Temporal Assessment of River Stages and Discharge Regimes of the Cross River Basin, SE-Nigeria

AZUBUIKE EKWERE (zerratta77@yahoo.com)
UNIVERSITY OF CALABAR https://orcid.org/0000-0002-9831-1442
Ebenezer Kudamnya
University of Calabar

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Abstract

Hydrological basins commonly experience variations in flow and discharge regimes which are dominantly controlled by prevalent climatic conditions as well as other hydrological parameters. This study is being carried out to establish baseline documentation of water levels and discharge regimes in the Cross River hydrological basin in southeastern Nigeria. The focus of the study is on monitoring sections of the river basin underlain by varied geology and geomorphological settings and the computation of annual means of water levels and discharge with their fluctuations for a period of five years (2010–2014). The data for daily water levels and discharge were recorded at four river gauging stations within the hydrological basin during the study period. Annual mean values for the dataset were computed to establish low and peak flows in the river basin within the period of investigation. Analysis of data by principal component analysis (PCA) shows significant positive correlations for rainfall, mean of water level, and minimum discharge in the upstream and midstream sections of the basin. The mean water level and minimum discharge in the downstream section of the basin indicate no significant correlation with rainfall. Generally, discharge increased from the upstream to the downstream of the basin, and rainfall amounts also increased within the period. Drought analysis by calculation of water-bearing coefficients shows that the basin generally experienced a dry hydrological regime in the first three years of monitoring and a wet regime in the latter years. Variations within the basin over the study period indicate the effects of location, catchment size, and other hydrological parameters.

1. Introduction

Variations in hydrological conditions have important effects on water quality (Kuusisto, 1996). Also, hydrological cycles and associated processes can be useful in surface water use and management (Hu et al., 2018; Lian et al., 2018; Pascolini-Campbell et al., 2021). It is important to study regional and sub-regional hydrological basins in view of recent effects of climate change, typically global warming, on water circulation and hydrological processes (Wang et al., 2015; Xu et al., 2018s et al., 2021). It has also been adjudged that hydrological changes in certain regions can be attributed to global climatic changes (Zhao & Wu, 2019; Ma et al., 2019; Chu et al., 2019; Shen et al., 2020). Also, river discharge monitoring aids in detecting climatic and environmental change, because the discharge and quality of river water are functions of many climatic, biological, geological, and topographic variables coexisting in the basin (Depetris, 2021).

Surface water supports a wide range of uses in different environmental settings. These are usually in the form of rivers, streams and lakes serving human uses such as irrigation, human and stock drinking as well as industrial uses. However, these uses have to be monitored and managed to prevent attendant effects on in-stream uses such as recreational, aesthetic, ecological, and cultural values (Watts, 2005). In order to attain the envisaged sustainable management of these water bodies, it is important to understand the hydrological patterns, trends, and their dynamics as they operate within the hydrological basins.

The most important aspect of hydrological basin management strategies is the study of surface water quantity and trends within the basin. Some of the major natural factors that control this quantitative analysis of hydrological basins are rainfall patterns and river flow; connectivity between surface water bodies and subsurface aquifers (usually controlled by geological setting); and sediment load and movement within the basins. Human-induced factors may also affect these basins, and they include, but are not limited to, climate change, land-use changes, and abstraction (Watts, 2005).

The factors that affect hydrological basins can be assessed based on spatial and temporal variations to estimate both short- and long-term trends and make subjective predictions of surface water resources. This array of information helps in establishing pressure regimes on surface water quantity in the basin to meet uses and also factors that may compromise its life-supporting capacity.

Hydrological descriptions of rivers and their basins are mainly qualitative and practically aimed at the expert selection of basin-analogs carried out mainly on the basis of qualitative considerations (Gartsman, 2014). The commonly used set of major hydrographic data for basins (the size, mean height and slope, coefficients of forest coverage, etc.) is poor and insignificantly informative, especially in large basins that are inhomogeneous in runoff formation conditions (Gartsman, 2014).

Hydrological measurements are essential for the interpretation of water quality data and for water resource management (Kuusisto, 1996).

This study documents a baseline assessment of the hydrological monitoring of parts of the Cross River hydrological basin in southeastern Nigeria. The study focuses on the measurement of river stage and discharge. River discharge has a role in driving the climate system because freshwater flows from the mainland into the world's oceans can influence the oceanic circulation pattern. River discharge also serves as an indicator of climate change and variability as it reflects changes in precipitation and evapotranspiration. The river discharge is expressed as volume per unit time. It is the ratio at which water flows through a cross-section. The unit is usually m^3/s (i.e., cubic meters per second). In situ methods are the most cost-effective and reliable options for river discharge measurement.

The river basin provides support for irrigation and water resource conservation. The current study would possibly provide baseline support data for control and planning involving navigation improvement, development of hydropower (where suitable), fisheries and outdoor recreation, as well as flood control and land drainage, especially due to its proximity to the ocean.

2. Materials And Methods

2.1. Study area

One of the earliest works on the regional hydrology of Nigeria is the work of Ayoade (1975), in which he concludes that Nigeria is well drained with close networks of rivers and streams. The Cross River basin catchment area (which is part of the southeastern hydro-geographic region in Nigeria) spans over an area of 51,276 km2 (Fig. 1). It is a section of the larger Upper Cross River Basin (UCRB), which extends from western Cameroon into southeastern Nigeria (Ogarekpe et al., 2020; Ogarekpe & Nnaji, 2020). It makes up approximately 40% of the regional UCRB and ~ 10% of the territory of Nigeria. The meridional basin lies between latitudes 5–7 N and longitudes 8–10 E.

The basin area lies on an extensive heterogeneous geologic expanse, extending from the northern part, through the central section, down to the south, where it empties into the Atlantic Ocean. It includes the eastern parts of the Cameroonian volcanic mountain range, expressed as the Obudu plateau in the north and the Oban Massif in the central to southern expanse of the basin. These mountainous, rugged highlands, built on tectonically deformed complexes of igneous and metamorphic rocks (Ekwere and Edet, 2012 & 2015), are separated by an extensive sedimentary fill with intrusive volcanics (basalts), which is an extension of the southern Benue Trough known as the Mamfe Embayment. The southernmost part of the basin is the lowlands of the southern deltaic sedimentary basin, described as the Calabar Flank. The flank hosts a multi-geologic complex of extensive continental sandstone units (Awi Sandstone), karst and associated lithologies (Mfamosing Limestone), shales, and coastal sand plains (Benin Sands).

The Cross River basin catchment area is characterized by high rainfall, relatively low potential evaporation in the south, close to the sea, where most rainfall run-off from the inland part of the country enters the sea. It is therefore blessed with an abundant surface water system, as indicated by the several separate rivers that drain the area. As one moves further north away from the sea to the farthest parts of the basin catchment, the rain fall reduces from approximately 3000mm in the south to about 1000mm in the north, and the potential evaporation also becomes much higher.

The basin is characterized by a tropical climate with two distinct seasons: wet and dry. These are controlled by the movement of the Inter Tropical Discontinuity (ITD), a zone separating the warm, humid maritime tropical air mass from the dry continental tropical air mass. The wet season spans a period of about six months (May to October), and the dry season lasts from November to April. Temperatures are high, with negligible diurnal and annual variations. The average monthly temperature over the basin area ranges from 29 to 34^0 C. The catchment experiences mean annual rainfall of about 2,300mm with an annual mean daily relative humidity and evaporation of 76–86% and 3.85mm/day, respectively (Ekwere & Edet, 2012; Ekwere et al., 2021). The peaks of rainfall are usually between the months of June and August, and vary annually. The basin area exhibits a vast array of vegetation types; guinea savannah type in the northernmost part, with veldt and forest types in other parts of the north. The central and southern parts are dominated by luxuriant rainforest with tall trees as canopies and thick undergrowth, forming a stratified forest appearance.

Based on studies, the level of elongation of the basins is influenced by various factors such as main stream lengths; relief; geology; ground slopes; climate; vegetation factors, etc (Nageswara et al., 2010; Rawat et al., 2011; Ivanova et al., 2011). The hydrographic specifics of the Cross River basin catchment area are defined by the geographic distribution of drainage density, river configuration, differences in river orders of flow, and the entire network that ultimately discharges into the Atlantic Ocean. The drainage patterns within the basin are a mix of rectilinear (structurally controlled by geology) and dendritic (free flowing along un-configured channels). The somewhat extensive area of the Cross River basin entails the complex hydrological inputs getting homogenized into a single annual transition from low flow to high flow. This is based on the consistency of the duration of wet-seasonal peaks with abundant rain falls and the regularity of their onset across the basin. Annual land surface run-off is estimated to be 1501-6631mm in the region, with annual natural discharge estimated to be 100-1000m3/sec (Döll et al., 2003).

2.2 Data collection

For the current research work, four hydro-meteorological monitoring stations were established along major river channels of the Cross River basin. One was mounted on the upper course of the river basin at Ogoja (Aya River), two on the mid-sections of the basin at Ikom (Ikom River) and Obubra (Owakande River), while the fourth was mounted on the lower downstream section of the basin at Itu (Calabar River). The data used in this study are a result of a sixteen-year-long continuous data acquisition program on the Cross River basin. The dataset represents continuous, undisturbed, and reliable data collected within the specified period of reference (2010–2014). The dataset includes water level measurements, discharge measurements, and rainfall data.

The daily water levels, or river stages, were read from graduated staff gauges installed at each station along the river basin. The RIO Grande Acoustic Doppler Current Profiler (ADCP) was deployed to undertake the discharge measurements across river sections at each installed gauging station in the basin (Fig. 2).

3. Results And Discussions

A statistical summary of data collected across the rivers over the study period is presented in Table 1. The table documents the locations and coordinates of the monitoring stations; minimum, maximum, and means river stage levels along the river basin within the study period. Annual averages of rainfall measurements as well as annual means of minimum and maximum discharge measurements along the basin for the period are also presented. Figures 3–6 present plots of river stages from the different locations along the basin during the study period.

Results of measurements on the upstream section of the river basin (Ogoja station) show that the low levels of river stage (within the dry seasons) fluctuate with no definite trend during the study period.

Table 1
Statistical summary of data collected over the study period

Location	Coordinates	Parameter	2010	2011	2012	2013	2014
Ogoja	N06˚ 31´	Low Water (m)	0.14	0.22	0.06	0.30	0.08
	N009˚ 07´	High Water(m)	1.62	2.47	2.70	3.08	2.79
	Elevation 120m	Ave. Water(m)	0.72	1.08	1.16	2.26	1.20
		Rainfall (mm)	1,570.3	1,798.8	2,276.9	2,288.2	2,189.4
		Ave. Disc. Max. (m^3/s)	87.2	76.8	92.4	106.5	127.5
		Ave. Disc. Min. (m^3/s)	3.2	4.8	12.4	8.8	10.4
Ikom	N06° 15′	Low Water (m)	0.71	0.85	0.75	0.38	0.46
	E008° 45′	High Water(m)	9.38	9.34	9.80	9.03	9.55
	Elevation 40m	Ave. Water(m)	3.58	3.52	3.60	3.14	4.02
		Rainfall (mm)	1,487.6	1,524.3	1,545.0	1,564.5	2,223.9
		Ave. Disc. Max. (m^3/s)	1,881	2,021	1,825	1,920	2,114
		Ave. Disc. Min. (m^3/s)	94	145	44	275	485
Obubra	N06° 03′	Low Water (m)	0.83	0.39	0.10	0.18	0.16
	E008° 15′	High Water(m)	4.75	5.90	6.99	7.62	7.92
	Elevation 26m	Ave. Water(m)	2.23	2.82	2.76	3.20	2.86
		Rainfall (mm)	1,461.0	1,541.4	1,661.0	1,957.0	1,859.0
		Ave. Disc. Max. (m^3/s)	2,840	3,180	3,320	2,960	3,884
		Ave. Disc. Min. (m^3/s)	308	348	139	463	630
Itu	N05° 08′	Low Water (m)	0.56	0.88	1.02	0.07	0.08
	E008° 14′	High Water(m)	4.51	4.43	4.55	2.75	5.06
	Elevation 16m	Ave. Water(m)	2.16	2.28	2.60	1.04	3.14
		Rainfall (mm)	2,281.6	2,660.0	1,425.8	2,305.8	2,973.3
		Ave. Disc. Max. (m^3/s)	3,040	3,150	2,920	3,210	3,470
		Ave. Disc. Min. (m^3/s)	438.6	421.4	305	544.5	775.8

The mean high levels of river stages (recorded within the wet seasons) and mean water levels indicate a steady increase over the period of study, with peaks recorded in 2013. River discharge also increased over the study period, alongside average annual rainfall.

Within the midstream section of the basin, measurements at Ikom station show an increase in mean river stage levels over the period. Obubra station also recorded slight increases in mean river stage levels over the study period, with a peak in 2013. Both stations recorded a steady and gradual increase in rainfall over the period. River discharge also increased over the study period at both stations, though with intermittent fluctuations across the years.

The downstream section of the basin (Itu station) recorded somewhat stable average high river stage levels (wet season measurements) during the study period only, with a drop in 2013. However, annual average river stage levels increased over the period of study. The annual average of maximum discharge also increased over the period.

Plots of river stages as well as discharge measurements over the study period are presented in Figs. 7–10.

Figure 7 shows relatively steady annual rainfall amounts with minor fluctuations over the study period at Ogoja station. Averages of the minimum and maximum discharge of the river indicated a gradual increase over time.

Measurements on the midstream section of the basin at Ikom station show slight increases in rainfall over the period. The mean maximum annual drainage was generally stable with minimal variations over the study period. Contrarily, the annual minimum drainage increased over the period, with a slight dip only in 2012. For the other midstream station (Obubra), rainfall amounts were relatively stable over the period, with increases in both the annual means of minimum and maximum drainage measurements.

Measurements at the southernmost part of the basin at Itu station show a relatively steady amount of rainfall during the study period. The annual mean of minimum discharge dropped between the years 2010 and 2012. The discharge levels later increased from 2013 to 2014. The annual means of maximum discharge exhibited a similar pattern during the study period at Itu station.

The hydrology of the river basin is obviously controlled by rainfall and runoff during the wet seasons as well as contributions from tributaries linked to the river basin. Possible in-flows from tributaries within the basin’s catchment provide intermittent wet season high discharge regimes, with localized floods in surrounding communities.

Principal Component Analysis (PCA)

Correlation analysis is a bivariate method employed to establish the degree of relationship between two variables. Correlation analyses were conducted to establish possible interrelationships between measured parameters across the river basin.

Parameters showing $r > 0.7$ were considered to be strongly correlated. At a significance level (p) of 0.05, values of 0.5–0.7 are described as moderate correlation, while values less than 0.5 are considered weak. The results of the computation are as presented in Table 2.

Table 2
Correlation matrices of measured parameters

Ogoja					Ikom			
	MWL	R	Max.AD	Min.AD	MWL	R	Max.AD	Min.AD
MWL	1				1			
R	0.689	1			0.761	1		
Max.AD	0.373	0.607	1		0.546	0.779	1	
Min.AD	0.382	0.931	0.573	1	0.42	0.893	0.825	1
Obubra					Itu			
MWL	1				1			
R	0.844	1			0.167	1		
Max.AD	0.264	0.389	1		0.222	0.872	1	
Min.AD	0.384	0.606	0.501	1	-0.038	0.037	-0.223	1
MWL – mean water level R – rainfall Max.AD – mean of maximum annual discharge								

Min.AD - mean of minimum annual discharge

Results from correlation analyses showed that rainfall had a moderate positive correlation (0.689) with mean water level at Ogoja station during the period. At Ikom and Obubra stations, rainfall exhibited a strong positive correlation of 0.761 and 0.844, respectively, with mean water levels. Itu station recorded a very poor positive correlation of 0.167 between rainfall and mean water levels. From this, it can be deduced that water levels within the upper reaches of the basin are related to rainfall, but the levels diminish due to quick flows relative to surface elevations over dominantly basement and consolidated sedimentary rocks. Within midstream sections of the basin, water levels and rainfall have a strong relationship. This is further supported by lower elevations with corresponding low flow velocities. This section of the basin is underlain by sedimentary rocks, dominantly shale, with drainage morphology that has shown that the bifurcation ratio in this section is lower than the one for the basement-underlain sections (Eze & Efiong, 2010).

Rainfall exhibited a strong positive correlation with average minimum discharge at Ogoja (0.931) and at Ikom (0.893). The correlation was a moderate positive one at Obubra (0.606) and a poor positive correlation at Itu (0.037). These indicate that the amount of discharge, especially during the dry seasons, is greatly influenced by the amount of rainfall on the upstream and midstream within the basin. The downstream discharge regimes are invariably affected by rainfall amounts but rather more by inflows from contributing tributaries from the hinterland drainages.

The correlations of annual averages of minimum and maximum discharges within the upstream and midstream over the study period recorded significant positive correlations, indicating seasonality to be a major control on the discharge regimes in those sections of the river basin. The downstream section showed a negative correlation of the same parameters over the study period. This means seasonality doesn't have a bearing on river discharge regimes downstream. Its discharge fluctuations depend more on inflows from surrounding tributaries into the lower end of the basin that empties into the Atlantic Ocean consequently. The Cross River tributaries provide most of the wet-season peak discharge and this may occasion intermittent floods in certain communities (Eze & Efiong, 2010).

Drought Analysis

Hydrological drought is characterized by low flow periods and is caused by decreasing river discharges. Comparing discharge data between different rivers with a variety of sizes, characteristics, and annual mean discharge is not possible without using relative values (Almikaeel et al., 2022). The introduction of these relative values establishes the comparability of discharge data measured across the hydrological basin relative to the study period. According to Almikaeel et al. (2022), the long-term mean discharge (Q_a) can be computed over the study period at each gauging station and then used to normalize the annual mean discharge (Q_{mean}). From these, drought analysis can be estimated by the percentage ratio of discharge variations based on mean annual discharge (Q_{mean}) and long-term mean discharge (Q_a) for the reference period (Fendeková & Blaškovičová, 2018). The mean annual discharge used in this estimation is that of annual minimum data as presented in Table 1.

Tables 3a and 3b present results for computation of Q_a and Q_{mean}, ratios of variations in percentages, and descriptions of relative river status across the different gauging stations over the reference period.

Table 3
(a) Hydrological drought assessments of Ogoja and Ikom Rivers over the period.

	Ogoja			**Ikom**		
Year	Q_{mean}	Q_{mean}/Q_a(%)	Status	Q_{mean}	Q_{mean}/Q_a(%)	Status
2010	3.2	40.5	Dry	94	45.1	Dry
2011	4.8	60.8	Dry	145	69.5	Dry
2012	12.4	157	Wet	44	21.1	Dry
2013	8.8	111.4	Wet	275	131.8	Wet
2014	10.4	131.6	Wet	485	232.5	Wet

Table 3
(b) Hydrological drought assessments of Obubra and Itu Rivers over the period.

	Obubra			**Itu**		
Year	Q_{mean}	Q_{mean}/Q_a(%)	Status	Q_{mean}	Q_{mean}/Q_a(%)	Status
2010	308	81.6	Dry	438.6	88.2	Dry
2011	348	92.2	Normal	421.4	84.8	Dry
2012	139	36.8	Dry	305	61.4	Dry
2013	463	122.6	Wet	544.5	109.5	Normal
2014	630	166.8	Wet	775.8	156.1	Wet

The computed ratio is defined as the water-bearing coefficient, and this ratio is compared to standard intervals described as dry, normal, and wet to evaluate the hydrological status of a river (Almikaeel et al., 2022). The standard intervals are divided into three categories: dry (10%-89%), normal (90%-110%), and wet (> 111%) (Almikaeel et al., 2022).

Computations, as presented in Tables 3a and 3b, show that the river basin generally experienced a dry regime for the years 2010 and 2011. The river basin was also dry in 2012, with the exception of the upstream section (Ogoja), which was determined to be wet. The wet regime in the upper course of the stream could be occasioned by inflows from interconnected tributaries of the adjoining Benue River basin, which lies in proximity to the north-western part of the Cross River basin. The effects tend to diminish further into the basin area. All the rivers measured across the basin experienced wet regimes for the years 2013 and 2014. The lowest water-bearing coefficient (36.8%) was recorded at Obubra in 2012 and that may have resulted from localised water losses during the hydrological year. The general trend indicates increased discharge regimes occasioned by a general increase in rainfall over the study period. These increases are in tandem with flood vulnerability projections in some communities, as documented by Eze & Efiong (2010).

4. Conclusion

This current research confirms that the Cross River basin is underlain by varying geologic and geomorphological settings. These combine variably to characterise the orientation of flow, runoff, and discharge capacity along subsections of the hydrological basin. Seasonality also has a major control in terms of rainfall amounts, which increase within the wet period of May to October, as evidenced within the study period. The dry season records the lowest water levels, surface runoff, and consequently the least discharge measurements across the basin.

Principal component analyses indicate significant positive correlations for rainfall, means of water level, and minimum discharge within the upstream and midstream sections of the basin. The mean water level and minimum discharge in the downstream section of the basin indicate no significant correlation with rainfall. It is assumed that inflows from surrounding tributaries within the proxy of the lower course of the river basin may have a dominant control on water levels and discharge regimes.

Interpretations over the study period show that discharge generally increases from the upstream to the downstream of the basin and rainfall amounts also increased within the period. However, localised fluctuation events were recognised within certain sections of the river within the period.

Water-bearing coefficients show that the basin generally experienced a dry hydrological regime in the first three years of monitoring and a wet regime in 2013 and 2014.

Noticeable differences between the four measured rivers within the basin with respect to location, catchment size, and other hydrological factors had a dominant effect on the river basin over the period of study.

This study provides baseline data for the study area and can be used for future basin management and resource development.

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Figures

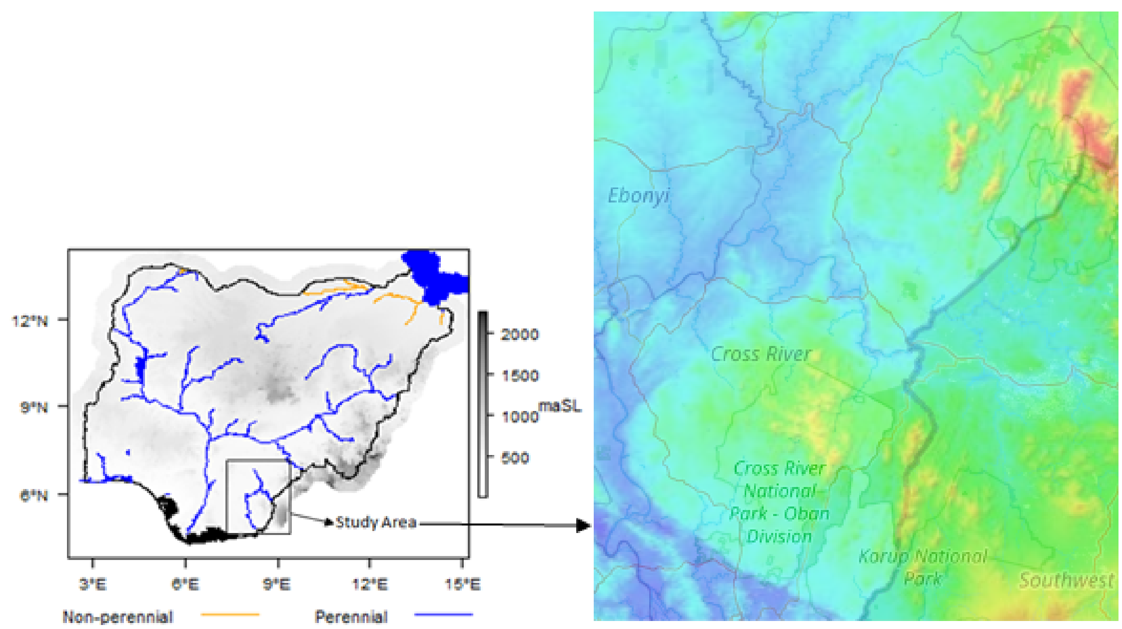

Figure 1

Hydrological map of Nigeria showing the study area; Cross River basin catchment area (adapted and modified from topographic-map.com)

Figure 2

ADCP/River Science deployment from an outboard engine boat on section of the Cross River basin.

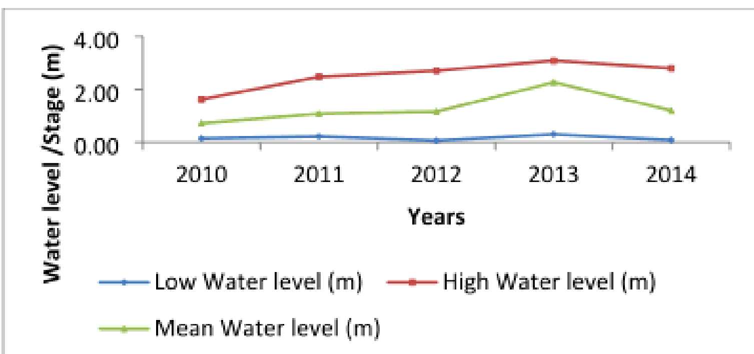

Figure 3

River stage trends over the study period at Ogoja station

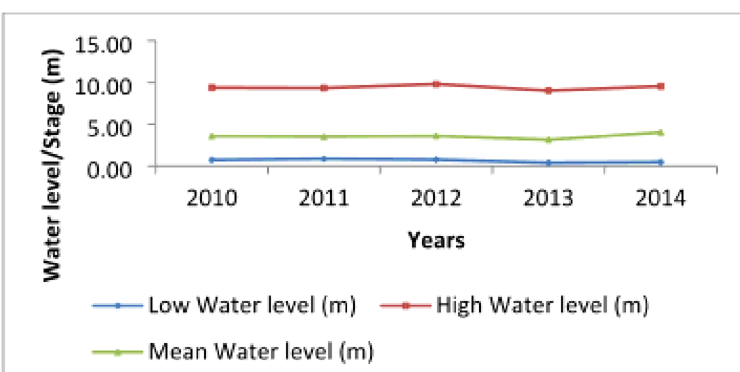

Figure 4

River stage trends over the study period at Ikom station

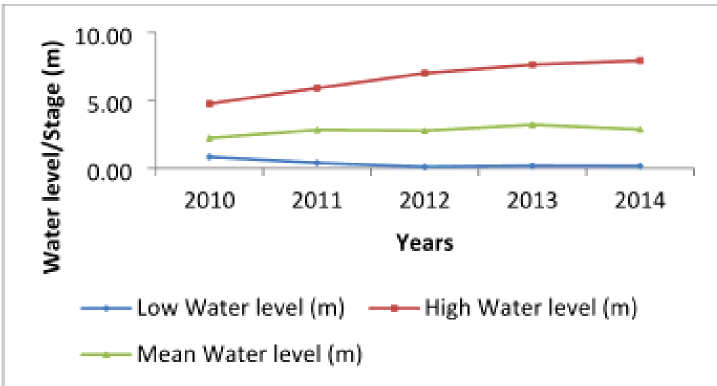

Figure 5

River stage trends over the study period at Obubra station

Figure 6

River stage trends over the study period at Itu station

Figure 7

Discharge and rainfall trends within the study period at Ogoja station

Figure 8

Discharge and rainfall trends within the study period at Ikom station

Figure 9

Discharge and rainfall trends within the study period at Obubra station

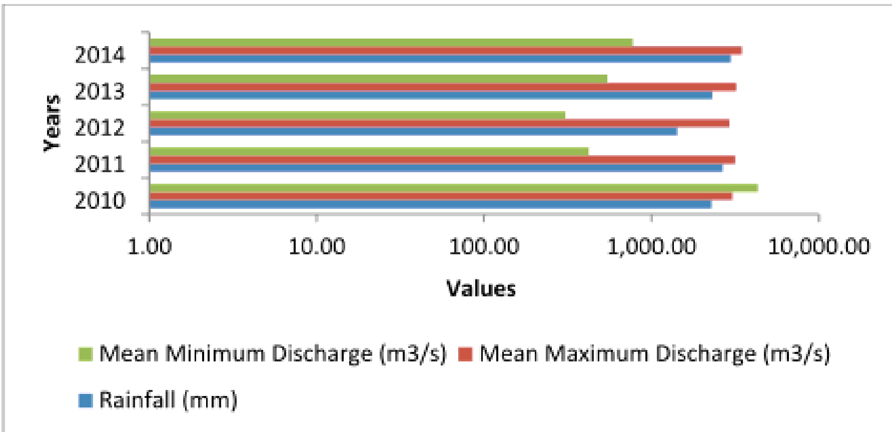

Figure 10

Discharge and rainfall trends within the study period at Itu station