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THE IMPACT OF HUMAN ALTERED GEOMORPHOLOGY ON THE SEASONAL DISTRIBUTION PATTERN OF WATER PHYSICOCHEMICAL AND NUTRIENT PARAMETERS IN THE TERENGGANU RIVER ESTUARY, MALAYSIA

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Abstract: River estuaries are under intense pressure and tremendous changes due to development. Such changes will affect water quality and circulation and add pressure on the aquatic environment. In this study, we determine the seasonal distribution pattern of water physicochemical and nutrient parameters in the Terengganu River estuary after significant geomorphological changes. Our results show dissolved inorganic nitrogen had the highest values during fall inter-monsoon (19.61 ± 8.61 µmol N/L). Heavy rainfall during the northeast monsoon reduced the water temperature (25.5 ± 0.68°C), improved dissolved oxygen level (5.9 ± 0.5 mg/L), lowered pH values (5.6 ± 0.5), increased suspended particulate matter (71.9 ± 24.2 mg/L) and turned the estuary into a freshwater system. Extreme dry weather during spring inter-monsoon (2016) resulted in the incoming tide pushing coastal seawater inwards, reaching stations located 10.24 km (S1-Nerus River) and 9.43 km (S4-Terengganu River) away and turned the water column slightly saline (1.4 – 2.92 psu). In comparison to year 1999-2000, saltwater was only detected 5.27 km from the estuary mouth. These data are crucial for future estuarine dynamic modelling to improve development planning and coordination of upstream water discharge at Kenyir dam and downstream water extraction for human consumption.

Keywords: Saltwater intrusion, estuary hydrology, water quality, hypoxia, microtidal.

Introduction

River estuaries and adjacent areas are always the focus of infrastructure development plans to improve economic growth and the quality of life. Along with intense pressure from the fluctuation of climate conditions, the additional effects from human activity on the geomorphology of river estuaries will strain an already fragile aquatic environment (Ijaz *et al.,* 2020; Oorschot *et al.,* 2018; Patil *et al.,* 2018; Wetzel *et al.,* 2012). The Terengganu River estuary, the present study area, has gone through significant landscape changes in the last few decades. Its riverine and estuarine ecosystem face constant changes in river-tide dynamics. The estuary is also subject to the effects of a cocktail human activities, such as aquaculture, agriculture, as well as domestic waste from urban-rural residential and industrial areas (Hasrizal *et al.,* 2009). Terengganu, Nerus and Seberang Takir Rivers are the three main rivers that flow into the estuary before the water is dispersed into the South China Sea. The history of Terengganu River development began in 1978, when the Kenyir dam (approximately 43 km from river estuary) began construction and was completed in 1985. Other significant river landscape changes were the completion of a symmetrical bow-shape equal arms breakwater in year 2008 at the Terengganu River estuary mouth, subsequent land reclamation at the estuary and coastal area (Figure 1) and the construction of a drawbridge. The modified estuary is about 1 km^2 larger than the original. The breakwater with an opening of 200 m in the middle is to reduce the wave action and facilitate te safe entry of small vessels into the estuary.

Annually, the estuary experiences two main monsoon seasons, the Northeast (November to March) and Southwest (May to September). The periods in between are the shorter inter-monsoon seasons, which usually occur in the months of April and October. The Terengganu River estuary experiences diurnal or semidiurnal microtidal conditions with tidal ranges of less than two meters (Lee *et al.,* 2017). Therefore, upstream freshwater flow may be the dominant factor of estuary circulation in comparison to tidal influence (Perales-Valdivia *et al.,* 2018). In the study conducted by Law and Jong published in 2006, which was before the construction of the present structures and reclaimed land at the estuary, heavy rainfall during the Northeast monsoon would flush freshwater directly into the South China Sea and the estuary of the Terengganu River would become a freshwater regime (well-mixed estuary) while the less intense Southwest and inter-monsoon seasons generated physicochemical stratification patterns in the estuary.

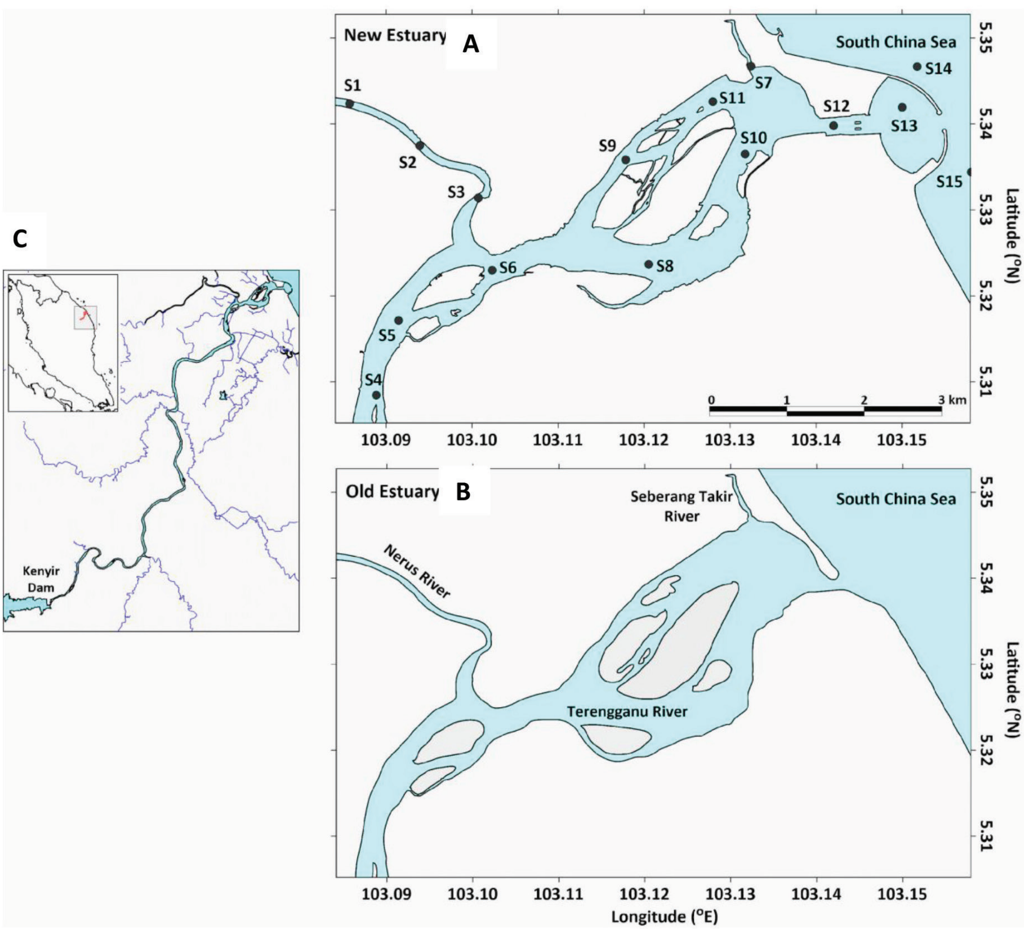


Figure 1: Map A shows the new estuary sampling stations conducted in 2016 and 2017. Map B is the old estuary before construction of breakwater and land reclamation. Map C shows the location of Kenyir Dam, which is approximately 43 km from Terengganu River estuary

After the construction of the breakwater at the river mouth, no extensive study has been conducted on water movement and circulation within the semi-enclosed new breakwater-estuary area and how it may affect the overall water flushing time and rate out from the whole estuary system. Studies of other estuaries with similar circumstances usually reveal changes in the flow rates and water exchange with the open sea, river tide dynamics, water depth, sediment accumulation and water residence time within the estuary (e.g., Jickells *et al.,* 2014; Reimer *et al.,* 2015; Hoitink & Jay, 2016; Rasmussen & Josefson, 2002). The study by Lee *et al*. (2016a) showed that the breakwater construction at the estuary mouth of Terengganu River had resulted in retained nutrients in the estuary and reduced the level of nutrient concentration in coastal waters. In the long run, this will have huge impact on the local fishery industry as the Terengganu River is one of the most important rivers that provides nutrients to the nearby coastal waters (Hee *et al.,* 2020; Sharples *et al.,* 2017; Pelage *et al.,* 2021; Pearson *et al.,* 2021).

In this study, we report the spatial and temporal distribution patterns of selected physicochemical parameters in the river waters and how these parameters changed during the Northeast, Southwest and inter-monsoons seasons. These data are important to help our understanding of the estuary's natural dynamics and how the geomorphological changes of the last few decades had shaped the environmental quality. The level of the water's pH, dissolved oxygen (DO), suspended particulate matter (SPM) and nutrients were compared with quality status outlined in the Malaysian Marine Water Quality Standard (MMWQS) by Department of Environment Malaysia (DOE, 2019). We also analysed the hydrodynamics, in particular salinity values, based on the data collected between year 1999-2000 (Law & Jong, 2006; Jong, 2002) and data from this study to assess the overall impact of human intervention on seawater movement and intrusion within the estuarine system.

Materials and Methods

Study Area, Tides and Rainfall Data

Terengganu River Estuary is in the district of Kuala Terengganu at the latitude and longitude of 05° 18' N to 05° 21' N and 103° 5' E to 103° 10' E on the east coast of Peninsular Malaysia by the South China Sea (Figure 1). 15 sampling stations were chosen with 13 stations within the estuary area and two stations (stations 14 and 15) at coastal waters. Stations 1, 2 and 3 were along the Nerus River, stations 4, 5 and 6 were along the Terengganu River and station 7 was along the Seberang Takir River. All the rivers channel water into the Terengganu River estuary (stations 8, 9, 10, 11, 12 and 13).

Tides and precipitation data for 2016 and 2017 were obtained from tides table and rainfall data published by Malaysia National Hydrography Centre and Malaysia Meteorological Department, respectively. Data from National Hydrographic Centre Malaysia, (2016; 2017), during the sampling period, showed that the study area experienced diurnal tidal pattern in August 2016 and December 2016 and semidiurnal tidal pattern in October 2016 and April 2017. The water column depth within the estuary during low tide generally varied between 1.0 m (S4) and 10.2 m (S3). High and low tide levels varied between 1.9 and 2.5 m and 0.6 and 1.1 m respectively. The highest tidal range was observed in August and December 2016 (1.5 m) (Table 1). Thus, the Terengganu River estuary can be classified as having a microtidal pattern and experience either diurnal or semidiurnal tidal patterns. During our study period of 2016 and 2017, the NEM recorded total rainfall of 1927 mm and 1815 mm and the SWM brought total rainfall of 489.2 mm and 415.6 mm respectively. Both years' inter-monsoon months had rainfall in the range of 1.0 mm to 309.4 mm (Figure 2).

Table 1: Water column depth (m) and tides data of Terengganu River estuary during the sampling period

Station	2016			2017
	SWM (August)	FIM (October)	NEM (December)	SIM (April)
S1	4.0	3.5	4.5	4.2
S2	5.0	3.3	4.5	3.9
S3	7.5	10.2	9.0	6.2
S4	2.1	1.3	1.8	1.0
S5	2.0	1.4	1.8	1.6
S6	3.5	3.2	4.6	4.0
S7	2.3	3.3	2.6	2.6
S8	2.7	2.3	2.8	3.0
S9	3.3	2.3	3.0	2.6
S10	2.3	3.4	3.5	3.1
S11	4.4	4.2	5.5	5.7
S12	7.4	7.7	5.4	8.1
S13	8.1	7.4	7.5	6.8
S14	7.6	8.1	NA	8.9
S15	5.8	6.7	NA	7.2
Highest tide (m)	2.1	2.2	2.5	1.9
Lowest tide (m)	0.6	1.1	1.0	0.9
Tidal range (m)	1.5	1.1	1.5	1.0

*NEM: Northeast Monsoon, SIM: Spring Inter-monsoon, SWM: Southwest Monsoon, FIM: Fall Inter-monsoon

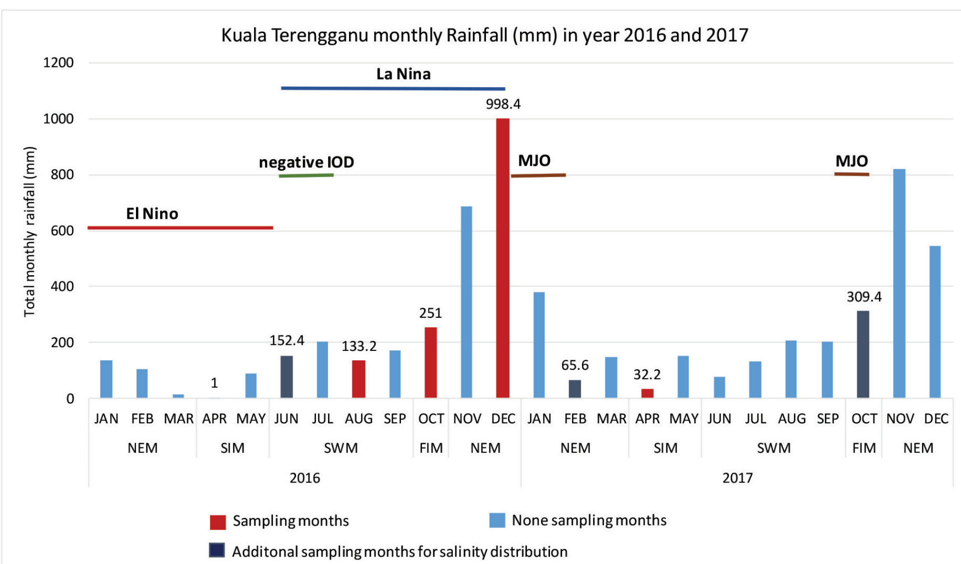


Figure 2: Rainfall data of Kuala Terengganu during different monsoon seasons, large- and small-scale climate variability in year 2016 and 2017. NEM: Northeast Monsoon, SIM: Spring Inter-monsoon, SWM: Southwest Monsoon, FIM: Fall Inter-monsoon, IOD: Indian Ocean Dipole, MJO: Madden Julian Oscillation

Water Physicochemical Parameters Analysis

The samplings were conducted in four periods: Southwest monsoon, August 2016 (SWM), fall inter-monsoon, October 2016 (FIM), Northeast monsoon, December 2016 (NEM) and spring inter-monsoon, April 2017 (SIM). All samplings were conducted during low tide. Physicochemical parameters including temperature, salinity, DO and pH were measured *in situ* using Hydrolab Quanta at 0.5 meters from water's surface at each station. Water samples were collected using Niskin water sampler to determine nitrogen, phosphorous and SPM. For ammonium (NH_4), nitrite (NO_2), nitrate (NO_3) and ortho-phosphorus (PO_4) analyses, all water samples were filtered using 0.45 µm pore-size membrane filter and were determined using American Public Health Association (APHA) (2012) methods. In brief, NH_4 was determined using phenate colorimetric method (APHA 4500-NH_3 F). NO_2 was determined by diazotizing with sulfanilamide and coupling with N-(1-napthyl) ethylenediamine dihydrochloride to form a highly colored azo dye that was measured colorimetrically (APHA 4500-NO_2 - B). NO_3 was reduced quantitatively to NO_2 in the presence of cadmium and the NO_2 was later determined colorimetrically (APHA 4500-NO_3 - E). Dissolved inorganic nitrogen (DIN) is the sum of NO_2, NO_3 and NH_4. PO_4 was reacted with ammonium molybdate and potassium antimonyl tartrate to form a heteropoly acid that was reduced to molybdenum blue by ascorbic acid. The colour compound was later determined colorimetrically (APHA 4500-P E). All samples were measured using a Shimadzu UV-VIS Spectrophotometer Model UV-1800 at wavelengths of 543nm (NO_2), 640 nm (NH_4) and 880nm (PO_4) (APHA, 2012). Surface water Chl-a and SPM concentrations were determined following APHA (2012). Particulates in water were filtered out using GF/F. For Chl-a determination, the residue was extracted in 90 % acetone, kept in the dark for 24-hours at 4^{o}C. The extracts were centrifuged and the supernatants were measured with spectrophotometer (Shimadzu UV-VIS Spectrophotometer Model UV-1800). For SPM analysis, the residue on GF/F was oven dried at ~105^{o}C until constant weight was obtained. The quality control process for sampling and analytical procedures strictly followed (APHA) guidelines. The standard curve for each nutrient parameter was established and the coefficient of determination (R2) was in the range of 0.998 – 1.000. The precision of each nutrient's analytical method was verified with the standard solution and resulting recovery was between 94.8 - 106.1%. Each field sample was properly homogenized before being separated into three sub-samples and analysed as independent samples. The mean and standard deviation values were calculated with the coefficient of variation (CV) within the range of 0.00 – 0.28.

As seasonal hypoxia was reported in Terengganu River estuary (Lee *et al.,* 2016c), we detailed our study by further examining the physicochemical and nutrient concentrations at station S10. For this purpose, we collected the surface and bottom water samples for selected months that represented different monsoon seasons from April 2016 until October 2017.

Statistical Analysis

Physicochemical and nutrient data for each monsoon season was analysed using principal component analysis (PCA) and factor analysis (FA) to determine the underlying relationships between variables and identify the most important parameters for a given season. These analyses were performed using the statistical computing software R (R version 3.6.0, R Core Team, 2020). Prior to analysis, the data were converted to standardized z-scores (zero mean and unit variance) in order to ensure that all variables had identical units and equal weight in the analysis. Preliminary analysis using the Kaiser-Mayer-Olkin (KMO) index (Kaiser, 1960) and Bartlett`s sphericity test (Bartlett, 1954) was then conducted to identify the sampling adequacy and feasibility for PCA and FA. The samples were considered adequate if the KMO index was larger than 0.50 and Bartlett sphericity test was smaller than 0.05 (Field, 2000; Pallant, 2016). PCA was calculated using the correlation matrix and decomposed by singular value decomposition (SVD) to obtain the loading or correlation matrix, eigenvalues and eigenvectors. The Kaiser-Guttman eigenvalue-greater-than-one criterion (Guttman, 1954; Kaiser, 1960) was adopted to determine the number of principal components (PCs) to retain. Similar to PCA, factor analysis was performed on the correlation matrix of the standardized data set. In this analysis, only the significant PCs (eigenvalues greater than one) were subjected to Varimax rotation, which maximizes the squared loading variance across variables while constraining the factors as orthogonal or to be uncorrelated. In this study the value of factor loading or the correlations between variables and components were classified into three groups, i.e., strong (> 0.75), moderate (0.50 - 0.75) and weak (0.30 - 0.50), following the criteria of Liu *et al*. (2003).

Seasonal Salinity Distribution Year 2016-2017

As mentioned in the previous section, four samplings were carried out to investigate the physicochemical and nutrient parameters during SWM, FIM, NEM and SIM for the surface water. However, to further understand the present status of salinity movement and their distribution within the estuary area, we also measured the surface and bottom salinity at different months that represented different seasons and tides from April 2016 until October 2017.

Comparison of Salinity Distribution Before and After Estuary Modification

In addition, to examine the extent of seawater intrusion within the estuary as a result of the construction of breakwater and land reclamation, we compared the present study's surface and bottom water salinity data with data from the year 1999-2000. Salinity data from the year 1999-2000 were adapted from the research published by Jong (2002). For both study periods, we compared the months of April 2000 with April 2016 representing high tide and SIM as well as October 1999 with October 2016 representing low tide FIM.

Results and Discussion

Seasonal Variation of Physicochemical and Nutrient Parameters

The statistical description of physicochemical parameters sampled during each monsoon season are summarized in Table 2. We classified the study area into upper (S1, S2, S3, S4, S5, S6), middle (S7, S8, S9, S10, S11), lower (S12, S13) estuarine and coastal water (S14, S15) zones (Figure 1A). Surface water temperature varied from 25.1 to 31.7^{o}C, presenting a progressive decrease in the seasonal mean from SIM (29.2 ± 1.1^{o}C) to NEM season (25.4 ± 0.4^{o}C). For all seasons, temperature differences were less pronounced between the sampling sites (lower, middle and upper estuaries). Surface salinity varied widely from 0 to 14.0 psu, showing larger variations in the dry SWM (2.4 ± 4.1 psu) and smaller variations for the wet NEM season (0.1 ± 0.2 psu). Seasonally, the highest salinity values were always observed in the lower estuary and the lowest values were observed in the upper estuary region. During the FIM and NEM especially, the water at upper estuary stations (stations 1 to 6) were relatively fresh from the surface to the bottom, with salinity of almost zero (Figures 5 and 6). The pH showed remarkable fluctuations, ranging from 4.3 to 7.8 during the study period. Relatively high pH values were observed during the SIM and SWM seasons (pH 7.1) and low values were observed during the FIM and NEM (pH 5.9). Such seasonal pH variability is largely influenced by the complex and dynamic nature of biotic and abiotic factors within the estuary. The large input of rainwater (pH ~ 5.6) during wet season could be the dominating factor that causes lower pH during the NEM and FIM. Heavy rainfall also increases river discharge that brings inorganic and organic substances downstream to the estuary, which could further stimulate aerobic respiration by bacteria and greatly affect the water pH (Omarjee *et al.,* 2020). Similar to the trend observed for salinity, the upper estuary zone consistently had the lowest pH values while the highest values were mostly recorded at the middle and lower estuary zones.

DO concentrations for the Terengganu River estuary were in the range of 4.2 – 6.5 mg/L. The highest DO value was recorded during the NEM period (5.2 – 6.5 mg/L) and stations located in the riverine zone (stations 1 – 7) generally had lower DO values compared with the other stations. SPM varied from 1.0 to 106.0 mg/L, with large variations between the wet NEM and dry monsoon seasons. Except during the NEM, concentrations of SPM presented higher values at the lower estuary zones. Chl-a values were the in the range of 0.1 – 2.0 µg/L, with higher Chl-a values recorded during FIM and NEM seasons while SIM had the lowest mean Chl-a values (0.2 ± 0.2) µg/L.

The results of surface water nutrient concentrations in the estuary water in different seasons are shown in Table 3. In general, a clear seasonal variability of nutrient concentrations was observed, where the score plot from PCA reveals that the physicochemical and nutrients values for NEM and SIM are separated from other seasons (Figure 3). From Table 3, the highest value of total DIN was recorded during the FIM season (19.61 ± 8.61 µmol N/L) while the lowest DIN values in the SIM season (7.21 ± 7.74 µmol N/L). NH_4 was the largest component of inorganic nitrogen, at between 1.48 – 33.62 µmol N/L. The stations in the riverine zone, especially in the Seberang Takir River and Nerus River, tended to have the highest NH_4 values during the SIM and NEM. Throughout the study period, NO_3 in Terengganu River estuary had mean value of 3.23 ± 2.46 µmol N/L. Stations at the Nerus dan Seberang Takir Rivers (S1 – S3 and S7) had concentrations of

Table 2: Statistical description of Terengganu River estuary surface water physicochemical parameters during each monsoon season

		Temp (°C)	Sal (psu)	pH	DO (mg/L)	Chl-a (ug/L)	SPM (mg/L)
SWM	Min-Max	28.4 - 30.4	0.0 - 14	4.3 - 7.7	4.2 - 5.2	0.1 – 1.0	1.0 - 22.2
	Mean ± SD	29.6 ± 0.7	2.4 ± 4.1	6.5 ± 1.3	4.7 ± 0.4	0.4 ± 0.3	8.4 ± 5.5
	Lower	30.1 ± 0.3	10.7 ± 4.7	7.6 ± 0.1	4.9 ± 0.2	0.2 ± 0.1	17.0 ± 7.4
	Middle	30.0 ± 0.4	1.8 ± 1.6	6.8 ± 0.5	4.7 ± 0.3	0.4 ± 0.2	7.6 ± 3.5
	Upper	29.0 ± 0.5	0.1 ± 0.2	6.0 ± 1.7	4.7 ± 0.4	0.4 ± 0.4	6.3 ± 3.9
FIM	Min-Max	27.7 - 28.9	0.0 - 7.9	4.1 - 7.4	4.2 - 5.2	0.1 – 2.0	2.8 - 14.2
	Mean ± SD	28.4 ± 0.4	1.7 ± 2.4	6.0 ± 1.1	4.4 ± 0.3	0.6 ± 0.5	7.5 ± 3.4
	Lower	28.8 ± 0.1	6.2 ± 2.4	7.1 ± 0.4	4.9 ± 0.5	0.3 ± 0.1	12.2 ± 2.8
	Middle	28.6 ± 0.2	1.9 ± 1.3	6.3 ± 0.6	4.4 ± 0.1	0.7 ± 0.7	7.4 ± 2.4
	Upper	28.2 ± 0.5	0.0 ± 0.0	5.4 ± 1.3	4.4 ± 0.1	0.5 ± 0.4	6.0 ± 3.0
NEM	Min-Max	25.1 - 26.4	0.0 - 0.7	4.6 - 6.6	5.2 - 6.5	0.3 - 1.3	15.2 - 106
	Mean ± SD	25.4 ± 0.4	0.1 ± 0.2	5.6 ± 0.5	5.9 ± 0.5	0.6 ± 0.3	71.9 ± 24.2
	Lower	25.6 ± 0.5	0.4 ± 0.5	6.0 ± 0.3	6.1 ± 0.3	0.7 ± 0.4	70.2 ± 50.6
	Middle	25.5 ± 0.5	0.1 ± 0.1	5.7 ± 0.3	6.0 ± 0.5	0.5 ± 0.1	61.8 ± 28.1
	Upper	25.3 ± 0.2	0.0 ± 0.0	5.4 ± 0.7	5.8 ± 0.7	0.7 ± 0.3	80.9 ± 7.7
SIM	Min-Max	28.0 - 31.7	0.0 - 4.5	5.9 - 7.8	4.8 – 6.0	0.1 - 0.7	4.6 - 14.4
	Mean ± SD	29.2 ± 1.1	0.8 ± 1.3	6.7 ± 0.7	5.5 ± 0.4	0.2 ± 0.2	8.0 ± 3.4
	Lower	28.5 ± 0.1	3.0 ± 2.1	7.7 ± 0.1	5.8 ± 0.0	0.1 ± 0.1	6.9 ± 0.1
	Middle	28.9 ± 0.3	0.7 ± 0.8	7.0 ± 0.4	5.7 ± 0.3	0.3 ± 0.3	5.8 ± 1.2
	Upper	29.7 ± 1.5	0.0 ± 0.0	6.1 ± 0.2	5.2 ± 0.3	0.2 ± 0.1	10.1 ± 4.0

*SWM: Southwest monsoon, FIM: Fall inter-monsoon, NEM: Northeast monsoon, SIM: Spring inter-monsoon

NO_3 higher than mean value in all seasons (> 4.74 µmol N/L) in comparison to other stations. NO_2 and PO_4, had concentrations ranging between 0.05 – 0.74 µmol N/L and 0.05 – 0.36 µmol P/L respectively. Station S7 at Seberang Takir River recorded the highest values of PO_4 and NO_2 during FIM season. Our study sites have mangroves fringing the rivers that play an important role in the cycling and export of nutrients into the adjacent riverine and estuarine systems. Nutrient concentrations in the estuary depend on natural processes such as tidally driven adsorption and desorption through sediments, pore-water exchange, groundwater discharge and remineralization/mineralization through biological processes (Wang *et al.,* 2021; Douglas *et al.,* 2021). However, the impact of monsoon seasons on nutrients, especially NH_4 depends on rainfall intensity. Heavy rain results in floodwaters which contained high concentration of eroded materials from upstream or nearby human settlement areas and these are ultimately deposited in the estuary (O'Mara *et al.,* 2019).

Principal Component Analysis (PCA) and Factor Analysis (FA) of Physicochemical and Nutrient Parameters

The physicochemical and nutrient spatial and temporal distribution of the entire dataset (all monsoon seasons) were further interpreted using PCA (Figure 3 and Table 4). The KMO index ranged between 0.50 and 0.55 while Bartlett's test (p-value) was less than 0.001, indicating that reliable factors could be produced to analyse

Table 3: Statistical description of nutrients parameters of Terengganu River estuary during each monsoon season

		PO_4 (µmol P/L)	**NO_2 (µmol N/L)**	**NO_3 (µmol N/L)**	**NH_4 (µmol N/L)**	**DIN (µmol N/L)**
SWM	Min-Max	0.05 - 0.12	0.12 - 0.25	0.19 - 6.60	7.62 - 13.44	9.69 - 17.34
	Mean ± SD	0.07 ± 0.03	0.18 ± 0.04	2.80 ± 2.45	10.52 ± 2.07	13.5 ± 2.54
	Lower	0.05 ± 0.00	0.16 ± 0.02	1.09 ± 1.17	9.13 ± 2.14	10.38 ± 0.99
	Middle	0.07 ± 0.04	0.18 ± 0.02	2.38 ± 1.49	12.72 ± 0.56	15.27 ± 1.22
	Upper	0.08 ± 0.03	0.19 ± 0.06	3.72 ± 3.17	9.16 ± 1.13	13.07 ± 2.62
FIM	Min-Max	0.05 - 0.36	0.05 - 0.74	0.80 - 6.53	9.69 - 33.62	11.66 – 37.96
	Mean ± SD	0.09 ± 0.09	0.19 ± 0.18	3.00 ± 1.97	16.41 ± 6.67	19.61 ± 8.61
	Lower	0.05 ± 0.00	0.16 ± 0.00	1.54 ± 1.04	13.46 ± 1.37	15.16 ± 0.33
	Middle	0.11 ± 0.14	0.26 ± 0.27	2.35 ± 0.72	17.37 ± 9.18	19.98 ± 10.14
	Upper	0.09 ± 0.04	0.15 ± 0.09	4.04 ± 2.48	16.59 ± 5.88	20.77 ± 8.23
NEM	Min-Max	0.05 - 0.28	0.05 - 0.21	0.61 - 5.62	2.51 - 13.9	5.26 – 19.62
	Mean ± SD	0.16 ± 0.07	0.12 ± 0.06	3.08 ± 1.56	7.33 ± 3.87	10.54 ± 4.88
	Lower	0.14 ± 0.05	0.14 ± 0.09	1.53 ± 1.30	9.34 ± 2.87	11.01 ± 4.09
	Middle	0.20 ± 0.07	0.09 ± 0.04	2.33 ± 1.04	6.36 ± 2.09	8.79 ± 2.76
	Upper	0.14 ± 0.07	0.13 ± 0.06	4.23 ± 1.26	7.48 ± 5.31	11.84 ± 6.52
SIM	Min-Max	0.05 - 0.12	0.07 - 0.19	0.29 - 12.07	1.48 - 5.62	3.49 – 17.83
	Mean ± SD	0.06 ± 0.02	0.14 ± 0.04	4.03 ± 3.52	3.04 ± 1.47	7.21 ± 4.74
	Lower	0.05 ± 0.00	0.14 ± 0.01	1.13 ± 1.18	2.82 ± 0.33	4.08 ± 0.84
	Middle	0.05 ± 0.00	0.17 ± 0.02	2.15 ± 1.25	2.26 ± 0.84	4.58 ± 2.00
	Upper	0.07 ± 0.03	0.13 ± 0.05	6.56 ± 3.68	3.75 ± 1.83	10.44 ± 5.22

*SWM: Southwest monsoon, FIM: Fall inter-monsoon, NEM: Northeast monsoon, SIM: Spring inter-monsoon the data. The first principal components (PC1) account for 31.2% of the total variance and are characterized by strong positive and negative loadings for SPM and temperature, respectively and moderate positive loadings for DO and PO_4 (Figure 3 (a)). Positive and negative loadings of SPM and temperature indicate the influence of seasonality in the temporal variation of SPM with lower concentrations during SIM, SWM and FIM and higher concentrations during NEM. PC2 which explains 25.3% of the total variability in the dataset is strongly, positively contributed by Chl-a and NO_2, moderately impacted PO_4 and NH_4, suggesting some positive influence of nutrients on Chl-a concentrations. Other parameters (salinity, pH and NO_3) seem to be less important in explaining physicochemical variations during the study period because the coefficient of each loading is relatively low (loading < 0.5). The score plot in Figure 3 (b) indicates that the sampling stations can be clearly separated into three statistically significant clusters which represent similar water quality characteristics and source. Cluster 1 comprises all stations (S1 to S13) sampled during the NEM season and is separated from the other seasons (clusters 2 and 3) with higher values of PC1. As shown in Figure 3 (b), the environmental conditions during NEM season are strongly associated with high values of SPM. Cluster 2 groups the stations mostly in the lower and middle estuary sampled during the FIM and SWM seasons, while cluster 3 comprises of all stations (S1 to S13) for the SIM season and the upper estuary stations (S1 to S3) sampled during the SWM and FIM seasons. The physicochemical data of these two clusters are separated along PC2 but were similar along PC1 (Figure 3 (b)). Temperature, NH_4 and NO_3 are amongst the important parameters influencing variations of water quality in both clusters. Table 4 provides the rotated correlation matrix of physicochemical parameters for the first four factors obtained from the principal FA. The selection of the number of factors used for data extraction is based on the eigenvalue of greater than one. In this analysis, the most important parameters contributing to variations of water quality were determined by an absolute correlation coefficient of 0.9 or higher. Data in Table 4 reveal that only two parameters are identified as the most important parameters influencing water quality variations in the study area. Water temperature and NO_3 are positively loaded with PC1 which explains 31.2% of the total variance. The results of this analysis demonstrate that temporal variations in the quality of surface water are strongly influenced by climatic conditions (SWM, FIM, NEM and SIM) and estuary regions (lower, middle, upper).

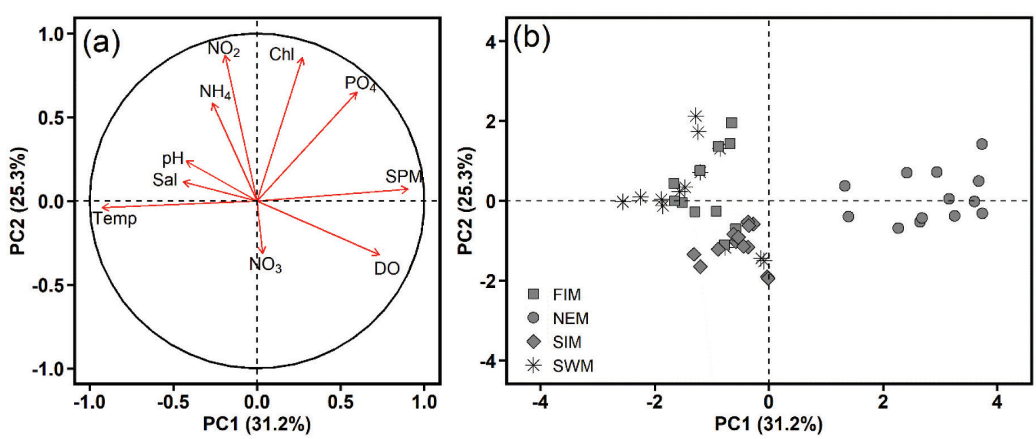


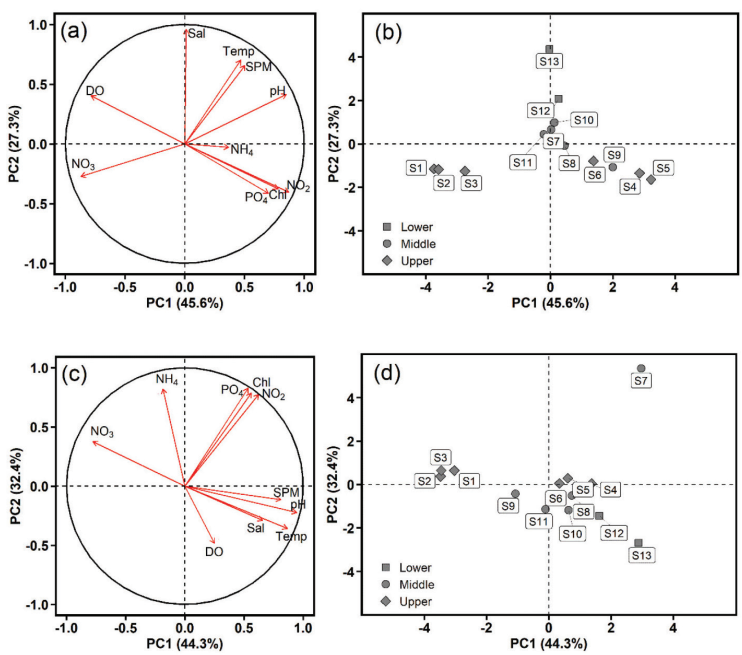
Figure 3: Ordination (a) and score plots of PCA (b) for physicochemical and nutrients parameters during all monsoon seasons of Terengganu River estuary. SWM: Southwest monsoon, FIM: Fall inter-monsoon, NEM: Northeast monsoon, SIM: Spring inter-monsoon

Table 4: Rotated factor correlation coefficients for all monsoon seasons of Terengganu River estuary

	Temp	Sal	pH	SPM	Chl-a	DO	PO_4	NO_2	NO_3	NH_4	Eigen	% Cum
F1	**0.97***	0.37	0.57	-0.75	-0.20	-0.46	-0.40	0.31	**0.99***		2.48	25
F2	-0.13		0.18	0.22	0.79		0.75	0.82		0.31	2.06	45
F3	-0.19		0.28	0.35	-0.24	0.83	0.13	-0.20		-0.80	1.68	62
F4		-0.26	-0.60					-0.15		0.12	1.46	77

*Factor correlation coefficients of 90% or greater

Figure 4 shows the first two principal components of PCs for each season with the eigenvalues ranging between 65.8% and 76.7% of the total variance. For the SWM, PC1 explains 45.6% of the total variance, showing a strong positive contribution of pH, Chl-a and NO_2, but a strong negative contribution for DO and NO_3 (Figure 4 (a)). This component also reveals a moderate positive contribution by PO_4, while the remaining variables (salinity, NO_3, NH_4 and SPM) either contribute little to the component or are not significant (loading < 0.30). PC2 which explains 27.3% of the total variance that is characterized by a strong positive impact of salinity and moderately affected by temperature and SPM. During this season, the sampling locations are divided into four major groups, with stations in the upper estuary (S1 - S3 and S4 - S6, S9) and lower estuary (S13) clearly separated from the other stations along lower/ higher values of PC1 and higher values of PC2, respectively (Figure 4 (b)). Groups that are close to the center of the score plot are considered less important in accounting for variations in physicochemical data. As seen in Figure 4 (b), the upper estuary stations are strongly associated with high values of NO_3 (S1 to S3) and PO_4, NO_2 and Chl-a (S4 to S6, S9) while station S13 is strongly related to salinity.



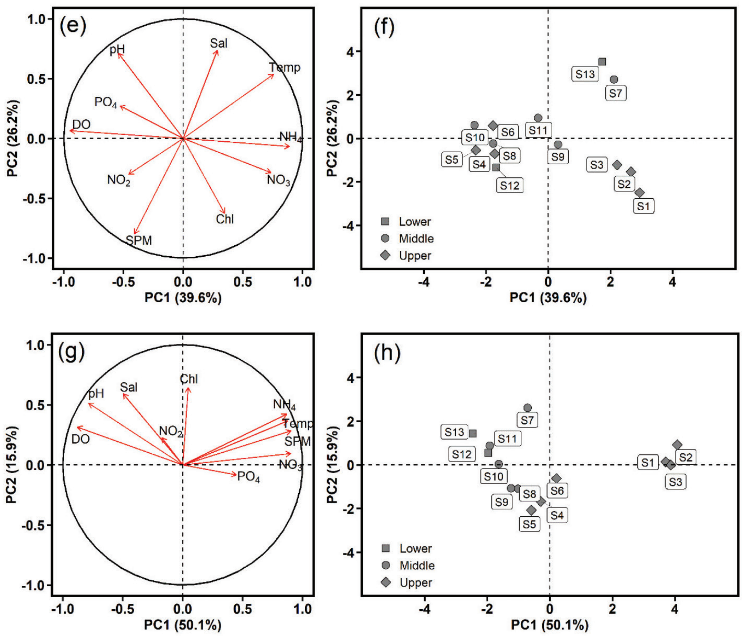


Figure 4: Ordination (left panel) and score plots of PCA (right panel) for physicochemical and nutrients parameters during (a-b) southwest monsoon (SWM), (c-d) fall inter-monsoon (FIM), (e-f) northeast monsoon (NEM) and (g-h) spring inter-monsoon (SIM) of Terengganu River estuary

For FIM season, PC1 accounts for 44.3% of the total variance, showing a strong positive influence of temperature, pH and SPM, strong negative contribution of NO_3 and moderate positive impact of salinity, Chl-a, PO_4 and NO_2 (Figure 4 (c)). The second component PC2 explains 32.4% of the total variance has a strong positive effect of nutrient-related variables (Chl-a, PO_4, NO_2 and NO_4). Similar to SWM season, four groups of sampling locations are identified on the score plot of PCA (Figure 4 (d)). Stations in the upper estuary (S1 - S3 and S7) and lower estuary (S13) are clearly separated from the other stations along PC1 and PC2. Stations S1 to S3, again, show a strong association with NO_3 while station S7 is significantly influenced by high values of Chl-a, PO_4 and NO_2 (Figure 4 (d)). In contrast, station S13 is most strongly associated with pH, salinity and temperature.

For the NEM season, the contribution of PC1 to the total variance is 39.6% showing strong positive impacts of DO and NH_4 and a negative influence by temperature (Figure 4 (e)). This component also reveals that NO_3, pH, PO_4 moderately contribute to the variation of water quality in NEM. PC2 has a strong negative association with SPM, moderate positive effects of temperature and salinity and a moderate negative contribution of Chl-a. The distribution of sampling locations in the data shows a clear formation of four clusters separated along PC1 and PC2 (Figure 4 (f)). The upper estuary stations (S1 - S3) which are separated along higher PC1 values show a strong relation to NO_3 while station S7 and S13 display strong associations with temperature and salinity along high PC2 values. The third group which comprises different stations from the upper to lower estuary (S4 to S6, S8, S10 and S12) are marked by a strong influence of DO along lower values of PC1. Similar patterns of PC1 loading were obtained for the SIM season. PC1 explains 50.1% of the total variance and is strongly, positively driven by temperature, SPM, NO_3 and NH_4 and negatively affected by pH and DO (Figure 4 (g)). PC2 explains 15.9% and is moderately positively associated with salinity, pH and Chl-a. Unlike the cases in other seasons, the sampling locations during this season are divided into three major clusters (Figure 4 (h)). The first cluster which comprises the upper estuary stations (S1 - S3) and are separated along higher values of PC1 show strong associations with temperature, SPM, NO_3 and NH_4. Stations in the upper and middle estuary (S7 and S10 - S13) are grouped together along higher PC2 values, corresponding to relatively high levels of pH and DO. Cluster 3, which comprises of the rest of the stations and separated along lower values of PC2 is marked by relatively lower values of all parameters.

To identify the most important parameters, FA was performed for each season using the same extraction criteria as the annual analysis. Table 5 summarizes the rotated correlation coefficients of physicochemical parameters for the first three or four components for each season. During the SWM season, the FA results indicate that salinity, SPM and PO_4 are the most important variables contributing to water quality variations. All these parameters are positively loaded to PC1 and PC2 which explain 52% of the total variance. For the FIM season, temperature, SPM and NH_4 are identified as the most important variables and are positively loaded to PC1 (39% of the total variance). On the other hand, PC2 which accounts for 8% of the total variance shows a significant positive contribution of NO_2 to water quality variations. Only two parameters (SPM and PO_4) are identified as the most important variables contributing to water quality variations during NEM season. SPM is negatively loaded, while PO_4 is loaded with an opposite trend to PC2, which explains 23% of the total variance. Results in Table 5 further reveal that temperature, Chl-a, DO, PO_4 and NO_3 are the most important components influencing water quality variations

Table 5: Rotated factor correlation coefficients for each monsoon season of Terengganu River estuary

	Temp	**Sal**	**pH**	**SPM**	**Chl-a**	**DO**	**PO_4**	**NO_2**	**NO_3**	**NH_4**	**Eigen**	**% Cum**
SWM												
F1	0.57	**0.92**	0.63	**0.92**		0.12			-0.47	-0.20	2.68	27
F2		-0.32	0.44	0.20	0.72	-0.40	**0.99**	0.71	-0.22		2.56	52
F3		-0.19	0.33	0.15	0.45	-0.83	0.13	0.62	-0.74	0.22	2.06	73
F4	0.82		0.45			-0.18		0.14	-0.36	0.77	1.66	90
SIM												
F1	**0.97**	-0.10	-0.40	**0.91**	0.25	-0.59	0.18		0.80	**0.95**	3.92	39
F2	-0.20	0.79	0.84		0.32	0.67	-0.15		-0.37		2.08	60
F3	0.11		0.31					**1.00**	-0.34		1.23	72
NEM												
F1	-0.36	0.40	0.72		-0.42	0.86	0.23	0.20	-0.79	-0.64	2.85	29
F2	0.85	0.58	0.29	**-0.93**	-0.26	-0.39	**0.96**	-0.23	0.18	0.16	2.34	52
F3		-0.20	0.26		-0.33			0.21	-0.15	-0.17	1.25	64
F4	0.32	0.62			0.12	-0.31	-0.14	-0.27		0.73	1.22	77
FIM												
F1	0.13		0.29	0.31	**0.97**	-0.26	**0.98**	**0.99**		0.61	3.51	35
F2	**0.92**	0.29	0.87	0.47	0.17			0.11	**-0.99**	-0.72	3.44	70
F3	0.28	0.88	0.35	0.62	-0.13	**0.90**		0.10		0.11	2.22	92

*Factor correlation coefficients of 90% or greater. SWM: Southwest monsoon, FIM: Fall inter-monsoon, NEM: Northeast monsoon, SIM: Spring inter-monsoon during the FIM season. With the exception of NO_3, all important parameters are positively loaded to the first three factors (PC1 - PC3) that account for 90% of the total variability in data.

Factors Contributing to Variability of Physicochemical and Nutrient Distribution at Estuary

Overall, our results demonstrate that important water quality parameters can differ significantly during different monsoon seasons and are dependent on estuary regions. Here, it is instructive to briefly explain the major climate events that affected the monsoon and rainfall pattern during our study period. All these long- and short-term climate events will affect rainfall intensity, which will affect the hydrodynamics and water quality at the estuary. Apart from the usual annual monsoon seasons, our region is also affected by large-scale climate variability, such as El Niño-Southern Oscillation (ENSO), Madden Julian Oscillation (MJO) and Indian Ocean Dipole (IOD) (Met Malaysia, 2016; MSS, 2016, 2017). Based on the report by the Malaysia Meteorological Department (Met Malaysia, 2016) and Meteorological Service Singapore (MSS, 2016), during our study period, a strong El Niño had developed in the second half of 2015 and lasted until mid-2016. This resulted in hot and dry weather in Terengganu in April 2016 (Figure 2). La Niña slowly took over in the second half of 2016 and brought higher rainfall during the usually dry southwest monsoon season. June and July 2016 also saw the emergence of the negative phase of IOD which co-existed with La Niña, resulting in wetter conditions compared with the same period in 2017. In 2017, two strong MJO events were reported, i.e., January-February and October. These MJO events influenced the NEM (enhancing the cold surge) and FIM seasons by bringing higher rainfall (MSS, 2017) (Figure 2).

A draw bridge was built across a narrow passage where the river and coastal water enter and exit the estuary. The narrow passage and the breakwater opening are aligned and this has created a straight flow of water in and out of the estuary and coastal area. Lower estuary station S13, which was inside the breakwater structure, was clearly separated from other stations at the upper and middle estuary regions and developed strong seasonal water characteristics (Table 2, Figure 4). Water entering the breakwater area (S13) either from upstream, coastal area or as a result of waves produced by passing ships will be diverted, spread and circulated, forming eddies in the lower estuary. The curvature of the breakwater in the lower estuary mimics a natural river's curvature. Such river morphology has been reported to effect tidal oscillation and can create residue eddies (Li *et al.,* 2008). However, detailed studies on the current circulation in the Terengganu River estuary is needed to further confirm the strength and magnitude of the eddies formed as they are a significant consideration in controlling the transport, mixing and dilution of material within the estuary (Li *et al.,* 2008). The strength of the eddy's circulation in this area could be influenced by rainfall, tides and wind speeds (Jovanovic *et al.,* 2019; Kuang *et al.,* 2011; Lai *et al.,* 2018). During dry and warm SWM seasons, lesser rainfall caused surface water at station S13 to record the highest salinity and temperature in comparison to other seasons. Such conditions prevented atmospheric oxygen diffusion and resulted in the lowest DO concentrations during SWM seasons. To some extent, these conditions also hindered the process of nitrification (low NO_3 concentration) (Figures 4 (a) and 4 (b)). This station also developed a strong salinity stratification with surface and bottom salinity ranging between 0.72 and 14.02 psu and 21.67 and 32.62 psu, respectively (Figure 4 (b)). Our data for both stations outside the estuary mouth (coastal stations: S14 and S15) had average salinity of 32.45 ± 0.40 psu, compared to water at the lower estuary (S12 and S13) with the average salinity of 5.09 ± 4.63 psu. This indicates that local/regional climatic conditions and river-tide discharge had no significant influence on coastal stations. However, the extent of the monsoon rain impact on coastal water physicochemical parameters is unknown because no data were collected at coastal stations during the peak of the NEM season (December 2016) that had recorded the highest monthly rainfall (998.4 mm). For safety reasons, access to coastal waters for sampling activities is always not permitted during the peak of the NEM. Marine scientific studies in Terengganu coastal waters or the South South China Sea usually publish data collected during non-NEM season (Ariffin *et al.,* 2019; Hee *et al.,* 2020; Idris *et al.,* 2020; Kok *et al.,* 2019), resulting in huge data gaps for the December and January timeframe.

For other stations in the estuary, we saw some distinct water parameter distribution trends occurring in different seasons. Cloudy condition and heavy rainfall during the NEM season significantly reduced the river water temperature by 2 – 3^{o}C in comparison to the other seasons. Heavy surface runoff during the NEM has resulted in total freshwater on the surface layer reaching the breakwater entrance (Figure 6c). High surface runoff during the NEM not only greatly increased the water's SPM and DO, but also turned the condition of the entire river estuary slightly acidic (pH 4.63 – 6.62) (Table 2, Figure 3). Our results also revealed that nutrients and Chl-a were affected by environmental conditions to a different degree and were dependent on the seasons. During the SWM season, DO affected the concentrations of nitrogen in the river estuary with higher DO concentration favoring the presence of NO_3 while NO_2 was found to be higher in areas of lower DO values. We observed that temperature variation of higher than 3^{o}C between stations would strongly facilitate the presence of NO_3 and NH_4 in the estuary. Chl-a distribution was also strongly related to PO_4 and NO_2 concentrations, especially during the SWM and FIM seasons.

Terengganu River estuary receives both waters from upstream natural wetlands and drainage discharge from human settlements. This could be a mixture of wastewater and natural storm runoff that contains nutrients, organic matter, inorganic matter, debris and pollutants. The natural wetlands, to some extent, support the growth of phytoplankton and benthic communities and provide water infiltration, thus preventing extreme environmental fluctuation and maintaining the estuary's physicochemical parameters within a moderate range throughout the seasons (Kasai *et al.,* 2010; Kanandjembo *et al.,* 2006). We found that the form of nutrients presents in the estuary changes seasonally and is closely related to water pH, DO, temperature and SPM (Figure 4). Nutrients levels were consistently high in both the upper estuary at Nerus River (S1, S2, S3) and Seberang Takir River (S7) especially during the FIM with dissolved inorganic nitrogen (DIN) reaching as high as 29 µmol N/L. The small mangroves fringing the rivers has continuously exported substantial amount of nutrients into the rivers. We noticed that the high rainfall during NEM did not significantly increase the nutrients concentration in the upper estuary, but rather were moderately elevated (Table 3, Figures 4 (e) and 4 (f)). This could be due to the high freshwater runoff and low-tide phenomena, where water would dilute and flush out nutrients at a faster rate, thus reducing the nutrients retention time in the estuary. In addition, lower temperature during NEM could reduce nutrients retention time as cooler weather may greatly affect biological assimilation and denitrification in the estuary (Bukaveckas *et al.,* 2018). Similarly, dry season (SIM) also reduced the DIN source from mangroves areas and this had greatly affected the phytoplankton production, indicated by low Chl-a content in the river estuarine zones.

Hypoxia Conditions in Terengganu River Estuary

Seasonal hypoxia was reported in Terengganu River estuary during the SWM season and disappeared during NEM (Lee *et al.,* 2016c). In this report, we focus on station S11 to further relate the surface (0.5 m from surface) and bottom (0.5 m from bottom) layers' hypoxia conditions with other environmental parameters to provide better insight into temporal hypoxia formation (Table 6). We observed that station S11 had high surface and bottom DO variability with value at surface water in the range of

4.36 – 6.04 mg/L but the bottom water DO concentrations had average value of 2.78 ± 1.94 mg/L, even recording zero during some seasons. These hypoxic conditions developed during the SIM (April 2016), disappeared during early SWM and slowly redeveloped towards the end of SWM. The hypoxia condition reached its worst (0.0 mg/L) during the FIM (October 2016) and persisted throughout the NEM season. However, the level of DO for April in the following year and October 2017 inter-monsoon improved (> 4.0 mg/L) in comparison to the same seasons in year 2016 (< 1.0 mg/L).

Our findings seem to contradict previous reports that stated hypoxic conditions are dependent on monsoon seasons. Our data showed no specific trend of hypoxia formation time and period. It developed in April and October 2016 but not in April and October 2017. Such differences in observation are possible because a micro-tidal estuary has tidal range of 1.0 – 1.5 m (Table 1) and the Terengganu River estuary is much affected by different rainfall intensity (Figure 2) which could determine surface and ground water runoff, water flow rate and the quantity of organic debris brought into the river and their retention time in the estuary.

The latest river estuary geomorphology change had resulted in the northern part of the middle estuary (areas surrounding stations S9

Table 6: Environmental parameters of Station S11 at different sampling months (S – Surface water, B – Bottom water)

		April 16	June 16	August 16	October 16	December 16	February 17	April 17	October 17
DO (mg/L)	S	5.02	5.93	4.64	4.54	6.04	5.95	5.85	4.36
	B	0.75	5.95	3.22	0.00	1.92	2.29	3.65	4.43
Sal (psu)	S	2.2	30.7	1.31	1.20	0.05	0.05	0.32	0.05
	B	32.2	31.2	27.0	24.9	13.6	11.0	22.2	21.6
Temp (^oC)	S	29.9	28.8	30.31	28.65	25.35	27.74	28.77	30.1
	B	29.8	28.8	30.21	30.08	25.50	27.56	30.35	30.3
pH	S	7.97	7.83	6.89	6.55	5.76	6.54	7.68	6.74
	B	7.42	7.84	6.10	6.92	6.46	6.99	7.36	8.78
Chl-a (mg/m^3)	S	0.69	0.79	0.23	0.22	0.46	0.83	0.45	1.00
	B	1.70	2.49	1.07	3.45	0.78	1.36	0.06	2.67
SPM (mg/L)	S	-	33.0	2.8	4.6	56.0	5.2	6.6	9.60
	B	139.2	72.0	33.8	77.4	72.8	76.8	28.0	144.0
NO_2 (µmol N/L)	S	0.25	0.02	0.16	0.12	0.05	0.06	0.16	0.15
	B	0.09	0.14	0.13	0.13	0.05	0.13	0.09	0.32
NO_3 (µmol N/L)	S	1.87	1.20	1.78	2.01	1.89	2.22	1.84	1.98
	B	2.95	2.86	2.94	3.40	3.30	3.28	2.88	2.84
NH_4 (µmol N/L)	S	9.83	1.19	12.36	14.00	7.12	3.75	1.56	10.12
	B	0.89	0.86	4.59	13.04	7.10	3.73	12.09	15.25
DIN (µmol N/L)	S	11.95	2.41	14.30	16.13	9.06	6.03	3.56	12.25
	B	3.92	3.86	7.66	16.58	10.45	7.13	15.06	18.40
PO_4 (µmol P/L)	S	0.05	0.25	0.05	0.05	0.17	0.18	0.05	0.10
	B	0.05	0.17	0.05	0.05	0.15	0.22	0.05	0.05

and S11) becoming narrower due to intensive land reclamation (Figure 1). This could divert more water towards the southern part of the middle estuary (S8 and S10), at the same time result in a slower water flow for incoming and outgoing tides at the northern part of the middle estuary (S9 and S11). This geomorphological modification had impacted the current circulation and water column mixing process, thus affecting the residence time and accumulation rate of the organic matter in northern part of the middle estuary (Santos *et al.,* 2020). This area also showed strong salinity stratification and this had prevented the water column from mixing and hindered the transfer of oxygen from the surface layer (Geyer and Ralston, 2011). Another reason that triggered the hypoxia at station S11 was high bottom water Chl-a concentration (0.06 – 3.45 mg/m^3), indicating substantial quantity of phytoplankton in the estuary, which could have induced aerobic microbial activity. This station is downstream of the rivers. Therefore, it might have received sufficient inorganic nutrients and high amount of organic matter from the upstream mangroves and residential areas (Table 3) (Wang *et al.,* 2021; Bukaveckas *et al.,* 2018). This is further supported by an exceptional high concentration of DIN at bottom water of station S10 (ranged from 3.858 – 18.404 µmol/L) which indicated autochthonous organic matter decomposition that had severely depleted the bottom water DO levels.

According to the Malaysian Marine Water Quality Standard (MMWQS) Interim Class E set by the Department of Environment Malaysia (DOE, 2019), the Terengganu River estuary should fall under Class E1 coastal plain with following standards: DO > 5 mg/L, pH 6.5 – 9.0, SPM < 30 mg/L, NO_3 < 14.28 µmol/L, PO_4 < 3.23 µmol/L. The presence of the natural wetlands in the rivers upstream could support phytoplankton growth and water infiltration, thus preventing extreme environmental fluctuation and maintaining estuary nitrate and phosphate within moderate range throughout the seasons. All stations had nutrients levels within the range prescribed by MMWQS. However, during the NEM (December 2016) the Terengganu River estuary had more than 90% of pH and SPM values falling outside the range prescribed by MMWQS. Our data analysis also confirmed that SPM was the most important variable affecting water quality during the NEM (Table 5). Heavy rainfall during the NEM had caused turbidity to spike due to the increase of water flow and water runoff along the riverbank. Stations at the upper estuary (S1, S2 and S3) mostly had pH value of lower than 6.22, with the lowest reaching 3.72 in October 2016. For most stations, better pH quality was usually achieved during the SIM and SWM. DO in Terengganu River estuary was much dependent on rain intensity because during low rainfall seasons, surface DO concentration tended to fall below 5 mg/L.

Seasonal Salinity Distribution in Year 2016 – 2017

In general, rainfall and tides were the dominant factors determining the movement of seawater into the estuary. High rainfall (Figure 2) during NEM caused higher freshwater runoff, brought huge volumes of freshwater to the lower estuary, turning the entire surface water (from 0 – 5.5 m depth) in the estuary into a freshwater system (Figures 5 (c) and 6 (c)). During the dry monsoon seasons, tides carry the saltier and denser seawater from the coastal waters through the opening of the breakwater. The seawater moves underneath the freshwater layer resulting in salinity stratification and turning the estuary into a partially mixed estuary. During seasons with heavy rainfall, freshwater runoff from upstream completely cancels out the tidal effect, turning the whole system into a well-mixed estuary. The strong El Nino phenomenon from mid-June 2015 until mid-2016 had strongly reduced the rainfall intensity for 2016's SIM and SWM (Met Malaysia, 2016). Dryer weather that persisted from March until May 2016 had reduced upstream freshwater discharge and failed to create a freshwater ecosystem at the river estuary in comparison to the wetter condition in the 2017 SIM (Figures 2, 5 and 6). During this extreme dry period and together with the present estuary geomorphological setting, tidal range greater than 1.5 m was strong enough to push coastal seawater to move inward along the riverbed, reaching stations 10.24 km (S1 – Nerus River) and 9.43 km (S4 – Terengganu River) from the estuary mouth. This turned the entire water column at these two stations slightly saline (1.4 – 2.92 psu). A much higher bottom salinity of up to 21 psu was also recorded in the confluence zone of both rivers, which is 6.81 km from the estuary mouth. However, such strong intrusion was not seen in the 2017 SIM, when Peninsular Malaysia experienced a normal monsoon year and was without any impact from other long- or short-term climate events. Apart from the impact of climate variability, the regular impact of monsoon seasons and tides on salinity distribution was also clearly seen in the middle and upper estuaries. NEM, which lasted for three months (November 2016 until January 2017) clearly had the seasonal baseflow effect (Price, 2011) on river discharge in February 2017. Even though February, March and April 2017 had low rainfall in comparison to both August 2016 SWM and October 2016 FIM (Figure 2), an almost entirely freshwater system of up to station S9 in the lower estuary was formed in April 2017. However, the temporal or spatial occurrence of baseflow into the Terengganu River system needs further support analysis from the use of tracer-based (Tetzlaff & Soulsby, 2008; Muñoz-Villers *et al.,* 2016) or non-tracer-based methods (Mo *et al.,* 2021).

Comparison on Salinity Distribution Before and After Estuary Modification

We compared our data to the seawater movement within the estuary before the natural sand bar was completely replaced by a permanent symmetrical bow-shape equal arms breakwater structure. We have selected the inter-monsoons months (April and October) of years 1999/2000 and 2016, respectively. The impact of tidal movement was carefully examined to further understand the impact of tides on seawater intrusion at this micro-tidal estuary. Figures 7 and 8 compare the salinity distributions of the surface and bottom layers during high tide and low tide. The modification of the river estuary mouth geomorphological structure has changed the movement of seawater in and out of the estuary. The bow-shape breakwater structure (year 2016) allows more seawater to enter the estuary, reaching what used to be the riverine zones of the Terengganu and Nerus Rivers during year 1999 - 2000. The surface salinity at stations in the riverine zones had increased from 0 psu (years 1999 - 2000) to nearly 4.5 psu in year 2016 (stations S1 – S5). We also noticed an obvious salinity stratification, with more seawater transported through the bottom layer moving upstream during high tide, with station S3 at the Nerus River recorded salinity reaching > 21 psu. Such salinity intrusion did not happen in 1999 - 2000, where the same areas remained freshwater zones from surface to bottom throughout the inter-monsoon seasons.

On the other hand, years 1999 - 2000 were normal years with no other major climate events recorded. The salinity data for October 1999 and April 2000 collected before major transformation of the river estuary, showed that the upstream movement of seawater was much restricted, where it did not reach the riverine zone of the Nerus and Terengganu Rivers (Figures 5 to 8). Apart from the newly constructed lower estuary entrance, the middle estuary had also undergone intensive land reclamation where the water passageway along the northern part of the middle estuary had been reduced (Figure 1). Both features could change the estuary circulation and the water flushing time into and out of the estuary, thus affecting the inward movement of seawater within the estuary. This is especially obvious when we observed that poor water quality with higher salinity was recorded in the area surrounding station S11 during dryer seasons, indicating poor water circulation. However, a detailed study on the estuary bathymetry and circulation is needed to further support the findings from this study. Apart from the arguments presented here, the scale of seawater intrusion involves complex mechanisms and could be a combination of many factors. The discharge characteristics of upstream water catchment area, water reservoirs

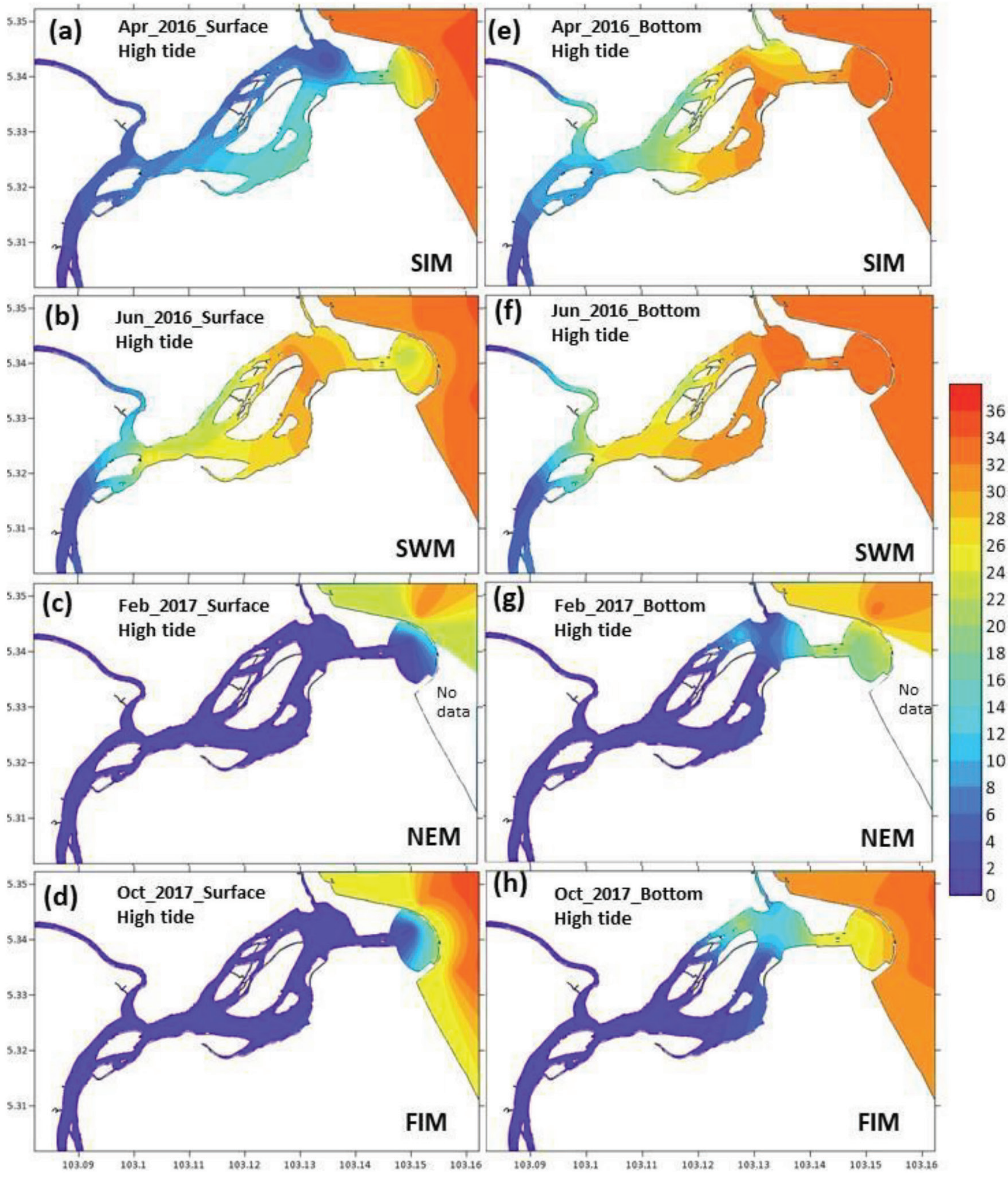


Figure 5: Salinity distribution during high tide at the surface (a, b, c, d) and bottom (e, f, g, h) along the Terengganu River estuary in April 2016, June 2016, February 2017 and October 2017. Unit of Salinity: Practical Salinity Unit (psu). SIM: Spring inter-monsoon, SWM: Southwest monsoon, NEM: Northeast monsoon, FIM: Fall inter-monsoon

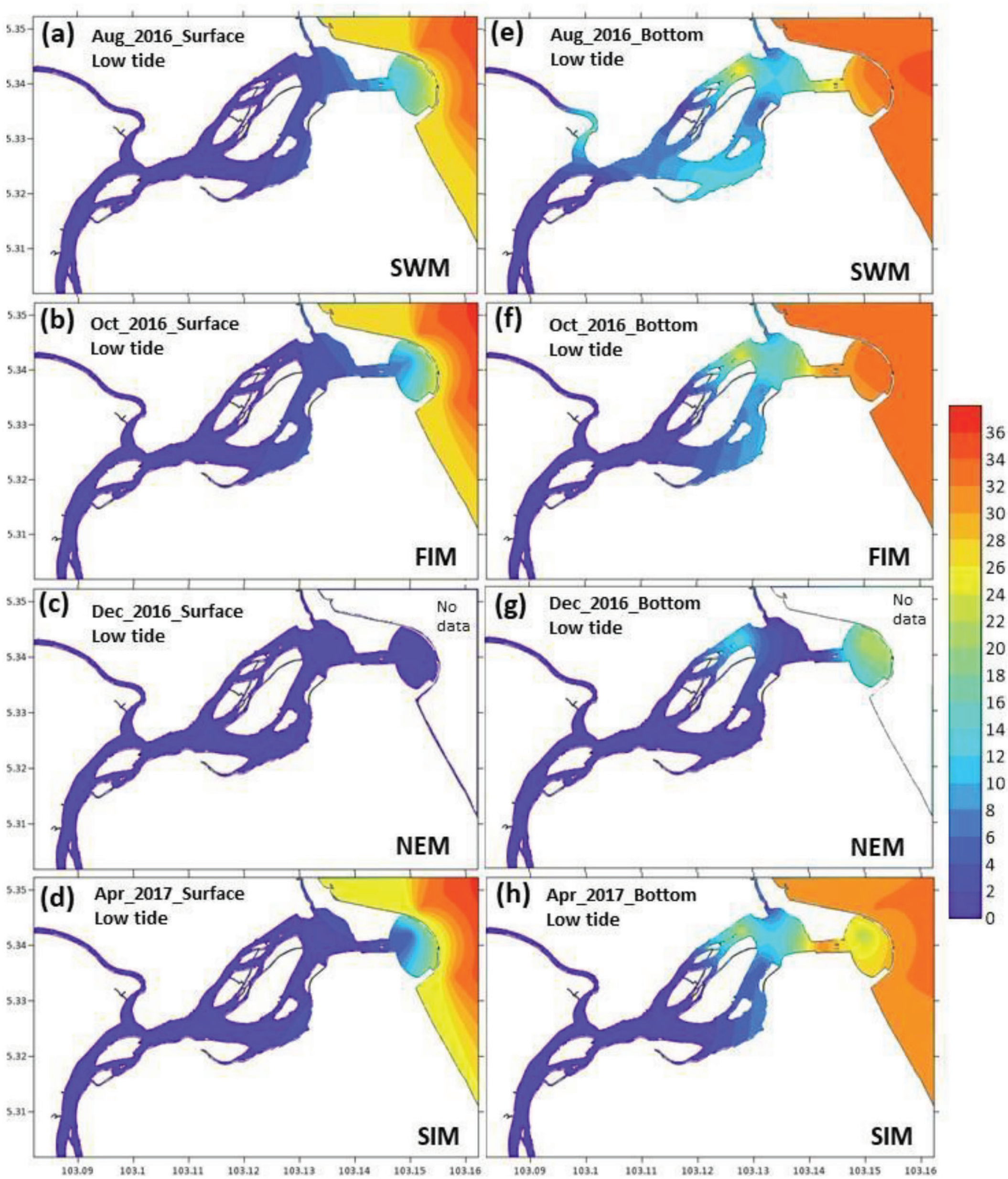


Figure 6: Salinity distribution during low tide at the surface (a, b, c, d) and bottom (e, f, g, h) along the Terengganu River estuary in August 2016, October 2016, December 2016 and April 2017. Unit of Salinity: Practical Salinity Unit (psu). SIM: Spring inter-monsoon, SWM: Southwest monsoon, NEM: Northeast monsoon, FIM: Fall inter-monsoon

and the withdrawal patterns of downstream water for domestic, industrial and agriculture usage could have strong influences on the equilibrium and dynamics of freshwater and seawater in the estuary system. A careful examination of every possible factor is necessary to ensure a more effective management and mitigation for the issue of saltwater intrusion to safeguard our aquatic environment and the future of water resources (Prusty & Farooq, 2020; Lee *et al.,* 2016b).

Conclusion

This study shows that the Terengganu River estuary water's physicochemical parameters are determined by seasonal rainfall intensity and could be intermittently affected by large or small-scale climate variability. By referring to Malaysian Marine Water Quality Standard (MMWQS) Interim Class E (DOE, 2019), water pH and SPM values are greatly affected by the NEM season. During low rainfall seasons, DO concentrations fell below 5 mg/L and a clear hypoxia zone developed in bottom water of station S11. We observed seasonal temperature differences with temperature dropping to as low as 25°C during the NEM seasons in comparison to other seasons with temperature reaching > 31°C. Nutrient concentrations had less extreme fluctuation from season to season and were within the range prescribed by MMWQS. The present study observed a more massive bottom saltwater upstream movement during the dry SWM and inter monsoon seasons with salinity of up to 26 psu being detected at the confluence flow zone of Terengganu and Nerus Rivers. In comparison to the years 1999 - 2000, a much smaller scale of seawater intrusion was recorded where salinity value of only up to 5 psu was recorded at approximately the same area. In addition, the present study found that during unusually dry seasons, seawater (1.4 - 2.92 psu) could reach as far as upstream stations 9.43 km (Terengganu River) and 10.24 km (Nerus River) from the estuary mouth. Such intrusion was not

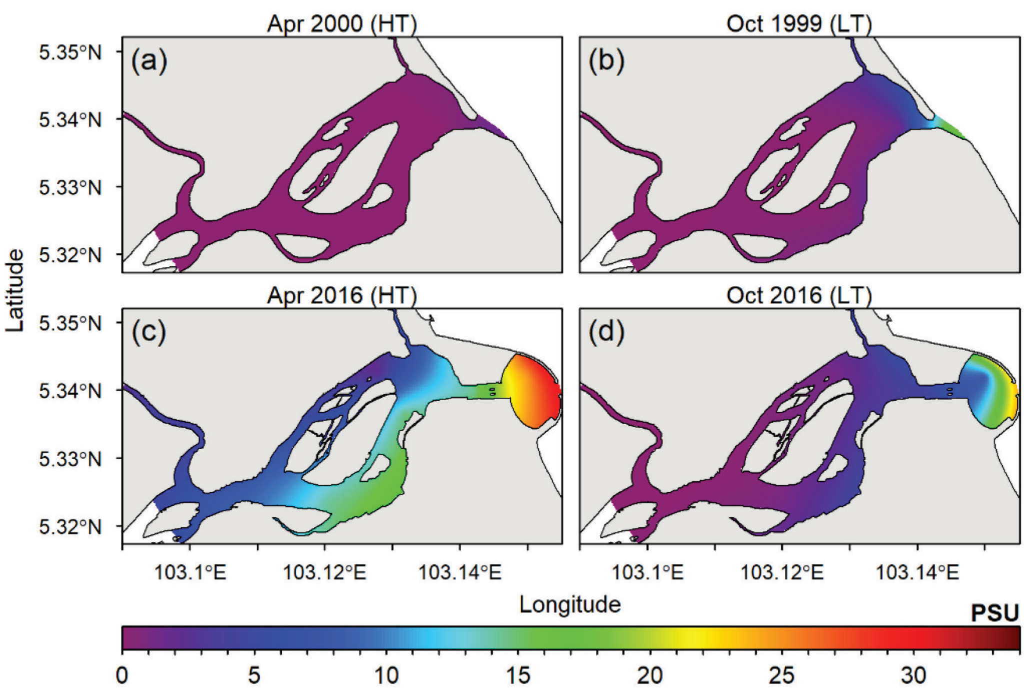


Figure 7: Distribution of surface salinity (psu) during high and low tides before (a and b) and after the construction of wave breakers (c and d). (Rainfall: April 2000 – 93.8 mm, October 1999 – 145.2 mm, Tidal range: April 2000 – 1.3 m, October 1999 – 1.26m) (Jong, 2002)

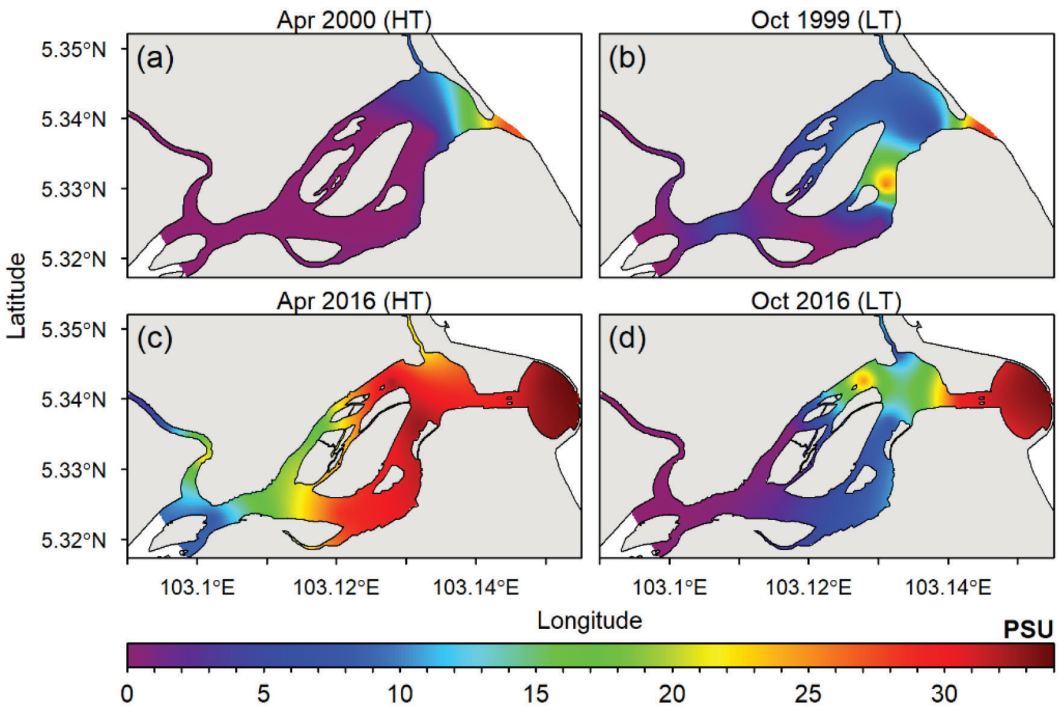


Figure 8: Distribution of bottom salinity (psu) during high and low tides before (a and b) and after the construction of wave breakers (c and d)

recorded in years 1999 - 2000, where the upper estuary remained a freshwater zone throughout the seasons. From the physicochemicals and nutrients data gathered, we could facilitate a more detailed estuarine dynamic modelling in relation to climate variability and devise strategies to mitigate the seawater intrusion by controlling the release of water from the upstream Kenyir Dam and the uptake rates of water downstream for human consumption. In addition, we suggest that a thorough study to link the resilience and survivability of the riverine and estuarine organisms with the present living conditions, to provide deeper insight on the ecosystem balance for better management of river and coastal ecosystems.

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