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**INTERPLAY OF
PHYSICAL AND
BIOGEOCHEMICAL
FACTORS IN THE
DEVELOPMENT OF
HYPOXIA IN TELUK
BAHANG, PENANG:**

**A CASE STUDY FROM
JULY-AUGUST 2024**



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INTERPLAY OF PHYSICAL AND BIOGEOCHEMICAL FACTORS IN THE DEVELOPMENT OF HYPOXIA IN TELUK BAHANG, PENANG: A CASE STUDY FROM JULY-AUGUST 2024

1. ABSTRACT

Dissolved oxygen (DO) plays a critical role in marine ecosystems, influencing biogeochemical processes and overall ecosystem health. Hypoxia, or low oxygen levels, can lead to biodiversity loss and reduced productivity, making it an important factor to monitor. This study investigates the relationships between physical-biogeochemical processes and the spatial variations in hypoxia in Teluk Bahang, Penang, during July-August 2024. In situ observations were conducted to examine the influence of neap and spring tidal conditions on various hydrological and biochemical parameters, including temperature, salinity, DO, turbidity, pH, and chlorophyll-a (Chl-a). Nutrient and Chl-a levels were analyzed using fluorometric techniques via Aquatroll 600, while hydrological parameters specifically the river flow were examined using the oceanic front detection algorithm via Sontek Bathymetric Survey M9. The results revealed that during neap tides, the water column exhibited significant stratification, with pronounced gradients in thermocline, halocline, and pycnocline, which facilitated localized phytoplankton production near the pycnocline. In contrast, spring tides enhanced nutrient redistribution and increased surface Chl-a concentrations. Additionally, sensor-derived Chl-a concentrations showed a high correlation ($r = 0.884$, $p < 0.001$) with fluorometric analyses, validating the reliability of the in situ data. The study highlighted how tidal dynamics, seasonal monsoon shifts, and anthropogenic nutrient inputs interact to create complex patterns of DO distribution in Teluk Bahang. Spring tides promote vertical mixing and oxygen exchange, mitigating hypoxia, while neap tides and the transition from the Southwest to Northeast Monsoon exacerbate hypoxia, particularly in deeper waters. The unique features of Teluk Bahang, including its confined bay structure, localized nutrient loading, and seasonal monsoonal influences, make it particularly vulnerable to hypoxia compared to other coastal systems. These findings deepen our understanding of spatially variable hypoxia in estuarine environments and lay the groundwork for future three-dimensional simulations and hypoxia predictions.

2. INTRODUCTION

Dissolved oxygen (DO) is a critical factor in marine ecosystems, influencing various biogeochemical processes and maintaining ecosystem health. The concentration of dissolved oxygen plays a key role in the biogeochemical cycles of essential elements like nitrogen, phosphorus, and carbon, which are vital for marine organisms. It also affects habitat quality, where low oxygen levels, or hypoxia, can lead to biodiversity loss and reduced marine productivity (Breitburg et al., 2018; Diaz & Rosenberg, 2008). In recent decades, increasing anthropogenic disturbances, such as pollution and coastal development, and natural environmental changes, have exacerbated eutrophication in coastal and estuarine regions. Eutrophication refers to the enrichment of water with nutrients, particularly nitrogen and phosphorus, which stimulate excessive phytoplankton growth (Jakobsen et al., 2015). This process leads to the increased decomposition of organic matter when phytoplankton die, consuming oxygen in the water and promoting the formation of hypoxia, particularly in

subsurface or bottom waters (Oschlies et al., 2008). Hypoxia has been increasing globally, posing significant threats to marine ecosystems' health and sustainable productivity. The formation of hypoxia is directly dependent on the balance between oxygen supply (primarily from photosynthesis and air-sea exchange) and its consumption by microorganisms during organic matter decomposition. The supply of oxygen is further hindered by stratification, which is the separation of water layers with different densities (due to temperature or salinity differences). Stratification impedes vertical mixing, preventing oxygen replenishment in deeper waters, thus enhancing hypoxic conditions (Cifuentes et al., 1990; Simpson & Hunter, 1974). In estuarine ecosystems, hypoxia is often associated with density barriers, which are caused by temperature, salinity, or both, restricting vertical mixing and resulting in organic matter accumulation without sufficient oxygen replenishment (Hardiman et al., 2011). These physical changes are more pronounced in areas with high phytoplankton biomass, where organic matter decomposition is excessive as dead phytoplankton sink to the bottom. As a result, estuaries are highly susceptible to hypoxia due to the combined biological activities and physical changes influenced by environmental conditions (Vaquer-Sunyer & Duarte, 2008). Although hypoxia is generally linked to organic matter decomposition and stratification, other complex factors, such as wind, riverine discharge, and offshore currents, also affect hypoxic conditions. Upwelling and offshore advection introduce oxygen-depleted water into coastal zones, exacerbating hypoxia (Pingree & Griffiths, 1978). These factors contribute to spatial and temporal variations in hypoxia across different marine systems. For example, significant spatial variability in oxygen patterns along the California coast has been linked to heterogeneity in coastal upwelling and subsequent biogeochemical responses. This variation in hypoxia can result in persistent "hot spots" in specific geographic locations (Massicotte et al., 2019).

The eutrophication process is intensified by the high nutrient load in the river discharge, particularly nitrogen and phosphorus, which leads to excessive growth of phytoplankton (chlorophyll-a concentrations can peak at 50 $\mu\text{g/L}$ during blooms). This results in frequent harmful algal blooms (HABs) during the peak of the rainy season in August, which depletes oxygen levels in the water as organic matter from decaying algal cells consumes oxygen through microbial respiration. The sediment oxygen demand (SOD) can reach values between 1 to 5 $\text{g O}_2/\text{m}^2/\text{day}$, further exacerbating hypoxic conditions. These blooms can create localized hypoxic zones at the bottom of the bay (with DO levels dropping below 2 mg/L), affecting benthic organisms and overall marine biodiversity. The dynamic environment in Teluk Bahang is further influenced by local upwelling, which brings nutrient-rich subsurface waters to the surface. This upwelling, driven by both wind and tidal forces (with maximum current speeds during spring tides reaching up to 0.5 m/s), fosters the growth of phytoplankton at the surface. The waters that upwell in this region are often oxygen-depleted (DO levels can drop to 1.5 mg/L), further exacerbating the occurrence of hypoxia, particularly in deeper regions of the bay. Additionally, topographical features such as steep bathymetry (with depths reaching over 20 meters close to shore) and the interaction between river plume fronts and upwelling-induced fronts contribute to sharp gradients in water quality parameters, such as salinity, temperature, and dissolved oxygen. These gradients enhance spatial heterogeneity of biogeochemical and ecological conditions in the region. In-situ observations further highlighted localized phytoplankton production near the pycnocline during neap tides. In contrast, spring tides facilitated nutrient redistribution, leading to increased surface Chl-a concentrations, illustrating the influence of tidal cycles on nutrient dynamics and the potential occurrence of red tide events as noted by Jakobsen et al. (2015) and Massicotte et al. (2019). These findings align with previous studies indicating that larger tidal ranges during spring tides enhance sediment and nutrient transport, subsequently affecting suspended solid concentrations and deposition rates (Pingree & Griffiths, 1978). Additionally, tidal forcing was shown to influence the distribution

of salinity, temperature, and other oceanographic parameters, supporting the findings of stratification changes and vertical mixing under varying tidal conditions as discussed by Cifuentes et al. (1990) and Diaz & Rosenberg (2008).

In August 2024, in situ observations in the waters of Teluk Bahang revealed significant hydrodynamic and biochemical variability driven by neap and spring tidal conditions measured using the AquaTroll 600 multiparameter instrument. The findings align with stratification and mixing processes where oceanic fronts and vertical gradients such as thermoclines ($\sim 0.5^{\circ}\text{C m}^{-1}$), haloclines ($\sim 0.2 \text{ PSU m}^{-1}$), and pycnoclines ($\sim 0.05 \text{ kg m}^{-3} \text{ m}^{-1}$) during neap tides enhanced localized nutrient retention and phytoplankton production (Belkin & O'Reilly, 2009; Grasshoff et al., 2009). During spring tides, enhanced vertical mixing reduced stratification intensity ($\sim 0.2^{\circ}\text{C m}^{-1}$, $\sim 0.05 \text{ PSU m}^{-1}$, $\sim 0.01 \text{ kg m}^{-3} \text{ m}^{-1}$), redistributing nutrients into the surface layer and increasing surface chlorophyll-a (Chl-a) concentrations consistent with their dynamics (Pingree & Griffiths, 1978; Jakobsen et al., 2015). The observed correlations ($r = 0.884$, $p < 0.001$) between AquaTroll 600 sensor-derived Chl-a concentrations and fluorometric analyses corroborated the reliability of in situ data akin to precision protocols established by Massicotte et al. (2019).

Understanding how and why hypoxia varies spatially is crucial, as this variation has substantial implications for the biogeochemical and ecological structure of marine systems. The complex dynamics involved in hypoxia and its significant influence on biogeochemical-ecological processes in river-dominated ecosystems make it challenging to understand the mechanisms governing estuarine hypoxia variation. Teluk Bahang, Penang, is a coastal area known for its complex estuarine and coastal ecosystem features. The dynamics in Teluk Bahang are further complicated by the presence of rivers entering the bay, local upwelling, sedimentation processes, and interactions between estuaries and the adjacent continental shelf. The region is also influenced by factors such as river discharge, wind, offshore currents and local upwelling, all of which can exacerbate hypoxic conditions along the coastline. These factors play a role in enhancing water column stratification and increasing the risk of hypoxia in the region. Observations show seasonal oxygen depletion in Teluk Bahang, particularly during August, contributing to the enlargement of the hypoxic zone along the coast. Hypoxia in Teluk Bahang is governed by various factors, including river discharge, winds, offshore currents, and upwelling, as well as tidal forcing and topography. These factors are closely tied to water column stratification, which in turn impacts oxygen levels. In general, hypoxia in the area is controlled by both physical and biogeochemical processes. However, due to the complexity and interaction of multiple factors, the distribution of dissolved oxygen within the hypoxic zone in Teluk Bahang is uneven. Despite significant efforts to study hypoxia formation, studies focusing on the heterogeneity of hypoxia driven by physical and biogeochemical drivers remain limited. Furthermore, the processes governing the boundaries, extent, and magnitude of common summer hypoxia in Teluk Bahang remain unclear.

This study aims to identify the key relationships between physical-biogeochemical processes and spatial variations in hypoxia in Teluk Bahang. Specifically, the analysis will examine how river input, stratification, physical boundaries, upwelling, and high phytoplankton biomass shape the spatial morphology, intensity, and boundaries of hypoxia in August. Also, this study provides valuable insights into the relative importance of physical-biogeochemical drivers in regulating spatially variable hypoxia. The findings will significantly contribute to our understanding of spatially variable hypoxia in estuarine systems, providing a strong foundation for three-dimensional simulations and hypoxia predictions under expected future conditions. It also extends the principles of tidal modulation to the specific hydrodynamic context of Teluk

Bahang, emphasizing that neap tides promote localized stratification and production while spring tides enhance nutrient fluxes and surface productivity. These insights provide a localized perspective on broader frameworks highlighting Teluk Bahang's susceptibility to tidal influences particularly in regulating nutrient availability and potential harmful algal bloom (HAB) risks. Therefore, this study provides a foundational basis for predictive modelling empirical equations for sustain the ecosystem management in Teluk Bahang.

3. STUDY AREA

Teluk Bahang is located along the North East cost of Penang Island and the beach is one of the local attraction of Penang among the tourist. It is just 11 km from the Georgetown with the stretch of beach along 5 km. All tourist attraction such as street market, beach activity, restaurant, hotel and chalet have been established to cater the need of the tourism industry. Due to its attraction, it gain a lot of local and foreign tourist every year and one of the economic contribution to the country. Teluk Bahang (TB) is in the north of Pulau Pinang. In addition, it is surrounded by the Penang National Park and is famous for its fishing landing area for various fishing vessels and the aquaculture industry with at least ten fish cages. Apart from being the largest fishing village in Pulau Pinang, the coastal area of Teluk Bahang has undergone minimal development without any reclamation by comparison to Pantai Jerejak and Tanjung Bungah.

Inshore fishing and floating-cage aquaculture are major economic activities in Teluk Bahang. Also, along the shoreline Teluk Bahang Permanent Forest Reserve (TBPFR) (latitude 100° 12' 55.79" U and longitude 5° 15' 56.88" T) is located near to sampling site which has been designated as an educational and recreational forest. This particular forest is bordered by Bukit Laksamana Permanent Forest Reserve on the west side and Bukit Kerajaan Permanent Forest Reserve on the east. Pantai Acheh and National Reserved Park, Teluk Bahang has currently more than 500 fish cages operating by six different owners or fish farmers. The highest number of cultured fish is groupers (5 tonnes), followed by red snappers (4.5 tonnes), golden snappers (3 tonnes) and barramundi (3 tonnes). On 18th April 2019, fish farmers in Teluk Bahang experienced mass mortality of cultured fishes with an estimated loss of USD 175, 000 due to unknown sources of marine pollution (personal communication with fish breeders). Marine pollution occurs when unsustainable element gain entry to water masses, potentially causing spread of diseases, turn water quality to potentially toxic and also brings in invasive species.

Most sources of marine pollution are 1) land-based, such as from industrial/ domestic pollutant discharged, 2) wind blow debris 3) potential spill overs from freight ocean carries and 4) excessive nutrients inlet from the river. When toxins are concentrated within the ocean food chain, many elements combine in a manner of highly depletive oxygen, causing estuaries to become anoxic and create many ecological problems. The possible marine pollution factors that had caused the death of cultured fish in Teluk Bahang comes from by heavy metals pollution or harmful phytoplankton bloom (HAB). Harmful phytoplankton bloom (HAB) is an outcome of the natural process of rapid and high biomass accumulation of phytoplankton (algae, blue green algae, or cyanobacteria) in the water column that can cause a negative impact on the aquatic ecosystem. It can occur in any water bodies such as rivers, lakes and oceans, from freshwater or brackish waters to open ocean ecosystem around the world, and can cause mainly economic loss of aquaculture industries in a country.

However, it is uncertain that heavy metals and hypoxia conditions (dissolved oxygen is below than 2 mg/L) were the main cause of the death of tonnes of cultured fishes. Since the depth of seawater around the cages mostly are very shallow (about 4 to 7 m) and the water current and circulation are quite poor and stagnant (anaerobic condition) it could contribute in death of fishes. This in-situ measurement is to evaluate the linkage between chlorophyll -A distribution characteristics and plume dynamics (involved salinity, density, pH, dissolved oxygen (DO), total suspended solids and water temperature) by each water column stratification. This data collection also explore if there have any hypoxia condition (DO below 2 mg/L) with upwelling condition (nearshore current).

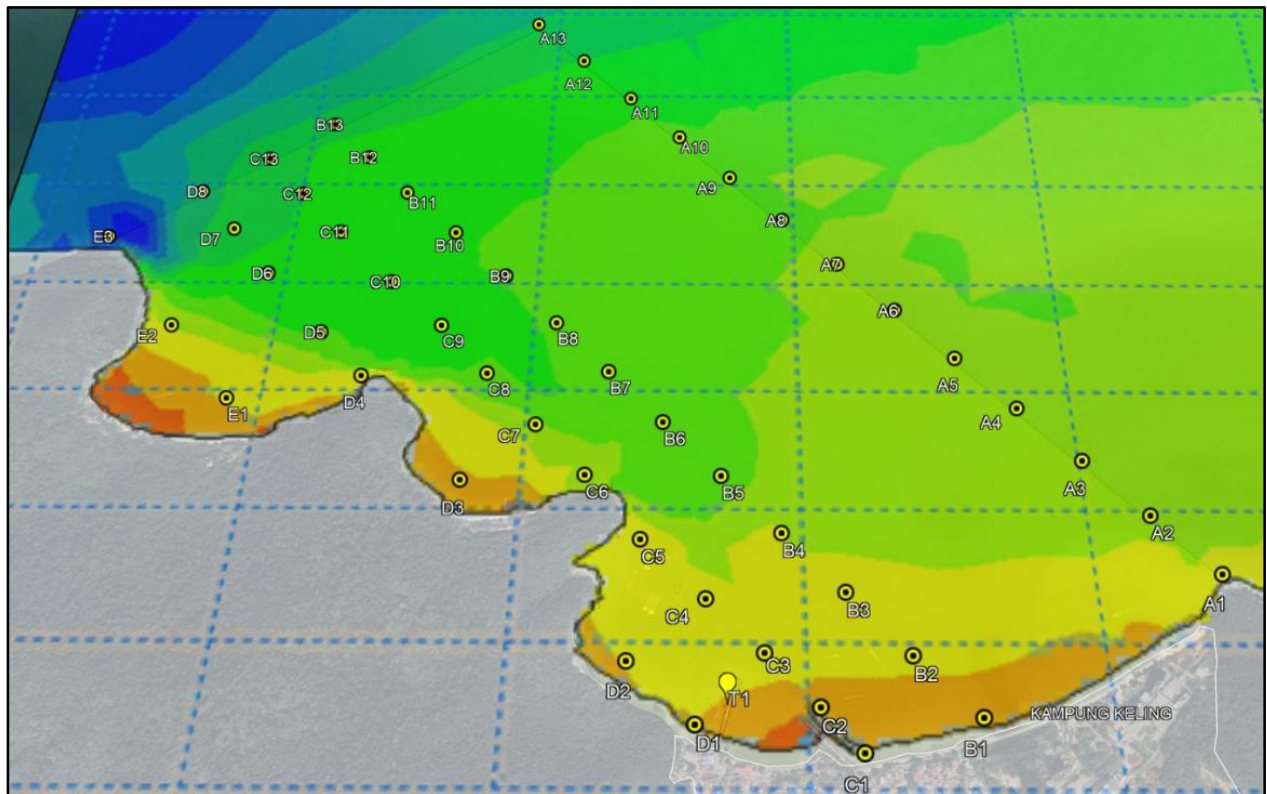


Figure 1.1 The sampling in-situ physical and biogeochemical parameter site consisted 50 points at Teluk Bahang, Pulau Pinang

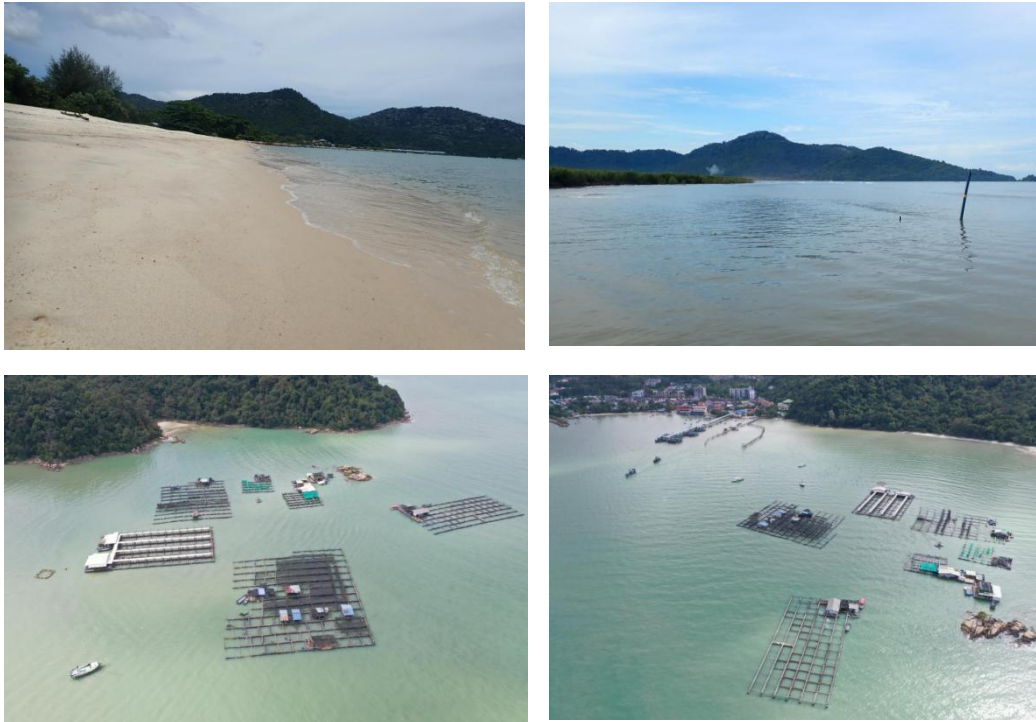


Figure 1.2 The site observation at Teluk Bahang and socio economic activities near to sampling points



Figure 1.3 The jetty that locate the tide gauge and scenary during calm weather

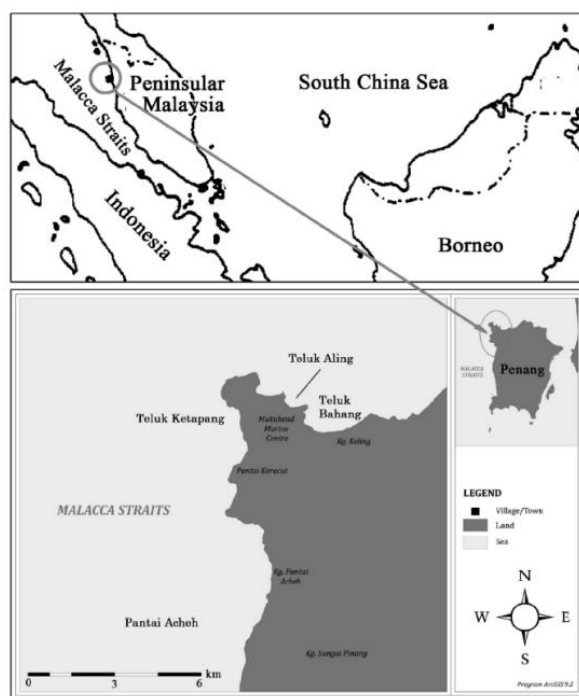


Figure 1.4 The exact location of Teluk Bahang, Pulau Pinang

4. SAMPLING AND METHODS

In-situ observations were conducted on board during the period three (3) phases of Neap and three (3) phases of Spring Tide. The period is stated in Table 2.1 below during the South-West Monsoon with fifty (50) points oriented in Figure 2.1. The parameters were involved as Salinity, Total Suspended Solids (TSS), Water Density, pH, Ocean Temperature, Dissolved Oxygen (DO) and Chlorophyll-A. These seven (7) parameters were measured using the Aquatroll model 600 Multi Parameter Sonde and Sontek Hydroboard M9 Flow. All sensors had been calibrated before the cruise and apply it to the water stratification in-situ measurement. During the cruise for determine ocean current, M9 flow Hydroboard was attached to the boat with constant speed (Figure 2.2) whereas for Aquatroll 600 the instrument was tested the accuracy by checking the signals of its bluetooth paired with its cabel (Figure 2.3). Also, the process to install the tide gauge and the tide gauge location is shown at Figure 2.4.

In situ observations were conducted in the waters off Teluk Bahang, Pulau Pinang, during August 2024 to investigate the influence of neap and spring tidal conditions on hydrological and biochemical parameters. Sampling was performed at all layers but detail observation was observed for surface, 1 m, and 2 m depths. However, DO concentrations were further validated through site-specific methods. Eventhough, Nutrient and Chl-a levels were obtained from the Aquatroll 600 measurementwere then brought to the laboratory to validated using fluorometric techniques, demonstrating a significant correlation ($r = 0.884$, $p < 0.001$) between sensor-derived and extracted Chl-a concentrations, confirming the reliability of the sensor as outlined by Grasshoff et al. (2009). Physical parameters such as temperature, salinity, and density gradients were analyzed using in-situ measurement and validated with the oceanic front detection algorithm developed by Belkin and O'Reilly (2009). The results revealed stratified

conditions during neap tides, characterized by pronounced thermocline ($\sim 0.5^{\circ}\text{C m}^{-1}$), halocline ($\sim 0.2 \text{ PSU m}^{-1}$), and pycnocline ($\sim 0.05 \text{ kg m}^{-3} \text{ m}^{-1}$) intensities. Conversely, spring tides exhibited mixed water column conditions with diminished gradients ($\sim 0.2^{\circ}\text{C m}^{-1}$, $\sim 0.05 \text{ PSU m}^{-1}$, and $\sim 0.01 \text{ kg m}^{-3} \text{ m}^{-1}$) due to enhanced vertical mixing.

In addition to these observations, SonTek M9 applications by YSI instruments were utilized for accurate bathymetric depth values and assessments of freshwater and coastal current flows in Teluk Bahang during the same period. The process began with deploying the SonTek M9 for acoustic Doppler profiling to measure water depth through echo sounding; this involved emitting sound pulses from the device and recording the time taken for echoes to return after bouncing off the seabed. Calibration was performed according to YSI's manual to ensure precision in measurements. Following calibration, hydrographic surveys were conducted with GPS-enabled equipment integrated with SonTek M9 to accurately map underwater features across various locations in Teluk Bahang while continuously recording depth data along predetermined transects. To analyze freshwater flow dynamics from local rivers into Teluk Bahang, current velocities at various depths were measured using SonTek M9's capabilities; this assessment provided insights into how riverine discharge impacts salinity gradients.

Coastal currents influenced by tidal actions were also measured throughout different tidal phases using SonTek M9 to understand their role in nutrient transport within the estuary. Data collected from SonTek M9 were processed using specialized software that enabled visualization of current patterns alongside bathymetric features. The integration of bathymetric data obtained from SonTek M9 with measurements from other instruments like AquaTroll allowed for a comprehensive analysis of how depth influences hydrological parameters such as temperature gradients, salinity distributions, and dissolved oxygen levels. This multi-faceted approach aimed to provide a thorough understanding of hydrodynamic interactions affecting hypoxia dynamics in Teluk Bahang during August 2024.

Table 2.1 Time of sampling for 50 points for seven biogeochemical parameters and nearshore current

Type of Tide	Date and Month of Sampling	Duration of Sampling
Spring	23 July 2024 (Tuesday)	9:00 am to 2:00 pm
	25 July 2024 (Thursday)	10:05 am to 3:00 pm
	6 August 2024 (Tuesday)	8:30 am to 1:30 pm
Neap	30 July 2024 (Tuesday)	8:30 am to 3:30 pm
	1 August 2024 (Thursday)	11:10 am to 4:10 pm
	13 August 2024 (Tuesday)	12:30 pm to 5:00 pm

Spring Tide Period

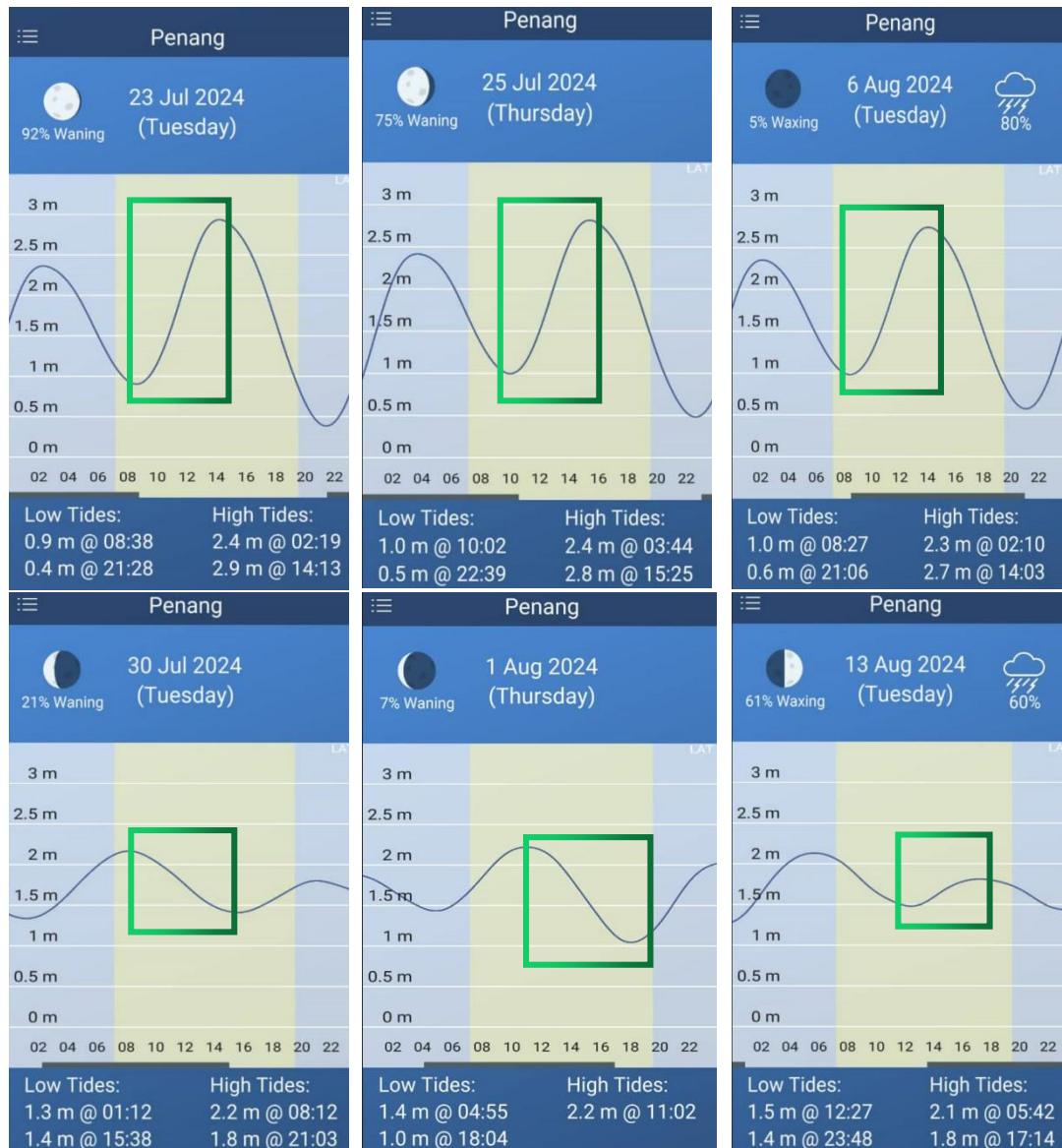


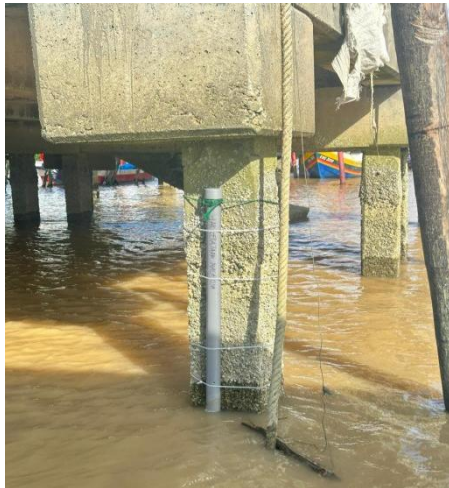
Figure 2.1 Three phase of in-situ data collection based on neap tide and spring tide periods



Figure 2.2 M9 Hydroboard velocity meter to measure the ocean current data at 50 points in-situ sampling



Figure 2.3 The process of Aqua-TROLL 600 calibration. This process must be done before in-situ sampling of 7 biogeochemical parameters.



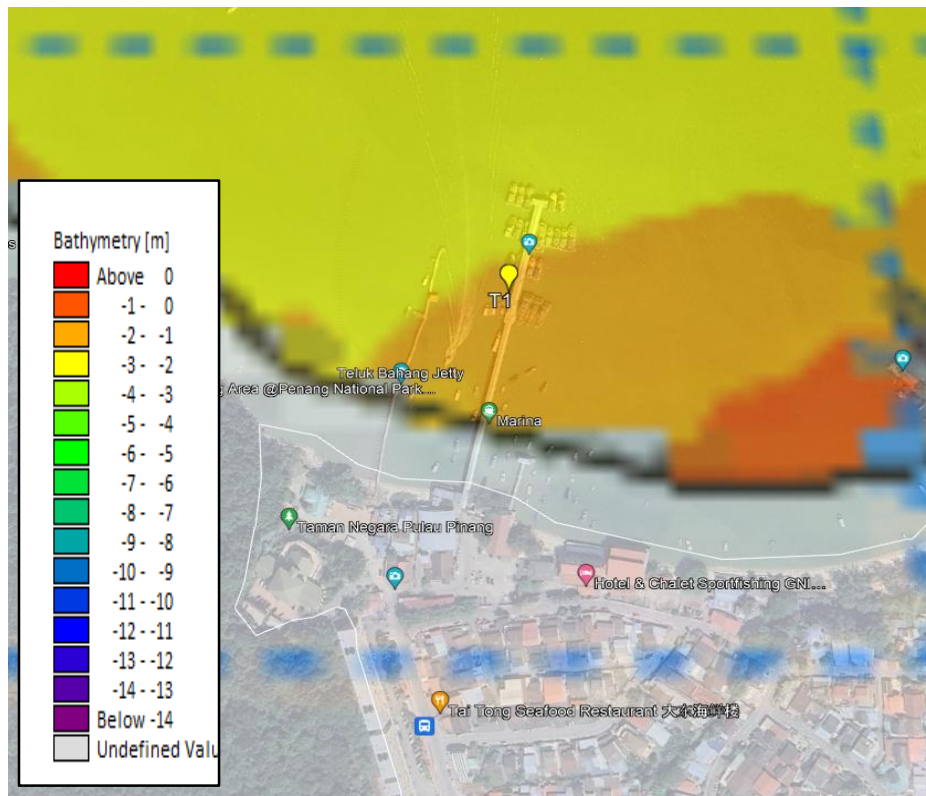


Figure 2.4 The process of tide gauge installation at the proposed area (T1) near to the fisherman jetty

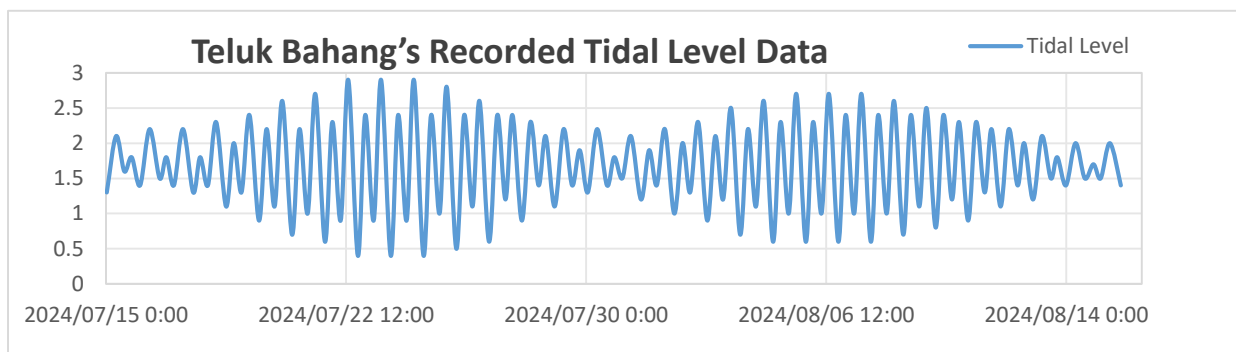


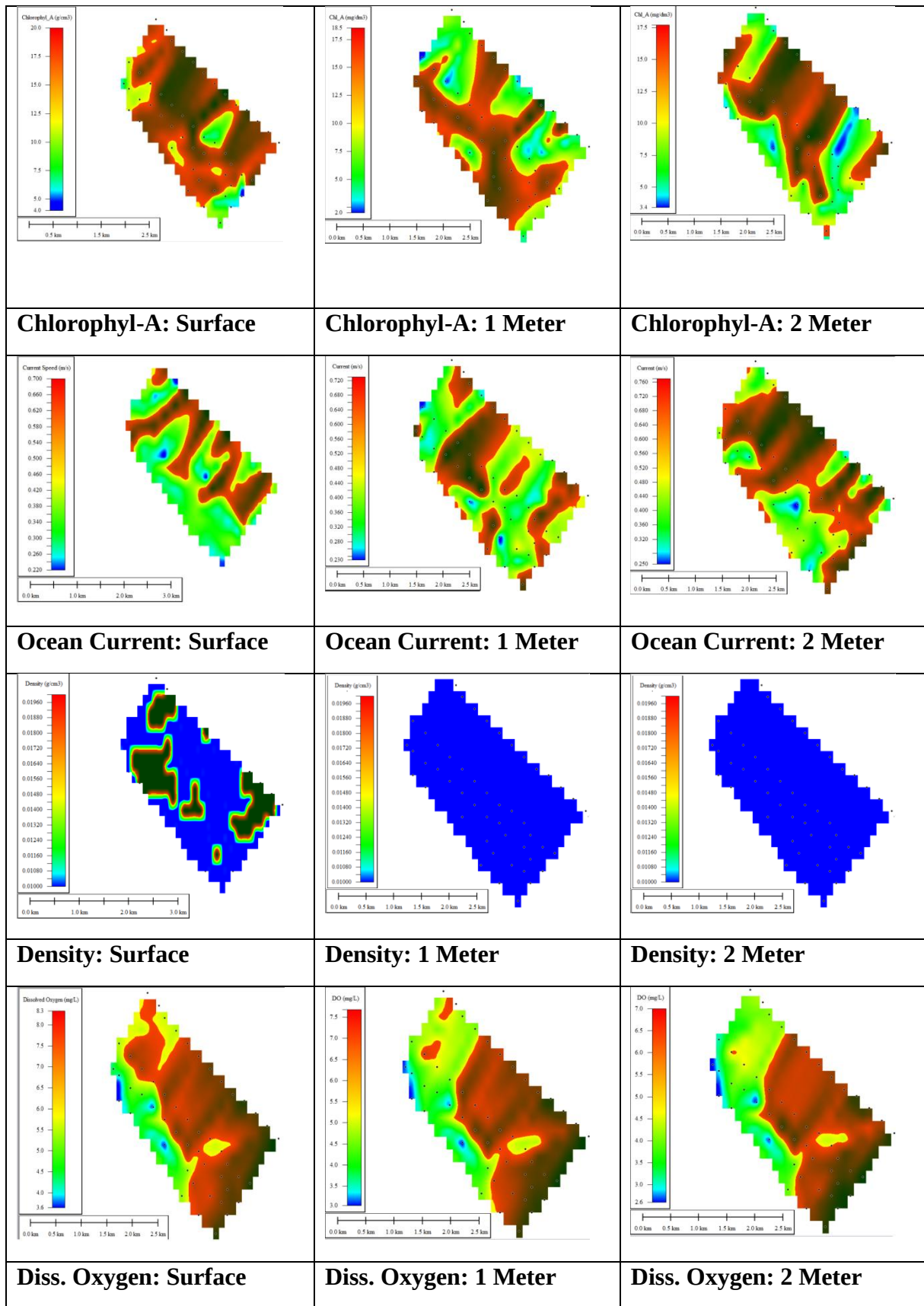
Figure 2.5 Tidal data measurement at Teluk Bahang

Teluk Bahang, located on the northwest coast of Penang Island, Malaysia, experiences significant hydrodynamic and biogeochemical interactions that shape its seasonal dynamics, particularly in August 2024. The region is influenced by a variety of physical processes, including freshwater discharge from rivers such as the Teluk Bahang River and seasonal upwelling phenomena. During the rainy season, especially in August, substantial freshwater input from river discharge significantly impacts the hydrography of the coastal environment. This results in the formation of a river plume that extends into the bay, creating a strong gradient in salinity (ranging from 0 PSU at river mouths to over 30 PSU in marine areas) and temperature (with surface temperatures reaching up to 30°C), as well as a complex nutrient distribution pattern. The river plume, carrying high concentrations of nutrients (with total nitrogen levels often exceeding 0.5 mg/L and total phosphorus above 0.1 mg/L), plays a critical role in driving the dynamics of the local marine ecosystem, leading to conditions that are

conductive to eutrophication. In August 2024, Teluk Bahang faces a particularly complex interplay of these physical and biogeochemical processes, leading to significant seasonal variability in oxygen concentrations. The interaction between river discharge, local upwelling, stratification (with thermocline depths around 5 meters), and nutrient dynamics creates a fluctuating environment with both hypoxic and normoxic zones. This variability requires detailed monitoring and modeling to predict future trends and mitigate impacts on local marine ecosystems. Given the complexity and variability of these factors such as nutrient concentrations exceeding critical thresholds during rainy seasons Teluk Bahang provides an ideal setting for identifying and understanding the spatial variability of hypoxia in tropical estuarine systems.

5. RESULTS

Figure 3.1 shows the spatial distributions of sensor-observed Chl-a in upper layers (surface, 1 meter and 2 meter) off the Teluk Bahang in July to August 2024. Overall, Chl-a was high in nearshore area and gradually decreased seaward, presenting significant gradients. From surface to 2-m layers, the distribution pattern of Chl-a was similar, and its concentration was relatively high in both of the northern and southern parts of study area, but much higher in the north than that in the south; a low-Chl-a region existed along the offshore and in the southeastern/eastern part of the study area, respectively. In 2-m layer, Chl-a concentration was much lower than that in other upper layers, but it was still higher in the north than that in the south. Notably, there were two or three high-Chl-a centers in the northern area, especially in surface and 2-m layers; surface Chl-a concentration could reach $18 \mu\text{g dm}^{-3}$ and $12.5 \mu\text{g dm}^{-3}$ during neap and spring phase, respectively. A relative high Chl-a center ($> 15 \mu\text{g dm}^{-3}$) was also observed from surface to 2-m layers in the northern area. As shown by the vertical distributions of ocean current off the Teluk Bahang for both neap and spring phase, the speed of current was high in lower layers in the northern nearshore region of each transect, presenting a decreasing trend to nearshore area; a relatively low ocean speed region was observed in the southern deep-water area. Meanwhile, the bottom waters in steep area along each transect were also characterized by dissolved oxygen (DO) concentration at the southern area. Regarding the vertical distributions of DO concentration, it generally varied from low to high in both of the downward and seaward directions, and the surface or subsurface DO maximum existed along each section. Moreover, the depth of subsurface DO maximum was deeper in the offshore area than that in the nearshore shallow region. Figures 3.1 and 3.2 exhibits the vertical distributions of salinity, temperature, density and total suspended solids (TSS) along the Teluk Bahang shoreline. Generally, a low-salinity and low-density area existed in upper layers in the western part of both neap and spring phase, suggesting the Teluk Bahang bathymetry expansion. The saline, cold and dense bottom waters were mainly concentrated on the steep area along each section, tending to be significantly uplifted in a shoreward direction. The upwelled bottom waters could even reach the surface layer, leading to a saline, cold and dense area. Moreover, the water column was stratified for each section, exhibiting distinct halocline, thermocline, and pycnocline. Notably, the pattern of stratification was related to the interactions of the upper Teluk Bahang plume and the bottom upwelled waters. The TSS was moderate and vertically uniform in coastal area but greater at the nearly sea bottom. In contrast, it was relatively low in upper layers (10 mg/L) in the nearshore surface region, which indicates that enhanced light penetration could be achieved. As a result, a noticeable turbidity front formed in the shallow area.



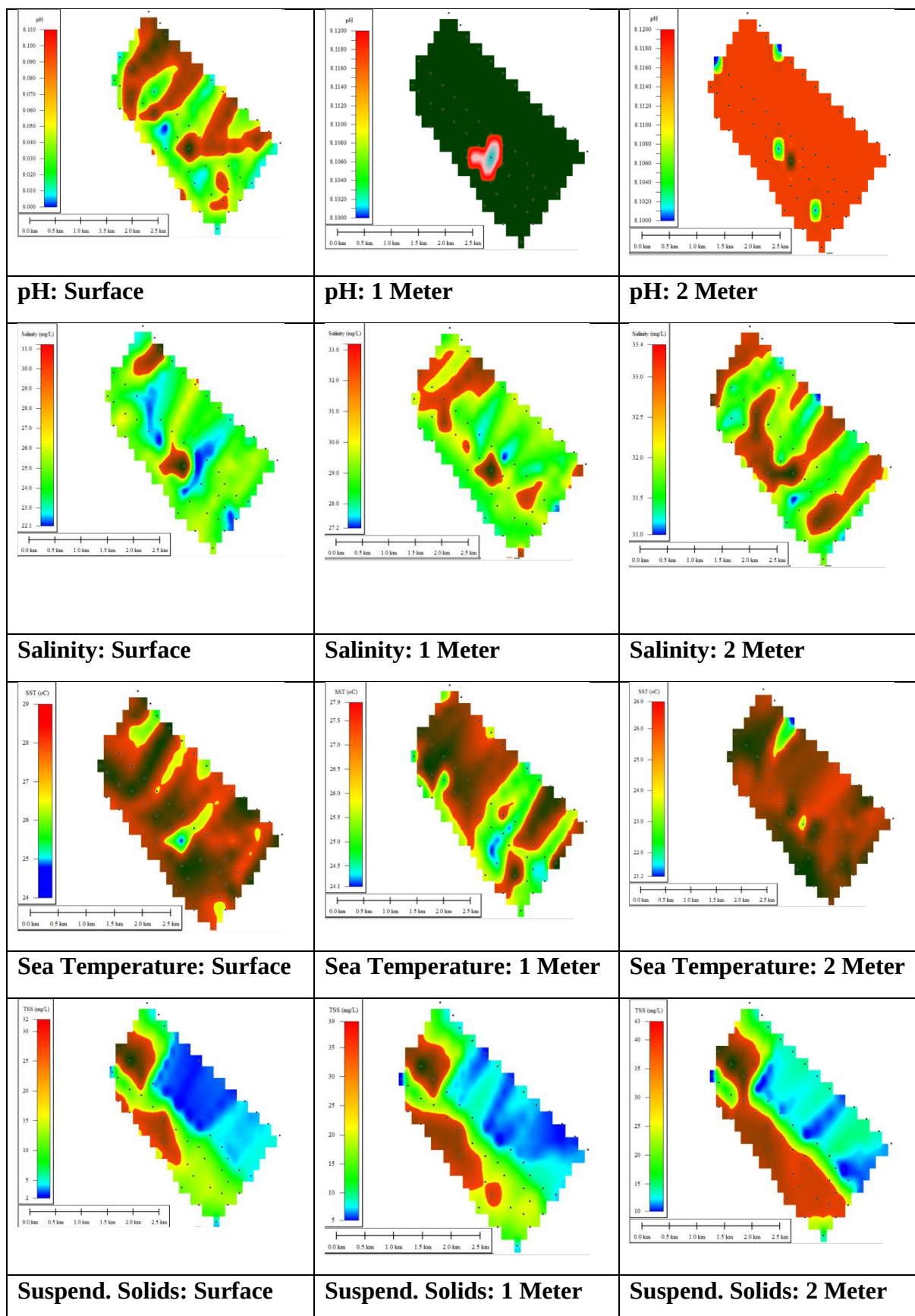
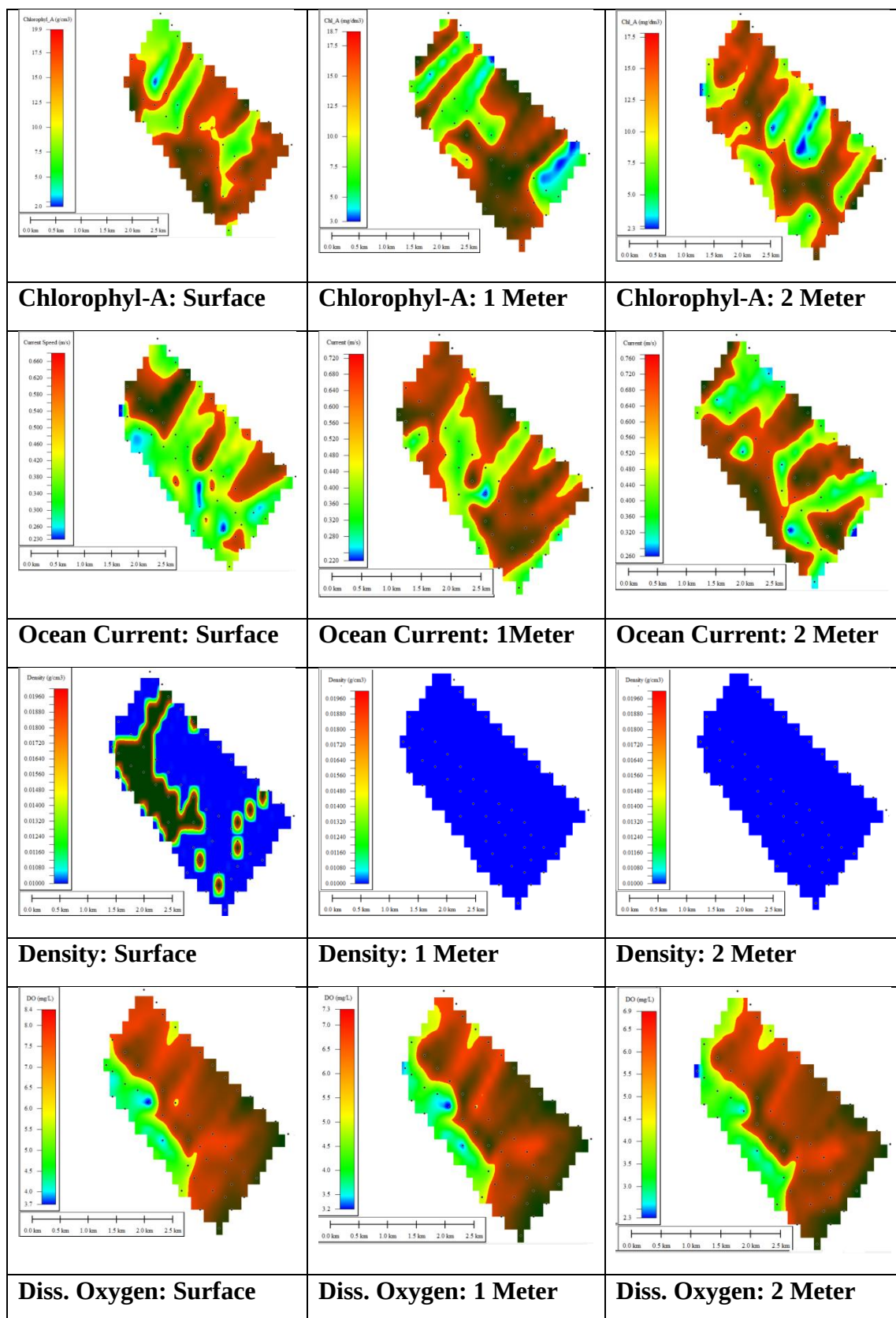


Figure 3.1 : Spatial distribution at different depths for 8 parameters to determine physical bio chemistry during neap phase.



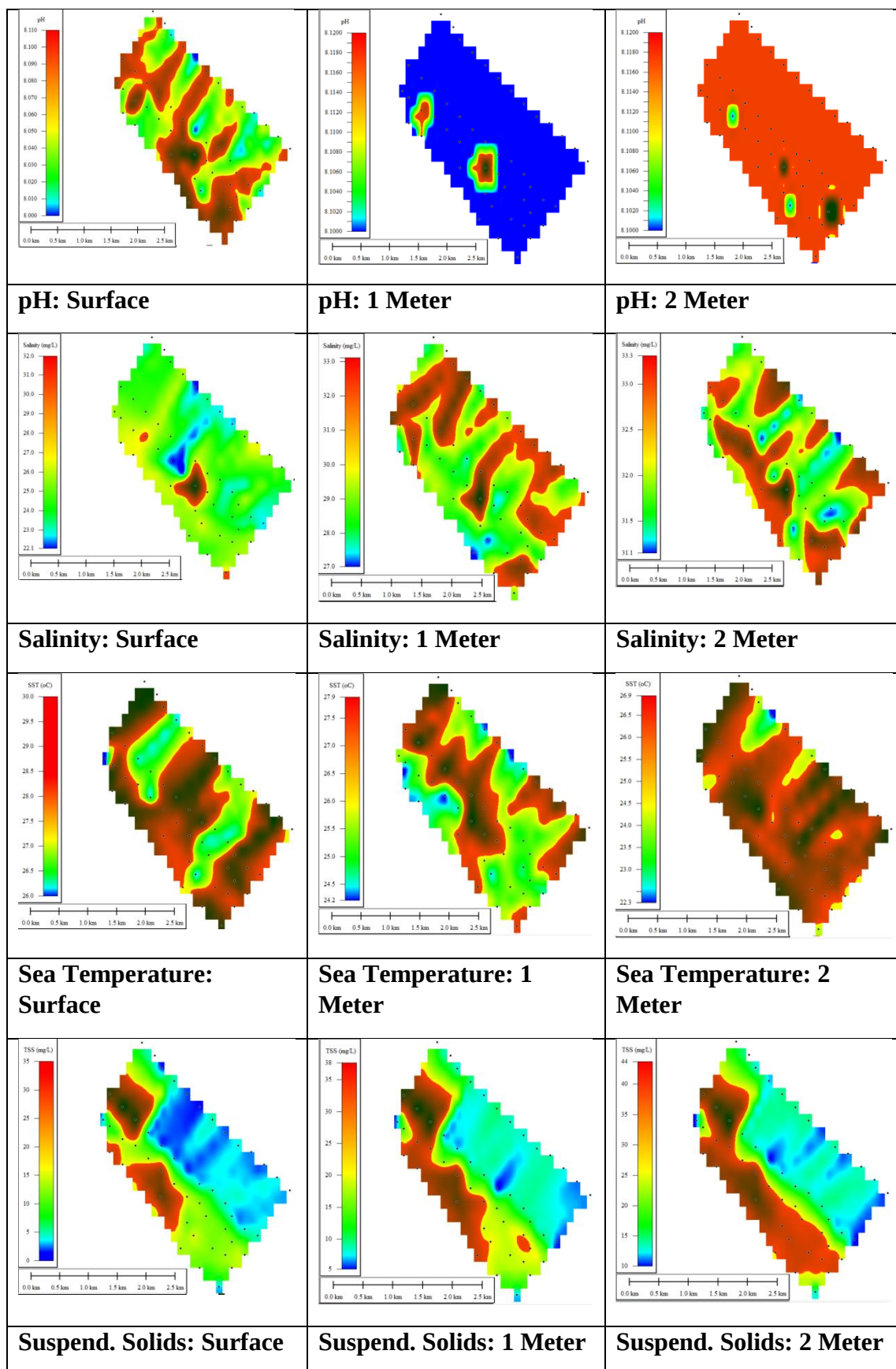


Figure 3.2 : Spatial distribution at different depths for 8 parameters to determine physical bio chemistry during spring phase.

5.1 Dissolved Oxygen distributions and Hypoxia off The Teluk Bahang, Penang

Impact of the blooms can be subtle to the marine environments; decomposition of localized blooms creates hypoxic or anoxic condition that subsequently caused fish kills. As DO is intimately related to the photosynthetic production and algal respiration, it is significantly correlated with algal biomass. Variation in dissolved oxygen and chlorophyll can be observed due to photosynthetic production during the day and respiration at night. In general, both the chlorophyll and DO varied gradually from the surface to bottom.

5.2 Chlorophyll-A Patterns

Phytoplankton is the main primary producer in the marine ecosystems and is a key component of pelagic food webs. Phytoplankton bloom events frequently occur in estuarine and coastal regions, where the waters are influenced by the input of terrigenous materials. The mechanisms controlling the algal blooms can be generalized as physical and biological controls. Despite algal behaviors and its biological growth kinetics such as vertical migration, hydrodynamic processes control the general migration characteristics of phytoplankton and determine the influences of phytoplankton growth. In estuarine and coastal waters, the relevant frontal dynamic processes, such as turbulence and cross-frontal circulation, play significant roles in phytoplankton blooms. Phytoplankton distribution is induced by fluvial nutrient availability and water properties such as salinity, temperature, and turbidity. Among three of water properties, turbidity is clear indicator to determine where the location of tidal mixing is strong. The regular semidiurnal tides that occur in this area are weak to moderate. Tidal currents reach 0.2-0.4 m/s, and tidal amplitude can be 2.3-2.9 m during spring tide.

The complicated hydrodynamics create a fluctuation of turbidity gradient, which results in variable euphotic depths across the shelf. Another factor that may cause this are suitable light and nutrient conditions that are both determined by plume dynamics consequently influence the spatiotemporal phytoplankton distribution. Since chlorophyll-a is commonly used as a measure of algal biomass and phytoplankton, there should be an inherent connection between river plume dynamics and phytoplankton distribution. Chlorophyll hotspots were distributed in a long curving Teluk Bahang shoreline around 122.5 °E, which detect by in-situ monitoring data. The reason for this was not clear but may be due to the difficulty in representing biological processes in pelagic nearshore waters where phytoplankton growth conditions. It can be observed that the Chlorophyll-a was uniformly high with higher values at the surface. The reading exceeded 15 $\mu\text{g}/\text{dm}^3$, which is a threshold value for Chl-a set by the research team to determine a red tide. The red tide detected occurred in the middle water layer, e.g. 3m below the water surface. Algal growth may be directly subject to the influences of various factors such as temperature, oxygen supply, light and salinity

5.3 Characteristics of Tides

During observation periods, the maximum, minimum and mean tidal ranges and spring tides in the Teluk Bahang Pulau Pinang are 2.9 m, 0.4 m, and 1.8 m, respectively (**Table 1**). The mean tidal range gradually decreases from sea to land. The tidal amplitude attenuations of maximum, minimum and mean tides from offshore end to upper end of the Bahang River Channel are 22.3%, 41.2% and 30.2%, respectively. Mean flood durations in maximum, minimum and mean tides are 7 h, 5.5 h and 5 h, respectively. The along-channel variation of flood duration is not significant, and the decrease in flood duration is obvious only between the C1, E1 and E2 stations during spring tide. The mean flood current velocities of the maximum, minimum and mean tides are 0.78 m/s, 0.13 m/s and 0.44 m/s, respectively, while the mean ebb current velocities are 0.80 m/s, 0.22 m/s and 0.55 m/s; the latter is 1.0, 1.2, 1.4 times the former, respectively. The tidal mean velocities of flood and ebb tide in spring tide are 1.5 and 1.8 times of that in neap tide. The flood mean velocity increases from the C1 to the E2 station and then decreases from the E3 to the D3 station, while the ebb mean velocity increases from the C1 to the E3 station and then decreases from the E2 to the C2 station. Generally, the tidal current in the middle reaches is stronger than that of the upper and lower reaches, and the tidal dynamics in spring tide are much stronger than those in neap tide. The ebb mean velocity is greater than flood mean velocity, indicating ebb-dominated dynamics. The lateral velocity is much smaller than the longitudinal velocity, indicating the dominance of longitudinal dynamics.

5.4 Characteristics of Salinity

According to the spatial distribution of the tidal mean salinity, during neap tide, the salinity difference between the surface and bottom layer is significant, and the distribution of salinity is characterized by a highly stratified estuary. During mean and spring tide, there are vertical and longitudinal gradients of the salinity, but the vertical salinity gradient is much smaller than that in the neap tide, the distribution of salinity is characterized as a partially mixed estuary. The analysis is shown as Figure 3.3 below.

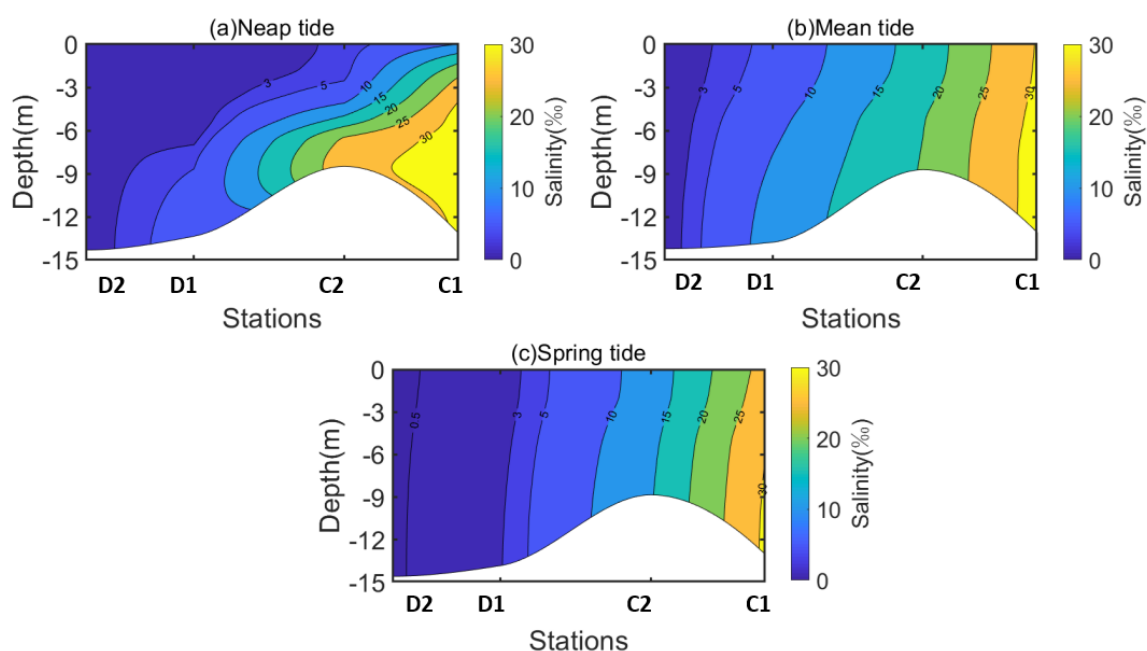


Figure 3.3 : Spatial distribution at different depths for salinity at Teluk Bahang Jetty for Neap Tide, Spring Tide and Mean Tide (an average of Spring and Neap tide value).

6. DISCUSSION

6.1 Dissolved Oxygen Dynamics and Hypoxia in Teluk Bahang: The Role of Tides, Monsoons, and Nutrient Loading

In Teluk Bahang, Penang, the dynamics of dissolved oxygen (DO) distribution and the development of hypoxic zones during neap and spring tides in August 2024 reveal distinct characteristics compared to other coastal regions, driven by tidal dynamics, seasonal shifts, and anthropogenic factors. Spring tides, which exhibit stronger tidal forces, play a crucial role in enhancing vertical mixing and oxygen exchange across the water column. In Teluk Bahang, this mixing significantly mitigates hypoxic conditions in deeper waters, providing a notable contrast to other regions such as the coastal areas of the Gulf of Thailand, where spring tidal mixing may still struggle to alleviate hypoxia due to weaker tidal forces and complex interactions with riverine nutrient inputs (Cifuentes et al., 1990; Diaz & Rosenberg, 2008). The higher intensity of tidal currents during spring tides in Teluk Bahang replenishes oxygen in both surface and bottom waters, which is essential for sustaining ecological health, highlighting that stronger tidal forces lead to more effective oxygen distribution, reducing hypoxic stress in estuarine environments (Pingree & Griffiths, 1978; Helly & Levin, 2004). However, the situation changes during neap tides, when tidal forces are weaker, leading to reduced vertical mixing and increased stratification of the water column. This stratification exacerbates hypoxia, especially in the deeper layers where oxygen consumption from organic matter decomposition is highest. The phenomenon is more pronounced in Teluk Bahang compared to other systems like the Andaman Sea, where neap tide-induced stratification is often moderated by broader circulation patterns (Vaquer-Sunyer & Duarte, 2008; Breitburg et al., 2018). In Teluk Bahang, the confined nature of the bay increases the susceptibility to localized hypoxic zones, particularly in bottom waters, which experience insufficient oxygen replenishment during neap tides. This pattern aligns with findings emphasizing the importance of tidal dynamics in determining hypoxia intensity, particularly in semi-enclosed coastal systems (Jakobsen et al., 2015; Massicotte et al., 2019). The seasonal transition from the Southwest Monsoon to the Northeast Monsoon further complicates DO dynamics in Teluk Bahang, especially as nutrient loading increases during the Southwest Monsoon, promoting higher primary productivity and increased oxygen consumption. During this period, nutrient-rich runoff from agriculture and urban areas, coupled with the southwestward winds, significantly contributes to the depletion of oxygen, particularly in the deeper layers. However, when the Northeast Monsoon sets in, weaker winds and reduced mixing exacerbate the persistence of hypoxia in these areas (Helly & Levin, 2004; Oschlies et al., 2008). This effect has been noted in other coastal regions in Southeast Asia, such as the Gulf of Thailand and South China Sea, where similar seasonal transitions lead to eutrophication and hypoxic conditions. However, the localized nature of nutrient enrichment in Teluk Bahang makes it more vulnerable compared to larger, more dynamic ecosystems (Vaquer-Sunyer & Duarte, 2008). The combined influence of tidal dynamics, seasonal monsoonal shifts, and anthropogenic nutrient inputs results in complex patterns of DO distribution in Teluk Bahang. In this context, spring tides facilitate a more oxygenated environment by enhancing mixing, while neap tides and the seasonal transition from the Southwest Monsoon to the Northeast Monsoon lead to more intense hypoxia, especially in the deeper waters of the bay. The unique characteristics of Teluk Bahang, including its confined bay structure, localized nutrient loading, and pronounced seasonal monsoonal impacts, make it particularly susceptible to hypoxia compared to other coastal systems in the region. These findings contribute to a growing body of research on coastal hypoxia, highlighting the role of tidal and seasonal dynamics in shaping oxygen depletion patterns in coastal ecosystems (Grasshoff et al., 2009; Belkin & O'Reilly, 2009). Furthermore,

nutrient-driven eutrophication, combined with reduced tidal mixing during neap tides, can significantly increase the severity of hypoxic conditions in such semi-enclosed bays, offering new insights into the vulnerability of Teluk Bahang to hypoxic stress.

6.2 Tidal Shifts and Hypoxic Drifts: Unraveling Teluk Bahang's Secrets

In Teluk Bahang, Penang, the interplay between neap and spring tides, the Indian Ocean Dipole (IOD), and the monsoonal transition in August 2024 reveals a complex network of hydrological processes that modulate the region's oxygen dynamics and turbidity conditions. The spring tides, characterized by stronger tidal forces, facilitate vertical mixing in the water column, leading to a more uniform distribution of temperature, salinity, and dissolved oxygen (DO) levels. However, during neap tides, weaker tidal currents exacerbate stratification, leading to localized hypoxia in bottom waters, especially in areas where vertical mixing is limited (Helly & Levin, 2004; Pingree & Griffiths, 1978). This pattern has been observed in the Bay of Bengal, where upwelling associated with the IOD positively affects nutrient availability but simultaneously increases hypoxia due to limited mixing. In Teluk Bahang, the IOD (particularly during its positive phase) can influence upwelling dynamics along the western coast of Peninsular Malaysia, contributing to an increase in nutrient availability and primary production. Strong stratification during neap tides prevents the vertical mixing of oxygen-rich surface waters, exacerbating hypoxic conditions at the bottom. Similar dual impacts of nutrient enrichment and oxygen depletion during IOD phases have been observed in the Bay of Bengal (Oschlies et al., 2008; Breitburg et al., 2018). The observed oxygen depletion in deeper waters of Teluk Bahang could thus be linked to this complex interaction between tidal dynamics, oceanographic events like the IOD, and the region's specific water column structure, where upwelling contributes to localized nutrient hotspots that enhance primary production, leading to further oxygen depletion in poorly mixed zones. The transition from the Southwest Monsoon to the Northeast Monsoon also plays a pivotal role in determining the temporal variation of salinity, temperature, and density in Teluk Bahang, further influencing DO distribution and hypoxia formation. During the Southwest Monsoon, nutrient-rich freshwater inflow from rivers increases primary production and contributes to oxygen consumption in the coastal waters, enhancing the likelihood of hypoxia, particularly in areas with reduced vertical mixing. Similar monsoonal effects have been observed in the Arabian Sea, where changes in wind patterns and freshwater influx controlled the extent of hypoxia formation in coastal zones (Vaquer-Sunyer & Duarte, 2008; Diaz & Rosenberg, 2008). During the Northeast Monsoon, the drier conditions reduce river runoff, which weakens stratification and leads to more mixing in the water column. However, this also leads to cooler and denser waters influencing deeper regions of Teluk Bahang, exacerbating hypoxia formation in the poorly mixed layers. In the Andaman Sea, upwelling induced by the Northeast Monsoon brings nutrient-rich water masses with low oxygen, impacting hypoxic conditions observed in coastal waters. Proximity to the Andaman Sea influences Teluk Bahang's hydrological setting, particularly during monsoonal transitions, with shifts from nutrient-rich, oxygen-depleted waters to more stratified, cooler waters enhancing the potential for hypoxic events in the deeper, less-mixed layers of the bay (Helly & Levin, 2004; Grasshoff et al., 2009). Turbidity patterns in Teluk Bahang are strongly influenced by sediment resuspension, particularly in nearshore areas, where freshwater influxes during both monsoons increase the sediment load. Similar turbidity dynamics have been observed in the South China Sea, where tidal and monsoonal variations lead to the formation of turbidity fronts that impact light penetration and primary productivity (Belkin & O'Reilly, 2009; Jakobsen et al., 2015). In Teluk Bahang, the turbidity front during neap tides shows sharp gradients between nearshore and offshore waters, reflecting reduced tidal mixing and increased sediment concentration near the shore. During spring tides, stronger tidal mixing disperses

sediments, leading to a decrease in nearshore turbidity and a shift of the front seaward. High turbidity, associated with increased suspended particles and lower light penetration, creates an environment where oxygen production is diminished, further promoting the development of hypoxic conditions, especially in areas of high biological productivity. The relationship between turbidity and hypoxia has been noted, with elevated turbidity often linked to reduced light penetration, which decreases photosynthetic activity and exacerbates oxygen depletion (Massicotte et al., 2019; Pingree & Griffiths, 1978). Thus, the combined effects of tidal variations, oceanographic events like the Indian Ocean Dipole, and seasonal transitions in monsoonal winds create a highly dynamic system in Teluk Bahang. The role of upwelling in the deeper waters, particularly during monsoonal transitions, leads to the redistribution of nutrients and the formation of hypoxic conditions in poorly mixed zones. Furthermore, the influence of sediment resuspension and turbidity patterns exacerbates hypoxic tendencies by limiting light penetration and reducing oxygen production in the water column. These factors underscore the need for targeted monitoring and management strategies to address the complex interplay of hydrological forces shaping the ecological health of Teluk Bahang and similar coastal regions in Southeast Asia.

6.3 Nutrient Dynamics and Productivity in Teluk Bahang's Coastal Waters

The findings from Teluk Bahang, Penang, reveal hydrodynamic and biogeochemical patterns that distinguish this region from other coastal systems in Southeast Asia and the Indian Ocean. Unlike areas where nutrient cycling is predominantly influenced by large-scale upwelling events or substantial freshwater discharge from major river systems, Teluk Bahang experiences a more localized interaction between tidal cycles (neap and spring), monsoonal transitions, and localized upwelling. These factors, in combination with the influence of the Indian Ocean Dipole (IOD), lead to highly dynamic nutrient cycling and primary productivity patterns modulated on a smaller scale compared to coastal ecosystems in regions like the Bay of Bengal or the Arabian Sea. In these regions, nutrient dynamics are primarily driven by intense upwelling associated with seasonal monsoons and large-scale freshwater discharge, resulting in strong gradients in primary productivity and nutrient availability (Oschlies et al., 2008; Vaquer-Sunyer & Duarte, 2008). In contrast, the localized nature of hydrodynamics in Teluk Bahang, with influences from tidal mixing and small-scale upwelling, underscores a more intricate relationship between tidal cycles and nutrient dynamics, as observed in other semi-enclosed or shelf regions (Pingree & Griffiths, 1978). The relationship between nitrate and Chl-a distributions in Teluk Bahang is strongly influenced by these local hydrodynamic processes. During both neap and spring tides, high concentrations of nitrate and Chl-a are observed in the northern and southern parts of the study area, while a low-Chl-a region is present along the nearshore and southeastern sections. This variation reflects the interactions between tidal dynamics, nutrient availability, and primary productivity. The observed high Chl-a concentrations, especially in surface and 5-m layers, indicate a region of enhanced phytoplankton growth, likely triggered by the seasonal nutrient pulses associated with tidal mixing and localized upwelling (Jakobsen et al., 2015; Massicotte et al., 2019). These conditions are similar to other regions influenced by the Northeast Monsoon, where phytoplankton dynamics are closely tied to shifts in nutrient concentrations linked to monsoonal winds, as documented in studies of Indian Ocean coastal systems (Helly & Levin, 2004; Breitburg et al., 2018). The nitrate and Chl-a concentrations in Teluk Bahang also exhibit clear gradients, with concentrations decreasing seaward, a trend consistent with findings from other monsoonal coastlines where nutrient availability diminishes in offshore waters. This gradient is particularly evident in the vertical distribution of Chl-a, which shows a peak at the surface or subsurface layers, a typical feature of eutrophic coastal waters influenced by

upwelling or localized nutrient inputs (Grasshoff et al., 2009). In Teluk Bahang, the spatial variability of Chl-a is further accentuated by the Indian Ocean Dipole, which has been shown to influence ocean circulation patterns, nutrient upwelling, and primary productivity in coastal ecosystems, particularly in the Andaman Sea and surrounding regions (Belkin & O'Reilly, 2009; Diaz & Rosenberg, 2008). This demonstrates that the localized nutrient dynamics in Teluk Bahang are not only influenced by local hydrodynamics but also by broader climatic phenomena such as the IOD, which contributes to the variability in nitrate concentrations and Chl-a productivity. Thus, the unique characteristics of Teluk Bahang, influenced by tidal cycles, monsoonal shifts, and IOD-related hydrodynamic changes, offer an important case study for understanding nutrient cycling and primary productivity in a semi-enclosed coastal system with limited freshwater runoff. This localized nutrient cycling, particularly in relation to Chl-a distribution, presents a distinctive pattern compared to more heavily studied regions with stronger upwelling or riverine influences, providing valuable insights into the ecological functioning of coastal ecosystems under changing climatic and hydrodynamic conditions. Future research on the effects of the Indian Ocean Dipole and monsoon dynamics on nutrient availability and primary productivity in Teluk Bahang could offer further clarity on the resilience of these systems to large-scale climatic fluctuations and their role in supporting coastal marine biodiversity.

6.4 Driving Coastal Blooms: The Role of Tides and Nutrient Cycling

In August 2024, the hydrodynamic conditions in Teluk Bahang, Pulau Pinang, demonstrate a unique interplay of factors that govern nutrient dynamics and primary productivity. The Diluted Water (DW) in the surface layers, primarily influenced by freshwater input during the Southwest Monsoon, interacts with the Pulau Pinang Warm Currents (PWC) from deeper waters. This results in a localized yet dynamic system where nutrient availability and chlorophyll-a (Chl-a) concentrations fluctuate significantly due to tidal cycles, the Indian Ocean Dipole (IOD), and seasonal monsoon transitions. The low-salinity, low-density DW is a prominent feature of Teluk Bahang, as it results from rainfall and river discharge during the Southwest Monsoon. This surface water mass, typically characterized by a salinity of less than 29 PSU, moves northeastward into Teluk Bahang, where it is partially mixed with the surrounding waters. Previous studies have shown that these low-salinity waters are restricted to shallow coastal areas, where tidal mixing influences their distribution (Cifuentes et al., 1990; Grasshoff et al., 2009). During neap tides, the water column remains stratified, limiting mixing and keeping the DW closer to the surface. In contrast, during spring tides, the increased tidal forces facilitate deeper mixing, leading to the redistribution of nutrients within the coastal zone. This behavior contrasts with larger systems such as the Bay of Bengal, where river discharge plays a more dominant role in determining nutrient dynamics (Breitburg et al., 2018). The Pulau Pinang Warm Currents (PWC), which originate from deeper, warmer waters of the Straits of Malacca and the Andaman Sea, flow northward and are more stable compared to the DW. These currents exhibit high salinity (>30 PSU) and relatively constant temperatures (28–30°C) that influence deeper layers in the 10-m to 20-m range. The movement of PWC provides a warm water mass that contrasts with the cooler, nutrient-rich upwelled waters. Previous research in other regions has shown that such warm currents can create distinct thermal stratification in the water column, with colder, nutrient-rich bottom waters upwelling to the surface during spring tides (Pingree & Griffiths, 1978; Vaquer-Sunyer & Duarte, 2008). This is particularly evident in Teluk Bahang, where upwelling along steep coastal regions contributes significantly to nutrient cycling. The upwelling process, enhanced by tidal mixing, brings nutrient-rich waters to the surface, resulting in increased concentrations of nutrients such as nitrates and phosphates, which in turn support phytoplankton growth (Jakobsen et al., 2015;

Massicotte et al., 2019). As a result of this upwelling, Teluk Bahang experiences localized nutrient enrichment, particularly in the northern and southern parts of the bay, where the highest Chl-a concentrations are observed. This localized phytoplankton bloom is supported by the influx of nutrients from upwelled waters, particularly during the spring tides when tidal mixing is strongest. Previous studies have shown that such nutrient dynamics foster high primary productivity in coastal regions with significant tidal influence (Oschlies et al., 2008; Helly & Levin, 2004). In Teluk Bahang, Chl-a concentrations peak at over 40 mg dm⁻³ in the surface layers during the spring tide, further supporting the idea that nutrient availability during these times is key to primary productivity in the region. Additionally, the seasonal transition from the Southwest to the Northeast Monsoon impacts the dynamics of nutrient distribution and primary productivity in Teluk Bahang. During this period, changes in wind patterns and the establishment of the Northeast Monsoon can alter the circulation of both the DW and the PWC, thereby influencing nutrient cycling and phytoplankton growth. Some researchers have demonstrated that such monsoon-driven changes in hydrodynamics significantly affect the seasonal distribution of nutrients in tropical coastal ecosystems (Belkin & O'Reilly, 2009; Diaz & Rosenberg, 2008). In Teluk Bahang, this transition period is characterized by shifts in water properties, with varying nutrient concentrations at different depths as a result of changes in tidal mixing, upwelling intensity, and circulation patterns. In summary, the hydrodynamic and biogeochemical conditions in Teluk Bahang, Pulau Pinang, during August 2024, are shaped by complex interactions between the Diluted Water (DW), Pulau Pinang Warm Currents (PWC), and tidal upwelling. These interactions promote localized nutrient cycling and primary productivity in the region, setting Teluk Bahang apart from other coastal ecosystems in Southeast Asia. The upwelling processes, influenced by tidal mixing and seasonal monsoonal shifts, create an environment conducive to high nutrient availability and enhanced primary productivity, making Teluk Bahang a unique system for studying coastal biogeochemistry and nutrient dynamics.

6.5 Exploring Hypoxia: How Monsoons, Upwelling, and Human Activity Shape Coastal Ecosystems

The analysis of the spatial variability and heterogeneity of hypoxia in Teluk Bahang, Pulau Pinang, during the transitional monsoon period towards the Northeast Monsoon, reveals the complex interplay of several oceanographic, climatic, and anthropogenic factors that contribute to the development and persistence of hypoxic conditions in this coastal region. During the Southwest Monsoon, the region experiences higher rainfall and nutrient influx, leading to an increased nutrient load in the waters of Teluk Bahang. This nutrient influx, combined with reduced vertical mixing during the monsoon transition, supports the growth of phytoplankton, which can lead to oxygen depletion in the deeper layers of the water column. This mechanism is particularly important for understanding the observed spatial variability of hypoxia in Teluk Bahang, as nutrient enrichment tends to be more pronounced in the shallower, northern parts of the bay, where there is less vertical mixing and the water column is more stratified (Jakobsen et al., 2015; Massicotte et al., 2019). This phenomenon contributes to the observed heterogeneity of hypoxia, with the northern regions being more prone to hypoxia due to the accumulation of low-oxygen waters in the bottom layers (Vaquer-Sunyer & Duarte, 2008). The influence of the Indian Ocean Dipole (IOD) further complicates this spatial variability. During a positive IOD phase, upwelling events in the northern Andaman Sea bring nutrient-rich waters to the surface. This leads to the creation of hypoxic zones, particularly in the northern and shallower parts of Teluk Bahang, where the upwelled nutrients fuel phytoplankton blooms that subsequently deplete oxygen as they decompose. These findings suggest that the hypoxic conditions in the region may be exacerbated during a positive IOD phase, contributing to the

increased frequency and severity of hypoxia observed in the northern regions of Teluk Bahang, as seen in previous studies of Southeast Asian coastal systems (Oschlies et al., 2008; Breitburg et al., 2018). The transition towards the Northeast Monsoon also plays a critical role in shaping hypoxic conditions. This transition is characterized by increased stratification of the water column, which limits the mixing of surface waters with deeper waters. This enhanced stratification exacerbates hypoxia by preventing the influx of oxygenated waters into the bottom layers, thus sustaining low-oxygen conditions in the deeper regions of the bay. In Teluk Bahang, this stratification effect is particularly evident in the northern part of the bay, where the bathymetry is shallower, further concentrating low-oxygen waters near the seabed (Pingree & Griffiths, 1978; Helly & Levin, 2004). The northeastern monsoon may also influence the direction and intensity of upwelling, potentially intensifying the spatial variability of hypoxia across different parts of the bay. Moreover, the bathymetric features of Teluk Bahang are key to understanding the heterogeneity of hypoxia in this region. Shallow coastal zones with steep bathymetry, such as the northern regions of Teluk Bahang, are particularly vulnerable to hypoxia due to the limited vertical mixing and the tendency for nutrient accumulation in the bottom waters. These areas experience more frequent and severe hypoxic episodes, especially during periods of increased nutrient runoff and upwelling, and are more affected by hypoxic conditions compared to the deeper southern parts of the bay. This bathymetric influence on hypoxia dynamics highlights the importance of this parameter in controlling the distribution of hypoxia in shallow coastal systems (Cifuentes et al., 1990; Diaz & Rosenberg, 2008). Anthropogenic factors also contribute to the spatial heterogeneity of hypoxia in Teluk Bahang. Agricultural runoff and urbanization around the bay increase the nutrient load in the coastal waters, exacerbating eutrophication and promoting the development of hypoxia. During the Southwest Monsoon, when runoff is at its peak, the nutrient enrichment leads to intense phytoplankton blooms that deplete oxygen in the bottom waters, particularly in the shallower northern areas of Teluk Bahang. This local human impact reinforces the spatial variability of hypoxia, making the northern regions more prone to eutrophication and oxygen depletion (Grasshoff et al., 2009). In conclusion, the spatial variability and heterogeneity of hypoxia in Teluk Bahang, especially during the transitional monsoon period towards the Northeast Monsoon, result from a combination of factors, including large-scale climatic drivers such as the Indian Ocean Dipole, seasonal shifts in monsoonal winds, bathymetric features, and anthropogenic influences. The northern regions of Teluk Bahang are particularly vulnerable to hypoxia due to nutrient loading, limited mixing, and upwelling, and these areas experience more frequent and severe hypoxic episodes compared to the southern, deeper regions of the bay. Understanding the complex interplay of these factors is crucial for managing hypoxia and maintaining the health of coastal ecosystems in this region.

6.6 Stratification Unveiled: How River Plumes and Upwelling Drive Coastal Hypoxia

Stratification is a key factor that governs oxygen renewal in bottom waters. This phenomenon occurs as a result of the interaction between the freshwater river plume at the surface and the deeper nutrient-rich waters from upwelling. In Teluk Bahang, Pulau Pinang, strong stratification forms when the freshwater influx from rivers meets deeper nutrient-rich waters, creating a density difference that inhibits vertical mixing between oxygen-rich surface waters and oxygen-depleted bottom waters. This, in turn, contributes to the formation of hypoxic zones in shallow coastal areas (Helly & Levin, 2004; Grasshoff et al., 2009). In the northern part of Teluk Bahang, where the depth is around 20–30 meters, stronger stratification is observed compared to the deeper southern regions. The surface waters in this area are dominated by the river plume, while the bottom waters are influenced by upwelled, nutrient-

rich water, leading to hypoxic conditions. Upwelling, often occurring around steep bathymetric features, transports deeper, nutrient-rich waters to the surface, increasing the density of surface waters and worsening hypoxia in the northern part of Teluk Bahang (Jakobsen et al., 2015; Vaquer-Sunyer & Duarte, 2008). The shoaling of stratification also impacts hypoxia dynamics in Teluk Bahang. As oxygen-depleted bottom waters are upwelled to the surface, the halocline (salt concentration gradient), thermocline (temperature gradient), and pycnocline (density gradient) are uplifted, creating low-oxygen waters near the surface, which can extend to shallower depths. This results in a more expansive hypoxic zone in the northern region of Teluk Bahang, where shallower waters allow low-oxygen waters to accumulate at the bottom (Oschlies et al., 2008). The river plume and upwelling play a central role in influencing the depth and intensity of stratification throughout the year. Areas with stronger stratification, particularly in the northern region, are more prone to hypoxia as the bottom water oxygen concentration decreases in tandem with increasing stratification intensity. This phenomenon becomes more pronounced during the transitional monsoon season, when the influence of the river plume and upwelling alters the vertical distribution of oxygen in the bay's waters (Cifuentes et al., 1990; Pingree & Griffiths, 1978). By understanding the relationship between stratification, river plume, and upwelling in Teluk Bahang, it is possible to better comprehend how these factors contribute to hypoxia formation in the region. This knowledge is crucial for developing effective management strategies to mitigate hypoxic events, especially in the face of seasonal changes and increased human activities that impact the coastal ecosystem.

6.7 Decoding Hypoxia in Teluk Bahang: The Impact of River Plumes, Warm Currents, and Upwelling

During July and August 2024, the waters of Teluk Bahang, Penang, Malaysia are expected to experience complex interactions between various physical factors, including the river plume, the Andaman Sea Warm Current (ASWC), cold currents, and upwelling activities. These interactions form physical fronts that influence key marine parameters such as temperature, salinity, density, turbidity, and dissolved oxygen (DO) levels, which are crucial for understanding the formation of hypoxic zones and their impact on the marine ecosystem.

The density ρ of seawater is influenced by temperature (T) and salinity (S), as described by the equation of state for seawater:

$$\rho = \rho_0 + \alpha(S - S_0) + \beta(T - T_0)$$

Where:

- ρ_0 is the reference density,
- α and β are the coefficients of thermal expansion and saline contraction, respectively,
- S is the salinity, and T is the temperature.

The river plume introduces freshwater with significantly lower salinity and temperature compared to the surrounding seawater, creating a sharp gradient. The stratification between the less saline, cooler river plume and the saline, warmer waters of the ASWC results in limited vertical mixing, leading to reduced oxygen exchange between the surface and deeper waters. This stratification contributes to the formation of hypoxic conditions at the seafloor (Breitburg et al., 2018). Vertical mixing in the water column, which governs oxygen distribution, is inhibited by turbulent diffusion within the stratified layers. Organic material decaying in the

hypoxic bottom waters consumes oxygen at a higher rate than it is replenished, exacerbating oxygen depletion (Grasshoff et al., 2009; Oschlies et al., 2008)

Vertical mixing in the water column, which plays a role in the distribution of oxygen, is governed by turbulent diffusion, and can be described by the diffusion equation:

$$\frac{\partial C}{\partial t} = D \nabla^2 C$$

Where:

- C is the concentration of a substance (e.g., dissolved oxygen),
- D is the diffusion coefficient, and
- ∇^2 is the Laplacian operator describing spatial changes in the vertical direction.

Limited vertical mixing due to stratification inhibits the replenishment of oxygen in deeper waters, particularly beneath the river plume and ASWC interface. As organic material decays in the hypoxic bottom waters, oxygen is consumed at a higher rate than it is replenished, further exacerbating oxygen depletion. The rate of oxygen consumption due to bacterial decomposition of organic matter is represented by:

$$R_{O_2} = k_b C_{org}$$

Where:

- k_b is the rate constant for bacterial respiration,
- C_{org} is the concentration of organic matter.

As phytoplankton decay and settle to the bottom, the oxygen in the deeper layers is consumed, resulting in the formation of hypoxic zones, especially in the benthic layer.

The relationship between turbidity (TTT) and light penetration is described by the Beer-Lambert Law:

$$I = I_0 e^{-\alpha L}$$

Where:

- I_0 is the initial light intensity,
- I is the light intensity at depth L ,
- α is the attenuation coefficient, which depends on turbidity, and
- L is the depth.

Turbidity levels in Teluk Bahang, influenced by suspended solids from the river plume, reduce light penetration and hinder photosynthesis by phytoplankton. The resulting diminished primary production, coupled with the decomposition of settled organic matter, further intensifies hypoxic conditions. These dynamics align with findings in other stratified coastal regions, where high turbidity and low light penetration exacerbate oxygen depletion (Belkin & O'Reilly, 2009; Helly & Levin, 2004).

The boundaries of hypoxic zones are determined by the interplay of temperature, salinity, and oxygen gradients. The hypoxic boundary can be described by the following equation:

$$DO_{\text{boundary}} = \int_{\text{surface}}^{\text{bottom}} \left(\frac{\partial DO}{\partial z} \right) dz$$

Where:

- DO_{boundary} is the dissolved oxygen level at the hypoxic zone boundary,
- $\frac{\partial DO}{\partial z}$ is the vertical gradient of dissolved oxygen,
- z is the depth.

This equation quantifies how oxygen levels decline with depth due to the reduction in oxygen production at the surface and the increased consumption at depth. The greater the vertical gradient, the more pronounced the hypoxic zone at the seafloor.

The interactions between the river plume, the ASWC, and upwelling activities are key drivers of stratification in Teluk Bahang. These physical fronts shape the distribution and intensity of hypoxic zones. The flow velocity induced by density gradients is governed by the geostrophic equation:

$$fU = -\frac{g}{\rho_0} \nabla \rho$$

Where:

- f is the Coriolis parameter,
- g is the gravitational constant,
- ρ_0 is the reference density, and
- $\nabla \rho$ is the gradient in density.

This equation describes how the river plume and ASWC interact to form physical fronts, influencing the extent of hypoxic zones. The interplay between the river plume, ASWC, and upwelling activities significantly influences the boundaries and intensity of hypoxic zones. Warm, saline waters of the ASWC interact with the less saline river plume to form physical fronts that limit mixing and sustain hypoxia in the deeper waters. Simultaneously, upwelling at depths around 20 meters transports nutrient-rich but oxygen-poor waters to the surface, contributing to oxygen minimum zones (OMZ) that isolate bottom waters from oxygenated

surface layers (Pingree & Griffiths, 1978; Massicotte et al., 2019). By applying these equations to the observed data from Teluk Bahang during July and August 2024, these interactions provide critical insights into the formation of hypoxic zones in Teluk Bahang. Stratification, vertical mixing limitations, and physical fronts combine to shape oxygen dynamics, significantly impacting benthic and pelagic communities in this region.

6.8 Hydrographic and Biological Interactions Contributing to Hypoxia in Teluk Bahang

In August 2024, the waters of Teluk Bahang, Penang, Malaysia, will experience a complex interplay of physical and biogeochemical processes that will significantly influence the formation and intensity of hypoxic zones in this region. The combination of increased nutrient input from river runoff, intensified upwelling, and the shift from the southwest to the northeast monsoon is expected to contribute to the development of hypoxia (Breitburg et al., 2018; Diaz & Rosenberg, 2008). These interactions, driven by several factors such as river plume dynamics, bathymetric features, rainfall intensity, and associated biological productivity, will alter the water column's structure and oxygen content, leading to hypoxic or anoxic conditions in bottom waters, particularly in the northern part of Teluk Bahang.

The river plume, influenced by the Bahang River, will introduce freshwater with salinity levels typically below 5 PSU into the bay. This freshwater will be cooler than the surrounding seawater, with temperatures ranging from 26 to 28°C compared to the warmer Andaman Sea waters, which range from 30 to 32°C. This sharp contrast in both salinity and temperature between the river plume and surrounding ocean waters will lead to the formation of a distinct surface front. The surface front will inhibit vertical mixing, contributing to water column stratification that traps organic matter, including phytoplankton, and prevents effective oxygenation of deeper waters. Consequently, oxygen depletion will be observed in the bottom waters, particularly as biological oxygen demand (BOD) increases due to the decomposition of organic material that settles from the surface layers (Oschlies et al., 2008).

In addition to river discharge, which typically averages around 20-25 m³/s in wet months with peak discharge reaching 30-35 m³/s, nutrient concentrations associated with the river plume will be significant. Nitrate (NO₃⁻) concentrations will range between 5-15 µM, phosphate (PO₄³⁻) concentrations will range from 0.2-2 µM, and silicate (SiO₃²⁻) will range from 4-12 µM in surface waters during river runoff. The nutrient input will lead to eutrophication (Jakobsen et al., 2015), which promotes phytoplankton growth; however, high turbidity associated with runoff will limit light penetration, further restricting photosynthesis in surface waters and contributing to a higher accumulation of organic matter that will decay in deeper waters, resulting in oxygen consumption.

The transition from the southwest monsoon (SWM) to the northeast monsoon (NEM) in August 2024 is likely to enhance rainfall intensity, with historical data indicating rainfall levels ranging from 150 to 250 mm. This rainfall will increase river runoff (Cifuentes et al., 1990), further elevating nutrient influx and suspended solids, which will boost biological productivity in the region. The nutrient concentrations in upwelling waters typically range between 10-20 µM for nitrate (NO₃⁻), 1-3 µM for phosphate (PO₄³⁻), and 5-12 µM for silicate (SiO₃²⁻), supplementing surface phytoplankton biomass and promoting additional growth of phytoplankton while contributing to high chlorophyll-a (Chl-a) concentrations. During this period, surface Chl-a concentrations are expected to range from 5 to 20 mg/m³, with peaks often exceeding 10 mg/m³ in the northern portion of the bay, particularly near river plume fronts and upwelling zones.

This phytoplankton growth will increase biological oxygen demand (BOD), leading to oxygen drawdown in deeper waters when organic matter from phytoplankton blooms sinks and decomposes.

Upwelling events along the northern and western parts of Teluk Bahang will bring cold, nutrient-rich waters from depths of 20-30 meters to the surface (Massicotte et al., 2019), further fueling primary production. This upwelling is a critical mechanism for replenishing surface nutrients and is expected to increase biological productivity's intensity. However, upwelling also contributes to low-oxygen water being brought up from deeper layers (Pingree & Griffiths, 1978), potentially forming an oxygen minimum zone (OMZ) and accelerating hypoxic conditions' development. The oxygen depletion observed in bottom waters—particularly at depths exceeding 10 meters—will be exacerbated by organic material decomposition from phytoplankton blooms. This process may lead to oxygen concentrations falling below 2 mg/L, a threshold commonly associated with hypoxia.

As the monsoon transitions to the northeast monsoon, changes in wind direction from southwest to northeast will induce alterations in surface currents and upwelling dynamics. The wind direction shift typically occurs at an angle of 60-75° relative to southwest winds and will increase upwelling intensity along Penang's western coast while enhancing nutrient delivery to the surface. This increased upwelling alongside nutrient influx from river runoff will contribute to both high phytoplankton biomass and hypoxia in the region. The interaction between riverine nutrient input and upwelling will create an environment conducive to increased phytoplankton growth; however, subsequent oxygen depletion in deeper waters will significantly contribute to hypoxic zone development.

Nutrient concentrations in upwelled waters are expected to be significantly higher than at the outer boundary of the river plume; nitrate concentrations may reach 10-20 μM in upwelled waters compared to 5-15 μM at the river plume. These nutrients will fuel primary productivity leading to high Chl-a concentrations in surface waters. In northern Teluk Bahang where high Chl-a concentrations are observed, bottom hypoxia's scope will closely correspond with surface phytoplankton blooms' extent. As biological oxygen demand increases due to high phytoplankton biomass, bottom water oxygen concentration will decrease; DO levels often dip below 2 mg/L particularly in northern regions.

The nutrient input during the transition between southwest and northeast monsoons significantly contributes to coastal and estuarine systems hypoxia development. The monsoon shift enhances both upwelling and nutrient influx that promote phytoplankton blooms leading to higher oxygen demand in deeper waters (Vaquer-Sunyer & Duarte, 2008). Nutrient-rich upwelled waters can stimulate primary productivity but also exacerbate hypoxia when stratification prevents vertical mixing.

The interaction between riverine freshwater input, monsoon-driven upwelling, bathymetric features, and biological productivity in Teluk Bahang creates a highly dynamic environment. The decomposition of organic matter and its subsequent impact on oxygen depletion is critical for developing hypoxic zones in coastal regions. In Teluk Bahang, expected nutrient load from river runoff intensified by upwelling during southwest-to-northeast monsoon shifts contributes significantly to increased primary production followed by subsequent hypoxia—particularly within northern and central bay bottom waters. These processes impact spatial distribution of hypoxic zones with most severe oxygen depletion occurring where biological oxygen demand is highest such as areas with dense phytoplankton blooms. Monitoring key parameters

including Chl-a concentrations salinity temperature DO levels turbidity and nutrient concentrations is essential for understanding managing hypoxia impacts within this region.

By integrating these physical and biological factors with seasonal patterns and regional dynamics researchers can develop strategies aimed at mitigating hypoxia impacts particularly within regions like Teluk Bahang where complex interactions between physical fronts drive formation of oxygen-depleted zones.

6.9 Understanding the Complex Dynamics of Hypoxia in Teluk Bahang, Penang

The dynamics of dissolved oxygen (DO) distribution and hypoxia in Teluk Bahang, Penang, during August 2024, are governed by a complex interplay of tidal forces, seasonal monsoonal shifts, river runoff, nutrient dynamics, and upwelling events. The combined effect of spring and neap tidal cycles significantly influences the vertical mixing processes in the water column. Spring tides enhance oxygen exchange, reducing the intensity of hypoxia, while neap tides exacerbate stratification, particularly in the deeper waters of the bay (Pingree & Griffiths, 1978).

During the Southwest Monsoon, nutrient-rich freshwater influxes enhance primary productivity but also contribute to higher oxygen consumption, exacerbating hypoxia, especially in poorly mixed areas (Harris et al., 2019). Conversely, during the Northeast Monsoon, while river runoff decreases, cooler and denser water masses increase stratification, promoting oxygen depletion in deeper waters (Vaquer-Sunyer & Duarte, 2008). This seasonal transition highlights the vulnerability of Teluk Bahang to prolonged hypoxia, driven by nutrient loading and decreased tidal mixing, compounded by anthropogenic factors such as agricultural and urban runoff (Kennish, 2021). The Indian Ocean Dipole (IOD), particularly during its positive phase, enhances upwelling along the western coast of Peninsular Malaysia, increasing nutrient availability but simultaneously contributing to hypoxia due to limited vertical mixing during neap tides (Gouveia et al., 2018). This upwelling, combined with sediment resuspension and high turbidity, creates an environment where light penetration is reduced, further limiting primary productivity and exacerbating oxygen depletion in bottom waters (Alvarez-Borrego, 2004). Similar patterns have been observed in other regions like the Bay of Bengal, where upwelling events enhance primary productivity but also contribute to hypoxia due to concurrent nutrient-driven oxygen consumption (Breitburg et al., 2018).

The unique hydrological and oceanographic settings of Teluk Bahang make it especially susceptible to hypoxia, with its confined bay structure, localized nutrient inputs, and pronounced monsoonal effects (Drushka et al., 2019). The region's vulnerability to hypoxic stress is further intensified by the dynamic interaction between tidal processes, seasonal transitions, and nutrient-driven eutrophication (Last et al., 2016). These findings emphasize the need for comprehensive monitoring and management strategies that account for the complex interactions shaping oxygen dynamics in coastal ecosystems. The spatial variability and heterogeneity of hypoxia in Teluk Bahang during August 2024 are influenced by a mix of oceanographic, climatic, and anthropogenic factors. This interplay shapes the distribution and intensity of hypoxic conditions within the bay, particularly affecting the northern regions, which are more susceptible to oxygen depletion due to shallow bathymetric features, limited vertical mixing, nutrient enrichment, and upwelling events (Diaz & Rosenberg, 2008). The transition from the Southwest Monsoon to the Northeast Monsoon exacerbates water column stratification, leading to reduced mixing of surface waters with deeper layers (Howe &

Simenstad, 2014). This stratification, particularly pronounced in the northern, shallower parts of Teluk Bahang, prevents the replenishment of oxygen in bottom waters, contributing to prolonged hypoxic conditions (Grasshoff et al., 2009). Additionally, the influence of the IOD complicates this process, with upwelling during a positive IOD phase bringing nutrient-rich waters to the surface, triggering phytoplankton blooms that subsequently deplete oxygen as they decompose (Mann & Lazier, 2005). Anthropogenic factors, such as agricultural runoff and urbanization, also significantly contribute to the spatial variability of hypoxia. Increased nutrient loading during the Southwest Monsoon, compounded by runoff from surrounding human activities, enhances eutrophication, leading to intense phytoplankton blooms (Smith, 2003). These blooms, particularly in the northern regions, further deplete oxygen in bottom waters, exacerbating hypoxic conditions (Cifuentes et al., 1990).

The formation of hypoxic zones in Teluk Bahang is a result of a complex interaction between physical and biogeochemical processes during the transitional period between the Southwest and Northeast Monsoons. The interplay of river plumes, upwelling phenomena, and local currents creates strong stratification in the water column, limiting vertical mixing and leading to oxygen depletion in bottom waters (Purdie, 1996). The influx of freshwater introduces low-salinity, nutrient-rich waters that promote phytoplankton growth, increasing biological oxygen demand (BOD) when organic matter decomposes at depth (Oschlies et al., 2008). The study underscores the need for continuous monitoring of key environmental parameters, including temperature, salinity, turbidity, nutrient concentrations, and dissolved oxygen levels, to better understand and mitigate the impacts of hypoxia in coastal regions like Teluk Bahang (Massicotte et al., 2019). Integrating physical and biological processes into management strategies is essential to address the challenges posed by hypoxia, increasingly influenced by both natural and anthropogenic factors in this unique and ecologically sensitive coastal ecosystem. In summary, the development and intensity of hypoxia in Teluk Bahang during August 2024 reflect the combined influence of tidal dynamics, seasonal shifts, nutrient loading, and upwelling. Understanding the intricate relationships between these factors is crucial for predicting and mitigating the impacts of hypoxia in this and similar semi-enclosed coastal systems in Southeast Asia. Targeted efforts to reduce nutrient loading, enhance tidal mixing, and manage seasonal transitions will be vital in safeguarding the ecological health of Teluk Bahang and similar vulnerable coastal regions.

6.10 The novelty equations based on Teluk Bahang conditions via physical and biogeochemistry parameters

Based on the research conducted in Teluk Bahang, a significant novelty arises from the integration of multiple hydrodynamic and biogeochemical factors to develop a comprehensive model of dissolved oxygen (DO) dynamics. This model could be represented by the following equation, which captures the interplay between various parameters influencing hypoxia:

The Main Equation:

$$DO(t) = DO_{in} + \left(\frac{N.P}{R}\right) \cdot f(T,S) \cdot M(t) - D(t)$$

Parameters Explained:

DO(t)

Definition: The concentration of dissolved oxygen at time t

Context in Teluk Bahang: This parameter is crucial for assessing the health of the marine ecosystem, as low DO levels can lead to hypoxia, threatening local biodiversity, particularly during periods of stratification and high nutrient loading.

DO_{in}

Definition: Background dissolved oxygen levels influenced by atmospheric exchange and freshwater inputs.

Context in Teluk Bahang: This value reflects baseline DO levels, which are affected by factors such as tidal mixing and freshwater discharge from local rivers. The region's strong hydrodynamic interactions can enhance oxygen replenishment during certain tidal cycles.

N

Definition: Nutrient concentration, typically nitrogen or phosphorus.

Context in Teluk Bahang: Elevated nutrient levels, particularly during the Southwest Monsoon, can lead to eutrophication, fueling phytoplankton blooms that significantly impact oxygen levels as they decompose.

P

Definition: Primary productivity rate, indicating the growth rate of phytoplankton and other photosynthetic organisms.

A common way to quantify primary productivity can be expressed as:

$$PP = \alpha \cdot I \cdot e^{-k \cdot z}$$

Where:

PP: Primary productivity ($\text{mg C m}^{-2} \text{ d}^{-1}$)

α : Photosynthetic efficiency, representing the rate of carbon fixation per unit of light ($\text{mg C } \mu\text{mol}^{-1} \text{ photons}$)

I : Incident light intensity ($\mu\text{mol photons m}^{-2} \text{ s}^{-1}$), which varies with depth and time of day

k : Light attenuation coefficient (m^{-1}), which describes how quickly light decreases with depth due to absorption and scattering

z : Depth (m), indicating how light penetration affects productivity, as light availability decreases with increasing depth

Context in Teluk Bahang: The productivity rate is influenced by nutrient availability and light conditions, which fluctuate with seasonal changes. High productivity during monsoonal periods can enhance oxygen production but may also lead to subsequent hypoxic conditions when organic matter decomposes.

R

Definition: Respiration rate, the rate at which organisms consume oxygen. The respiration rate can be expressed in a simplified equation as follows:

$$R = r_m \cdot N$$

Where:

- **R:** Total respiration rate ($\text{mg O}_2 \text{ m}^{-2} \text{ d}^{-1}$)
- **r_m :** Specific respiration rate ($\text{mg O}_2 \text{ g}^{-1} \text{ d}^{-1}$), which indicates the amount of oxygen consumed per gram of biomass per day
- **N:** Biomass concentration (g m^{-3}), representing the total mass of respiratory organisms (e.g., zooplankton, fish, bacteria) in a given volume of water

Context in Teluk Bahang: This rate can vary with the abundance and activity levels of zooplankton and other benthic organisms. Increased respiration during phytoplankton die-offs can lead to rapid declines in DO, especially in stratified waters.

f (T,S)

Definition: A function representing the effects of temperature (T) and salinity (S) on DO solubility.

A common way to represent the effects of temperature and salinity on the solubility of oxygen is through the following equation:

$$\text{DO}_{\text{solubility}}(T,S) = \text{DO}_{\text{max}} \cdot (1 - \beta_T \cdot (T - T_{\text{ref}})) \cdot (1 - \beta_S \cdot (S - S_{\text{ref}}))$$

Where:

$\text{DO}_{\text{solubility}}(T,S)$: The solubility of dissolved oxygen at temperature T and salinity S ($\text{mg O}_2 \text{ L}^{-1}$).

DO_{max} : The maximum solubility of oxygen in fresh water at a reference temperature T_{ref} and S_{ref}

β_T : Temperature sensitivity coefficient, reflecting the rate of change in oxygen solubility with temperature (typically negative).

β_S : Salinity sensitivity coefficient, indicating the rate of change in oxygen solubility with salinity (also typically negative).

T: Temperature ($^{\circ}\text{C}$).

S: Salinity (practical salinity units, PSU).

T_{ref}: Reference temperature (often 0°C or another standard).

S_{ref}: Reference salinity (often 0 PSU for fresh water).

Context in Teluk Bahang: Higher temperatures typically decrease DO solubility, while salinity gradients from freshwater inputs can create stratified layers, affecting the overall oxygen distribution. Seasonal temperature variations during the rainy season can exacerbate hypoxic conditions.

M (t)

Definition: Mixing coefficient, impacted by tidal dynamics and water movement.

Context in Teluk Bahang: This parameter reflects the degree of vertical mixing due to tidal forces. Spring tides enhance mixing, improving oxygen exchange, while neap tides can lead to increased stratification and localized hypoxia, particularly in deeper areas of the bay.

D(t)

Definition: Deoxygenation factors, including organic matter decomposition and anthropogenic impacts. The deoxygenation rate was obtained from Hydrosience empirical equation (1971) which is using the physical condition, its water depth.

$$D(t) = 0.3 \times (H/8)^{-0.434}$$

Where: D(t) = deoxygenation rate (per day), H = water depth (ft).

Context in Teluk Bahang: This parameter accounts for oxygen consumption due to the breakdown of organic material, including phytoplankton blooms and inputs from urban runoff. Increased organic matter during algal blooms can lead to significant reductions in DO as bacteria decompose the organic material.

This equation effectively captures the complex interactions influencing dissolved oxygen levels in Teluk Bahang, highlighting the importance of both natural processes and anthropogenic factors in shaping local marine ecosystem health. Each parameter reflects specific conditions and dynamics unique to this coastal environment, providing a valuable tool for understanding and managing hypoxia in response to changing environmental conditions.

7. CONCLUSIONS

In August 2024, the dynamics of dissolved oxygen (DO) distribution and hypoxia in Teluk Bahang, Penang, were influenced by a complex interplay of physical, biogeochemical, and anthropogenic factors. The initial phase of these dynamics was shaped by tidal cycles, with the spring and neap tides playing a critical role in vertical mixing in the water column. Spring tides facilitated oxygen exchange between surface and bottom waters, reducing the intensity of hypoxia, whereas neap tides exacerbated stratification, particularly in deeper areas of the bay

where vertical mixing was restricted. Additionally, the seasonal transition from the Southwest Monsoon (SWM) to the Northeast Monsoon (NEM) further complicated this scenario. During the SWM, nutrient-rich river runoff promoted primary productivity but also increased biological oxygen demand (BOD), leading to more severe hypoxia, particularly in poorly mixed areas. The onset of the NEM, with cooler and denser water masses, intensified stratification, inhibiting vertical mixing and promoting oxygen depletion in deeper waters.

Riverine nutrient influxes during the SWM stimulated phytoplankton blooms that, upon decomposition, contributed significantly to the depletion of oxygen in the bottom waters, particularly in the shallower northern regions of the bay where vertical mixing was minimal. In addition, upwelling events, especially during the positive phase of the Indian Ocean Dipole (IOD), brought nutrient-rich waters from the deep to the surface, further stimulating primary productivity. However, these upwelling events also led to the development of oxygen minimum zones (OMZs) as the nutrient-driven oxygen consumption exceeded the oxygen replenishment capacity. The reduction in light penetration due to high turbidity further suppressed primary productivity, exacerbating the oxygen depletion in bottom waters. These upwelling events, combined with sediment resuspension, created a challenging environment for oxygen recovery, particularly in the northern parts of the bay where stratification was most pronounced.

The bathymetric features of Teluk Bahang, with its shallow, steep northern regions, played a crucial role in the spatial variability of hypoxia. The lack of vertical mixing in these areas resulted in the accumulation of low-oxygen waters, prolonging hypoxic conditions. In contrast, the deeper southern sections of the bay experienced less severe hypoxia due to more efficient mixing and better oxygenation. Furthermore, anthropogenic activities, including agricultural runoff and urbanization, significantly contributed to the exacerbation of eutrophication, particularly during the SWM, by increasing nutrient loading into the bay. These anthropogenic influences enhanced phytoplankton blooms, which further increased BOD, leading to a more frequent and severe occurrence of hypoxia, especially in the northern regions. The combined effects of physical processes, nutrient loading, and anthropogenic influences underscored the vulnerability of Teluk Bahang to prolonged hypoxic conditions, particularly during transitional periods between the SWM and NEM.

In conclusion, the development and intensity of hypoxia in Teluk Bahang during August 2024 were driven by the complex interaction of tidal dynamics, seasonal transitions, nutrient loading, and upwelling. These factors collectively contributed to stratification in the water column, limiting vertical mixing and promoting oxygen depletion in bottom waters. The influx of freshwater from rivers, rich in nutrients, triggered phytoplankton growth that, upon decomposition, increased biological oxygen demand and exacerbated oxygen depletion. Upwelling further fueled primary productivity but also contributed to the formation of oxygen minimum zones, complicating efforts to replenish oxygen in the deeper waters. This study highlights the importance of continuous monitoring of key environmental parameters—such as temperature, salinity, turbidity, nutrient concentrations, and dissolved oxygen levels—in order to better understand and mitigate the impacts of hypoxia in coastal ecosystems like Teluk Bahang. Moreover, it emphasizes the need for integrated management strategies that account for the intricate interactions between physical, biological, and anthropogenic factors in order to address the challenges posed by hypoxia in vulnerable coastal regions.

8. REFERENCES

- Abdelrhman, K. F. A., Bacci, G., Nistri, A., Mengoni, A., & Ugolini, A. (2017). *Diet and gut microbiota of two supralittoral amphipods Orchestia montagui and Talitrus saltator living in different microhabitats. Estuarine, Coastal and Shelf Science*, 197, 119–125. doi:10.1016/j.ecss.2017.08.016
- Aleman, D., Iribarne, O. O., & Acha, E. M. (2018). Marine fronts as preferred habitats for young Patagonian hoki *Macrurus magellanicus* on the southern Patagonian shelf. *Marine Ecology Progress Series*, 588, 191-200.
- Alvarez-Borrego, S. (2004). Nutrient and phytoplankton dynamics in a coastal lagoon strongly affected by coastal upwelling. *Ciencias marinas*, 30(1A), 1-19.
- Bergillos, R. J., Ortega-Sánchez, M., Masselink, G., & Losada, M. A. (2016). *Morpho-sedimentary dynamics of a micro-tidal mixed sand and gravel beach, Playa Granada, southern Spain. Marine Geology*, 379, 28–38. doi:10.1016/j.margeo.2016.05.003
- Billiones, R. G., Tackx, M. L., & Daro, M. H. (1999). *The Geometric Features, Shape Factors and Fractal Dimensions of Suspended Particulate Matter in the Scheldt Estuary (Belgium). Estuarine, Coastal and Shelf Science*, 48(3), 293–305. doi:10.1006/ecss.1999.0420
- Breitburg, D., Levin, L. A., Oschlies, A., Grégoire, M., Chavez, F. P., Conley, D. J., ... Zhang, J. (2018). *Declining oxygen in the global ocean and coastal waters. Science*, 359(6371), eaam7240. doi:10.1126/science.aam7240
- Buesseler, K. O., & Lampitt, R. S. (2008). *Introduction to "Understanding the Ocean's biological pump: Results from VERTIGO." Deep Sea Research Part II: Topical Studies in Oceanography*, 55(14-15), 1519–1521. doi:10.1016/j.dsr2.2008.04.009
- Cifuentes, L. A., Schemel, L. E., & Sharp, J. H. (1990). Qualitative and numerical analyses of the effects of river inflow variations on mixing diagrams in estuaries. *Estuarine, Coastal and Shelf Science*, 30(4), 411-427.
- Chauhan, A., Singh, R. P., Dash, P., & Kumar, R. (2020). *Impact of tropical cyclone "Fani" on land, ocean, atmospheric and meteorological parameters. Marine Pollution Bulletin*, 111844. doi:10.1016/j.marpolbul.2020.11184
- Diaz, R. J., & Rosenberg, R. (2008). *Spreading Dead Zones and Consequences for Marine Ecosystems. Science*, 321(5891), 926–929. doi:10.1126/science.1156401
- Drushka, K., Asher, W. E., Jessup, A. T., Thompson, E. J., Iyer, S., & Clark, D. (2019). Capturing fresh layers with the surface salinity profiler. *Oceanography*, 32(2), 76-85.
- Du, H., Wang, H., Chi, Z., Song, N., Wang, C., & Xu, H. (2021). *Burst of hydroxyl radicals in sediments derived by flooding/drought transformation process in Lake Poyang, China. Science of The Total Environment*, 772, 145059. doi:10.1016/j.scitotenv.2021.1450
- FEYZİOĞLU, A. M., & ÖĞÜT, H. (2006). Red tide observations along the eastern Black Sea coast of Turkey. *Turkish Journal of Botany*, 30(5), 375-379.
- Giglio, E., Liquori, A. M., & Mazzarella, L. (1968). Van der Waals interactions and the packing of molecular crystals. *Il Nuovo Cimento B Series* 10, 56(1), 57–61. doi:10.1007/bf02711953
- Girjatowicz, J. P., & Łabuz, T. A. (2020). *Forms of piled ice at the southern coast of the Baltic Sea. Estuarine, Coastal and Shelf Science*, 239, 106746. doi:10.1016/j.ecss.2020.106746

- Gouveia, V., Almeida, C. M. R., Almeida, T., Teixeira, C., & Mucha, A. P. (2018). *Indigenous microbial communities along the NW Portuguese Coast: Potential for hydrocarbons degradation and relation with sediment contamination*. *Marine Pollution Bulletin*, 131, 620–632. doi:10.1016/j.marpolbul.2018.04.063
- Grasshoff, K., Kremling, K., & Ehrhardt, M. (Eds.). (2009). *Methods of seawater analysis*. John Wiley & Sons.
- Hardiman, S. C., Butchart, N., Charlton-Perez, A. J., Shaw, T. A., Akiyoshi, H., Baumgaertner, A., ... & Shibata, K. (2011). Improved predictability of the troposphere using stratospheric final warmings. *Journal of Geophysical Research: Atmospheres*, 116(D18).
- Harris, L. R., Harris, K. A., & Nel, R. (2019). *Food preferences of two sandy beach scavengers with different foraging strategies*. *Estuarine, Coastal and Shelf Science*. doi:10.1016/j.ecss.2019.02.001
- Huang, Y., Ou, D., Chen, S., Chen, B., Liu, W., Bai, R., & Chen, G. (2017). *Inhibition effect of zinc in wastewater on the N₂O emission from coastal loam soils*. *Marine Pollution Bulletin*, 116(1-2), 434–439. doi:10.1016/j.marpolbul.2017.01.0
- Heide-Jørgensen, M. P., & Laidre, K. L. (2004). *Declining Extent of Open-water Refugia for Top Predators in Baffin Bay and Adjacent Waters*. *AMBIO: A Journal of the Human Environment*, 33(8), 487–494. doi:10.1579/0044-7447-33.8.487
- Helly, J. J., & Levin, L. A. (2004). *Global distribution of naturally occurring marine hypoxia on continental margins*. *Deep Sea Research Part I: Oceanographic Research Papers*, 51(9), 1159–1168. doi:10.1016/j.dsr.2004.03.009
- Howe, E., & Simenstad, C. A. (2014). *Using Isotopic Measures of Connectivity and Ecosystem Capacity to Compare Restoring and Natural Marshes in the Skokomish River Estuary, WA, USA*. *Estuaries and Coasts*, 38(2), 639–658. doi:10.1007/s12237-014-9831-4
- Hydroscience, Inc. Simplified Mathematical Modeling of Water Quality, prepared for the Mitre Corporation and the USEPA, Water Programs, Washington, D.C. (1971)
- Irola-Sansores, E. D., Delgado-Pech, B., García-Mendoza, E., Núñez-Vázquez, E. J., Olivos-Ortiz, A., & Almazán-Becerril, A. (2018). *Population Dynamics of Benthic-Epiphytic Dinoflagellates on Two Macroalgae From Coral Reef Systems of the Northern Mexican Caribbean*. *Frontiers in Marine Science*, 5. doi:10.3389/fmars.2018.00487
- Jakobsen, H. H., Carstensen, J., Harrison, P. J., & Zingone, A. (2015). *Estimating time series phytoplankton carbon biomass: Inter-lab comparison of species identification and comparison of volume-to-carbon scaling ratios*. *Estuarine, Coastal and Shelf Science*, 162, 143–150. doi:10.1016/j.ecss.2015.05.006
- Janiak, D. S., Osman, R. W., Freeman, C. J., & Paul, V. J. (2018). Artificial structures versus mangrove prop roots: a general comparison of epifaunal communities within the Indian River Lagoon, Florida, USA. *Marine Ecology Progress Series*, 607, 85-98.
- Kadiri, M., Ahmadian, R., Bockelmann-Evans, B., Rauen, W., & Falconer, R. (2012). A review of the potential water quality impacts of tidal renewable energy systems. *Renewable and sustainable energy reviews*, 16(1), 329-341.
- Karydis, M., & Kitsiou, D. (2019). *Marine eutrophication: a global perspective*. CRC Press.

- Kennish, M. J. (2021). Drivers of change in estuarine and coastal marine environments: an overview. *Open Journal of Ecology*, 11(3), 224-239.
- Kirkpatrick, B., Fleming, L. E., Squicciarini, D., Backer, L. C., Clark, R., Abraham, W., ... & Baden, D. G. (2004). Literature review of Florida red tide: implications for human health effects. *Harmful algae*, 3(2), 99-115.
- Last, K. S., Hendrick, V. J., Beveridge, C. M., Roberts, D. A., & Wilding, T. A. (2016). *Lethal and sub-lethal responses of the biogenic reef forming polychaete Sabellaria alveolata to aqueous chlorine and temperature*. *Marine Environmental Research*, 117, 44–53. doi:10.1016/j.marenvres.2016.04.0
- Li, F., Jiang, L., Zhang, T., Qiu, J., Lv, D., Su, T., ... Wang, H. (2021). *Combined effects of seawater acidification and benzo(a)pyrene on the physiological performance of the marine bloom-forming diatom Skeletonema costatum*. *Marine Environmental Research*, 169, 105396. doi:10.1016/j.marenvres.2021.1053
- Mann, K. H., & Lazier, J. R. (2005). *Dynamics of marine ecosystems: biological-physical interactions in the oceans*. John Wiley & Sons.
- Massicotte, P., Peeken, I., Katlein, C., Flores, H., Huot, Y., Castellani, G., ... Babin, M. (2019). *Sensitivity of phytoplankton primary production estimates to available irradiance under heterogeneous sea-ice conditions*. *Journal of Geophysical Research: Oceans*. doi:10.1029/2019jc015007
- Michelsen, H. K., Svensen, C., Reigstad, M., Nilssen, E. M., & Pedersen, T. (2017). *Seasonal dynamics of meroplankton in a high-latitude fjord*. *Journal of Marine Systems*, 168, 17–30. doi:10.1016/j.jmarsys.2016.12.001
- Oschlies, A., Schulz, K. G., Riebesell, U., & Schmittner, A. (2008). Simulated 21st century's increase in oceanic suboxia by CO₂-enhanced biotic carbon export. *Global Biogeochemical Cycles*, 22(4), n/a–n/a. doi:10.1029/2007gb003147
- Paar, M., Lebreton, B., Graeve, M., Greenacre, M., Asmus, R., & Asmus, H. (2019). Food sources of macrozoobenthos in an Arctic kelp belt: trophic relationships revealed by stable isotope and fatty acid analyses. *Marine Ecology Progress Series*, 615, 31-49.
- Passos, T., Penny, D., Sanders, C., De França, E., Oliveira, T., Santos, L., & Barcellos, R. (2021). *Mangrove carbon and nutrient accumulation shifts driven by rapid development in a tropical estuarine system, northeast Brazil*. *Marine Pollution Bulletin*, 166, 112219. doi:10.1016/j.marpolbul.2021.1122
- Piatt, J. F., Wetzel, J., Bell, K., DeGange, A. R., Balogh, G. R., Drew, G. S., ... Byrd, G. V. (2006). *Predictable hotspots and foraging habitat of the endangered short-tailed albatross (Phoebastria albatrus) in the North Pacific: Implications for conservation*. *Deep Sea Research Part II: Topical Studies in Oceanography*, 53(3-4), 387–398. doi:10.1016/j.dsr2.2006.01.008
- Pingree, R. D., & Griffiths, D. K. (1978). *Tidal fronts on the shelf seas around the British Isles*. *Journal of Geophysical Research*, 83(C9), 4615. doi:10.1029/jc083ic09p04615
- Purdie, D. A. (1996). Marine phytoplankton blooms. *Oceanography*, 89-95.
- Polsenaere, P., Deborde, J., Detandt, G., Vidal, L. O., Pérez, M. A. P., Marieu, V., & Abril, G. (2013). *Thermal enhancement of gas transfer velocity of CO₂ in an Amazon floodplain lake revealed by eddy covariance measurements*. *Geophysical Research Letters*, 40(9), 1734–1740. doi:10.1002/grl.50291

- Sans-Piché, F., Kluender, C., Altenburger, R., & Schmitt-Jansen, M. (2010). *Anchoring metabolic changes to phenotypic effects in the chlorophyte Scenedesmus vacuolatus under chemical exposure*. *Marine Environmental Research*, 69, S28–S30. doi:10.1016/j.marenvres.2009.12.0
- Schintu, M., Marrucci, A., Marras, B., Atzori, M., & Pellegrini, D. (2018). Passive sampling monitoring of PAHs and trace metals in seawater during the salvaging of the Costa Concordia wreck (Parbuckling Project). *Marine Pollution Bulletin*, 135, 819–827. doi:10.1016/j.marpolbul.2018.08.011
- SIMPSON, J. H., & HUNTER, J. R. (1974). *Fronts in the Irish Sea*. *Nature*, 250(5465), 404–406. doi:10.1038/250404a0
- Smith, V. H. (2003). Eutrophication of freshwater and coastal marine ecosystems a global problem. *Environmental Science and Pollution Research*, 10, 126-139.
- Spall, M. A. (2008). *Low-frequency interaction between horizontal and overturning gyres in the ocean*. *Geophysical Research Letters*, 35(18). doi:10.1029/2008gl035206
- Tanaka, T., Rassoulzadegan, F., & Thingstad, T. F. (2004). *Orthophosphate uptake by heterotrophic bacteria, cyanobacteria, and autotrophic nanoflagellates in Villefranche Bay, northwestern Mediterranean: Vertical, seasonal, and short-term variations of the competitive relationship for phosphorus*. *Limnology and Oceanography*, 49(4), 1063–1072. doi:10.4319/lo.2004.49.4.1063
- Taucher, J., Stange, P., Algueró-Muñiz, M., Bach, L. T., Nauendorf, A., Kolzenburg, R., ... Riebesell, U. (2018). *In situ camera observations reveal major role of zooplankton in modulating marine snow formation during an upwelling-induced plankton bloom*. *Progress in Oceanography*, 164, 75–88. doi:10.1016/j.pocean.2018.01.004
- Trigueros, J. M., & Orive, E. (2000). Tidally driven distribution of phytoplankton blooms in a shallow, macrotidal estuary. *Journal of Plankton Research*, 22(5), 969-986.
- Vaquer-Sunyer, R., & Duarte, C. M. (2008). *Thresholds of hypoxia for marine biodiversity*. *Proceedings of the National Academy of Sciences*, 105(40), 15452–15457. doi:10.1073/pnas.0803833105
- Wang, Y., Wu, H., Lin, J., Zhu, J., Zhang, W., & Li, C. (2019). Phytoplankton blooms off a high turbidity estuary: A case study in the Changjiang River Estuary. *Journal of Geophysical Research: Oceans*, 124(11), 8036-8059.
- Wei, Q., Yuan, Y., Song, S., Zhao, Y., Sun, J., Li, C., & Wang, B. (2022). Spatial variability of hypoxia and coupled physical-biogeochemical controls off the Changjiang (Yangtze River) Estuary in summer. *Frontiers in Marine Science*, 9, 987368.
- Xu, S., Wang, W., Xu, B., He, X., Chen, Z., Zhao, X., ... & Wang, Q. (2023). In vitro exposure to environmentally relevant concentrations of norgestrel affects sperm physiology and reproductive success of the Pacific oyster *Crassostrea gigas*. *Marine Environmental Research*, 186, 105938.

9. APPENDICES

Spatial Distribution Data for 8 parameters during Neap and Spring Phase at Surface

				NEAP								SPRING							
Point	Latitude	Longitud	condition	TSS	Density	Salinity	pH	SST	DO	CHL-A	Current	TSS	Density	Salinity	pH	SST	DO	CHL-A	Current
A1	5.466	100.223	surface	4.058	0.007	22.285	8.087	27.054	5.900	15.870	0.474	2.126	0.012	22.533	8.012	28.365	6.600	6.790	0.373
A2	5.468	100.221	surface	2.224	0.017	24.151	8.083	28.399	6.200	11.622	0.623	3.447	0.012	25.010	8.070	28.459	6.200	6.169	0.254
A3	5.469	100.219	surface	6.178	0.019	30.349	8.101	25.573	5.600	14.739	0.228	1.913	0.018	24.042	8.006	27.542	6.300	7.196	0.312
A4	5.471	100.217	surface	3.499	0.011	23.332	8.081	28.479	5.500	17.598	0.673	4.868	0.005	25.767	8.063	26.217	5.600	13.433	0.684
A5	5.473	100.215	surface	2.779	0.006	24.037	8.070	26.422	6.400	18.502	0.511	2.041	0.015	22.061	8.004	27.067	6.300	8.056	0.378
A6	5.475	100.213	surface	2.536	0.016	26.285	8.074	26.623	6.700	16.105	0.692	1.472	0.008	23.413	8.066	27.380	6.500	12.730	0.492
A7	5.477	100.211	surface	3.193	0.006	23.737	8.005	26.004	7.300	13.047	0.398	4.857	0.014	22.807	8.035	28.211	7.400	13.683	0.439
A8	5.479	100.209	surface	3.179	0.012	24.551	8.051	26.890	7.100	19.853	0.697	2.207	0.012	22.670	8.056	26.486	7.300	11.005	0.373
A9	5.481	100.207	surface	2.720	0.013	23.077	8.083	26.705	7.500	11.821	0.459	3.888	0.006	25.064	8.035	26.794	7.200	18.532	0.465
A10	5.483	100.206	surface	4.193	0.017	24.152	8.022	28.482	8.200	18.304	0.373	2.580	0.006	26.921	8.000	26.987	8.500	8.644	0.461
A11	5.485	100.204	surface	3.596	0.016	22.793	8.040	28.500	7.621	15.639	0.262	1.690	0.017	26.069	8.048	28.200	7.589	16.724	0.538
A12	5.487	100.202	surface	4.178	0.017	25.362	8.081	26.489	7.600	15.555	0.641	3.872	0.005	24.828	8.013	28.451	7.800	13.397	0.599
A13	5.489	100.200	surface	4.884	0.015	23.466	8.003	28.284	8.500	12.774	0.351	2.730	0.008	24.021	8.060	27.035	8.600	14.269	0.347
B1	5.461	100.215	surface	27.380	0.011	23.910	8.014	26.963	5.500	10.851	0.275	28.622	0.011	24.328	8.071	28.201	5.900	10.534	0.622
B2	5.463	100.213	surface	31.416	0.014	24.890	8.085	27.022	6.800	17.075	0.341	33.059	0.012	24.599	8.065	27.328	7.300	11.284	0.638
B3	5.465	100.211	surface	26.016	0.011	22.752	8.059	27.029	6.600	11.481	0.629	31.673	0.018	24.777	8.063	26.251	7.200	2.030	0.684
B4	5.467	100.209	surface	4.046	0.017	22.250	8.014	28.331	5.900	18.776	0.301	3.222	0.013	26.057	8.078	26.581	6.300	11.593	0.623
B5	5.469	100.207	surface	3.141	0.013	23.160	8.074	26.415	7.100	18.176	0.295	2.374	0.009	24.743	8.047	27.652	7.200	4.348	0.361
B6	5.471	100.205	surface	2.410	0.006	25.922	8.042	28.039	6.100	17.348	0.544	2.672	0.014	22.223	8.069	28.257	5.800	13.701	0.320
B7	5.473	100.203	surface	2.631	0.016	24.032	8.030	27.796	6.300	19.054	0.274	2.067	0.015	26.437	8.004	28.027	6.500	10.033	0.666
B8	5.475	100.201	surface	2.856	0.009	22.219	8.047	26.170	7.100	7.165	0.216	3.505	0.007	25.197	8.037	28.153	6.900	10.529	0.384
B9	5.477	100.200	surface	4.679	0.010	22.228	8.069	26.949	5.800	5.964	0.708	3.663	0.007	23.781	8.096	26.669	6.200	8.436	0.268
B10	5.479	100.198	surface	4.184	0.012	26.047	8.069	26.505	5.400	17.647	0.454	4.759	0.015	22.461	8.004	26.015	5.800	4.626	0.523
B11	5.480	100.196	surface	3.769	0.018	24.650	8.009	28.161	7.300	17.170	0.518	2.749	0.014	26.046	8.063	28.229	6.900	17.192	0.462
B12	5.482	100.194	surface	4.878	0.015	25.651	8.026	26.338	7.100	11.755	0.622	3.085	0.016	22.735	8.068	27.598	6.900	12.924	0.226
B13	5.484	100.193	surface	4.296	0.013	23.383	8.011	28.205	8.000	17.641	0.278	4.713	0.008	22.718	8.010	27.180	7.900	12.339	0.337

				NEAP								SPRING							
Point	Latitude	Longitud	condition	TSS	Density	Salinity	pH	SST	DO	CHL-A	Current	TSS	Density	Salinity	pH	SST	DO	CHL-A	Current
C1	5.460	100.211	surface	4.846	0.014	25.265	8.025	28.256	4.400	7.058	0.479	4.051	0.014	25.678	8.066	26.001	4.700	12.799	0.231
C2	5.461	100.210	surface	7.497	0.015	23.756	8.043	28.483	3.800	10.747	0.681	5.249	0.018	25.661	8.017	28.210	4.000	17.449	0.480
C3	5.463	100.208	surface	9.776	0.022	26.583	8.091	28.147	5.100	10.568	0.299	13.461	0.021	26.360	8.101	27.511	4.700	13.510	0.260
C4	5.465	100.207	surface	13.798	0.019	24.742	8.025	28.410	4.900	12.575	0.316	12.817	0.020	26.977	8.023	27.109	4.400	11.604	0.301
C5	5.467	100.205	surface	11.912	0.016	22.592	8.088	26.856	3.800	15.304	0.217	13.318	0.017	24.695	8.044	26.260	3.700	7.976	0.368
C6	5.469	100.203	surface	21.091	0.019	22.093	8.002	28.097	6.000	15.282	0.533	22.976	0.018	22.103	8.045	27.762	6.500	7.565	0.351
C7	5.471	100.201	surface	14.148	0.011	26.929	8.033	27.647	7.100	11.818	0.470	14.225	0.013	22.239	8.084	27.376	7.000	14.475	0.330
C8	5.473	100.199	surface	10.024	0.021	31.219	8.106	24.787	7.100	17.149	0.410	14.551	0.022	31.966	8.110	27.862	7.300	16.498	0.238
C9	5.475	100.198	surface	12.275	0.011	22.344	8.062	27.728	5.800	18.760	0.634	13.888	0.010	26.870	8.050	26.006	5.900	14.181	0.506
C10	5.476	100.196	surface	12.791	0.005	22.390	8.009	28.432	6.300	10.990	0.284	11.649	0.006	23.453	8.050	26.793	6.800	10.427	0.337
C11	5.479	100.194	surface	10.217	0.007	26.197	8.087	27.299	6.900	10.390	0.261	11.790	0.016	23.325	8.059	27.955	6.800	10.068	0.389
C12	5.480	100.192	surface	10.258	0.009	22.258	8.036	28.168	7.500	17.046	0.225	12.161	0.008	23.902	8.042	28.394	7.400	11.788	0.377
C13	5.482	100.190	surface	12.194	0.007	22.072	8.040	27.977	7.400	2.434	0.293	14.782	0.011	26.282	8.024	27.677	7.300	15.167	0.391
D1	5.461	100.206	surface	20.112	0.010	26.127	8.043	26.713	3.600	11.233	0.381	21.557	0.013	26.444	8.052	28.116	4.300	19.848	0.255
D2	5.463	100.204	surface	17.215	0.017	24.548	8.052	26.667	4.408	17.074	0.282	16.004	0.015	26.614	8.008	28.324	4.392	6.796	0.259
D3	5.469	100.199	surface	22.008	0.011	26.667	8.010	27.176	3.670	10.312	0.266	26.653	0.018	26.067	8.088	27.279	3.914	18.153	0.474
D4	5.473	100.195	surface	14.731	0.007	22.129	8.021	28.328	5.313	12.927	0.372	11.470	0.005	25.786	8.042	27.289	5.310	14.110	0.249
D5	5.474	100.193	surface	13.365	0.008	24.468	8.006	28.161	6.374	14.864	0.355	14.763	0.016	26.319	8.008	26.142	6.424	19.854	0.445
D6	5.477	100.191	surface	14.595	0.016	25.524	8.032	27.473	6.208	16.105	0.322	11.679	0.007	25.322	8.082	27.354	6.375	9.471	0.225
D7	5.479	100.190	surface	12.846	0.009	24.540	8.079	26.304	7.005	2.743	0.372	12.893	0.016	25.822	8.094	27.088	7.433	16.667	0.601
D8	5.480	100.188	surface	13.942	0.007	22.592	8.036	26.292	7.531	9.524	0.394	13.620	0.011	25.193	8.071	27.294	7.950	11.146	0.436
E1	5.472	100.191	surface	11.461	0.012	24.522	8.061	27.540	5.339	13.433	0.353	13.246	0.012	25.199	8.092	27.131	5.475	16.610	0.284
E2	5.475	100.188	surface	12.718	0.009	26.023	8.042	27.201	6.263	11.055	0.275	10.638	0.014	24.225	8.081	28.244	6.497	17.401	0.322
E3	5.478	100.185	surface	4.281	0.013	25.402	8.005	26.590	7.903	8.612	0.231	3.281	0.010	26.883	8.073	28.182	7.977	7.950	0.402

Spatial Distribution Data for 8 parameters during Neap and Spring Phase at 1 Meter

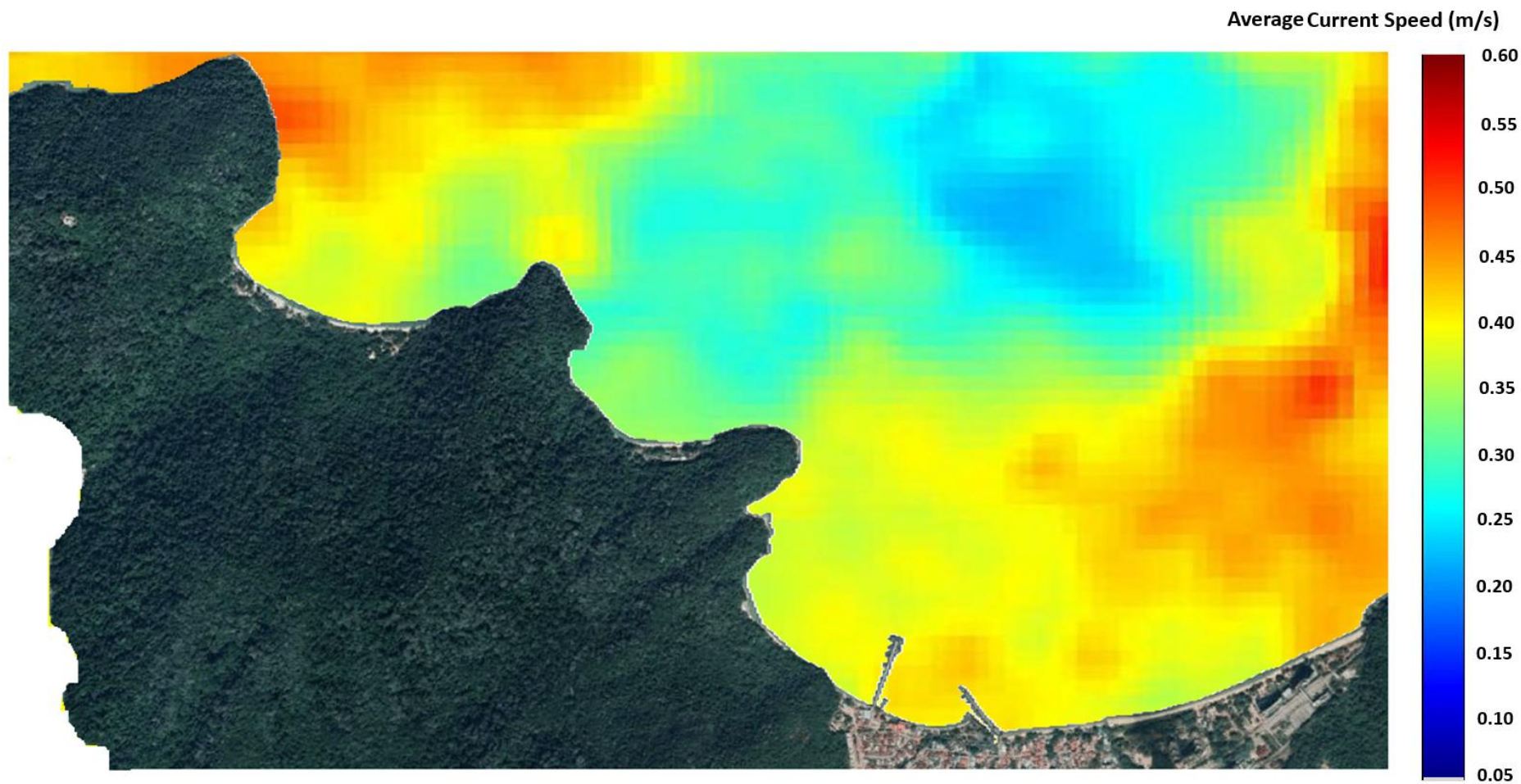
				NEAP								SPRING							
Point	Latitude	Longitud	condition	TSS	Density	Salinity	pH	SST	DO	CHL-A	Current	TSS	Density	Salinity	pH	SST	DO	CHL-A	Current
A1	5.466	100.223	1m	9.308	0.020	27.541	8.102	24.401	4.600	10.005	0.331	8.868	0.020	27.155	8.101	27.984	5.300	2.991	0.461
A2	5.468	100.221	1m	5.256	0.020	29.942	8.103	27.004	5.900	6.112	0.619	6.366	0.019	29.597	8.103	27.817	5.400	15.481	0.655
A3	5.469	100.219	1m	7.905	0.019	29.444	8.103	26.678	4.700	5.863	0.597	8.375	0.020	30.736	8.103	25.680	5.700	5.146	0.555
A4	5.471	100.217	1m	9.073	0.018	31.874	8.101	26.095	4.600	11.109	0.277	9.578	0.020	31.852	8.100	25.140	4.900	11.589	0.454
A5	5.473	100.215	1m	5.476	0.018	31.197	8.103	25.626	6.100	15.494	0.590	7.849	0.018	27.931	8.104	24.336	5.600	3.413	0.617
A6	5.475	100.213	1m	8.310	0.020	28.360	8.102	26.534	5.800	14.580	0.540	9.981	0.018	30.880	8.100	26.269	5.200	17.515	0.681
A7	5.477	100.211	1m	5.746	0.020	29.784	8.103	26.706	6.600	2.948	0.429	8.493	0.019	29.143	8.102	24.211	6.900	18.151	0.729
A8	5.479	100.209	1m	8.255	0.019	29.510	8.105	24.553	6.300	4.244	0.427	8.197	0.019	30.176	8.104	24.547	6.600	17.482	0.355
A9	5.481	100.207	1m	7.063	0.019	29.342	8.104	24.801	6.500	18.523	0.437	8.456	0.020	30.653	8.105	27.061	6.900	14.082	0.562
A10	5.483	100.206	1m	5.800	0.019	29.860	8.101	27.715	7.600	3.970	0.304	8.998	0.020	30.521	8.102	26.631	7.500	10.888	0.325
A11	5.485	100.204	1m	5.177	0.020	29.331	8.104	27.600	7.371	18.459	0.671	7.998	0.019	31.297	8.104	27.500	7.090	15.081	0.626
A12	5.487	100.202	1m	5.094	0.018	28.243	8.102	25.471	6.600	3.163	0.595	6.082	0.019	28.018	8.105	25.633	6.800	2.729	0.387
A13	5.489	100.200	1m	6.513	0.019	31.410	8.104	26.946	7.800	5.922	0.462	6.242	0.019	29.810	8.104	27.516	7.500	6.412	0.616
B1	5.461	100.215	1m	30.285	0.018	30.753	8.102	27.444	4.500	2.011	0.237	34.409	0.020	29.833	8.101	26.356	4.600	18.270	0.477
B2	5.463	100.213	1m	39.478	0.018	29.680	8.103	27.298	5.600	13.161	0.309	37.649	0.020	31.950	8.102	27.801	6.500	3.599	0.544
B3	5.465	100.211	1m	33.423	0.018	30.700	8.101	27.834	5.100	2.187	0.340	36.831	0.018	29.146	8.104	26.136	6.500	14.005	0.618
B4	5.467	100.209	1m	8.498	0.019	28.630	8.103	27.154	4.500	4.653	0.704	7.251	0.019	31.766	8.103	27.716	5.400	7.083	0.384
B5	5.469	100.207	1m	7.864	0.019	28.613	8.101	27.337	6.600	10.345	0.666	7.258	0.019	29.794	8.104	26.809	6.900	6.234	0.323
B6	5.471	100.205	1m	9.345	0.019	27.549	8.101	26.687	5.500	10.168	0.498	8.394	0.019	27.722	8.100	27.338	5.100	7.544	0.414
B7	5.473	100.203	1m	6.045	0.019	29.149	8.100	25.436	5.600	13.139	0.338	9.531	0.020	31.337	8.103	26.690	5.800	5.482	0.437
B8	5.475	100.201	1m	5.400	0.020	27.224	8.103	26.300	6.600	15.046	0.539	5.268	0.019	28.821	8.103	25.941	6.400	13.963	0.452
B9	5.477	100.200	1m	7.243	0.020	28.711	8.105	24.203	5.400	5.449	0.402	8.650	0.019	27.882	8.100	25.116	5.700	13.009	0.597
B10	5.479	100.198	1m	6.874	0.019	27.704	8.102	27.325	4.400	2.383	0.231	9.464	0.020	29.898	8.103	24.851	4.800	18.668	0.695
B11	5.480	100.196	1m	9.756	0.021	30.743	8.102	26.529	6.900	11.571	0.697	9.336	0.020	31.358	8.105	25.383	6.100	4.517	0.493
B12	5.482	100.194	1m	9.238	0.020	28.754	8.101	24.693	6.800	14.877	0.392	8.569	0.018	30.636	8.104	26.318	6.100	4.039	0.597
B13	5.484	100.193	1m	7.361	0.019	27.523	8.101	27.883	7.600	8.483	0.410	5.707	0.020	30.055	8.100	26.216	7.000	5.321	0.278

				NEAP								SPRING							
Point	Latitude	Longitud	condition	TSS	Density	Salinity	pH	SST	DO	CHL-A	Current	TSS	Density	Salinity	pH	SST	DO	CHL-A	Current
C1	5.460	100.211	1m	5.318	0.019	29.646	8.101	24.884	3.200	13.654	0.628	7.317	0.018	31.543	8.104	25.524	3.500	7.618	0.690
C2	5.461	100.210	1m	11.514	0.019	30.651	8.100	27.618	3.400	14.015	0.255	13.662	0.021	29.301	8.100	24.113	3.600	4.389	0.720
C3	5.463	100.208	1m	13.155	0.023	29.314	8.102	27.847	4.500	16.440	0.280	24.177	0.023	31.819	8.109	25.495	4.300	15.802	0.290
C4	5.465	100.207	1m	17.782	0.021	31.416	8.101	24.572	4.100	12.680	0.715	22.033	0.021	28.029	8.102	26.504	3.700	7.039	0.500
C5	5.467	100.205	1m	22.914	0.019	29.934	8.104	27.352	3.300	15.098	0.608	15.640	0.020	28.437	8.103	24.278	3.200	6.839	0.463
C6	5.469	100.203	1m	27.708	0.021	30.352	8.102	27.160	5.800	14.466	0.718	28.788	0.022	28.079	8.103	24.620	6.000	18.291	0.315
C7	5.471	100.201	1m	18.127	0.018	28.559	8.102	26.251	6.700	13.630	0.728	16.937	0.019	28.635	8.103	27.875	6.600	14.709	0.676
C8	5.473	100.199	1m	18.945	0.023	33.188	8.115	24.947	6.900	16.048	0.410	21.861	0.022	33.110	8.115	27.363	7.000	17.685	0.224
C9	5.475	100.198	1m	16.198	0.020	30.516	8.102	24.110	5.100	12.263	0.276	17.499	0.018	27.198	8.105	26.886	5.500	17.549	0.527
C10	5.476	100.196	1m	19.449	0.019	29.546	8.101	25.678	6.000	12.108	0.346	17.685	0.019	28.981	8.103	25.750	6.300	18.948	0.505
C11	5.479	100.194	1m	15.327	0.020	30.982	8.102	25.173	6.500	8.141	0.373	22.701	0.019	28.425	8.104	24.378	6.100	13.079	0.630
C12	5.480	100.192	1m	22.946	0.018	29.710	8.101	24.348	7.000	12.483	0.557	21.402	0.019	28.439	8.102	25.266	6.900	8.962	0.652
C13	5.482	100.190	1m	15.394	0.018	30.004	8.105	24.360	7.200	7.030	0.564	18.811	0.019	27.839	8.104	24.253	7.200	11.066	0.335
D1	5.461	100.206	1m	25.434	0.020	28.077	8.100	24.477	3.000	11.271	0.364	25.782	0.020	27.183	8.103	24.639	4.000	18.634	0.277
D2	5.463	100.204	1m	29.644	0.018	28.465	8.102	25.279	3.990	10.564	0.506	26.192	0.018	30.119	8.105	24.190	3.734	7.818	0.569
D3	5.469	100.199	1m	28.948	0.018	28.852	8.103	26.322	3.035	3.674	0.242	30.867	0.020	28.956	8.101	26.231	3.309	8.456	0.397
D4	5.473	100.195	1m	21.098	0.020	28.729	8.103	24.076	4.419	16.718	0.677	18.985	0.019	29.313	8.103	25.653	4.498	16.843	0.701
D5	5.474	100.193	1m	24.534	0.020	29.474	8.101	24.339	5.581	15.896	0.228	20.264	0.020	27.082	8.104	24.476	5.655	15.547	0.607
D6	5.477	100.191	1m	19.015	0.018	28.952	8.104	27.715	5.970	12.507	0.454	18.057	0.020	28.133	8.100	25.496	5.841	14.096	0.680
D7	5.479	100.190	1m	17.775	0.020	28.814	8.103	24.987	6.728	8.852	0.249	18.743	0.019	31.573	8.105	24.885	6.906	17.037	0.601
D8	5.480	100.188	1m	21.039	0.020	28.048	8.103	25.117	7.355	8.081	0.471	17.316	0.018	31.888	8.101	26.443	7.291	12.123	0.262
E1	5.472	100.191	1m	18.248	0.020	27.965	8.103	25.692	4.515	15.932	0.531	23.722	0.018	27.027	8.104	26.316	4.890	16.959	0.320
E2	5.475	100.188	1m	16.680	0.018	28.040	8.101	26.249	5.513	13.265	0.300	17.079	0.019	30.539	8.104	25.419	5.940	16.591	0.523
E3	5.478	100.185	1m	7.778	0.018	30.823	8.103	25.022	7.094	4.351	0.644	7.182	0.020	29.112	8.102	26.097	7.053	12.229	0.346

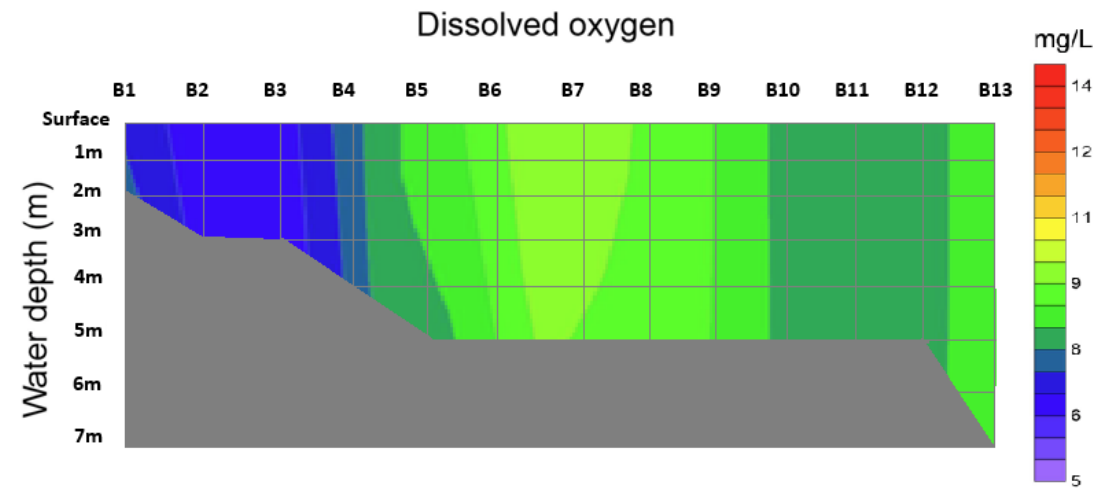
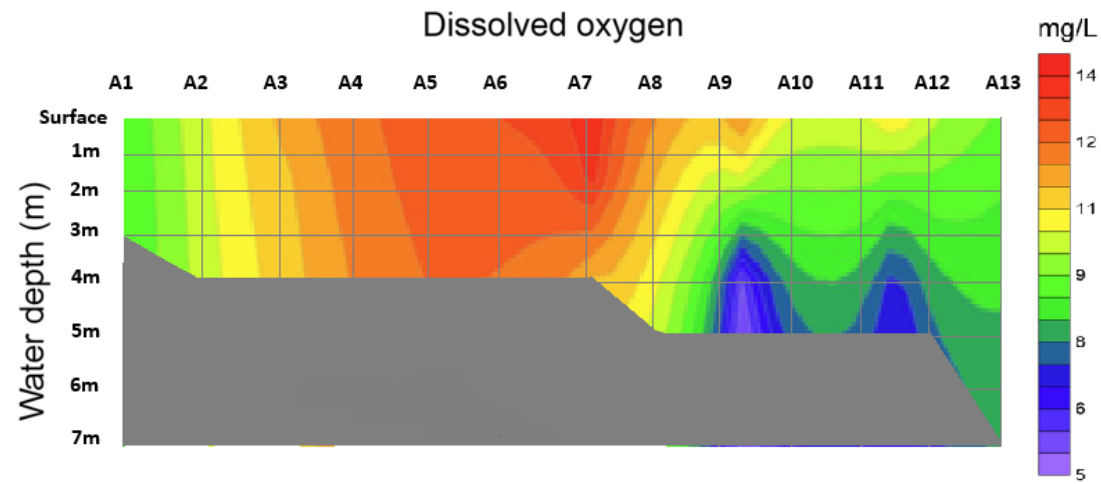
Spatial Distribution Data for 8 parameters during Neap and Spring Phase at 2 Meter

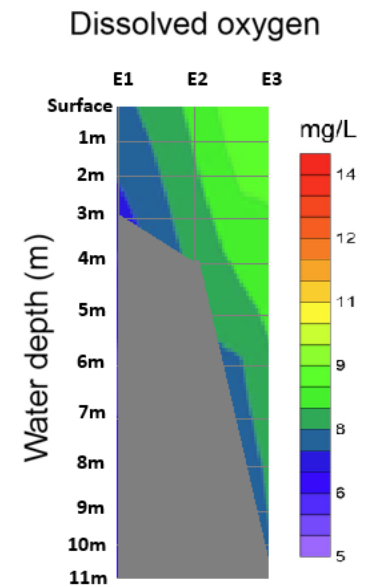
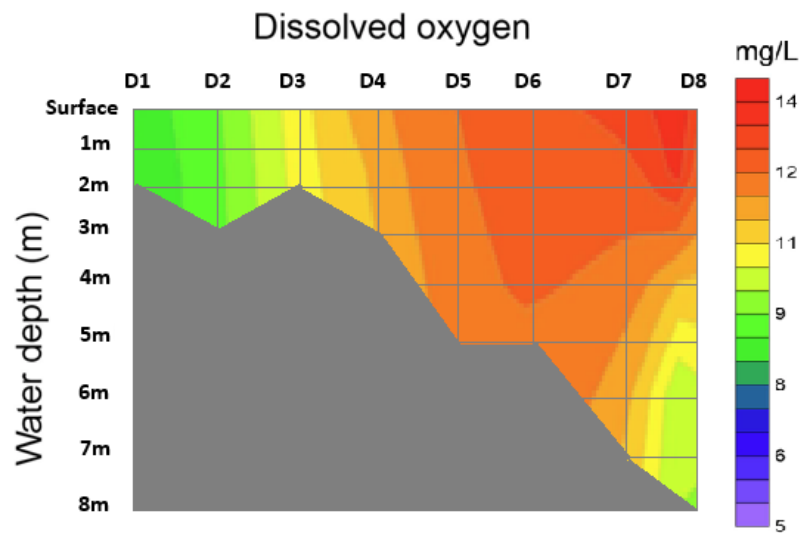
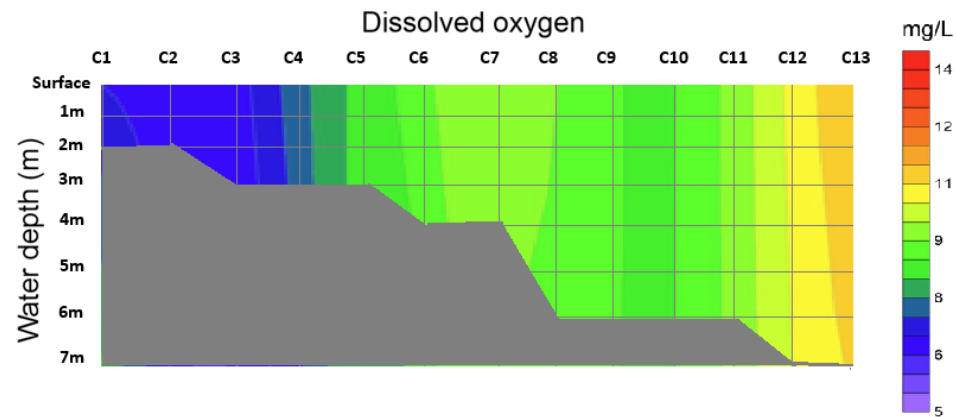
				NEAP								SPRING							
Point	Latitude	Longitud	condition	TSS	Density	Salinity	pH	SST	DO	CHL-A	Current	TSS	Density	Salinity	pH	SST	DO	CHL-A	Current
A1	5.466	100.223	2m	14.803	0.021	32.194	8.106	24.491	4.300	2.009	0.515	12.902	0.022	31.193	8.107	26.442	3.800	8.220	0.779
A2	5.468	100.221	2m	11.058	0.021	32.455	8.107	24.570	4.300	6.722	0.261	13.401	0.022	31.898	8.109	25.576	4.800	16.692	0.252
A3	5.469	100.219	2m	14.460	0.021	32.161	8.106	25.674	4.100	5.052	0.480	13.249	0.021	31.923	8.108	24.100	4.900	10.570	0.395
A4	5.471	100.217	2m	14.228	0.021	31.232	8.105	21.227	4.100	16.247	0.709	11.996	0.022	32.761	8.106	22.247	4.100	13.762	0.288
A5	5.473	100.215	2m	13.596	0.021	31.759	8.108	25.580	5.800	17.485	0.707	14.352	0.021	32.943	8.107	24.728	4.800	7.185	0.349
A6	5.475	100.213	2m	14.326	0.021	32.403	8.109	25.213	5.100	13.372	0.702	14.369	0.022	31.281	8.106	24.647	4.700	9.571	0.679
A7	5.477	100.211	2m	13.049	0.021	31.120	8.106	25.228	5.200	11.917	0.766	14.383	0.021	31.878	8.106	24.051	5.700	9.521	0.767
A8	5.479	100.209	2m	14.186	0.022	32.577	8.106	24.308	5.600	14.323	0.558	10.736	0.021	32.592	8.107	26.937	5.900	2.302	0.373
A9	5.481	100.207	2m	11.047	0.022	32.646	8.108	24.023	5.400	13.647	0.308	14.073	0.021	31.156	8.109	25.508	5.600	11.678	0.471
A10	5.483	100.206	2m	13.411	0.022	31.392	8.108	25.590	6.700	3.280	0.789	10.638	0.021	31.521	8.108	26.581	6.600	13.616	0.619
A11	5.485	100.204	2m	14.534	0.022	31.452	8.108	26.800	6.767	7.673	0.265	13.292	0.021	32.767	8.106	26.200	6.967	3.341	0.727
A12	5.487	100.202	2m	14.214	0.021	32.582	8.106	24.263	5.200	9.541	0.785	13.450	0.021	32.782	8.108	24.833	5.900	7.343	0.290
A13	5.489	100.200	2m	11.872	0.022	32.106	8.105	25.071	6.700	16.374	0.286	10.541	0.022	32.481	8.110	26.930	6.900	16.030	0.391
B1	5.461	100.215	2m	39.373	0.021	32.733	8.105	26.161	3.100	16.051	0.495	36.062	0.021	32.271	8.108	26.566	3.700	8.779	0.748
B2	5.463	100.213	2m	43.177	0.022	31.310	8.109	26.732	4.700	9.730	0.690	40.782	0.021	32.503	8.106	25.401	5.700	14.414	0.292
B3	5.465	100.211	2m	38.711	0.022	31.573	8.109	26.442	4.600	8.923	0.636	43.702	0.021	31.481	8.108	24.726	5.200	8.600	0.360
B4	5.467	100.209	2m	10.300	0.022	32.921	8.106	24.689	4.100	15.705	0.761	14.371	0.021	31.999	8.109	25.654	5.100	15.588	0.615
B5	5.469	100.207	2m	12.470	0.022	31.815	8.108	25.136	5.400	14.776	0.523	13.193	0.021	31.154	8.107	25.571	6.300	15.229	0.533
B6	5.471	100.205	2m	11.677	0.022	31.817	8.107	25.502	5.100	13.523	0.696	10.379	0.022	32.621	8.107	24.533	4.700	2.300	0.541
B7	5.473	100.203	2m	13.201	0.021	31.636	8.108	24.836	5.100	10.041	0.523	12.156	0.021	31.988	8.109	25.402	5.100	9.426	0.304
B8	5.475	100.201	2m	10.610	0.022	32.257	8.107	24.128	5.900	17.704	0.487	14.204	0.021	31.498	8.108	24.617	5.400	2.400	0.729
B9	5.477	100.200	2m	12.207	0.022	31.827	8.109	24.473	4.700	16.130	0.658	12.668	0.021	31.560	8.106	26.672	5.500	2.545	0.727
B10	5.479	100.198	2m	14.936	0.021	31.508	8.110	24.495	4.100	2.570	0.537	14.770	0.021	31.972	8.107	24.028	4.100	16.402	0.328
B11	5.480	100.196	2m	10.153	0.022	31.924	8.107	25.662	6.400	5.783	0.471	12.546	0.021	31.209	8.108	25.877	5.600	12.061	0.438
B12	5.482	100.194	2m	10.536	0.021	32.464	8.109	24.886	6.100	10.983	0.520	12.120	0.021	31.384	8.107	25.152	5.400	4.783	0.712
B13	5.484	100.193	2m	11.119	0.021	31.383	8.110	26.146	7.000	9.516	0.696	10.055	0.021	32.813	8.109	24.451	6.900	17.797	0.262

				NEAP								SPRING							
Point	Latitude	Longitud	condition	TSS	Density	Salinity	pH	SST	DO	CHL-A	Current	TSS	Density	Salinity	pH	SST	DO	CHL-A	Current
C1	5.460	100.211	2m	10.324	0.021	32.871	8.106	26.263	2.600	11.915	0.450	11.248	0.022	31.452	8.106	26.458	2.300	3.037	0.427
C2	5.461	100.210	2m	16.514	0.022	32.084	8.107	25.243	2.900	10.460	0.679	20.624	0.023	32.059	8.107	24.902	3.000	5.999	0.619
C3	5.463	100.208	2m	16.390	0.024	31.049	8.107	24.351	4.000	14.998	0.273	28.637	0.023	32.957	8.114	24.397	3.700	10.522	0.611
C4	5.465	100.207	2m	29.849	0.022	31.547	8.107	25.300	3.600	15.977	0.304	29.540	0.022	32.757	8.105	25.876	3.200	12.414	0.656
C5	5.467	100.205	2m	28.436	0.022	32.917	8.108	24.686	2.700	16.306	0.487	25.193	0.021	32.926	8.106	26.508	2.600	8.124	0.283
C6	5.469	100.203	2m	31.852	0.023	32.534	8.107	24.364	5.400	6.227	0.708	34.584	0.023	32.605	8.110	26.863	5.900	12.319	0.575
C7	5.471	100.201	2m	28.712	0.021	31.380	8.105	26.459	6.400	12.075	0.467	26.354	0.022	31.298	8.109	24.433	6.300	10.564	0.576
C8	5.473	100.199	2m	26.419	0.023	33.397	8.116	23.349	6.300	16.606	0.252	25.538	0.024	33.311	8.116	25.640	6.500	12.752	0.451
C9	5.475	100.198	2m	28.810	0.021	32.092	8.106	26.944	4.800	10.020	0.512	25.693	0.022	31.502	8.109	26.816	4.400	12.584	0.494
C10	5.476	100.196	2m	28.791	0.022	31.214	8.106	24.773	5.700	14.514	0.373	26.351	0.021	32.028	8.110	25.852	5.700	15.287	0.449
C11	5.479	100.194	2m	28.649	0.021	32.982	8.108	24.378	5.700	2.557	0.573	28.862	0.022	31.045	8.106	25.181	5.700	17.219	0.716
C12	5.480	100.192	2m	27.051	0.021	32.451	8.110	26.927	6.700	6.787	0.323	25.416	0.021	32.855	8.106	26.200	4.679	13.133	0.759
C13	5.482	100.190	2m	27.808	0.021	31.379	8.106	25.839	6.900	3.867	0.767	28.141	0.022	32.413	8.107	24.183	6.700	12.526	0.672
D1	5.461	100.206	2m	32.261	0.021	31.398	8.107	24.648	2.500	2.741	0.325	34.547	0.022	31.340	8.105	24.083	3.700	12.925	0.596
D2	5.463	100.204	2m	32.247	0.022	32.283	8.107	24.570	3.487	7.748	0.597	33.235	0.021	31.915	8.110	25.801	3.206	10.065	0.620
D3	5.469	100.199	2m	33.519	0.021	32.953	8.106	26.040	2.691	3.516	0.326	38.452	0.021	32.326	8.107	24.595	2.774	4.713	0.742
D4	5.473	100.195	2m	27.408	0.021	31.046	8.108	25.753	3.850	15.648	0.406	29.693	0.022	32.304	8.108	24.867	3.042	16.164	0.537
D5	5.474	100.193	2m	28.361	0.021	31.810	8.107	26.752	5.395	6.672	0.439	29.715	0.022	31.183	8.105	25.560	5.423	12.630	0.258
D6	5.477	100.191	2m	28.741	0.021	32.956	8.105	25.096	5.179	16.205	0.310	29.139	0.022	32.881	8.106	25.226	5.119	4.034	0.326
D7	5.479	100.190	2m	27.805	0.021	32.529	8.109	24.677	6.479	2.270	0.733	26.341	0.021	32.531	8.108	24.256	6.405	11.556	0.434
D8	5.480	100.188	2m	26.740	0.021	31.054	8.106	25.451	6.983	8.465	0.639	28.974	0.021	32.287	8.109	24.705	6.673	10.077	0.269
E1	5.472	100.191	2m	29.585	0.022	31.421	8.110	26.792	3.936	9.135	0.485	25.921	0.021	32.282	8.109	26.462	3.393	9.598	0.663
E2	5.475	100.188	2m	28.013	0.021	31.741	8.110	26.908	5.469	7.734	0.248	28.947	0.021	31.879	8.110	26.089	5.451	4.639	0.727
E3	5.478	100.185	2m	14.487	0.022	31.764	8.108	25.364	6.638	10.719	0.644	13.574	0.022	32.678	8.108	24.137	6.522	14.666	0.298

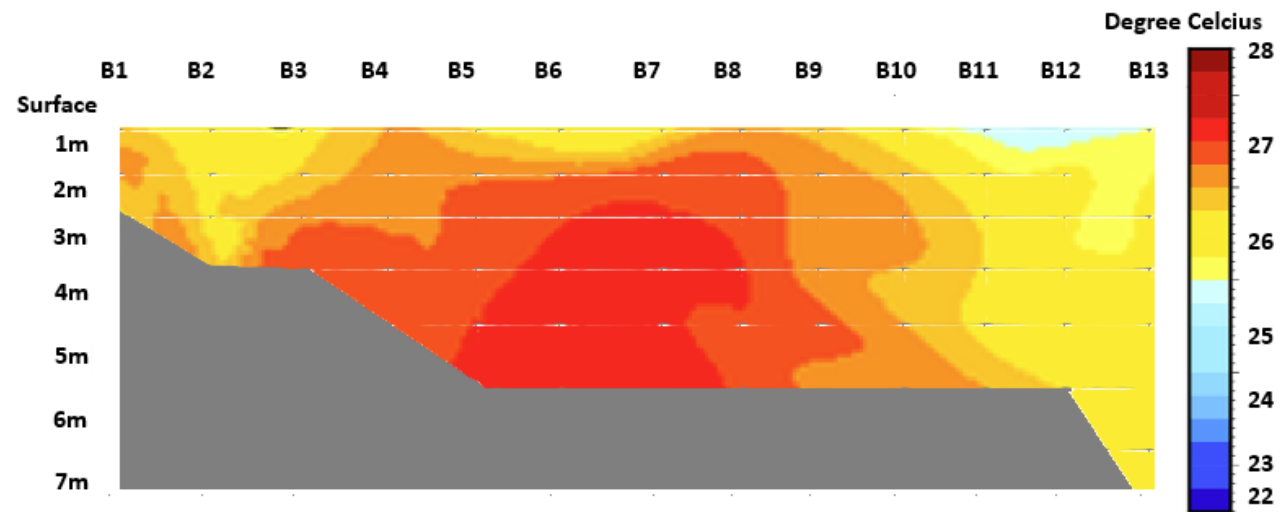
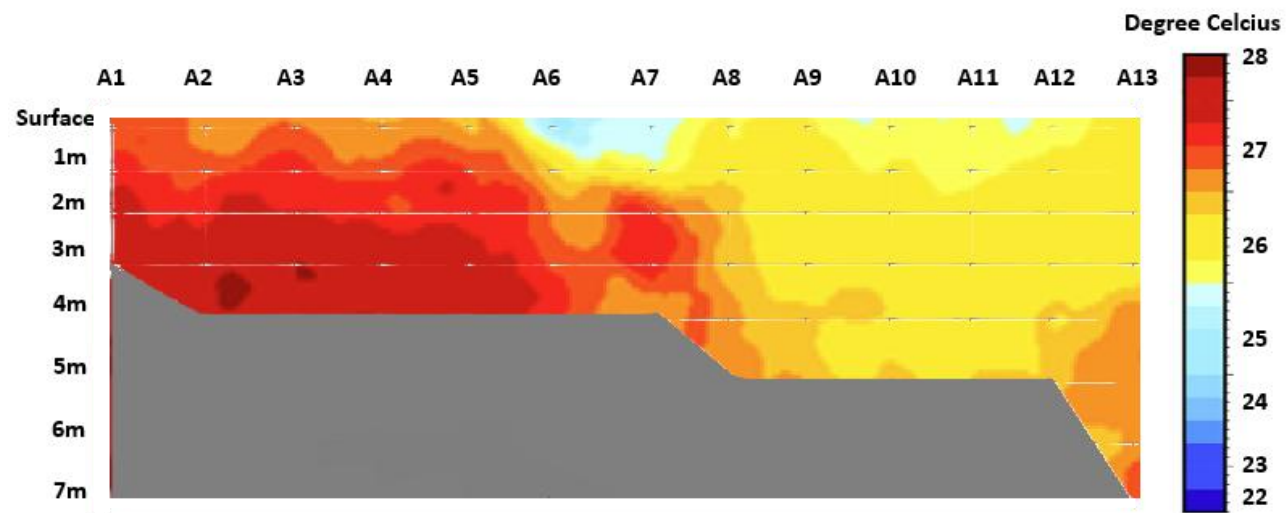


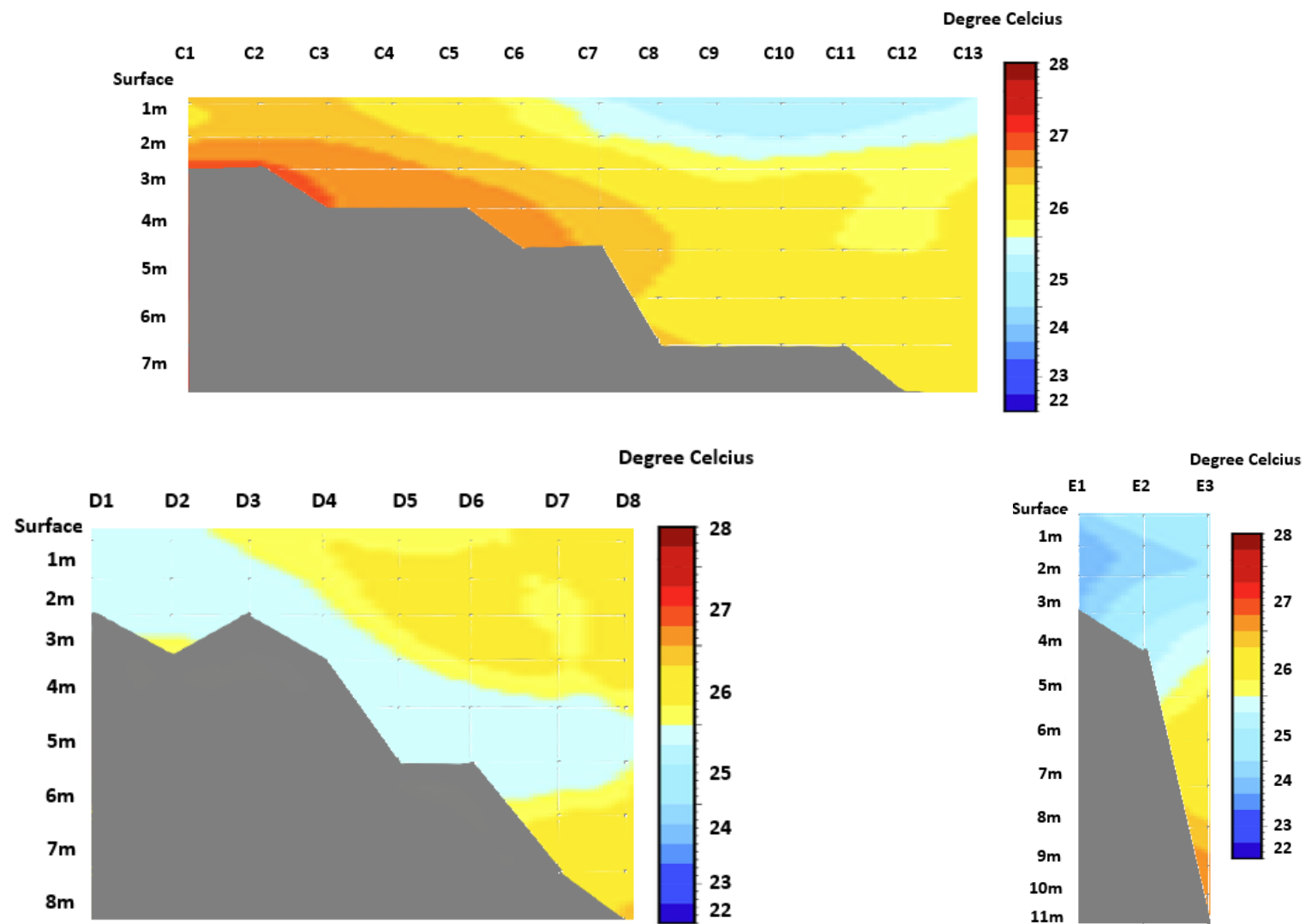
Mean Current Speed around Teluk Bahang, Pulau Pinang via dated August 2024 by integrated in-situ observations and historical NetCDF data value from ERA5-The European Centre for Medium-Range Weather Forecasts (ECMWF)



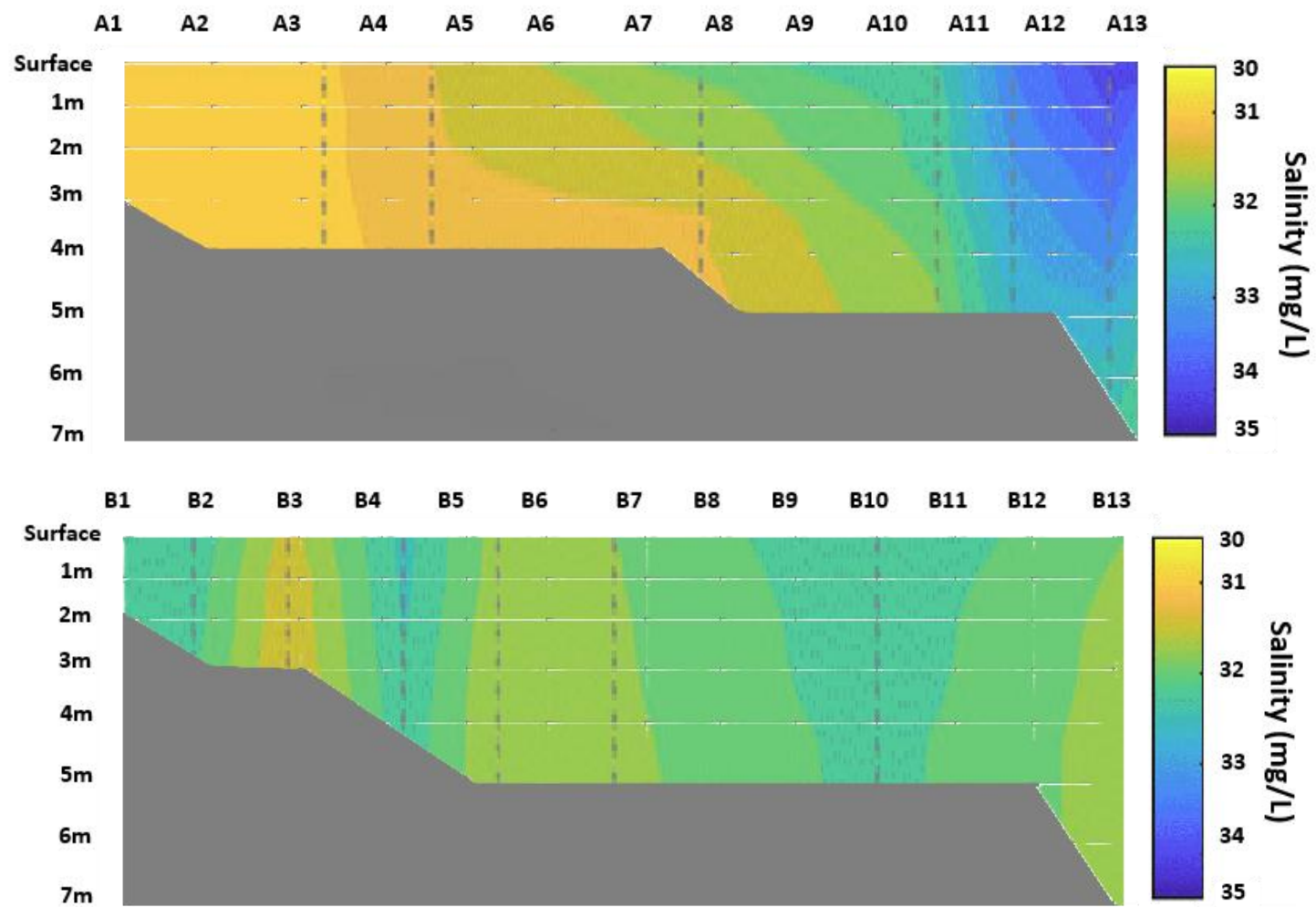


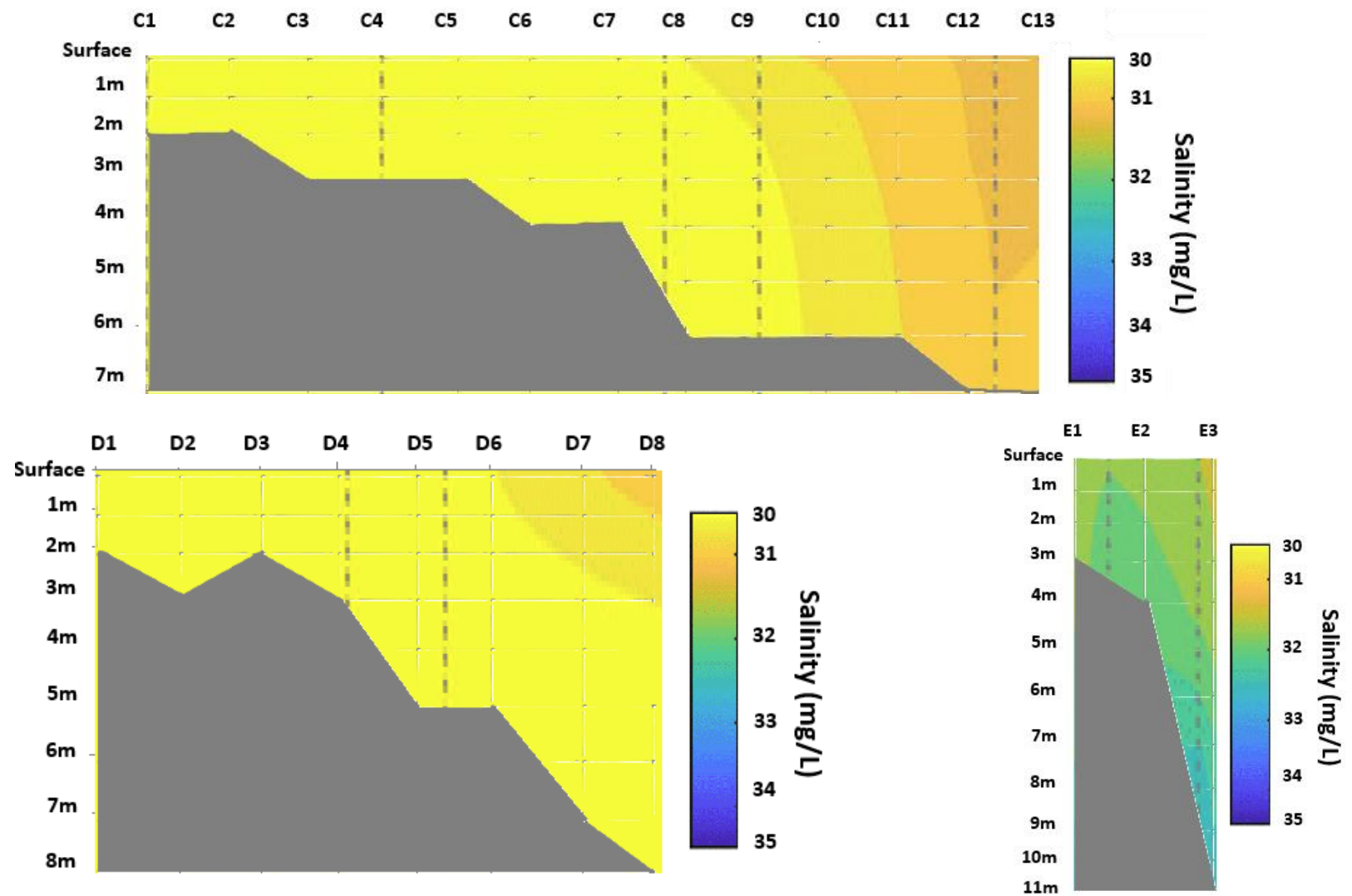
Vertical Distribution of Dissolved Oxygen (DO) along typical sections off the Teluk Bahang, Pulau Pinang in July-August 2024.



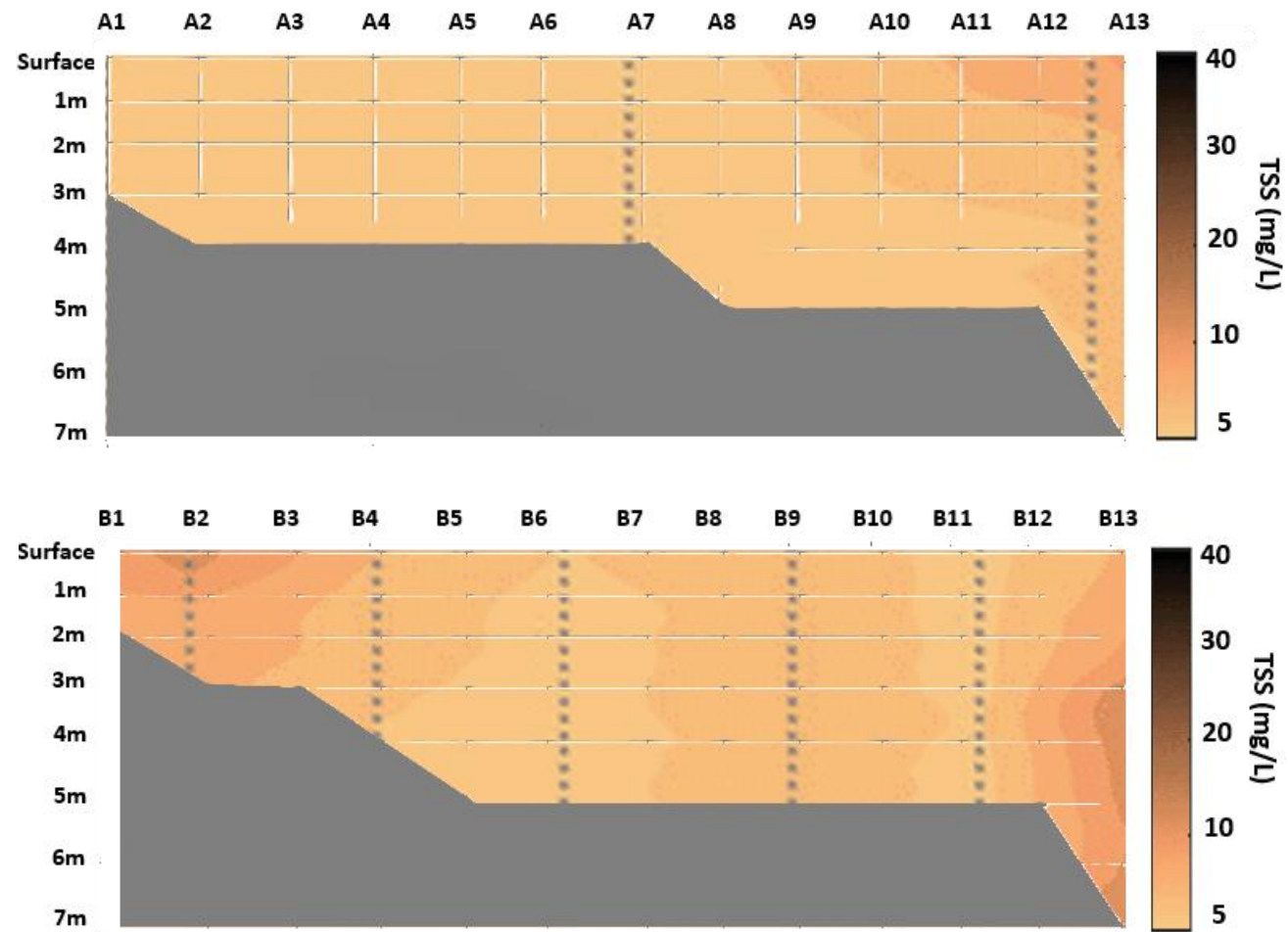


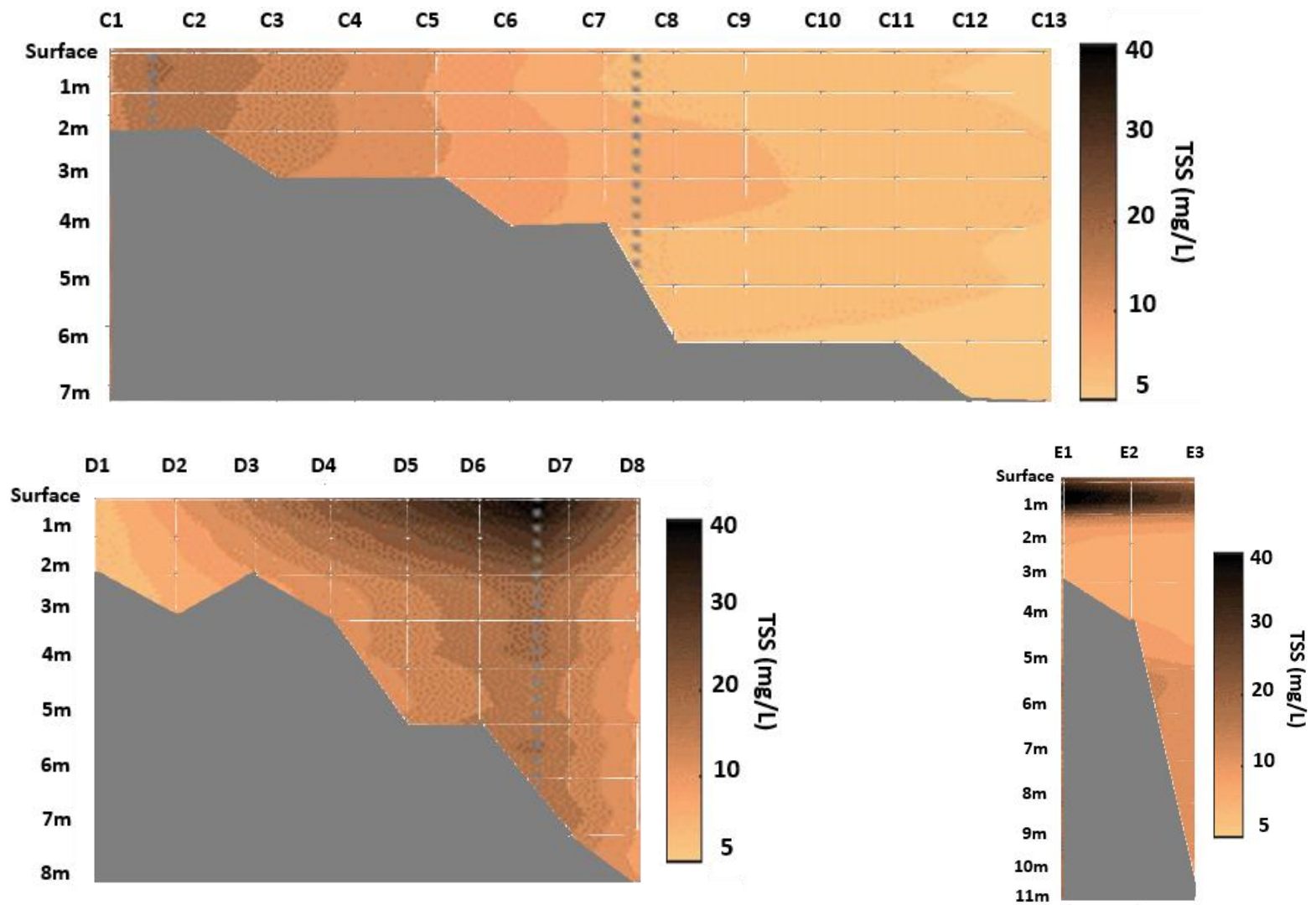
Vertical Distribution of Sea Temperature along typical sections off the Teluk Bahang, Pulau Pinang in July-August 2024.



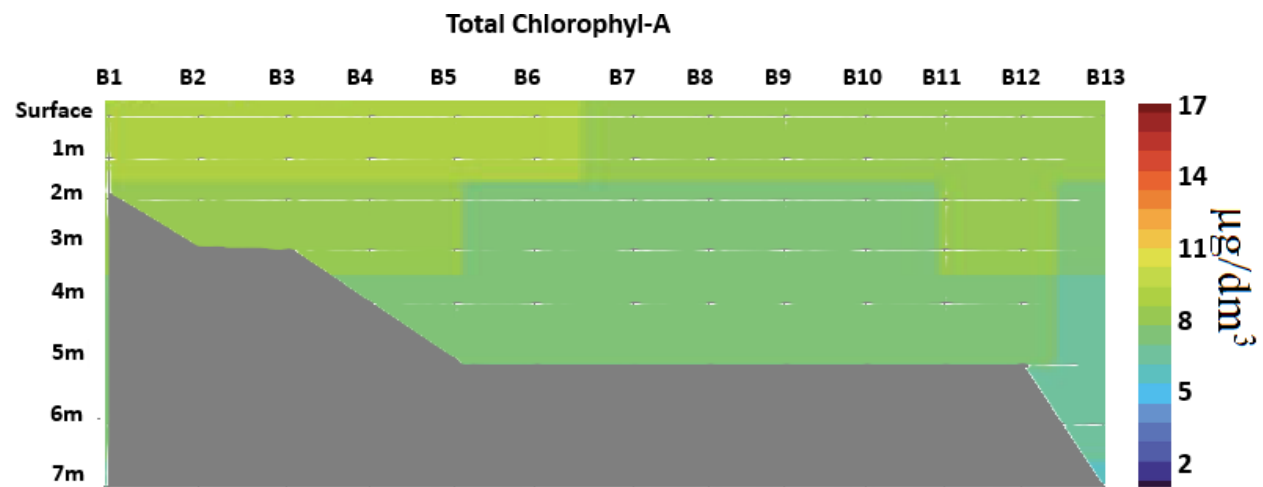
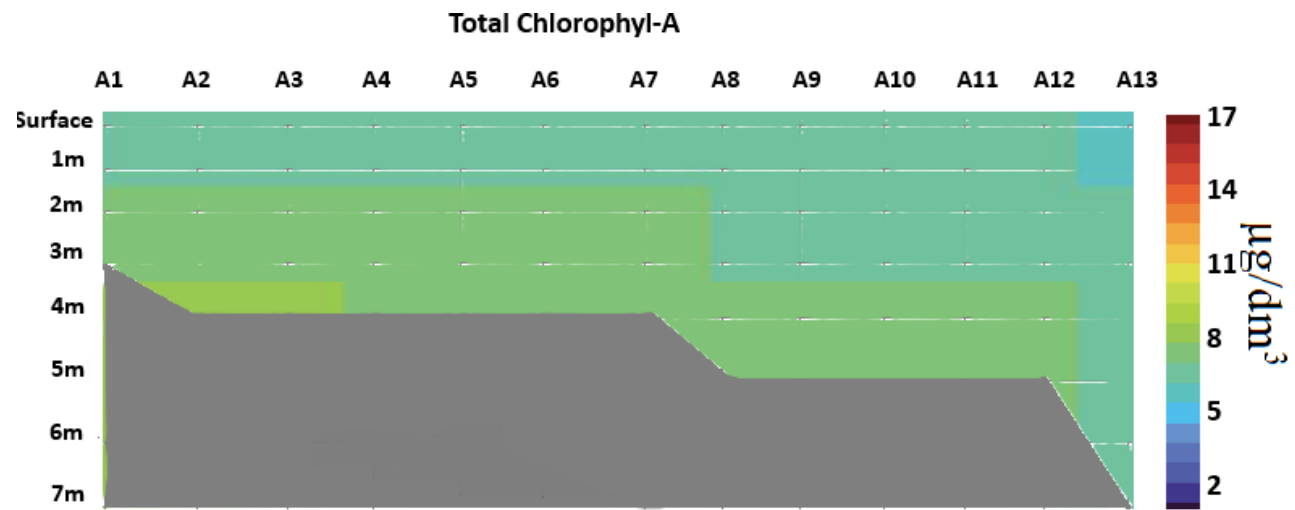


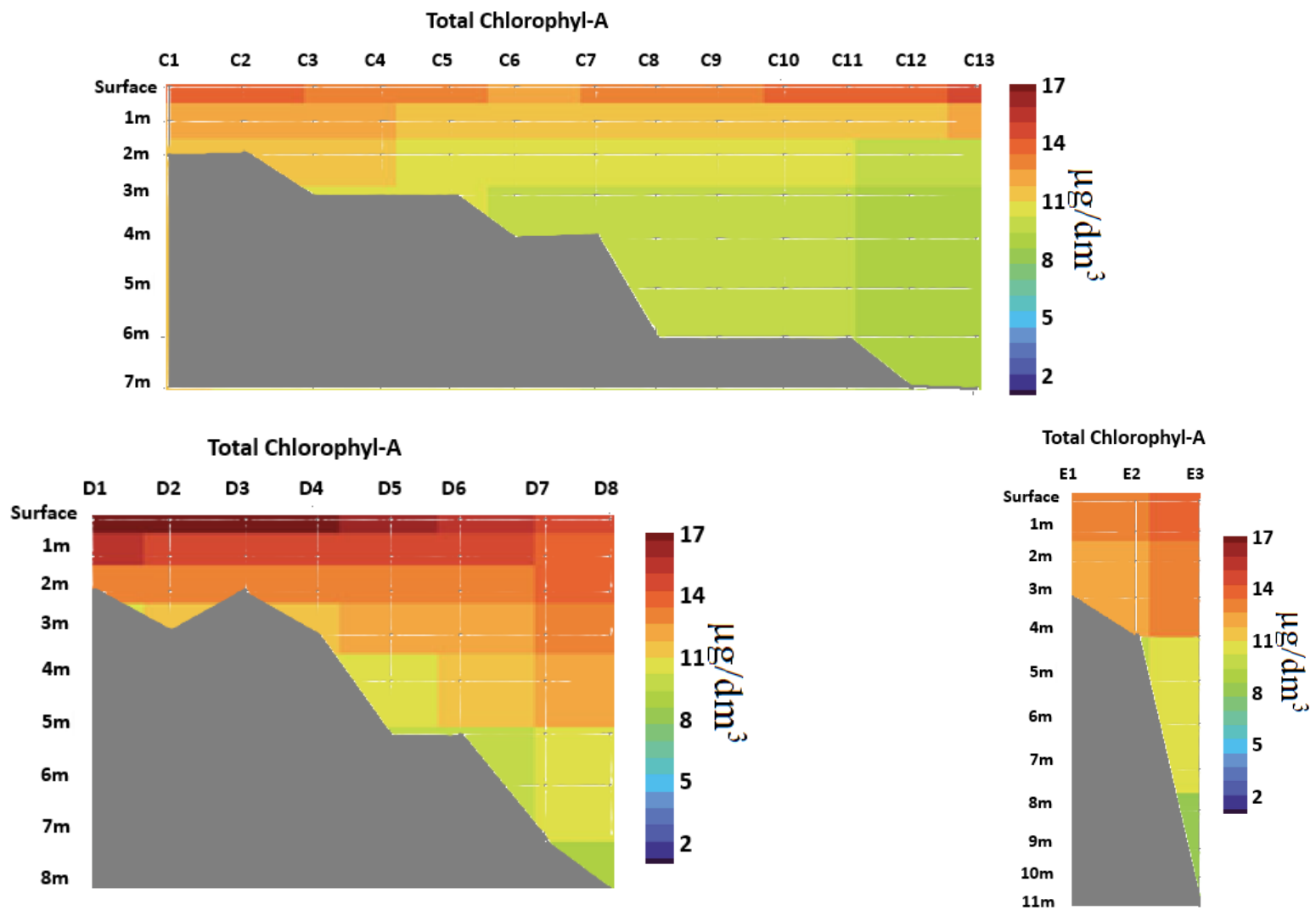
Vertical Distribution of Salinity along typical sections off the Teluk Bahang, Pulau Pinang in July-August 2024.



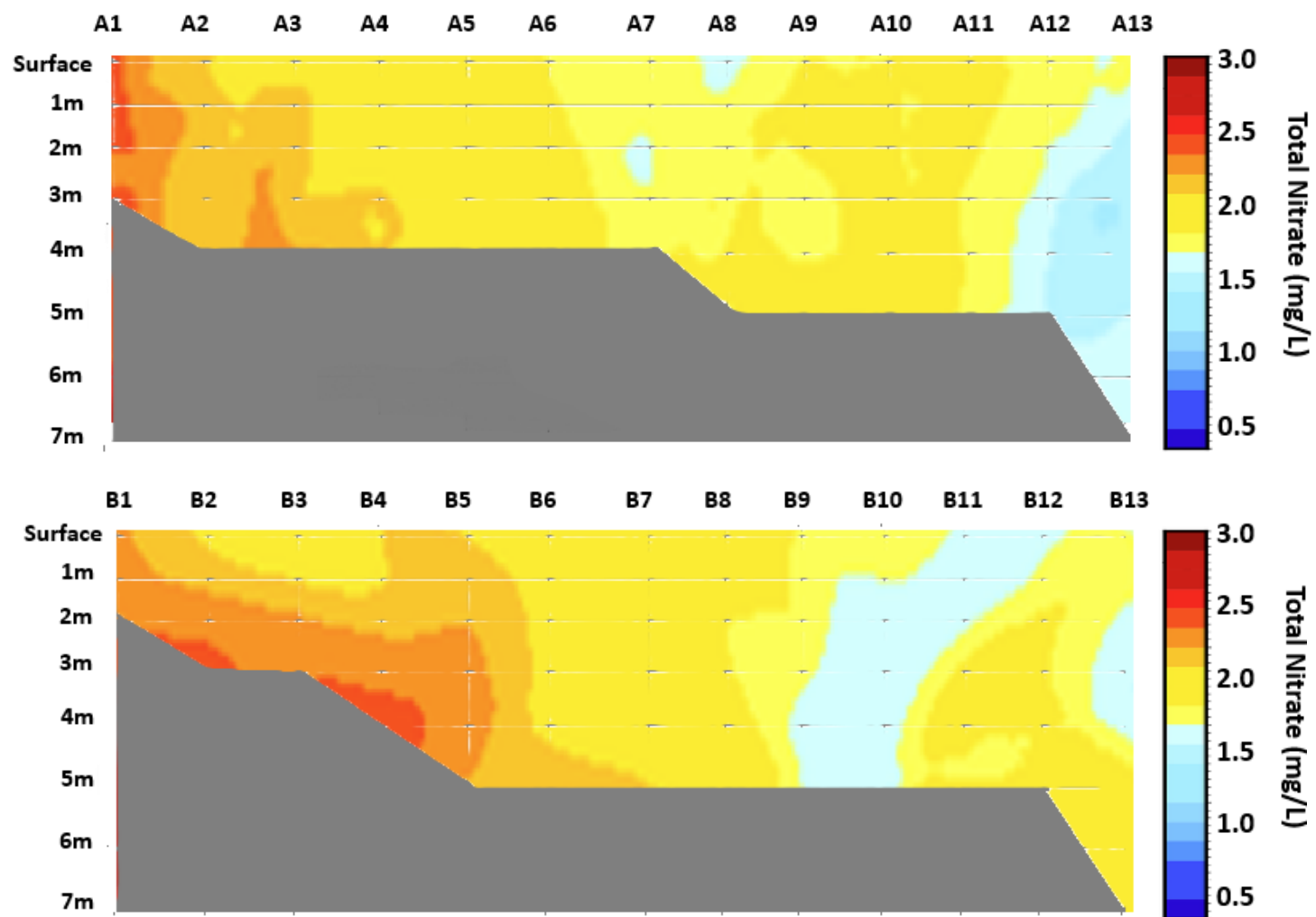


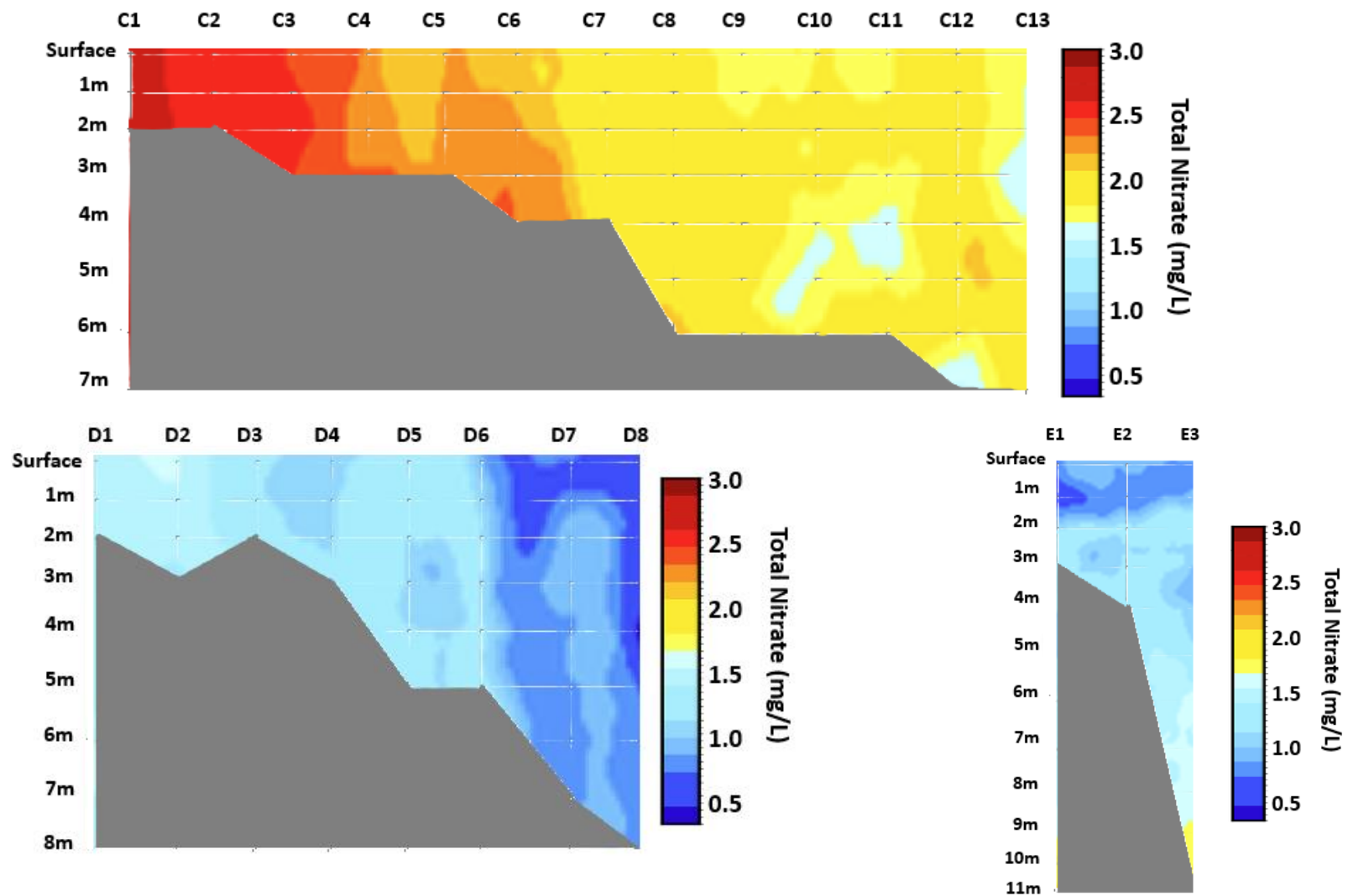
Vertical Distribution of Total Suspended Solids (TSS) along typical sections off the Teluk Bahang, Pulau Pinang in July-August 2024.





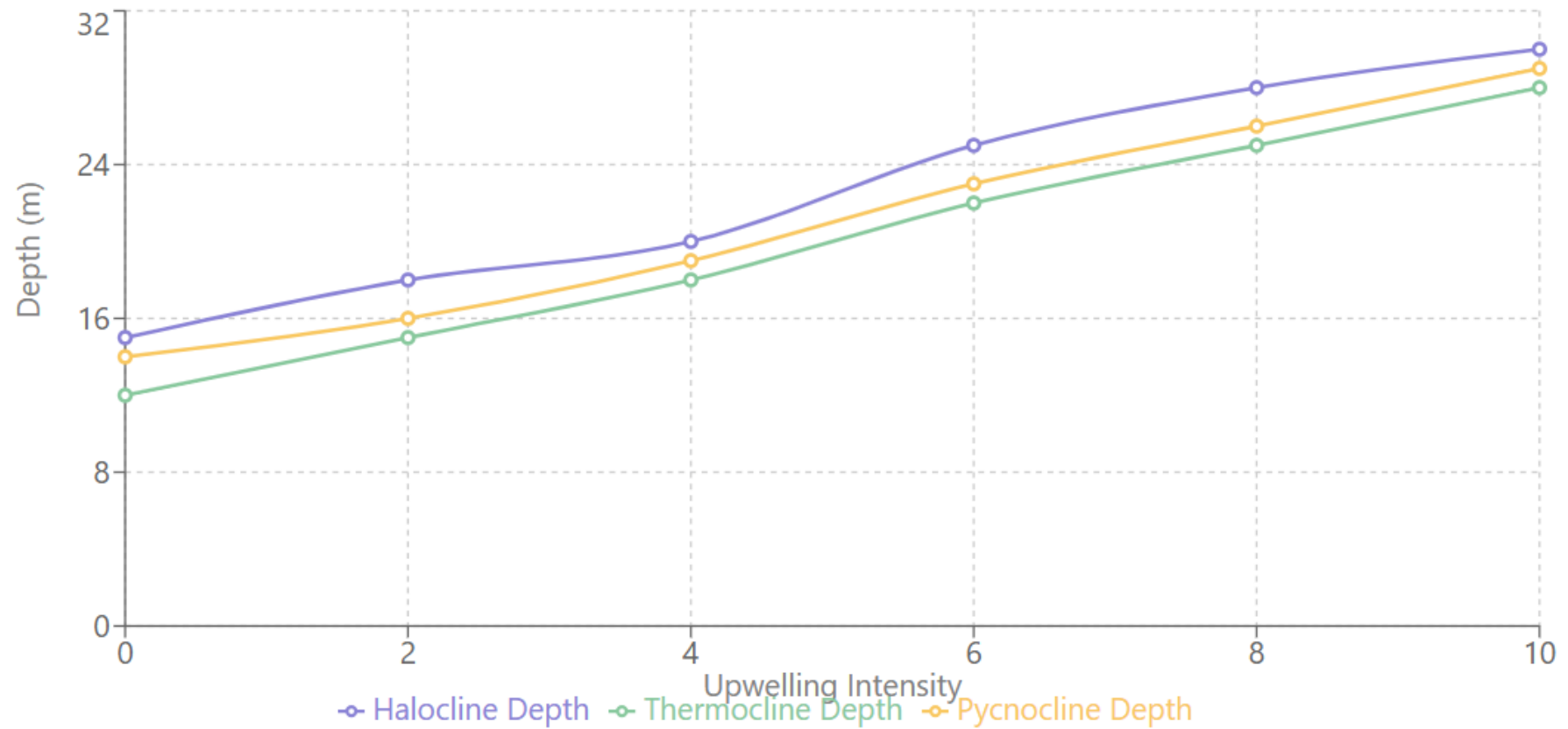
Vertical Distribution of Total Chlorophyll-A along typical sections off the Teluk Bahang, Pulau Pinang in July-August 2024.





Vertical Distribution of Total Nitrate along typical sections off the Teluk Bahang, Pulau Pinang in July-August 2024.

Ocean Properties vs Upwelling in Teluk Bahang



The vertical relationship strength of halocline, thermocline and pycnocline in each depth off the Teluk Bahang, Pulau Pinang in July-August 2024 via in-situ observations

Data Collection Activities



The boat had been used for survey and aquaculture farms off the Teluk Bahang, Pulau Pinang in July-August 2024.



Erosion conditions via high waves off the Teluk Bahang, Pulau Pinang in July-August 2024.



The beach characteristics and physical condition adjacent off the Teluk Bahang, Pulau Pinang in July-August 2024.



The Centre of marine and Coastal Studies (CEMACS, Universiti Sains Malaysia)



The beach tour and wave conditions during in-situ observations based on proposed site in July-August 2024.