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WET SEASON PHYSICOCHEMICAL CHARACTERISTICS OF THE CROSS RIVER ESTUARY, SOUTHEAST, NIGERIA

CHIMEZIE NDUNAGUM EMEKA, VICTORIA INYANG EMEKA, EDAK KANU AGI-ODEY, ANTIGHA ANTIGHA AMBO, GRACE ORLANDO EDEM

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ABSTRACT

The physico-chemical properties of the lower reaches of the Cross River estuary were studied in the wet season month of September, 2011. A total of 50 bottom water samples were obtained using a Nansen Bottom Water Sampler, at 50 geo-referenced stations within the channel. Depth measurements were simultaneously taken at each station using an echo-sounder, while turbidity was measured using a secchi-disc. Temperature, salinity and pH were analysed for each sample, using a HANNA hand held combo meter (HI 98129). Within the channel, bottom water temperature ranged between 23 and 30°C, turbidity (transparency) ranged between 30 and 100 cm, pH ranged between 5 and 9, while bottom water salinity ranged between 0.15 and 0.20 ‰. Based on salinity, the channel was divided into 3 physico-chemical facies: the Upper Facies is fairly saline, characterized by temperatures ranging from 25 to 26°C, is the least turbid segment of the channel and isalkaline the Middle Facies, the least saline part of the channel, characterized by temperatures ranging from 24 to 29°C, most turbid, and neutral,; and the Lower Facies, the most saline portion of the channel, with temperatures ranging from 25 to 29°C, is the more, acidic, part of the channel. The estuary appeared to have been greatly diluted. This may be attributed to the fact that the study was carried out during the rainy season. As a result of the high freshwater discharge into the channel during this season, the freshwater-brackishwater interface has been driven further downstream, towards the Atlantic Ocean

KEYWORDS: Salinity, pH, Temperature, Turbidity, Physico-Chemistry, Cross River estuary

INTRODUCTION

Dalrymple et al. (1992) geologically defined an estuary as the seaward portion of a drowned river valley system that receives sediments from both fluvial and marine sources and which contains facies influenced by tides, waves and fluvial processes. An estuary would occupy the area at a river mouth where salinities range from approximately 0.1‰ to 35‰ (Pritchard, 1967) and is considered to extend from the landward limit of tidal facies at its head to the seaward limit of coastal facies at its mouth (Dalrymple et al., 1992) (Figure 1).

Chimezie Ndunagum Emeka, Department of Geology, University of Calabar, Calabar, Nigeria
Victoria Inyang Emeka, Department of Physical Oceanography, University of Calabar, Calabar, Nigeria
Edak Kanu Agi-Odey, Department of Physical Oceanography, University of Calabar, Calabar, Nigeria
Antigha Antigha Ambo, Department of Fisheries and Aquaculture, University of Calabar, Calabar, Nigeria
Grace Orlando Edem, Department of Geology, University of Calabar, Calabar, Nigeria

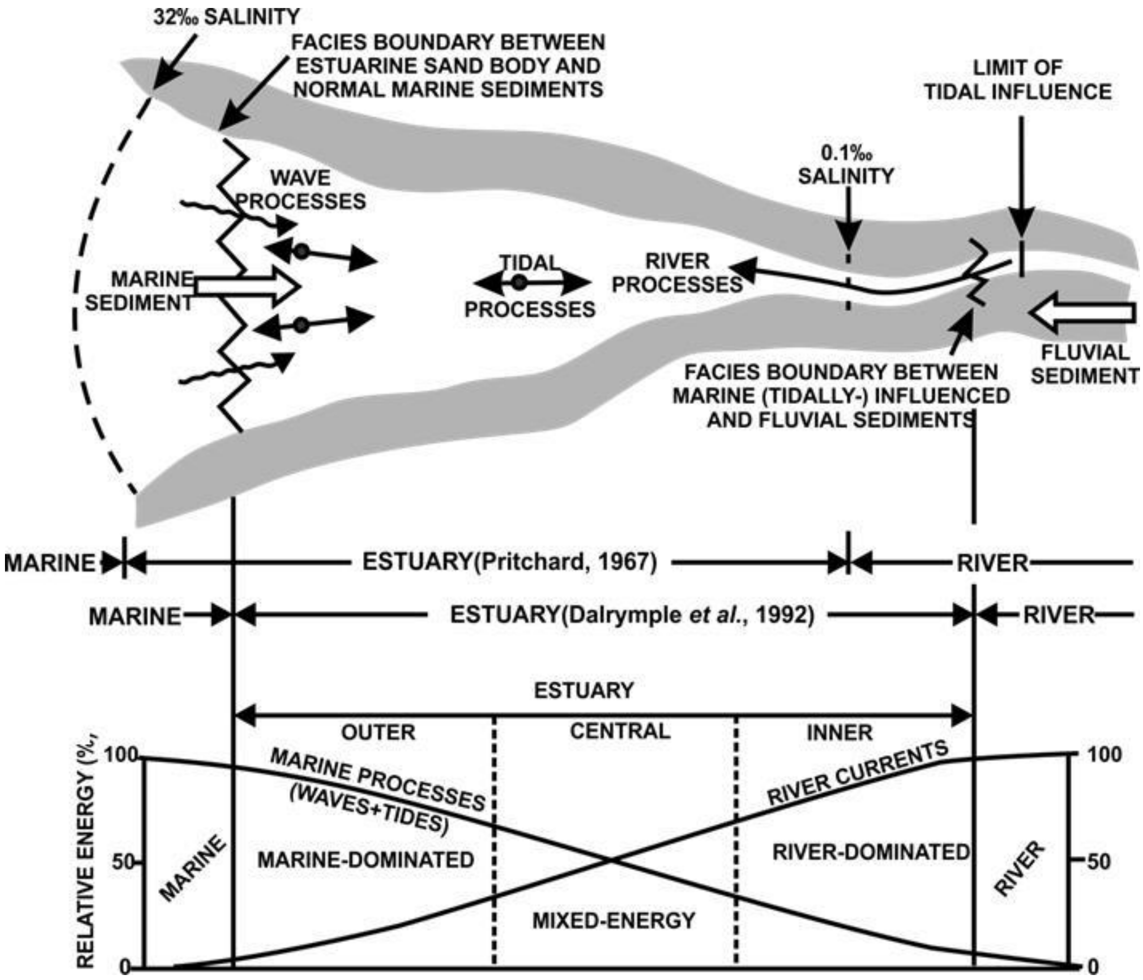


Figure 1: A schematic representation of the tripartite division of an estuary (adapted from Dalrymple et al. 1992).

Salinity is the most distinctive property used in chemically characterizing water bodies (Perrillo, 1996). Estuaries classified on the basis of salinity have been grouped into two major categories by two different definitions. The first is by Cameron and Pritchard (1963): “an estuary is a semi enclosed body of water which has a free connection with sea and within which seawater is measurably diluted with freshwater derived from land drainage”. Estuaries defined by this definition are known as positive estuaries (Umgiesser and Zonta, 2010). The second definition is by Tomczak (2002): “an estuary is a narrow, semi-enclosed coastal body of water which has a free connection with the open sea at least intermittently and within which the salinity of the water is measurably different from the salinity in the open ocean”. These are called inverse estuaries (Umgiesser and Zonta, 2010). Pritchard (1967) gave salinity values for: freshwater bodies as ≤0.1‰; estuaries to vary from 0.1‰ to 32‰; marine waters to vary from 32‰ to 40‰; and hypersaline water bodies as ≥40‰. Armstrong and Brassier (2005) delineated four main salinity ranges as: freshwater (<0.5‰), brackish-water (0.5 to 30‰), marine (30 to 40‰) and hypersaline water (>40‰).

Estuaries are influenced by physical phenomena such as waves, tides, winds and fluvial processes which make them complex systems. They may be classified based on geomorphology, tidal range and salinity distribution. There are also tectonic classifications of estuaries. Based on geomorphology, Pritchard (1952, 1967) classified them into Coastal plain estuaries, Fjords and Bar-built estuaries. Based on tidal range, they have been classified into micro-tidal estuaries (0-2 m), meso-tidal estuaries (2-4 m) and macro-tidal estuaries (> 4m) (Dyer, 1973; Hayes, 1976; Dyer et al., 2000). Based on salinity/circulation pattern and by comparing the volume of fresh water that enters from the river during ebbing, and the volume of marine water brought into the estuary by tide (during flooding) which is removed over each tidal cycle, four types of estuaries can be highlighted; thus: 1. salt wedge estuary, 2. highly stratified estuary, 3. slightly stratified estuary, 4. vertically mixed estuary, and 5. inverse or reverse estuary. (Pritchard, 1955, 1967;

Bowden, 1967; Fischer, 1972; Dyer, 1973, 1997; Umgiesser and Zonta, 2010).

Geomorphology of estuaries strongly affects the transport of pollutants and ultimately impacts water quality characteristics (Dyer, 1973; Martin and McCutcheon, 1999). Tide, river discharge, bathymetry, wind, Coriolis force etc. control the processes in an estuary (Fischer et al., 1979). Circulation and transport mechanisms in estuaries are complex and subject to a large spatial and temporal variability derived from the interaction of river discharge, tides and winds (Manoj, 2008). These forces drive the gravitational circulation and turbulent diffusion which are the main processes controlling the transport of properties in estuaries (Mantovanelli et al., 2004). Salinity distribution in an estuary varies from place to place due to their geographical locations, prevailing climate systems and tidal range (Manoj, 2008). Fischer (1972) pointed out that as a result of differential pressure forces due to landward moving saline water and seaward moving freshwater from the upstream end, resultant longitudinal density currents give rise to mixing both longitudinally and vertically, within estuaries, therefore, the higher the influence of tides in the estuary, the better the mixing. Bathymetry in an estuary regulates the speed of propagation of tides (Manoj, 2008). Estuaries are often better mixed in shallow regions than in deeper regions. Freshwater inflow into an estuary normally has a significant impact on mixing and the increased freshwater inflow can change the character of an estuary from well mixed to partially mixed or highly stratified (Martin and McCutcheon, 1999).

The lower reaches of the Cross River estuary was studied to ascertain the spatial and temporal distribution of its bathymetry and physico-chemical properties, which include bottom water temperature, salinity, pH, and turbidity. The work aimed to empirically examine the relationship between the mentioned parameters within the channel, as well as to provide a baseline source of information for future studies of the channel and/or similar channels.

Location and regional setting

Cross River takes its source from the Adamawa Mountain Range (at an altitude of over 1km above mean sea level) in South-West Cameroon, and flows over a distance of about 500.7 km towards the south-east coast of Nigeria (Figure 2). It has a minimum channel width of less than 1 m at its source and a maximum channel width of about 25.8 km at its mouth. Cross River is a meandering stream in the upstream segment that forms its fluvial part and trends in a SE-NW, NE-SW, and NW-SE manner. It becomes anastomosing to braided in the estuarine part, (typical of most coastal plain estuaries, according to Wright et al., 1973), trending in a NW-SE manner until it empties into the Atlantic Ocean at the Bight of Biafra. Its estuary is the largest along the Gulf of Guinea (Nawa, 1982; Moses, 1988; Enyenihi, 1991).

The studied segment of the Cross River estuary stretches from the mouth of the Calabar River (north-westwards) to the mouth of the Great Kwa River (south-eastwards), covering a

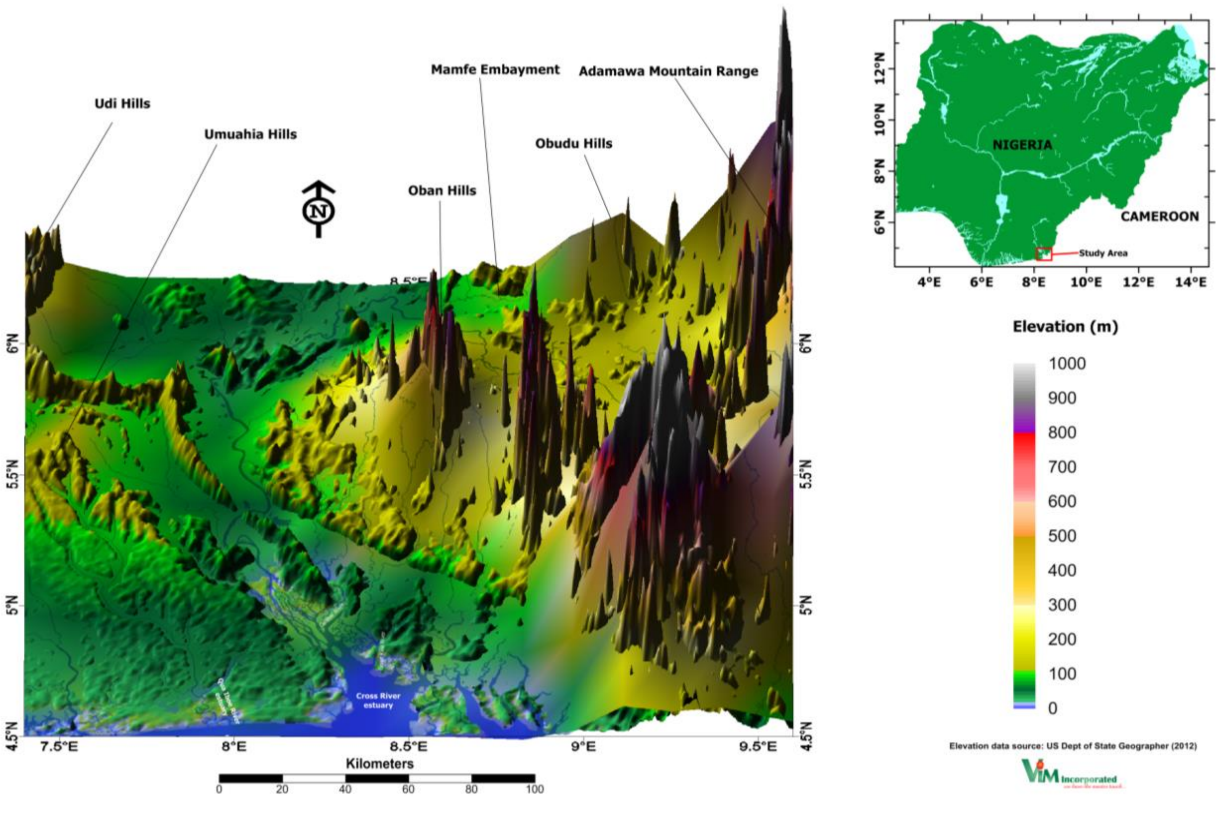


Figure 2: A 3D topographic model of the study area

stretch of approximately 31.656 km and a total surface area of 159.023346 km^2 (Figure 3). It lies within longitudes 8°27'31" E and 8°50' E; and latitudes 4°42'34" N and 4°56'22" N; covering a total surface area of 155.45 km^2. The minimum width of the segment (0.704 km) lies towards the head and its maximum width (10.809 km) lies towards the mouth.

The geological map of the study area, as presented in Figure 4, shows that the studied segment of the channel occurs within Alluvium (of Recent age) and part of the studied segment of the Cross River channel lies within Coastal Plain Sand, also known as the Benin Formation (Pleistocene/Pliocene age). Cross River cuts through the Precambrian Basement Complex at its source in the Adamawa Highlands, in Cameroon. It subsequently flows through the Asu River Group (Albian/Cenomanian), in the Mamfe Embayment of Cross River State, Nigeria, which consists of shales, sandstones and limestones. Further downstream, it flows through Coastal Plain Sands (Pleistocene/Pliocene age) and Alluvium (Recent age), before emptying into the Atlantic Ocean at the Bight of Biafra (NGSA, 2007).

MATERIALS AND METHODS

The field work was carried out in September, 2011. Parameters considered include tidal current velocity, water depth, and physico-chemical parameters (pH, temperature, turbidity and salinity). Tidal current velocity was measured at one station along the channel, over Spring, Mean, and Neap tidal cycles, using the Langrangian Technique. Bottom water tidal current velocity was extrapolated by multiplying the surface values by 0.7 (Antia, pers. comm.).

Fifty (50) bottom water samples were obtained from the channel near depth, in a manner as shown in Figure 5, from an outboard motorboat. While depth was measured using an echo-sounder, bottom water samples were obtained using a Nansen Bottom Water Sampler. The physico-chemical parameters of the water samples were measured insitu, using a a HANNA hand held combo meter (HI 98129).

1. Results and Discussions

1.1 Hydrodynamics

Cross River estuary is a meso-tidal, semi-diurnal, coastal plain estuary. Results of the surface and bottom tidal current velocities obtained from the channel are presented in Figure 6 and Table 1. The ebb dominance observed in the channel is as a result of the additive effects of fluvial discharge on the ebb component of the tidal flow (Emeka, 2007). Water waves in Cross River estuary was generated by wind and water transport vessels. The estuary also had cases of significant shallow-swell-wave turbulence.

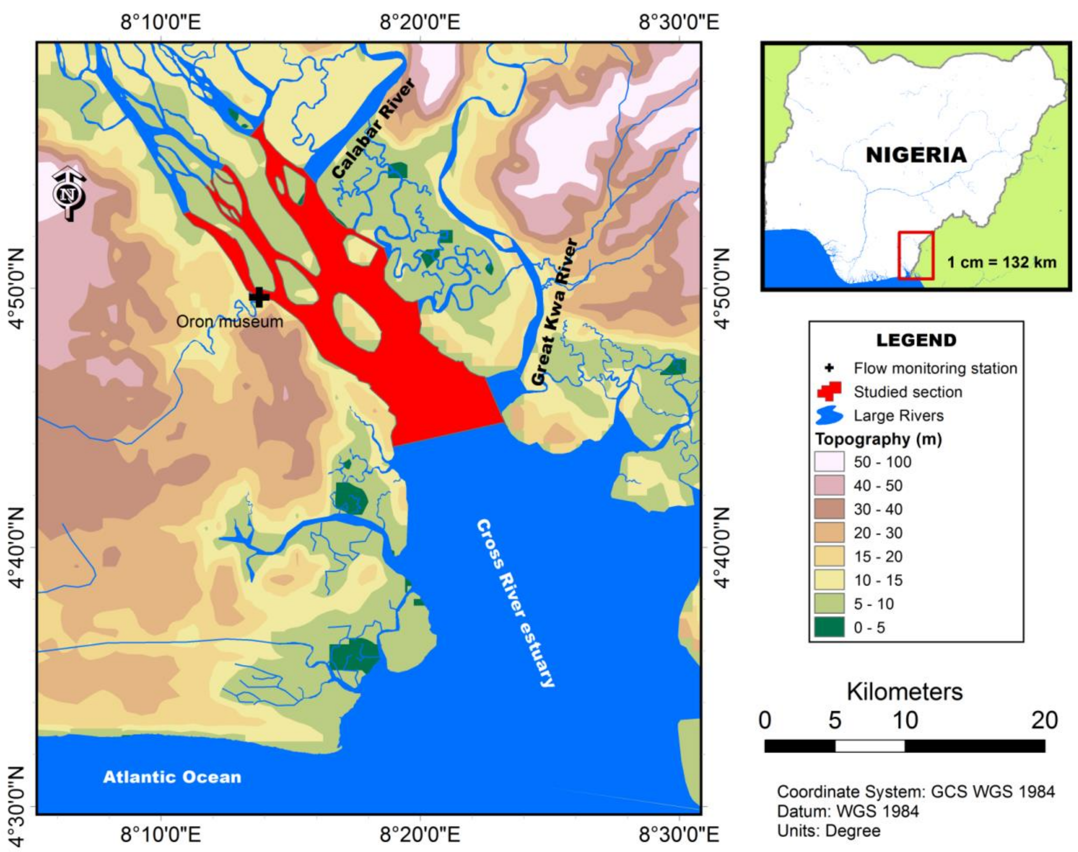


Figure 3: Topographic map of the study area (adapted from Google Earth, 2023)

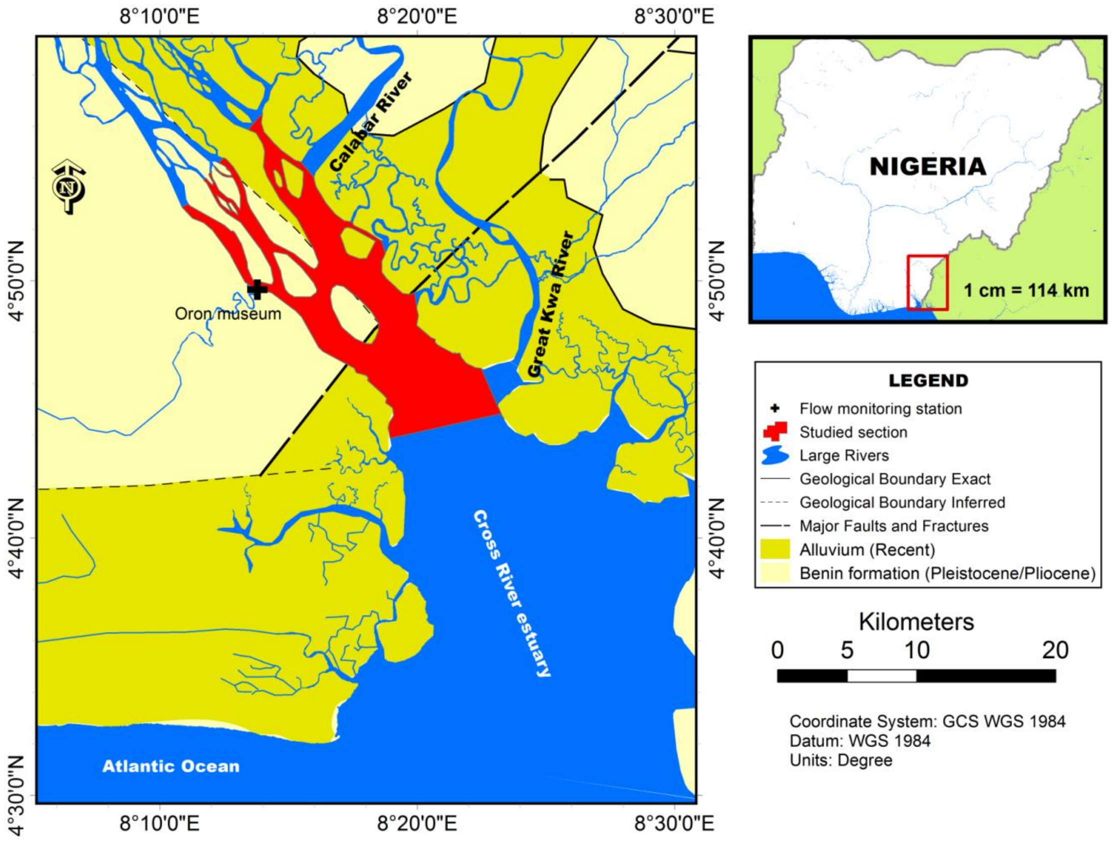


Figure 4: Geologic map of the study area (adapted from NGSA, 2010)

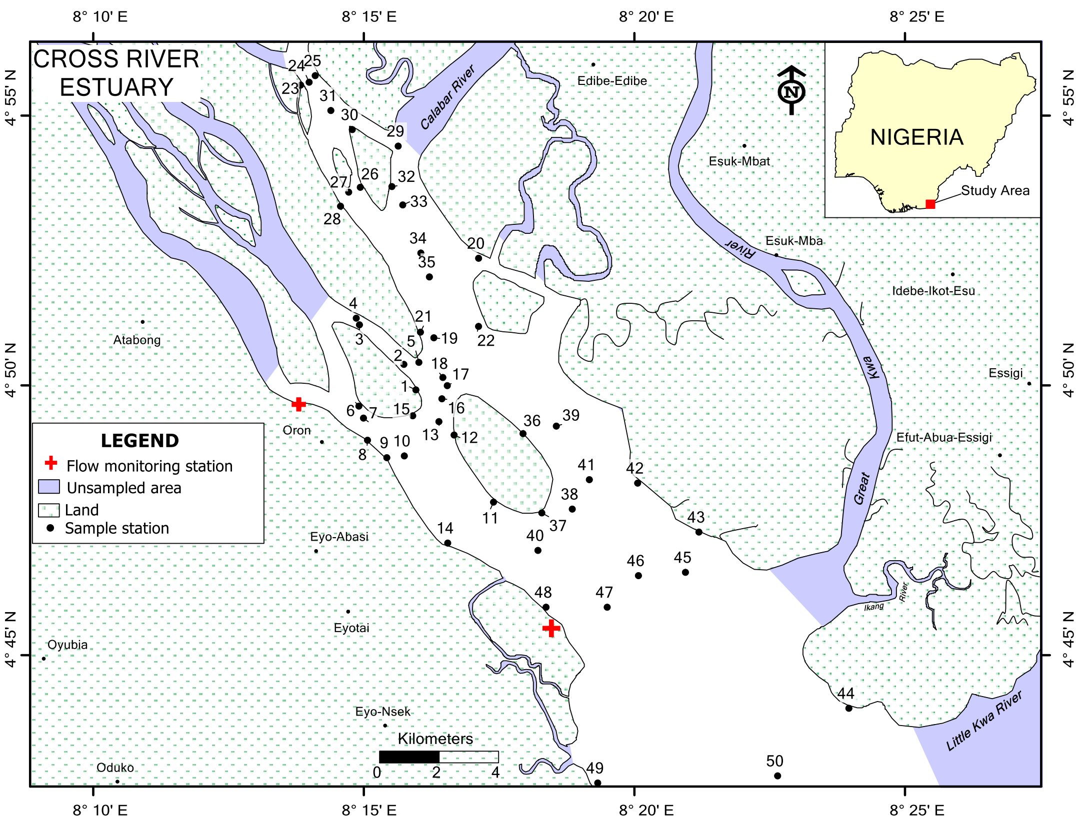


Figure 5: Sample distribution map of Cross River estuary

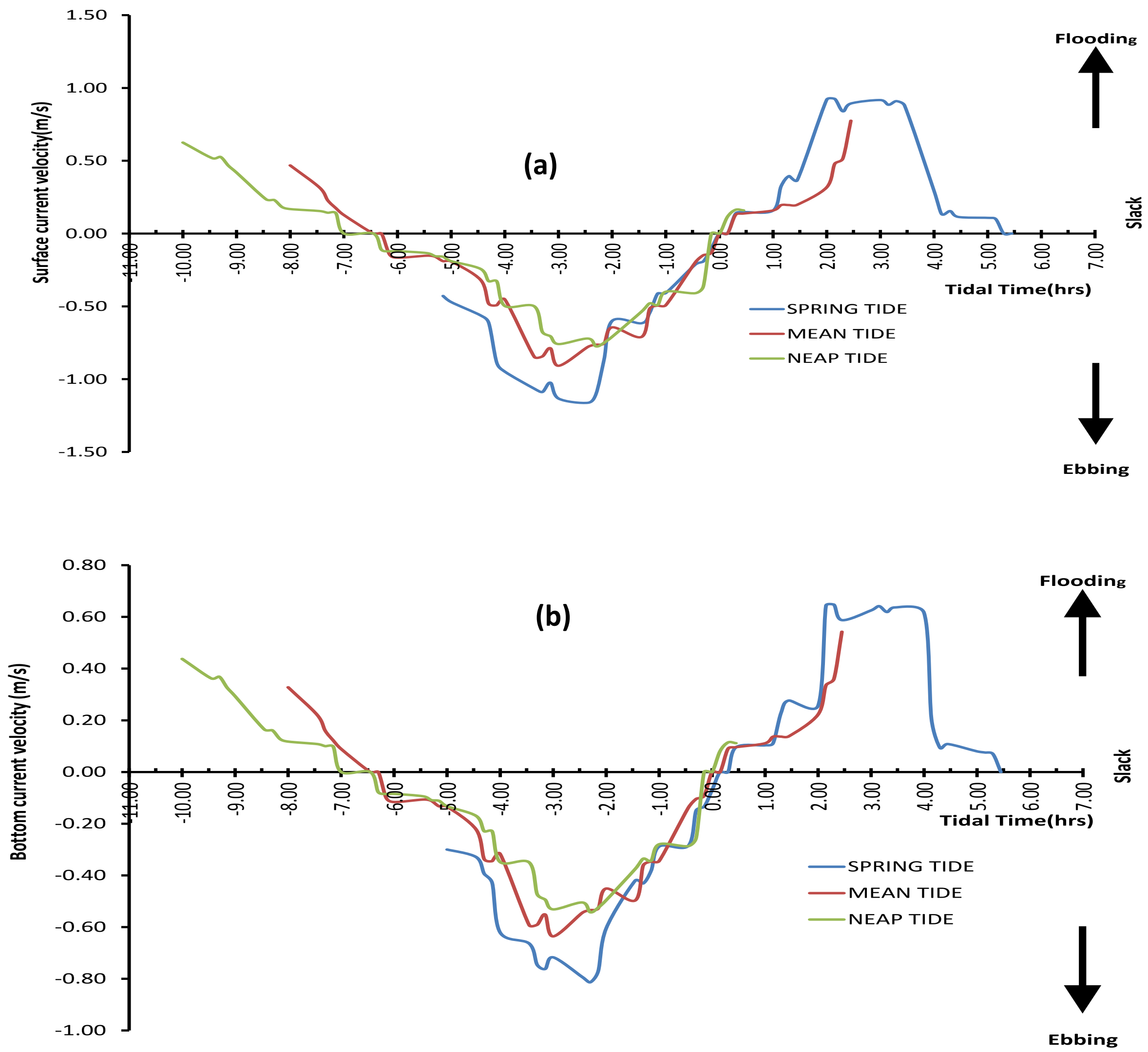


Figure 6: (a) Surface and (b) bottom tidal current velocity at Cross River estuary (Spring tide, 29/8/2011; Mean tide, 2/9/2011; and Neap tide, 4/9/2011)

Table 1: Maximum flood and ebb-tidal current velocities in Cross River estuary

Tidal Cycles	Flood current velocity (cm/s)	Ebb current velocity (cm/s)
Spring	92	116
Mean	78	91
Neap	63	78

Bathymetry

The bathymetry map of the studied segment of Cross River estuary is presented in Figure 7. It was produced relative to mean tide low water slack (MTLWS). The channel is relatively shallow, with an average depth of 4.492 m, maximum depth of 13.1 m, and minimum depth of 0.9 m. The shallowest parts of the channel are located along the banks, while the central channel bears the deepest portions. The cross channel section (Figure 8a) shows that the west bank is largely shallower than the east bank. Figure 8b is a linear trend of the along channel cross-sectional profile (Figure 8c) of the studied segment. It deepens downstream.

Turbidity

The distribution of turbidity within Cross River estuary is presented in Figure 9. Turbidity values varied between 20 cm and 100 cm, with an average of 67.6 cm. The most turbid regions of the channel occurred around the sand bars of the central segment of the channel and extended towards the western and eastern banks. These areas had values predominantly between 40 cm and 60 cm. The upstream segment had the clearest water, with values between 60 cm and 100 cm. In the downstream area, the turbidity varied between 60 cm and 80 cm.

Turbidity was predominantly affected by storm events and rapid deceleration of the channel's current as a result of contact with sandbars within the channel. This agrees with the observations of Glasgow and Burkholder (2000). 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 may be one explanation for the high turbidity in the central portion of the estuary.

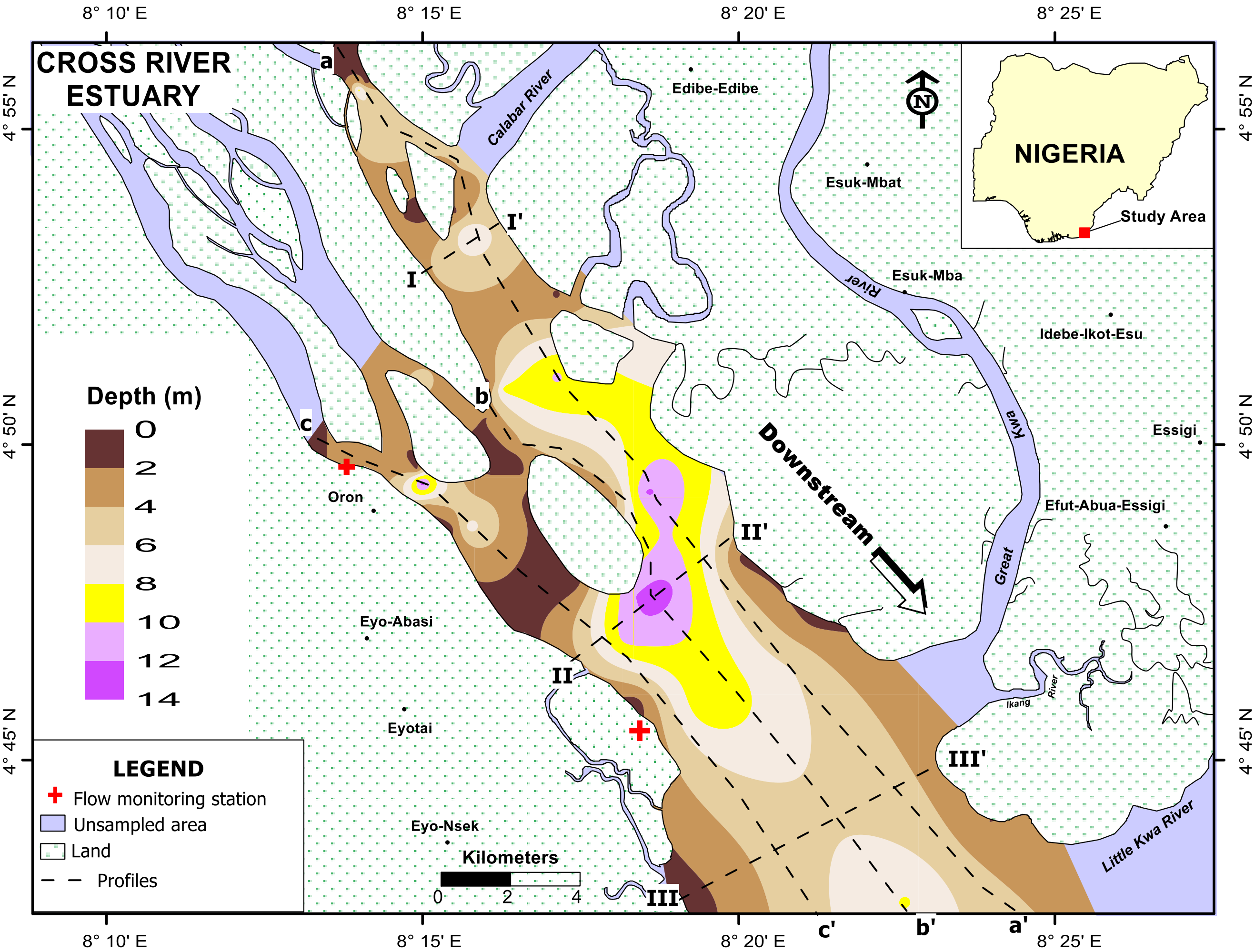


Figure 7: Bathymetric map of Cross River estuary (17/09/2011) relative to mean tide low water slack

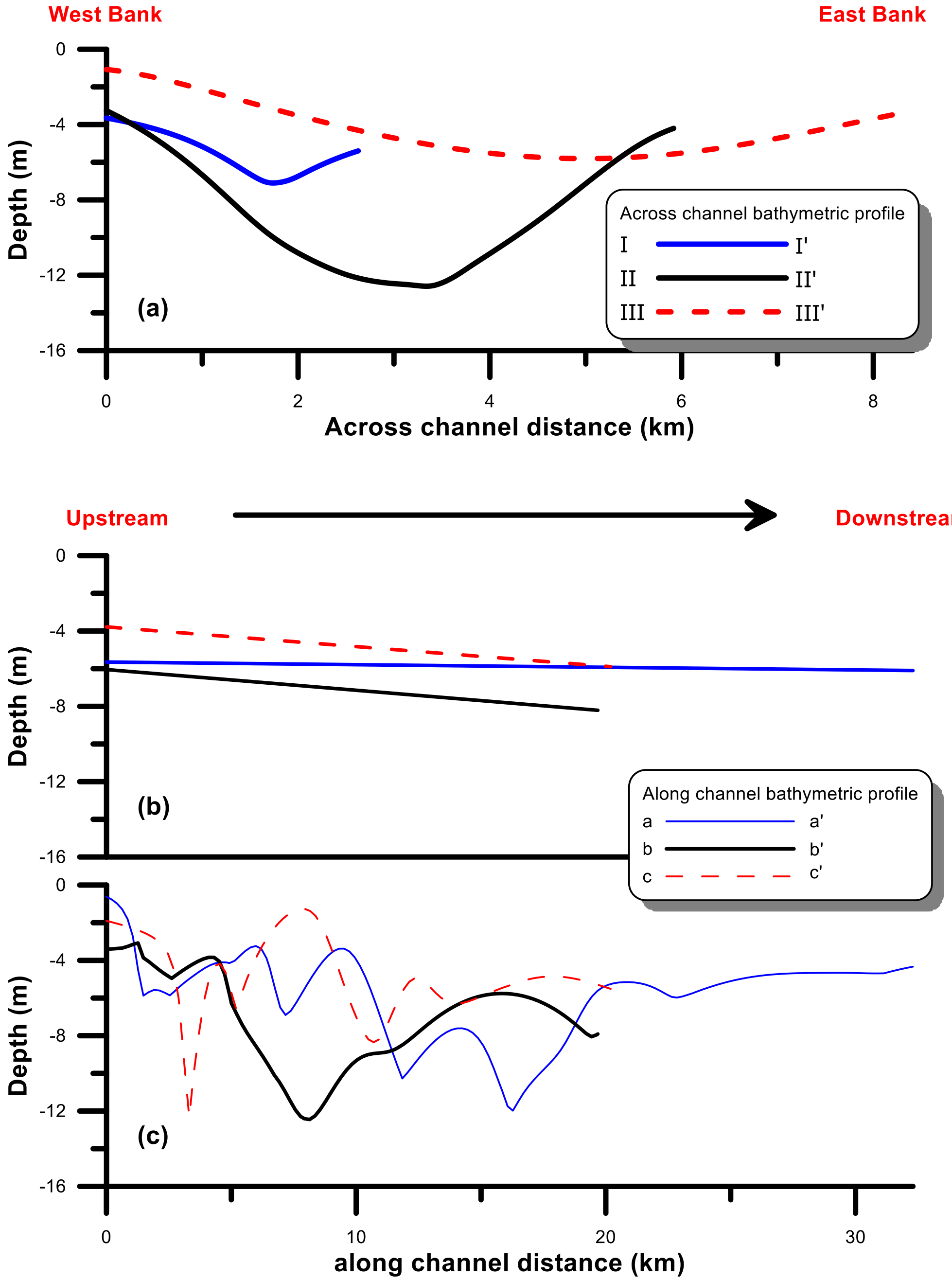


Figure 8: Bathymetric profiles of Cross River estuary showing (a) across channel sections (b) resolved along channel linear trends (c) along channel sections

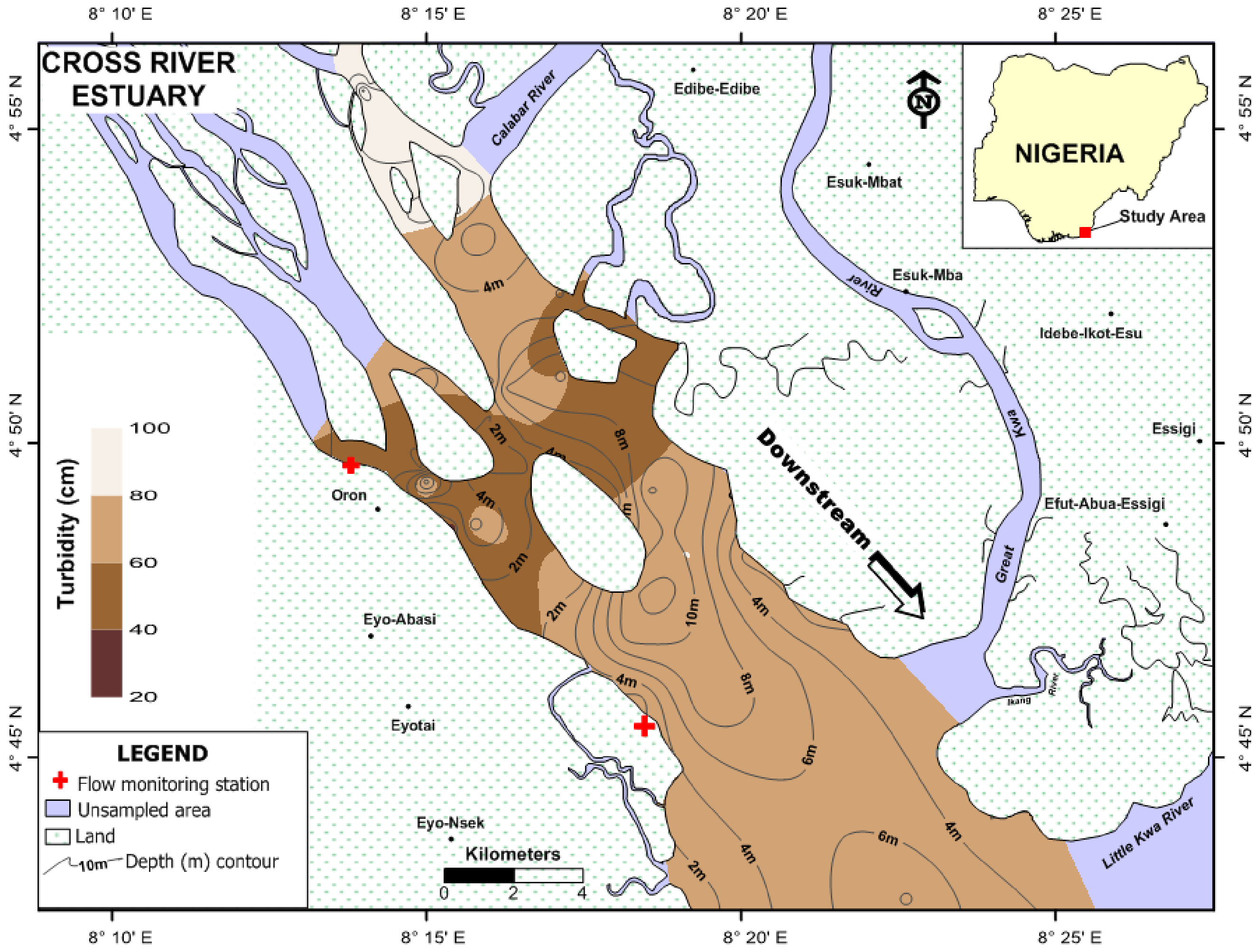


Figure 9: Distribution of bottom water turbidity in Cross River estuary

Bottom water temperature

The distribution of bottom water temperature within Cross River estuary is presented in Figure 10. Temperatures within the channel ranged from 23°C to 29°C, with an average value of 26.12°C. The channel primarily has a temperature range of from 25 to 26°C in the upstream segment and 26°C to 29°C downstream, having a downstream heating trend.

Bottom water pH

The distribution of bottom water pH within Cross River estuary is presented in Figure 11. pH values within the channel range from acidic to alkaline (5.47 and 8.7) and are averagely weakly acidic (6.63). The dominant pH range was between 6 and 7 (slightly acidic to neutral). This covers about 75% of the surface area of the channel. The upstream segment has the highest pH values of 8 to 8.7 (alkaline) while the western bank of the downstream segment the lowest range of 5 to 6 (acidic). The pH shows a decreasing trend downstream. This does not agree with the findings of Green (1990), who observed that the pH in Bonny River, Nigeria, had a downstream increasing gradient.

Bottom water salinity

The distribution of bottom water salinity within Cross River estuary is presented in Figure 12. Salinity values within the river channel range from 0.15‰ to 0.20‰. The average salinity value within the channel is 0.16‰. Salinity progressively increases downstream within the channel. The salinity range of the upstream segment of the channel is predominantly 0.15‰ to 0.16‰; that of the central segment is mainly 0.16‰ to 0.17‰; while the downstream segment occupies a range of 0.17‰ to 0.2‰, with the highest salinities occurring at the banks.

The dynamic fluctuation of salinity and water level may be attributed to the magnitude of river inflow (Harrison, 2004; Snow and Taljaard, 2007). The river discharge was accentuated by heavy rainfall within the period of sampling. Salinity stratification develops as a result of the difference in density between the inflowing fresh and saline water (Kaselowski and Adams, 2013).

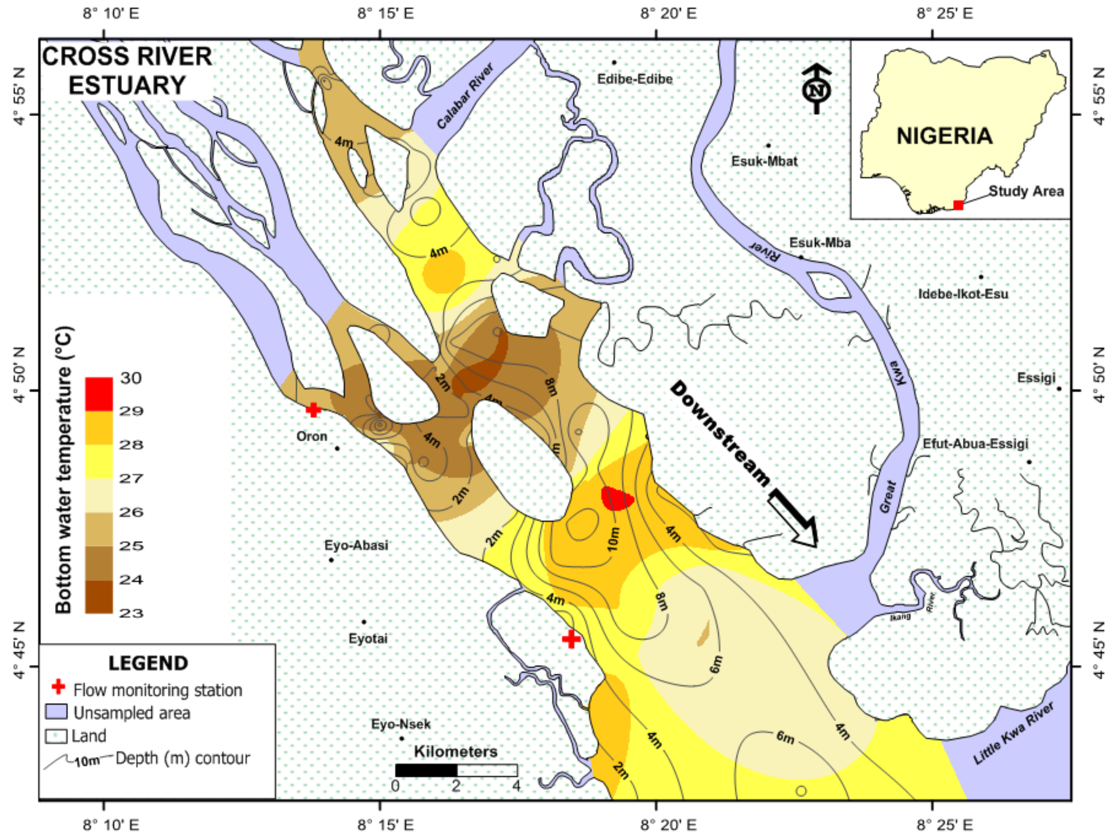


Figure 10: Distribution of bottom water temperature in Cross River estuary

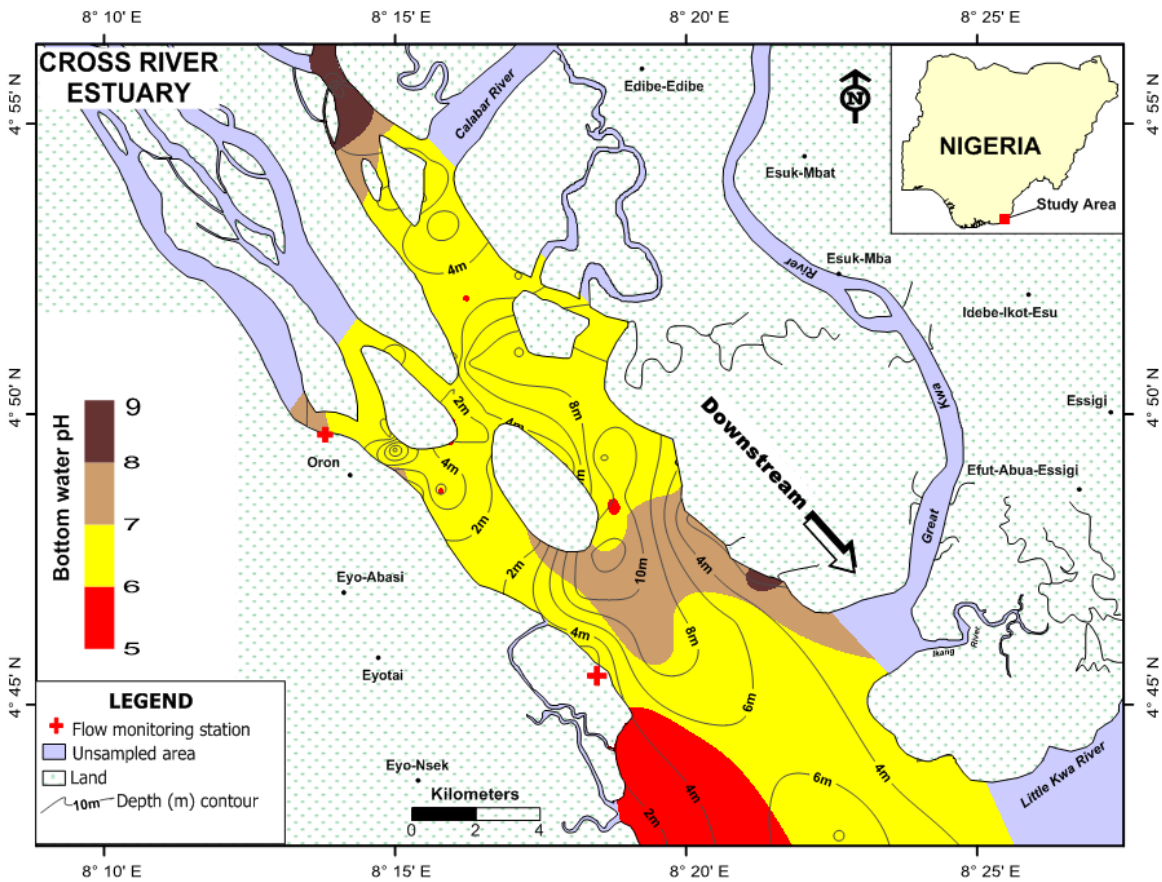


Figure 11: Distribution of bottom water pH in Cross River estuary

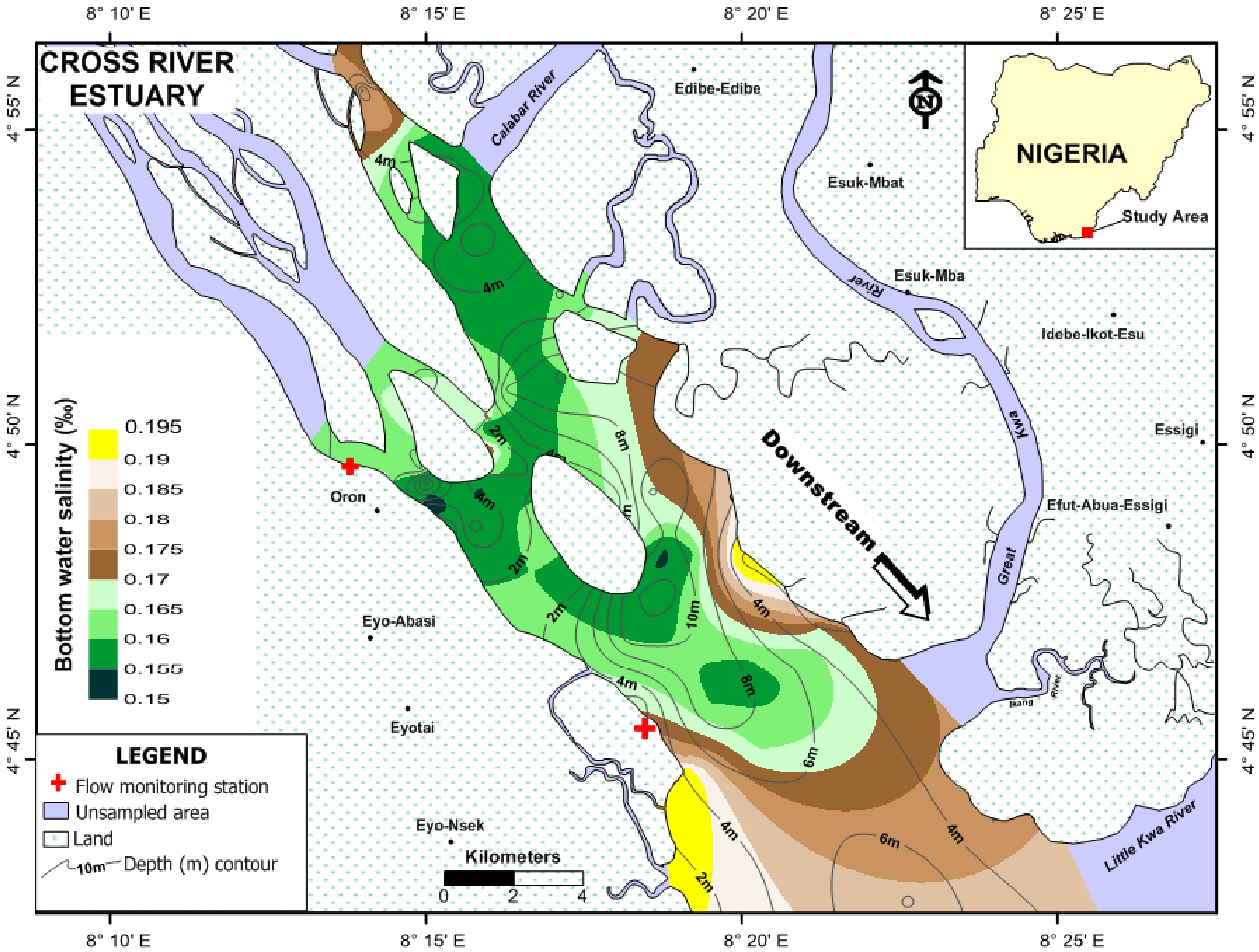


Figure 12: Distribution of bottom water salinity in Cross River estuary

Empirical properties of the physico-chemical parameters within Cross River estuary

The descriptive statistics of the parameters studied within the Cross River estuary are presented in Table 2. From this table, it is observed that the maximum depth is 13.1 m and the average is 4.492 m (Figure 8). This implies that the channel is relatively shallow, typical of most coastal plain estuaries (Mead and Moores, 2005). The maximum turbidity value is 98 cm while the average is 67.6 cm, implying that the water is reasonably clear. The maximum bottom water temperature is 29ºC, while the average is 26.12ºC. This falls within the range of tropical estuaries. The water pH ranged between slightly acidic and slightly alkaline. Its maximum pH value is 8.7, while the average value is 6.63. Bottom water salinity of the channel ranged from 0.15‰ to 0.20‰, with an average of 0.16‰. This implies that the studied part of the channel contains freshwater (Armstrong and Brassier, 2005). This may not be unconnected with the fact that sampling was done during the rainy season (September) which usually lasts from April to October. This increased the volume of fluvial discharge to the extent that it exceeded marine influence on the estuary.

Figure 13 shows the relationship between depth with salinity, pH and temperature. Generally, there appears to be a very weak to no defined relationship between depth and the other parameters. However, Figure 13a shows salinity very weakly reducing with depth (R^2 = 0.14). Figure 14 shows the relationship between turbidity with salinity, pH and temperature. Generally, there was no distinct trend. However, Figure 14c depicts turbidity values increasing gently as temperature increased (R^2 = 0.24). Figure 15 shows the relationship between temperature with salinity and pH. There was no distinct relationship between them, as there was no distinct relationship between pH and salinity (Figure 16).

Figure 17 shows correlation charts of the studied physico-chemical parameters within the Cross River estuary. The charts show that the strongest relationship occurred between turbidity and temperature (a positive correlation, R^2 = 0.24), followed by depth and salinity (a positive correlation, R^2 = 0.14). Salinity had no relationship with turbidity (R^2 = 1.4E-005) as pH had no relationship with depth (R^2 = 0.0024).

Hydro-physico-chemical facies of Cross River estuary

The studied segment of the Cross River estuary is differentiated into three distinct hydro-physico-chemical facies (Upper-, Middle- and Lower Facies) based on salinity (Figure 18). The Upper Facies is the smallest of the three facies. It covers a distance of 3.047 km and a total surface area of 3.128km^2.

Table 2: Descriptive statistics of the studied physico-chemical parameters within Cross River estuary

	DEPTH (m)	TURBIDITY (cm)	WATER TEMP(ºC)	pH	SALINITY (‰)
Mean	4.492	67.6	26.12	6.6298	0.16
Standard Error	0.53	2.12	0.26	0.09	0.00
Standard Deviation	3.73	14.99	1.83	0.66	0.01
Minimum	0.9	36	23	5.47	0.15
Maximum	13.1	98	29	8.7	0.20
Count	50	50	50	50	50

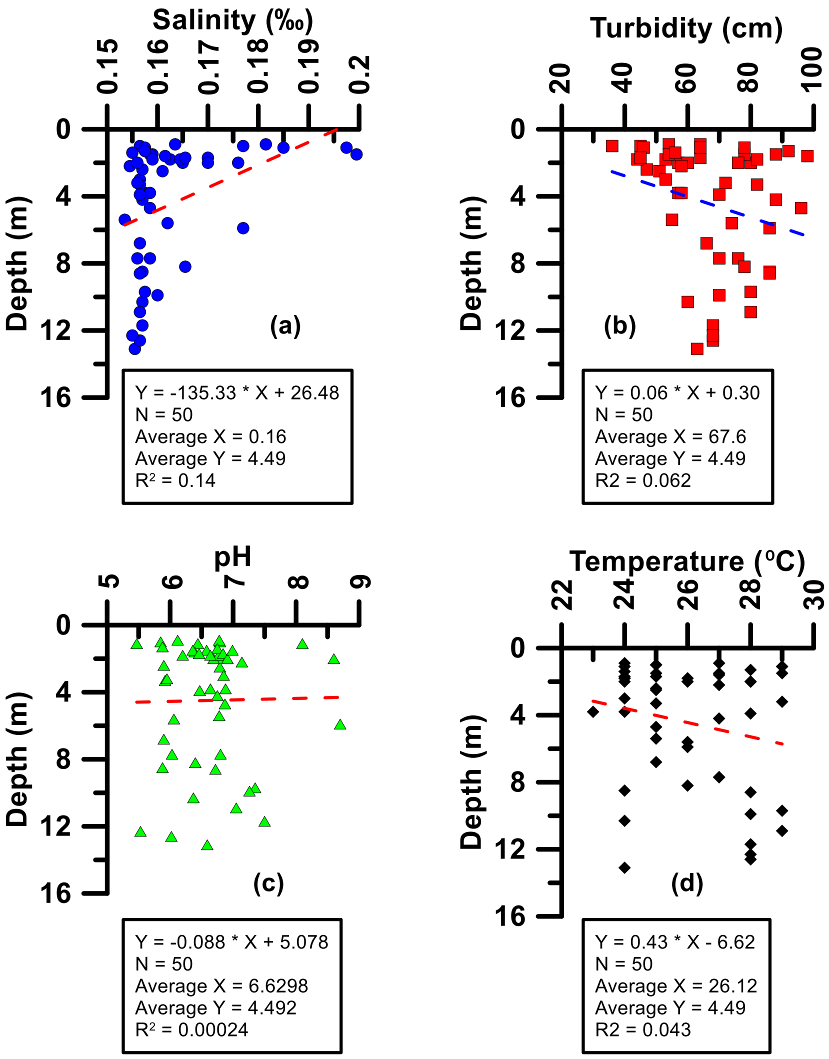


Figure 13: Bivariate plots of depth vs (a) Salinity (b) Turbidity (c) pH and (d) Temperature

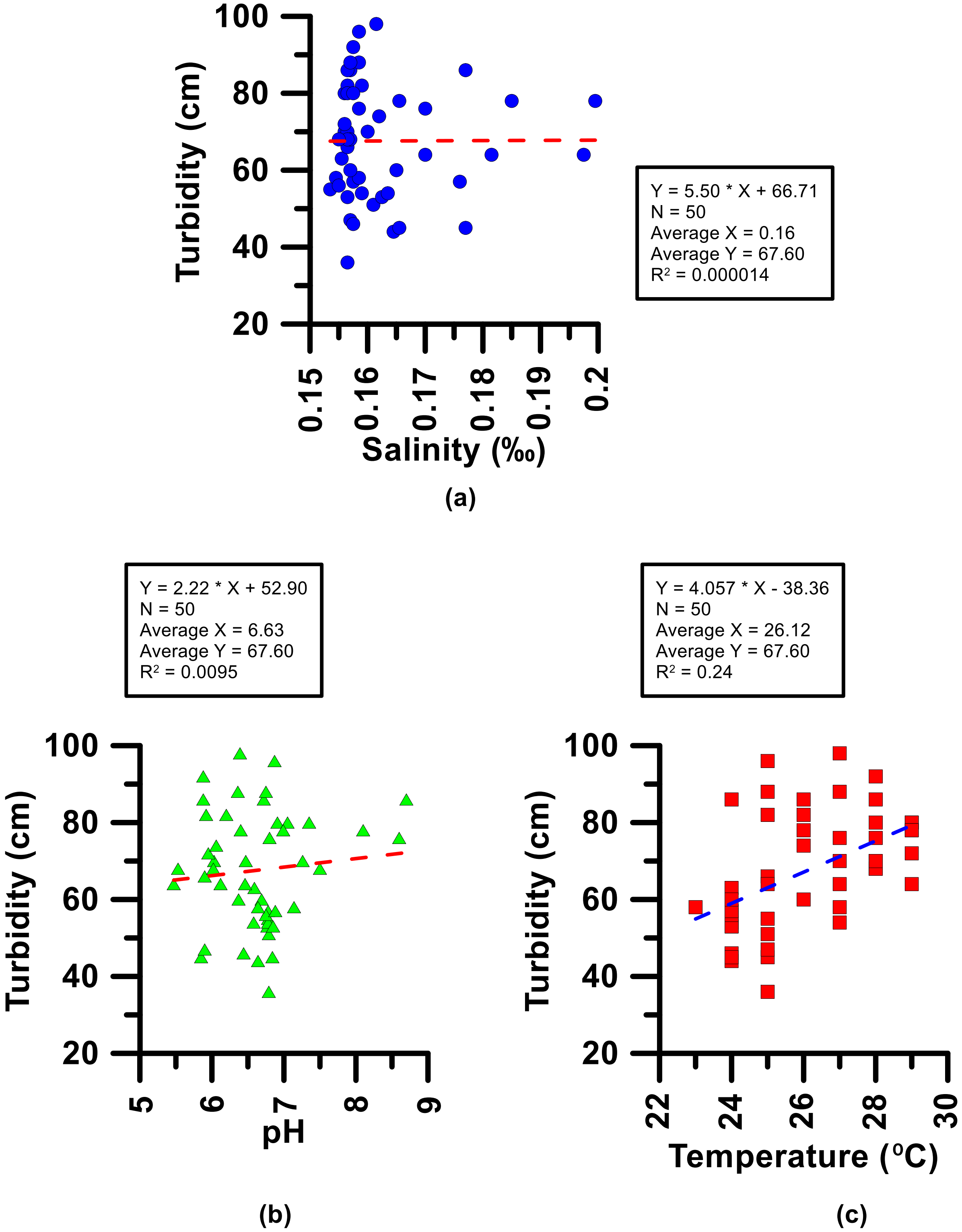
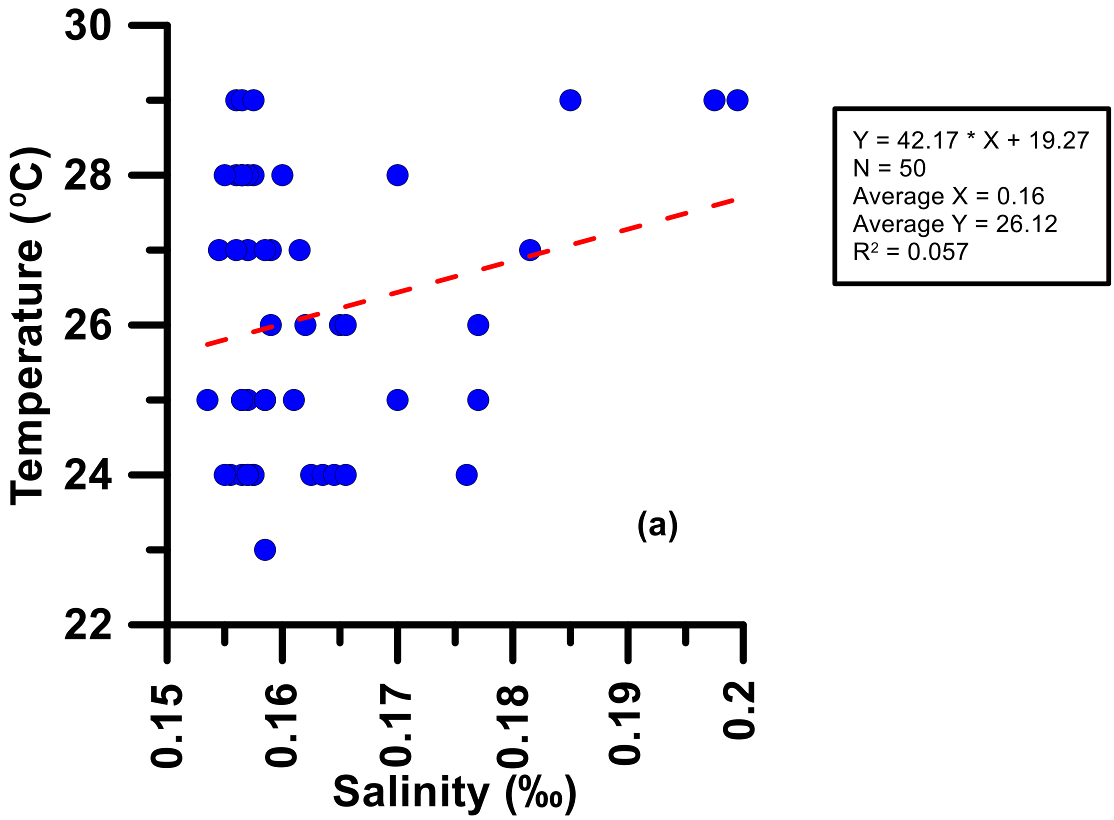


Figure 14: Bivariate plots of turbidity vs (a) Salinity (b) pH and (c) Temperature



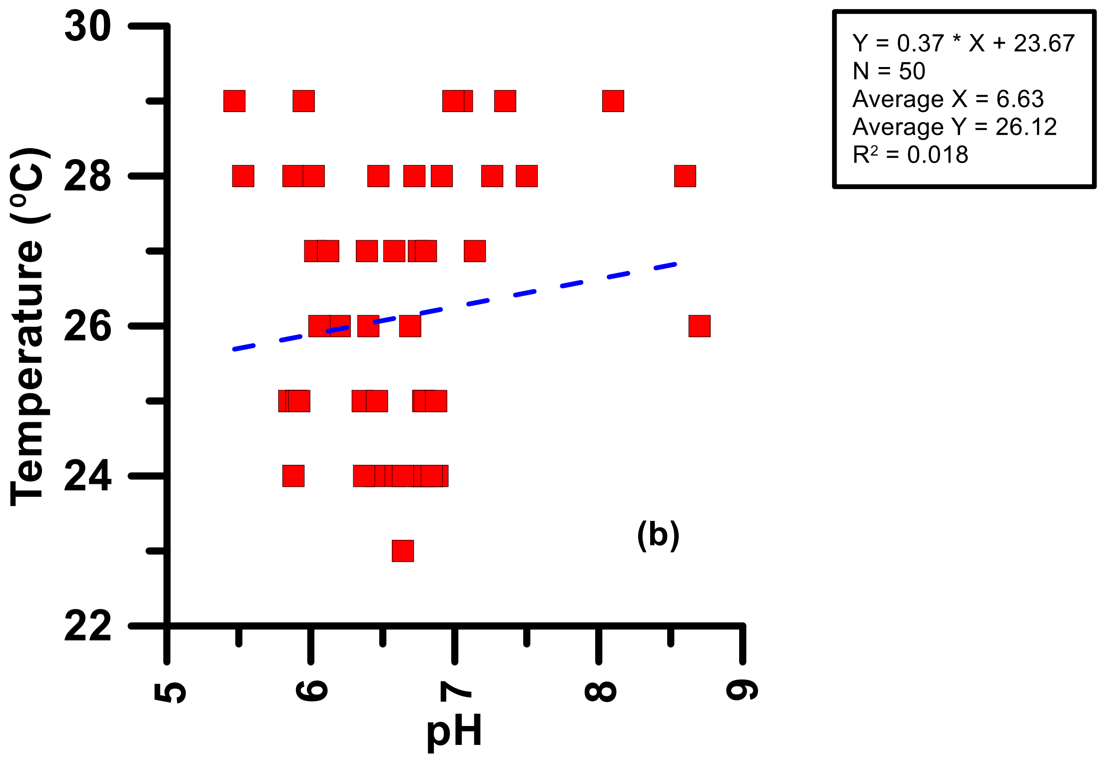


Figure 15: Bivariate plots of temperature vs (a) Salinity and (b) pH

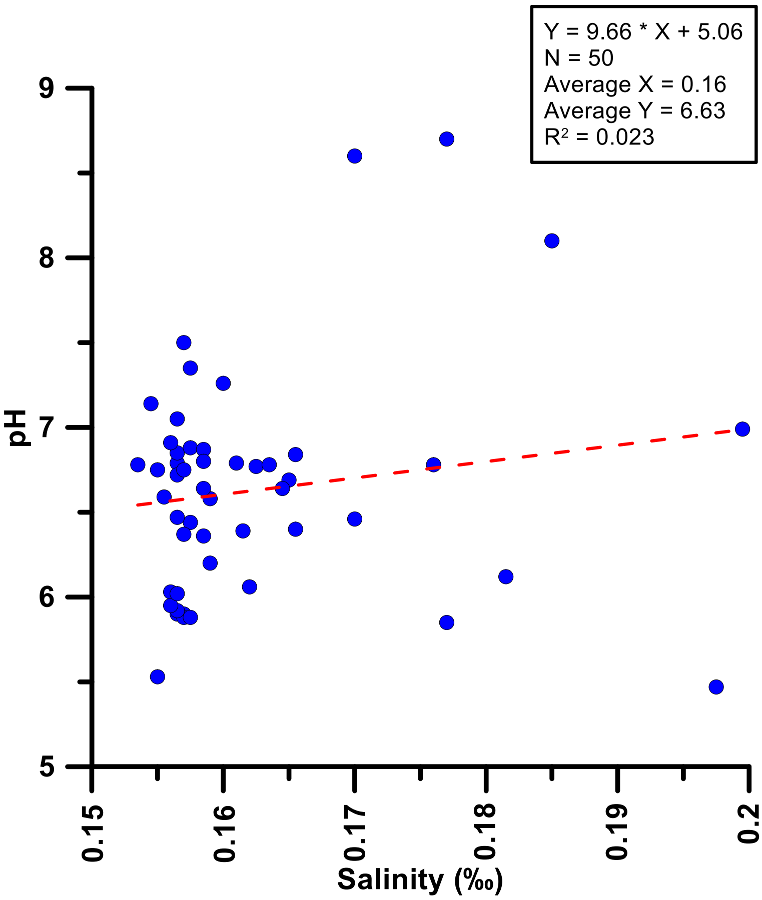


Figure 16: Bivariate plot of pH vs salinity

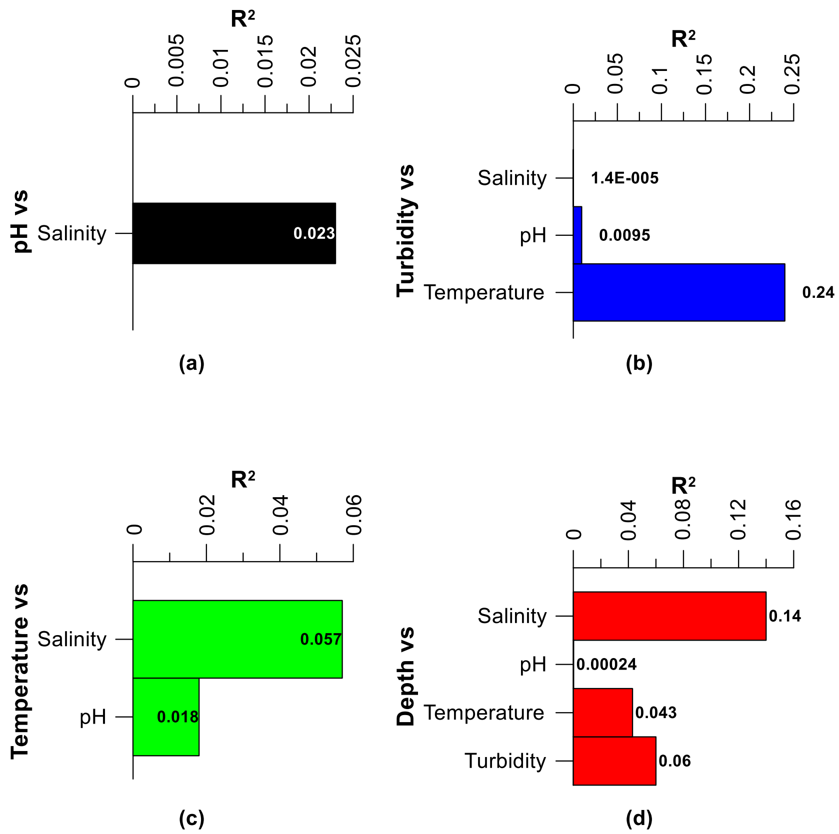


Figure 17: Correlation charts of the studied physico-chemical parameters (a) pH (b) Turbidity (c) Temperature (d) Depth

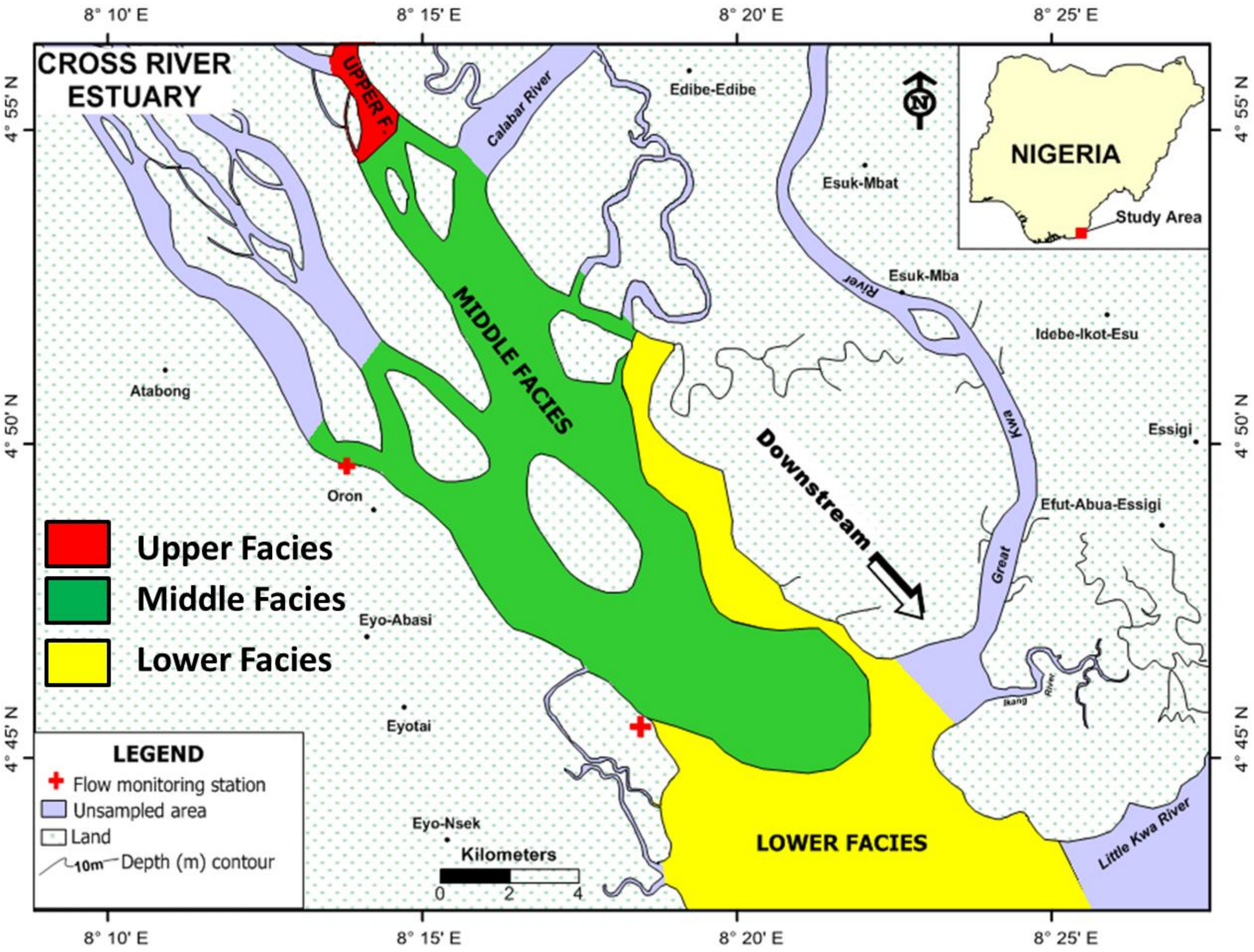


Figure 18: Hydro-physico-chemical facies of Cross River estuary

It has a maximum cross-channel width of 1.968 km and a minimum of 0.704 km, and occurs within longitudes 8° 13' 33.6"E and 8° 13' 26.4"E, and latitudes 4° 54' 28.8"N and 4° 56' 20.4" N. It is characterized by temperatures ranging from 25 to 26°C, turbidity ranging from 80 to 100 cm, pH ranging from 8 to 9, and salinity ranging from 0.17‰ to 0.18‰. The Middle Facies is the largest of the three facies. It covers a distance of 22.768 km, and a total surface area of 91.985 km^2. It has a maximum cross-channel width of 6.733km and a minimum of 0.776 km. It exists within longitudes 8° 13' 8.4"E and 8° 22' 8.4"E, and latitudes 4° 44' 34.8"N and 4° 55' 19.2"N. It is characterized by temperatures ranging from 24 to 29°C, turbidity ranging from 40 to 100 cm, pH ranging from 6 to 8, and salinity ranging from 0.15 to 0.17‰. The Lower Facies covers a distance of 21.613 km and a total surface area of 63.910 km^2. It has a maximum cross-channel width of 10.810km and a minimum of 8.141km. It exists within longitudes 8° 18' 7.2"E and 8° 25' 40.8"E, and latitudes 4° 42' 32.4"N and 4° 51' 46.8" N. It has temperatures ranging from 25 to 29°C, turbidity ranging from 60 to 80cm, pH ranging from 5 to 7, and salinity ranging from 0.17 to 0.2‰.

The Middle Facies, which had the least salinity values occurred as a wedge prying into the Lower Facies. This may be as a result of dominant ebb-currents (fluvial, freshwater currents) pushing the channel water downstream. Also, the region has a lot of freshwater input from the Calabar River, one of the three major tributaries (Calabar-, Great Kwa-, and Akpa-Yafe rivers) of the Cross River estuary.

CONCLUSION

The Cross River estuary is a meso-tidal, semidiurnal, coastal plain estuary. It is relatively shallow, with its maximum depth of 13.1 m occurring in its central portion. The channel's water is relatively clear (transparency range of 36 to 98 cm), warm (average temperature of 26.12 ºC) and ranged from slightly acidic (pH = 5.47) to slightly alkaline (pH = 8.7). With a salinity range of 0.15‰-0.20‰, the segment of the channel studied is fresh water (<0.5‰).

The channel has three hydro-physico-chemical facies, agreeing with the model postulated by Dalrymple et al. (1992). The Upper Facies, the smallest, coolest and least turbid of the three, is alkaline and more saline than the Middle Facies. The Middle Facies, the largest, most turbid and least saline of the three, has the widest temperature range, and is relatively neutral. The Lower Facies is the warmest, most saline and acidic region of the channel.

This preliminary study suggests that the Cross River estuary is a partially mixed estuary.

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