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DRY SEASON PHYSICOCHEMICAL CHARACTERISTICS OF A TROPICAL MESO-TIDAL ESTUARY: CROSS RIVER ESTUARY, SOUTHEAST NIGERIA

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ABSTRACT

The Cross River estuary is a tide-dominated coastal plain estuary which empties into the Atlantic Ocean at the Bight of Biafra, Gulf of Guinea. It receives fresh water from major tributaries including Calabar, Great Kwa, Akpa-Yafe, Mbo and Little Kwa rivers; and plays a significant role in anthropogenic activities such as fishing exploitation and commerce. This research focuses on the assessment data from the hydrodynamic variability of the Cross River estuary. Data from April 2017 to March 2018 were generated from monitoring tidal current velocity in the estuary as well as the tidal variations under spring and neap tidal conditions. The result shows that the average current velocity in the water column was 0.85 m/s during flood tides and 0.96 m/s during ebb tides. Residual currents were observed to be seaward, with ebb dominance. In-situ measurements of physicochemical parameters including dissolved oxygen, temperature, pH, salinity, density and transparency were recorded at 55 geo-referenced sampling stations throughout the estuary in the dry season month of January, 2018. Further to this, salinity, temperature and pH varied from 0 – 20 ppt; 27.9-31.4°C; 5.4-8.4 respectively, and in increased seaward direction. The relationship between physicochemical parameters were interpreted using Pearson's Correlation Matrix. Here, salinity showed significant correlations ($p<0.05$) with pH while density showed significant correlations with temperature, salinity and pH (add reasons). This research study reveals that changes in tidal cycles and current velocity are important factors contributing to the observed variations in physicochemical properties of the Cross River estuary and thus, useful for effective monitoring of the estuary and similar meso-tidal systems.

KEYWORDS: Fluvial discharge, Tides; Physicochemical parameters; Cluster analysis; Cross River estuary

INTRODUCTION

Estuaries are transitional environments which encompass freshwater and marine ecosystems. They are important habitats for many aquatic species and are beneficial for anthropogenic activities including domestic, agricultural and industrial. Estuaries constitute popular areas for tourism, transportation, food sources and waste disposal (Boon et al. 1992). However, estuaries and coastal zones around the world are increasingly vulnerable due to unprecedented pressures of industrialization and urban development. The impact of these human activities exert negative effects on estuaries leading to a decline in the health of these
co-systems. Estuaries are dynamic systems which can be dominated by waves, tides or represent some variation of both (Schröder-Adams, 2006). The spatial variability of physicochemical parameters are influenced by estuary dynamics. Fortune and Mauraud (2020) in their study of Jones Creek in Darwin Harbour (Australia) concluded that the water quality was majorly influenced by the fortnightly tidal cycle, with spring tides typically inducing larger variations in water quality expatiate. The degree of

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mixing of fresh river water and salty sea water affects the distribution of physical and chemical parameters within the estuary. The area of the estuary most influenced by fluvial flow may present low salinities and pH. Similarly, areas with close proximity to oceanic water will usually present higher salinity and pH (Mosley et al., 2010; Nascimento et al., 2021).

Estuaries and tidal rivers have been widely studied in their physical, chemical and biological characteristics (Day, 1980; Akpan,1999; Cooper, 2001; Schröder-Adams, 2006; Anitha and Kumar 2013; Agbugui and Deekae, 2014). Several investigations have been carried out on physicochemical characteristics of estuaries and river systems of the Gulf of Guinea (Dublin-Green, 1990; Akpan et al., 2002; Abowei, 2010; Emeka et al., 2010; Antia et al., 2012; Dimowo, 2013; Otogo et al., 2021). Ramanathan (1981) recorded an average water depth of 6 m along the dredged channel of the Cross River estuary and less than 1m depth along marshy areas bordering the river course. Antia et al. (2012) studied tidal current activities in Qua-Iboe River estuary and reported strong ebb-directed flow within the channel. Similar reports have been documented for Calabar and Great-Kwa Rivers (Emeka et al., 2010). Akpan et al. (2002) carried out an ecological baseline study of the Great Kwa River and observed low levels of salinity, transparency and dissolved oxygen concentration in the channel. They noted that phytoplankton productivity was limited due to the low levels of transparency, which resulted in low dissolved oxygen concentration in the water column. The authors reported fresh water discharge and precipitation as major influences on salinity variations in the river system. Dublin-Green (1990) investigated the physico-chemical parameters of Bonny estuary and attributed the seaward increase in bottom water salinity and pH to marine water incursion. Similar findings have been reported by Abowei (2010) for Nkoro River where?.

Many physicochemical studies conducted in the Cross River estuary have concentrated along tidal banks at well-spaced sample intervals (Akpan and Offem, 1993; Akpan, 1999; Otogo et al., 2021). Otogo et al. (2021) studied physicochemical fluxes along the tidal banks of the Cross River estuary and observed that dissolved oxygen is strongly and positively correlated with transparency and salinity. Spatial studies on nutrient biogeochemistry in the Cross River estuary system have been carried out by Dan et al. (2019). The authors investigated the concentrations, compositions, behavior, and biogeochemical dynamics of dissolved nutrients in the Cross River estuary and reported dissolved silicates as the most abundant dissolved nutrient in the estuary. Spatial variations of salinity and pH in the Cross River estuary have been reported by Ramanathan (1981). The author observed a pH of 7 along the main channel and recorded normal marine salinity near the mouth of the estuary. He reported that salinity at the estuary mouth gradually decreased upstream to about 20 km. A similar study with the current one was conducted in the Qua-Iboe River estuary by Emeka et al. (2023a). Their results indicated maximum and minimum salinities of 0‰ and 32‰, with higher bottom water salinities increasing further upstream than surface water salinities. By their results, Qua-Iboe River was classified as a partially mixed estuary. Emeka et al. (2023b) studied the spatial distribution of bottom water physicochemical parameters of the Cross River estuary, with data obtained in the rainy season of 2012. They observed that salinity maximum, minimum and mean, within the channel were, 0.2 ‰, 0.15 ‰, and 0.16 ‰, with values increasing in the downstream direction. They attributed this phenomenon to the large influx of freshwater into the channel, from its adjoining tributaries. This was supported by the predominantly acidic pH of the channel, with an average value of 6.6.

In this study, samples were obtained during the dry season of 2018, covering a longer stretch of the channel and both surface and bottom water samples will be examined. The distribution of physicochemical parameters is further compared with tidal current data, to evaluate the effect of the former on the latter. Presently, a detailed information on the hydrodynamics and spatial variations of surface and bottom water physicochemical parameters throughout the entire stretch of the estuary is lacking in literature despite its huge economic role. The effect of tides in the variability of physicochemical parameters in the Cross River estuary has not been fully explored. Thus, this work is aimed at understanding the influence of the tidal variability on the spatial distribution of physicochemical parameters in the Cross River estuary. Since the circulation pattern of the Cross River estuary is mainly tide-dominated, tidal variation may be considered as one of the key drivers of spatial heterogeneity of physicochemical parameters in the estuary.

STUDY AREA

The Cross River estuary is the largest estuary in the West African sub-region, covering an estimated area of about 54,000km^2 (Enyenihi, 1991). It a tide-dominated, coastal plain estuary, that empties into the Atlantic Ocean at the Bight of Biafra, Gulf of Guinea. It flows through Coastal Plain Sands (Pleistocene/Pliocene age) and Alluvium (Recent age), before emptying into the Atlantic Ocean at the Bight of Biafra (Figure 1). It has a minimum channel width of less than 1 m at its source and increases to a maximum width of about 25.8 km at the mouth. The estuary is tide-dominated and located within a meso-tidal (2-4m) setting. The study area lies between 4° 30′ 0″ and 5° 0′ 0″ N latitude and 8° 10′ 0″ and 8° 30′ 0″ E longitude (Figure 1). It covers an approximate length of 65 km and has a maximum mid-channel depth of 12 m (Figure 1). The average current velocities observed at Cross River estuary during Spring and Neap tidal cycles are 1.3 m/s and 0.85 m/s respectively (Emeka, 2012). The Cross River estuary lies within the equatorial rainforest belt region of Nigeria. Rainfall within this region is prevalent from April to October, with a peak in June. Air temperatures are high (22.5°C-30°C) with an average of 26°C over the estuarine surface water (Nigerian Meteorological Station, Calabar, 2012). Relative humidity varies from 82-85% between 2010 and 2011 (Nigerian Meteorological Station, Calabar, 2012). The Cross River estuary is inundated by several tributaries and numerous tidal creeks. It receives fresh water from important rivers like Calabar, Great-Kwa, Akpa-Yafe, Mbo and Little Kwa. The banks are fringed by mangrove swamps and sand bars are frequent within the mid-channel. It is a diverse wetland eco-system with numerous economic and commercial benefits. The highly productive waters of the Cross River estuary harbor a rich diversity of fauna. The channel is highly utilized for fish exploitation, crude oil exploitation, tourism, mari-time transportation and sand mining. It is also a major shipping route to the Nigerian Ports Authority in Calabar.

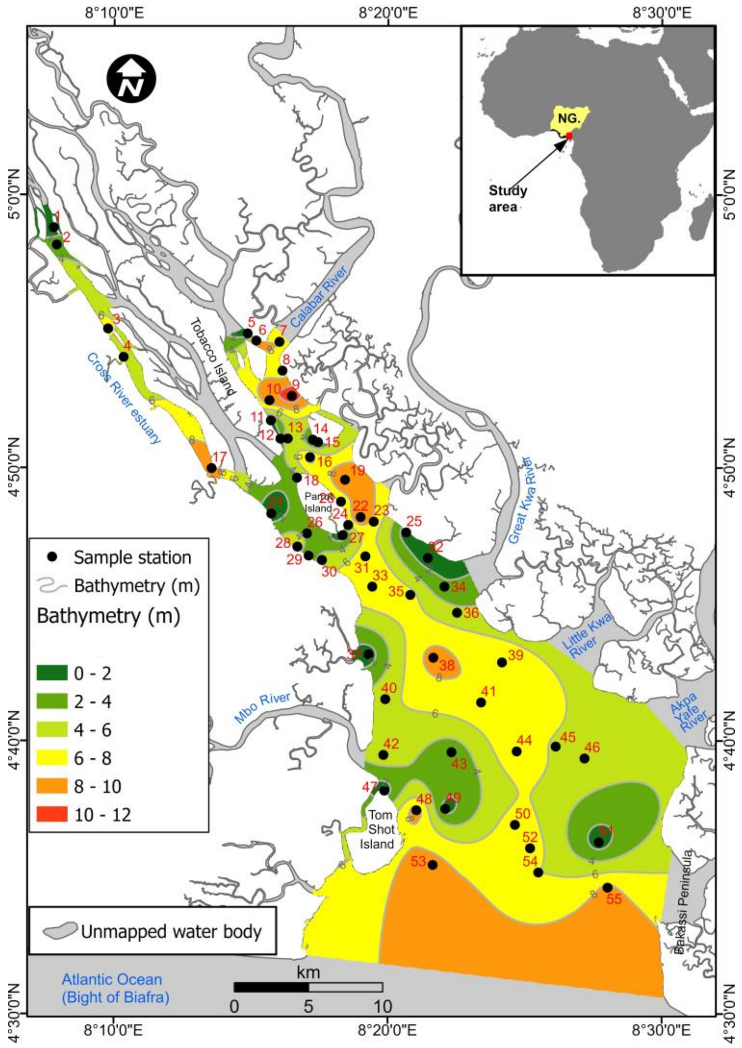


Fig. 1 Map of study area showing sample stations and bathymetry

Measurements of tidal current velocity and physico-chemical parameters

Tidal current velocity measurements were made in the Cross River estuary from April 2017 to March 2018 over Spring and Neap tidal cycles. Surface tidal current velocities were measured at specified stations along the estuary bank using the Langragian technique. Measurement was taken three times in every 15 minutes for 18 hours (6:00 am to 6:00 pm) along pre-established stations with fixed distance. The velocity at each 15-minutes interval was calculated from values of distance and average drift time recorded.

Fifty-five surface and bottom water samples were obtained in-situ from the Cross River estuary in February 2018. This study was designed for the dry season. The sampling area extended from the limit of tidal influence upstream of the estuary to the mouth, where it empties into the Atlantic Ocean. All sample location coordinates were recorded using Global Positioning System (GPS). At each station, surface samples were collected using a Teflon water sampler while bottom water samples were collected immediately above the sediment-water interface using a Nansen bottom water sampler. Physicochemical parameters of surface and bottom water samples were immediately measured. Water temperature and pH were measured using a hand-held multi-parameter device (Hanna HI 98130). Salinity and density were measured using a salinity refractometer. Dissolved oxygen and water transparency were measured using a portable dissolved oxygen meter (HI 198193) and a Secchi disk respectively. The channel depth was measured using single beam echo-sounder. Spatial distribution maps of surface and bottom water physico-chemical parameters were plotted using ArcGIS v.10.8.1 (Esri Inc, Berkeley, California). Hierarchical clustering was performed using PAST v.4.03 (Hammer, et al., 2001) on all 55 sampling stations. Hierarchical cluster analysis based on UPGMA method was performed to define the similarity or dissimilarity of groups between the sampling stations. Pearson's moment correlation analyses were conducted using Microsoft excel v.2108 to study the relationships between physicochemical parameters of the estuary surface and bottom waters.

RESULTS AND DISCUSSION

Tidal current velocity

Results of surface tidal current velocity at Spring and Neap tidal cycles for the estuary are presented in Figures 2a and b. At Spring tidal cycle, the maximum tidal current velocity recorded during flood and ebb tides are 1.08 m/s and 1.2 m/s respectively (Figure 2a). At Neap tidal cycle, the maximum tidal current velocity recorded during flood and ebb tides are 0.88 m/s and 1.15 m/s respectively (Figure 2b). The average tidal current velocities at Spring and Neap tidal cycles for the estuary is presented in Figure 2c. The average flood current velocity during Spring and Neap tidal cycles are 0.85 m/s and 0.66 m/s respectively. The average ebb current velocity during Spring and Neap tidal cycles are 0.96 m/s and 1.0 m/s respectively. The surface tidal current velocity curves in the Cross River estuary depicts strong ebb-directed flow at Spring and Neap tidal cycles respectively. The Cross River estuary is tide-dominated and located within a tropical meso-tidal setting (2 - 4 m). The strong ebb-directed flow reported in Cross River estuary may be related in addition to the movement of ebb tides in the direction of gravity and to the precipitation and fluvial input by numerous adjoining rivers and creeks. Increased tidal energy was observed at the mouth of the estuary where salinity reaches 20 ppt. Flood and ebb currents transport water and sediment into the estuary. Tidal energy increased towards the mid-channel but dissipated towards the banks. Waves were minimal upstream of the estuary but prevalent at the mouth of the channel. Wind-generated waves observed within the channel, rarely exceeded chops and swells. Water depths within the channel ranged from 0 to 12 m (Figure 1) with average mid-channel depth of 6 to 8 m. The deepest portion of the channel (10 to 12 m) occurs upstream, at the eastern bank, close the mouth of Calabar River (Figure 1). This may be attributed to dredging. Shallow depths (0 to 2 m) observed at the banks indicate tidal flats. These events were observed during sampling. The bathymetry of the tidal channel indicates erosion within the thalweg, especially at the mouth, and deposition at the banks.

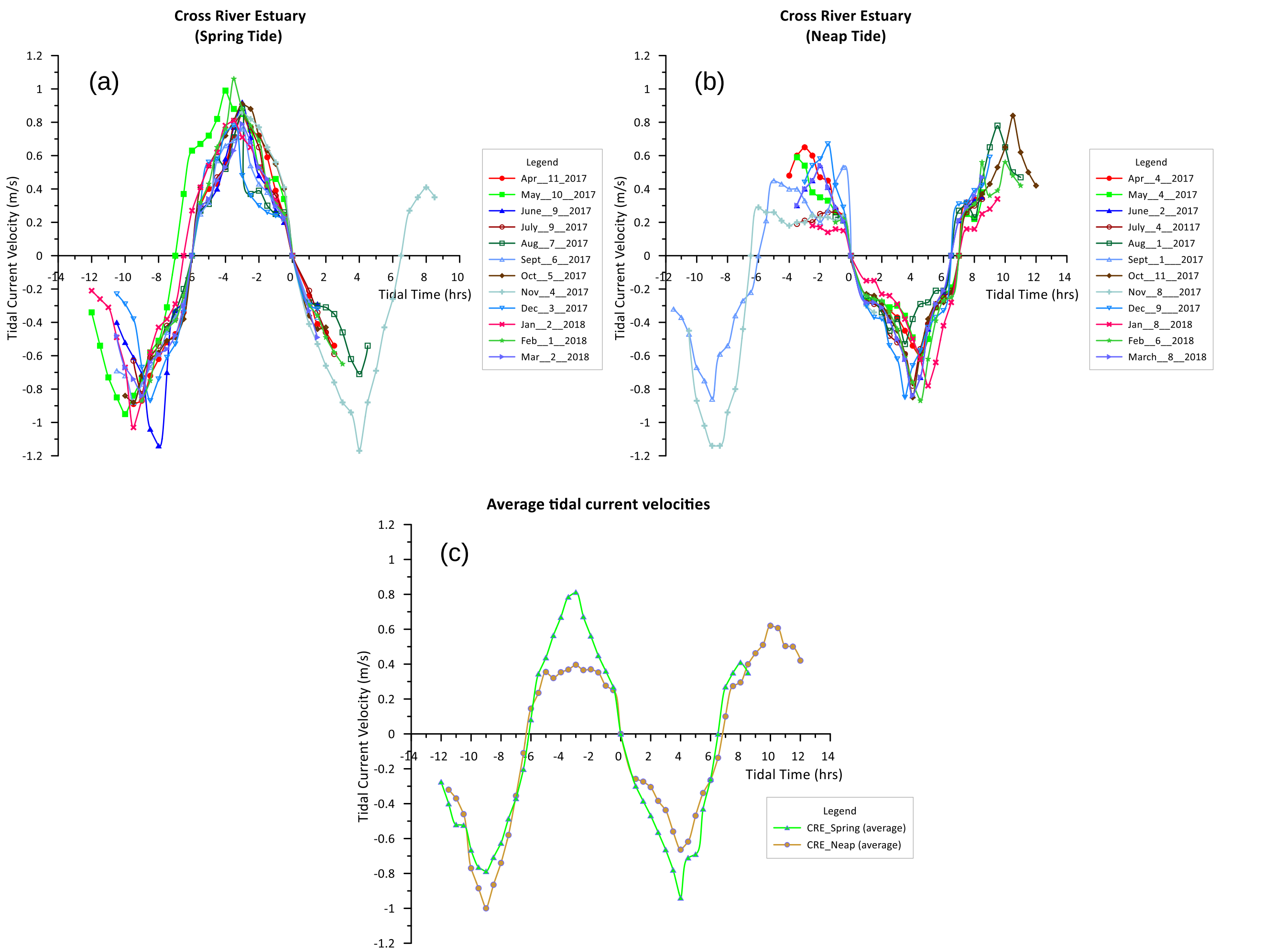


Fig. 2 Surface tidal current velocity charts for Cross River estuary at (a) Spring tide (April 2017 to March 2018) (b) Neap tide (April 2017 to March 2018); (c) average at spring and neap tides

Spatial Variation of Physicochemical Parameters
Transparency

The mean, standard deviation and range of physicochemical parameters in the Cross River estuary are presented in Tables 1 and 2. Data recorded for surface and bottom water physicochemical parameters at the different sampling stations in the Cross River estuary are shown in Tables 3 and 4. Spatial variations in physico-chemical parameters among 55 different sampling stations in the Cross River estuarine system are presented in Figures 3 – 8. Water transparency ranged from 0.1 m (stations 32, 33, 37, 52) to 1.4 m (station 2) with a mean value of 0.48 m (Tables 1). Maximum transparency values (1.0 - 1.4 m) are recorded at the upper limits of the estuary channel, in the central portions near Parrot Island and downstream at the mouth of Mbo River, near Tom Shot Island (Figure 3). The least water transparency values (0.1 – 0.2 m) are recorded on the eastern flank of the channel especially at the mouth of major tributaries and downstream of the estuary near the mouth of Bakassi Peninsula (Figure 3). Variations in water transparency throughout the channel may be associated with fluctuations in energy conditions within the channel. Low transparency was observed in the upstream limits of the estuary. Turbulence associated with high energy increases the suspension of fine-grained particles in the water column, thereby resulting in low transparency. Estuarine turbidity maximum, a phenomenon in which much higher concentrations of suspended sediment occur in the estuary than in either the river or in the sea, has been observed in most estuaries experiencing energetic tidal flow (Dyer, 1986). The high concentration is often reported near the upstream limit of salt intrusion (Schubel, 1968; Nichols and Poor, 1972; Nichols and Thompson, 1973; Uncles and Stephens, 1993; Lin and Kuo, 2001). This possibly explains the high turbidity observed in the upper and central portion of the estuary. The low transparency (high turbidity) recorded on the eastern flank near the mouth of rivers adjoining the estuary may be associated with influx of water and discharge of huge sediment load by major tributaries (Calabar, Great-Kwa, Akpa-Yafe Rivers) into the estuary.

Table 1: Mean, Standard Deviation (SD) and Range of surface water physicochemical parameters in the Cross River estuary

Parameters	Transparency (m)	Temp.(°C)	pH	Density (kg/m^3)	Salinity (ppt)	Dissolved oxygen (mg/l)
Mean	0.48	29.47	6.54	1.01	8.15	3.78
SD	0.32	0.72	1.06	0.00	5.50	2.82
Range	0.1-1.4	27.9-31.4	5.4-8.4	1-1.015	0-20	0.01-10.8

Table 2: Mean, Standard Deviation (SD) and Range of bottom water physicochemical parameters of the Cross River estuary

Parameters	Temp.(°C)	pH	Density (kg/m3)	Salinity (ppt)	Dissolved oxygen (mg/l)
Mean	29.34	6.56	1.01	8.42	4.09
SD	0.76	1.07	0.00	5.38	3.06
Range	27.5-31	5.5-8.4	1-1.015	0-20	0.2-10.8

Temperature

Surface water temperature varied from 27.9°C (station 7) to 31.4°C (station 46) with a mean value of 29.5°C (Tables 1 and 3). Bottom water temperatures ranged from 27.5°C (station 7) to 31°C (station 34) with a mean value of 29.3°C (Tables 2 and 4). Temperatures are generally warm, corresponding to the tropical climate setting of the study area. Akpan (1999) and Dan et al., (2019) observed similar temperature distribution pattern for the Cross River estuary. Surface and bottom water temperatures showed a nearly uniform distribution pattern, with no appreciable variation in temperature among the different stations (Figures 4a and b respectively). However, bottom water temperatures were slightly lower than surface temperatures by nearly 0.4°C. Maximum values of surface and bottom water temperatures (>31°C) were observed on the eastern sector of the lower channel, around the mouth of major tributaries. Surface and bottom water temperatures generally increased in the seaward direction. Minimum values of surface and bottom water temperatures (< 29°C) were recorded at the upper limits of the channel (Figures 4a and b). Temperature is an important factor for maintaining growth, survival and distribution of organisms in the physical environment (Langford, 1990). Slight changes in temperature observed throughout the channel may be related to the changes in atmospheric temperatures during the sampling period, with morning temperatures slightly lower than temperatures recorded in the late afternoons. The temperature increase observed on the eastern sector of the lower estuary may be related to the influx of warm water by the adjoining tributaries. The slight decrease in temperature of bottom waters compared to surface waters may be related to the reduction of sunlight intensity with depth. Temperature showed significant correlations with salinity and pH. Similar positive correlations of temperature with salinity and pH have been reported by Dan et al. (2014) for the Qua-Iboe River estuary.

Table 3: Surface water physicochemical characteristics of the Cross River estuary at 55 sampling stations

Sample point	Transparency (m)	Temp.(°C)	pH	Density (kg/m^3)	Salinity (ppt)	Dissolved oxygen (mg/l)
1	0.25	28.5	5.62	1	0	0.2
2	1.4	28.5	5.51	1	0	0.01
3	0.75	28.9	5.65	1	0	2.8
4	0.35	28.7	5.61	1	0	2.3
5	0.2	28.7	8.37	1.002	1	2.5
6	0.3	28.9	8.42	1.002	1	2.8
7	0.5	27.9	5.6	1.004	5	3.3
8	0.31	28.8	5.57	1.005	5	6.7
9	0.7	29	8.37	1.002	5	2.8
10	0.48	28	5.54	1.003	5	6.9
11	0.28	28.7	5.56	1.005	6	3
12	0.6	28.3	5.53	1.004	5	2.5
13	0.33	30.4	5.61	1.003	4	6
14	0.13	28.9	5.55	1.004	5	10.8
15	0.27	29.1	5.55	1.003	4	10.1
16	0.39	29.7	5.57	1.004	5	10.1
17	0.4	28.6	5.61	1	0	1.9
18	0.42	29.1	5.44	1	4	10.2
19	1	29.2	8.18	1	8	2.5
20	0.2	29.1	8.21	1	8	2.6
21	0.19	29.9	5.67	1	0	2.2
22	0.34	29.9	5.7	1.01	5	10.3
23	0.4	30	5.78	1.01	5	2.1
24	0.7	29.2	7.89	1.01	10	0.6
25	0.13	31	5.7	1.01	6	2.1
26	0.36	30	5.75	1	4	2.1
27	0.31	30	5.68	1.01	10	2.3
28	0.61	29.3	5.72	1.01	5	9.4
29	0.16	30	5.79	1.01	6	2.4
30	0.8	29.1	7.86	1.01	10	1.3
31	1.1	29.3	7.99	1.005	10	2.5
32	0.1	30	5.64	1.005	5	2.2
33	0.1	29.3	7.46	1.005	10	2.6
34	0.13	31	5.72	1.008	8	1.8
35	1	29.5	7.9	1.005	10	0.1
36	0.3	30	5.7	1.005	7	2.4
37	0.1	30.3	6.95	1.01	15	2.3
38	0.8	29.3	7.21	1.005	10	2.5
39	0.43	30.2	5.68	1.006	7	2.2
40	1	29.7	7.27	1.01	15	6.6
41	0.73	30	5.59	1.008	10	2.2
42	1.1	30	7.05	1.01	15	2.8
43	0.64	30	6.69	1.005	10	2.5
44	0.46	30.3	7.11	1.005	10	6.5
45	0.73	29.9	5.51	1.008	10	2.1
46	0.35	31.4	7.33	1.005	10	2.6
47	0.43	30	5.48	1.01	14	2.2
48	1	29	7.6	1.01	20	3.64
49	1.1	28.9	7.78	1.015	20	3.5
50	0.29	29.2	7.65	1.01	20	3.2
51	0.15	30	7.03	1.01	15	7
52	0.1	29.5	7.74	1.01	15	7.1
53	0.55	29.7	7.73	1.015	20	2.9
54	0.12	29.3	7.75	1.01	15	2.5
55	0.16	29.5	7.7	1.01	15	7.2

Table 4: Bottom water physicochemical characteristics of the Cross River estuary at 55 sampling stations

Sample point	Temp.(°C)	pH	Density (kg/m^3)	Salinity (ppt)	Dissolved oxygen (mg/l)
1	28.5	5.62	1	0	0.2
2	28.7	5.89	1	0	0.2
3	28.4	5.66	1	0	2.7
4	28.3	5.63	1	0	2.7
5	28.4	8.37	1.002	1	2.5
6	28.8	8.33	1.001	1	2.7
7	27.5	5.56	1.005	5	6.9
8	27.8	5.52	1.005	5	7.7
9	29	8.39	1.002	5	2.8
10	28.1	5.54	1.004	5	7.6
11	28.3	5.56	1.005	6	3
12	28	5.53	1.004	5	2.5
13	29.2	5.6	1.005	6	0.2
14	28.9	5.55	1.004	5	10.8
15	29.1	5.55	1.004	4	10.1
16	29.5	5.46	1.003	4	10.7
17	28.9	5.61	1	0	2
18	29	5.47	1.006	6	10.7
19	28.9	8.28	1.005	10	2.5
20	29.2	8.21	1.005	10	2.5
21	29.9	5.67	1	0	2.2
22	29.1	5.72	1.005	4	10
23	29.4	5.75	1.004	5	2
24	29.1	8.01	1.005	10	2.5
25	31	5.7	1.005	6	2.1
26	29.6	5.74	1.005	6	2.3
27	30	5.68	1.008	10	2.3
28	30.5	5.76	1.005	6	10
29	30	5.79	1.006	6	2.4
30	29.1	8.17	1.005	10	2.7
31	29.1	7.91	1.005	10	2.8
32	30	5.64	1.005	5	2.2
33	29.3	7.36	1.005	10	2.5
34	31	5.72	1.005	10	0.5
35	29.4	8.1	1.005	10	0.5
36	30.9	5.74	1.008	8	2.1
37	30.3	6.95	1.01	15	2.3
38	29.2	7.33	1.005	10	2.5
39	29.9	5.65	1.008	10	2.4
40	29.5	7.29	1.01	15	6.7
41	29.7	5.58	1.008	9	2.2
42	29.6	7.23	1.01	15	6.4
43	29.6	7.05	1.01	15	2.8
44	29.9	7.13	1.005	10	6.4
45	29.8	5.56	1.009	11	2.1
46	30.8	7.17	1.015	10	6.3
47	30	5.48	1.01	14	2.2
48	29	7.74	1.015	20	9.3
49	29.1	7.81	1.015	20	2.8
50	29.4	7.48	1.01	15	3.3
51	30	7.03	1.01	15	7
52	29.6	7.78	1.01	15	7.9
53	29.5	7.74	1.015	20	2.7
54	29.2	7.79	1.01	15	2.5
55	29.5	7.28	1.01	15	7.2

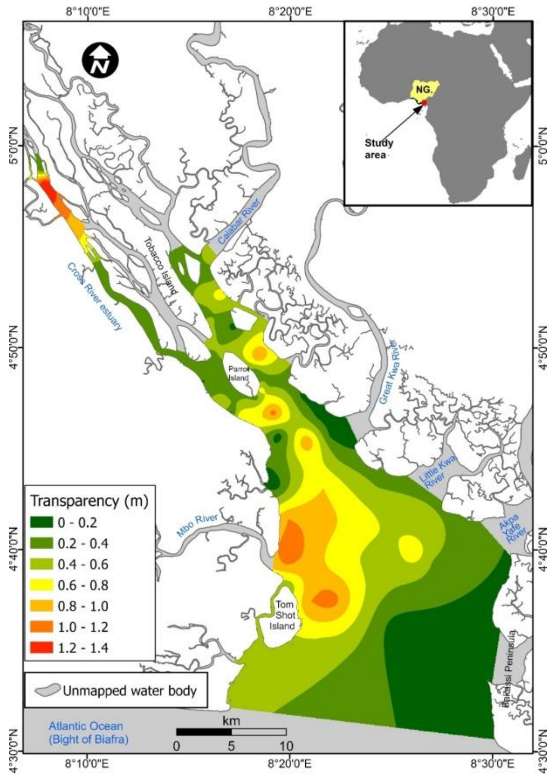
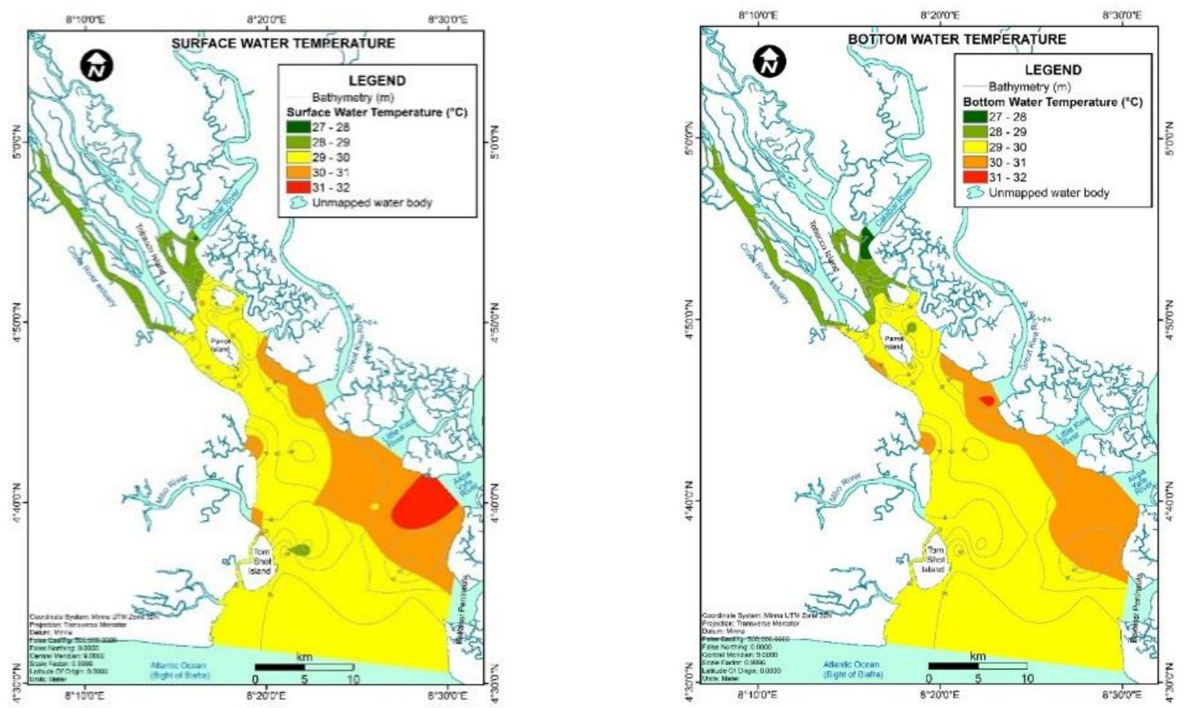


Fig. 3 Water transparency map of the Cross River estuary

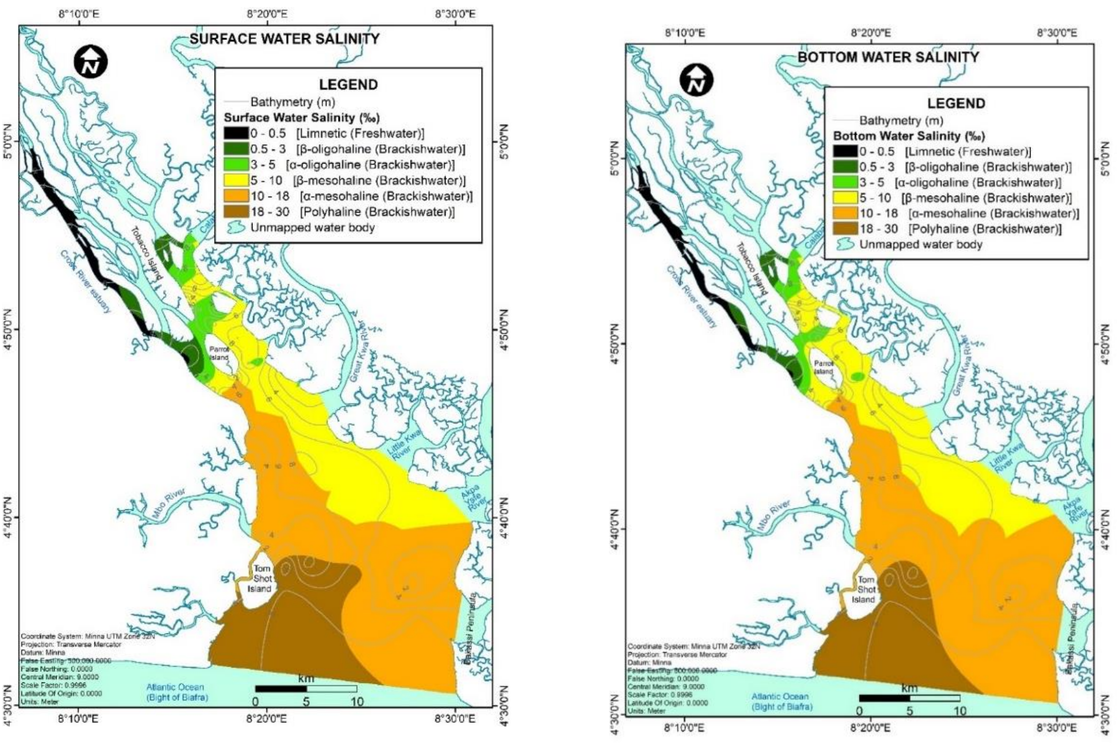


(a) (b)

Fig. 4 Temperature distribution in Cross River estuary (a) surface water (b) bottom water

Salinity

Surface water salinity ranged from 0 ppt (stations 1-4; 17 and 21) to 20 ppt (stations 48-50; 53) with a mean value of 8.15 ppt (Tables 1 and 3). Bottom water salinity ranged from 0 ppt (stations 1-4; 17 and 21) to 20 ppt (stations 48-49; 53) with a mean value of 8.42 ppt (Tables 2 and 4). Surface and bottom water salinities showed similar distribution patterns (Figures 5a and b respectively). Salinity classification was based on the Venice System of classification of marine waters (Venice, 1958). Surface and bottom waters around the upper limits of the channel were fresh (0 – 0.5 ppt), gradually becoming oligohaline (0.5 – 5 ppt) in the downstream direction. Mesohaline waters (5 – 18 ppt) predominantly occurred within the central and lower portions of the estuary. Polyhaline waters (18 – 30 ppt) were recorded at the mouth of the estuary, towards Tom Shot Island (Figures 5a and b). Surface and bottom water salinities showed an increasing downstream trend. However, the salinity of bottom water was slightly higher than that of the surface water. Spatial variations in salinity may be related to the amount of fresh water and sea water entering into the estuary. Fresh water enters into the estuary through its numerous adjoining rivers and creeks. The amount of fresh water discharged by fluvial current into the estuary varies with season. High precipitation and increased fresh water discharge by fluvial current occurs during the rainy season. During the dry season, the volume of fresh water discharged into the estuary decreases due to low precipitation. Fresh water conditions observed at the upper reaches of the channel may be associated with increased fluvial energy upstream. The upstream movement of seawater into the estuary during each flood tide, increases salinity in the lower estuary. Higher salinities have been reported in the lower reaches of the Cross River estuary by Ramanathan (1981) and in other brackish water settings of the Gulf of Guinea (Aseez et al., 1974; Dublin-Green, 1990; Abowei, 2010; Dimowo, 2013; Emeka et al., 2023c). Surface waters were slightly less saline and less dense than bottom waters. The salinity of surface water is slightly lower because precipitation and run-offs from adjoining tributaries has stronger influence on the dilution of surface waters.



(a) (b)

Fig. 5 Salinity distribution in Cross River estuary (a) surface water (b) bottom water (Modelled after Venice, 1958)

pH

Surface water pH ranged from 5.4 (station 18) to 8.4 (station 6) with a mean value of 6.5 (Tables 1 and 3). Bottom water pH ranged from 5.5 (stations 8, 10, 12, 16, 18) to 8.4 (stations 5 and 9) with a mean value of 6.6 (Tables 2 and 4). The overall value of pH was within the limit for environmental water quality standards in Nigeria as recommended by Nigerian Industrial Standards (6.5-8.5; NSDWQ, 2015). The pH of surface and bottom waters showed nearly uniform distribution patterns (Figures 6a and b respectively). The upper reaches of the channel are defined by slightly acidic (5 – 6) waters (Figures 6a and b). The slightly acidic (pH=5-6) waters of the upper reaches of the estuary and the slightly acidic to neutral (pH= 5-7) waters of the eastern banks of the channel may be attributed to increased freshwater influx and weak tidal penetration upstream. Slightly acidic to neutral surface and bottom waters (5 – 7) were recorded on the eastern sectors of the channel at the mouths of Great-Kwa and Little Kwa Rivers. Neutral to slightly alkaline waters (7 – 8) dominated the lower reaches of the estuary channel (Figures 6a and b). The increased alkalinity at the mouth of the estuary may be associated with the influx of seawater into the estuary. Anila Kumary et al. (2007) reported that the pH of water increases from acidic to alkaline when colloidal particles that mix with seawater become coagulated. The higher pH values (7-8) recorded at stations located further downstream within the estuary have been observed in other brackish water settings of the Niger Delta region of Nigeria (Dublin-Green, 1990; Abowei, 2009; Emeka et al., 2023c). Surface water pH (mean value=6.5) was slightly more acidic than bottom water pH (mean value=6.6) due to stronger fluvial influence on surface waters.

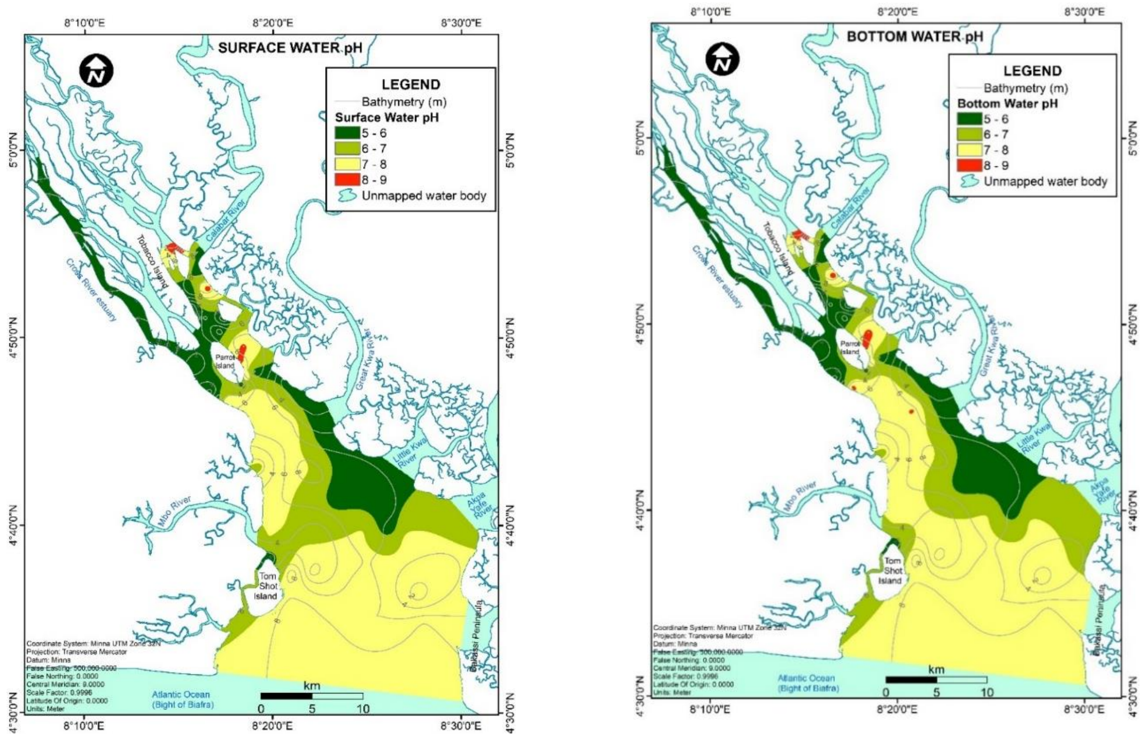
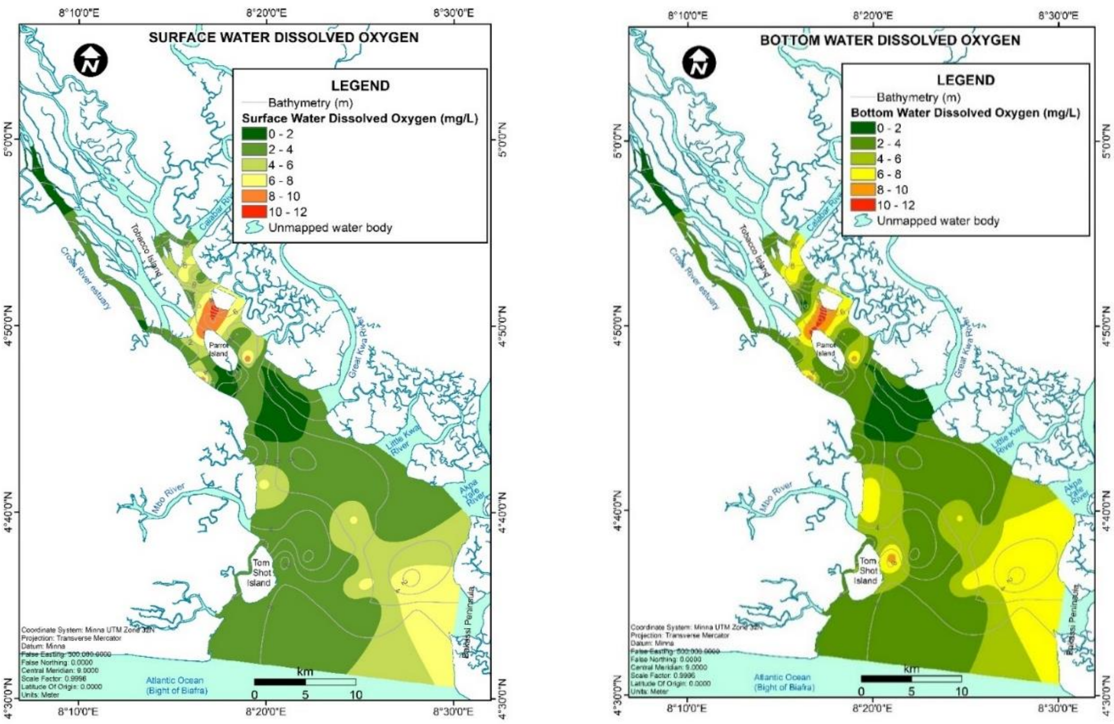


Fig. 6 pH distribution in Cross River estuary (a) surface water pH (b) bottom water pH

Dissolved oxygen

Surface water dissolved oxygen ranged from 0.01 mg/l (station 2) to 10.8mg/l (station 14) with a mean value of 3.78mg/l (Tables 1 and 3). Bottom water dissolved oxygen ranged from 0.2 mg/l (stations 1-2; 13) to 10.8 mg/l (station 14) with a mean value of 4.1 mg/l (Tables 2 and 4). The distribution pattern of surface and bottom water dissolved oxygen in Cross River estuary is presented in Figures 7a and b respectively. Low dissolved oxygen values (< 2 mg/l) of surface and bottom waters were recorded near the mouth of Great-Kwa River (Figures 7a and b). The central and lower portions of the channel were predominantly covered by waters with dissolved oxygen concentration values of 2-4mg/l. The low levels of dissolved oxygen (<4 mg/l) recorded around the central and lower portions of the channel were below the limit for environmental water quality standards in Nigeria as recommended by Nigerian Industrial Standards (>5 mg/l; NSDWQ, 2015). Dissolved oxygen values of 6-8 mg/l were observed at the eastern sector of the lower estuary. Dissolved oxygen levels were generally low (<4 mg/l) throughout the channel especially at the upstream reaches of the channel and towards the mouth of adjoining tributaries. These may be attributed to the low transparency (shallow photic depth) observed in the estuary. Low transparency limits phytoplankton productivity resulting in low levels of dissolved oxygen. The predominantly low levels of dissolved oxygen (2-4 mg/l) observed in the Cross River estuary are similar to those reported for the Cross River by Moses (1979) and Lowenberg and Kunzel (1992). Akpan et al. (2002) reported similar low levels of dissolved oxygen for the Great-Kwa River. Elevated concentrations of dissolved oxygen (6-12 mg/l) were recorded near mid-channel sand bars at the upper estuary channel and further downstream near the Bakassi Peninsula (Figures 7a and b). The observed increase may be related high photosynthetic activity by primary producers promoted by low turbidity and high incidence of sunlight. The dissolved oxygen levels of bottom waters were observed to be slightly higher than dissolved oxygen of surface waters (Tables 1 and 2). Bottom waters are associated with slightly lower temperatures and combination of lower temperature and higher pressure may lead to increased solubility of dissolved oxygen.

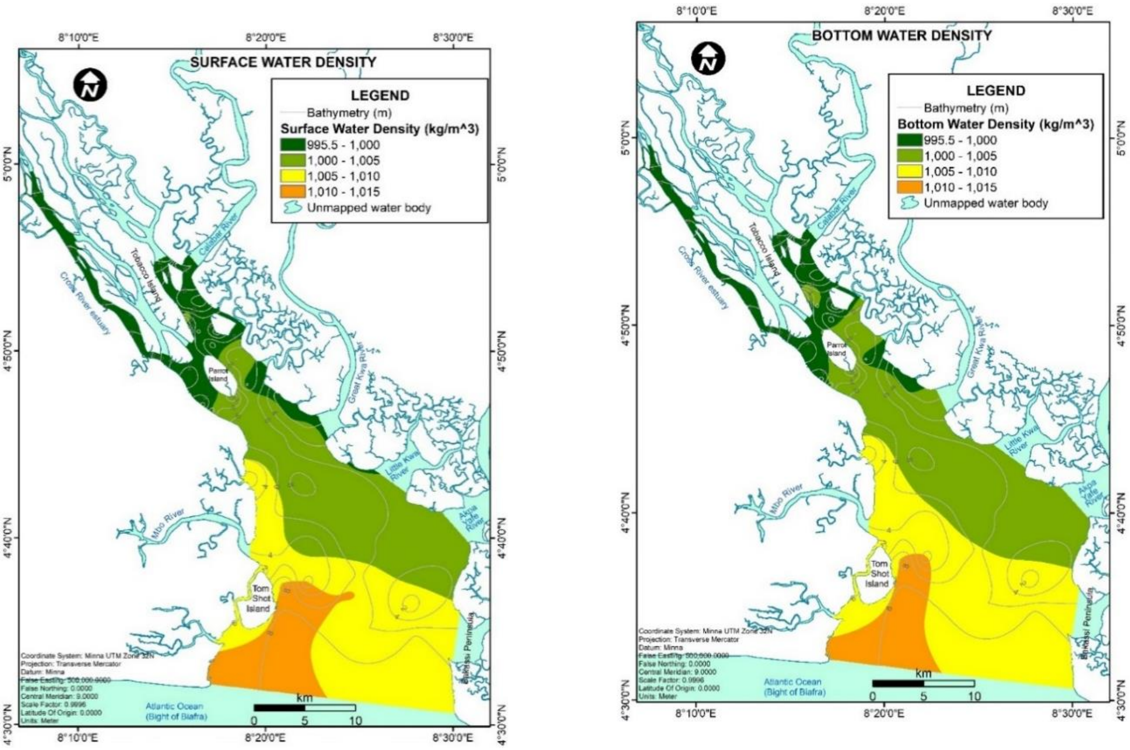


(a) (b)

Fig. 7 Dissolved Oxygen distribution in Cross River estuary (a) surface water (b) bottom water

Density

Surface water density ranged from 1 kg/m^3 (stations 1-4; 17; 21) to 1.015 kg/m^3 (station 49) with a mean value of 1.006 kg/m^3 (Tables 1 and 3). Bottom water density ranged from 1 kg/m^3 (stations 1-4; 17; 21) to 1.015 kg/m^3 (stations 46, 48-49; 53) with a mean value of 1.006 kg/m^3 (Tables 2 and 4). The lowest densities were observed upstream of the channel. Surface and bottom water densities increased towards the lower estuary. The distribution pattern of surface and bottom water density of the Cross River estuary is presented in Figures 8a and b respectively. Surface and bottom water densities showed similar distribution patterns. However, a slight increase in bottom water density was observed compared to surface waters. A combination of high salinity and lower temperature, makes bottom water denser than the surface waters. The upper fresh water reaches of the estuary are less dense compared to the more saline lower estuarine waters. Seawater is denser than fresh water due to the amount of dissolved ions present and tidal penetration decreases upstream of the estuary. The denser waters of the lower estuary are promoted by tidal mixing of estuarine waters with seawater.



(a) (b)

Fig. 8 Density distribution in Cross River estuary (a) surface water (b) bottom water

Pearson correlation matrix

Similarities between physicochemical parameters of surface and bottom waters within the Cross River estuary were analyzed using Pearson correlation matrix (Tables 5 and 6). In surface waters, transparency showed weak positive correlations with salinity (r=0.18) and pH (r=0.22); and negatively correlated with temperature (r=-0.23) and dissolved oxygen (r=-0.23) as shown in Table 5. Salinity showed significant correlations ($p<0.05$) with pH (r=0.51) while density showed significant correlations ($p<0.05$) with temperature (r=0.33), pH (r=0.33) and salinity (r=0.93). Density generally followed the salinity gradient of the estuary. A strong correlation exists between salinity and water density (Armstrong & Brasier, 2005; Pritchard, 1967; Venice, 1958). Dissolved oxygen negatively correlated with temperature (r=-0.05) and pH (r=-0.19). Temperature showed weak positive correlation with salinity (r=0.26) (Table 5). In bottom waters, salinity showed significant correlations ($p<0.05$) with temperature (r=0.35) and pH (r=0.49) while density showed significant correlations ($p<0.05$) with temperature (r=0.39), pH (r=0.31) and salinity (r=0.91) (Table 6). Dissolved oxygen negatively correlated with temperature (r=-0.10) and pH (r=-0.12) (Table 6).

Table 5 Correlation matrix showing r values of physicochemical variables in surface waters

Surface water	Transparency	Temperature	pH	Salinity	Dissolved Oxygen	Density
Transparency (m)	1					
Temperature	-0.23	1				
pH	0.22	-0.05	1			
Salinity	0.18	0.26	*0.51	1		
Dissolved Oxygen	-0.23	-0.05	-0.19	0.00	1	
Density	0.07	*0.33	*0.33	*0.93	0.06	1

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

Table 6 Correlation matrix showing r values of physicochemical variables in bottom waters

Bottom water	Temperature	pH	Salinity	Dissolved Oxygen	Density
Temperature	1				
pH	-0.02	1			
Salinity	*0.35	*0.49	1		
Dissolved Oxygen	-0.10	-0.12	0.08	1	
Density	*0.39	*0.31	*0.91	0.18	1

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

Cluster analysis

Cluster analysis was performed on all 55 sampling stations against both surface and bottom water physicochemical parameters. The analysis was performed in order to define the similarity or dissimilarity of groups between the sampling stations. Hierarchical cluster analysis using the UPGMA method based on Euclidean distance produced two distinct groups, reflecting different physicochemical properties in the study area. Cluster 1 occurred at a linkage distance of 8.5 (Figure 11) and cluster 2 occurred at a linkage distance of 16 (Figure 11). Cluster 1 consisted of 13 sampling stations (37, 40, 42, 43, 47, 48, 49, 50, 51, 52, 53, 54, 55). It occurred in the lower estuary, characterized by a maximum water depth of 10m. Transparency in this environment ranged from 0.4-1.2 m. Waters are brackish with neutral to slightly alkaline pH conditions. Dissolved oxygen varied between 2-8 mg/l. Cluster 2 which consisted of the remaining 42 sampling stations occurred within the upper and central portions of the estuary characterized by water depths ranging from 2-8 m. Transparency in this environment is generally low (0-0.6 m), waters are limnetic to brackish, slightly acidic (pH=5-6) with dissolved oxygen ranging from 4=10 mg/l. Of all the physico-chemical variables assessed, salinity had the strongest correlation with temperature and pH. It appears that salinity is an important water quality parameter in the Cross River estuary. Spatial heterogeneity observed in surface and bottom water physicochemical parameters of the estuary are influenced by a complex interplay of natural conditions such as rate of fluvial discharge, tidal mixing, light intensity and anthropogenic impacts such as channel dredging.

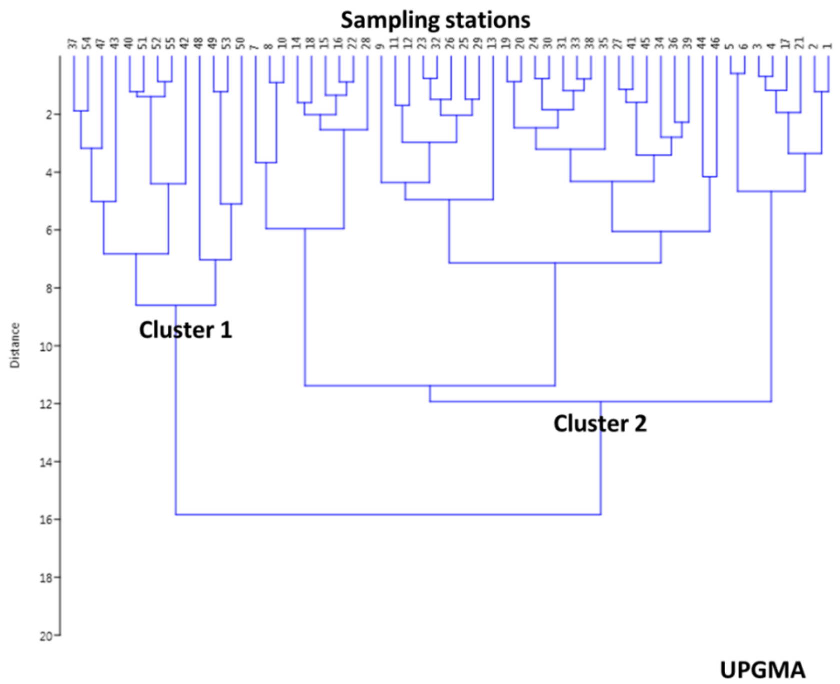


Fig. 9 Dendrogram of cluster analysis using UPGMA method and Euclidian distances for all 55 sampling stations according to surface and bottom physicochemical parameters of the Cross River estuary

CONCLUSION

Tidal variations and physicochemical parameters in the Cross River estuary were studied to establish the variations of hydro-physicochemical parameters within during the dry season. Results of tidal current velocity indicated ebb-dominance at Spring and Neap tidal cycles. Cluster analysis performed on 55 sampling stations revealed two distinct groups, reflecting different physicochemical properties in the study area. Cluster 1 which occurred in the lower estuary is characterized by a maximum water depth of 10 m. Transparency in this environment ranged from 0.4-1.2 m. Waters are brackish with neutral to slightly alkaline pH conditions. Dissolved oxygen varied between 2-8 mg/l. Cluster 2 which occurred within the upper and central portions of the estuary is characterized by water depths ranging from 2-8 m. Transparency in this environment is generally low (0-0.6 m), waters are limnetic to brackish, slightly acidic (pH=5-6) with dissolved oxygen ranging from 4=10 mg/l. Salinity and pH in the estuary are regulated by freshwater flow and tidal mixing. Salinity varied from limnetic at the upper reaches of the estuary to polyhaline downstream. The low salinity of the upper reaches of the estuary is related to strong fluvial current and weak tidal penetration upstream. The predominantly low levels of dissolved oxygen (2-4 mg/l) observed in the Cross River estuary may be attributed to the low transparency observed in the estuary channel. Low transparency limits phytoplankton productivity resulting in low levels of dissolved oxygen. The pH of both surface and bottom waters increased from slightly acidic at the upper estuary to slightly alkaline towards the lower estuary. Surface water pH was slightly more acidic than the pH of bottom waters due to stronger fluvial influence on surface waters. Results from Pearson's correlation matrix revealed that salinity showed better correlations with temperature and pH compared to other physicochemical variables. Salinity may be considered an important water quality parameter in the Cross River estuary. This study provides a better understanding of the ecological conditions and critical processes that occur in the estuarine system. Information from this study may be useful in the effective monitoring and management of the estuary as well as similar tropical estuarine systems.

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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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