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TIDAL DYNAMICS AND PHYSICOCHEMICAL PARAMETERS IN A TROPICAL ESTUARY: QUA-IBOE RIVER ESTUARY, SOUTHEAST COAST OF NIGERIA

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ABSTRACT

Estuaries are important ecosystems that support biodiversity and influence the economy of the regions they occupy. Major physicochemical variables of Qua-Iboe River estuary in the Niger Delta region of Nigeria were assessed for ecosystem quality. The influence of tidal current on the spatial distribution of physicochemical parameters in the estuary was examined. Physicochemical parameters, including transparency, temperature, salinity, dissolved oxygen, density and pH were measured in-situ during the dry season. Tidal current velocities were monitored over spring and neap tidal cycles using the Langragian method and results indicated ebb dominance. The relationships between physicochemical parameters were statistically analyzed using Pearson's correlation matrix. Based on Pearson's correlation, density showed significant correlations (p < 0.05) with temperature, pH and salinity. Surface and bottom water temperatures significantly correlated (p < 0.05) with density, salinity, dissolved oxygen and pH. Spatial distribution maps of physicochemical parameters were plotted using ArcGIS Pro. Similarities and dissimilarities of surface and bottom water parameters were interpreted using cluster analysis. Results revealed two groups reflecting distinct physicochemical characteristics in the study area. Group one, representing upper and central portions of the estuary is defined by waters which are limnetic to oligohaline, slightly acidic to neutral with low dissolved oxygen (<4mg/l) conditions. The estuary showed limnetic conditions at the upper reaches due to the strong fluvial input by the Qua-Iboe River. Group two, representing the lower estuary, is characterized by mesohaline to normal marine waters; neutral to slightly alkaline pH, and low dissolved oxygen (< 4mg/l) conditions. This study is relevant for future monitoring and assessment of the estuary and similar tidal ecosystems.

KEYWORDS: tides, physicochemical parameters, fresh water, estuary, Nigeria

INTRODUCTION

Estuaries are highly dynamic coastal ecosystems which act as a transitional zone between land and sea, and are influenced by physical processes such as waves, tides and fluvial currents. Estuaries can be classified based on tidal range, geomorphology and salinity distribution (Pritchard, 1952, 1955; 1967; Dyer, 1973; Hayes, 1975; Umgiesser & Zonta, 2010; Emeka et al., 2010, 2023a, 2023b, 2023c). They experience large spatial and temporal variations in biogeochemical processes and play a major role in biodiversity and global economy of the regions they occupy (Smith & Hollibaugh 1993). Estuaries and coastal areas are utilized for several human activities (i.e., domestic, agricultural and industrial). Estuaries are essential for fisheries exploitation, transportation, recreation and waste disposal (Boon et al. 1992; Akpan et al., 2002). They are unique ecosystems that hold vast species of aquatic organisms. The survival of these organisms is largely dependent on the water quality. Water quality parameters such as temperature, dissolved oxygen, salinity and pH, play an important role in the aquatic ecosystem and are important in the distribution of biodiversity.

Estuaries are impacted by a wide range of anthropogenic pressures. Discharge of municipal and industrial effluents, atmospheric deposition of acids and global effects of climate change have adverse effects on estuarine and brackish water systems (Maberly et al., 2020).

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Hydrodynamic data acquisition has become increasingly important in view of the pressures exerted on coastal and marine ecosystems in recent times. Natural and anthropogenic processes including weathering, urbanization, agricultural and industrial activities, tidal regime, precipitation rate, soil erosion and extraction of water resources are all major influences on the physicochemical properties of an estuary (Yang et al., 2012; Barboza et al., 2014; Shefat et al., 2020; Cereja et al., 2022).

These environments have been extensively studied for their physical, biological and sedimentological characteristics (Schröder-Adams, 2006). Hydrodynamic and sedimentological properties of meso-tidal estuaries along the Nigerian coastline have been documented by Emeka et al. (2010) and Antia et al. (2012). Antia et al. (2012) studied tidal regimes in Qua-Iboe River estuary and reported strong ebb dominance within the channel. Similar observations were made by Emeka et al. (2010) for the Calabar and Great-Kwa tidal rivers. Several authors (Akpan & Offem, 1993; Akpan, 1999; Akpan et al., 2002; Abowei, 2010; Dan et al., 2014; Agbugui & Deekae, 2014; Vincent-Akpu et al., 2015; Shefat et al., 2020; Otogo et al., 2021) have studied the physical and chemical characters of modern estuaries. Akpan et al. (2002) carried out an ecological baseline study of the Great-Kwa River and observed that pH correlated positively with salinity while DO showed positive correlations with salinity and temperature during the dry season. Vincent-Akpu et al. (2015) carried out a study on the spatial variation of physicochemical properties and metal contents of water and sediments of Bodo Creek, Niger Delta, Nigeria. The authors noted that DO ranged from 4.7 to 5.5mg/l, pH was alkaline (8.8-8.9) while water temperature varied from 26.7°C to 27.8°C, which is within the range typical for the Niger Delta region. Otogo et al. (2021) studied physicochemical properties along the banks of the Cross River estuary and observed a strong positive correlation between dissolved oxygen and water transparency.

Qua-Iboe River estuary is one of the most important estuaries in the Niger Delta region of Nigeria. The estuary was chosen for the present study in view of its numerous economic benefits. The study area lies between 4° 33′ 0″ and 4° 35′ 0″ N latitude and 7° 57′ 0″ and 8° 00′ 0″ E longitude (Figure 1). Qua-Iboe River estuary is located within the tropical equatorial rain forest belt of Nigeria. It takes its source from the Umuahia Hills and traverses Coastal Plain Sands and Alluvium before emptying into the Atlantic Ocean. The upper part of the estuary receives fresh water input from the Qua-Iboe River. Notable creeks adjoining the estuary include Douglas, Stubbs and Ukpenekang Creeks. Tidal regimes including flood and ebb are active within the channel. Hydrodynamic activities in Qua-Iboe River estuary have been reported by Antia et al. (2012). Average tidal current velocities of 0.5 m/s and 1.2 m/s during neap and spring tidal cycles have been recorded in the estuary (Antia et al., 2012). At flood tide, seawater penetrates into the estuary and pushes the estuary waters further upstream. The channel banks and surrounding mangrove vegetation are flooded. During ebb tide, the water retreats towards the sea and the banks are exposed. Waves are prevalent at the mouth of the estuary. The banks of the channel are fringed by mangrove swamps which serve as an important breeding ground for many species of fish. The estuary is a highly productive ecosystem that is rich in biodiversity. It is important for crude oil exploitation, commercial fisheries, maritime transportation, tourism, agriculture and sand mining. Several investigations have been carried out on the estuary’s water, sediment and biota. George et al. (2020) studied the physicochemical properties of surface waters including temperature, pH and dissolved oxygen during the dry season in Qua-Iboe River estuary. Dan et al. (2014) studied heavy metal contamination in surface waters of Qua-Iboe River estuary and attributed contamination of surface waters to atmospheric deposition, released of sediment bound metals to the surface, dissolution/erosion of coastal sediments and anthropogenic input. Antia et al. (2012) studied grain size distribution in Qua-Iboe River estuary and observed that the mean grain size of sediment decreased with an improvement in sorting downstream. Emeka et al. (2023) studied the ecology and distribution of foraminiferal assemblages in Qua-Iboe River estuary and observed a decrease in species diversity and abundance as salinity decreased upstream of the estuary.

Earlier physicochemical studies conducted in the Qua-Iboe River estuary were carried out mostly along the tidal banks (Dan et al., 2014; Harry et al., 2017). George et al (2020) carried out a physicochemical study along the tidal bank of the Qua-Iboe River estuary and reported surface temperature, pH and DO ranges of 26.5 to 27°C, 6.31 to 8.28 and 5.72 to 6.30 respectively. Temperature, salinity and dissolved oxygen play a key role in the survival and distribution of aquatic organisms. Although many multidisciplinary studies have been carried out, a detailed study on the spatial distribution of physicochemical parameters in surface and bottom waters throughout the estuary channel is lacking. This study seeks to provide a detailed assessment of the spatial variability of physicochemical parameters in the Qua-Iboe River estuary.

An attempt was made to understand how such variability is influenced by hydrodynamic processes and human activities. The inter-relationship between physicochemical parameters is assessed. Information from this study can provide insights for monitoring future changes in the ecosystem quality.

MATERIALS AND METHODS

Tidal current measurements were carried out in the Qua-Iboe River estuary from April 3, 2017 to March 30, 2018. Flood and ebb current velocities were measured during Spring and Neap tidal cycles using the Lagrangian technique. Surface and bottom water samples respectively were collected from an outboard motor boat at 55 geo-referenced sampling stations using a Teflon water sampler and a Nansen bottom water sampler. Physicochemical parameters such as temperature, transparency, dissolved oxygen, salinity, pH and density were directly measured in the field. Water temperature and pH were measured by using a hand-held multi-parametric meter (Hanna HI 98130). Dissolved oxygen was measured using a water-proof portable dissolved oxygen meter (HI 198193). Transparency was measured using a Secchi disk. Salinity and density values were determined using a salinity refractometer. The bathymetry of the channel was determined using an echo-sounder. Sampling stations extended from the tidal limit upstream of the estuary to the mouth where it empties into the Atlantic Ocean (Figure 1). Spatial maps of physicochemical parameters were plotted using ArcGIS v.10.8.1 (Esri Inc, Berkeley, California). Hierarchical clustering (Q-mode cluster analysis) was performed using Statistica v.10 (StatSoft, Inc, Tulsa, Oklahoma on surface and bottom water physicochemical parameters. Q-mode cluster analysis based on Ward's method was performed to define similarity of clusters between the sampling stations. Pearson's moment correlation was conducted using Statistica v.10 (StatSoft, Inc, Tulsa, Oklahoma) in order to examine the relationship between physicochemical parameters.

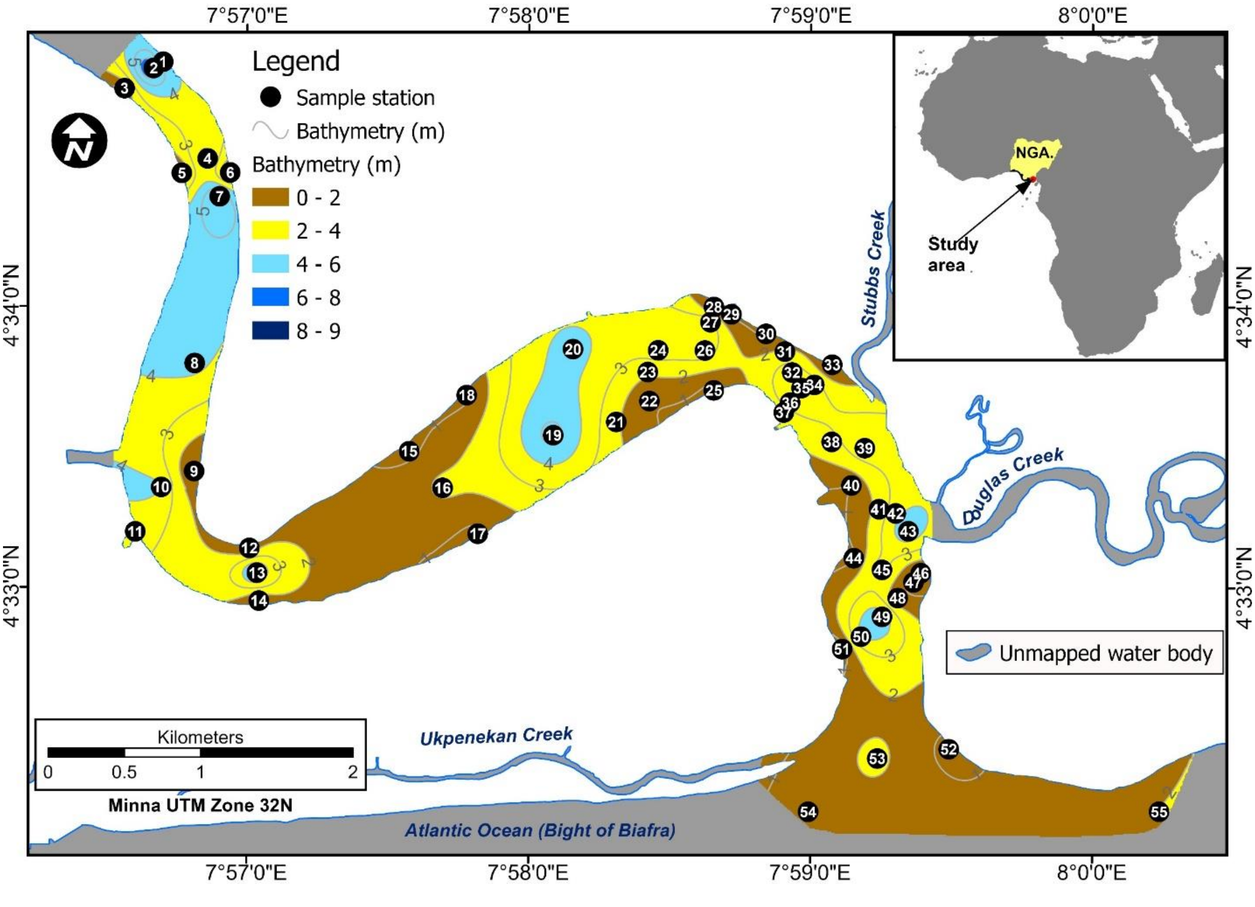


Figure 1: Location map of study area showing sample sites and bathymetry, Qua-Iboe River estuary, Southeast Coast of Nigeria.

RESULTS

Hydrodynamics and spatial variation of physicochemical properties

Tidal current velocity curves at spring and neap tides (Figures 2 and 3) are presented for Qua-Iboe River estuary. At spring tide, the maximum tidal current velocity recorded during flood and ebb tides are 1.0 m/s and 1.2 m/s respectively (Figure 2). During neap tidal cycle, the maximum surface tidal current velocity recorded at flood and ebb tides are 0.9 m/s and 1.1 m/s respectively (Figure 3). The average tidal current velocities during spring and neap tides for the estuary is presented in Figure 4. The average flood current velocity at spring and neap tides are 0.8 m/s and 0.6 m/s respectively. The average ebb current velocity at spring and neap tides were 1.0 m/s apiece.

Results of surface and bottom water physicochemical parameters recorded at 55 different sampling stations of the estuary are shown in Tables 1 and 2. Water transparency varied throughout the estuary. Figure 5 is a map depicting spatial variations in water transparency within the channel. Transparency ranged from 0.15 m (station 16) to 2 m (station 47) with a mean value of 0.85 m (Tables 1). Water transparency generally increased downstream of the estuary. The least water transparency values were recorded at the upstream limits of the estuary (Figure 5). Surface water temperatures ranged from 27.1°C (station 50) to 30.6°C (station 53) with a mean value of 28.8°C (Tables 1). Bottom water temperatures ranged from 27°C (station 50) to 31°C (station 53) with a mean value of 29°C (Tables 2). Spatial variations in water temperature is presented in Figure 6. A nearly uniform distribution pattern was observed for surface and bottom water temperatures (Figures 6a and b). The lowest temperature values were observed at the upstream limits of the estuary while maximum temperatures were recorded at the estuary mouth. Surface water salinity ranged from 0 ppt (stations 1-7; 9-11; 14-15) to 32 ppt (stations 52 and 54) with a mean value of 7.4 ppt (Tables 1). Bottom water salinity ranged from 0 ppt (stations 1-7; 10-11; 14-15) to 32 ppt (station 52) with a mean value of 8.1 ppt (Tables 2). Salinity was classified based on the Venice System of classification of marine waters (Venice, 1958). Bottom water salinity was generally higher than those of surface waters (Figures 7a and b). Fresh water (0 – 0.5 ppt) was observed in the upstream limit of the estuary.

Surface waters within the central portions of the channel were predominantly oligohaline (3–5 ppt). The lower portion of the estuary is characterized by mesohaline (10-18 ppt) and polyhaline (18-32 ppt) waters. Marine waters (30 -32 ppt) are prevalent at the mouth of the estuary. Bottom waters within the central portions of the channel were predominantly oligohaline (3–5 ppt) and mesohaline (5–10 ppt). The lower portion of the estuary is characterized by mesohaline (10-18 ppt), polyhaline (18-30 ppt) and euryhaline (30-32 ppt) waters. Surface and bottom water salinities showed an increasing downstream trend. Salinities of bottom waters were slightly higher than those of surface waters. Maximum salinities of 30-32ppt which was within the range typical of marine waters, were observed at the mouth of the estuary. Surface water pH ranged from 6.1 (stations 4, 18, 20 and 23) to 7.5 (stations 43 and 44) with a mean value of 6.7 (Tables 1). Bottom water pH ranged from 6 (stations 23 and 38) to 8 (station 43) with a mean value of 7 (Tables 2). Surface and bottom waters are predominantly slightly acidic to neutral throughout the channel. This may be suggestive of high fluvial input into the estuary since fresh waters generally have lower pH than marine waters. Reid (1961) observed that streams and rivers transporting large quantities of humic materials containing colloidal suspensions are generally acidic in nature. The lower reaches of the estuary is characterized by slightly acidic to slightly alkaline waters (Figures 8a and b). Surface water dissolved oxygen ranged from 1 mg/l (stations 44, 46-51) to 6.7 mg/l (station 34) with a mean value of 3.24 mg/l (Tables 1). Bottom water dissolved oxygen ranged from 0 mg/l (station 47) to 7 mg/l (station 34) with a mean value of 3.2 mg/l (Tables 2). The distribution pattern of surface and bottom water DO in Qua-Iboe River estuary is presented in Figures 9a and b respectively. Low DO values (0-2 mg/l) were recorded in the limnetic waters of the upper estuary. The low DO levels (0-2 mg/l) observed in the upper reaches of the estuary may be related to low transparency which limits photosynthetic activity resulting in low DO. Similar low levels of DO have been recorded for Great-Kwa River (Akpan, 2002). Generally, due to fluvial inputs, the upper reaches of the estuaries usually present higher levels of turbidity, sediment and nutrients (Cereja et al., 2022). Dissolved oxygen values of 2 - 4 mg/l were predominant in the central portions of the channel (Figures 9a and b). Surface water density ranged from 1 kg/m^3 (stations 1-7, 9-11, 14-15 and 31-32) to 1.02 kg/m^3 (stations 52 and 54) with a mean value of 1.004 kg/m^3 (Table 1). Bottom water density ranged from 1 kg/m^3 (stations 1-7, 9-11, 14-15 and 31-32) to 1.02 kg/m^3 (stations 52 and 54) with a mean value of 1.006 kg/m^3 (Tables 2). The distribution pattern of surface and bottom water density of the Qua-Iboe River estuary is presented in Figures 10a and b respectively.

Pearson's Correlation

The relationship between physicochemical parameters in Qua-Iboe River estuary were analyzed using Pearson correlation matrix (Tables 3 and 4).

Water transparency showed negative correlations with temperature (r=-0.24); pH (r=-0.14); dissolved oxygen (r=-0.11) and density (r=-0.06) as shown in Table 3. In surface waters, temperature showed significant correlations ($p<0.05$) with pH (r=0.67); salinity (r=0.44); dissolved oxygen (r=0.39) and density (r=0.38) while pH showed significant correlations ($p<0.05$) with salinity ($r=0.48$) and density ($r=0.42$). Density showed significant correlations ($p<0.05$) with salinity ($r=0.84$).

In bottom waters, temperature showed significant correlations ($p<0.05$) with pH ($r=0.63$); salinity ($r=0.38$); dissolved oxygen ($r=0.48$) and density ($r=0.38$). Density showed significant correlations ($p<0.05$) with salinity ($r=0.82$). pH showed significant correlations ($p<0.05$) with salinity ($r=0.49$) and density ($r=0.43$) as shown in Table 4. Similar significant correlations of temperature with pH, salinity and dissolved oxygen have been reported by Dan et al. (2014) for Qua-Iboe River estuary. They observed for the dry season that temperature showed significant correlations with pH and salinity.

Cluster analysis

The Q-mode cluster analysis performed on all samples using the Ward's method based on Euclidean distances yielded two distinct clusters. Group 1 occurred at a linkage distance of 165 and Group 2 at a linkage distance of 110 (Figure 11). Cluster 1 extends from the upper to the central estuary environment characterized by a maximum water depth of 10 m. Temperatures in this environment typically ranged from 27°C - 29°C. Waters are limnetic to oligohaline, slightly acidic to neutral with low dissolved oxygen (<4mg/l) conditions. Cluster 2 occurs in the lower estuary environment characterized by water depths ranging from 0 to 2 m. Temperatures in this environment predominantly ranged from 29°C - 31°C. Waters are mesohaline to euryhaline, slightly acidic to slightly alkaline with low dissolved oxygen (<4mg/l) conditions

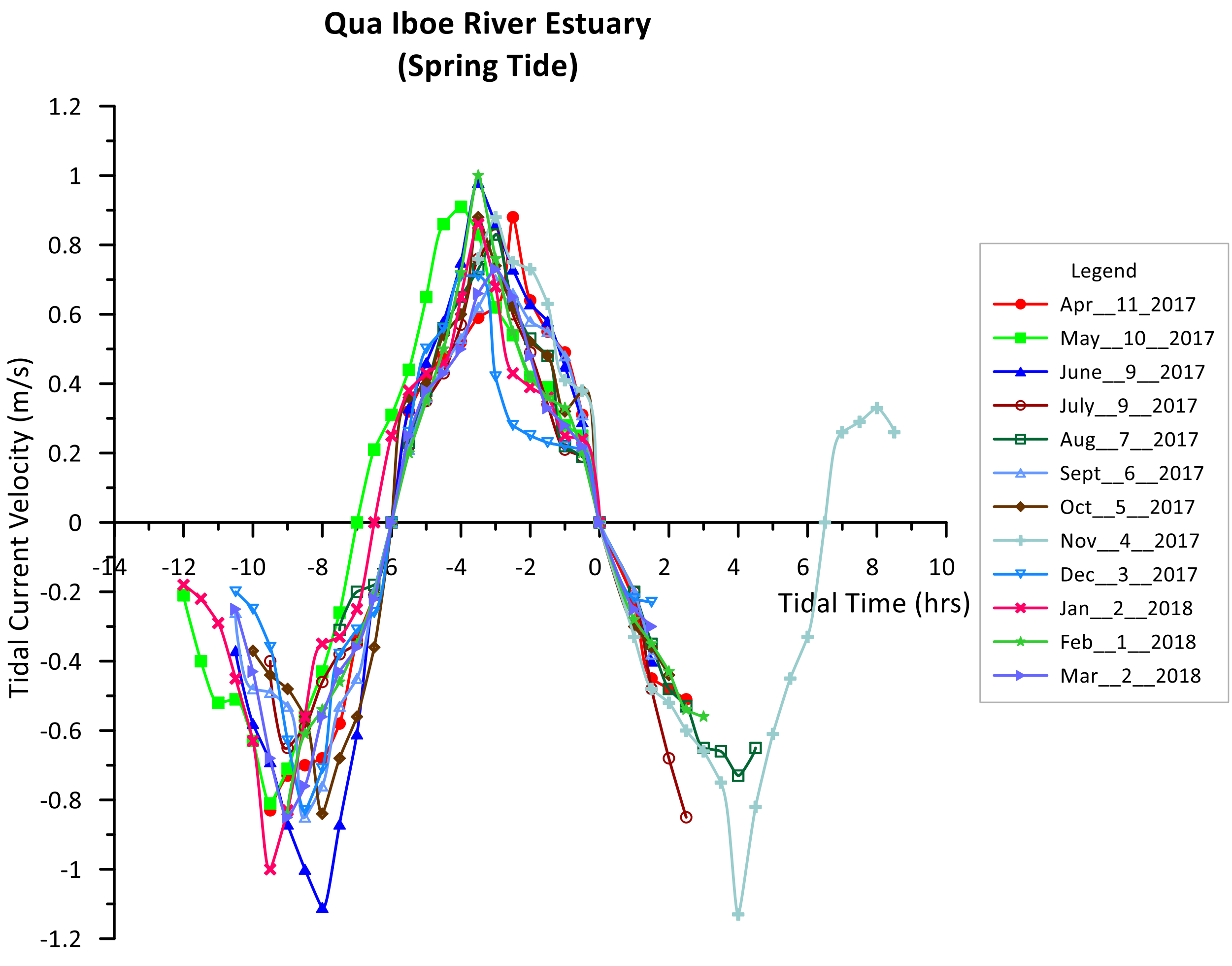


Figure 2: Surface tidal curves for Qua-Iboe River estuary at spring tide (April 2017 to March 2018)

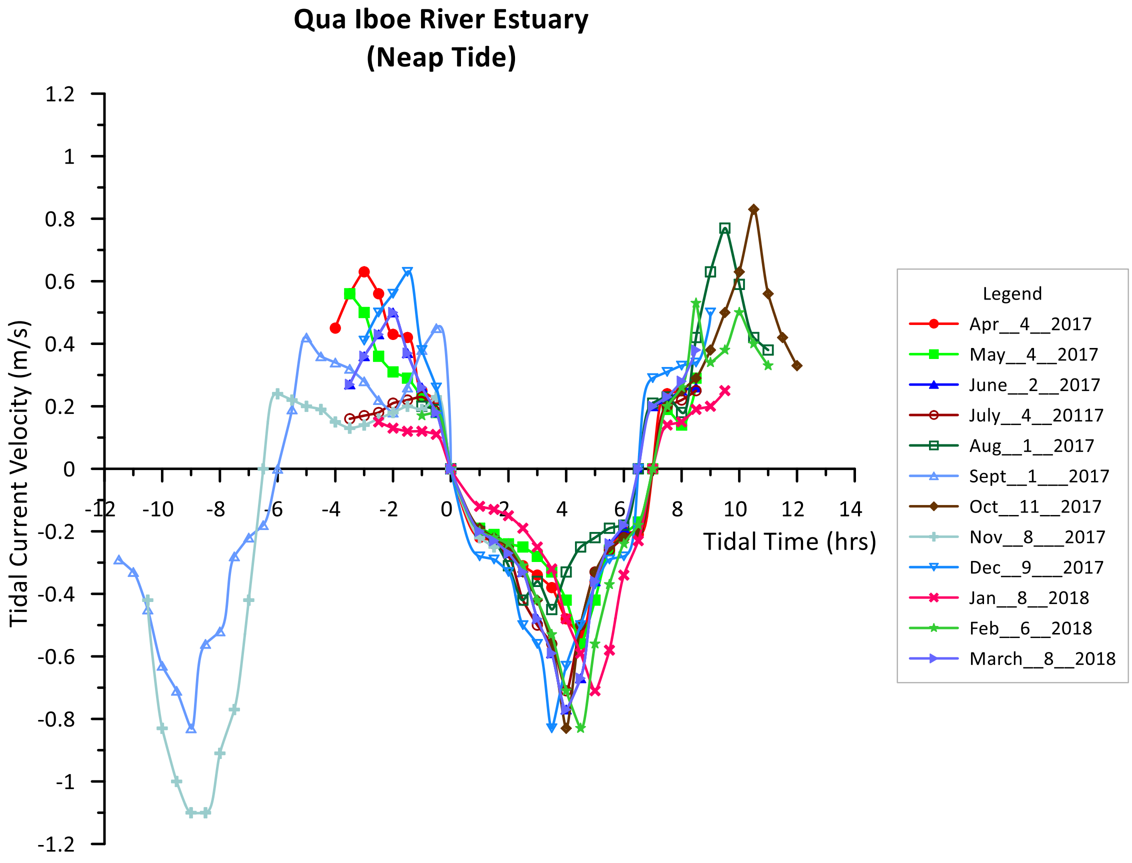


Figure 3: Surface tidal curves for Qua-Iboe River estuary at neap tide (April 2017 to March 2018)

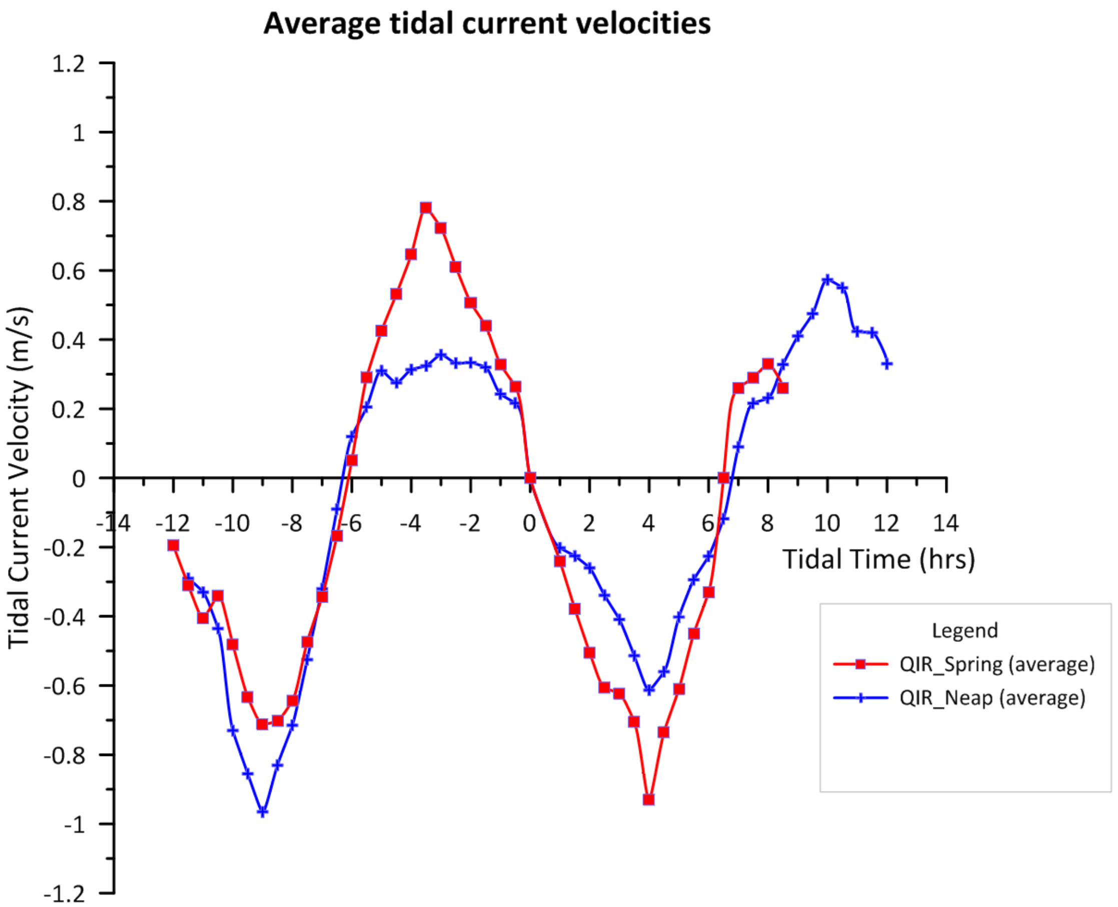


Figure 4: Average surface tidal curves for Qua-Iboe River estuary at spring and Neap tides

Table 1: Surface water physicochemical characteristics of the Qua-Iboe River estuary

Sample point	Transparency (m)	Surface Temp. (°C)	Surface pH	Surface Density (kg/m^3)	Surface Salinity (ppt)	Surface DO (mg/l)
1	0.86	27.6	6.2	1	0	1.8
2	0.26	28.2	6.2	1	0	1.9
3	0.61	27.8	6.2	1	0	1.5
4	0.26	28.1	6.1	1	0	1.9
5	0.45	27.5	6.2	1	0	1.6
6	0.96	27.8	6.2	1	0	1.7
7	0.86	28.2	6.5	1	0	1.8
8	1.06	27.6	6.3	1.003	4	2.1
9	0.68	28.3	6.4	1	0	1.8
10	0.86	28.7	6.3	1	0	2
11	0.76	29	6.7	1	0	2.1
12	0.66	29.3	6.9	1.015	5	2.3
13	0.23	28.7	7	1.005	5	2.4
14	0.8	29.4	6.6	1	0	1.9
15	0.8	28.6	6.8	1	0	2.2
16	0.15	29.5	6.8	1.005	7	2.4
17	1.31	28.9	6.5	1.002	2	4.4
18	1.27	27.8	6.1	1.003	5	2.2
19	1.05	29	6.8	1.001	4	4.4
20	1.27	27.9	6.1	1.002	5	2.1
21	1.26	28	6.5	1.003	4	2.4
22	1.01	29	6.5	1.002	4	5.2
23	1.24	27.8	6.1	1.003	5	2.2
24	1.26	27.9	6.2	1.005	5	2.3
25	0.35	28.7	6.7	1.002	3	6.1
26	0.7	29.2	6.8	1.003	5	6
27	0.42	30.2	6.8	1.002	2	5
28	0.4	29.8	6.6	1.001	2	4.5
29	0.65	29.5	6.7	1.002	5	6.2
30	0.45	29.5	6.8	1.004	5	4.5
31	0.68	29.8	6.7	1	6	5.2
32	1.21	28.6	6.8	1	3	4.5
33	0.46	29.5	6.9	1.005	10	4.8
34	1.7	28.9	6.9	1.001	9	6.7
35	1.71	28.6	6.9	1.001	9	6.6
36	1.05	28.7	6.5	1.008	10	5.8
37	1.02	28.6	6.2	1.006	10	5.5
38	0.68	27.9	6.4	1.005	11	5.6
39	0.69	29.3	6.6	1.003	10	4.6
40	0.7	30	7.2	1.01	11.14	2.1
41	0.67	29.9	7.3	1.005	12	2.5
42	0.65	30	7.2	1.004	12	2.6
43	0.65	29	7.5	1.003	10	2.58
44	0.7	29.3	7.5	1.008	10	1
45	0.38	29.7	7.2	1.01	15	6.1
46	1.48	29.4	6.9	1.001	11	1
47	2	29.5	6.9	1.01	10	1
48	1.05	29.2	6.9	1.01	12	1
49	1.22	27.8	6.5	1.001	11	1
50	1.1	27.1	6.7	1.01	14	1
51	1	27.3	6.8	1.01	15	1
52	0.21	30.6	7.1	1.02	32	5.9
53	1.5	30.2	6.6	1.01	20	2.8
54	0.67	29.8	6.7	1.02	32	2.7
55	0.76	29.7	7	1.01	25	5.6
Max	2	30.6	7.5	1.02	32	6.7
Min	0.15	27.1	6.1	1	0	1
Mean	0.85	28.83	6.66	1.00	7.40	3.24
SD	0.41	0.85	0.36	4.80E-03	7.25	1.80
Variance	0.16	0.72	0.13	2.31E-05	52.55	3.25

Table 2: Bottom water physicochemical characteristics of the Qua-Iboe River estuary
(Bottom water pH, Temperature, DO and Salinity cited from Emeka et al., 2023)

Sample point	Bottom Temp. (°C)	Bottom pH	Bottom Density (kg/m^3)	Bottom Salinity (ppt)	Bottom DO (mg/l)
1	28	6	1	0	2
2	28	6	1	0	2
3	28	6	1	0	2
4	28	6	1	0	2
5	28	6	1	0	2
6	28	6	1	0	2
7	28	6	1	0	2
8	27	6	1	10	2
9	28	6	1	1	2
10	28	6	1	0	2
11	28	7	1	0	2
12	29	7	1	5	2
13	29	7	1	5	2
14	29	7	1	0	2
15	28	6	1	0	2
16	30	7	1	7	2
17	30	7	1	5	5
18	28	6	1	5	2
19	29	7	1	4	4
20	28	6	1	8	2
21	28	6	1	6	2
22	29	7	1	4	5
23	28	6	1	7	2
24	28	6	1	8	2
25	28	7	1	10	6
26	29	7	1	5	6
27	30	7	1	2	5
28	30	7	1	2	5
29	30	7	1	5	6
30	30	7	1	5	5
31	30	7	1	6	5
32	29	7	1	3	5
33	30	7	1	10	5
34	29	7	1	9	7
35	29	7	1	9	7
36	29	7	1	8	6
37	29	7	1	9	6
38	28	6	1	10	5
39	30	7	1	11	4
40	30	7	1	11	2
41	29	7	1	13	1
42	29	7	1	13	2
43	28	8	1	12	2
44	29	8	1	10	1
45	30	7	1	15	6
46	29	7	1	11	1
47	29	7	1	20	0
48	29	7	1	14	1
49	28	7	1	12	1
50	27	7	1	16	1
51	27	7	1	15	1
52	31	7	1	32	6
53	30	7	1	20	3
54	30	7	1	28	3
55	30	7	1	25	6
Max	**31**	**8**	**1**	**32**	**7**
Min	**27**	**6**	**1**	**0**	**0**
Mean	**28.82**	**6.73**	**1.00**	**8.11**	**3.20**
SD	**0.94**	**0.52**	**0.00**	**7.18E+00**	**1.91**
Variance	**0.88**	**0.27**	**0.00**	**5.16E+01**	**3.65**

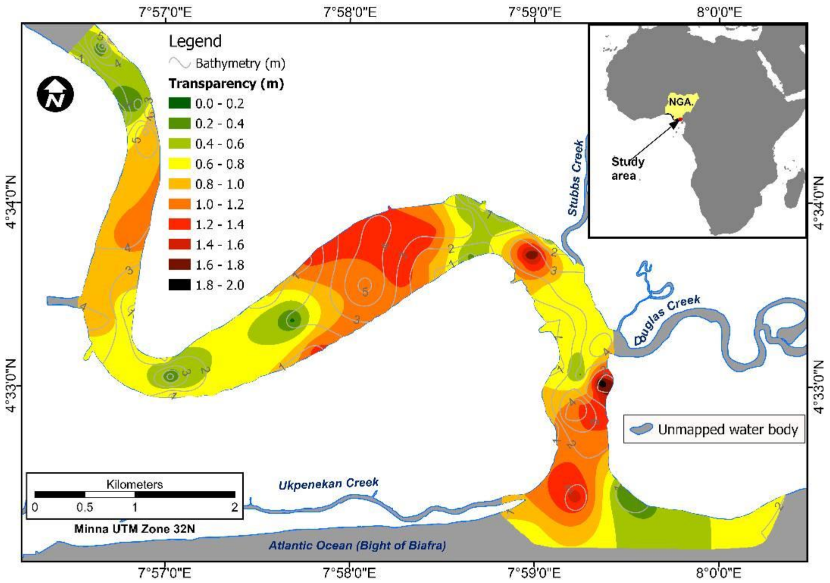


Figure 5: Water transparency map of the Qua-Iboe River estuary

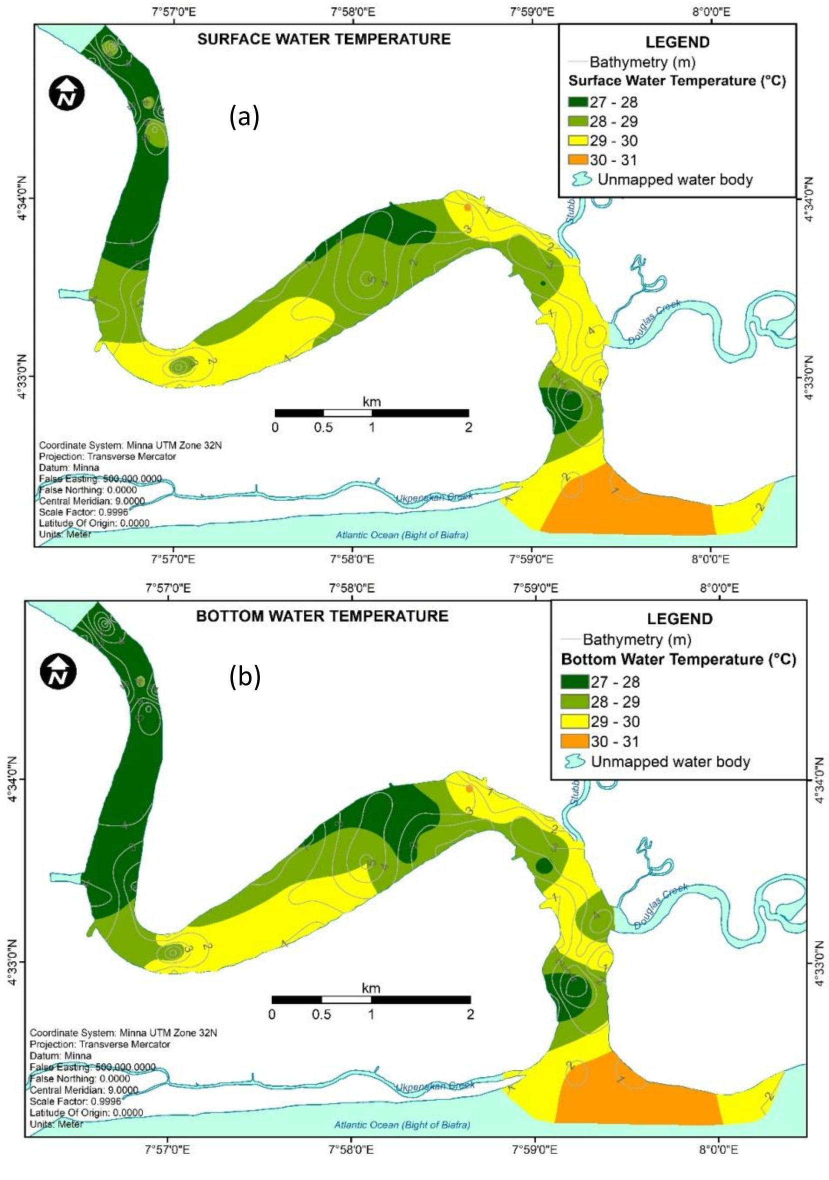


Figure 6: Temperature distribution in Qua-Iboe River estuary (a) surface water (b) bottom water

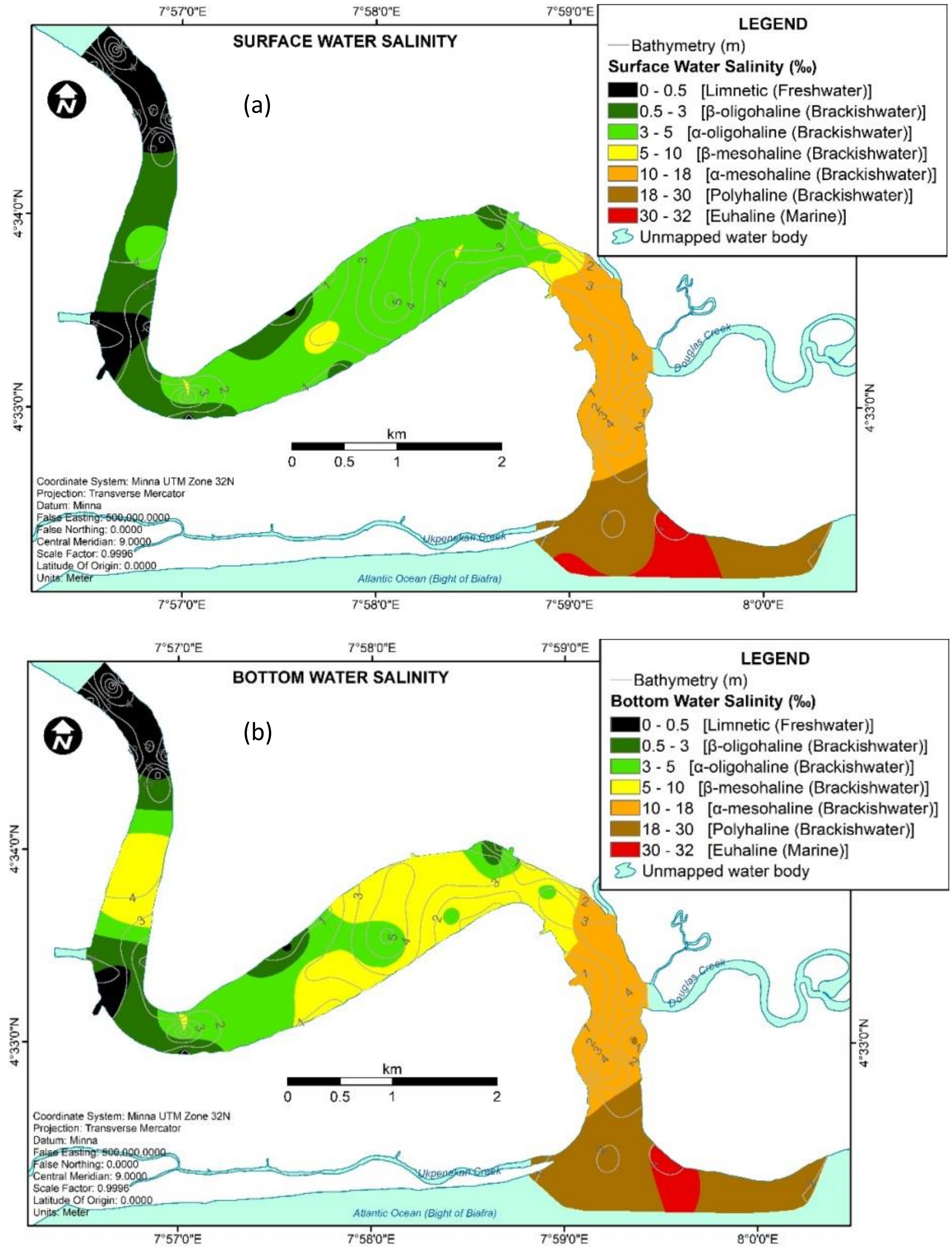


Figure 7: Salinity distribution in Qua-Iboe River estuary (a) surface water (b) bottom water (Modelled after Venice, 1958)

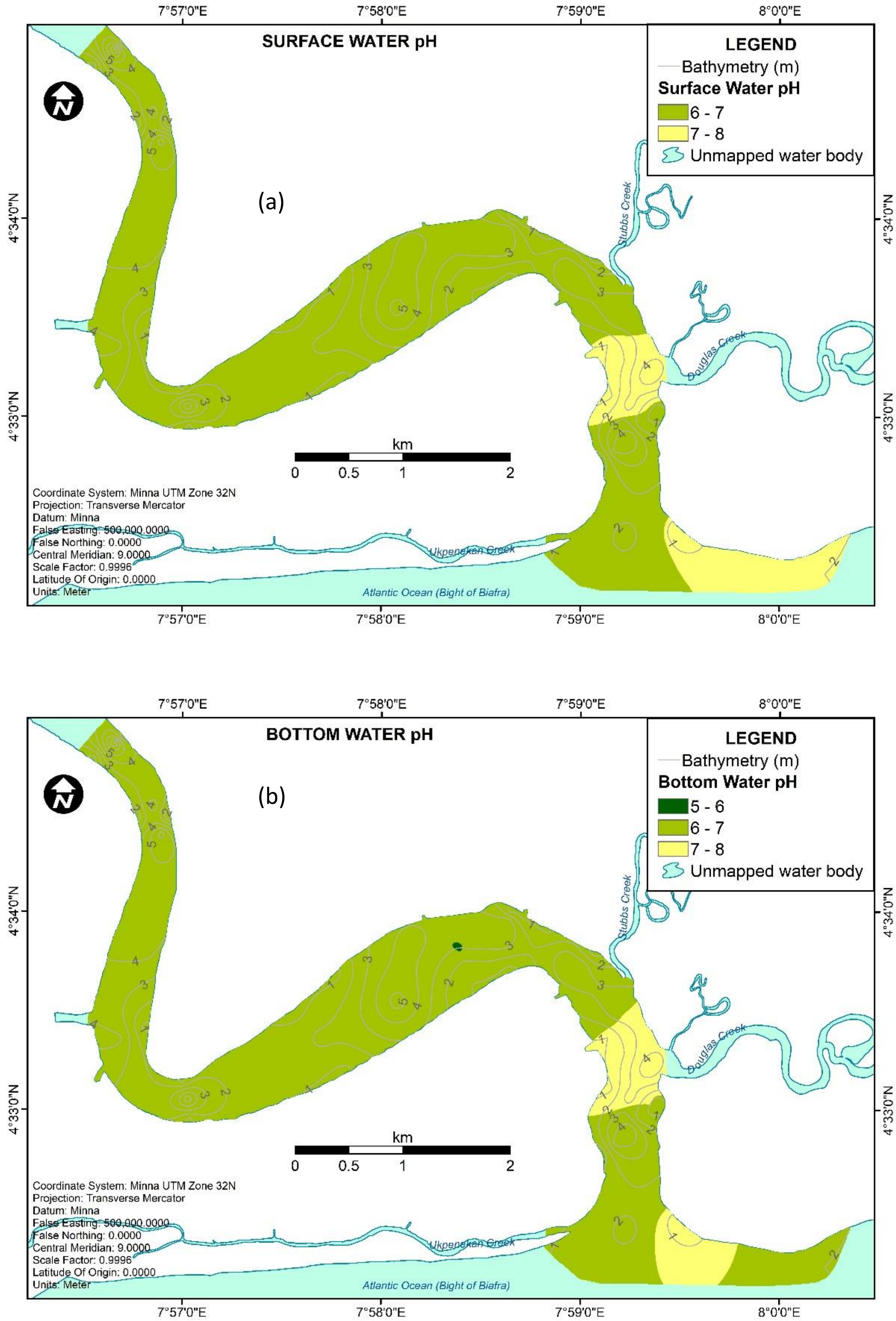
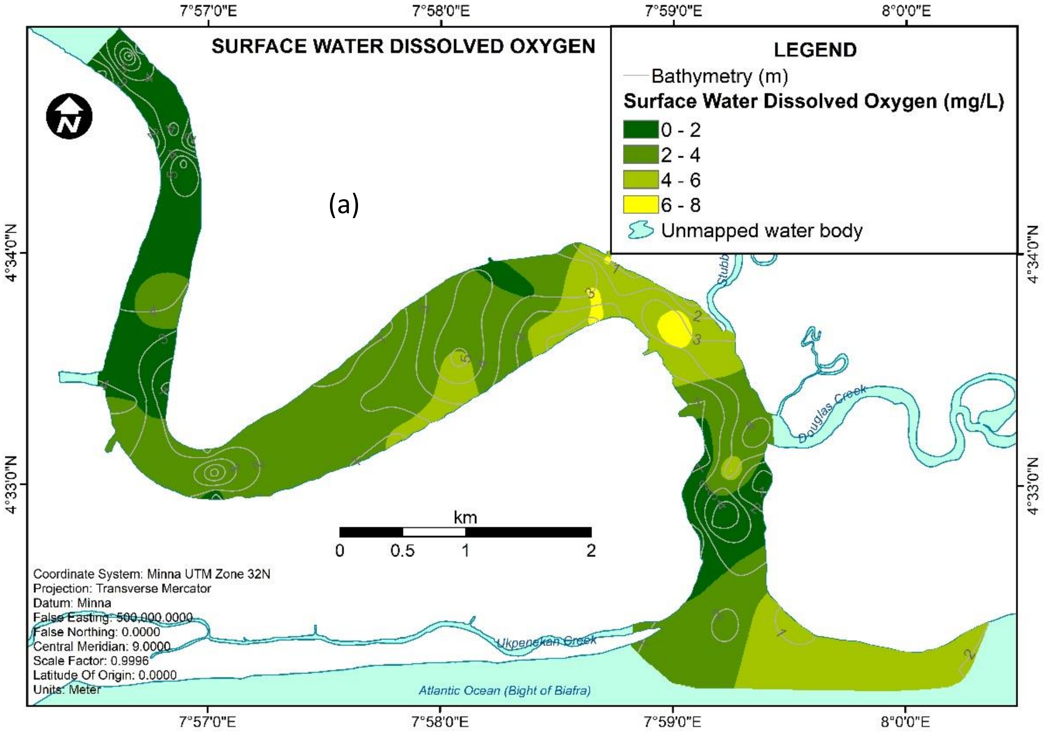


Figure 8: pH distribution in Qua-Iboe River estuary (a) surface water pH (b) bottom water pH



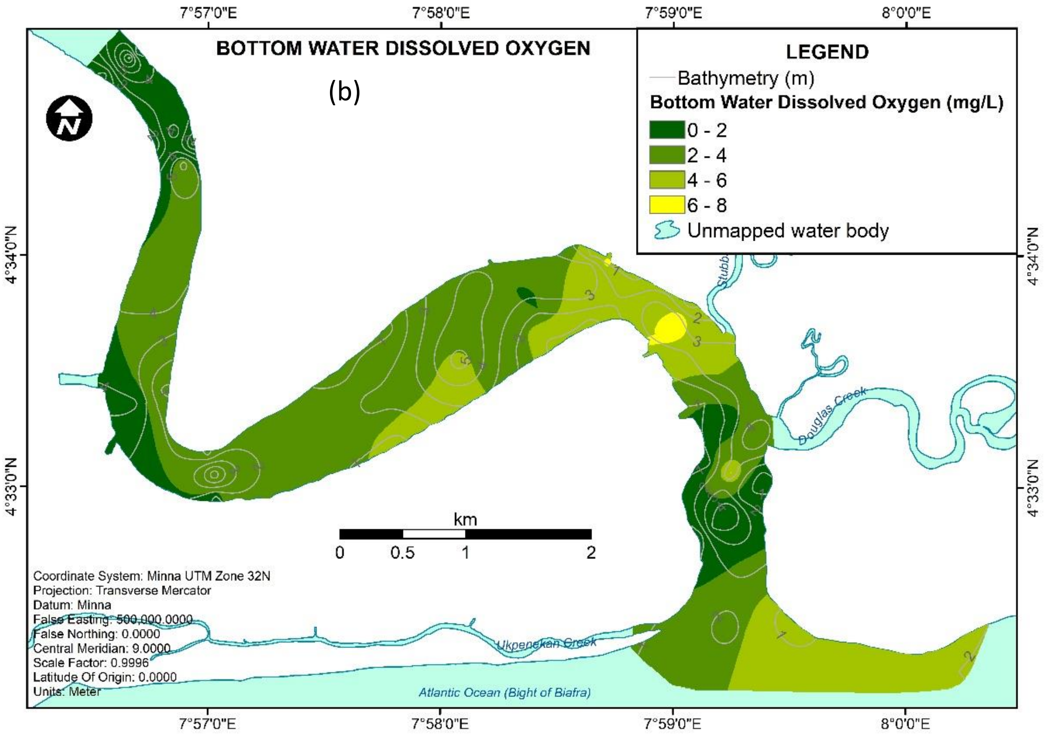


Figure 9: Dissolved Oxygen distribution in Qua-Iboe River estuary (a) surface water (b) bottom water

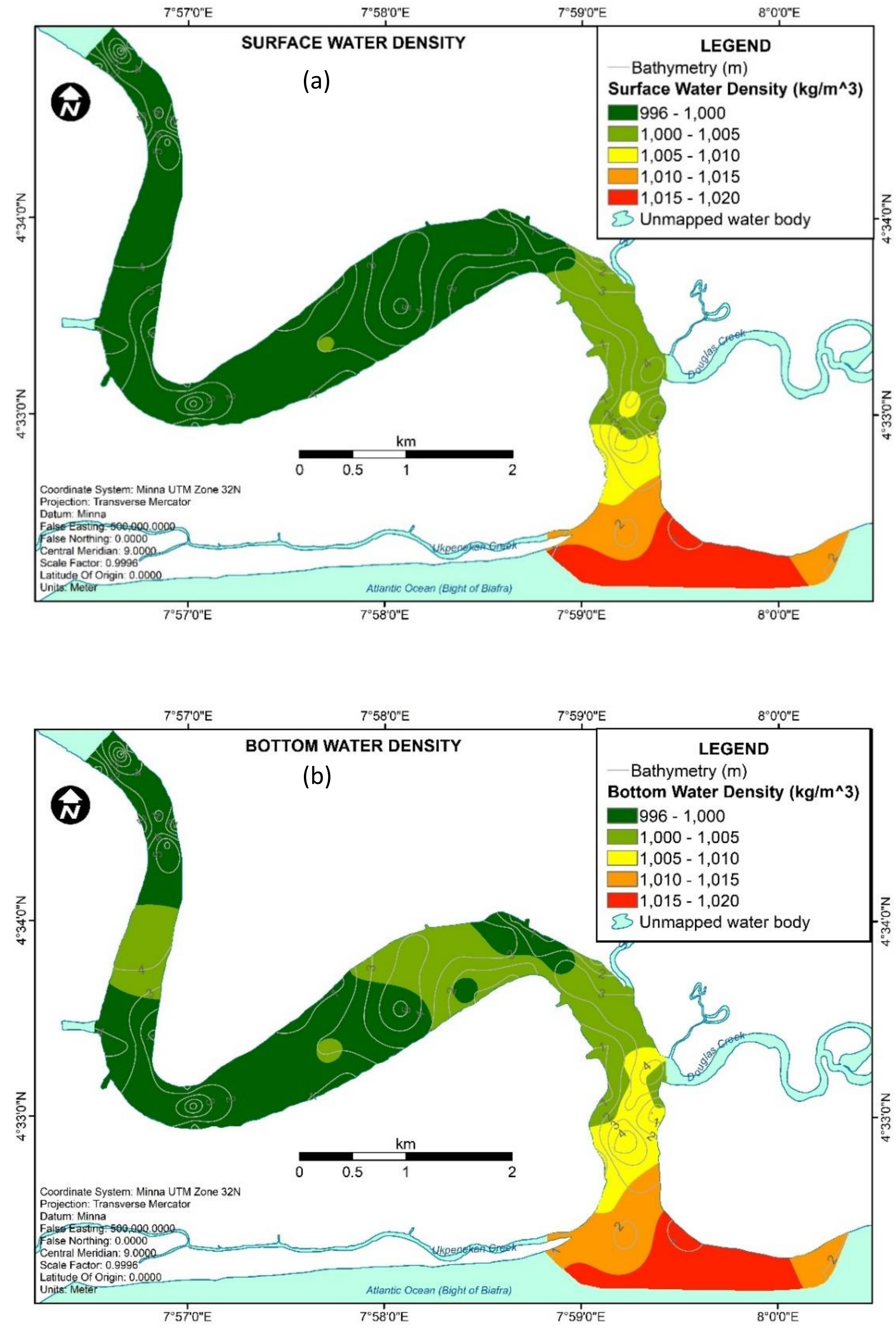


Figure 10: Density distribution in Qua-Iboe River estuary (a) surface water (b) bottom water

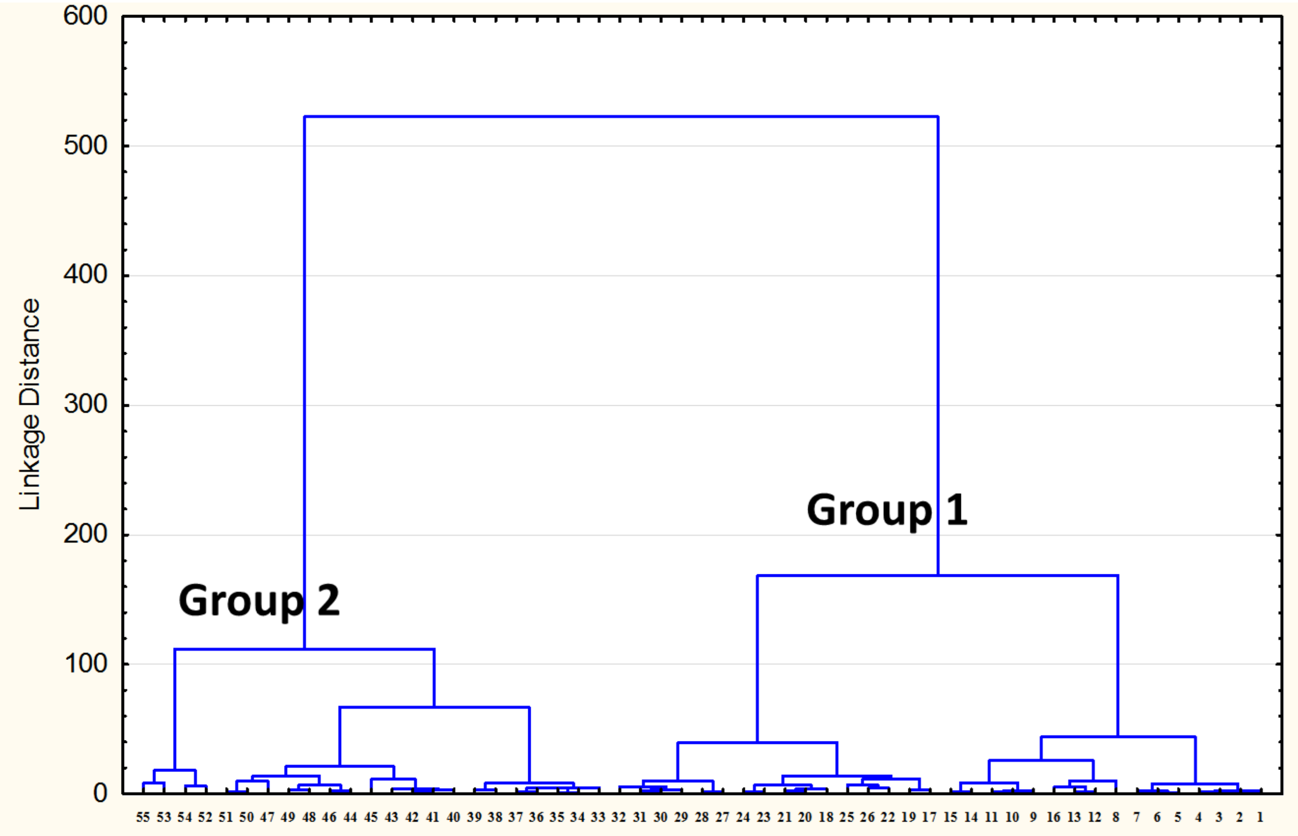


Figure 11: Cluster analysis of physicochemical parameters at 55 sampling stations

Table 3: Correlation matrix showing r values of physicochemical variables in surface waters

Variables	Transparency	Temperature	pH	Salinity	Dissolved Oxygen	Density
Transparency (m)	1.00					
Temperature	-0.24	1.00				
pH	-0.14	*0.67	1.00			
Salinity	0.04	*0.44	*0.48	1.00		
Dissolved Oxygen	-0.11	*0.39	0.18	0.20	1.00	
Density	-0.06	*0.38	*0.42	*0.84	0.04	1.00

N = 55;
r = coefficient of correlation
*correlation is significant at $p < 0.05$

Table 4: Correlation matrix showing r values of physicochemical variables in bottom waters

Variables	Temperature	pH	Salinity	Dissolved Oxygen	Density
Temperature	1.00				
pH	*0.63	1.00			
Salinity	*0.38	*0.49	1.00		
Dissolved Oxygen	*0.48	0.21	0.12	1.00	
Density	*0.38	*0.43	*0.82	-0.05	1.00

N = 55;
r = coefficient of correlation
*correlation is significant at $p < 0.05$

DISCUSSION

The increased ebb current velocity observed within the channel may be accentuated by the movement of ebb tides in the direction of gravity in addition to fluvial input by adjoining tidal creeks. Water depths recorded in Qua-Iboe River estuary ranged from 0 to 10 m (Figure 1). A maximum water depth of 10 m was recorded upstream of the estuary. Water depth values of 0 to 2 m were recorded at the mouth of the estuary. Variations in the water depths recorded within the channel may be associated with the meandering channel morphology, hydrodynamic regimes and anthropogenic activities such as sand mining. The shallow portions of the channel are indicative of low energy areas associated with high sediment deposition while the deeper portions are indicative of high energy with increased sediment erosion and transportation. Variations in water transparency within the tidal channel possibly reflect the energy of the existing hydrodynamic conditions during the sampling period. Increased water transparency values were recorded at shallow depths within the lower estuary associated with channel siltation. High turbidity observed at the upstream limits of the channel and at the mouth of tidal creeks towards the lower estuary may be related to high fluvial discharge, resulting in the re-suspension of sediments within the channel. Similar reports of increased turbidity at the upstream limits of salt intrusion have been documented in other tidal channels (Lin & Kuo, 2001; Uncles & Stephens, 1993). The slight increase in temperature from the upper estuary towards the lower estuary may be related to changes in sunlight intensity during the time of sampling as morning temperatures are slightly lower than temperatures observed in the late afternoons. The distribution of surface and bottom water salinity in the estuary may be related to the degree of tidal penetration and amount of fresh water influx. Salinity increased with increasing distance downstream. The limnetic waters of the upper estuary are associated freshwater influx from Qua-Iboe River. The estuary also receives freshwater inflow from adjoining creeks including Stubbs and Douglas creeks. The polyhaline to euryhaline waters of the lower estuary are associated with penetration of marine waters into the estuary. The slightly alkaline pH of estuary waters observed at the estuary mouth is indicative of sea water intrusion due to proximity to the open sea. The pH of surface water was slightly more acidic than those of bottom waters. The nature of effluents discharged into the channel can impact on the pH. The distribution pattern of surface and bottom water pH in the Qua-Iboe River estuary showed an increasing downstream pattern. Similar distribution patterns have been observed for the Cross River estuary (Ramanathan, 1981) and Bonny estuary (Dublin-Green, 1990). The distribution patterns of pH and salinity observed within the estuary may be closely associated with changes in tidal cycle. Sea water transported into the estuary at flood tides raises the salinities and pH of waters within the lower estuary.

The low levels of DO (<4 mg/l) in upper and central portions of the channel were below the limits for DO in water as recommended by Nigerian Industrial Standards (>5mg/l; NSDWQ, 2015). Slightly elevated values of dissolved oxygen (4 - 6 mg/l) were recorded towards the lower estuary (Figures 6a and b). The increased concentrations of DO observed towards the central (2-4mg/l) and lower (4-6mg/l) portions of the estuary channel coincided with areas of low turbidity (higher photic depth) which promotes photosynthetic activities by primary producers resulting in higher levels of DO in water. The distribution of DO concentration in surface and bottom waters of Qua-Iboe River estuary showed a downstream increasing trend. Maximum concentration values of dissolved oxygen (6 – 8 mg/l) were recorded downstream near Stubbs Creek in both surface and bottom waters (Figures 9a and b). Dissolved oxygen levels in surface waters were slightly higher than those of bottom waters. Density typically strongly followed the salinity distribution pattern of the channel, increasing with distance downstream. Like salinity, the density of bottom waters was slightly higher than those of surface waters. The increased density in surface and bottom waters downstream may be related to the influx of seawater into the estuary. Amongst all the physicochemical parameters analyzed, temperature showed better correlations with most parameters. Temperature showed significant correlations with pH, salinity and dissolved oxygen. Temperature may be regarded as an important water quality parameter in the Qua-Iboe River estuary. Spatial variations in physico-chemical parameters of the estuary are majorly influenced by the existing hydrodynamic regimes of the estuary.

CONCLUSIONS

The present research aims to assess hydrodynamic conditions as well as the quality of surface and bottom waters of Qua-Iboe River estuary. Flood and ebb current velocities were measured within the channel and results indicated ebb-dominance. Temperatures are generally warm and consistent with tropical climatic settings (<40°C). Cluster analysis performed on all samples using the Ward's method yielded two distinct clusters. Cluster 1 extends from the upper to the central estuary environment characterized by a maximum water depth of 10 m. Temperatures in this environment typically ranged from 27°C - 29°C. Waters are limnetic to oligohaline, slightly acidic to neutral with low dissolved oxygen (<4 mg/l) conditions. The strong fluvial input by the Qua-Iboe River and adjoining tributaries promotes limnetic conditions and low pH in the upper estuary. The low transparency recorded in the upper estuary limits phytoplankton productivity resulting in low levels of DO. Cluster 2 occurs in the lower estuary environment characterized by water depths ranging from 0 to 2 m. Temperatures in this environment predominantly ranged from 29°C - 31°C. Waters are mesohaline to euryhaline, slightly acidic to slightly alkaline with low dissolved oxygen (<4 mg/l) conditions. The euryhaline and slightly alkaline conditions at the mouth of the estuary may be due to penetration of seawater into the estuary and variations in tidal mixing. The slightly higher concentration of DO observed towards the lower estuary coincided with areas of low turbidity promoting photosynthetic activities by primary producers.

Results from Pearson's correlation matrix revealed that temperature showed better correlations with pH, salinity and dissolved oxygen compared to other parameters. Temperature may be regarded as an important water quality criterion in the Qua-Iboe River estuary. This study provides data for future monitoring and assessment of water quality in the estuary. It also has implications for paleo-environmental interpretation of the estuary and similar meso-tidal estuaries globally.

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STATEMENT AND DECLARATIONS

Competing Interests

The authors hereby declare that there are no known conflict of interest either financial or personal relationships which may have appeared to influence the work as reported in the manuscript.

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Authorship contribution statement

Victoria Emeka: Conceptualization, Methodology, Resources, Writing – original draft, Writing – review and editing.
Chimezie Emeka: Methodology, Figures preparation, Writing – review and editing.
Ebong Dickson: Writing – review and editing.
Romeo Ojong: Writing – review and editing.
Chikezie P.: Writing – review and editing.

Availability of data and material

All data used in this manuscript are original except those duly acknowledged and cited by the author.

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