen produced by photosynthesis, it can lead to a decrease in the dissolved oxygen levels in the water body [29]. Every organism has a certain dissolved oxygen (DO) tolerance range. Generally, DO levels below 5 mg/l are stressful for fish, while levels below 3 mg/l are insufficient to support fish as most fish species become distressed at levels of 2-4 mg/l. Dissolved oxygen levels below 1mg/L are classified as hypoxic and often do not support any life forms [30].

Biochemical Oxygen Demand (BOD)

BOD values ranged from 0.24 mg/l at site C spring tide and neap tide at site F to 7.14 mg/l at D during spring tide. Similar findings were reported by [31]. High BOD during spring tides can be attributed to increased water flow and mixing which result in the release of more organic matter into the river. Spring tides do not directly impact BOD levels, but they can indirectly influence BOD concentrations in aquatic ecosystems through their effects on water flow, pollutant dilution, nutrient dynamics, and ecological processes [32]. The sediment resuspension during the spring tides may lead to an increase in the release of sulfide and its oxidation which further increases the BOD in the water column [33].

Table 1. Mean concentration of the water quality parameters of Sungai Perai during the study period

Parameters	Site A	Site B	Site C	Site D	Site E	Site F	Site G	Site H	P Value
	Mean ±SD	Mean ±SD	Mean ±SD	Mean ±SD	Mean ±SD	Mean ±SD	Mean ±SD	Mean ±SD	
EC (µS/cm)	80.6±132	40.8±70	55.9±101	5.10±6.55	2.45±2.78	2.09±3.19	1.27±1.88	1.66±1.87	*p*>0.05
TDS (mg/l)	27992± 33066.	20671.± 31594	2126± 28654	3336.6± 4380	1588.5± 1755.05	1387.4± 2108.6	382.35± 415.89	747.76± 979.92	*p*>0.05
Salinity (ppt)	32.66±46.9	19.41±30	13.2±18.4	2.91±3.97	1.32±1.51	1.11±1.77	0.66±1.03	0.91±1.06	*p*>0.05
pH	7.17±0.43	6.99±0.32	6.98±0.43	6.92±0.36	6.82±0.35	6.89±0.3	6.89±0.32	6.96±0.3	*p*>0.05
DO (mg/l)	4.4±1.83	6.02±2.58	4.37±1.66	4.99±2.06	4.33±2.13	3.45±0.59	4.292.56	5.48±1.78	*p*>0.05
BOD (mg/l)	3.14±1.82	1.95±0.88	2.62±2.01	2.82±2.38	3.14±1.83	1.77±1.19	2.14±1.34	2.72±0.96	*p*>0.05
TSS (mg/l)	0.08±0.06	0.07±0.07	0.09±0.06	0.06±0.07	0.12±0.12	0.07±0.06	0.06±0.07	0.09±0.1	*p*>0.05
$P0_4$ (mg/l)	1.35±1.25	0.99±0.71	1.30±0.86	1.27±0.69	1.45±1.19	1.31±0.87	1.23±0.99	1.28±0.86	*p*>0.05
TRPC (m)	0.26±0.24	0.5±0.6	0.12±0.08	0.27±0.27	0.2±0.16	0.22±0.24	0.21±0.12	0.23±0.31	*p*>0.05
$N0_2$ (µg/l)	83.5±10.4	83.1±10.5	83.13±9.9	86.7±12.1	96.7±18.4	82.6±12.3	79.3±8.1	83.69±11.1	*p*>0.05
NH_3 mg/l	0.65±0.1	0.64±0.08	0.64±0.04	0.65±0.07	0.65±0.06	0.62±0.07	0.62±0.07	0.62±0.62	*p*>0.05
Temp (°C)	31.22±0.7	31.13±0.5	30.71±0.47	30.59±0.9	30.86±1.1	30.48±0.8	29.71±0.9	29.25±0.6	*p*>0.05
Chlrp a (µg/l)	2.29±2.13	0.81±0.84	1.67±1.22	0.52±0.24	1.33±0.69	0.99±0.69	2.31±1.21	1.0±0.93	*p*>0.05

**p* <0.05 indicates a significant difference, *p*> 0.05 indicates that there is no significant difference.

Total Suspended Solids (TSS)

Suspended sediment transport processes are crucial in the estuaries because fine-grained sediments are important carriers of various nutrients and pollutants [34]. Site E has the lowest TSS value of 0.01 mg/l during spring tide and the highest value of 0.43 mg/l during spring tide at site E. Spring tides, which are characterized by stronger tidal ranges and currents lead to the mobilization of more suspended solids compared to neap tides [35]. The variation in TSS between spring and neap tides may be due to the increased tidal range during spring tides, resulting in more robust currents and more water flow. This heightened water flow can lead to elevated levels of suspended silt caused by the stirring up of sediments at the bottom. Increased currents can boost the movement of suspended sediments, resulting in higher overall sediment transport during spring tides. Neap tides have a shorter tidal range and weaker currents, leading to lower suspended sediment concentrations and decreased sediment mobility [45,46]. The neap-spring tidal cycle effects on TSS in the present study agree with the findings of [36]

Nutrients

PO_4 concentrations ranged between 0.27 mg/l at site B to 4.41 mg/l at site A. Both the highest and the lowest values of PO_4 were recorded during the neap tides. High phosphate at site A during neap tide could be due to the stabilization period, less dilution from seawater, and high organic matter decomposition [37]. This is evident by the foul smell from the decomposition of dead animals and waste dumped around the area and the murky nature of the water around the site. The low phosphate in site B can be because the site is an undisturbed area with no drains from domestic, agricultural, or industrial areas emptying into the site. NO_2 values range from 63.83 mg/l at site A to 109.6 mg/l at site E. Both the highest and lowest values were recorded during neap tide. NH_3 ranges between 0.5 mg/l at site A to 0.74 mg/l at sites A and H. The highest and the lowest values were recorded during neap tide. Temperature values are between 28.9 °C to 31.27 °C. Nutrients (PO_4, NO_2, and NH_3) were found to be low during the spring tide as compared to neap tide when their concentrations were high. This could be because most nutrients were significantly impacted by the tidal variation. Coastal flooding can enhance seawater exchange capacity by diluting it with outside seawater, which helps reduce the negative impacts of nutrient enrichment [38]. Fluctuations in ammonia levels during neap and spring tides can impact the nutrient dynamics and ecosystem health of estuaries. High levels of ammonia during neap tides can cause eutrophication and hypoxia, whereas elevated ammonia fluxes during spring tides can affect the nutrient balance and productivity of coastal ecosystems [46].

Table 2. Descriptive statistics of physicochemical parameters of Sungai Perai during neap and spring tides

Parameter	Neap Tide	Spring Tide	Mean Total	t	df	P value
EC (µS/cm)	2.41	45.17	23.79	2.57	62.00	$p<0.05$
TDS (mg/l)	1393.00	1798.00	1595.50	3.58	62.00	$p<0.05$
Salinity (ppt)	1.15	16.95	9.05	2.91	62.00	$p<0.05$
pH	6.80	7.10	6.95	3.51	62.00	$p<0.05$
DO (mg/l)	5.06	4.28	4.67	1.53	62.00	$p<0.05$
BOD (mg/l)	2.51	2.58	2.55	0.21	62.00	$p<0.05$
TSS (mg/l)	0.06	0.11	0.09	4.03	62.00	$p<0.05$
$P0_4$ (mg/l)	1.20	1.35	1.28	0.79	62.00	$p<0.05$
TRPC (m)	0.39	0.12	0.85	3.42	62.00	$p<0.05$
$N0_2$ (mg/l)	85.84	83.79	84.82	1.02	62.00	$p<0.05$
NH_3 (mg/l)	22.79	21.23	22.01	0.48	62.00	$p<0.05$
Temp (°C)	33.20	31.10	32.15	0.03	62.00	$p<0.05$
Chlrp a (ug/l)	1.41	1.45	1.43	0.18	62.00	$p<0.05$

Transparency (TRPC)

Transparency was lowest at site F (0.03 m) during neap tide and was highest at site B during spring tide (1.83 m). Strong tidal currents during spring tides can mix the water vigorously, which can result in a more even distribution of silt in the water column. Through this mixing and dilution, the river's general transparency is increased by lowering isolated regions of high turbidity [39]. In estuaries, spring tides may lead to salinity stratification, where denser saline water pushes upstream beneath lighter freshwater, resulting in clearer surface waters as the saline layer may trap sediments below, contributing to higher transparency at the surface [40].

Temperature

The tree canopy cover, the width of the river, and the time of sampling are factors that affect the temperature of rivers in estuarine environments [39]. The lowest temperature was recorded during neap tide at site H while the highest temperature was recorded at site D during spring tide. In the present study, the time of sampling resulted in lower temperatures recorded upstream from site H because the sampling starts in the early morning from site H down to site A. Solar radiation is reported to be the main controlling factor of the temperature of estuaries [5].

Chlorophyll-a

An important marker of water quality and the general condition of aquatic ecosystems is chlorophyll-a [41]. Chlorophyll-a value ranges between 0.26 µg/l in site D to 6.89 µg/l in site A. The highest chlorophyll values were recorded during the spring tide while the lowest chlorophyll values were recorded during neap tides. Elevations of chlorophyll-a signify elevated phytoplankton concentrations, which are subject to fluctuations in nutrient levels, including phosphates and nitrates. This facilitates the monitoring and identification of any contamination incidents that routine nutrient sampling would miss. Spring tides exhibit high chlorophyll-a levels due to increased mixing and turbulent dissipation, resulting in nutritional replenishment and a subsequent rise in chlorophyll-a concentration. During spring tides, the heightened tidal currents result in enhanced vertical mixing and the upsurge of nutrient-rich water from deeper levels [42]. The neap-spring tidal effects on spatiotemporal variations of chlorophyll-a in the present study were also reported by [42].

Correlation of the Water Quality Parameters

As shown in Figure 2, EC has a strong positive correlation with TDS, salinity, and TSS while it is negatively correlated with pH, NO_2, and TRPC. Electrical conductivity (EC) and Total Dissolved Solids (TDS) are indicators of the salinity level in water [47]. Salinity is a measure of the amount of salts in the water. As dissolved ions (TDS) increase salinity so also conductivity [48]. Salinity was found to have a strong positive correlation with TSS. Salinity rises as suspended sediment concentrations increase. Tidal rivers experience elevated salinity and suspended sediment levels because of marine incursion caused by tides, which explains the positive correlation between the two [49].

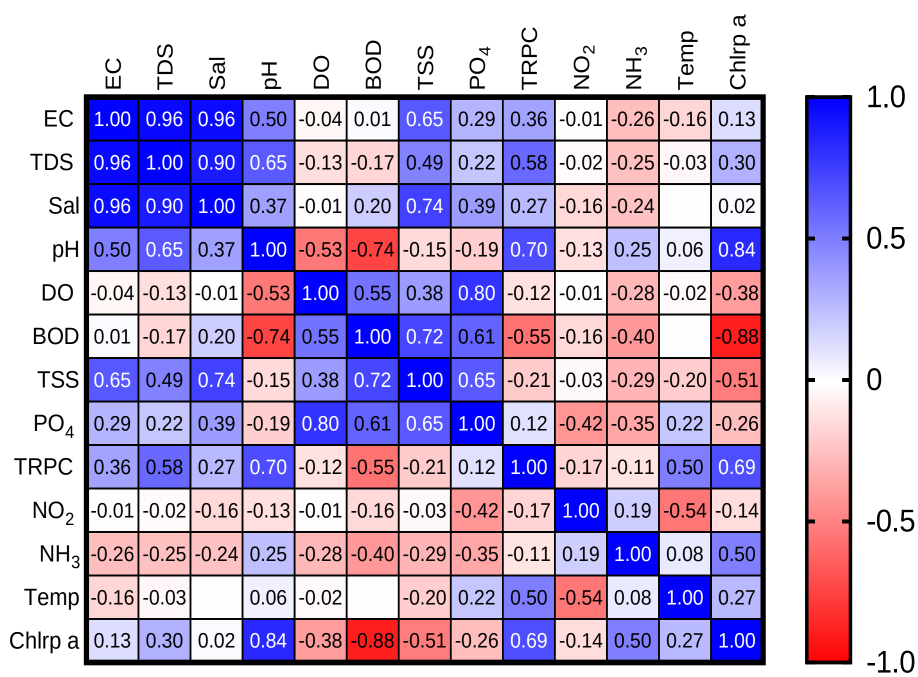
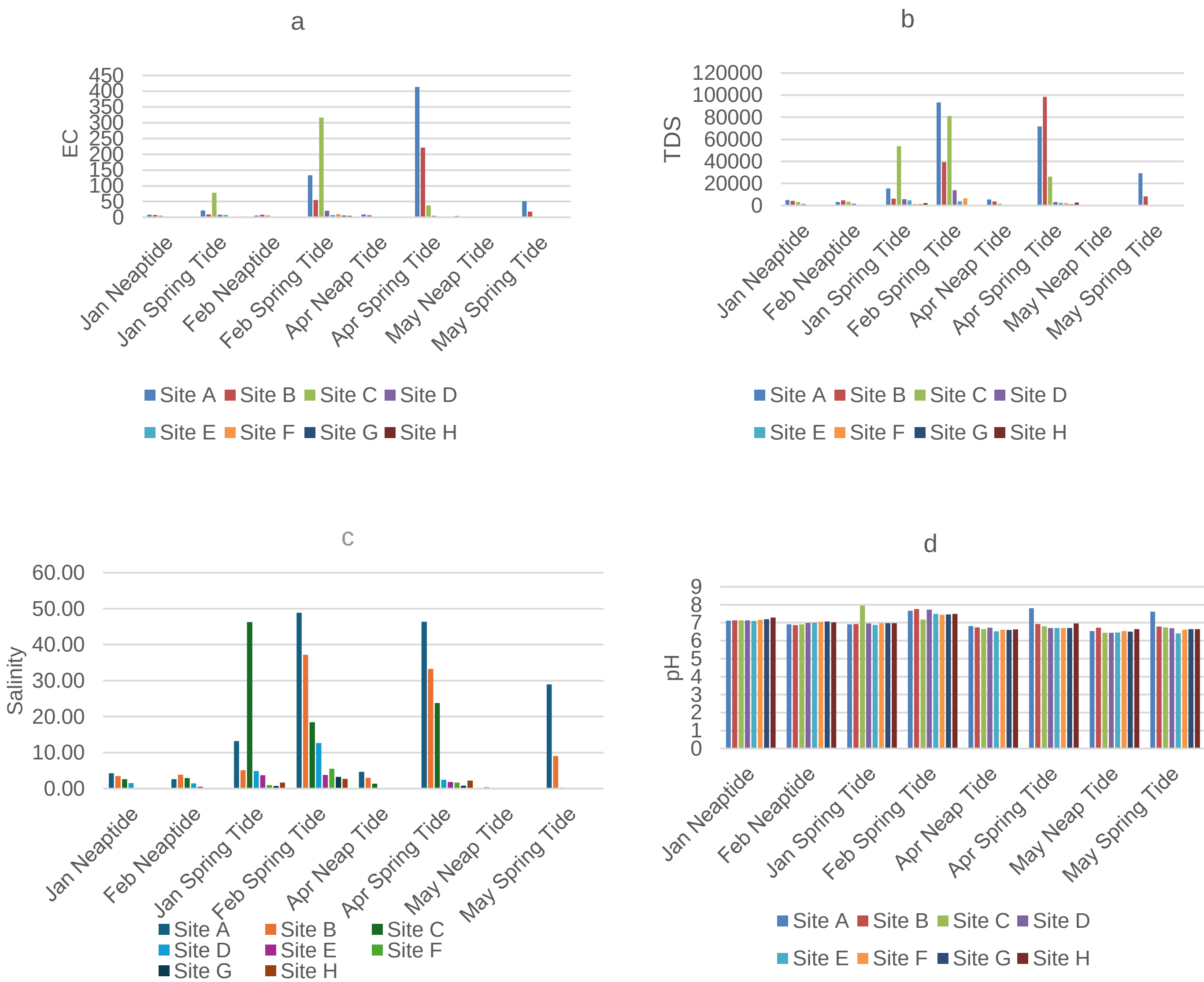


Figure 3. Pearson correlation matrix of the water quality parameters studied

DO and BOD showed a robust positive correlation and this shows that there are other factors affecting the DO/BOD fluctuations in the river such as flow velocity, tidal range and reaeration which tend to increase DO concentration in the presence of high BOD [50]. TSS and TRPC were negatively correlated and this because since the suspended particles scatter and absorb light, larger concentrations of total suspended solids in the water column result in less transparent and clear water [17]. Ammonia also showed a negative correlation with DO which can be explained by the consumption of oxygen during the oxidation of ammonia (Nitrification) and a decrease in oxygen levels increases ammonia levels by inhibiting nitrification [51]. Because higher ammonia levels demand more oxygen to break down organic waste, there is a negative link between ammonia and BOD. This is the reason why ammonia and BOD are negatively correlated [52].



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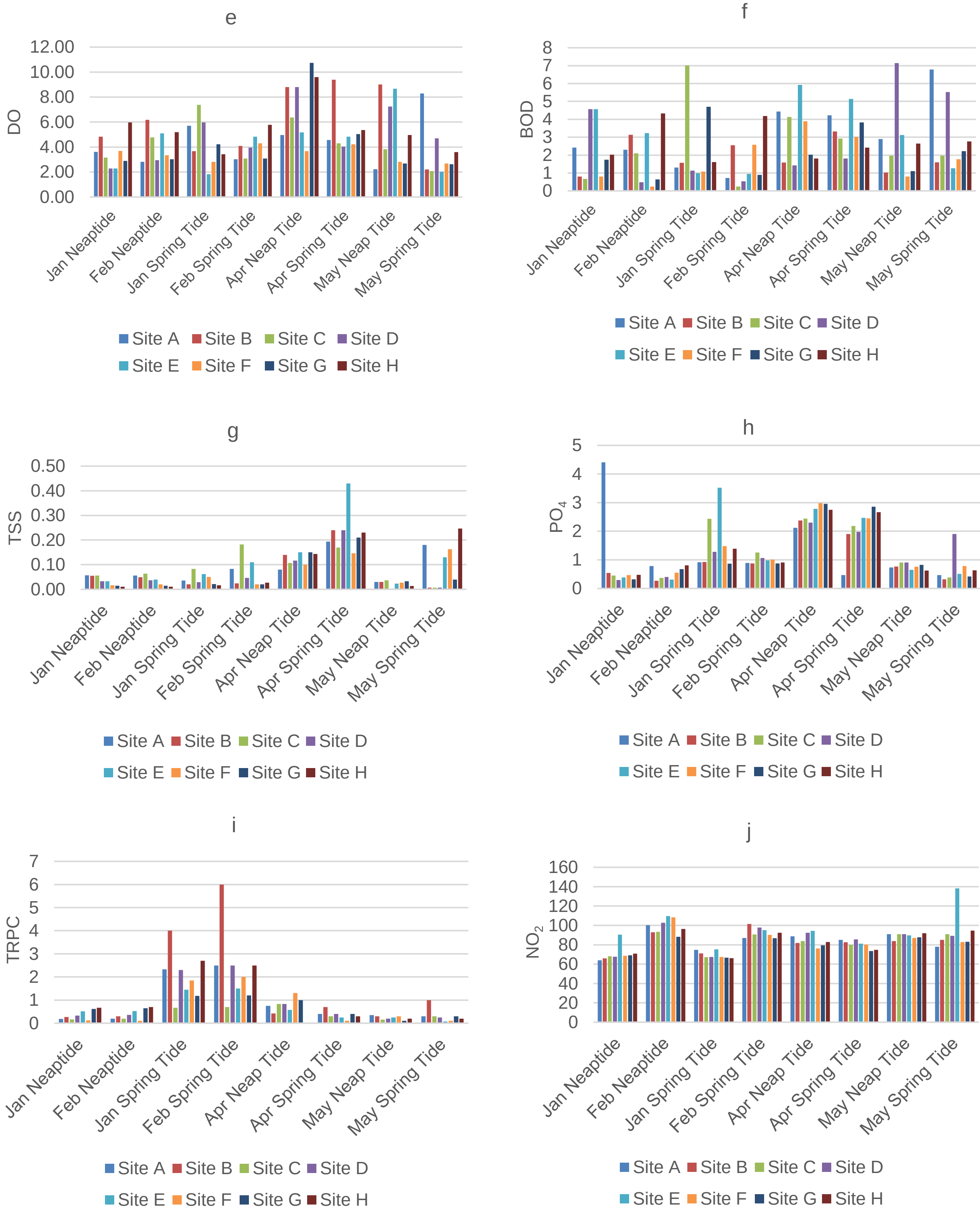

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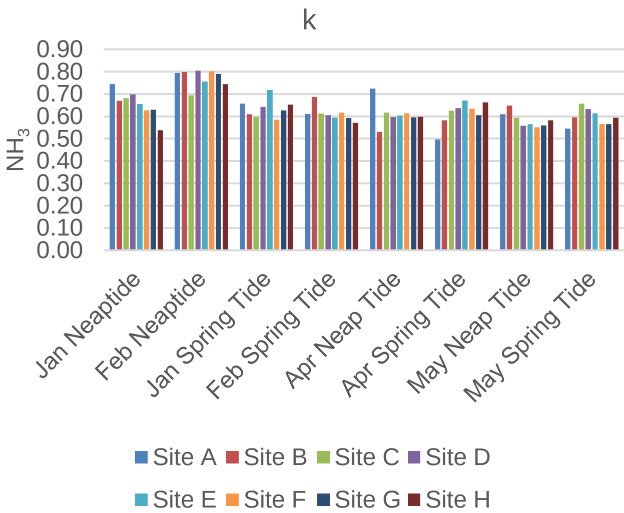

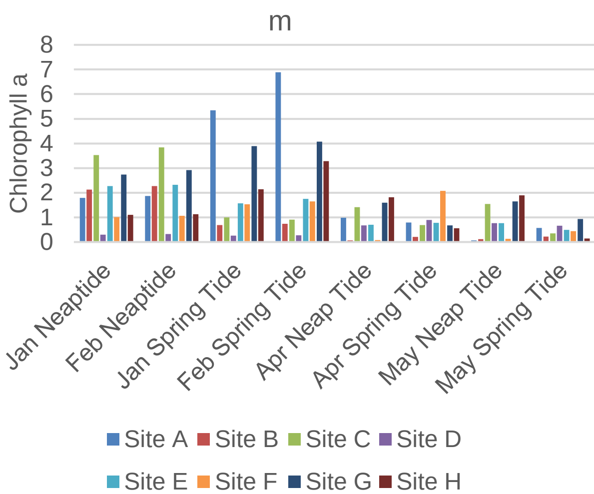

Figure 4. Water quality variations for spring and neap tides at Site A, B, C, D, E, F,G and H (a) EC (µS/cm); (b) Total dissolved solids (mg/l); (c) salinity (ppt) (d) pH (e) DO (mg/l); (f) BOD; (mg/l) TSS (mg/l); (h) PO4 (mg/l); (i) TRPC (m); (j) nitrite (mg/l); (k) ammonia (mg/l); (l) Temperature (ºC); (m) Chlorophyll a (µg/l)

Conclusions

Spring and neap tidal variations were shown to impact the water quality in several sites of the Perai River. Site A, being closer to the sea, is more affected by the tide and undergoes greater fluctuations in water quality compared to Site H, which is less impacted by tidal influences. Spring tide tends to have more effect on the river quality as compared to neap tide. This is because, during spring tides, the fluctuations in water level during the tide cycle are particularly pronounced. Mostly, the neap tide water quality fluctuations can be attributed to anthropogenic inputs into the river and diurnal cycle activities such as photosynthesis and respiration. Salinity, total dissolved solids, electrical conductivity, and total suspended solids yielded the highest differences in response to the tidal conditions, especially at sites A to D where the influence of tides was more evident. DO, BOD and Chlorophyll a are affected by other factors apart from tidal events such as photosynthesis, respiration, nutrients, and many others which could be why no significant difference was recorded during the spring and neap tide. This study reveals that the water quality of Sungai Perai is impacted by the combined effects of tidal influence, anthropogenic activities, and diurnal cycles. Therefore, it is essential to comprehend how tidal events affect water quality parameters and overall water quality evaluations to improve monitoring and management strategies.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

Acknowledgement

We are extremely thankful for thesupport of the aquatic lab USM for providing laboratory facilities and equipment for this study.

References

[1] Grizzetti, B., & Poikane, S. (2024). The importance of inland waters. In A. Wetzel (Ed.), *Wetzel's limnology* (pp. 7–13). Elsevier. ISBN: 978-0-12-822701-5.
[2] Chen, D., Elhadj, A., Xu, H., Xu, X., & Qiao, Z. (2020). A study on the relationship between land use change and water quality of the Mitidja watershed in Algeria based on GIS and RS. *Sustainability, 12*(9), 3510. https://doi.org/10.3390/su12093510
[3] Ameen, R. F. M., & Mourshed, M. (2017). Urban environmental challenges in developing countries—a stakeholder perspective. *Habitat International, 64*, 1–10. https://doi.org/10.1016/j.habitatint.2017.04.002
[4] Priya, K. L., Jegathambal, P., & James, E. J. (2012). Seasonal behaviour of a shallow estuary of lower Cauvery basin, India. *Environmental Research, Engineering and Management, 61*(3), 6–13. https://doi.org/10.5755/j01.erem.61.3.2041
[5] Fatema, K., Omar, W., & Isa, M. (2016). Effects of tidal events on the water quality in the Merbok estuary, Kedah, Malaysia. *Journal of Environmental Science and Natural Resources, 8*(2), 15–19. https://doi.org/10.3329/jesnr.v8i2.26858
[6] Center for Coastal Solutions. (n.d.). Researchers reveal astronomic link to water quality challenges. Center for Coastal Solutions. Retrieved April 3, 2024, from https://ccs.eng.ufl.edu/researchers-reveal-astronomic-link-to-water-quality-challenges/
[7] Rutledge, K., McDaniel, M., Hall, H., Ramroop, T., Sprout, E., Hunt, J., Boudreau, D., & Costa, H. (n.d.). Cause and effect: Tides. National Geographic. Retrieved April 3, 2024, from https://education.nationalgeographic.org/resource/cause-effect-tides/
[8] Panseriya, H. Z., Gosai, H. B., Gavali, D. J., & Dave, B. P. (2023). Assessment of surface water quality during different tides and an anthropogenic impact on coastal water at Gulf of Kachchh, West Coast of India. *Environmental Science and Pollution Research International, 30*, 28053–28065. https://doi.org/10.1007/s11356-022-24205-z
[9] Daud, H. (2008). Legislative approach to water quality management in Malaysia—Success and challenges.
[10] Azura, N. C. M. (2021). River & stream water quality monitoring. Surechem.
[11] Abdul Rahman, H. (2021). Water issues in Malaysia. *International Journal of Academic Research in Business and Social Sciences, 11*(8), 860–875. https://doi.org/10.6007/IJARBSS/v11-i8/10783
[12] Camara, M., Jamil, N. R., & Abdullah, A. F. B. (2019). Impact of land uses on water quality in Malaysia: A review. *Ecological Processes, 8*, 10. https://doi.org/10.1186/s13717-019-0164-x
[13] Department of Irrigation and Drainage. (n.d.). Sg Perai flood mitigation project. Department of Irrigation and Drainage Malaysia. Retrieved April 3, 2024, from https://www.water.gov.my/index.php/pages/view/839
[14] Radojević, M., & Baškin, V. N. (2006). *Practical environmental analysis* (2nd ed.). Royal Society of Chemistry. ISBN: 978-0-85404-679-9.
[15] Haris, H., & Omar, W. M. W. (2008). The effects of tidal events on water quality in the coastal area of Petani River Basin, Malaysia.
[16] Gasim, M. B., Khalid, N. A., & Muhamad, H. (2015). The influence of tidal activities on water quality of Paka River Terengganu, Malaysia.
[17] Fondriest Environmental. (2014). Fundamentals of environmental measurements: Turbidity, total suspended solids and water clarity.
[18] Samsudin, M. F., Shau Hwai, A. T., Amin, M. M. F., & Muhammad Sharifuddin, M. F. (2023). The influence of tidal on water quality in Sungai Semerak, Kelantan. *BIO Web of Conferences, 73*, 05005. https://doi.org/10.1051/bioconf/20237305005
[19] Matos, J., Costa, K., Pereira, L., & Marinho da Costa, R. (2011). Tide-induced changes in the phytoplankton communities of three Amazon estuaries (Pará—Northern Brazil). *Journal of Coastal Research, 64*, 1574–1578.
[20] Matos, J., Costa, K., Pereira, L., & Marinho da Costa, R. (2011). Tide-induced changes in the phytoplankton communities of three Amazon estuaries (Pará—Northern Brazil). *Journal of Coastal Research, 64*, 1574–1578.
[21] Haris, H., & Omar, W. M. W. (2008). The effects of tidal events on water quality in the coastal area of Petani River Basin, Malaysia.
[22] Cho, E.-B., Tak, Y.-J., Cho, Y.-K., & Na, H. (2022). Fortnightly variability of horizontal salinity gradient affects exchange flow in the Sumjin River estuary. *Frontiers in Marine Science, 9*. https://doi.org/10.3389/fmars.2022.1077004
[23] Proum, S., Santos, J. H., Lim, L. H., & Marshall, D. J. (2018). Tidal and seasonal variation in carbonate chemistry, pH and salinity for a mineral-acidified tropical estuarine system.
[24] Revina, S., Istiarto, & Pratiwi, E. (2022). The effect of tides on water salinity and acidity in the main channel of Anjir Serapat lowland irrigation area, Central Kalimantan: Bangka, Indonesia.
[25] Perkins, E. J. (1974). The biology of estuaries and coastal waters (Vol. 2). Academic Press.

[26] Hashem, A. O. A., Ahmad, W. A. A. W., & Yusuf, S. Y. (2021). Water quality status of Sungai Petani River, Kedah, Malaysia. *IOP Conference Series: Earth and Environmental Science, 646*, 012028. https://doi.org/10.1088/1755-1315/646/1/012028.

[27] Pearce, M., & Schumann, E. (2003). Dissolved oxygen characteristics of the Gamtoos Estuary, South Africa. *African Journal of Marine Science, 25*, 99–109. https://doi.org/10.2989/18142320309504003.

[28] Regier, P. J., Ward, N. D., Myers-Pigg, A. N., Grate, J., Freeman, M. J., & Ghosh, R. N. (2023). Seasonal drivers of dissolved oxygen across a tidal creek–marsh interface revealed by machine learning. *Limnology & Oceanography, 68*, 2359–2374. https://doi.org/10.1002/lno.12426.

[29] Kress, N., Coto, S. L., Brenes, C. L., Brenner, S., & Arroyo, G. (2002). Horizontal transport and seasonal distribution of nutrients, dissolved oxygen and chlorophyll-a in the Gulf of Nicoya, Costa Rica: A tropical estuary. *Continental Shelf Research, 22*, 51–66. https://doi.org/10.1016/S0278-4343(01)00064-4.

[30] US EPA, O. (2024). Indicators: Dissolved oxygen. Retrieved April 17, 2024, from https://www.epa.gov/national-aquatic-resource-surveys/indicators-dissolved-oxygen.

[31] Rizki, N., Maslukah, L., Sugianto, D., Wirasatriya, A., Zainuri, M., Ismanto, A., Purnomo, A., & Ningrum, A. (2021). Distribution of DO (dissolved oxygen) and BOD (biological oxygen demand) in the waters of Karimunjawa National Park using two-dimensional model approach. *IOP Conference Series: Earth and Environmental Science, 750*, 012014. https://doi.org/10.1088/1755-1315/750/1/012014.

[32] Rizki, N., Maslukah, L., Sugianto, D., Wirasatriya, A., Zainuri, M., Ismanto, A., Purnomo, A., & Ningrum, A. (2021). Distribution of DO (dissolved oxygen) and BOD (biological oxygen demand) in the waters of Karimunjawa National Park using two-dimensional model approach. *IOP Conference Series: Earth and Environmental Science, 750*, 012014. https://doi.org/10.1088/1755-1315/750/1/012014.

[33] Nelson, B. W., Sasekumar, A., & Ibrahim, Z. Z. (1994). Neap-spring tidal effects on dissolved oxygen in two Malaysian estuaries. *Hydrobiologia, 285*, 7–17. https://doi.org/10.1007/BF00005649.

[34] Chen, S. L., Zhang, G. A., Yang, S. L., & Shi, J. Z. (2006). Temporal variations of fine suspended sediment concentration in the Changjiang River Estuary and adjacent coastal waters, China. *Journal of Hydrology, 331*, 137–145. https://doi.org/10.1016/j.jhydrol.2006.05.013.

[35] Wisha, U., & Ondara, K. (2017). Total suspended solid (TSS) distributed by tidal currents during low to high tide phase in the waters of Sayung, Demak: Its relations to water quality parameters. *Journal of Marine and Aquatic Sciences, 3*, 154. https://doi.org/10.24843/jmas.2017.v3.i02.154-162.

[36] Chen, S. L., Zhang, G. A., Yang, S. L., & Shi, J. Z. (2006). Temporal variations of fine suspended sediment concentration in the Changjiang River Estuary and adjacent coastal waters, China. *Journal of Hydrology, 331*, 137–145. https://doi.org/10.1016/j.jhydrol.2006.05.013.

[37] Davies, O. A., & Ugwumba, O. A. (2013). Tidal influence on nutrients status and phytoplankton population of Okpoka Creek, Upper Bonny Estuary, Nigeria. *Journal of Marine Biology, 2013*, 1–16. https://doi.org/10.1155/2013/684739.

[38] Fu, M., Lin, J., Zhang, P., Luo, W., & Zhang, J. (2023). Tide drives nutrients variation and exchange flux in the semi-enclosed Shuidong Bay coastal water in winter, South China Sea. *Ocean & Coastal Management, 242*, 106710. https://doi.org/10.1016/j.ocecoaman.2023.106710.

[39] Nurhidayu, S., & Harun, N. (2024). Tidal and seasonal effects on water quality in the Matang Mangrove Forest Reserve, Malaysia. *Modern Applied Science, 18*, 39. https://doi.org/10.5539/mas.v18n1p39.

[40] Ndunagum Emeka, C., Inyang Emeka, V., Ben Akpan, E., Udo Essien, N., & Maduwuba Nwosu, F. (2023). Dry season physicochemical characteristics of a tropical meso-tidal estuary: Cross River Estuary, Southeast Nigeria. *Glo Jnl Geo Sci, 21*, 183–200. https://doi.org/10.4314/gjgs.v21i2.3.

[41] Fernandes, É., Teixeira, C., & Bordalo, A. A. (2019). Coupling between hydrodynamics and chlorophyll a and bacteria in a temperate estuary: A box model approach. *Water, 11*, 588. https://doi.org/10.3390/w11030588.

[42] Xing, Q., Yu, H., Yu, H., Wang, H., Ito, S., & Yuan, C. (2021). Evaluating the spring-neap tidal effects on chlorophyll-a variations based on the geostationary satellite. *Frontiers in Marine Science, 8*. https://doi.org/10.3389/fmars.2021.758538.

[43] Pastore, D. M., Peterson, R. N., Fribance, D. B., Viso, R., & Hackett, E. E. (2019). Hydrodynamic drivers of dissolved oxygen variability within a tidal creek in Myrtle Beach, South Carolina. *Water, 11*, 1723. https://doi.org/10.3390/w11081723.

[44] Clean Water Team. (2004). Electrical conductivity/salinity fact sheet. *The Clean Water Team Guidance Compendium for Watershed Monitoring and Assessment*, Version 2.0. Division of Water Quality, California State Water Resources Control Board (SWRCB), California.

[45] Dunn, R. J. K., Glen, J., Lin, H. H., & Zigic, S. (2021). Observations of suspended particulate matter concentrations and particle size distributions within a macrotidal estuary (Port Curtis Estuary, Australia). *Journal of Marine Science and Engineering, 9*, 1385. https://doi.org/10.3390/jmse9121385.

[46] Yang, S. L., Zhang, J., & Zhu, J. (2004). Response of suspended sediment concentration to tidal dynamics at a site inside the mouth of an inlet: Jiaozhou Bay (China). *Hydrology and Earth System Sciences, 8*, 170–182. https://doi.org/10.5194/hess-8-170-2004.

[47] Rusydi, A. F. (2018). Correlation between conductivity and total dissolved solid in various type of water: A review. *IOP Conference Series: Earth and Environmental Science, 118*, 012019. https://doi.org/10.1088/1755-1315/118/1/012019.

[48] Starrett, G. (2002). Electrical conductivity/salinity. Fact Sheet.

[49] Fang, L. G., Chen, S. S., Li, D., & Li, H. L. (2009). Use of reflectance ratios as a proxy for coastal water constituent monitoring in the Pearl River Estuary. *Sensors, 9*, 656–673. https://doi.org/10.3390/s90100656.

[50] Huhnke, C. R. (2018). Factors affecting minimum dissolved oxygen concentration in streams. Cleveland State University.

[51] US EPA, O. (2024). Ammonia. Retrieved April 18, 2024, from https://www.epa.gov/caddis/ammonia.

[52] Daphtary, N. (2023). Wastewater treatment plant issues – reducing BOD and ammonia levels. *Chemtech International*.