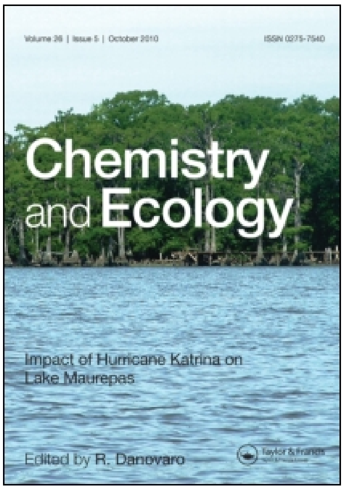

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Chemical composition of rivers and streams in the forest and savanna zones of Nigeria

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The aim of this study is to investigate the differences in the chemical conditions of lotic waterbodies in the two major ecosystems in Nigeria, the forest and savanna zones. The forest waters were slightly acidic (mean ± SD pH = 6.72 ± 0.58) while the savanna waters were slightly alkaline (pH = 7.11 ± 0.33). The cationic order of dominance in the forest waters was $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ in contrast to $Ca^{2+} > Mg^{2+} > Na^+ > K^+$ in savanna waters. The forest waters were chlorided (typical of coastal and/or marine waters) whereas the savanna waters were carbonated in nature, typical of the worldwide freshwater. Organic carbon was significantly higher in forest waters than in the savanna waters ($p < 0.05$) while nutrient compounds were significantly higher in savanna waters than in forest waters. The seasonal variation of the chemical parameters was generally more evident in savanna than in forest waters. The differences in water quality between the two major vegetation zones reflect the differences in the biogeochemical processes and nutrient cycling that characterise forest and savanna ecosystems.

Keywords: water quality; nutrient cycling; vegetation zonation; savanna; forest; Nigeria

1. Introduction

The relationship between water quality and terrestrial vegetation, generally has received little attention compared to the known relationship between soil and terrestrial vegetation. Water quality is principally controlled, to varying extents, by climate, mineral composition (including mantle rock and bedrock) and many processes involving the growth of vegetation (including the accumulation and decomposition of organic substances and the formation of new chemical compounds) within the water's drainage basin [1]. In general, the complex of plants, soil and animals living in them is comparable to the aquatic biota, water quality, terrestrial vegetation and soil in a drainage basin. For instance, invertebrates and the fishes inhabiting rivers are also influenced by terrestrial vegetation [2] since many animals eat vegetable detritus (such as dead leaves and grass stems). Studies on water chemistry and terrestrial vegetation in West Africa are rather limited. In this African sub region, terrestrial vegetation, comprising forests and savannas, i.e. tropical

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grasslands, is characterised by different ecological zones that display some important distinctions in the faunistic composition of waterbodies. For instance the blackflies fauna of the region is often grouped broadly into the forest and savanna types while their immature stages (particular the larvae) are known to require different hydro-chemical conditions [3–6]. In East Africa, the extent to which nutrients are leached from terrestrial to aquatic systems is a measure of the efficiency of nutrient cycling in the terrestrial system [7]. The present study therefore investigates the differences in the chemical composition of rivers and streams in the two major vegetation zones in Nigeria, the forests and savanna. The vegetation of the country is the most typical of that of West Africa [8,9] and details information on the floristic composition, structure, physiognomy and ecological aspects of these two vegetation types in Nigeria is reported in previous studies [9–13].

2. Materials and methods

2.1. *Study area*

The two areas investigated in this study are the savanna zone located in the Gurara River Basin, in the new Federal Capital Territory (FCT) of Nigeria, and the forest zone located in the Benin-Owena River Basin (Figure 1). The new Federal Capital Territory refers roughly to the portion of Nigeria between latitudes 08°25′N and 09°25′N and longitudes 006°45′E and 007°45′E, covering approximately 8000 km^2 of land (i.e. about 0.9% surface area of Nigeria) and is well drained by the River Gurara (about 350 km long) (Figure 1C). Information on the general features of this area, that is a part of the African Pre-Cambrian Basement which has not been overlain by the sea, is reported in [14–21]. The Pre-Cambrian granite has given rise to rocky bedded rivers with rapids and falls (notably the Gurara Fall) and to a characteristic landscape with isolated domes of smooth bare rocks i.e. inselbergs [14,19].

The Benin-Owena River Basin (Figure 1B) is one of the 11 major river basins in Nigeria. It lies approximately between latitudes 05°N and 08°N and longitudes 004°E and 007°E, and covers about 6.0% (approximately 56×10^3 km^2) of the entire surface area of Nigeria. The northern part belongs to the undifferentiated basement complex of the pre-Cambrian to Cambrian age, the middle part to the Tertiary sediment and the most southern portion to the alluvium plain sand of the Quaternary period. The Benin-Owena River Basin is drained into the Atlantic Ocean through a series of north-south parallel rivers. River Benin (the principal river of the basin) together with its main headwater tributaries (Rivers Ogbesse, Osse, Ofosu, Siluko, Ossiomo, Ethiope, and Jaimeson) drains nearly 70% of the entire basin.

The typical climates of the two vegetation zones are compared in Figure 2, based on Minna (savanna zone) and Benin City (forest zone). Following the classification of Papadakis [22], the climate of Minna (09°37′N, 006°12′E, *ca* 260 m above mean sea level) area is of the Moist Dry Monsoon type with humid season from May to October, rainfall surplus (Ln) about 665 mm and drought stress (S) about 1240 mm. Benin (06°20′N, 005°36′E, 80 m amsl) area is of the Humid Semi-Hot Equatorial climate with humid season from April to October, rainfall surplus (Ln) about 1220 mm and drought stress (S) of about 335 mm.

2.2. *Sampling strategy*

Thirteen perennial rivers (see Figure 1 and Appendix 1 for details) comprising River Gurara and its major tributaries were investigated in the FCT of Nigeria to characterize the water quality of the savanna zone of the country. The study was performed in the framework of the Environmental

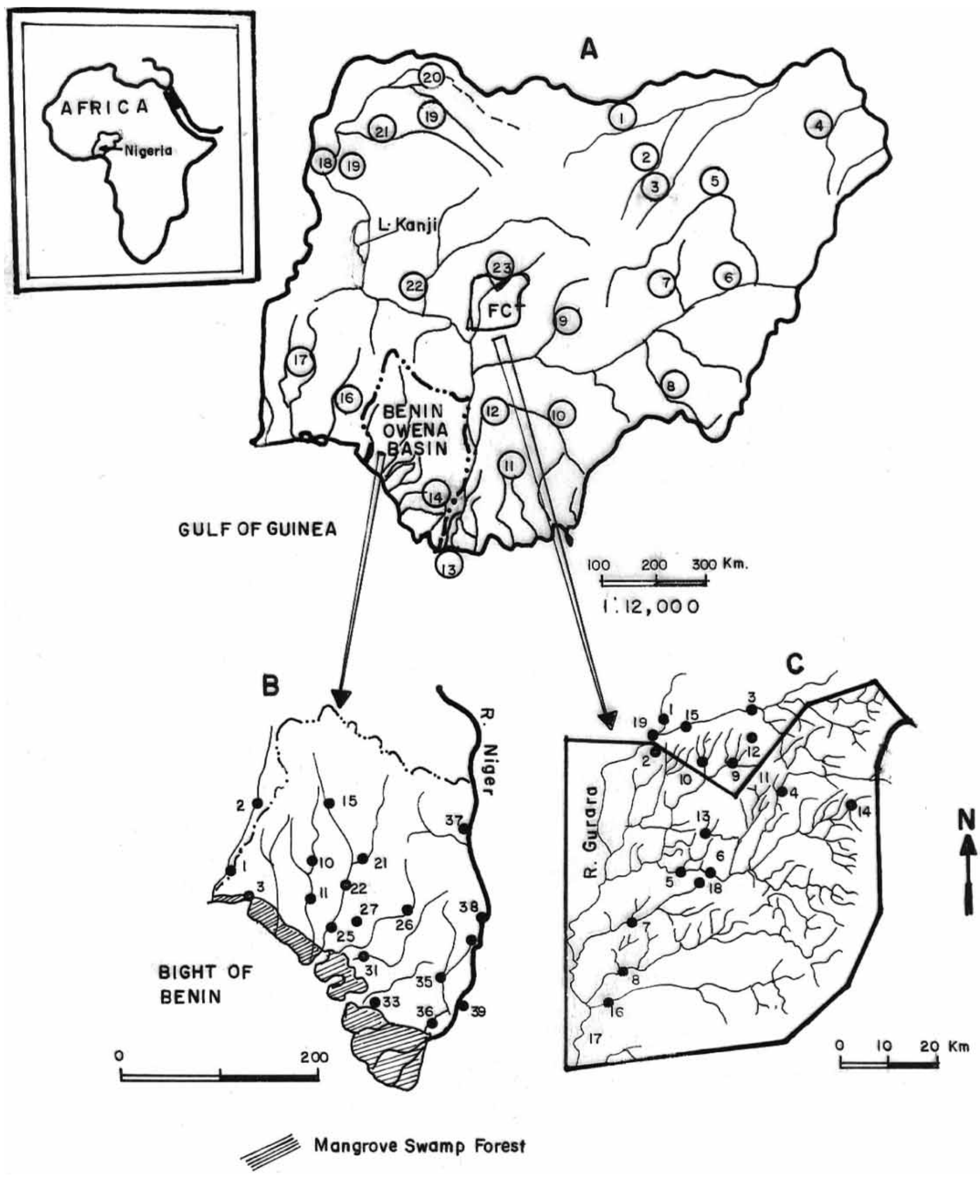

Figure 1. Map of Nigeria showing the major rivers and drainage pattern (A), Benin-Owena River Basin (B), Federal Capital Territory of Nigeria (C) showing investigated rivers and streams.

Pollution Monitoring Programme of the Territory during the period 1996–1998. Surface water samples were collected bimonthly in two sites at each of the selected rivers during the dry and rainy seasons, respectively. During our study (1997–1999) most of the major rivers in the Benin-Owena Basin were also investigated. On the whole, 23 rivers and streams were sampled at 29 sites in the basin (representing the forest zone). The number of sampling stations per river was directly related to the catchments area of each river. A total of 140 water samples (each in duplicate) were collected from the FCT while 230 samples were collected from the Benin-Owena basin (30 samples from mangrove swamp forest, 60 samples from freshwater swamp forest and 140 samples from rainforest).

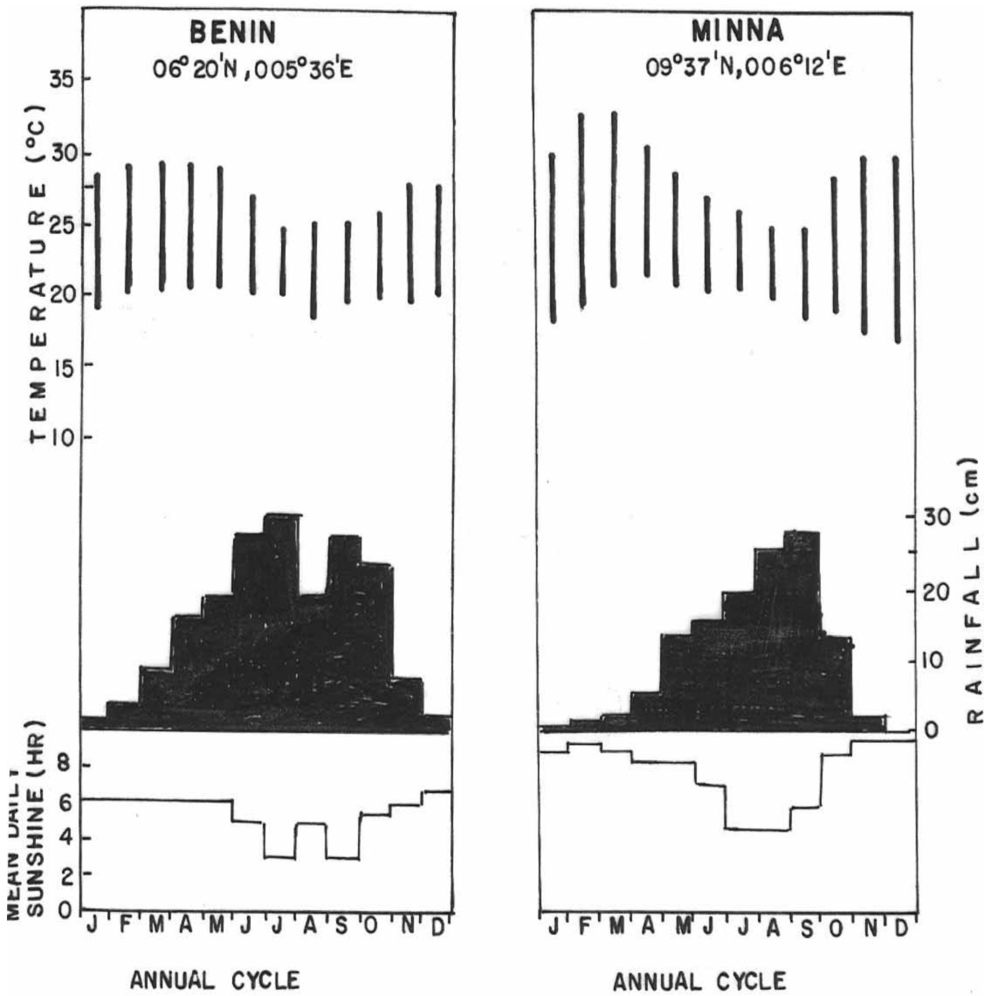

Figure 2. Climate diagram of Benin (forest-zone) and Minna (savanna zone).

2.3. *Chemical analyses of samples*

The standard methods (photometric, colorimetric and titrimetric methods) were carried out directly on unfiltered water for the chemical analysis of samples collected in FCT and the Benin-Owena Basin. Dissolved oxygen (DO) was immediately fixed after collection and determined later in the field base by Winkler's titrimetric method [23]. Samples for biochemical oxygen demand (BOD_5) were collected for DO and incubated in the dark for five days after which they were fixed and analysed. Hydrogen ion activity (expressed in pH scale) was also measured in the field immediately after sample collection with a Lovibond pH comparator using an appropriate disc and indicator solution. All other analyses were carried out in the laboratory within the holding time of the respective parameters involved [24].

The specific conductance (electrolytic conductivity) of water was measured using a conductivity meter (expressed in micro Siemens/cm at 25 °C). Total organic carbon was determined by chromic acid oxidation method [25] while chloride was determined using a calibrated automatic chloride titrator (the Marius chloro-o-counter). The two divalent major cations (calcium and magnesium) were determined titrimetrically (Ca^{++} separately and Ca^{++} and Mg^{++} jointly) according to Golterman et al. [25] using a 0.02M sodium versanate, i.e. disodium ethylene diamine tetra acetate (Na_2 EDTA) as titrant. The major monovalent cations (sodium and potassium) were each analysed using a flame emission photometer.

Total alkalinity was estimated titrimetrically using a standard dilute sulphuric acid (0.02N) and mixed methyl red-bromocresol green indicator [26]. Colorimetric methods were used for sulphate (by barium chloride), nitrate (by phenodisulphonic acid method), reactive silicate (by molybdisilicate method), ortho-phosphate (using stannous chloride as reductant for orthophosphate) and soluble iron (using Thioglycolic acid method), all according to the standard methods of APHA et al. [26]. The most abundant salts in the different water sources were estimated from the mass concentrations of the major anions and cations according to Holden [27] while dissolved acids and bases were calculated from their mean equivalent concentrations by the method of Kemp [28].

3. Results

3.1. *Total mineral content (conductivity) and pH of forest and savanna waters*

The frequency distribution of water pH displayed a different pattern in the forests and the savanna (Figure 3a). In the savanna, pH showed a normal distribution with a single peak around the neutral pH values of 6.90–7.05 while in the forests, two modes were observed: one in the acidic range (6.00–6.25) and the other (the lower peak) in the moderate alkaline range (7.10–7.25). The overall mean pH value (6.72 ± 0.58) reported in the forest waters is significantly different to the value (7.11 ± 0.33) for the savanna zone ($p < 0.001$). In terms of milliequivalent weight values ($meql^{-1}$), the overall mean value of free hydrogen ions activity in the forest waters was about 2.5 times higher than that of savanna waters. The 34% of the total pH values of forest waters was below 6.45 whereas for the savanna waters only 2%.

The frequency distribution of water conductivity was comparable to the pattern observed for water pH in the two investigated zones. The savanna water conductivity showed a normal distribution whereas the forest waters displayed more than one peak (Figure 3b). However, the overall mean value for the savanna (66.4 ± 45.4 $microScm^{-1}$) was not significantly different from that reported in the forest waters (67.5 ± 22.0 micro Scm^{-1}; $p > 0.05$). In both vegetation zones, the annual cycle of pH and conductivity showed that the two maxima coincided with the peak of the dry season while the minor value occurred at the peak of the rainy season. Over the observed range of pH values, forest waters were generally more saline than savanna waters even for the same pH values (Figure 4). There was a very highly significant difference between the slopes of the two regression lines in Figure 4 ($t = 33.7$, $p < 0.001$) confirming that the relationship between the two parameters (pH and conductivity) was significantly different in the two vegetation zones.

3.2. *Dissolved oxygen, BOD, plant nutrients and organic carbon contents of waters*

The concentration of dissolved oxygen varied between 1.1 and 11.0 mgl^{-1} in the forest waters and between 0.8 and 16.0 mgl^{-1} in the savanna waters. The mean values were not significantly different in the two zones although was slightly higher in savanna than in forest waters ($p > 0.05$). The mean values correspond roughly to 93% and 72% oxygen saturation respectively. Many reaches of the savanna waters (especially along the upper reaches and falls on R. Gurara) were over-saturated with dissolved oxygen most of the time.

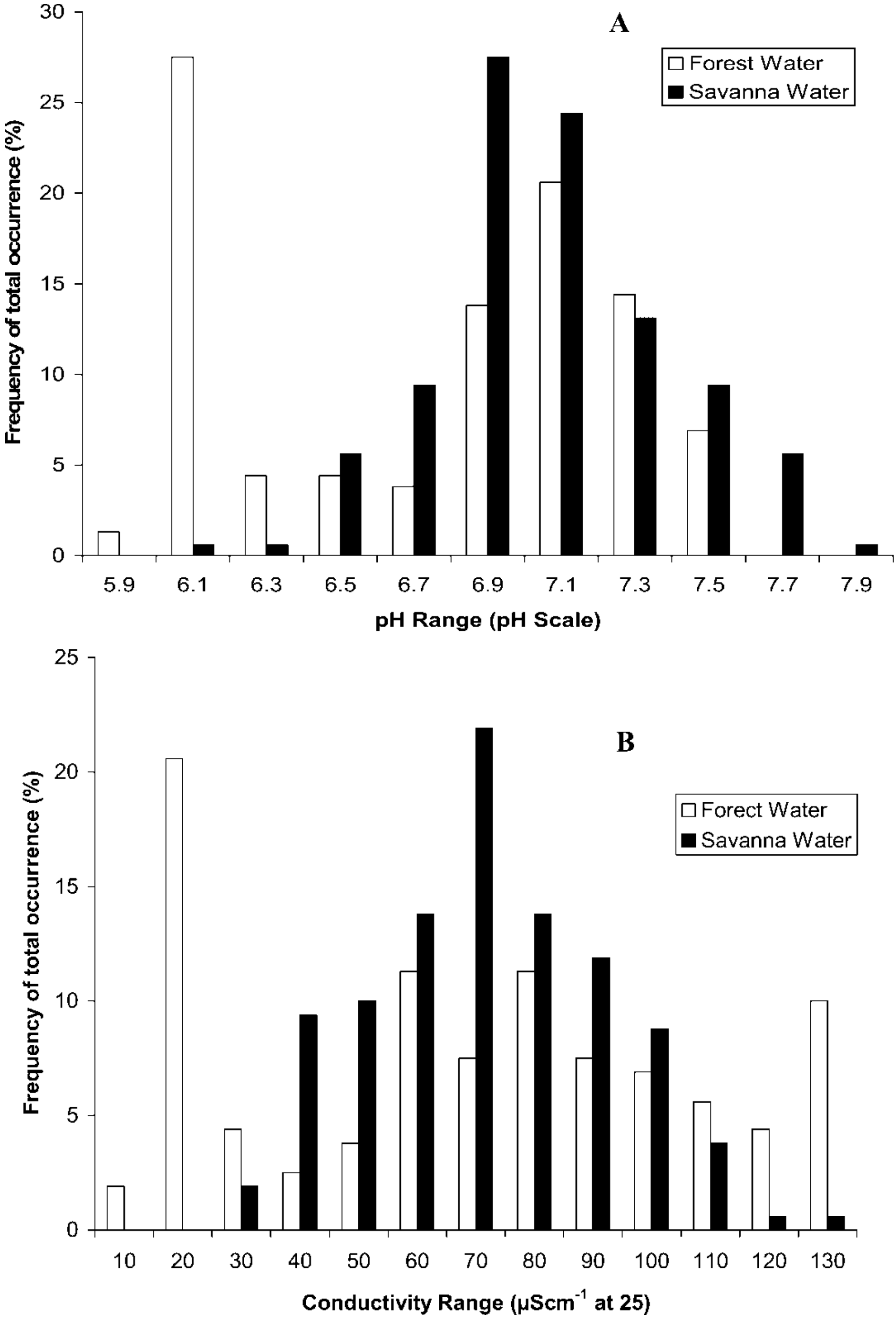

Figure 3. Frequency distribution pattern of water pH and conductivity in the forest and savanna zones of Nigeria.

The values of BOD_5 were generally below 8 mgO_2l^{-1} with the mean value for savanna waters being slightly higher ($p > 0.05$) than that for forest waters. About one half of the total values were less 2 mgO_2l^{-1} (i.e. clean water), about 40% ranged between 2–5 mgO_2l^{-1}(fairly clean water) and only 12% of the values were higher than 5 mgO_2l^{-1}, i.e. water of doubtful purity, according

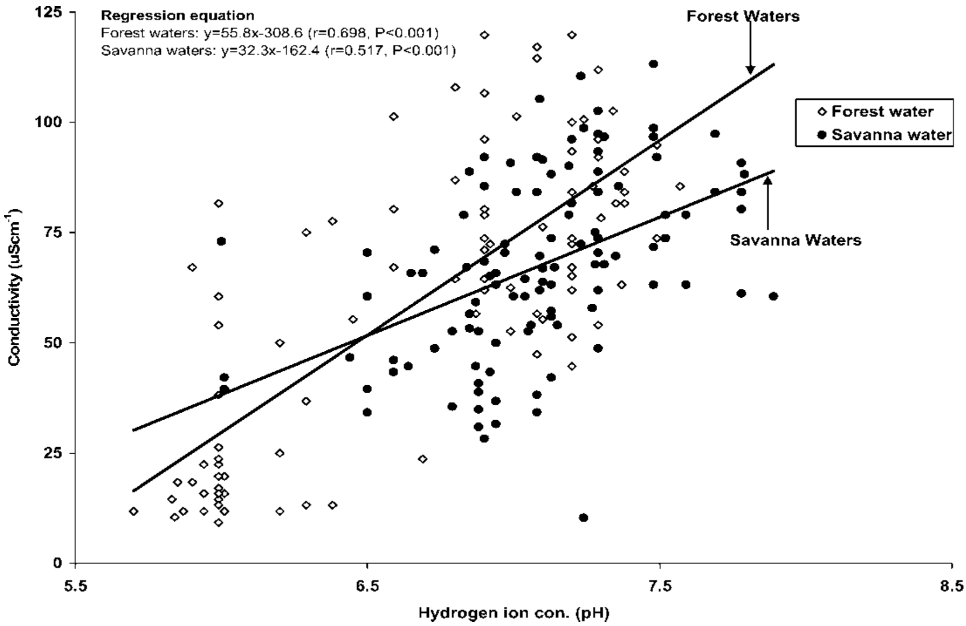

Figure 4. Comparison of the Regression of water conductivity at different pH values in the forest and savanna zones, respectively.

Table 1. The chemical composition of rivers and streams in Benin-Owena River Basin (forest zone) and FCT (savanna zone) of Nigeria.

		Benin-Owena Basin (forest) waters			FCT (savanna) waters			Student
Chemical parameter	unit	Range	Mean	SD	Range	Mean	SD	t value
Hydrogen ion activity	pH	5.60–8.05	6.7	0.61	6.5–8.00	7.1	0.3	−6.5***
Conductivity (K_{25})	μScm^{-1}	10.0–245	66.4	45.4	27.0–180.0	67.7	22.3	−0.3
Total alkalinity, $CaCO_3$	mgl^{-1}	3.0–214.0	25.8	24.9	13.5–83.0	35.1	12.7	−4.0***
Chloride, Cl^-	mgl^{-1}	0.0–64.4	5.6	6.6	0.5–1.4	1.0	0.1	7.2***
Sulphate, SO_4^{2-}	mgl^{-1}	0.0–5.8	1.6	2.1	0.0–7.2	0.9	1.2	0.5
Calcium, Ca^{2+}	mgl^{-1}	0.2–9.8	3.1	2.4	1.9–16.8	6.8	2.6	−10.0***
Magnesium Mg^{2+}	mgl^{-1}	0.1–3.3	1.1	1.0	0.3–16.5	3.7	4.4	−5.9***
Sodium, Na^+	mgl^{-1}	0.0–22.5	4.6	3.2	1.8–18.4	5.4	2.4	−2.1*
Potassium, K^+	mgl^{-1}	0.0–19.6	3.5	5.5	1.1–7.5	2.4	1.1	−2.1*
Dissolved Oxygen, DO	mgl^{-1}	1.1–11.0	6.3	2.0	0.8–16.0	7.4	1.5	−0.6
$B.O.D_5$, O_2	mgl^{-1}	0–6.4	2.1	1.6	0.0–7.8	2.3	1.9	0.5
Organic carbon	mgl^{-1}	0.0–3.9	0.9	0.5	0.0–2.9	0.6	0.6	2.2*
Silica, SiO_2	mgl^{-1}	0.0–32.0	6.7	5.0	1.2–25.1	9.7	4.3	−5.6***
Nitrate, NO_3^-	ugl^{-1}	0.0–143	45	24.0	23–552	238	151	14.3***
Phosphate, PO_4^{3-}	ugl^{-1}	0–48	9	10.0	0–288	39	43	−2.1*
Iron, Fe	ugl^{-1}	0–790	110	160.0	0–3,294	372	467	−6.12***

+ = Rainy season data only. ++ = Dry season data only.
SD, standard deviation of the mean.
$^*p \leq 0.05$; $^{**}p \leq 0.01$; $^{***}p \leq 0.001$
FCT, Federal Capital Territory of Nigeria.

to the classification of Hynes [2]. Organic carbon was significantly higher in the forest than in savanna waters (Table 1). The savanna waters were significantly richer in nitrate, phosphate, iron, and silica (in the ratio of 5.5:1, 4.5:1, 3.4:1 and 1.5:1 respectively) than the forest waters ($p < 0.05$).

3.3. *Major ionic contents (cations and anions) of waters*

The mean concentrations of chloride ion (Cl^-), potassium ion (K^+), and sulphate ion (SO_4^{2-}) were significantly higher in the forest than in the savanna waters (Table 1) whereas calcium and total alkalinity were higher in the savanna than in the forest waters. Although the levels of sodium in water from the two vegetation zones were comparable, the range was slightly higher in the forest while the mean value was higher in the savanna ($p > 0.05$).

Table 2 summarises the data of the forest while Table 3 reports data on Guinea savanna and Sahel savanna water in lakes, including the Chad area [29]. The analyses and comparison between savanna and forest waters showed that intrazonal waters were different (Table 1). The result of

Table 2. The chemical composition of rivers and streams from mangrove forest, freshwater forest and rain forest in Benin Owena River Basin, Nigeria.

	Forest waters							
	Mangrove forest (I)		Rain forest (II)		Freshwater forest (III)		Student t−test	
Chemical parameter	Mean	SD	Mean	SD	Mean	SD	(I & III)	(II & III)
pH	7.28	0.09	6.91	2.88	5.95	0.22	23.7***	9.1***
Conductivity, K_{25} (μScm^{-1})	2241	744	83.11	21.36	15.2	2.4	74.9***	10.4***
Total Alkalinity, $CaCO_3$ (mgl^{-1})	54.5	12.9	28.86	8.21	4.96	1.29	8.1***	9.1***
Chloride Cl^- (mgl^{-1})	7230	23.4	5.69	5.2	3.44	3.46	12.8***	1.4
Sulphate SO_4^{2-} (mgl^{-1})	895	275.4	1.46	0.19	1.60	2.39	8.5***	0.2
Calcium Ca^{2+} (mgl^{-1})	135.6	59.3	2.27	0.96	0.56	0.30	10.2***	5.1***
Magnesium Mg^{2+} (mgl^{-1})	496	164.8	0.79	0.58	0.35	0.30	14.5***	1.8
Sodium Na^+ (mgl^{-1})	4161.7	1282	4.57	1.20	0.99	0.76	8.8***	9.4***
Potassium K^+ ($mglL^{-1}$)	137	45.3	3.79	1.63	0.77	0.46	3.7**	6.1***
Silica SiO_2 (mgl^{-1})	2.9	1.0	6.72	2.06	3.40	1.25	7.9***	4.9***
Phosphate PO_4^{3-} (ugl^{-1})	12.4	8.2	11.3	5.52	6.1	2.77	0.2	2.5*
Iron Fe (mgl^{-1})	0.06	0.09	0.01	0.10	0.10	0.09	2.0*	0.5
Nitrate NO_3^- (mgl^{-1})	0.22	0.24	0.04	0.10	0.48	0.10	7.2***	0.6
Dissolved Oxygen O_2 (mgl^{-1})	6.34	0.94	6.65	1.10	5.57	1.33	1.0	2.9**
Organic carbon (mgl^{-1})	1.04	0.75	0.93	0.34	0.73	0.22	1.0	1.7

*$p \leq 0.05$);**$p \leq 0.01$; ***$p \leq 0.001$.

Table 3. The chemical composition of Nigerian Guinea Savanna and Sahel Savanna waters.

	Savanna waters				
	Guinea Savanna (I)		Sahel Savanna (II)		Student t-test
Parameter	Mean	SD	Mean	SD	(I & II)
pH	7.1	0.02	8.23	0.13	57.3***
Conductivity (K_{25}), μScm^{-1}	67.7	11.4	741.0	69.3	53.2***
Bicarbonate Alkalinity ($mgCaCO_3l^{-1}$)	35.1	5.6	466.0	45.0	60.33***
Carbonate Alkalinity ($mgCaCO_3l^{-1}$)	0.0	0.0	18.3	20.2	12.8***
Chloride Cl^- (mgl^{-1})	1.0	0.05	7.3	5.0	0.2
Sulphate SO_4^{2-} (mgl^{-1})	0.9	0.64	4.8	0.0	0.3
Calcium Ca^{2+} (mgl^{-1})	6.8	1.22	54.5	4.1	1.4
Magnesium Mg^{2+} (mgl^{-1})	3.7	2.28	24.3	3.4	12.6***
Sodium Na^+ (mgl^{-1})	5.4	1.27	66.1	7.4	1.5
Potassium, K^+ (mgl^{-1})	2.4	0.58	37.1	4.9	44.3***
Silica SiO_2 (mgl^{-1})	9.7	2.01	64.5	16.0	24.1***

***$p \leq 0.001$. SD, standard deviation of the mean.

the Student's t-test show that the concentrations of four of the seven major ions considered ($CO_3^{2-} + HCO_3^-$, Ca^{2+}, Na^+, K^+) were significantly higher ($p < 0.05$) in the rainforest waters than in the freshwater swamp forest waters. For all the major ions, the mean concentrations in water from the mangrove forest were from 1 to 3 times higher than the corresponding values for water from the rain forest. Like the three forest types, the differences in the levels of water chloride (Cl^-) and sulphate (SO_4^-) were not significant in the two savanna types compared (Guinea savanna and Sahel savanna). The mean levels of sodium (Na^+) and calcium (Ca^{2+}) in the two savanna waters were not significantly different ($p > 0.05$) while the concentrations of total alkalinity ($HCO_3 + CO_3^{2-}$), magnesium (Mg^{2+}) and potassium (K^+) were significantly higher ($p < 0.001$) in the Sahel savanna.

The order of dominance of the respective anions to the sum of all the anions was the same for both the forest and the savanna waters, being $CO_3^{2-} > Cl^- > SO_4^{2-}$.The exception to this pattern was the mangrove forest in which the order was $Cl^- > SO_4^{2-} > CO_3^{2-}$ just like the sea. The mean equivalent proportion of magnesium to total cations in the savanna was generally higher than that of the forest water. In contrast, the mean sum of the monovalent cations (Na^++ K^+) in the forest waters was ca 2 times higher than in the savanna waters. On the whole, the cationic order of dominance was $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ in the forest and $Ca^{2+} > Mg^{2+} > Na^+ > K^+$in the savanna waters.

3.4. *Probable salts, dissolved acids and base contents of waters*

With regard to probable salt contents (see Table 4) the investigated waters can be classified into two of the three potential types of world waters: the chlorided waters (comprising mangrove swamp

Table 4. The mean probable salt composition and dissolved acids and bases of rivers and streams in diffrerent forest and savanna vegetation zones of Nigeria.

		Forest zone			Savanna zone	
Salt/Acid/Base	Parameter	MS	FWS	Rain	Guinea	Sahel
	Total salts, TS (mgl^{-1})	13,089	13.5	41.4	42.5	550
Probable salts	$CaCO_3$ (% TS)	0.4	14.1	24.9	40.0	30.0
	Ca_2SO_4 (% TS)	3.0	0.0	0.0	0.0	0.0
	$MgCO_3$ (% TS)	0.0	13.3	10.0	30.1	18.6
	$MgSO_4$ (% TS)	6.0	0.0	0.0	0.0	0.0
	$MgCl_2$ (% TS)	10.1	0.0	0.0	0.0	0.0
	Na_2CO_3 (% TS)	0.0	0.0	29.7	7.5	33.8
	Na_2SO_4 (% TS)	0.0	17.5	3.5	3.1	1.1
	NaCl (% TS)	79.5	41.5	19.8	3.9	1.6
	Na_2NO_3 (% TS)	0.0	0.0	0.0	0.6	0.0
	K_2CO_3(% TS)	0.0	0.0	12.1	0.0	14.8
	KCl (% TS)	0.0	13.8	0.0	0.0	0.0
	Other salts (% TS)	1.0	0.7	0.0	14.8	0.0
	Total carbonate salts (% TS)	0.4	27.5	76.7	77.6	97.3
	Total chloride salts (% TS)	89.6	55.3	19.8	3.9	1.6
	Total sulphate salts (%TS)	9.0	17.5	3.5	3.1	1.1
	Total Ions, TI (mM)	422.7	0.39	1.31	1.36	15.07
Dissolved acids/bases	Ca $(OH)_2$ (% TI)	0.8	4.9	6.5	12.5	9.0
	Mg $(OH)_2$(% TI)	4.8	5.7	3.0	11.3	6.6
	NaOH (% TI)	42.8	14.3	16.8	17.3	19.1
	KOH (% TI)	0.8	5.7	5.3	4.4	6.3
	H_2CO_3(% TI)	0.4	26.8	49.5	51.7	57.2
	HCl (% TI)	48.2	38.2	17.7	2.1	1.3
	H_2SO_4(% TI)	2.2	4.4	1.2	0.92	0.5

FWS, Freshwater swamp; MS, Mangrove swamp.

Table 5. Mean seasonal variations in the chemical composition (0 ± SD) of Nigerian forest and savanna inland waters.

		Rain Forest waters				Guinea Savanna waters			
		Rainy season		Dry season		Rainy season		Dry season	
Chemical parameter	Unit	Early	Late	Early	Late	Early	Late	Early	Late
Hydrogen ion con.	pH	6.5 ± 0.6	6.8 ± 0.6	6.8 ± 0.6	6.9 ± 0.5	7.2 ± 0.3	6.9 ± 0.2	7.1 ± 0.2	7.3 ± 0.3
Conductivity 25^0C	μScm^{-1}	53.3 ± 32.2	64.1 ± 42.2	47.6 ± 39.1	75.4 ± 34.3	62.6 ± 20.4	54.7 ± 17.0	69.1 ± 15.1	92.6 ± 31.2
Total dissolved solids*	mgl^{-1}	39 ± 8	41 ± 9	42 ± 12	45 ± 12	48 ± 12	41 ± 7	59 ± 6	61 ± 7
Dissolved Oxygen, DO	mgl^{-1}	5.9 ± 2.0	6.0 ± 2.1	5.9 ± 1.9	6.2 ± 2.0	6.8 ± 0.9	7.5 ± 0.9	7.9 ± 2.9	6.9 ± 1.1
DO saturation	%	73 ± 5	74 ± 4	73 ± 4	76 ± 7	87 ± 2	96 ± 8	100 ± 1	88 ± 4
B.O.D.$_5$, O_2	mgl^{-1}	2.3 ± 1.3	2.0 ± 6.7	2.4 ± 0.9	2.1 ± 1.6	1.7 ± 1.4	1.7 ± 1.1	2.5 ± 1.1	2.3 ± 1.8
Total Alkalinity, $CaCO_3^-$	mgl^{-1}	24.9 ± 13.4	23.9 ± 17.2	25.9 ± 21.9	27.5 ± 25.0	35.4 ± 10.8	25.8 ± 7.1	33.6 ± 8.2	38.1 ± 15.2
Chloride, Cl^-	mgl^{-1}	4.9 ± 1.6	7.0 ± 3.7	5.0 ± 4.6	6.1 ± 7.2	1.0 ± 0.0	0.9 ± 0.1	1.0 ± 0.0	1.1 ± 0.1
Sulphate, SO_4^{2-}	mgl^{-1}	1.8 ± 1.9	1.6 ± 2.1	2.1 ± 0.9	2.4 ± 1.2	0.9 ± 1.2	0.7 ± 1.2	0.8 ± 1.6	1.1 ± 1.0
Calcium, Ca^{2+}	mgl^{-1}	3.1 ± 2.3	2.7 ± 2.9	2.7 ± 1.9	3.3 ± 2.4	5.3 ± 1.5	5.1 ± 1.8	6.2 ± 1.3	9.4 ± 3.4
Magnesium, Mg^{2+}	mgl^{-1}	1.4 ± 0.6	1.1 ± 0.8	1.0 ± 0.6	1.2 ± 1.3	2.8 ± 1.7	3.7 ± 3.7	3.9 ± 3.7	4.8 ± 2.0
Sodium , Na^+	mgl^{-1}	4.3 ± 2.4	3.6 ± 3.0	3.7 ± 3.8	7.0 ± 7.4	3.7 ± 0.9	4.5 ± 1.6	7.9 ± 4.0	5.4 ± 1.4
Potassium, K^+	mgl^{-1}	5.9 ± 4.2	2.6 ± 2.3	1.8 ± 2.0	2.8 ± 2.5	3.0 ± 0.6	2.1 ± 0.6	1.5 ± 0.4	5.0 ± 7.9
Organic carbon, OC	mgl^{-1}	0.8 ± 0.2	1.0 ± 1.1	1.3 ± 0.8	0.5 ± 0.4	0.5 ± 0.4	1.7 ± 0.8	0.2 ± 0.2	0.6 ± 0.3
Silica, SiO_2	mgl^{-1}	1.4 ± 0.9	7.6 ± 4.2	5.5 ± 3.7	7.5 ± 2.5	8.8 ± 2.3	6.3 ± 2.9	16.5 ± 3.7	10.2 ± 3.8
Nitrate NO_3^-	ugl^{-1}	62 ± 19	58 ± 21	44 ± 26	30 ± 9	168 ± 78	208 ± 93	503 ± 108	278 ± 174
Phosphate, PO_4^{3-}	ugl^{-1}	4 ± 6	15 ± 11	7 ± 11	9 ± 9	25 ± 21	47 ± 38	40 ± 10	55 ± 78
Iron, Fe	ugl^{-1}	100 ± 19	150 ± 90	70 ± 60	120 ± 40	242 ± 100	624 ± 308	96 ± 65	431 ± 247

*Calculated value; n.d., no data.

forest water, and freshwater swamp forest water) and carbonated waters (including rainforest water, Guinea savanna water and Sahel savanna water). The probable salt content of the mangrove forest water was only 13.1 parts per thousand (i.e. about one third the mean salinity of the sea). Although NaCl was still the dominant salt in the freshwater forest waters, over one quarter of the salts also comprised the carbonate salts of calcium and magnesium. It was also relatively richer in sulphate salts than the mangrove forest waters.

The concentrations of chloride and sulphate salts steadily decreased from the rainforest through guinea savanna to Sahel savanna waters while that of carbonate salts increased (Table 4). The classification of the waters based on the dissolved acids and bases was strictly related with that of their salt composition (Table 4). Hydrochloric acid (HCl) was dominant in the mangrove and freshwater forest waters whereas carbonic acid (H_2CO_3) was dominant in the rain forest and the savanna waters.

3.5. *Seasonal variation in chemical parameters of forest and savanna waters*

The seasonal variation of the chemical composition of water collected in the two major vegetation zones is reported in Table 5. Seasonal variation was obvious and more pronounced in savanna waters particularly among the inorganic parameters than in forest waters. In most cases, the lowest annual values were recorded during the late rainy season while the highest values were recorded during the late dry season. In both vegetation zones, the seasonal pattern of dissolved oxygen, plant nutrients and organic carbon were different to the trend observed for the inorganic parameters. Their highest values were recorded mostly during the late rainy season or the early dry season. The range was 0.5–0.99, (mean value: 0.70 ± 0.30) for forest during the late dry–late rainy season and was 1.17–1.62 (mean value: 1.43 ± 0.20) for savanna waters. The mean ratio was about 2 times higher in the savanna than in the forest zone. The corresponding values for pH, conductivity and the major ions were: 0.8–1.94, 1.23 ± 0.30 and 1.11–1.41, 1.50 ± 0.49 for forest and savanna waters respectively. For dissolved oxygen and organic carbon, the ratio was lower in the savanna than in the forest waters.

4. Discussion

The present work suggests that the composition of lotic waters in the two major vegetation zones in Nigeria (i.e. the forest and savanna zones) is significantly different. These differences are mainly due to (i) the higher levels of acidity (or lower pH values) and organic carbon in forest waters than in the savanna waters, (ii) the higher contents of total alkalinity, base metals, dissolved oxygen, nutrient compounds (N, P, Si and Fe), and (iii) to the evident seasonal variability of all these parameters in savanna waters than forest waters (Tables 1–3).

The higher content of organic carbon in the typical Nigerian forest water than in the savanna water is comparable to the values reported in other areas, including West Africa [33]. In the forest, organic matter (i.e. humus) is constantly formed (from the decomposition of litter and animal sources) and, among the several factors involved in its decomposition, the rainfall regime plays a key role, This process is rather rapid at the beginning and end of the wet season when it is wetted and dried out several times in fairly quick succession [31,32]. This has been reported also in Nigeria [33]. During humus formation in the forest, the materials are characterised by a dark colour which, when drained into waterways, colours waters all over the world including the black forest waters of the Niger Delta basin of Nigeria [34]. On the other hand, in the typical Nigerian savanna, litter is less abundant (compared to the forest zone) and the soil can be bare or greatly devoid of organic matter (usually due to the yearly bush burning and fluvial erosion) which could be leached into waterways.

However, savanna soils being more porous and with greater surface area for bacterial action than forest soils are characterised by higher decomposition of organic matter and greater release of associated nutrient compounds, notably those of nitrogen and phosphorus than forest soils. Again the proportion of mineralised organic matter products from terrestrial ecosystem through drainage into aquatic ecosystems is usually less in the forest than in the savanna zone [35]. Thus only a small proportion of mineralised products are lost from the forest by leaching and runoff. Hence waters bearing the highest average proportion of nutrients such as nitrogen compounds are in savanna regions. In the case of nitrogen (notably nitrate which is averagely about five times higher in the savanna than the forest, Table 1) the relatively high levels in the savanna can also be attributed to contribution from leguminous plants which occur widely (comprising about 284 species) in the Nigerian savanna [36]. Based on their high incidence of nodulation, it is generally believed that litter from legumes is richer in nitrogen than those of other plants.

The higher content of silica in savanna waters (where the beds are mostly of sand) than in the forest water (where the beds are in most cases made up of fine mud and/or decaying vegetal materials) is expected. The selective weathering of silica is enhanced by the relatively high temperatures in the Nigerian savanna. The mean monthly minimum and maximum temperature here are usually 13–21 °C and 35–41 °C respectively [30] and results are more variable than in the forest zone. The moderating effects of savanna on climate are very slight when compared with the forest vegetation. This and the associated greater range in temperatures are most probably responsible for the more pronounced seasonal variation in the hydrochemical conditions of savanna waters than the forest waters. Forest waters, especially the swamps, are known for their high acidity, the acidity being partly due to free carbon dioxide (CO_2) and organic acids which are usually plentiful. Low oxygen here is usually due to rapid removal through the mineralisation of organic matter and poor photosynthetic production owing to vegetal shading. On the other hand, there is high aeration in the Nigerian savanna due to its considerable relief (notably the incidence of water falls) and the slightly lower water salinity.

The typical Nigerian savanna water is more alkaline (with higher pH) than the forest water probably due to its better aeration and lower content of organic matter. Organic matter under forest generally has a much lower content of bases (notably calcium carbonate) than those under savanna. In contrast, grasses absorb, in general, large amount of bases and likewise return them to surface soil from where they are easily leached into waterways. In general, the higher content of bases in savanna soils than in the forest soil can also be attributed to the regular annual burning in the savanna. Regular annual burning helps to raise the pH of soil and increase the concentrations of cation exchange capacity (CEC), available P, and base saturation in addition to increasing the population the leguminous plants in the savanna [37,38].

5. Conclusions

There are significant differences in the chemical composition of waterbodies in the forest and savanna zones. These differences occur in water chemical reaction (pH), ionic order of dominance, potential salt contents, organic matter and a number of plant nutrient compounds (NO_3^-, PO_4^{3-}, SiO_2). The differences can be explained in terms of the prevailing biogeochemical processes and interactions in the two zones, notably with regard to soil (composition and structure), vegetation (taxa composition and shading), climate (regime and runoff) and human activities (bush burning) in the investigated zones.

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Appendix 1. Major Nigerian rivers and the location of the investigated rivers and streams in Benin-Owena River Basin and the Federal Capital Territory of Nigeria.

Location no.	Rivers of Nigeria (Figure 1A)	Rivers in Benin-Owena Basin (Figure 1B)	Rivers in Federal Capital Territory (Figure 1C)
1.	R. Hadejia	R. Oni on Ore-Shagamu Road; 6^0 44′ N, $4^0$24′ E	R. Gurara at the Falls; $9^0$19N′ 70 19′E
2.	R. Katagun	R. Oni at Okeigho; 7^0 11′N, 4^0 24′E	R. Gurara at Izom; $9^0$14′N, 7^0 07′E
3.	R. Komadugu Gana	R. Ofara at Atijere; 6^0 44′N, 4^0 28′E	R. Tapa at Daku Cross; 9^0 20′N, 7^0 12′E
4.	R. Ngadda	R. Ominla on Benin- Ore Road; 6^0 44′N, $4^0$41′E	R. Usman at Gwagwa; 9^0 05′N, 7^0 18′E
5.	R. Gongola	R. Ominla on Ore-Okitipupa Road; 6^0 45′N, 4^0 46′E	R. Usman at Gwagwa-lada; 8^0 56′N, 7^0 05′E
6.	R. Benue	R. Oluwa on Ore- Ode Aye Road; 6^0 37′N, $4^0$47′E	R. Usman at Tsibiri; 8^0 54′N, 7^0 02′E
7.	R. Pai	R. Oluwa on Ore-Shagamu Road; 6^0 45N, 4^0 46′E	R. Mangol at Dafa ; 8^0 49′N, 7^0 02′E
8.	R. Donga	R. Owena at Owena; 7^0 11′N, 5^0 01′E	R. Bobo at Kwaita; 8^0 41′N, 6^0 57′E
9.	R. Mada	R. Otu on Benin-Ore Road; 6^0 45′N, 4^0 57′E	R. Iku at Suleja Pottery; 9^0 12′N, 7^0 08′E
10.	R. Cross	R. Ofosu at Ofosu; 6^0 44′N, 5^0 09′E	R. Paa at Gwari Road; 9^0 15′N, 7^0 15′E
11.	R. Imo	R. Siluko at Siluko; 6^0 22′N, 5^0 11′E	R. Paa at Saboji; 9^0 00′N, 7^0 10′E
12.	R. Anambra	R. Omo at Ikole-Ekiti; 7^0 48′N, 5^0 31′E	R. Iku at Kofa; 9^0 15′N, 7^0 15′E
13.	Niger Delta	R. Ogbesse at Ogbesse; 7^0 48′N, 5^0 19′E	R. Guri at Rafin Paa; 9^0 00′N, 7^0 10′E
14.	R. Forcados	R. Ogbesse near Ikere-Ekiti; 7^0 28′N, 5^0 19′E	R. Jabi at Wuse; 9^0 04′N, 7^0 29′E
15.	R. Ose	R. Ogbesse on Akure-Owo Road; 7^0 16′N, 5^0 22′E	R. Tapa at Gwachipe; 9^0 16′N, 7^0 03′E
16.	R. Osun	R. Ero at Ido-Ekiti; 7^0 51′N, 5^0 11′E	R. Afarabukwoi on Suleja Road
17.	R. Ogun	R. Ero at Ikun-Akoko;7^0 24′N, 5^0 47′E	R. Gurara at Yewuni; 8^0 35′N, 6^0 53′E
18	R. Niger	R. Auga at Auga-Akoko; 7^0 33′N, 5^0 55′E	R. Illi at Etsche; 8^0 53′N, 7^0 11′E

(*continued*)

Appendix 1. Continued.

Location no.	Rivers of Nigeria (Figure 1A)	Rivers in Benin-Owena Basin (Figure 1B)	Rivers in Federal Capital Territory (Figure 1C)
19.	R. Sokoto	R. Ose at Imesin near Ode – Ekiti; 7^0 34′N, 5^0 35′N	R. Oke at Ruhu; 9^0 02′N, 7^0 16′E
20.	R. Rima	R. Ose near Ogbesse; 6^0 42′N, 5^0 33′E	R. Koko at Izom; 9^0 15′N, 7^0 07′E
21.	R. Zamfara	R. Ose near Sobe; 6^0 42′N, 5^0 23′E	
22.	R. Kaduna	R. Ose on Benin-Ore Road; 6^0 30′N, 5^0 29′E	
23.	R. Gurara	R. Ose at Ekenhuan; 6^0 11′N, 5^0 22′E	
24.		R. Ose at Gilligilli; 6^0 11′N, 5^0 23′E	
25.		R. Ossiomo at Abudu; 6^0 03′N, 5^0 23′E	
26.		R. Ossiomo at Abudu; 6^0 17′N, 6^0 03′E	
27.		R. Ikpoba at the Dam, Benin-City; 6^0 22′N, $5^0$39′E	
28.		R. Benin at Ajagbeodudu; 5^0 58′N, 5^0 33′E	
29.		R. Benin at Koko; 6^0 11′N, 5^0 28′E	
30.		R. Atakpo at Ibusa; 6^0 11′N, 5^0 56′E	
31.		R. Ethiope at Sapele; 5^0 55′N, 5^0 42′E	
32.		R. Ethiope at Aghalokpe; $5^0$45′N, 5^0 56′E	
33.		R. Edor at Ughelli; 5^0 28′N, 5^0 56′E	
34.		R. Warri at Efunrun	
35.		R. Adofi at Kwale; 6^0 01′N, 6^0 32′E	
36.		R. Ase at Asabase; 5^0 22′N, 5^0 19′E	
37.		R. Niger at Agenegbode; 7^0 06′N, 6^0 40′E	
38.		R. Niger at Asaba bridge; 6^0 12′N, 6^0 45′E	
39.		R. Niger at Aboh; 5^0 42′N, 6^0 31′E	