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Comparative Hydrodynamic and Physicochemical Characteristics of the Calabar River and Qua-Iboe Estuary, Gulf of Guinea

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ABSTRACT

Hydrodynamic forcing and physicochemical processes jointly regulate mixing, water quality, and ecological functioning in coastal systems. This study presents a comparative evaluation of hydrodynamic regimes and physicochemical structure in the Calabar River (tidal river) and the Qua-Iboe River estuary along the south-eastern Gulf of Guinea. Bottom-water environmental variables, including temperature, pH, salinity, transparency, conductivity, and tidal current velocity, were recorded at 50 stations during spring, mean, and neap tidal conditions for each system. Hierarchical cluster analysis resolved longitudinal zonation in both systems. Both channels exhibit upstream freshwater-dominated reaches and downstream estuarine transition zones, but with contrasting gradients and energy levels. The Calabar River is characterised by weak salinity intrusion (≤0.17‰), limited turbidity gradients, and near-neutral pH, reflecting a river-dominated, confined setting. In contrast, the Qua-Iboe estuary displays stronger estuarine mixing, higher salinity (8–14‰), reduced transparency, and slightly alkaline conditions associated with marine intrusion. Hydrodynamic observations indicate ebb-dominated flow in both systems; however, spring-tide current velocities are substantially higher in the Qua-Iboe estuary, reaching 1.30 m s^{-1}, compared with lower velocities in the Calabar River. These results highlight fundamental contrasts in hydrodynamic energy and mixing efficiency between tidal rivers and tropical estuaries, providing process-based baseline information for coastal management in the Gulf of Guinea.

Keywords: Tidal river; Estuarine hydrodynamics; Physicochemical structure; Tidal mixing; Gulf of Guinea; Tropical estuaries; Water quality gradients

INTRODUCTION

Estuaries and tidal rivers represent dynamic interfaces between freshwater and marine environments, responding continuously to hydrodynamic forces such as tidal fluctuations, wave action, fluvial discharge, and sediment resuspension. These coastal water bodies provide essential economic and ecological benefits to the ecosystem and human communities. They serve as critical habitats that support diverse aquatic biota, including finfish and shellfish populations, and also provide valuable ecosystem services such as tourism and recreation (Inyang-Etoh et al., 2025; Emeka et al., 2024a). However, these ecosystems are increasingly subjected to anthropogenic pressures that compromise their ecological integrity and water quality (Agi-Odey et al., 2025; Emeka et al., 2023a; Yeleliere et al., 2018). The discharge of untreated sewage, frequent oil spills from outboard motorboats, and effluents from larger vessels have collectively contributed to the progressive degradation of these aquatic environments. The results of these activities can alter ecosystem functions, leading to poor water quality and deoxygenation (Emeka et al., 2024b). Understanding the environmental characteristics of these ecosystems is vital to their protection and restoration.

Infrastructure development has altered many coastal environments. Calabar River is the major tributary of the Cross River estuary, which is one of the largest estuaries along the Gulf of Guinea (Emeka et al., 2024b; Emeka et al., 2024c). The river has been heavily industrialised along its western bank. Freshwater conditions are prevalent upstream of the channel; however, tidal activity is evident towards the lower parts of the channel. On the other hand, the Qua-Iboe River estuary, located in the Niger Delta region of Nigeria, is a significant estuarine system connecting the Qua-Iboe River to the Atlantic Ocean. The upper estuary receives substantial freshwater input from the river, while the lower estuary opens directly into the ocean. The estuary is ecologically and economically important, supporting commercial fisheries. Notable creeks adjoining the estuary include Douglas, Stubbs and Ukpenekang Creeks. Tidal regimes, including flood and ebb, are active within the channel (Emeka et al., 2023a). The estuary is in proximity to a jetty and a crude oil treatment facility. Recent studies have reported increased downstream salinity attributed to seawater intrusion (Emeka et al., 2023a).

Tidal rivers and estuaries are dynamic ecosystems which exhibit diverse physicochemical characteristics (Emeka et al., 2023b; Emeka et al., 2023c; Akpan, 1999; Akpan and Ofem, 1993). This property can affect the phytoplankton community that supports primary productivity, thereby affecting the distribution of zooplankton species across the food chain (Ke et al., 2014; Ukpong et al., 2015; Emeka et al., 2023d; Emeka et al., 2024a). About

80% of all human diseases result from poor water quality (Kavitha and Elangovan, 2010). In view of this, it is imperative to regularly monitor the water quality of these vital ecosystems. In this study, physicochemical characteristics of the Calabar River and the Qua Iboe River estuary were investigated during the peak of the rainy season in September 2021. Spatial variations in key physicochemical parameters were measured and analysed to assess water quality dynamics across the study areas. Understanding the physicochemical properties of estuaries and tidal rivers is essential for developing effective monitoring frameworks and management strategies to sustainably conserve these coastal ecosystems.

DESCRIPTION OF STUDY LOCATIONS AND SAMPLING METHODS

The study locations were the Calabar River and the Qua-Iboe River estuary. The Calabar River, a major tributary of the Cross River, originates in the Oban Hills (Fig. 1). The studied river channel traverses sedimentary terrains of Tertiary to Recent age. It cuts through coastal plain sands and alluvial deposits. Qua-Iboe River estuary is a tropical estuary sourced from Umuahia Hills, Southeast Nigeria (Figure 1). It was formed during the Post-glacial Pleistocene rise in sea level. The estuary is a North-South trending channel that traverses mainly sedimentary terrains of Recent ages and develops into extensive meanders before emptying directly into the Atlantic Ocean (Emeka et al., 2010; Antia et al., 2012). Qua-Iboe River estuary consists of numerous tidal creeks, including Stubbs Creek, Douglas Creek, and Ukpenekang Creek. The estuary is characterised by varying width, generally narrowing upstream and broadening seawards. It cuts through Recent-age sediments (alluvial deposits) and consists predominantly of coastal plain sands (Antia et al., 2012). Coarse to medium-grained sands occur mostly at the mouth of the estuary and in the main channels where tidal current activity is intense (Ekwere et al., 1992). The studied Qua-Iboe River estuary bottom consists mainly of fine- to medium-grained sands with grain sizes ranging from 1-3φ. The study areas are within the hot, humid equatorial rainforest belt, winds.

The Calabar River lies within Cross River State. The region has a rainy season from April until October, during which 80% of the annual rain falls, with a peak in June. Rainfall in Cross River State is distributed throughout the year, reflecting its humid tropical climate, with interannual variations in intensity (Weather and Climate, 2010). The total annual rainfall in Calabar is approximately 3000 mm (Akpan and Offem, 1999). Air temperatures in the Cross River region are relatively high, ranging between 22.5°C and 33°C, while relative humidity fluctuates seasonally, reaching a maximum in February and a minimum in October (Weather

and Climate, 2010). At the Qua Iboe River estuary, annual temperatures range from 26°C to 29°C, and mean annual rainfall varies between 2,000 mm and 3,000 mm. Relative humidity remains high throughout the year, with peak values in June and the lowest in January (Climate-Data.org, n.d.). The shorelines of the study areas are surrounded by dense vegetation dominated by mangrove swamps and *Nypa fruticans* (Nypa palm). The western banks of both the Calabar River and the Qua Iboe River estuary exhibit more extensive vegetation than their eastern counterparts. Along the eastern bank of the Calabar River, several industrial and commercial establishments, including the Marina Resort, Calabar Cement Company, and the Nigerian Ports Authority, are situated. Similarly, the eastern bank of the Qua Iboe River estuary hosts major oil and gas operations, notably Mobil Producing Nigeria Limited.

METHODS

Tidal current measurement

In the Calabar River, surface tidal currents were recorded at Adiabo Bridge and Marina Beach. The current measurement stations for the Qua-Iboe River estuary were the Qua-Iboe mission and the Mobil Jetty. In the Calabar River, tidal currents were measured during spring (22/08/2021), mean (26/08/2021), and neap (30/08/2021) at Adiabo Bridge and Spring (8/08/2021), Mean (12/08/2021), and Neap (15/08/2021) at Marina Beach. In the Qua-Iboe River estuary, tidal currents were also recorded during Spring (21/09/2021), Mean (25/09/2021), and Neap (29/09/2021) at both Qua-Iboe Mission and Mobil Jetty. The Lagrangian method was employed for tidal current measurements. This approach involved using a stopwatch to record the time taken for a floating object (float) released at the mid-channel of the river to drift across a predetermined distance, measured with a measuring tape. The procedure was repeated at 15-minute intervals over a 12-hour observation period each day. Tidal current velocity was calculated as the ratio of the distance travelled by the float to the average time taken to cover that distance during both flood and ebb tidal phases.

Depth sounding

Depth measurements were obtained using a portable echo sounder operated from an outboard motorboat along the longitudinal transects of the Calabar River and the Qua Iboe River estuary. Soundings were taken systematically at predetermined intervals across the river channels to capture spatial variation in depth. The geographical coordinates of each sounding

point, along with the inter-point distances, were recorded using a hand-held Global Positioning System (GPS) receiver to ensure positional accuracy. The depth and coordinate data were subsequently processed and interpolated to generate bathymetric contour maps representing areas of equal depth for both river systems. These maps provide a visual interpretation of channel morphology, depth variation, and possible depositional or erosional zones within the study areas.

Bottom water

A total of fifty (50) bottom-water samples were collected immediately above the sediment–water interface at each geo-referenced sediment sampling station across the two study areas. Sampling was carried out using a Nansen water bottle equipped with an in-built thermometer, which was also used to measure the bottom water temperature. At each station, the collected water samples were transferred into clean plastic containers and analysed *in situ* for salinity, temperature, and pH. Salinity and pH were determined using a Hanna hand-held combo pH/EC/TDS/temperature meter (Model HI 98130), while water turbidity was measured with a Secchi disc. Ambient air temperature at each station was also recorded *in situ* using a mercury-in-glass thermometer.

RESULTS

Hydrodynamics

The Calabar River and Qua Iboe River estuary are located within a meso-tidal setting and exhibit semi-diurnal tidal cycles. Each channel experiences two primary tidal phases: flood and ebb tides. Periods of minimal water movement, known as slack water, occur at the transition between these phases, with high slack water marking the end of the flood tide and low slack water marking the end of the ebb tide.

Surface current velocity profiles for the Calabar River and Qua Iboe River estuary are presented in Figures 2 and 3. Maximum current velocities observed during Spring, Mean, and Neap tides are summarised in Tables 1a and 1b. Analysis of the flow time-velocity asymmetry indicates ebb dominance in both tidal channels. Furthermore, tidal forcing, freshwater discharge from tributaries and rainfall-driven fluvial inputs contribute to the observed ebb dominance.

Bathymetry

The Calabar River is a northeast–southwest (NE–SW) trending tidal river exhibiting a distinct meandering channel pattern. The investigated segment covers approximately 17.45 km² and extends over a 24 km stretch of the river channel, with water depths ranging from 2 to 20 m. Depth profiles indicate that the eastern bank is generally deeper than the western bank, suggesting asymmetrical channel morphology. The complex bathymetric configuration of this section is influenced by historical and ongoing dredging activities, which have modified the natural channel geometry. The bathymetric map of the Calabar River (Figure 4a) illustrates this variability, showing the deepest zones (up to 20 m) concentrated along the central thalweg.

The Qua Iboe River estuary segment examined in this study spans about 3.92 km², with a channel length of 7 km and depths ranging from 1 to 10 m. The bathymetric map of this estuarine section (Figure 4b) reveals that the deepest portion (10 m) occurs near the eastern bank of the lower channel. In contrast, the western bank remains relatively shallow, with depths of 2-4 m. This spatial variation in depth likely reflects differences in flow velocity, sediment deposition, and tidal influence across the channel.

Bottom Water Characteristics

Bottom water samples were collected at depths ranging from 2 to 20m in the Calabar River and 1 to 10m in the Qua-Iboe River estuary using a Nansen bottom water sampler. The measured parameters reflect distinct patterns in the tidal river and estuary under investigation.

Temperature

Bottom-water temperatures in the upper channel ranged from 23°C to 26°C in the Calabar River (Figure 5a). In contrast, slightly higher temperatures, ranging from 25°C to 27°C, were recorded in the central and lower portions of the river. The gradual downstream increase in temperature may be attributed to enhanced tidal mixing, reduced freshwater inflow, and greater solar heating in the broader lower reaches. This pattern suggests a transition from relatively cooler upstream conditions, possibly influenced by freshwater input and shading from riparian vegetation to warmer, more thermally mixed conditions toward the estuarine zone.

In the upper portion of the Qua Iboe River estuary, temperatures ranged from 26°C to 27°C, whereas the central and lower portions recorded slightly greater variability, ranging from 24°C to 28°C (Figure 5b). The observed temperature pattern suggests that freshwater inflow, tidal mixing, and solar heating influence thermal conditions along the estuary. The slightly lower temperatures in the central and lower reaches may reflect increased mixing with cooler, deeper waters or upstream freshwater contributions, highlighting the dynamic thermal regime characteristic of tropical estuaries.

Transparency

Water transparency exhibited a distinct spatial pattern along the Calabar River channel (Figure 6a). In the upper portion, transparency ranged from 0.60 to 0.80 m, indicating relatively clear water. The central section of the river recorded transparency values between 0.40 and 0.80 m, showing moderate variability across sampling points. In contrast, the lower section of the river showed a marked decline in transparency, with values ranging from 0.40 to 0.60 m. This downstream reduction in transparency suggests an increase in suspended particulate matter and sediment concentration toward the river mouth.

The distribution of water transparency in the Qua Iboe River estuary showed that the upper portion ranged from 1.2 to 1.8 m. In comparison, the central portion showed slightly broader variation between 1.0 and 1.8 m (Figure 6b). In the lower reaches, transparency values decreased slightly, ranging from 0.40 to 1.40 m. Overall, transparency increased downstream, reflecting the cumulative effects of sediment resuspension, tidal mixing, and upstream sediment input. The spatial variation suggests that the estuary experiences greater particulate matter accumulation and sediment transport dynamics toward its downstream segment, consistent with a typical tropical estuarine setting influenced by both riverine discharge and tidal processes.

pH

Across the entire study segment, bottom waters ranged from slightly acidic to neutral (pH 5–7) in the Calabar River. (Figure 7a) This pattern indicates a generally stable chemical environment, with minor acidity likely influenced by organic matter decomposition, freshwater input, and the river's natural buffering capacity. The near-neutral conditions

observed throughout the channel are typical of tropical rivers receiving substantial freshwater inflow and suggest limited impact from strong acidifying sources in the study area.

The distribution of pH of bottom waters in the Qua Iboe River estuary is presented in Figure 7b. Across the upper, middle, and lower portions of the estuary, pH values ranged from 6 to 8, indicating conditions that were slightly acidic to slightly alkaline. This variability reflects the influence of freshwater inflow, tidal mixing, and local biogeochemical processes, such as organic matter decomposition and ion-buffering. Overall, the slightly acidic to slightly alkaline conditions suggest a moderately stable chemical environment, typical of tropical estuarine environments with dynamic freshwater–marine interactions.

Salinity

The lowest salinity values, ranging from 0.15‰ to 0.16‰ (Figure 8a) were recorded in the upper and middle sections of the river channel, reflecting the dominance of freshwater inflow in these regions. In contrast, the highest salinity (0.165‰) was observed near the western bank in the lower portion of the channel, indicating the initial influence of tidal intrusion and estuarine mixing. This gradual downstream increase in salinity highlights the transition from predominantly freshwater conditions upstream to slightly brackish conditions toward the river mouth.

The salinity distribution of bottom waters in the Qua Iboe River estuary indicates that the upper portion salinity values ranged from 6 to 10‰, while the middle portion showed slightly broader variation between 6 and 12‰. In the lower portion of the estuary, salinity ranged from 8 to 12‰, with a maximum value of 14‰ observed in the central and lower reaches (Figure 8b). Overall, salinity increased downstream, reflecting the progressive influence of tidal intrusion and mixing with marine waters. This pattern is typical of estuarine systems, where the interplay between freshwater inflow and seawater intrusion creates a longitudinal salinity gradient along the channel.

Spearman's Rank Correlation Analysis

The summary statistics of parameters analysed in the study areas, which included pH, salinity, transparency, temperature, depth, conductivity, and elevation are presented in Table 2. To examine the relationships among the measured physicochemical parameters, Spearman's rank correlation coefficient (ρ) was computed. This nonparametric statistical test does not

assume normality and is suitable for monotonic relationships. In the Calabar River, significant relationships were observed among several variables (Table 3a). Transparency exhibited significant negative correlations with temperature ($\rho = -0.46$, $p < 0.01$), conductivity ($\rho = -0.43$, $p < 0.01$), and salinity ($\rho = -0.43$, $p < 0.01$), indicating that higher temperature and ionic content are associated with reduced water clarity. Similar observations have been made by Nitish and Indu (2025) in their evaluation of the interdependencies of lake water surface temperature and clarity across various climate zones. Transparency also decreased with elevation ($\rho = -0.30$, $p < 0.05$), suggesting greater turbidity at higher-altitude stations, possibly due to runoff and sediment input. Depth showed significant negative correlations with conductivity ($\rho = -0.41$, $p < 0.01$) and salinity ($\rho = -0.41$, $p < 0.01$), implying that deeper sampling sites tended to have lower ion concentrations. Elevation was positively correlated with temperature ($\rho = 0.30$, $p < 0.05$), suggesting local thermal variation along elevation gradients.

In the Qua-Iboe River estuary, Spearman's rank correlation analysis (Table 3b) revealed a moderate, significant positive relationship between transparency and depth ($\rho = 0.45$, $p < 0.01$), indicating that deeper areas of the Qua-Iboe River estuary tend to be clearer, possibly due to reduced turbidity or sediment resuspension. Conductivity and salinity were perfectly and positively correlated ($\rho = 1.00$, $p < 0.01$), reflecting their shared dependence on ionic concentration. Other physicochemical parameters, such as temperature, pH, and elevation, showed weak, non-significant correlations ($p > 0.05$), suggesting that these variables remained relatively stable across sampling stations.

Physicochemical data collected from 50 sampling stations along the Calabar River and the Qua-Iboe River estuary were subjected to a hierarchical cluster analysis (Figure 9). The analysis employed Euclidean distance as the measure of similarity and Ward's method as the linkage criterion, which aims to minimise the variance within clusters.

Calabar River

The resulting dendrogram for the Calabar River (Figure 9a) revealed the formation of two distinct clusters: Cluster A and Cluster B.

Cluster A (Lower Reach / Estuarine Transition Zone):

Cluster A comprised stations 1, 2, 3, 14, 17, 19, 22, 28, 32, 33, 35, 36, 38, 39, 41, 44, 45, 47, 48, 49, 50. These stations are within the central and lower portions of the river, where temperature and salinities are slightly elevated (25–27°C and up to 0.165‰, respectively), and transparency is low to moderate (0.40–0.60 m). These variations reflect increased tidal mixing, higher particulate resuspension, and progressive intrusion of brackish water toward the river mouth. The physicochemical conditions in this cluster suggest a transitional zone where freshwater from the upper catchment interacts with saline water influenced by the Cross River estuary.

Cluster B (Upper Reach / Freshwater Zone):

Cluster B included the remaining stations (4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 15, 16, 18, 20, 21, 23, 24, 25, 26, 27, 29, 30, 31, 34, 37, 40, 42, 43, 46). Stations in this cluster are located in the upper portion of the Calabar River, where freshwater influence dominates. These stations are characterised by lower temperatures (23 – 26°C), higher transparency (0.60 – 0.80 m), and very low salinity (0.15–0.16‰), with slightly acidic to near-neutral pH (5 – 7). The combination of cooler temperatures, clearer water, and minimal salinity indicates reduced tidal influence and a strong dominance of freshwater inflow from upstream sources. These physicochemical traits suggest that Cluster A represents less disturbed, freshwater-dominated environments with relatively stable chemical conditions and lower suspended particulate matter.

Qua Iboe River estuary

The cluster analysis (Figure 15) based on Euclidean distance and Ward's linkage method classified the 50 sampling stations in the Qua Iboe River estuary into two main clusters (A and B). These clusters correspond to distinct physicochemical environments along the estuarine gradient: Cluster A represents the upper (upstream) portion, and Cluster B represents the central to lower (downstream) estuarine reaches. The grouping pattern reflects spatial variation in temperature, turbidity, pH, and salinity, which are controlled by freshwater inflow, tidal mixing, and marine water intrusion.

Cluster A (Upper Estuary/Upstream Zone)

Cluster A comprised stations: 4, 5, 11, 12, 15, 16, 17, 21, 22, 29, 30, 31, 32, 33, 35, 36, 43, 44, 45, 46, 47, 48, 49, 50. Stations grouped in Cluster A are located in the upper reaches of the estuary where freshwater influence dominates. These stations are characterised by lower salinity (6 – ‰), moderate temperature (26–27°C), higher water clarity (transparency 1.2–1.8 m), and slightly acidic to neutral pH (6–7). The relatively low ionic content and higher transparency indicate minimal tidal intrusion and a stronger influence from riverine discharge. This cluster thus represents the freshwater–brackish transition zone, reflecting less anthropogenic and marine influence, typical of upstream estuarine environments.

Cluster B (Central/Downstream Zone)

Cluster B included the remaining stations (1, 2, 3, 6, 7, 8, 9, 10, 13, 14, 18, 19, 20, 23, 24, 25, 26, 27, 28, 34, 37, 38, 39, 40, 41, 42), representing the central and lower portions of the Qua Iboe River estuary. These areas experience stronger tidal and marine influences, with higher salinity (8–14‰), greater temperature variability (24–28°C), and lower transparency (0.4–1.4 m). The pH values in this zone range from 7 to 8, indicating slightly more alkaline conditions due to seawater mixing and buffering effects from dissolved salts. The increased turbidity and salinity suggest enhanced sediment resuspension, tidal mixing, and ionic enrichment, characteristic of brackish and marine-influenced estuarine environments.

DISCUSSION

The Calabar River and Qua Iboe River estuary are meso-tidal systems exhibiting semi-diurnal tidal cycles, characterised by alternating flood and ebb tides with periods of slack water at the phase transitions. Hydrodynamic measurements indicate ebb-dominated flow in both systems, driven by the combined effects of tidal forcing and tributary freshwater discharge. Current velocity profiles show that the Qua Iboe estuary experiences stronger tidal currents than the Calabar River, with maximum surface velocities reaching 1.30 m/s at Mobil Jetty during Spring tides, compared to 0.95 m/s at Marina Beach in the Calabar River. Velocities

decreased progressively from Spring to Neap tides, reflecting variations in tidal amplitude (Antia et al 2012).

The stronger tidal influence in the Qua Iboe estuary, particularly near the mouth, contrasts with the more confined upstream conditions of the Calabar River, where lower velocities suggest reduced marine intrusion. Overall, the hydrodynamics of both tidal channels influence water-column mixing, salinity gradients, sediment transport, and estuarine ecology, with the Qua Iboe River estuary exhibiting greater tidal energy and hydrodynamic variability (Harry et al., 2017; Antia et al., 2012).

Fluctuations in temperatures within the Calabar River and Qua-Iboe River estuary are largely controlled by the combined effect of freshwater inflow, tidal mixing, solar heating, and prevailing weather conditions during the sampling period. Bottom-water temperatures in the Calabar River (23–27 °C) and Qua-Iboe River estuary (24–28 °C) indicate moderate variability typical of tropical coastal systems.

Similar downstream temperature patterns have been previously reported in the Calabar River (Akpan and Offem, 1999; Asuquo, 1999) and in the Qua-Iboe estuary (Harry et al., 2017; Emeka et al., 2023c). In both systems, temperatures tended to increase downstream, consistent with the transition from shaded, freshwater-dominated upstream reaches to broader, tidally influenced lower sections where solar heating and saline intrusion enhance warming (Akpan and Offem, 1999; Jones et al., 2008). Spatial temperature differences may therefore relate more closely to weather conditions during sampling, including variations in solar radiation, cloud cover, and rainfall intensity, which directly influence water–air heat fluxes (Fagade, 2003; Akinpelu et al., 2012; Emeka et al., 2023c; Akinnigbagbe et al., 2025). Overall, the observed thermal gradients are consistent with findings from other West African estuarine systems, where local meteorological forcing and tidal exchange jointly regulate short-term temperature dynamics (Akpan and Offem, 1999; Akinpelu et al., 2012; Akita et al., 2020).

Salinity variations in the Calabar River are controlled by freshwater inflow. The high freshwater input during the wet season led to marked dilution of the river, resulting in a significant drop in salinity. The marked increase in salinity at the stations suggests the influence of freshwater inflows into the (Akpan and Offem, 1999).

The dominant influence of upstream freshwater discharge maintained a relatively stable salinity. Earlier investigations by Asuquo (1999) on the physicochemical characteristics and anthropogenic pollution of the Calabar River suggest that it is a relatively fresh tidal river. Salinity variations in the Calabar River are primarily controlled by freshwater inflow, with seasonal differences strongly influencing the observed values. During the wet season, high

freshwater discharge significantly dilutes the river water, leading to a marked decline in salinity. In contrast, the lower reaches of the river exhibit slightly elevated salinity due to tidal intrusion and mixing with estuarine waters, reflecting the gradual transition from predominantly freshwater upstream to slightly brackish conditions downstream. These patterns are consistent with typical tidal river dynamics observed in tropical estuarine systems, where the balance between freshwater input and marine influence regulates longitudinal salinity gradients (Emeka et al., 2010; Klubi & Akita, 2019; Klubi et. al, 2019).

In the Qua-Iboe estuary, salinity similarly shows a downstream increase, reflecting the progressive influence of tidal mixing and seawater intrusion. Upper reaches recorded relatively low salinity (6 – 10‰), while middle and lower reaches showed slightly higher and more variable values (6 – 14‰), indicative of enhanced marine influence and estuarine mixing. Such longitudinal salinity patterns are characteristic of tropical estuaries, where riverine discharge, tidal cycles, and local meteorological conditions jointly modulate salinity distribution (Akpan and Offem, 1999; Harry et al., 2017; Emeka et al., 2023c). Overall, in both systems, salinity dynamics are governed by the interplay of freshwater inflow, tidal exchange, and seasonal variability, highlighting the sensitivity of tropical rivers and estuaries' responses to hydrological and climatic fluctuations.

The pH of bottom waters in both study areas remained slightly acidic to near neutral, ranging from approximately 5 to 7 in the Calabar River, but was acidic to alkaline (6 to 8) in the Qua-Iboe estuary. This suggests a moderately stable chemical environment, influenced by freshwater inflow, dissolved-ion buffering, and biogeochemical processes such as organic matter decomposition. Minor spatial variation suggests that local factors such as upstream inputs, tidal mixing, and decomposition of organic matter, but no extreme acidification was observed, consistent with other West African tropical aquatic systems (Akita et al., 2020; Apau et al., 2022).

Water transparency in the Calabar River and Qua-Iboe River estuary exhibited clear longitudinal patterns. In the Calabar River, upstream sections showed higher transparency (0.60–0.80 m), reflecting relatively clear waters with lower suspended sediment loads. Transparency decreased downstream (0.40 – 0.60 m) due to increased sediment resuspension, tidal mixing, and particulate matter input, consistent with typical tropical river-estuarine dynamics. In the Qua-Iboe River estuary, a similar pattern was observed, with higher transparency upstream (1.2–1.8 m) and lower values downstream (0.40–1.40 m), highlighting the combined effects of sediment transport, tidal currents, and anthropogenic inputs on water clarity (Emeka et al., 2023d).

CONCLUSION

This study elucidates the interrelationships between hydrodynamics and the spatial variability of key physicochemical parameters in the Calabar and Qua Iboe River estuaries. Hydrodynamics revealed ebb-dominated flow regimes in both channels, with maximum surface current velocities of up to 1.30 m/s during spring tides at the Qua Iboe River estuary mouth, and 0.95m/s in the Calabar River. Statistical analyses demonstrated that transparency increased significantly with depth ($\rho = 0.45$, $p < 0.01$), suggesting reduced turbidity and sediment resuspension in deeper zones. Conversely, in the Calabar River, negative correlations among transparency, temperature, conductivity, and salinity indicate that elevated ionic content and thermal conditions contribute to diminished water clarity. Cluster analysis further delineated two major station groups in each system, reflecting clear longitudinal gradients. Upstream clusters were 14haracterized by higher transparency and lower temperature, conductivity, and salinity. In contrast, downstream clusters exhibited higher salinity and temperature and reduced transparency, consistent with tidal mixing and marine influence.

Spatial patterns of temperature, salinity, and transparency collectively support these observations, showing downstream increases in salinity and temperature zones. At the same time, there was a decline in transparency toward estuarine conditions; pH remained relatively stable, indicating moderately buffered conditions. Overall, the integration of hydrodynamic, statistical, and spatial analyses highlights that tidal forcing, freshwater inflow, and sediment dynamics jointly regulate water quality in these tropical estuarine environments. These findings provide baseline data for future hydrological and environmental assessments, contributing to informed management and conservation of the Calabar River and Qua Iboe River estuary channels.

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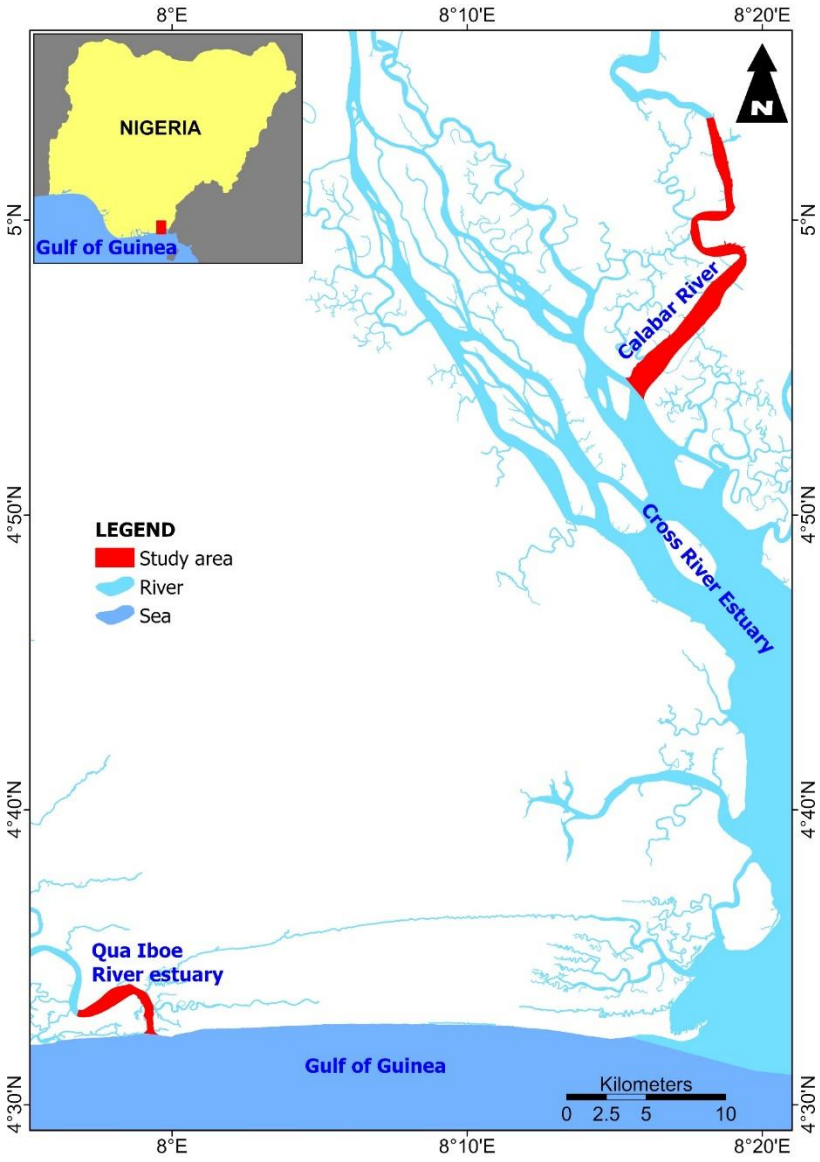
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575 Figure 1: Study area map of Calabar River and Qua Iboe River estuary

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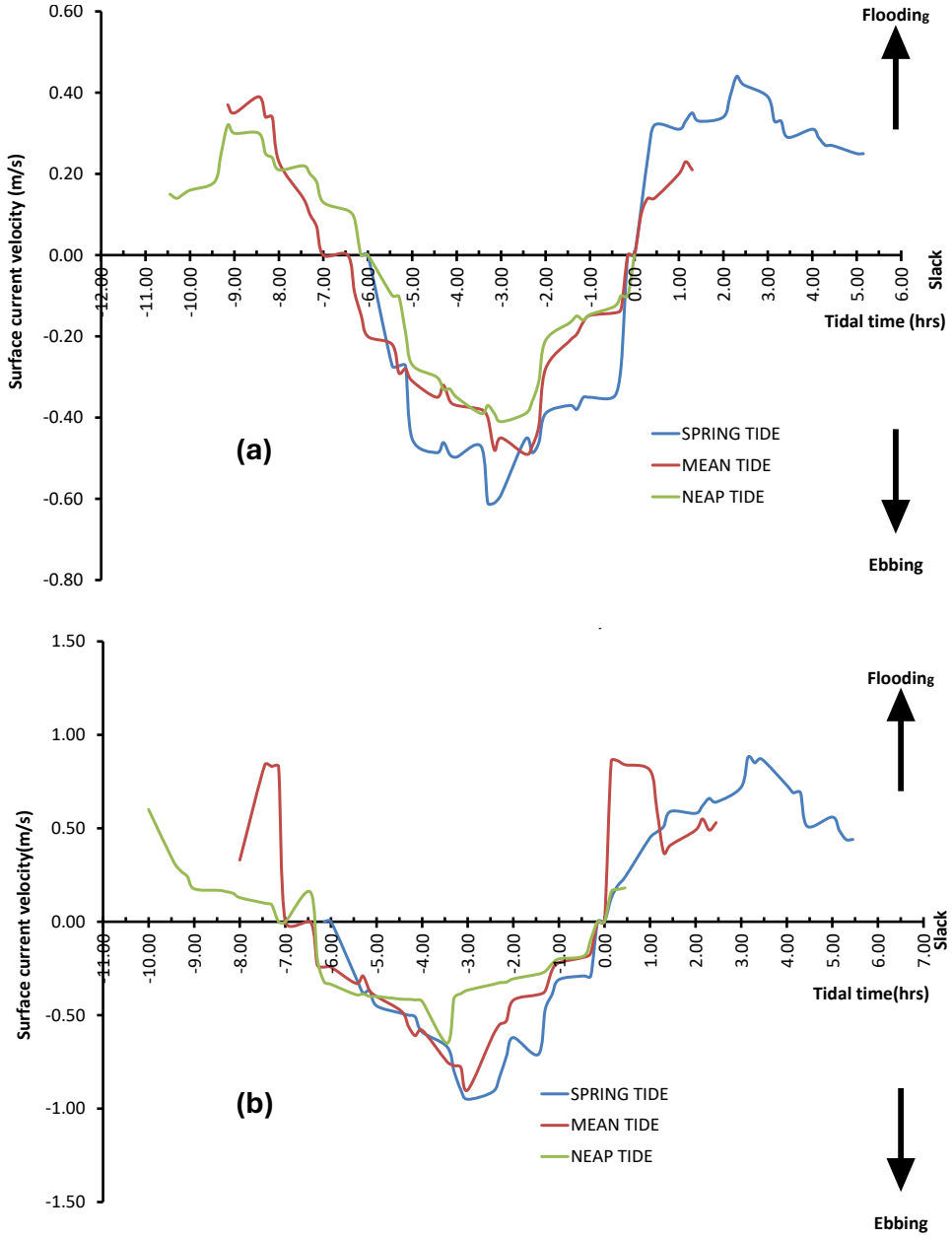


Figure 2: Surface tidal current velocity profiles for Calabar River (a) spring (22/08/2021), mean (26/08/2021), and neap (30/08/2021) at Adiabo Bridge and (b) Spring (8/08/2021), Mean (12/08/2021), and Neap (15/08/2021) at Marina Beach.

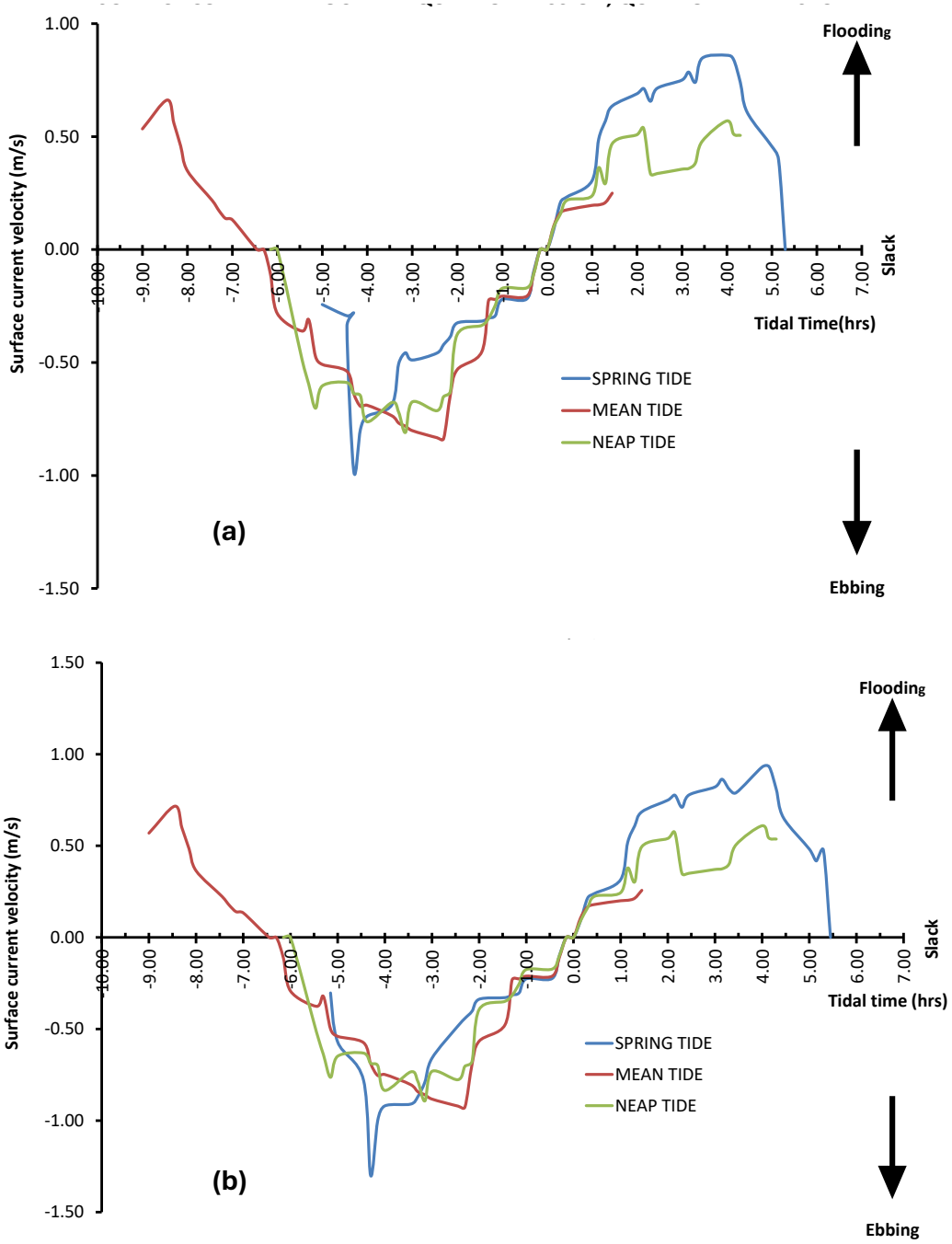


Figure 3: Surface tidal current velocity profiles for Qua-Iboe River estuary (a) Spring (13/09/2021), Mean (19/09/2021), and Neap (22/09/2021) at Qua-Iboe Mission (b) Spring (13/09/2021), Mean (19/09/2021), and Neap (22/09/2021) at Mobil jetty.

(a)

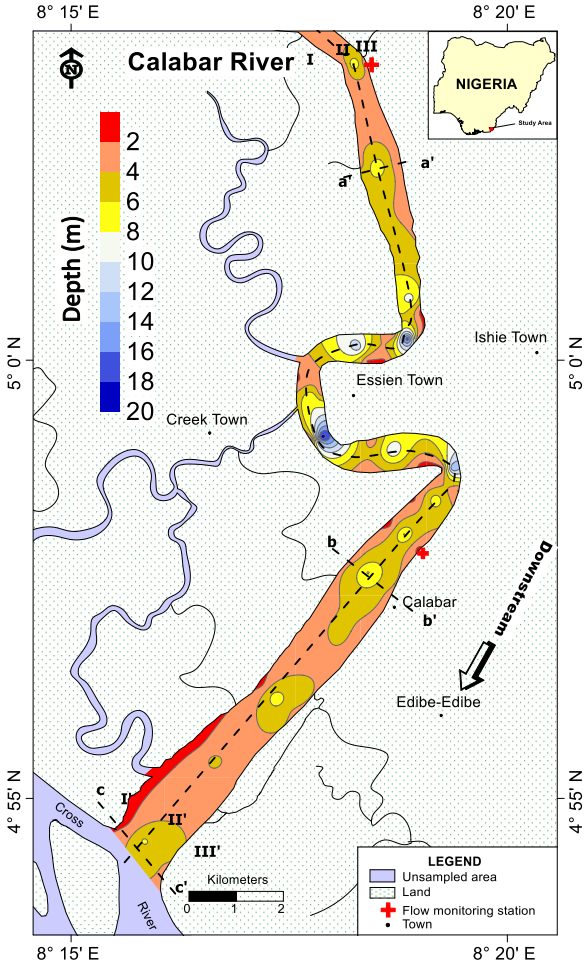
Table 1: Maximum tidal current velocities attained during Spring, Mean and Neap at Calabar River and Qua-Iboe River estuary (a) Surface tidal current velocities (b) Bottom tidal current velocities

(a)

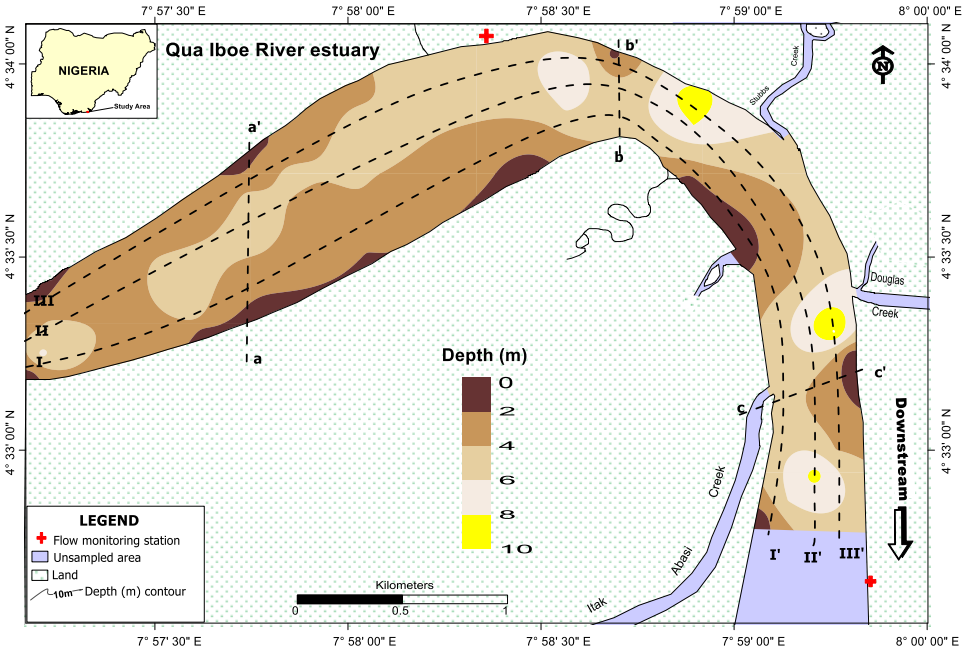
Tidal cycles	**Surface current velocities for Calabar River (m/s)**		**Surface current velocities for Qua-Iboe River estuary (m/s)**	
	Adiabo Bridge	Marina Beach	Qua-Iboe Mission	Mobil Jetty
Spring	0.61	0.95	0.99	1.30
Mean	0.49	0.90	0.84	0.93
Neap	0.41	0.65	0.81	0.89

(b)

Tidal cycles	**Bottom current velocities for Calabar River (m/s)**		**Bottom current velocities for Qua-Iboe River estuary (m/s)**	
	Adiabo Bridge	Marina Beach	Qua-Iboe Mission	Mobil Jetty
Spring	0.43	0.67	0.69	0.91
Mean	0.34	0.63	0.59	0.65
Neap	0.27	0.46	0.57	0.63

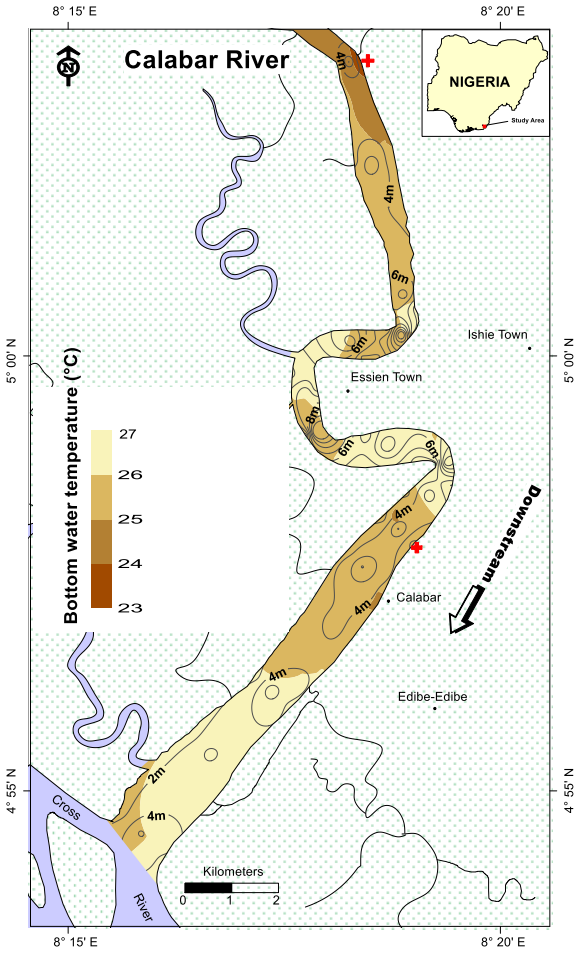


(a)

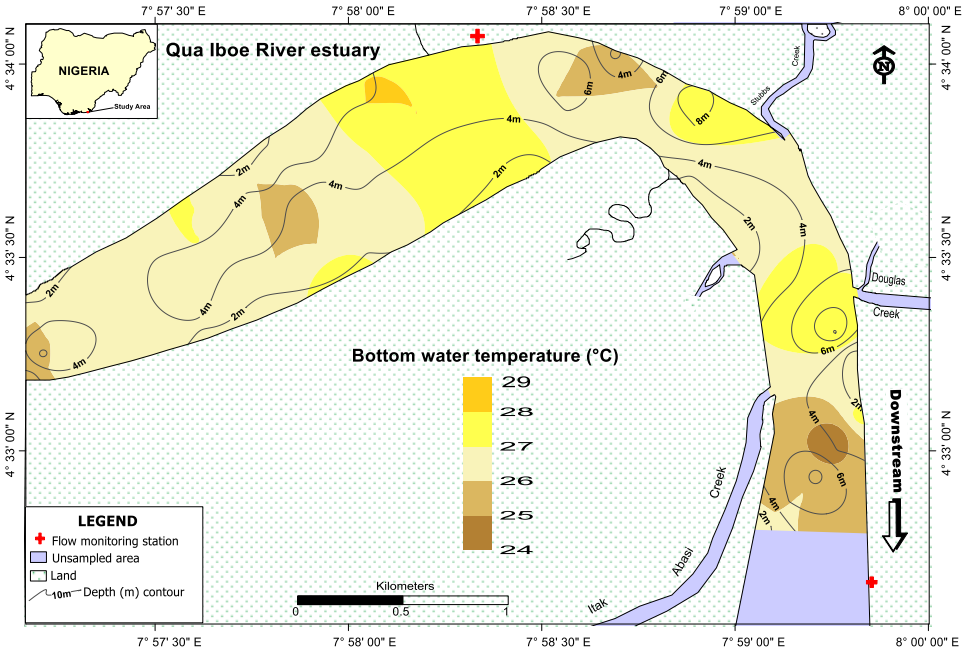


(b)

Figure 4: Bathymetry map of (a) Calabar River and (b) Qua-Iboe River estuary



(a)



(b)

Figure 5: Spatial distribution of bottom water temperature in (a) Calabar River and (b) Qua-Iboe River estuary

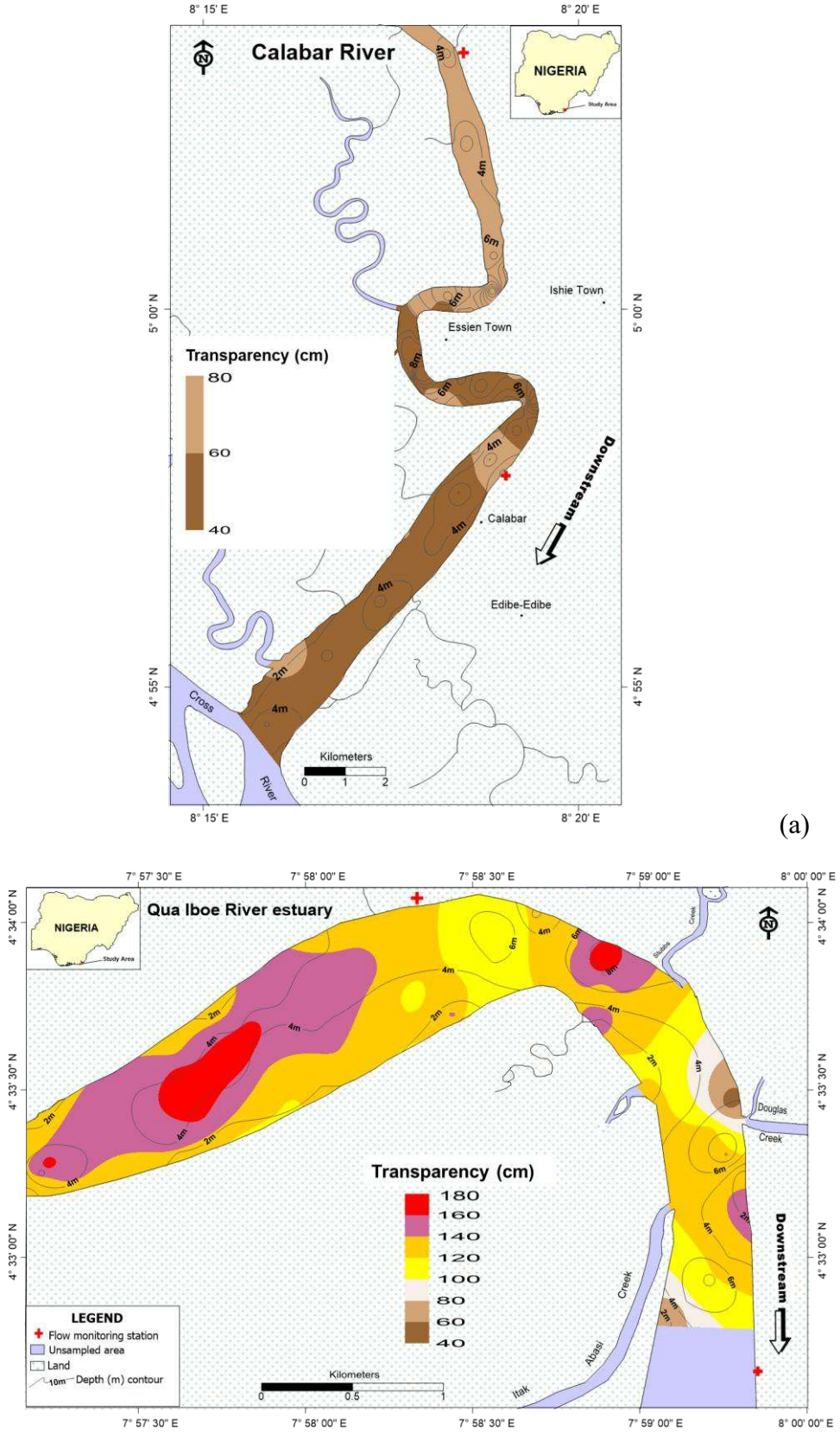


Figure 6: Spatial distribution of bottom water transparency in (a) Calabar River and (b) Qua-Iboe River estuary

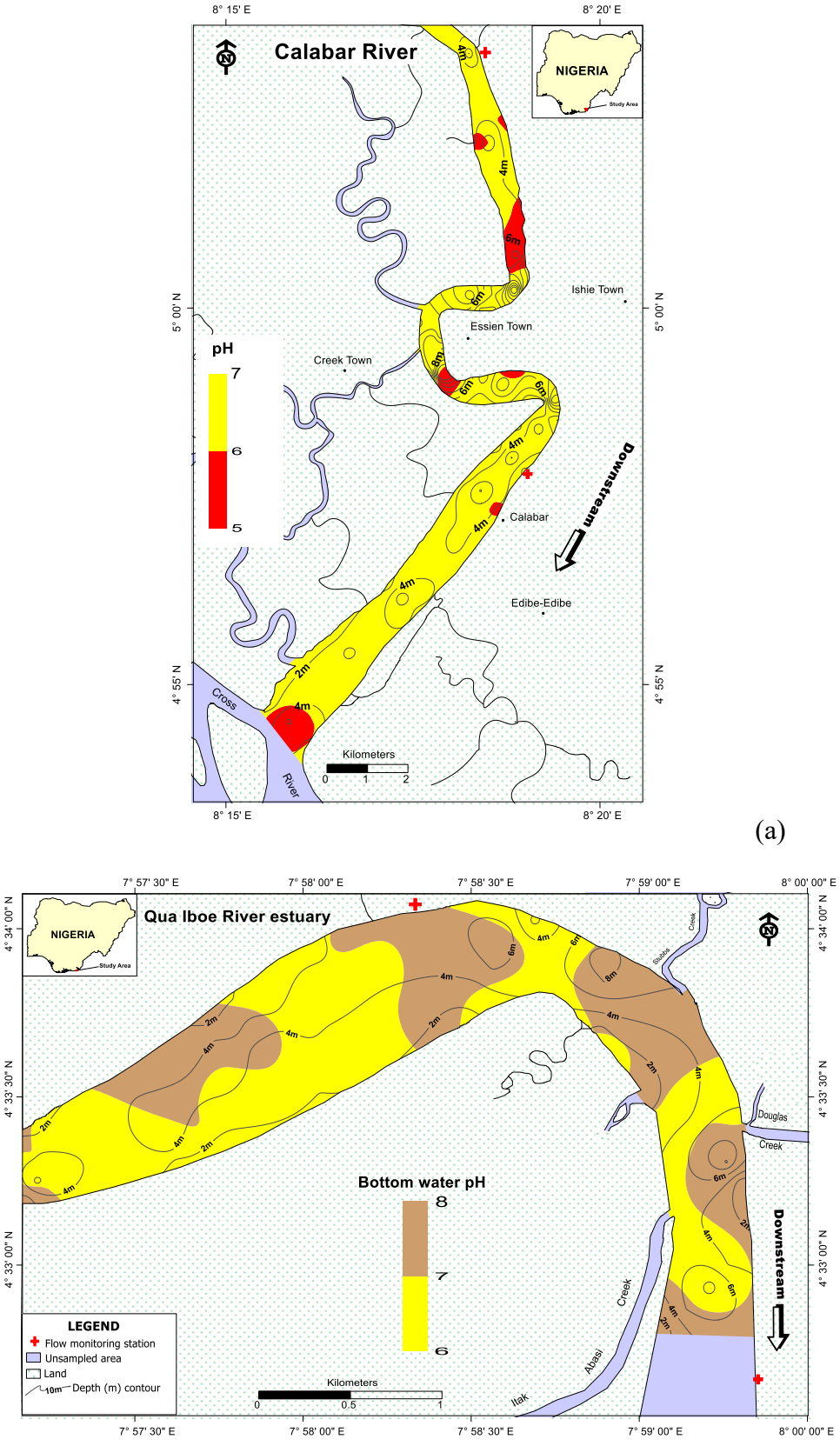


Figure 7: Spatial distribution of bottom water pH in (a) Calabar River and (b) Qua-Iboe River estuary

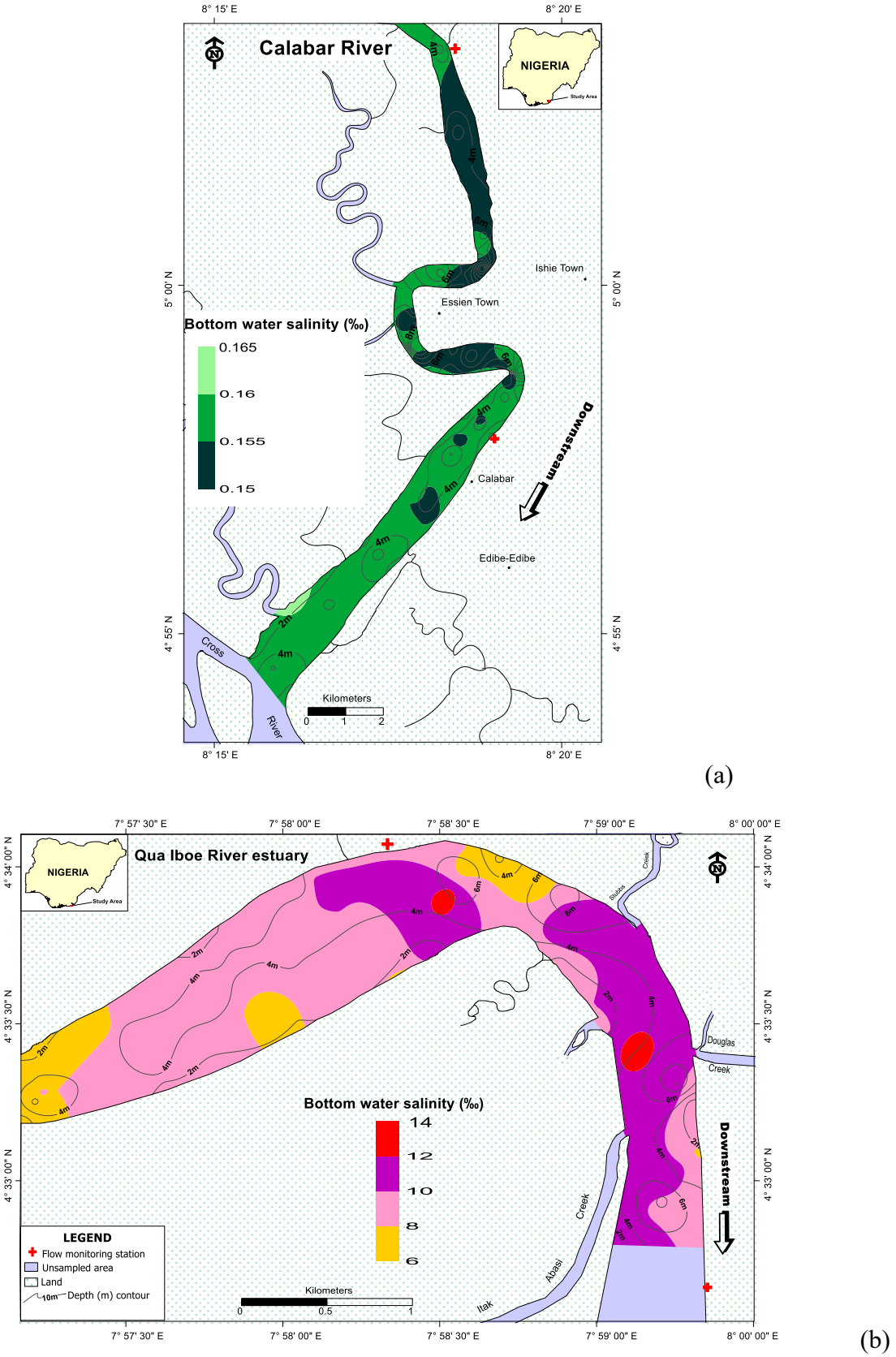


Figure 8: Spatial distribution of bottom water salinity in (a) Calabar River and (b) Qua-Iboe River estuary

Table 2: Summary statistics of the physicochemistry of (a) Qua-Iboe River estuary and (b) Calabar River

(a)

	Temperature (ºC)	Depth (m)	Transparency (cm)	Salinity (‰)	pH
N	50	50	50	50	50
Min	24	0.5	50	6.35	5.93
Max	28	10.2	176	13.58	7.8
Mean	26.72	3.796	128.86	9.1386	6.865
Stand. dev	0.948468	2.307482	27.32869	1.686997	0.451109

(b)

	Temperature (ºC)	Depth	Transparency	Salinity (‰)	pH
N	50	50	50	50	50
Min	23	0.9	45	0.1515	5.57
Max	27	19.5	80	0.1605	7.2
Mean	25.64	4.61	60.22	0.15555	6.4618
Stand. dev	0.776176	4.257059	6.594029	0.002103	0.385485

Table 3: Spearman's Correlation for (a) Qua Iboe River estuary (b) Calabar River

(a)

	Temperature	Depth	Transparency	Salinity
Depth	0.01			
Transparency	0.02	0.45**		
Salinity	0.10	0.09	-0.17	
pH	0.02	0.27	0.09	0.06

**Correlation significant at p < 0.05, **Correlation significant at p < 0.01*

(b)

	Temperature	Depth	Transparency	Salinity
Depth	-0.08			
Transparency	-0.46**	0.04		
Salinity	0.11	-0.42**	-0.41**	
pH	-0.11	0.25	-0.12	0.14

**Correlation significant at p < 0.05, **Correlation significant at p < 0.01*

(a) (b)

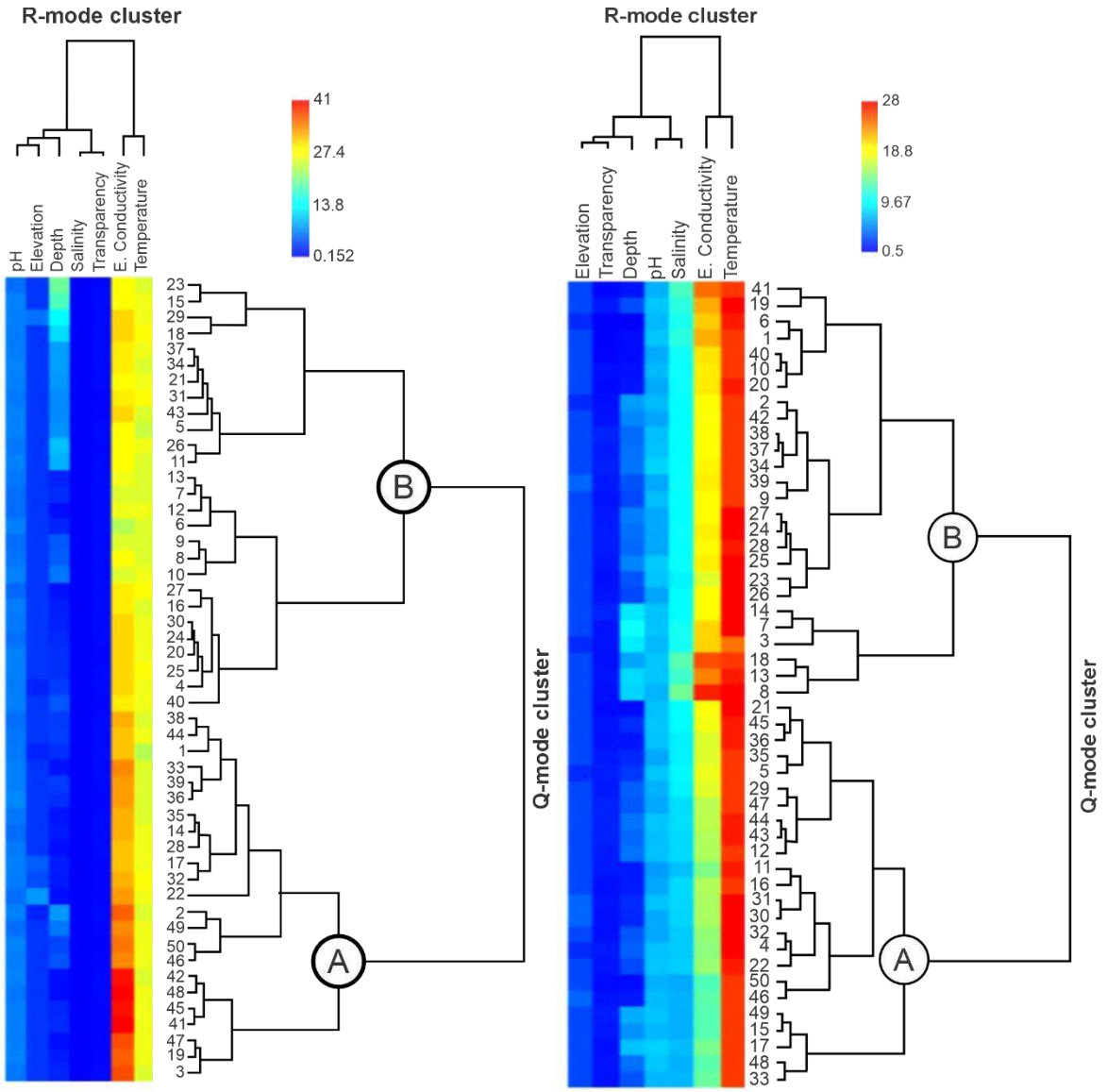


Figure 9: Dendrogram of Q and R-mode cluster analysis of physicochemical characteristics (a) Calabar River (b) Qua Iboe River estuary