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Streamflow Variability in Ossiomo River Catchment and Implications for Basin-wide Water Resources Management

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Abstract

Time series analysis of streamflow data from gauges installed in the main rivers of the Ossiomo River catchment has been undertaken using the Australian Cooperative Research Centre for Catchment Hydrology's Time Series Analysis computer code. The results show that all the rivers are perennial, receive groundwater contribution all the year round throughout their entire lengths and that this groundwater contribution is on the average, responsible for more than 70 per cent of total flow. This large percentage contribution also modulates the response of the rivers to the higher flows in the wet season, and as such, mitigates flood risks. The results also show that there are tremendous groundwater reserves available for development in the Benin Formation that releases the groundwater to the rivers from only its upper layers. The Flow Duration Curve for the Ikhowan River, the smallest river with a gauge, shows that Q50 is on the average about 5.5 $m^3 s^{-1}$, and thus, has good potential for small hydropower development. Finally, while flow characteristics have been determined from the very short and patchy records that are available, they give an insight into the water resources potential of Ossiomo River catchment and could have application, in some respects, for other rivers that flow on the Benin Formation but are ungauged.

Key words: Base flow, streamflow analysis, climate change , Ossiomo River catchment, Benin Formation

Introduction

The understanding of long-term flow variability in river systems is crucial for the management of rivers in terms of quantity, water quality and overall water resources management. Flow variability is thus critical in climate change issues related to the occurrence of floods, reliability of dry weather flows for water supply, irrigation, power generation, aquifer recharge and environmental management of aquatic ecosystems.

In the wetter southern states of Nigeria, the occurrence of an abundance of streams and plentiful rainfall has over the years made it seem unnecessary to invest in water data collection systems. The occurrence of droughts in parts of the northern states in the seventies led to the establishment of stream gauging stations on many rivers, many of which have unfortunately been abandoned. However, climate change concerns and related occurrence of devastating floods have re- awakened the interest in streamflow data collection in all parts of the country. The Benin - Owena River Basin Development Authority initiated the collection of stream flow data in the Western Littoral Hydrologic Area of Nigeria in 1980 and some data has been collected since that time. The Ossiomo River catchment (ORC) falls within this area. Oteze (2011) has used data from the gauging station established on the Ikpoba River as input in the evaluation of water budgets for Benin City. Izinyon et al. (2011) have also used data from the same gauging station to undertake flood frequency analysis of the Ikpoba River. Akpoborie and Osula (1999) and Akpoborie (2011, 2012) performed time series analyses of the Ethiope and Adofi Rivers on the basis of data obtained from gauging systems established under the programme.

The purpose of the present study is to describe the flow characteristics of the rivers in the ORC (Figure 1) for which datasets are available in order to provide, for the first time, an insight into the hydrologic conditions of the river systems, and in the process, attempt to identify and make specific statements about water resources management in the watershed, including the prediction of potential impacts of climate change and adaptability.

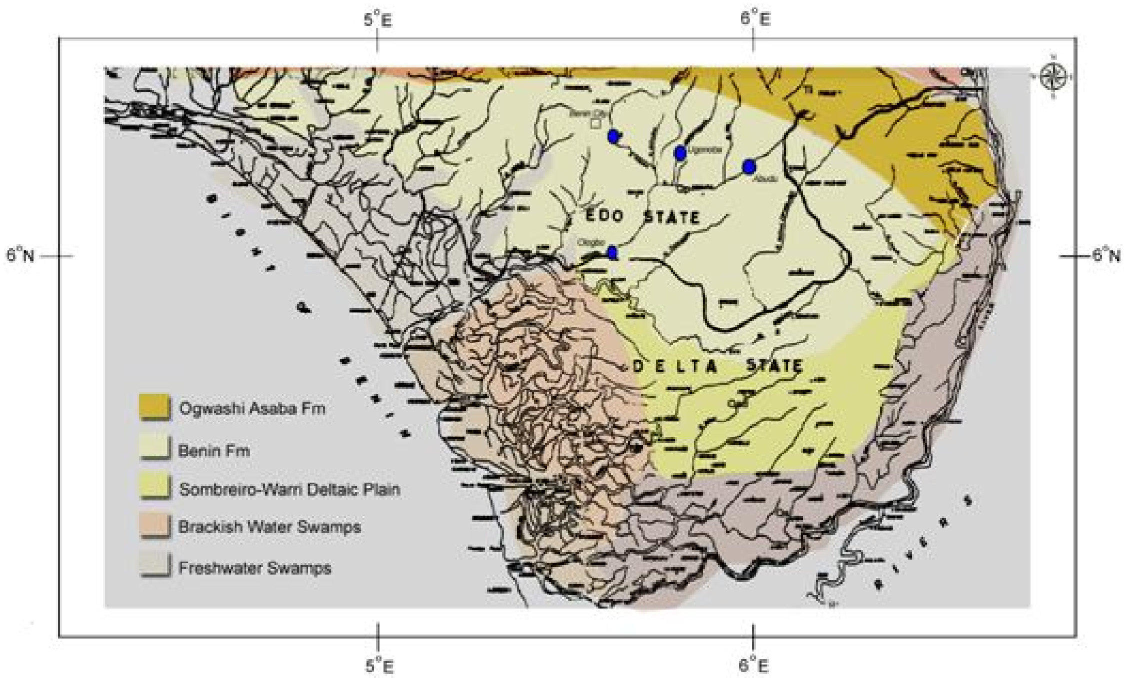

Figure 1: Location map of the Ossiomo River Catchment, drainage and geology of the western Niger Delta Basin. (Blue solid circles indicate the approximate location of gauging stations in the ORC).

Physiography and Climate

The Ossiomo River and its tributaries flow entirely on the Coastal Plain and indeed, the deep valley of the river separates the Coastal Plain from the Ishan Plateau in the north. The Coastal Plain itself is low lying, and slopes gently from about 125 m in the north to sea level westwards. It is drained by numerous north east to southwestwards flowing rivers, including the Ossiomo drainage system, all of which, except the Osse River, arise from the northern base of the Coastal Plain. These rivers are intercepted by the Ethiope River-Benin River system that flows westwards into the Atlantic, Figure, 1.

Typical tropical climatic conditions prevail in the ORC. Oteze (2011) reports that rainfall records from 104 years from Benin City show an annual rainfall range from a low of 1228 mm to a high of 3039 mm, with a mean of 2100 mm and a 15- year annual mean evapotranspiration of 1026 mm. Mean monthly distribution of rainfall from records at the Benin Airport from 1989 to 1994, and published by the Benin – Owena River Basin Authority, are shown in Figure 2. Temperatures are typically about 28^{0}C.

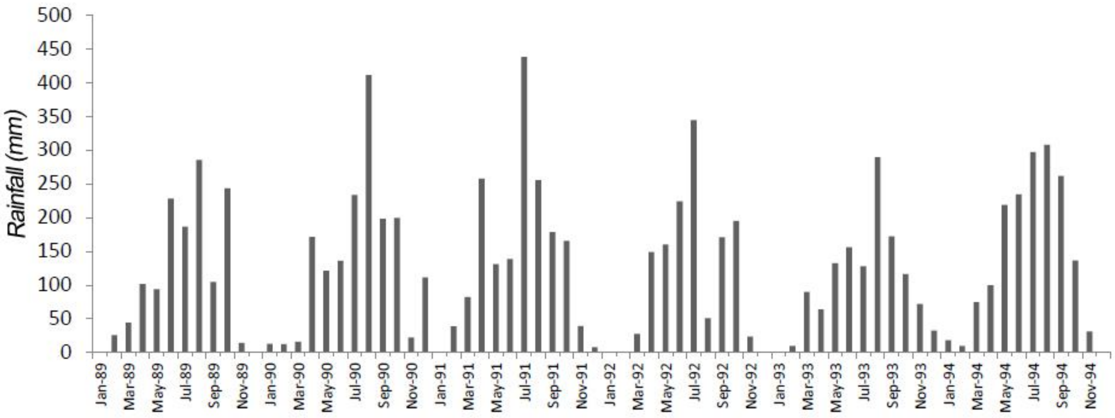

Figure 2: Mean monthly Rainfall at Benin City Airport (1989-1994)

Catchment Geology

The geological map of parts of the Niger Delta basin in which the ORC is located is shown in Figure 1. The Niger Delta, one of the most important petroleum provinces in the world, is much studied and detailed geological descriptions of its development may be found in Short and Stauble (1967) and Reijers (1996). Briefly, there is universal agreement that the Niger Delta Basin was formed as a result of an aulacogen type development that was triggered by the separation of the African and South American continents. The resulting trough has been filled by a series of deposits resulting from alternating episodes of marine transgressions, regressions and deltas, the present delta being the most recent. The trough is now filled by both marine and continental sediments ranging from Aptian age to Recent. The ORC is underlain entirely by the Benin Formation, the youngest of these deposits. This Formation occupies and forms the physiographic feature known as the Coastal Plain that bestrides the River Niger and coincides somewhat with the Niger Delta Basin (Nwajide, 2006). Short and Stauble (1967) have argued that the Coastal Plain, which is a seaward southwesterly sloping continuation of the Asaba - Ishan plateau, is the remnant of a pre-Pleistocene delta. The Benin Formation underlies and is masked westwards by the younger Holocene deposits of the Sombreiro-Warri Deltaic Plain. This plain in turn merges west and south with the Freshwater Swamps and Brackish water Swamps wetlands respectively that separate it from the sea. The Benin Formation is estimated to be about 2000 m thick and is a very prolific and heterogeneous aquifer. Porosity is reported to be about 30 per cent (Oteze, 2011) and tranmissivity has been estimated to range from about 350 m^2 per day (Akpoborie, 2011) to 30,000 m^2 per day (Oteze, 2011).

Catchment Characteristics

The Ossiomo River (Figure 3) arises from the base of the Ishan Plateau, and as is characteristic of most of the rivers in the Coastal Plain, flows southwards, first in a slightly northeast direction, then northwestwards just before Abudu town and consistently westwards till it joins the Ethiope-Benin River, west of Koko.

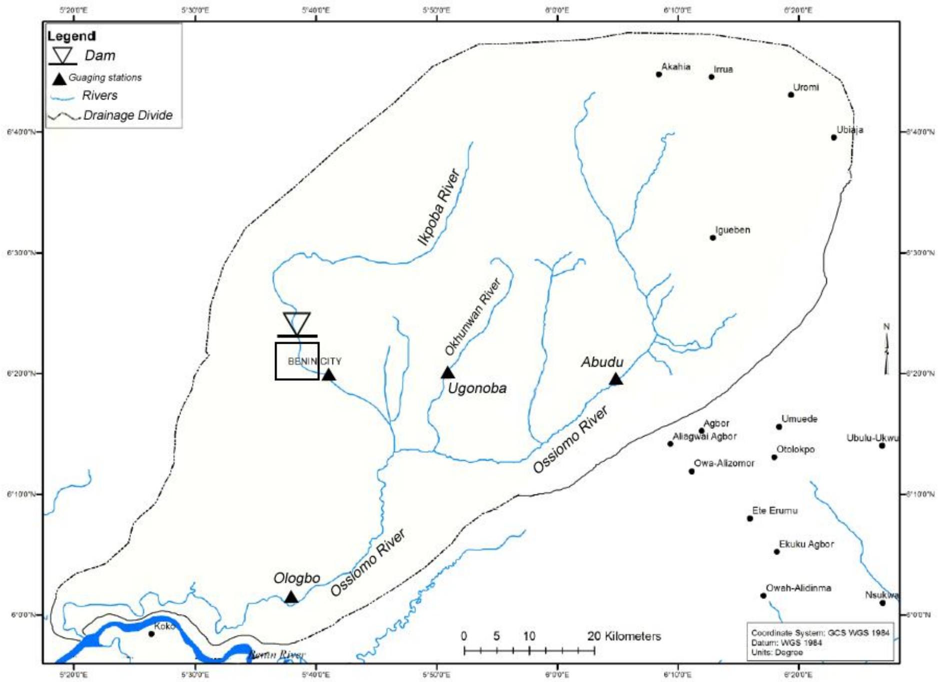

Figure 3: Drainage distribution in the Ossiomo River watershed and the various gauging stations

The Ikpoba River, which likewise drains the base of the Ishan Plateau, flows northwestwards and then swings slightly eastwards to join the main trunk of the Ossiomo River. The Okhuwan flows directly southwestwards to join the Ossiomo. The Ikpoba River flows through Benin City and a dam was constructed on it there in 1987 for water supply purposes. The 320 m long dam impounds up to 1.5 million cubic metres of water. The gauging station is about 5 km downstream of the dam.

The catchment is oval in shape and is uniformly underlain by the porous Benin Formation. This high porosity allows for high infiltration rates and associated recharge. This is also probably responsible for the low drainage density, as only first and second order streams exist in the catchment. The same characteristic is shown by the Ethiope River catchment, which shares a drainage divide with the ORC to the west and is also underlain by the Benin Formation (Akpoborie, 2012).

Methodology

Streamflow data for the analysis were obtained from the Hydrologic Year Books published by the Benin-Owena River Basin Development Authority (BORBDA) in several volumes (BORBDA, 1990, 1992, 1997, 2005, 2007). Baseflow separation techniques were then applied to process the data. Baseflow separation techniques are based on the fact that a hydrograph is a time series representation of streamflow measured at some point in a stream and as such is a representation of the different sources that contribute to the flow of water in the stream. These components include quickflow (runoff, channel precipitation, interflow) and baseflow, which is the steady discharge of groundwater into the stream. For rivers that are underlain by water table aquifers, groundwater discharge is the main contributor to baseflow provided the aquifer is adequately recharged and possesses reasonable transmission properties that enhance the release of groundwater. Hydrograph analysis based on the original ideas of Horton (1933), Barnes (1939) and Meyboom (1961) among others, is an attempt to quantify these components. While manual hydrograph separation into various components is feasible and has been used in several studies in Nigeria, for example, by Oteze (1989, 2011) and Offodile (1992), the procedure is tedious, repetitive and subjective. The availability of several computer codes (for example, FREND, 1989; Sloto and Crouse, 1996) for hydrograph analysis has greatly simplified the rapid processing of large data sets.

The Time Series Analysis Module (TSA) of the River Analysis Package (Marsh, 2004) developed by the Australian Cooperative Research Centre for Catchment Hydrology and based on a recursive digital filter used in routine signal analysis and processing (Nathan and McMahon, 1990) was preferred over manual separation for analyzing the streamflow data in this study. This is because the technique is objective, repeatable and allows for the rapid processing of large amounts of data. The estimation of the Base Flow Index for a specified period of record in the technique is based on the general form of a single parameter filter (Brodie and Hostetler, Undated) as shown in Equation 1

$$q_{b(i)} = \frac{(1-BFI_{\max})aq_{b(i-1)} + (1-a)BFI_{\max}q_i}{1-aBFI_{\max}} \qquad (1)$$

where $q_{b(i)}$ is the baseflow at time step *i*, $q_{b(i-1)}$ is the baseflow at the previous time step *i-1*, q_i is the streamflow at time step *i*, a is the recession constant and BFI_{max} is the maximum value of the baseflow index that can be measured.

Each run of the model generates all the appropriate parameters that are required for baseflow and flood analysis, including Flow Duration Curves (FDC).

Streamflow Data

BORBDA installed staff gauges and automatic recorder units on each of the rivers in the ORC. These gauges and many others in the West Littoral Hydrologic Area of Nigeria were set up in 1980 by BORBDA in collaboration with the World Meteorological Organization (Osula, 2007). Characteristics of each station are shown in Table 1. Although the gauges were installed in 1980 and data gathering commenced almost immediately, raw data processing, storage and dissemination was a problem at BORBDA and it was not until ten years later in 1990 that BORBDA initiated the publication of Hydrological Yearbooks. Unfortunately, by that time, ten years of data had been lost. Furthermore, publication had continued till 2007 but without data for some stations as a result of which many gaps exist in the published data.

Table 1: Gauging station characteristics (Source: BORBDA, 1992).

River/Gauging Station	Coordinates	Effective Drainage Area (km^2)
Okhunwan/Ugonoba	6^0 19N; $5^0$51E	245.35
Ikpoba/Benin City	$6^0$21N; $5^0$39'E	922.00
Ossiomo/Abudu	$6^0$18N; $6^0$02'E	1230
Ossiomo/Ologbo	$6^0$03N; $5^0$40'E	3974

Results and Discussion

Streamflow data available for each gauging station were input into the TSA module of the River Analysis Package computer code to yield hydrographs that are identical with manual plots. Typical hydrographs for the three rivers for 1990 are shown in Figure 4. The hydrograph for the Ikpoba River, Figure 4 (c) is somewhat atypical, perhaps due to the fact that the river is impeded (regulated) by the dam. As is expected, all hydrographs exhibit similar characteristics, although there are some slight differences, which in the main, could be explained by the different sizes of the effective catchment areas upstream of each gauging station. As can be seen in Figure 2, the highest rains occur in July and August and the hydrographs indicate an almost immediate response to the heavy rains. Baseflow in all rivers, however, peaks in late September and October and in the case of the Ikpoba River (Figure 4), continues peaking way into late December. This delayed baseflow response is better observed in the composite multiple-year hydrographs drawn for each river in Figure 5. Furthermore, it may also be observed from all three composite hydrographs that groundwater contribution to flow in each river is continually increasing from year to year. Tables 2 and 3 contain the summary of the statistics of flow for the rivers and for which records are available.

Total annual flow is consistently largest at Ologbo with the least being recorded at Ugonoba on the Okhuwan River that has the smallest effective catchment area of all the rivers. It is interesting, however, that the dam seems to have very limited effect on the flow of the Ikpoba River.

Baseflow Indices show an interesting trend in the watershed. The Base Flow Index (BFI), the ratio of total baseflow to total flow for the period of record, ranges from a low of 0.62 at Abudu (1992) to a high of 0.94 (1990 and 1996) at Ologbo. Indeed, mean daily baseflow (MDBF) at Ologbo for the four-year period is 77.19 m^3/sec, which is consistently more than the total flow recorded for the smaller Okhuwan River at Ugonoba. This should expected, because all the tributaries contribute to the flow of the Ossiomo River at Ologbo and the associated effective drainage area is larger than that of the individual tributaries, as well as the sum of all the tributaries. The very high contribution of groundwater to flow results in modulated peak flows because groundwater flow rates are slow when compared to surface water movement and arrival times of groundwater at the stream channel are usually long after the cessation of rains, as shown in Figures 3 and 4.

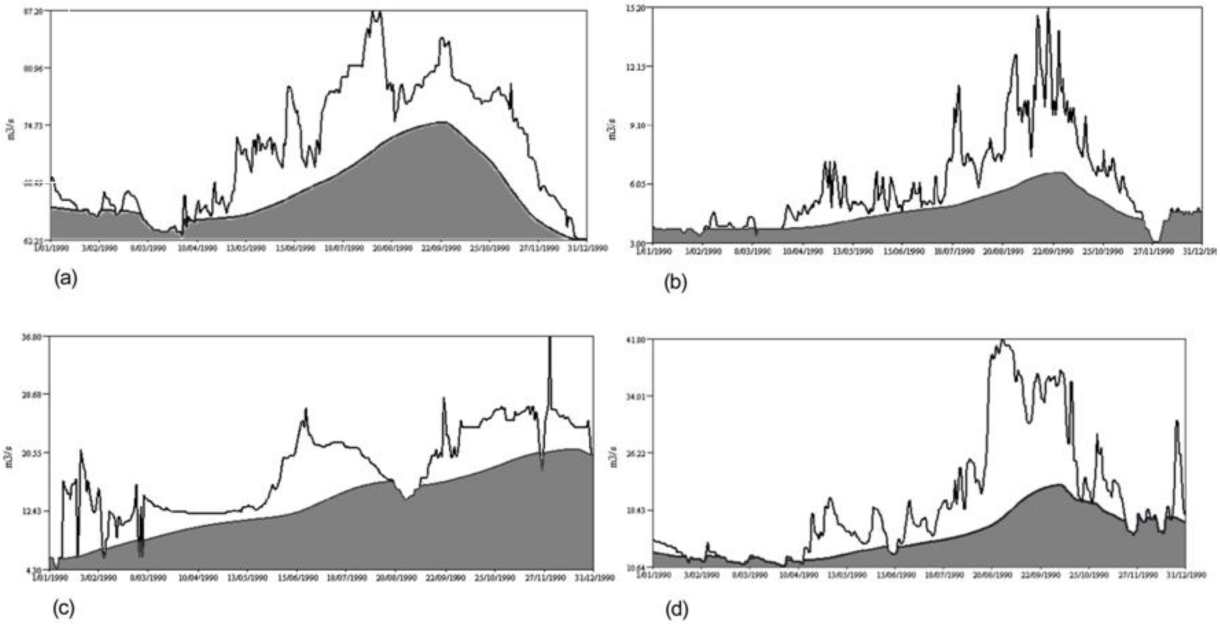

Figure 4: Hydrographs from the Ossiomo River Watershed in 1990: (a) Ossiomo at Ologbo (b) Okhuwan at Ugonoba (c) Ikpoba River at Benin City (d) Ossiomo at Abudu

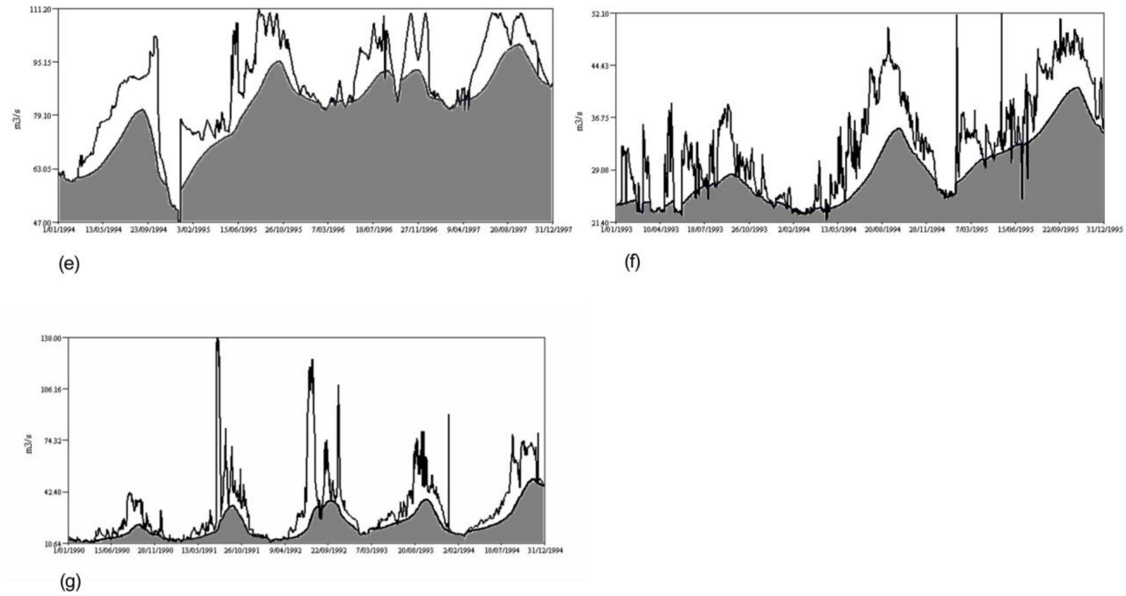

Figure 5: Composite hydrographs from the ORC: (e) Ossiomo at Ologbo, 1994 -1997; (f) Ikpoba River at Benin City, 1993-1995; (g) Ossiomo at Abudu, 1990-1994.

Table 2: Summary streamflow Statistics (1989 – 1995)

Year	Parameters	Rivers			
		Ossiomo (Abudu)	**Ikpoba**	**Okhuwan**	**Ossiomo (Ologbo)**
	Total Flow (x10^9)				2.519
	Minimum flow				63.75
	Maximum Flow				100.75
1989	Mean Daily Flow	{P}	{P}	{P}	79.88
	Std. Deviation				9.407
	Base Flow Index				0.92
	Mean Daily Base Flow				73.48
	Total Flow (x10^9)	0.608	0.56	0.186	2.274
	Minimum flow	10.64	4.3	3	62.25
	Maximum Flow	41.8	36.8	15.2	87.2
	Mean Daily Flow	19.4	17.84	5.882	72.02
1990	Std. Deviation	8.5			
	Flood Flow Index		0.25		
	Base Flow Index	0.75	0.75	0.77	0.94
	Mean Daily Base Flow	14.69	13.39	4.52	67.44
	Total Flow (x10^9)	0.888		0.231	
	Minimum flow	11.1		3.48	
	Maximum Flow	138		22.5	
1991	Mean Daily Flow	28.4	{P}	7.41	{NR}
	Std. Deviation	24.2			
	Flood Flow Index				
	Base Flow Index	0.63		0.72	
	Mean Daily Base Flow	17.5		5.35	
	Total Flow (x10^9)	1.093			
	Minimum flow	11.3			
	Maximum Flow	125			
1992	Mean Daily Flow	34.7	{P}	{P}	{NR}
	Std. Deviation	27.2			
	Base Flow Index	0.62			
	Mean Daily Base Flow	21.6			
	Total Flow (x10^9)	1.037	0.885		
	Minimum flow	15.12	22	5.14	
	Maximum Flow	90.7	38.8	14.74	
1993	Mean Daily Flow	32.9	28.19	8.26	
	Std. Deviation	15.4			{NR}
	Flood Flow Index		0.115		
	Base Flow Index	0.76	0.89	0.90	
	Mean Daily Base Flow	25.1	24.95	7.40	
	Total Flow (x10^9)	1.1709	1.538		2.336
	Minimum flow	14.2	21.4		47
	Maximum Flow	78.8	50		102.9
1994	Mean Daily Flow	37.5	31.6		74.07
	Std. Deviation	19.9		{NR}	
	Flood Flow Index		0.15		
	Base Flow Index	0.73	0.85		0.87
	Mean Daily Base Flow	27.3	26.85		64.22
	Total Flow (x10^9)		1.1867		2.8047
	Minimum flow		24.4		71.5
	Maximum Flow		52.1		111.2
1995	Mean Daily Flow		37.44		88.57
	Std. Deviation	{NR}		{NR}	
	Flood Flow Index		0.133		
	Base Flow Index		0.87		0.92
	Mean Daily Base Flow		32.72		81.70

Notes: Flow is in m^3/sec.; NR = No record; P = Partial record.

Table 3: Summary streamflow statistics (1996-2000)

Year	Parameters	Rivers			
		Ossiomo(Abudu)	Ikpoba	Okhuwan	Ossiomo (Ologbo)
1996	Total Flow ($x10^9$)				2.9416
	Minimum flow				80.25
	Maximum Flow				110
	Mean Daily Flow				92.71
	Std. Deviation	{NR}	{NR}	{NR}	
	Flood Flow Index				
	Base Flow Index				0.94
	Mean Daily Base Flow				87.15
1997	Total Flow ($x10^9$)				2.93
	Minimum flow				80.4
	Maximum Flow				110
	Mean Daily Flow				95.51
	Std. Deviation	{NR}	{NR}	{NR}	
	Flood Flow Index				
	Base Flow Index				0.93
	Mean Daily Base Flow				89.12
1998	Total Flow ($x10^9$)				
	Minimum flow				
	Maximum Flow				
	Mean Daily Flow				
	Std. Deviation	{NR}	{NR}	{NR}	{NR}
	Flood Flow Index				
	Base Flow Index				
	Mean Daily Base Flow				
1999	Total Flow ($x10^9$)		1.375	1.318	
	Minimum flow		27	25	
	Maximum Flow		65.4	70	
	Mean Daily Flow		43.31	41.87	
	Std. Deviation	{NR}			{NR}
	Flood Flow Index		0.19		
	Base Flow Index		0.81	0.81	
	Mean Daily Base Flow		35.13	34.02	
2000	Total Flow ($x10^9$)		1.41	1.43	
	Minimum flow		27	32	
	Maximum Flow		65.1	67	
	Mean Daily Flow		46.11	45.36	
	Std. Deviation	{NR}			{NR}
	Flood Flow Index		0.19		
	Base Flow Index		0.81	0.88	
	Mean Daily Base Flow		37.20	39.70	

Notes: Flow is in m^3/sec.; NR = No record; P = Partial record.

In addition, the total amount of groundwater that flowed from the ORC through Ologbo in 1990 is $2.274x10^9$ m^3 of which 94 per cent or $2.13x10^9$ m^3 is groundwater recharge, which could have been extracted from the catchment without any effect on the amount of groundwater in storage in the aquifer. That is to say, this is "excess" water that was rejected by the aquifer (Oteze, 2011). When it is recognized that this is from the upper layers of a mere fraction of the total area occupied by the Benin Formation, which bestrides both sides of the River Niger, the enormous quantities of water available for development in Benin Formation terrain may be visualized. Thus, the perennial nature of the rivers in the ORC is due to groundwater contribution, as has been reported for the Ethiope River and the Adofi River (Akpoborie, 2011 and 2012) that also flow on and gain water from the formation. Thus, the gauge on the Ikpoba River that is a mere 5km or less downstream of the dam in Benin City recorded a total flow of $0.56 \times 10^9\ m^3$ also in 1990, with groundwater contributing an average of 80% of this flow, despite the tremendous quantities of groundwater withdrawn for water supply purposes in the city (Oteze,2011).

Finally, Figure 6 is the FDC for the Okhuwan River, the smallest stream gauged in the watershed. Smakhtin (2001) suggests that the 'lowflow section' of a FDC, which corresponds to the discharge equaled or exceeded 50 per cent (Q50) of the time, may be interpreted as an indication of groundwater contribution to flow because a small slope of this low flow indicates significant, steady and sustainable groundwater contribution. A steep slope, on the other hand, is an indication of small and/or variable baseflow contribution. The slope below Q50 in Figure 6 is small and the BFI of 0.77 confirms the high contribution of groundwater. Beyond this, Q50 is more than 5 m^3/s, which is an indication of the useful potential of the river type for small hydropower development.

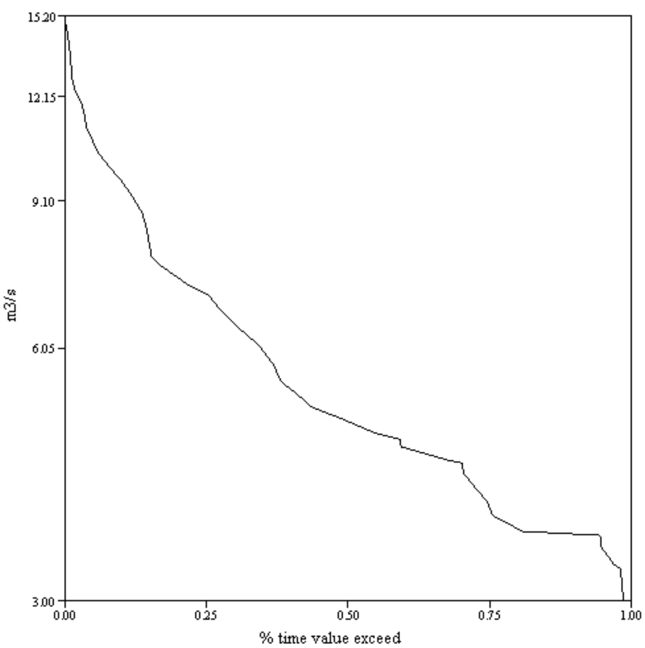

Figure 6: Flow Duration Curve for Okhuwan River (1990).

However, the statistics discussed in the foregoing also highlight the important issue of inconsistency in data collection. Gauge installation was initiated by BORBDA in 1980 and no records were published till 1990 and even so, eight years of record were not made available in the maiden edition of the year book. The station at Abudu has data for only five years, 1990-1994, which is indeed the longest continuous record in the watershed, Table 2 and Table 3. Records from the other stations are patchy with several years missing. It is also surprising that Volume I of the Hydrologic Year Books contains entries for 19 gauging stations and the number of stations kept being reduced in subsequent editions, such that by 2007 when Volume 7 was published, data entries covered only 6 gauges. It is not clear why

this was so, but discussions at the agency indicate that this problem was not unrelated to scarce resources. It may also well be that because the River Basin Authorities nationwide are under pressure to produce tangible results in the form of visible structural projects, investment in data collection and research in general is a low priority. The antipathy towards investments in research and data gathering is prevalent in all National and State water institutions and not limited to BORBDA, who it appears, are one of the very few Agencies that are making an effort at data collection. Without the collection of raw primary data, however, efforts at determining solutions to perceived climate change problems will be fruitless. The fourth report of the International Panel on Climate Change (IPCC, 2007) is emphatic that developing countries are lagging behind in the collection of data that is crucial for climate change predictions and adaptability efforts. The results presented in the foregoing are thus based on these limited data and should be viewed as such. Notwithstanding, they provide an insight into existing conditions in the watershed.
With respect to the ORC, it has been shown, with the limited data, that there should not be climate change adaptability problems that are related to the quantum of water resources that are and should be available for development in the long term. However, there is some concern that increased rain fall frequency and associated increase in runoff could result in high flood risks IPCC (2007). The results also give an insight to conditions that might be expected in similar ungauged catchments that occur in the extensive Benin Formation terrain.

Conclusion

Analysis of limited streamflow data from gauges installed in the main rivers in the Ossiomo River Catchment indicate that all the rivers are perennial, receive groundwater throughout their entire lengths and that groundwater contribution is on average , responsible for more than 70 per cent of total flow. This large percentage contribution also modulates the response of the rivers to the higher flows in the wet rainy season, and as such, reduces flood risks. The results also show that there are tremendous groundwater reserves available for development in the Benin Formation that releases the groundwater to the rivers from only its upper layers. The Flow Duration Curve for the Ikhowan River, the smallest river with a gauge, shows that Q50 is on the average about 5.5 m^3s^{-1} , and thus has, good potential for small hydropower development. The implication is that other small rivers in the Benin Formation terrain that are ungauged may have the same potential for hydropower development. Finally, while flow characteristics have been determined from the very short and patchy records, it is important that existing gauges be maintained and data collection be resumed at all locations.

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