Seasonal Hypoxia Occurrence At Terengganu Estuary, Malaysia And its Potential Formation Mechanisms

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Abstract. Hypoxia is commonly defined as oxygen depletion when the dissolved oxygen (DO) levels fall below 2 mg L\(^{-1}\). In this paper, physical factors contributed to hypoxic condition in the diurnal tide, Terengganu Estuary has been experimentally and analytically studies. Hourly profiles on DO, current speed and nutrient were measured during the wet and dry seasons for continuous period approximately 30 hours, which cover both high and low tide at two fixed stations, located at the river mouth and 9.50 km upstream from the river mouth, respectively. It was observed that the entire estuary was free from hypoxia during the wet season. However, hypoxia was developed at the river mouth during the dry season with lowest reading of the DO level was 0.78 mg L\(^{-1}\). It was demonstrated that the combination of high contamination of nutrient, low current speed, the geometrical formation and water stratification are recognized as important role in formatting the hypoxia at the Terengganu river mouth.

Keywords: hypoxia, dissolve oxygen (DO), estuary dynamics, river discharge, nutrient.

1. Introduction

The oxygen depletion in the estuarine environment is a global problem and reported increasing in severity and frequency [1,2,3]. Dissolved oxygen levels in the water columns are maintained through the interaction of numerous physical and biological factors, i.e., water column stratification, exchanges between the atmosphere and sea and its transport, biological oxygen production and consumption processes [4, 5]. Imbalances among these factors may lead to the development of hypoxia in the estuary. However, it was reported that since 1960s, excessive of anthropogenic inputs nutrients into the marine water has dramatically increased cases of hypoxia occurrences in the estuarine and coastal areas [6, 4, 7].

Dissolved Oxygen (DO) is an important water quality metric because it affects the wellbeing of marine organisms. Low DO can lead to catastrophic consequences for marine ecosystems and local economies that rely on commercial and recreational fisheries resources [8, 2]. Hypoxia is commonly defined as occurring when DO levels fall below 2 mg L\(^{-1}\) [9, 8, 2, 4, 10]. However, it was recognized that detecting hypoxia is difficult because DO value is extremely variable over short time scales, i.e., less than a day [8] or few days in estuaries [11].

Previous study on the DO dynamics and factors affecting the incidence of hypoxia in the estuary off the tropical area is limited [6, 1]. The main objective of this paper is to investigate the status of hypoxic event at Terengganu Estuary and to examine factors that contributed to its occurrences. The Terengganu Estuary, which is located in the east coast of the Peninsular Malaysia, is considered as a rain forest estuary of salt-wedge type that facing southern region of South China Sea.
2. Materials and Methods

2.1 Study area
The Terengganu River basin is located at 5.34°N and 103.15°E on the east coast of Peninsular Malaysia (Fig. 1a). The catchment area of the basin is about 4,600 km², consists of two main tributaries that drained into the Terengganu Estuary, namely the Terengganu River and Nerus River (Fig. 1b). At the river mouth, a breakwater has been constructed with an opening width of 200 m with the water depths for navigation channel is 8 to 10 m depth. The Terengganu River is the main stream in the catchment area, where its length is approximately 65 km, it drains from the Kenyir Dam that located at mountainous area with elevation of 100 m above the local mean sea level datum and flows eastwards (Fig. 1a), draining into South China Sea.

2.2 Data Sampling
The dissolved oxygen (DO) was measured at fixed stations, at the river mouth (the YB station with water depth approximately 7 m) and at upstream reaches 9.50 km from the river mouth, the Manir station with water depth approximately 5 m (Fig. 1b). Data campaign was done during the wet (5 to 6 March 2012) and dry (15 to 16 July 2012) seasons for duration of approximately 30 hours. Both data campaigns were carried up during end stage of neap tide, or early stage of spring tide. The measurements were made by two teams with fibre boats that anchored at the fixed stations. Hourly DO profiles were measured using YSI Professional Plus instrument with appropriate weight at the bottom, where measurements were made at 0.5 m below the water surface and at subsequent depth intervals of 1.0 m till it reached the bed layer. The YSI equipment was calibrated and verified before being deployed at the site.

In addition, the total organic carbon (TOC) was also been measured during the data campaign. Replicate samples of TOC were collected at the sub-surface (0.5 m below the water surface) and mid-depth of water depth. The measurements were carried out in hourly and continuous for 30 hours durations, which cover high and low water for wet and dry seasons. The Horizontal Van Dorn water sampler was used to collect water samples while high density polyethylene (HDPE) plastic bottles (1000 ml) were used as a water sample container. All the samples were preserved in Coleman ice-container box temperature below 4°C at the time of collection and were sent immediately to laboratory for TOC analysis. The determination of TOC concentration was based on [12], which related to method 2540C and 2540D in APHA (2005).

Two units of Nortek Aquadopp current profiler with a transducer head of 2 MHz were used to measure profiles current at the YB and Manir stations. Measurements were made during the wet (5 to 6 March 2012) and dry (15 to 16 July 2012). The instrument was installed within a stainless steel frame and deployed at the bed layer. These equipments were calibrated and verified upon being used at the site.

2.3 Oxygen concentration
The effects of low DO in the water columns were of particular concern for all the aquatic and marine habitats. Under this study, five categories of oxygen concentration were assigned [13]:

i) hypoxic or severe biological stress (0 to 2 mg L⁻¹);
ii) moderate biological stress (> 2 to 4 mg L⁻¹);
iii) mild biological stress (> 4 to 6 mg L⁻¹);
iv) normoxic (> 6 to 9 mg L⁻¹); and
v) supersaturated (> 9 or 10 mg L⁻¹)

3. Results

3.1 Seasonal changes in dissolved oxygen (DO) within Terengganu Estuary
It was observed that the depletion of the DO was severe during the dry season compared to the wet season (Fig. 2a). Moreover, water column was critical and in the hypoxic level at the river mouth (the YB station) compared to the upstream (the Manir station). The temporal and spatial DO concentrations at both stations (Fig. 2b), illustrated the DO levels were fairly homogenous in the entire estuary during the wet season; with DO concentration in the range of approximately 6 mg L⁻¹ from the upstream to river mouth and almost
consistence from the surface layers to bottom layers. On the other hand, during the dry season, the DO levels at these two stations were markedly different with average concentration of $3.76 \pm 0.56$ mg L$^{-1}$ ($n=159$) and $1.81 \pm 0.62$ mg L$^{-1}$ ($n=260$) for the Manir and YB station, respectively. In addition, it was observed that 93% throughout the measurement period the bottom layer of DO levels at the YB station (river mouth) were below the hypoxic threshold (2 mg L$^{-1}$), with the minimum value was recorded 0.78 mg L$^{-1}$ that occurred during the high water slack associated with local time from 6 to 10 o’clock in the morning.

Figure 1. Location of the Terengganu Estuary with defined measurement stations.

Generally it can conclude that entire estuary is free from hypoxia during the wet season and hypoxia is only occurred at the river mouth during the dry season. It was observed that the DO concentration at the upstream reach of estuary (Manir station) was absolved from hypoxic condition regardless of season. However, the hypoxic conditions occurred at the river mouth (YB station) might be due to seasonality factors controlling the hypoxia at this station. Thus, the remainder of this paper focuses on understanding various roles of physical factors that may contribute to hypoxic condition at only the YB station.

3.2 The Formation Mechanism Of Hypoxia At The YB Station

3.2.1 Seasonal variation of hydrodynamic and DO

The temporal evolutions of current for the wet and dry season are displayed in Figures 3a and 3b respectively. It indicated the estuary is forced by diurnal tides, with the main tidal forcing is due to the K1 tidal constituent, which has a tidal period of approximately 24 hours. Analysis on average seasonal tidal period for both seasons, which illustrated that approximately 30% (7 hours) of the tidal period was driven by the baroclinic gradient during flood tide while the remaining 70% (17 hours) was driven by barotropic pressure during ebb tide, thus the estuary is experiencing longer durations downstream discharge compared to upstream flow.
Homogenous current profiles flow was observed during the wet season (Fig. 3a) compared to the dry season (Fig. 3b), higher freshwater discharge during the wet season (approximately 300 m$^3$s$^{-1}$, recorded at river gauging station at Kpg Tanggol, about 30 km upstream from river mouth) compared to the dry season (approximately 180 m$^3$s$^{-1}$) perhaps contributed to this phenomenon. [14] reported most of the Asia regions estuaries experiences big volume of freshwater flow during the monsoon season or the wet season and it makes the estuary behaviour almost like a river. Both seasons illustrated the magnitude of the ebb current was higher than the flood current, with the median flow magnitude of the ebb and flood tide were 0.32 ms$^{-1}$ and 0.11 ms$^{-1}$ respectively for both seasons. [15] finding on the Maipo River in Chile, which is also subjected to diurnal tides, recorded almost similarly magnitude of tidal currents of approximately 0.2 ms$^{-1}$ and 0.1 ms$^{-1}$ during the ebb and flood tide respectively.

The DO profiles as shown in Figure 4 illustrated the DO magnitude during the wet and dry season vary from 4.76 to 7.25 mg L$^{-1}$ and 0.78 to 3.89 mg L$^{-1}$ respectively. Low DO in the hypoxic condition was observed during the dry season, particularly two meters from the bottom layers (Fig. 4b). Critical extent of hypoxic events with the magnitude lowest then 1.00 mg L$^{-1}$ was observed during the high water slack, where the entire water column was in the hypoxic level. Relationship between current flow and hypoxia in the water columns (Fig. 3b and 4b) during the dry season illustrated that hypoxia was developed associated with current flow less than 20 cms$^{-1}$. Finding by [16], reported the hypoxia is developed under the weak gravitation circulation mode of less than 5 cms$^{-1}$. 

**Figure 2.** Seasonal changes of DO in the estuary where the Manir station located at upstream, the YB station at the river mouth.
Figure 3. Comparison on current flow magnitude a) the wet season and b) the dry season. *negative current magnitude presents current flow towards upstream.

Figure 4. Comparison on the DO profiles for the YB station during a) the wet season and b) the dry season.
3.3 Water column profiles stratification during dry season
Analysis on the vertical distribution of the salinity and DO profile during the high water slack (Fig. 5a) and low water slack (Fig. 5b), illustrated during the high water slack, 80% of water column in the YB station was intruded by saline water concentrations of 31 ppt., apparently entire station at this particular moment was categorized as hypoxic stage as 100% of DO level was lesser than 2 mg L$^{-1}$(Fig. 5a). Meanwhile, during the low water slack, evident of sharp halocline that separated fresh and saline water was observed at the YB station (Fig. 5b), thus it strengthen the stratification and weaker the movement of vertical water column across the halocline [17, 16] developed significant depletion of the DO within 2 m water depth from bed level, where magnitude of the DO was 2.2 mg L$^{-1}$ at the surface and 1.74 mg L$^{-1}$ at the bed layer.

Figure 5. Water profiles stratification during high water slack a) and low water slack b) at the YB station.

3.4 Seasonal nutrient conditions
Analysis on the temporal and spatial nutrient effluents namely total organic carbon (TOC) in the water column at the YB station (Fig. 6), indicates the TOC level was approximately 167 ± 40 µM and 377.5±187.7 µM during the wet and dry season respectively. Similarly, the high contamination of TOC (> 300 µM) also been reported by [18] at the study site in the Gold Coast, Australia. It was reported the high ratio of TOC contents generally the key factors in enhancing biochemical process that required higher demand of oxygen for respiration and organic breakdown processes that causes the depletion of oxygen in the water column [4; 19].

Figure 6. Comparisons on the levels of TOC (µM) during the dry and wet season at the YB station.
4. Discussion and Conclusion

The temporal analysis on the distribution of the DO in the study area indicated the DO level during the wet season was higher compared to the dry season. Large fresh water inputs from the upstream and high density of rains during the wet season enhanced advection pressure in the estuary (Fig. 2), which has transported out most of the contamination in the estuary into near-shore area, resultant to high level of oxygen concentration in the water column during the wet season. However in the dry season, low freshwater released from Kenyir Dam associated with lesser rains [20], developed shallow water column at the study site that weaken the advection process and enhance the residence time in the estuary [21, 22]. When this scenario happen coupled with warmer water temperature and water column stratification (Fig. 5) during the dry season enhancing microbial productivity through biochemical process, thus it consumes more oxygen for respiration and decomposition of organic matter [21, 8, 23] which perhaps contributed to oxygen depletion. Similar finding was reported by [9] on tropical region estuary, northern Gulf of Mexico estuary, where the study shows that vertical diffusive oxygen exchange and advective oxygen transport are slow during dry season leading to significant extent of hypoxic events during summer.

The YB station located at the river mouth situated in town center and undergoing rapid developments in the industry sector and urbanization [24], where from morning to noon is the peak hours in daily activities, effluents input from the excessive organic matter loaded from adjacent main wet market[20] into water column could lead to accumulation of nutrients in the water column. Moreover if this situation associated with flood tide during the morning peak hours from 6 to 10 am (Fig. 3b) that minimized the outflow of contaminated blackish water with high concentration of nutrients (Fig. 6) into nearshore, associated with the low current flow magnitude (less than 10 cms\(^{-1}\), Fig. 3b) and strong stratification in the water column (Fig. 5a), which has enhanced the biochemical process and activated the respiration processes, result in significant oxygen depletion took place (Fig. 4b).

Occurrence of the hypoxia is subjected to variations, such as resident time particularly in hydrodynamic flow, contamination of nutrient concentrations in the water column, stratification levels in water column, geometry condition at the study site and others. It was observed that at the study area, hypoxia was developed through combination of low hydrodynamic flow associated with high concentration of nutrient. During the wet season, even though the current flow was low, which was less than 20 cms\(^{-1}\) (Fig. 3a) but due to low level of nutrient (Fig. 6), it could not trigger the formation of hypoxia at the study area (Fig. 4a). However, during the dry season, high concentration of nutrient (Fig. 6) coupled with low current magnitude that was lesser than 20 cms\(^{-1}\) (Fig. 3b), it developed hypoxia in the water column (Fig. 4b). Thus, perhaps hydrodynamic is not the main cause of hypoxia at the study area, but have to be combined with others variation to generate hypoxic condition. In addition, geometrical conditions too contribute to main consequence on leading the hypoxia [23, 19]. Position of the YB station was located at the deep navigation channel and semi enclosed breakwater’s arms (Fig. 1b & 7), where the deep trough and semi enclosed arms is favorable for sedimentation trapping of fine sediments from upper stream [23],it would isolate the bottom water in the navigation from exchange with surrounding oxygen rich water, through advection process due to stratification between fresh and saline water (Fig. 5a &b), making the bottom water inside the trough to be rather stable, leading to the hypoxic events.
In conclusion, hypoxia was developed during dry season at the study area particularly at the river mouth. It has demonstrated the linkage between the nutrients contamination, hydrodynamics, stratification and geometrical formation were the major controlling factors in developing hypoxic levels in the Terengganu river mouth.

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