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Physicochemical Characteristics of the Great Kwa River (Gulf of Guinea): Controls of Tidal Dynamics and Environmental Sustainability in a Tropical Mesotidal System

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Abstract: *The Great Kwa River, a tidal tributary of the Cross River Estuary in the Gulf of Guinea, was investigated to evaluate the influence of tidal dynamics on physicochemical characteristics and environmental sustainability in a tropical mesotidal system. A total of 50 bottom-water samples were collected along a 17.65 km tidal reach during the rainy season and analyzed in situ for temperature, pH, electrical conductivity (EC), salinity, turbidity, transparency, and total dissolved solids (TDS), while tidal current velocity and bathymetry were simultaneously measured. The river exhibited a semi-diurnal, ebb-dominated tidal regime, with maximum ebb current velocities of 81–84 cm s^{-1}, exceeding flood velocities (68–76 cm s^{-1}), indicating strong fluvial–tidal interaction. Physicochemical parameters remained within freshwater limits, with temperature ranging from 25 to 28 °C (mean 26.4 ± 1.03 °C), pH from 6.0 to 7.5 (mean 6.9 ± 0.4), EC from 22 to 58 µS cm^{-1} (mean 33.5 ± 8.4 µS cm^{-1}), salinity from 0.014 to 0.037‰ (mean 0.021 ± 0.005‰), transparency from 26 to 106 cm (mean 68.3 ± 16.6 cm), turbidity from 1.51 to 12.71 NTU (mean 5.31 ± 2.36 NTU), and TDS from 12.1 to 31.9 ppm (mean 18.4 ± 4.6 ppm). A distinct downstream increase in salinity, EC, and TDS, accompanied by decreasing temperature and pH, reflected progressive tidal influence and limited estuarine mixing. Three hydro-physicochemical facies—upper fluvial, middle transitional, and lower tidally influenced—were identified, representing successive zones of freshwater transport, active sediment reworking, and fine-sediment deposition. Strong positive correlations among salinity, EC, and TDS confirmed ionic concentration as the principal control on water chemistry. Although the river presently maintains good freshwater quality, localized turbidity maxima and increasing downstream ionic concentrations indicate emerging environmental sensitivity. These findings provide an important baseline for long-term monitoring and support sustainable management of the Great Kwa River and comparable tropical tidal rivers within the Gulf of Guinea.*

Keywords: Great Kwa River; tidal dynamics; water quality; hydro-physicochemical facies; environmental sustainability; Gulf of Guinea.

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1.0 Introduction

Tidal rivers are dynamic transitional environments located between freshwater and estuarine ecosystems, where riverine discharge interacts continuously with tidal forcing to produce distinctive hydrological, sedimentological, and physicochemical conditions. These systems serve as critical interfaces within the land–sea continuum, regulating the exchange of water, sediments, nutrients, and dissolved constituents between terrestrial and coastal environments. Because they respond rapidly to variations in freshwater discharge, tidal oscillations, sea-level fluctuations, and human activities, tidal rivers have become increasingly important for understanding watershed processes, aquatic ecosystem functioning, and environmental sustainability.

Tidal rivers are generally associated with meso- to macro-tidal environments and are characterized by periodic tidal fluctuations superimposed on downstream freshwater discharge. They are naturally channelized water bodies that originate from freshwater headwaters and discharge into estuarine systems without direct exposure to the open ocean (Antia et al., 2012; Emeka et al., 2010; Emeka et al., 2024b; Emeka et al., 2023). Functionally, these systems represent transitional zones where fluvial and estuarine processes interact to produce complex hydrodynamic, sedimentological, and physicochemical regimes.

Beyond their hydrological significance, tidal rivers perform essential ecological functions by regulating nutrient cycling, sediment transport, carbon storage, and habitat connectivity. They provide freshwater resources for domestic consumption, agriculture, fisheries, navigation, and industrial development, while simultaneously supporting diverse aquatic ecosystems. Consequently, understanding the physical and chemical processes governing these systems is fundamental for sustainable watershed management and environmental conservation.

The physicochemical characteristics of tidal rivers are strongly controlled by the interplay between river discharge and tidal forcing, including flood, ebb, and slack-water conditions. These processes regulate mixing intensity, sediment resuspension, and the spatial distribution of dissolved and particulate constituents. The degree of tidal penetration inland plays a critical role in determining salinity gradients, ionic composition, and overall water quality (Uncles, 2002; Winterwerp & Van Kesteren, 2004). In many tropical mesotidal systems, ebb dominance—driven by fluvial input and tidal asymmetry—enhances downstream transport of sediments and limits saline intrusion, thereby maintaining predominantly freshwater conditions in upstream reaches (Dyer et al., 2004; Emeka et al., 2010; Emeka et al., 2024a, 2024b; V. I. Emeka et al., 2024a, 2024b, 2024c). These dynamics are critical in shaping the physicochemical structure and ecological functioning of tidal river environments.

Climate variability, changing rainfall patterns, land-use modifications, and projected sea-level rise have increased concerns regarding the long-term stability of tidal river systems worldwide. These factors have the potential to alter tidal propagation, freshwater discharge, sediment transport, and salinity intrusion, thereby affecting water quality and ecosystem resilience. Establishing present-day physicochemical baseline conditions is therefore essential for detecting future environmental changes and developing adaptive management strategies for tropical coastal watersheds.

Physicochemical properties including transparency, turbidity, temperature, pH, electrical conductivity (EC), salinity, and total dissolved solids (TDS) are widely recognized as reliable indicators of river health because they respond rapidly to both natural hydrodynamic processes and anthropogenic disturbances. Transparency and turbidity reflect suspended sediment concentrations and influence light penetration, primary productivity, and sediment transport dynamics (WHO, 2017, 2022). Temperature controls biochemical reactions, dissolved oxygen availability, and microbial activity, whereas pH regulates chemical equilibrium, nutrient availability, and aquatic biological processes. Electrical conductivity, salinity, and TDS represent the dissolved ionic composition of water and integrate geological weathering processes, tidal mixing, and anthropogenic influences such as agricultural runoff, urbanization, and industrial discharge (Hem, 1985; Winterwerp & Van Kesteren, 2004). Consequently, the combined evaluation of these parameters provides valuable insight into water quality, hydrodynamic processes, and the environmental sustainability of tidal river systems.

Previous investigations of estuarine and tidal freshwater systems have demonstrated that physicochemical characteristics vary significantly with tidal phase, freshwater inflow, seasonal rainfall, channel morphology, and anthropogenic activities. Studies have consistently shown that salinity, electrical conductivity, turbidity, and dissolved solids exhibit pronounced spatial and temporal variability due to the interaction between river discharge and tidal mixing, while human activities such as dredging, sand mining, urban development, and industrial expansion can further modify natural hydrochemical conditions. Continuous monitoring of physicochemical characteristics is therefore widely recognized as an essential component of estuarine management and sustainable water-resource conservation.

The Great Kwa River is one of the principal tidal tributaries of the Cross River Estuary in southeastern Nigeria and represents an important tropical freshwater system within the Gulf of Guinea (Fig. 1). Originating from the Oban Hills in central Cross River State, the river flows southward into the Cross River Estuary and supports numerous ecological and socio-economic activities throughout its watershed.

The river traverses diverse geological formations, including Precambrian Basement Complex rocks, Cretaceous sediments of the Calabar Flank, and younger Coastal Plain Sands. It is of considerable socio-economic importance, serving as a primary source of potable water for Calabar and adjacent communities, while also supporting navigation, sand mining, fisheries, agriculture, and coastal infrastructure development. Increasing anthropogenic pressures within the basin, including urban expansion, sediment extraction, and catchment disturbances, raise growing concerns regarding water quality deterioration, habitat degradation, and long-term environmental sustainability.

Despite the ecological, hydrological, and economic importance of the Great Kwa River, relatively few studies have comprehensively examined the influence of tidal hydrodynamics on the spatial distribution of physicochemical characteristics within its lower tidal reaches. Most previous investigations have focused on regional geology, sedimentology, or general water-quality assessments, with limited integration of tidal current dynamics, channel morphology, and physicochemical variability. Consequently, the hydro-physicochemical controls governing water quality and sediment dynamics in this tropical mesotidal river remain insufficiently understood, thereby limiting effective environmental monitoring, ecosystem conservation, and sustainable water-resource management.

This study aims to investigate the physicochemical characteristics of the lower reaches of the Great Kwa River and evaluate how tidal dynamics control the spatial distribution of water-quality parameters within a tropical mesotidal environment. Specifically, Secchi disc transparency, turbidity, temperature, pH, electrical conductivity, salinity, and total dissolved solids were measured to characterize hydro-physicochemical variability and identify the dominant environmental controls influencing water chemistry. The findings provide an important baseline dataset for future environmental monitoring, pollution assessment, and sustainable water-resource management within the Great Kwa River basin. Furthermore, the study contributes to a broader understanding of the interactions among tidal dynamics, sediment transport, water chemistry, and environmental sustainability in tropical tidal river systems of the Gulf of Guinea, thereby supporting evidence-based conservation and long-term ecosystem management.

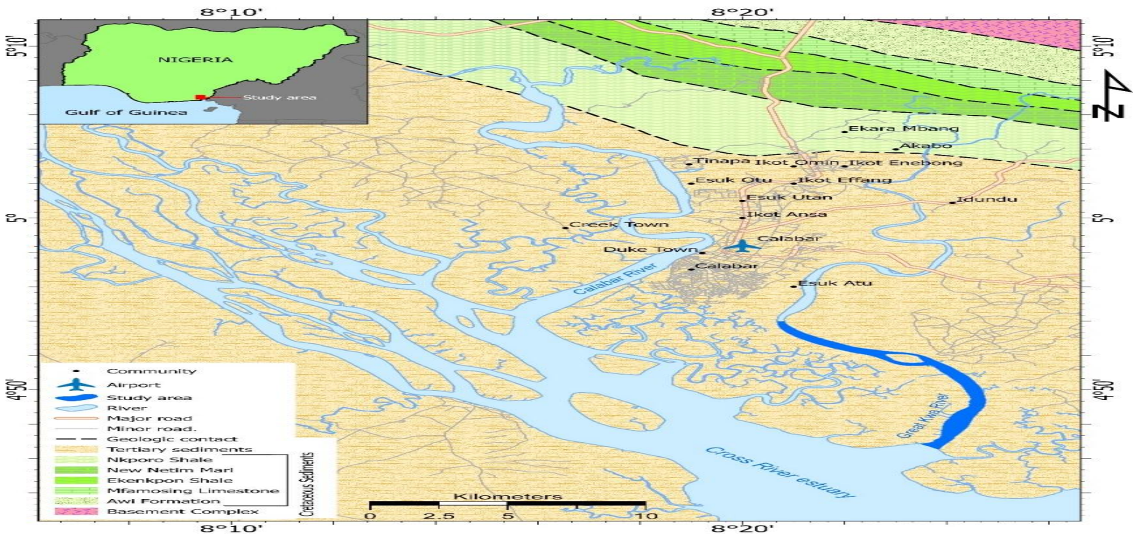

Fig. 1: Map of the Cross River estuary system showing the studied segment of Great Kwa River and the geology of the environs

2.0 Materials and Methods

Field investigations were conducted along the lower reaches of the Great Kwa River during the rainy season (August–September 2020) to characterize tidal hydrodynamics, channel morphology, and physicochemical properties of the river. Measurements included tidal current velocity, bathymetry, Secchi disc transparency, turbidity, temperature, pH, electrical conductivity, salinity, and total dissolved solids. Tidal current velocities were monitored at two representative stations during spring, mean, and neap tidal cycles, whereas bathymetric surveys and physicochemical sampling were undertaken simultaneously at fifty georeferenced stations distributed along the 17.65 km study reach (Fig. 2).

2.1 Measurement of tidal current velocity

Surface tidal current velocity and direction were measured at two stations along the western bank of Great Kwa River namely, Obufa Esuk Orok (OEO) and Esuk Mba (EM). Readings were obtained at Spring, Mean, and Neap Tide.Surface current measurements were selected because floating-drift techniques provide reliable estimates of near-surface tidal flow under low-wave conditions and have been widely applied in tidal river investigations. The two hydrodynamic monitoring stations were selected to represent the upstream and downstream tidal reaches of the river, while the fifty physicochemical sampling stations were distributed to capture longitudinal variations in channel morphology and water quality along the study reach.

The Lagrangian float-tracking method was employed to estimate surface tidal current velocity. A floating object was released on the water surface and allowed to drift over a predetermined distance of 10 m parallel to the channel. The travel time was measured using a calibrated stopwatch. Measurements were repeated three times at 15-minute intervals over a continuous 12-hour tidal cycle, and the mean travel time was used for velocity computation. Current direction was determined using a Brunton compass.Tidal current velocity (v) was obtained by dividing the distance travelled (x) by the average drift time (t') for every 15-minute interval (equation 1) at both ebb and flood tide.

$$V = \frac{x}{t'} \qquad (1)$$

where V = tidal current velocity (m s^{-1}), x = measured distance (m) and $\bar{t}$ = average travel time (s)

2.2 Depth sounding

A total of 50 sample stations were established in Great Kwa River, using a portable Garmin global positioning system. Depth soundings were made at these stations using a portable single beam echo sounder. The instruments were calibrated according to the manufacturers' specifications before field deployment.

2.3 Secchi disc transparency

Transparency readings were obtained simultaneously with depth sounding, using a Secchi disc. This was done by dipping the disc into water at each geo-referenced station until it just disappeared. The depth at which this happened was obtained by measuring the length of the rope, from the disc-to the water mark at the point of disc disappearance. The recorded in a notebook.

2.4 Bottom water sampling and physicochemistry

Fifty bottom water samples were obtained from the channel, using a Nansen water sampler, simultaneously with depth sounding and turbidity measurement. Immediately after collection, each water sample was transferred into a clean polyethylene container for in-situ measurement. These samples were analysed in-situ for physicochemical parameters (pH, electrical conductivity, salinity and temperature), using a HANNA hand-held combo pH/EC/TDS/Temperature meter (HI 98130), by dipping it into a cup containing the sample. The corresponding values were read off its screen, after they had stabilized.

Turbidity was measured in situ using a Hanna Instruments HI93703 portable nephelometric turbidimeter. Water samples were transferred into clean cuvettes free of air bubbles, after which measurements were performed according to the manufacturer's operating procedures. Recorded values were expressed in Nephelometric Turbidity Units (NTU).

2.5 Quality Assurance and Quality Control

All instruments were calibrated before and during field measurements following the manufacturers' recommendations. Triplicate measurements were obtained where applicable, and average values were used for subsequent analyses. Sampling containers were thoroughly rinsed with sample water before collection to minimize contamination. Field observations and instrument readings were cross-checked immediately after acquisition to ensure data consistency and accuracy.

3/0 Results and Discussion

3.1 Results

3.1.1 Hydrodynamics

The results of tidal current velocity measurements in the Great Kwa River are presented in Fig. 3 and Table 1.Fig.The highest velocities occurred at Spring Ebb (84 cm/s) clearly showing ebb-dominance (Table 1). Surface waves generated by wind and passing watercraft were observed during the survey but were generally of low amplitude and had negligible influence on tidal current measurements.

Overall, the measured tidal currents demonstrate a semi-diurnal, ebb-dominated hydrodynamic regime, with maximum current velocities occurring during spring tides and progressively decreasing through mean and neap tidal conditions.

3.1.2 Bathymetry

The bathymetry map and sections of the studied segment of Great Kwa River, as presented in Fig.Fig. 4, were produced relative to mean tide low water slack (MTLWS). The channel was relatively shallow, with an average depth of 2.8 m ±1.9 m, and maximum depth of 7 m (Fig. 4a, Table 2). The shallowest parts of the channel were located towards the upstream segment, while the downstream segment bore the deepest portions. The cross-channel section (Fig. 4b) showed that the channel was deepest in the mid channel and shallowest at the banks, the west bank being generally shallower than the east bank. Fig. 4c is a linear trend of the along channel cross-sectional profile (Fig. 4d) of the studied segment. It shows a downstream deepening trend. The observed downstream increase in channel depth corresponds with increasing tidal influence toward the Cross River Estuary.

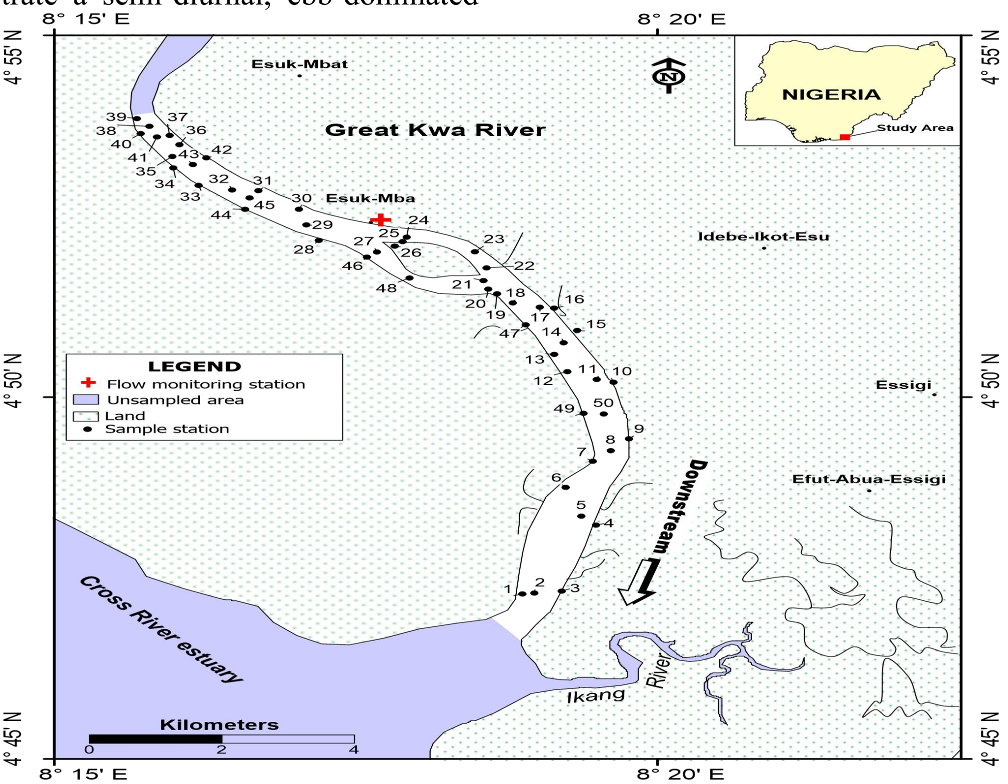

Fig. 2: Great Kwa River sample distribution map

31..3 Transparency

The distribution of transparency within Great Kwa River is presented in Fig. 5a. Turbidity values varied between 26 cm and 106 cm, with an average of 68.28 cm ± 16.6 cm (Table 2). Secchi disc transparency ranged from 26 cm to 106 cm, with an average value of 68.28 ± 16.6 cm (Table 2). The least transparent part of the channel occurred around the sand bar at the central segment of the channel, with values ranging from 20 cm to 80 cm. The upstream segment had the clearest water, with values between 60 cm and 106 cm. The downstream area had transparency values between 60 cm and 80 cm. Secchi disc transparency exhibited a significant moderate positive correlation with channel depth (Table 3).

3.1.4 Turbidity

Turbidity values within the channel ranged from 1.51 and 12.71 NTU (Table 2), clearly demarcating the channel into three zones (Fig. 5b). The upper zone, which extended from the upper limit of the study area to the upper end of the central tidal bar, was the clearest part of the channel (1 – 5 NTU). The central zone was the most turbid, with variegated turbidity values between 1 – 13 NTU. The lower zone had turbidity values between 1 and 8 NTU, making it more turbid than the upper zone, but less than the central zone. Turbidity significantly weakly positively correlated with electrical conductivity, salinity, and total dissolved solids (Table 3). It also significantly negatively correlated with depth and Secchi disc transparency, moderately and strongly, respectively (Table 3). Localized increases in turbidity were primarily observed within the central reach of the river where sediment reworking appeared most pronounced.

3.1.5 Temperature

The distribution of bottom water temperature within Great Kwa River is presented in Fig. 5c. Temperatures varied between 25 °C and 28 °C, having an average value of 26.4 °C ± 1.03 °C (Table 2). In the upstream segment, the channel had a predominant temperature range of 26 °C to 28 °C and was principally 25 °C to 26°C downstream, indicating a gradual downstream decrease in bottom-water temperature.. Bottom water temperature within the channel had a non-significant weak negative correlation with depth and no correlation with turbidity (Table 3). The relatively narrow temperature range indicates a thermally stable freshwater environment during the sampling period.

3.1.6 pH

The distribution of bottom water pH within Great Kwa River is presented in Fig. 5d. pH values within the channel ranged from slightly acidic to slightly alkaline (6 to 7.5) and with a mean value of 6.9 ± 0.4, indicating near-neutral conditions (Table 2). There was an even distribution of slightly acidic to neutral (6.5 to 7) and neutral to slightly alkaline (7 to 7.5) bottom waters all through the channel. However, slightly acidic waters (6 to 6.5) occur as large patches in the downstream segment of the channel. The distribution of pH within the channel showed a downstream decreasing trend. pH had non-significant, weak, negative correlations with depth and turbidity but a significant positive correlation with temperature within the channel (Table 3). The observed pH distribution indicates only minor spatial variability throughout the study area.

3.1.7 Electrical Conductivity

The distribution of Electrical Conductivity within the Great Kwa River is presented in Fig. 6a. The map shows a dominant conductivity of 20 – 30 µS/cm in the upstream segment of the channel. The central segment was dominated by a mix of 30 – 40 µS/cm, while the downstream segment of the channel was predominantly 40 – 50 µS/cm. The Descriptive statistics of Electrical conductivity within the Great Kwa River is shown in Table 2. Electrical conductivity had significant weak negative correlations with Secchi disc transparency and turbidity, a very strong positive correlation (r = 1) as shown in Table 3. The downstream increase in electrical conductivity reflects increasing dissolved ionic concentrations associated with tidal influence.

3.1..8 Salinity

The distribution of bottom water salinity within Great Kwa River is presented in Fig. 6b. Salinity values within the channel ranged from 0.014 ‰ to 0.039 ‰, indicating a freshwater tidal channel. The average salinity value within the channel was 0.021 ‰ ± 0.005 ‰ (Table 2). Salinity progressively increased downstream within the channel. Salinity had non-significant weak negative correlations with depth and temperature, but a significant negative correlation with turbidity (Table 3). The observed salinity distribution confirms that the study reach remained within the freshwater tidal zone during the sampling period despite increasing downstream tidal influence.

3.1.9 Total Dissolved Solids (TDS)

Total dissolved solids (TDS) within the Great Kwa River ranged from 12.1 to 31.9 ppm, with a mean value of 18.43 ± 4.62 ppm (Table 2). The spatial distribution of TDS is presented in Figure 6c, which reveals a clear longitudinal zonation of the channel into three hydrochemical zones. TDS concentrations exhibited a progressive downstream increase, with the upstream reach characterized by the lowest concentrations (10–15 ppm), the middle reach by intermediate concentrations (15–20 ppm), and the downstream reach by the highest concentrations (20–35 ppm). This spatial pattern closely mirrors the distributions of electrical conductivity and salinity, reflecting increasing dissolved ionic concentrations toward the estuary under tidal influence. Pearson correlation analysis showed that TDS exhibited a significant weak negative correlation with Secchi disc transparency and a significant weak positive correlation with turbidity (Table 3).

3.10 Hydro-Physicochemical Facies Associations

Based on the integrated distributions of bathymetry, Secchi disc transparency, turbidity, temperature, pH, electrical conductivity, salinity, and total dissolved solids, three hydro-physicochemical facies were identified within the Great Kwa River (Figure 7). These comprise an Upper Fluvial Facies, a Middle Transitional Facies, and a Lower Tidally Influenced Facies, each displaying distinct morphological and physicochemical characteristics that reflect progressive downstream tidal influence.

The Upper Fluvial Facies, located at the head of the study reach and furthest from the Cross River Estuary, occupied an area of 1.41 km² and extended over a channel length of 2.76 km. This reach was relatively shallow, with a maximum depth of 5.2 m and dominant depth ranges of 1–2 m, 2–3 m, and 3–4 m. Secchi disc transparency reached a maximum value of 106 cm, with dominant transparency ranges of 60–80 cm and 80–100 cm, indicating relatively clear water conditions. Bottom-water temperatures ranged up to 28 °C, with dominant temperatures between 26–27 °C and 27–28 °C. The maximum pH recorded was 7.4, while values between 6.0 and 7.0 predominated. Salinity ranged from 0.014‰ to 0.019‰, representing the lowest salinity values within the study area and confirming the predominantly freshwater character of this facies.

The Middle Transitional Facies was the largest hydro-physicochemical unit, extending over 10.16 km and covering an area of 6.96 km². Channel depth increased progressively downstream, with depth ranges of 1–2 m and 2–3 m dominating the upstream portion, while 3–4 m and 4–5 m became increasingly common toward the downstream end of the facies. Secchi disc transparency was predominantly between 60 and 80 cm, although the lowest transparency values (20–60 cm) occurred near the western bank of the central reach, reflecting localized sediment resuspension. In contrast, the clearest waters (80–100 cm) occurred in isolated upstream patches. Bottom-water temperature showed a gradual downstream decrease, with temperatures of 27–28 °C restricted to the upstream portion, whereas 25–26 °C and 26–27 °C dominated most of the facies. The pH ranged from 6.0 to 8.0, with slightly alkaline conditions occurring mainly upstream and predominantly neutral conditions downstream. Salinity increased progressively downstream, ranging predominantly between 0.019‰ and 0.024‰, while values of 0.014–0.019‰ characterized the upstream portion and 0.024–0.029‰ became increasingly common toward the downstream limit of the facies.

The Middle Transitional Facies was characterized by Secchi disc transparency predominantly ranging from 60 to 80 cm. The lowest transparency values (20–60 cm) occurred mainly along the western bank of the central portion of the facies, indicating localized zones of increased suspended sediment concentration and sediment reworking.

In contrast, isolated patches of relatively high transparency (80–100 cm) were observed in the upstream portion of the facies. Bottom-water temperature exhibited a gradual downstream decrease, with temperatures of 27–28 °C occurring exclusively in the upstream section, whereas the dominant temperature ranges throughout the facies were 26–27 °C and 25–26 °C. The pH varied between 6.0 and 8.0, with slightly alkaline waters (pH 7.0–8.0) occurring mainly in the upstream reach, while neutral to slightly acidic waters (pH 6.0–7.0) predominated downstream.

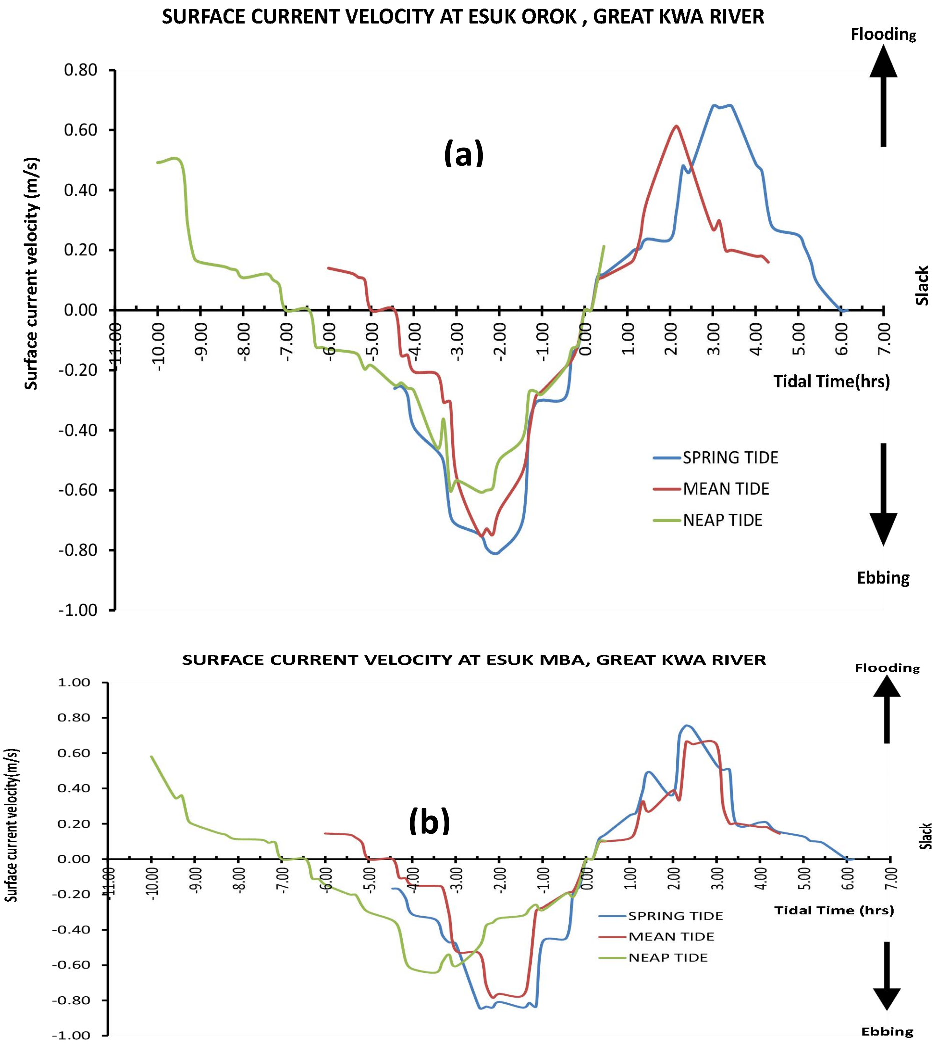

Fig. 3: Surface tidal current velocity at Great Kwa River (a) Esuk Orok (Spring tide, Mean tide, and Neap tide) and (b) Esuk Mba (Spring tide; Mean tide; and Neap tide)

Table 1: Maximum flood and ebb-tidal current velocities in Great Kwa River

	Flood current velocity (cm/s)		Ebb current velocity (cm/s)	
Tidal Cycles	Obufa Esuk Orok	Esuk Mba	Obufa Esuk Orok	Esuk Mba
Spring	68	76	81	84
Mean	61	66	75	78
Neap	49	58	61	64

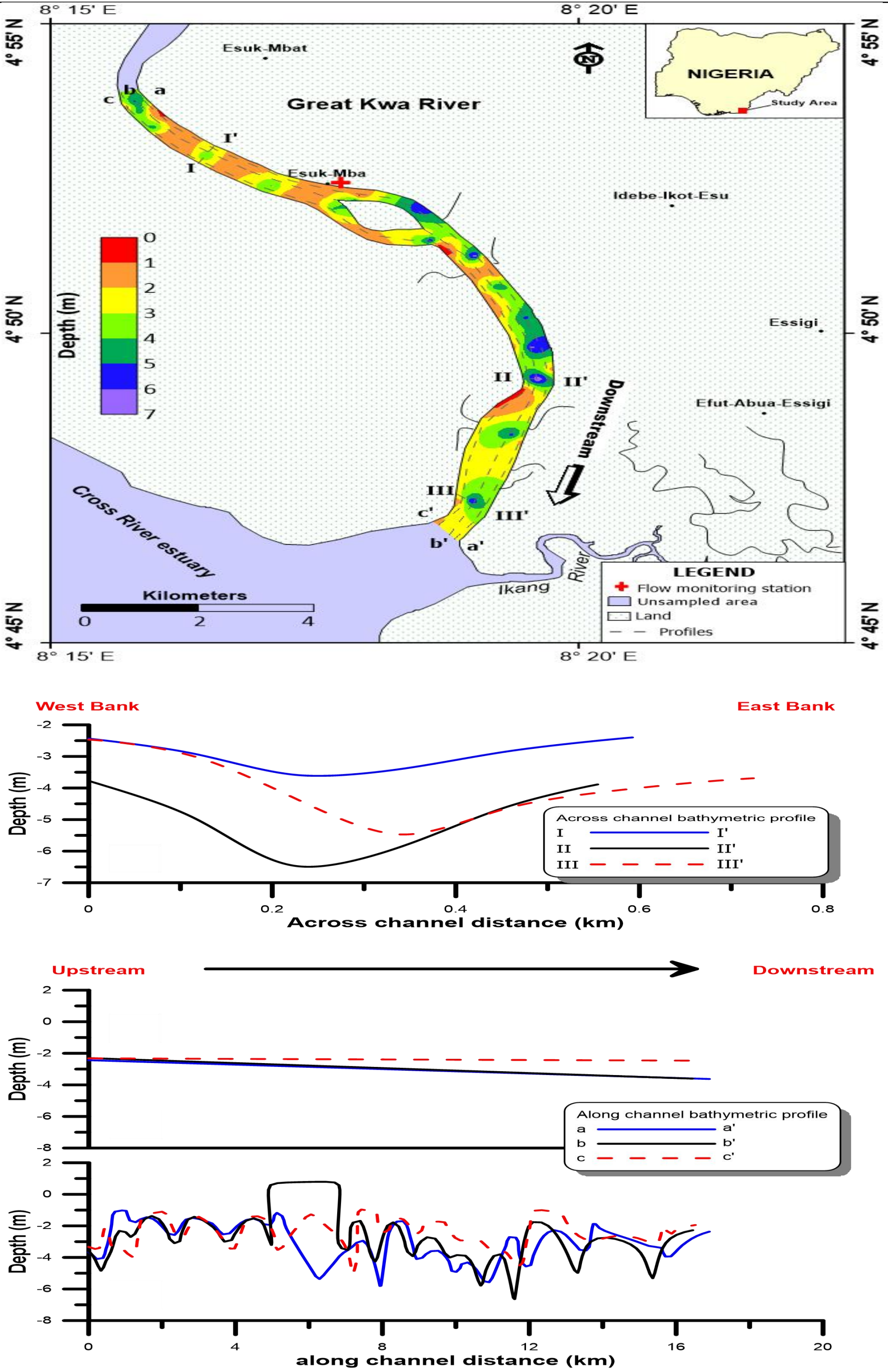

Fig. 4: (a) Bathymetric map of Great Kwa River relative to mean tide low water slack (b) across channel sections (c) resolved along channel linear trends (d) along channel sections

Salinity displayed a progressive downstream increase, with values predominantly ranging between 0.019‰ and 0.024‰. Lower salinity values (0.014–0.019‰) characterized the upstream portion of the facies, whereas higher salinity values (0.024–0.029‰) became increasingly dominant toward the downstream end, reflecting increasing tidal influence.

The Lower Tidally Influenced Facies occurred near the mouth of the Great Kwa River and was the most proximal facies to the Cross River Estuary. It extended over 4.73 km, covering an area of 3.49 km². This facies was characterized by a dominant water depth of 2–3 m, with a maximum recorded depth of 5.9 m. Secchi disc transparency was predominantly between 60 and 80 cm, although localized upstream areas exhibited lower transparency values ranging from 40 to 60 cm. Bottom-water temperature was relatively uniform, with temperatures predominantly between 25 and 26 °C, indicating cooler conditions than those observed upstream. The pH showed a distinct longitudinal pattern, with slightly alkaline waters (pH 7.0–8.0) occurring predominantly in the upstream portion of the facies and neutral waters (pH 6.0–7.0) dominating the downstream section.

Based on salinity distribution, the Lower Tidally Influenced Facies was further subdivided into three hydrochemical subfacies. The upper subfacies was dominated by salinity values ranging from 0.029‰ to 0.034‰, with minor occurrences of 0.034–0.039‰. The central subfacies, occupying approximately 70% of the Lower Facies, was characterized predominantly (approximately 90%) by salinity values between 0.024‰ and 0.029‰. The lower subfacies, nearest the estuarine outlet, consisted almost entirely of salinity values ranging from 0.029‰ to 0.034‰, representing the greatest tidal influence within the study area.

Table 2: Descriptive statistics of Great Kwa River physicochemistry

	Depth (m)	Secchi disc transparency (cm)	Turbidity (NTU)	Water temp (°C)	pH	Electrical conductivity (µS/cm)	Salinity (‰)	TDS (ppm)
N	50	50	50	50	50.00	50	50	50
Min	0.9	26	1.51	25	6.00	22	0.01408	12.1
Max	7	106	12.71	28	7.50	58	0.03712	31.9
Mean	2.8	68.28	5.3138	26.4	6.90	33.5	0.02144	18.425
Std. error	0.2671	2.3455	0.3336	0.1457	0.06	1.1892	0.0008	0.6540
Variance	3.5673	275.0629	5.5632	1.0612	0.15	70.7041	2.90E-05	21.3880
Stand. dev	1.8887	16.5850	2.3586	1.0302	0.39	8.4086	0.0054	4.6247
Median	1.6	70	4.82	26	6.90	30.5	0.0195	16.7750
Geom. mean	2.2404	65.7904	4.8993	26.3803	6.88	32.5478	0.0208	17.9013
Coeff. var	67.4551	24.2897	44.3871	3.9021	5.70	25.1002	25.1002	25.1002
WHO (2011, 2022)			1		6.5 – 8.5			600
NIS (2007,			5	Ambient	6.5 – 8.5	1000		500

2015)

****NIS= Nigerian Industrial Standard**

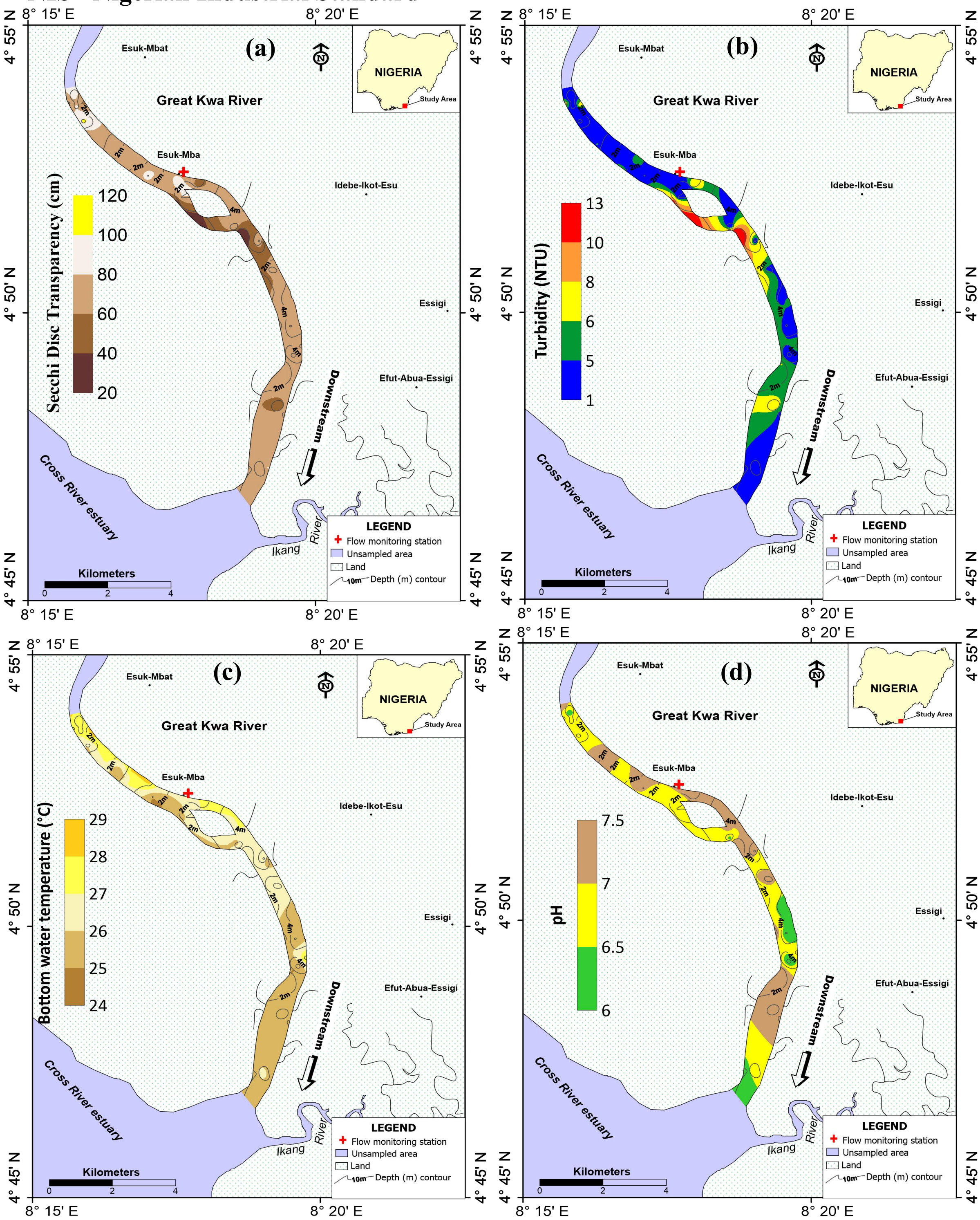

Fig. 5: Spatial distribution of (a) Secchi disc transparency, (b) turbidity, (c) bottom water temperature, and (d) pH, in Great Kwa River

From the entire work, it is indicative that the three hydro-physicochemical facies exhibit a clear longitudinal transition from fluvial-dominated freshwater conditions in the upstream reaches to progressively stronger tidal influence toward the estuary. This spatial organization is reflected by increasing channel depth, salinity, electrical conductivity, and total dissolved solids downstream, together with localized variations in water transparency associated with sediment resuspension and channel morphology

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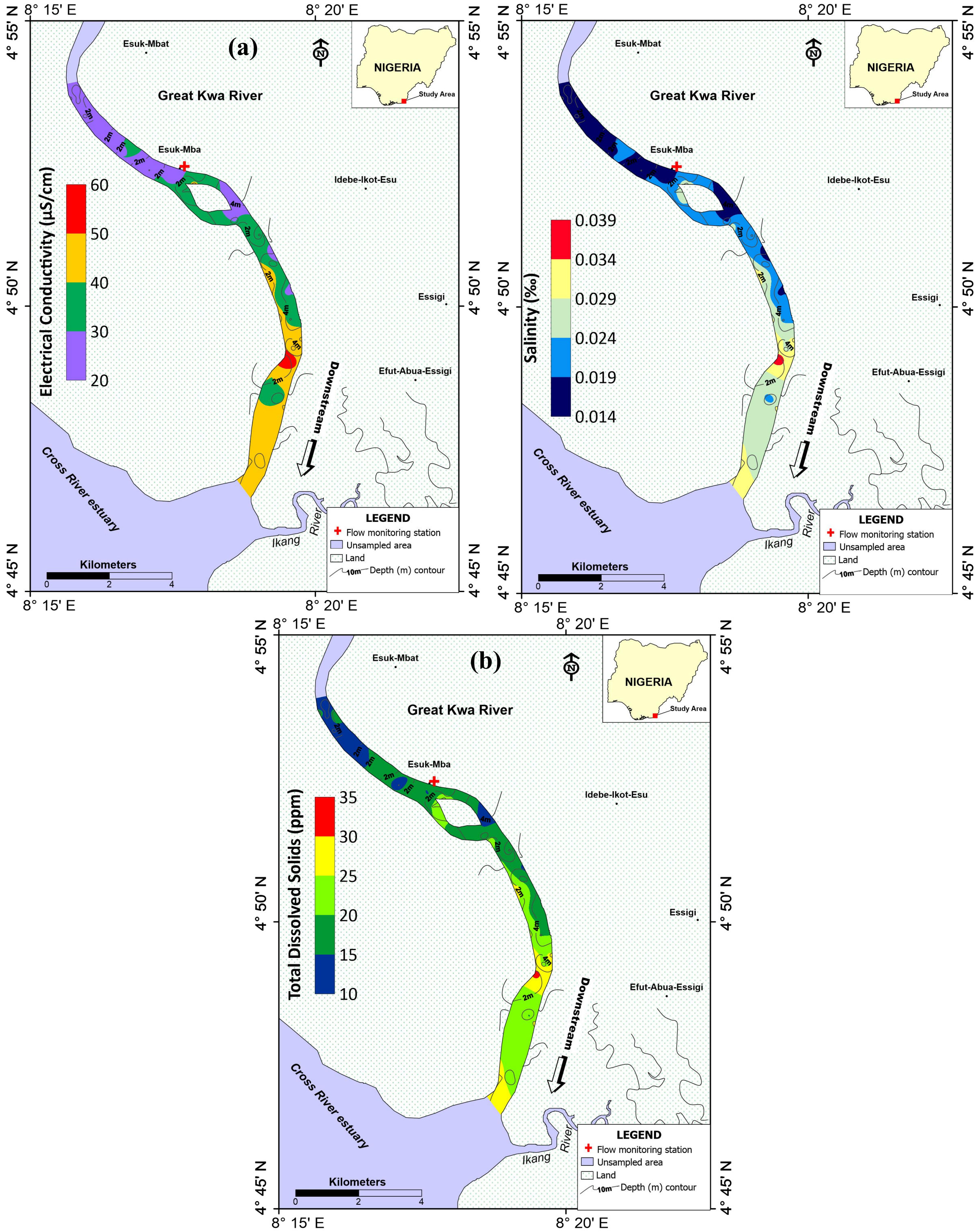

Fig. 6: Spatial distribution of bottom water (a) electrical conductivity (b) salinity, and (c) total dissolved solids in Great Kwa River

Table 3: Pearson moment correlation of Great Kwa physicochemistry (a) Coefficient of correlation (r)

	Depth (m)	Secchi disc transparency (cm)	Turbidity (NTU)	Water temp (°C)	pH	Electrical conductivity (µS/cm)	Salinity (‰)
Secchi disc transparency (cm)	0.497						
Turbidity (NTU)	-0.475	-0.982					
Water temp (°C)	-0.233	0.010	-0.023				
pH	-0.262	-0.104	0.102	0.332			
Electrical conductivity (µS/cm)	-0.153	-0.360	0.310	-0.231	-0.011		
Salinity (‰)	-0.153	-0.360	0.310	-0.231	-0.011	1	
TDS (ppm)	-0.153	-0.360	0.310	-0.231	-0.011	1	1

(b) Probability of significance (P)

	Secchi disc transparency (cm)	Turbidity (NTU)	Water temp (°C)	pH	Electrical conductivity (µS/cm)	Salinity (‰)	TDS (ppm)
Depth (m)	0.00024	0.00049	0.10367	0.06588	0.29029	0.29029	0.29029
Secchi disc transparency (cm)		3.14E-36	0.94487	0.47300	0.01020	0.01020	0.01020
Turbidity (NTU)			0.87642	0.48018	0.02829	0.02829	0.02829
Water temp (°C)				0.01854	0.10670	0.10670	0.10670
pH					0.94228	0.94228	0.94228
Electrical conductivity (µS/cm)						1.92E-234	1.92E-234
Salinity (‰)							1.92E-234

* Highlighted data are significant at $p \leq 0.05$

3.2 Discussion

The hydrodynamic and physicochemical characteristics of the Great Kwa River demonstrate the strong influence of tidal forcing on the evolution of a predominantly freshwater tropical mesotidal system. Although the river remains overwhelmingly fluvial in character during the rainy season, the observed spatial gradients in current velocity, bathymetry, and water chemistry indicate that tidal processes exert significant control over channel morphology, sediment transport, and hydrochemical variability. The integrated results reveal that the Great Kwa River represents a transitional fluvial–estuarine environment where the interaction between river discharge and semi-diurnal tides governs both the physical and chemical characteristics of the channel.

The measured tidal current velocities confirm that the Great Kwa River is a semi-diurnal mesotidal river characterized by pronounced ebb dominance (Figure 3; Table 1). Maximum ebb current velocities exceeded corresponding flood velocities during spring, mean, and neap tidal conditions, indicating that freshwater discharge enhances downstream flow during the ebb phase. Such tidal asymmetry is a characteristic feature of many tropical estuarine rivers and has been widely reported for the southeastern Nigerian coastline, including the Calabar River and other tributaries of the Cross River estuary (Antia et al., 2012; C. N. Emeka et al., 2024a, 2024b; C. N. Emeka, V. I. Emeka, Agi-Odey, et al., 2023; Davies, 1964; Hayes, 1979; Nigerian Navy, 2018). Similar hydrodynamic behaviour has also been documented in tide-dominated estuaries worldwide, where interactions between tidal oscillations and river discharge generate asymmetric current velocities that regulate sediment transport, channel morphology, and estuarine circulation (Dalrymple et al., 2012; Davis & Dalrymple, 2012; Geyer & MacCready, 2014; Gong et al., 2016; Uncles, 2002).

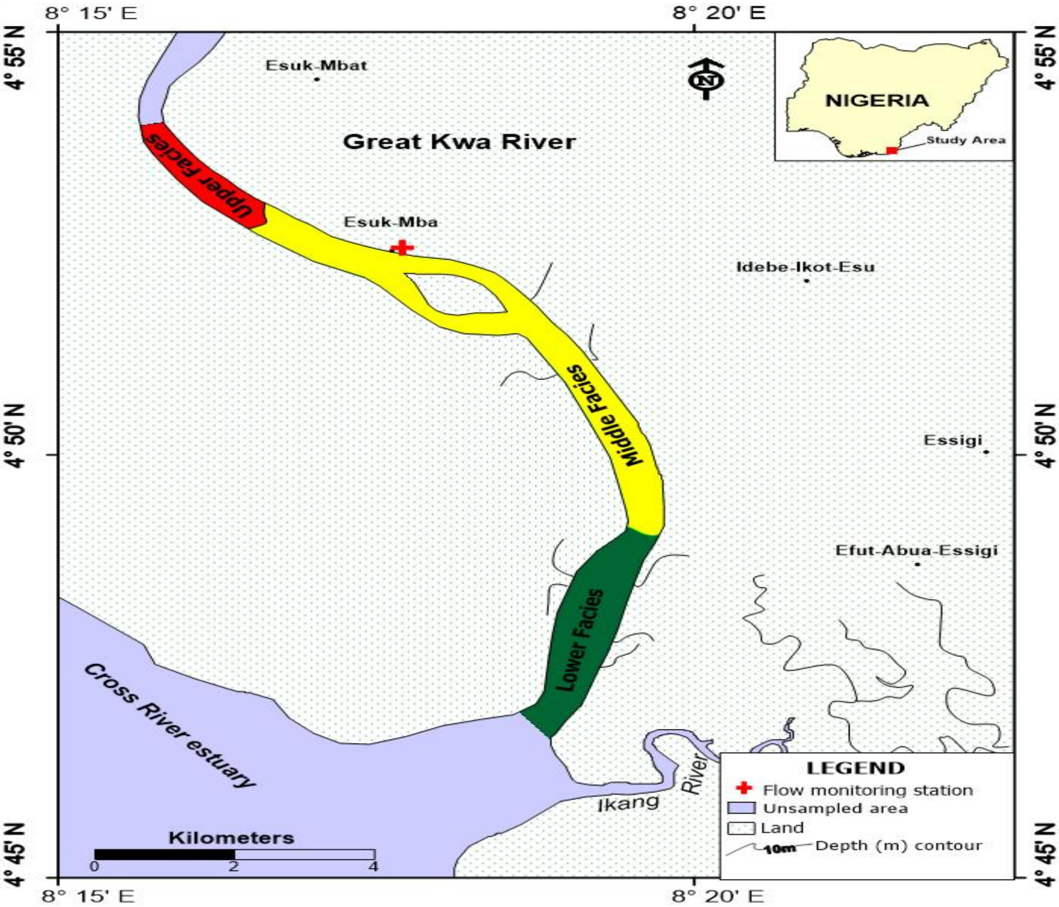

Fig. 7: Hydro-physicochemical facies of the Great Kwa River

The dominance of ebb currents has important geomorphological implications because it promotes the net export of suspended sediments toward the estuary and adjacent continental shelf. Under ebb-dominated conditions, sediment transport is directed predominantly seaward, reducing long-term sediment accumulation within the upper reaches of the channel while enhancing channel scour along the principal flow path. Such conditions favour the development of elongated tidal channels with relatively stable thalwegs and promote downstream hydraulic adjustment through differential erosion and deposition (Asp et al., 2018; Whitehouse et al., 2000; Winterwerp & van Kesteren, 2004). The weak wave climate observed during the study further indicates that hydrodynamic processes are controlled primarily by tidal and fluvial currents rather than by wave action. Consequently, bedform migration, sediment entrainment, and channel evolution are governed principally by tractional processes associated with tidal currents, including rolling, saltation, and localized suspension of sediment particles. Similar current-dominated hydrodynamic conditions have been reported for other tropical mesotidal estuaries where wave energy contributes minimally to sediment redistribution (Asp et al., 2018; Freitas et al., 2012).

The bathymetric characteristics of the Great Kwa River provide further evidence of downstream tidal control on channel morphology. The gradual increase in channel depth toward the estuary and the concentration of maximum depths along the channel thalweg indicate progressive tidal scouring and downstream enlargement of the channel cross-section. These observations are consistent with classical models of tidal river evolution, where increasing tidal prism toward the estuary enhances flow competence and erosional capacity, producing deeper channels and greater accommodation space for sediment transport (Dalrymple et al., 1992; Whitehouse et al., 2000). Similar downstream deepening has previously been documented in the neighbouring Calabar River, suggesting that both systems have evolved under comparable hydrodynamic conditions associated with the Cross River estuarine complex (Emeka et al., 2026b). The asymmetric channel profile, characterized by a deeper mid-channel and shallower margins, further reflects preferential erosion along the principal current pathway and lateral sediment accretion along channel banks, a characteristic morphology of mature tidal rivers.

The physicochemical characteristics measured during the study demonstrate that the Great Kwa River remained predominantly freshwater despite continuous tidal influence. Water temperatures (25–28 °C), pH (6.0–7.5), electrical conductivity (22–58 µS cm^{-1}), salinity (0.014–0.037‰), and total dissolved solids (12.1–31.9 ppm) all remained within ranges typical of tropical freshwater systems and generally satisfied the recommended limits for potable water established by the World Health Organization (WHO, 2011, 2022) and the Nigerian Industrial Standard (NIS, 2007; 2015). These relatively narrow physicochemical ranges indicate that the river currently maintains a stable hydrochemical environment despite tidal fluctuations, reflecting the dominant influence of freshwater discharge during the rainy season.

The exceptionally low salinity values measured throughout the study reach indicate that marine intrusion was extremely limited during the sampling period. Although tidal oscillations propagated upstream, freshwater discharge effectively suppressed saltwater penetration, maintaining freshwater conditions along the investigated channel. Similar seasonal suppression of saline intrusion has been observed in other humid tropical estuaries where river discharge exceeds tidal inflow during the wet season (Geyer & MacCready, 2014; MacCready et al., 2018). Nevertheless, the gradual downstream increase in salinity, electrical conductivity, and total dissolved solids clearly demonstrates the onset of estuarine mixing toward the river mouth. These parameters exhibited nearly identical spatial distributions because they are all controlled primarily by dissolved ionic concentrations within the water column (Hem, 1985; Rahman et al., 2022). Compared with neighbouring estuarine systems such as the Calabar River, Cross River Estuary, and Qua Iboe River, the Great Kwa River exhibited considerably lower salinity values, suggesting weaker marine influence resulting from its relatively high freshwater discharge, channel configuration, and restricted tidal exchange (C. N. Emeka et al., 2024a, 2024b; C. N. Emeka, V. I. Emeka, Agi-Odey, et al., 2023). The downstream decline in bottom-water temperature provides additional evidence of increasing tidal influence. Slightly cooler temperatures toward the estuary may result from several interacting factors, including increased channel depth, enhanced vertical and longitudinal mixing, and reduced solar heating associated with higher suspended sediment concentrations. Such longitudinal cooling trends are common in well-mixed tidal rivers where turbulence continually redistributes thermal energy throughout the water column, thereby limiting thermal stratification (Geyer & MacCready, 2014; MacCready et al., 2018; Uncles, 2002). The absence of pronounced temperature gradients further supports the interpretation that the Great Kwa River functions as a vertically well-mixed tidal system during the rainy season.

Similarly, the observed pH values indicate a chemically stable aquatic environment. Values ranged from slightly acidic to slightly alkaline, with an average close to neutrality, suggesting effective buffering by dissolved carbonate species and natural biogeochemical processes within the river. The slight downstream decrease in pH may reflect increased microbial respiration, decomposition of organic matter, and elevated carbon dioxide concentrations associated with estuarine mixing processes (Kaselowski & Adams, 2013). Nevertheless, the measured pH values remain within internationally accepted limits for drinking water and aquatic ecosystem health (WHO, 2011, 2022), indicating that acidification has not yet reached environmentally significant levels.

Water transparency and turbidity exhibited distinct spatial variability that reflects localized sediment dynamics within the channel. Reduced Secchi disc transparency and corresponding increases in turbidity occurred predominantly within the central portion of the river, particularly around the sand bar where channel convergence promotes flow acceleration and sediment resuspension. This area likely represents a localized zone of enhanced turbulence where tidal currents repeatedly entrain bottom sediments into the water column. Conversely, greater transparency in the upstream reach reflects lower suspended sediment concentrations associated with predominantly fluvial conditions and reduced tidal disturbance. The strong inverse correlation between transparency and turbidity confirms their complementary roles as indicators of suspended sediment concentration, while their relationships with water depth suggest that deeper sections sustain stronger currents capable of maintaining fine particles in suspension for longer periods (Dijkstra et al., 2018; Winterwerp, 2007; Winterwerp & Wang, 2021).

The longitudinal variation of the principal physicochemical parameters clearly demonstrates a progressive transition from fluvial dominance upstream to increasing tidal influence downstream. This downstream evolution is summarized in Table 4, which integrates the major hydrodynamic and hydrochemical characteristics of the three hydro-physicochemical facies identified within the study area.

Table 4. Integrated downstream variation of hydro-physicochemical characteristics in the Great Kwa River

Parameter	Upper Fluvial Facies	Middle Transitional Facies	Lower Tidally Influenced Facies
Water depth	Shallow to moderate	Deepest	Moderate
Secchi disc transparency	Highest	Variable	Moderate
Turbidity	Lowest	Highest	Moderate
Temperature	Highest	Decreasing downstream	Lowest
pH	Near neutral	Variable	Slightly acidic to neutral
Electrical conductivity	Lowest	Increasing	Highest
Salinity	Lowest	Increasing	Highest
Total dissolved solids	Lowest	Increasing	Highest
Dominant hydrodynamic process	Fluvial transport	Mixing and sediment reworking	Tidal deposition

Collectively, these hydrochemical gradients demonstrate that the Great Kwa River represents a tidally influenced freshwater system undergoing progressive physicochemical modification toward the estuary. Although freshwater discharge remains the dominant control during the rainy season, tidal forcing increasingly influences ionic concentrations, sediment suspension, and channel morphology downstream, establishing the environmental conditions that govern the development of distinct hydro-physicochemical facies within the river

4.0. Conclusion

This study provides a comprehensive assessment of the physicochemical characteristics of the Great Kwa River and demonstrates that tidal dynamics exert a fundamental control on water quality, sediment transport, and environmental sustainability within this tropical mesotidal system. The river is characterized by a semi-diurnal, ebb-dominated tidal regime, in which the interaction between tidal forcing and freshwater discharge governs hydrodynamic behaviour and the spatial distribution of physicochemical properties. Water quality parameters, including temperature (25–28 °C), pH (6.0–7.5), salinity (0.014–0.039‰), electrical conductivity (20–58 µS cm^{-1}), and transparency (0.3–1.0 m), remained within acceptable limits for freshwater systems, indicating that the river currently maintains good ecological condition and is largely unaffected by significant pollution.

Progressive downstream increases in salinity, electrical conductivity, and total dissolved solids, together with decreases in temperature and pH, reflect increasing tidal influence and the onset of estuarine mixing. These gradients define three distinct hydro-physicochemical facies—upper fluvial, middle transitional, and lower tidally influenced—which collectively illustrate the downstream evolution of the river system. The middle facies represents the most dynamic zone of sediment reworking and physicochemical variability, whereas the lower facies functions primarily as a fine-sediment depositional environment.

Although the Great Kwa River presently exhibits stable freshwater conditions, localized turbidity maxima, slight downstream acidification, and increasing ionic concentrations indicate emerging environmental sensitivity. The findings establish an important baseline for long-term environmental monitoring and demonstrate that sustainable management should prioritize continuous water-quality surveillance, regulation of dredging and sediment extraction, pollution control, and protection against future saline intrusion associated with climate change and anthropogenic activities. Overall, this study enhances understanding of hydrodynamic–hydrochemical interactions in tropical tidal rivers and provides a scientific basis for integrated environmental management and conservation of the Great Kwa River and similar coastal systems within the Gulf of Guinea.

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Compliance with Ethical Standards

Declaration of Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Consent for Publication

Not applicable.

Availability of Data and Materials

The datasets generated and/or analysed during the current study are available from the corresponding author upon reasonable request. Where applicable, processed data supporting the findings of this study are included within the article.

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The authors declare that they have no competing interests.

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1