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RESEARCH ARTICLE

Application of Basin Morphometry Laws in catchments of the south-western quadrangle of south-eastern Nigeria

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Abstract The relationship between process and form has been at the core of research in fluvial geomorphology. Form-process relationships of a natural river basin are strongly influenced by its hydrologic and sedimentologic processes as basin morphometric properties of length, shape, and relief, change in response to various hydrologic stimuli from the environment, but usually in line with well established laws. In the four river basins (Orashi, Otamiri, Sombreiro, New Calabar) examined in this study, however, empirical evidence does not conform neatly with theoretical postulates. Remarkable variations are noted in the morphometric properties of the catchments, when compared with established morphometric laws. The most varied in conformity are the Orashi and New Calabar basins, although the Sombreiro and Otamiri catchments also show some level of variation. Prime explanation for the morphometric and topographic non-conformity is caused by the nature of surficial material and the profoundly shallow relief of much of the study area, especially the alluvial flood and deltaic plains to the south and south-west of the study area.

Keywords catchments, watershed morphology, morphometric analysis, Nigeria, Africa

1 Introduction

Watershed characteristics in time and space are shaped and controlled by an integrated set of dependent and independent variables. These include long erosional periods, time, initial relief, geology and climate influence, vegetation, sediment yield, hill slope morphology and hydrology (Splinter et al., 2011). The causative factors of climate, soil and geology, vegetation and morphology strongly impact on ecosystem characteristics in a region in general (Omernik, 1987) and the differences in stream channel characteristics in particular (Splinter et al., 2011). Watershed morphology is therefore a derivative of the matrix of the aforestated factors and a function of relief, drainage density, circularity ratio, relief ratio, and ruggedness (Liébault et al., 2002). These morphometric matrices are the result of the interaction between the resisting framework of geologic and lithologic factors and the driving forces of climate and land use over a time frame (Ritter et al., 2002; Splinter et al., 2011).

Morphometric analysis has been used to investigate watershed morphology quantitatively at different scales (Horton, 1945; Langbein, 1947; Strahler, 1952, 1964; Schumm, 1956; Gregory and Walling 1973; Chorley et al., 1984). More recently, morphometric analysis has been applied in paleo-drainage investigations in the deserts of Kuwait (Al-Sulaimi et al., 1997), in process-based studies for environmental management (Jamieson et al., 2004), and also in the study and delineating of ecoregions for watershed and stream resources management (Splinter, 2006).

Other uses of morphometric analysis have also been described (Splinter et al., 2011). For instance, drainage density — a function of climate, lithology, and relief (Chorley et al., 1984) with stream frequency are used to predict peak discharge for watersheds in regions with unlike characteristics (Patton and Baker 1976).

Drainage basin morphometry can also be used to describe and compare basins of different sizes and the relationships between drainage basin parameters and flood potential (Cooke and Doornkamp, 1978). It has also been discovered that the higher the drainage density, the faster the runoff and the more significant the degree of channel activity for a given quantity of rainfall. The drainage density of a catchment therefore provides a link between form attributes and the erosional process in the basin. Consequently, the measurement of drainage density provides hydrologists and geomorphologists with a useful

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numerical measure of landscape dissection and runoff potential (Eze and Efiong, 2010).

Watershed circularity parameters also play a prominent role in flood hydrography and discharge. In watersheds with similar patterns of stream networks, circular watersheds will supply a more copious flow (hence more pollutants in polluted basins) to outlets more quickly than elongated watersheds (Singh, 1992), thereby making contaminant management more difficult. High circularity therefore affects pollutant delivery time as their shorter distances (delivery time) and copious flow do not allow suspended and dissolved pollutants enough time to precipitate and settle out of water. This may increase water quality degradation and decrease the biodiversity of aquatic macroinvertebrates, thereby affecting river health (Potter et al., 2004).

Morphometric analysis has also been applied in fish habitat studies. Lanka et al. (1987) found positive relationships among morphometric variables, stream habitats, and fish abundance in small streams in the Rocky Mountain area of the North America. They also used the same matrices to predict trout habitat disposition and concluded that low drainage density, low basin relief, and low relief ratio produced better trout habitats.

In his classic paper on erosional development of streams and drainage basins, Horton (1945) showed that the composition of stream systems in a drainage basin can be expressed quantitatively in terms of stream order, drainage density, bifurcation ratio, and stream length ratio. Other works have explained drainage composition, basin area, stream gradients, and the use and importance of some other drainage basin parameters related to the structure and geology of basins (Strahler, 1956, 1964; Schumm 1956; 1963; Morisawa, 1962, 1968).

Our aim in this study is to see how the study area conforms to some of these postulates or "laws" of drainage systems bearing in mind that these laws were formulated based on studies conducted almost exclusively in arid-semi arid environments of the temperate world.

It is therefore pertinent to examine how well these empirically derived postulates can apply to a humid deltaic environment characterized by relatively low basinal relief. In addition, this study will improve an understanding of the fluvial geomorphology of the study area. It may also serve as an input into stream and fish resources management and pollution hydrology, thereby enhancing prediction in a generally ungauged basin which absorbs unfriendly environmental practices from oil exploration and production.

2 Study area

2.1 Geology

The study area is characterized by the sediments of the Tertiary Niger Delta and the undulating lowland coastal plains. The Niger Delta lowlands occupy the extreme west of the study area while the Sombreiro-Warri Deltaic Plain (Fig. 1) occupy the eastern flanks and run parallel to the Niger River flood plains. The northern flank is bounded by the Awka-Orlu Uplands, while the eastern and southern flanks of the study area are uniformly undulating, although a relatively vigorous topography is noticeable in the north-eastern corner (Fig. 2).

The regional boundary of the study area is within 6° 40′ E and 7° 10′ E longitude, and 4° 45′ N and 6° 00′ N latitude. The area covers about 7,600 km^2, and encompasses four catchments (Orashi, Sombreiro, New Calabar, and Otamiri) of varying sizes (Figs. 3–6).

Short and Stauble (1967) described the general geological framework of the study area and placed it within the modern Niger Delta. The area is underlain by a series of cyclic regressive-transgressive sedimentary deposits ranging from Paleocene to Recent. Three main geologic formations found in the study area include recent alluvium (marine deltaic deposits), Coastal Plain Sands (Benin Formation) of the Miocene–Pleistocene age and the lignite series including the Ogwashi–Asaba Formation of Oligocene–Miocene age. The sediments grade vertically from the Paleocene marine-shale (Akata Formation) through an intervening unit of alternating sandstones and shale (Agbada Formation), to the continental gravelly and sandy terrestrial deposits of the Benin Formation in most places (Short and Stauble, 1967).

2.2 Relief

Structurally, the area is characterized by a seaward regional dipping and a general absence of surface and subsurface structures over the Coastal Plain Sands. Tectonic structures (mainly growth faults and roll over folds) caused by gravitational sliding can however be found in the thick deltaic deposits of the marine fluviatile alluvium of the Agbada Formation (Allen, 1970; Weber, 1987). The formations dip gently south-westward at angles of 1°–5°, but no significant structural control on the evolution of the drainage network and surface forms is discernible (Okonny et al., 1989). The predominant morphology is the Coastal Lowland or more appropriately the Coastal Plain Terrace, which is characterized by gently rolling low-relief landforms that trend to the south and south-west of the study area. Seen as a landform complex, the study area exhibits typical elevations of 120–350 m in the upper quadrants but reliefs as low as 10 m are found in the southernmost mouths of the Sombreiro and New Calabar rivers. Slopes are rarely in excess of 10% for most of the micro relief of the study area (Izeogu and Aisuebeogun, 1989).

2.3 Climate and soils

The climate of the study area using the Koppen's climate

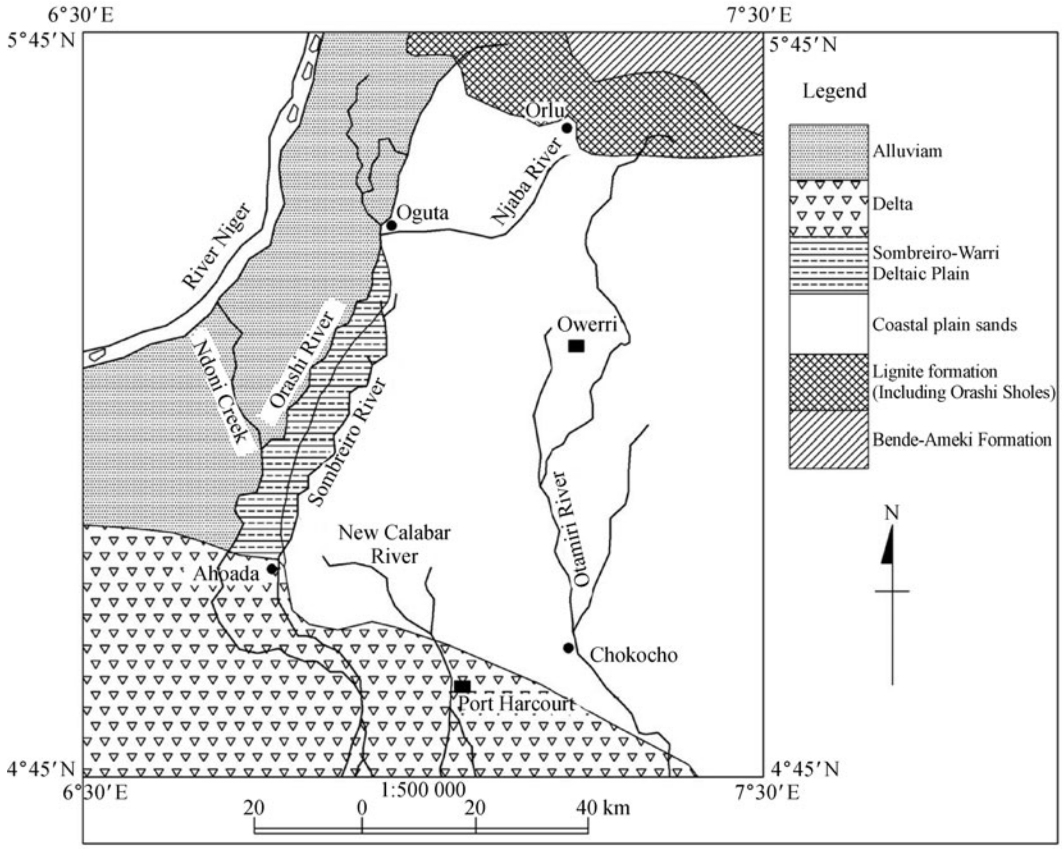

Fig. 1 Geology of study area

classification is the Af Tropical rainforest climate type with all 12 months having average precipitation of at least 60 mm and the Am Tropical monsoon climate types, marked by a distinct wet and dry season. The wet season lasts between March and November while the dry season lasts between December and February. Total annual rainfall ranges between 2,000 mm and 2,500 mm while mean annual temperatures range from 26°C to 27°C. The coastal zones in the Niger Delta have relative humidity of up to 90% all year round (Ofomata, 1975; Nigerian Meteorological Agency, 2003).

The soils in the study area may be summarized as porous, acidic sands, rich in free iron and generally low in natural fertility. The study area has three main soil types including the deep porous red soils of the coastal plains commonly called “acid sands”, the deep porous brown soils derived from sandy deposits, and the pale brown loamy alluvial deposits derived from recently deposited materials. These soil types are of low natural fertility, lacking adequate organic matter and humus due to excessive leaching (Agboola, 1979).

2.4 Vegetation

The area falls within the Cross-Niger transition forests, the tropical moist broadleaf forest ecoregion of south-eastern Nigeria, located between the Niger River on the west and the Cross River on the east. It was once mainly a tropical rain forest region but today supports one of the most densely-populated areas of Africa. These forests have been adversely affected and currently most of the vegetation in the northern parts of the study area is more of guinea savannah than the original rainforest. The ecoregion has sustained a dense human population for centuries, and much of the original forest cover has been cleared for agriculture, forest plantations, and urban development. The Niger River separates the Cross-Niger transition forests from the Nigerian lowland forests to the west, which probably resembles most closely the original environment of the Cross-Niger ecoregion. To the south and south-west lies the Niger Delta swamp forests (Werre, 2013).

A large proportion of the study area is covered by the lowland rain forest characterized by the ubiquitous presence of the stately Oil palm tree (*Elaeis guineensis*) and an abundance of diverse plant species. A few isolated pockets of primary forests may still be found, but largely the area now supports secondary forests of increasingly less diversity, biomass productivity, and community energetics. The vegetation type in the west of the study area is dominated by the Raphia palm and Calamus

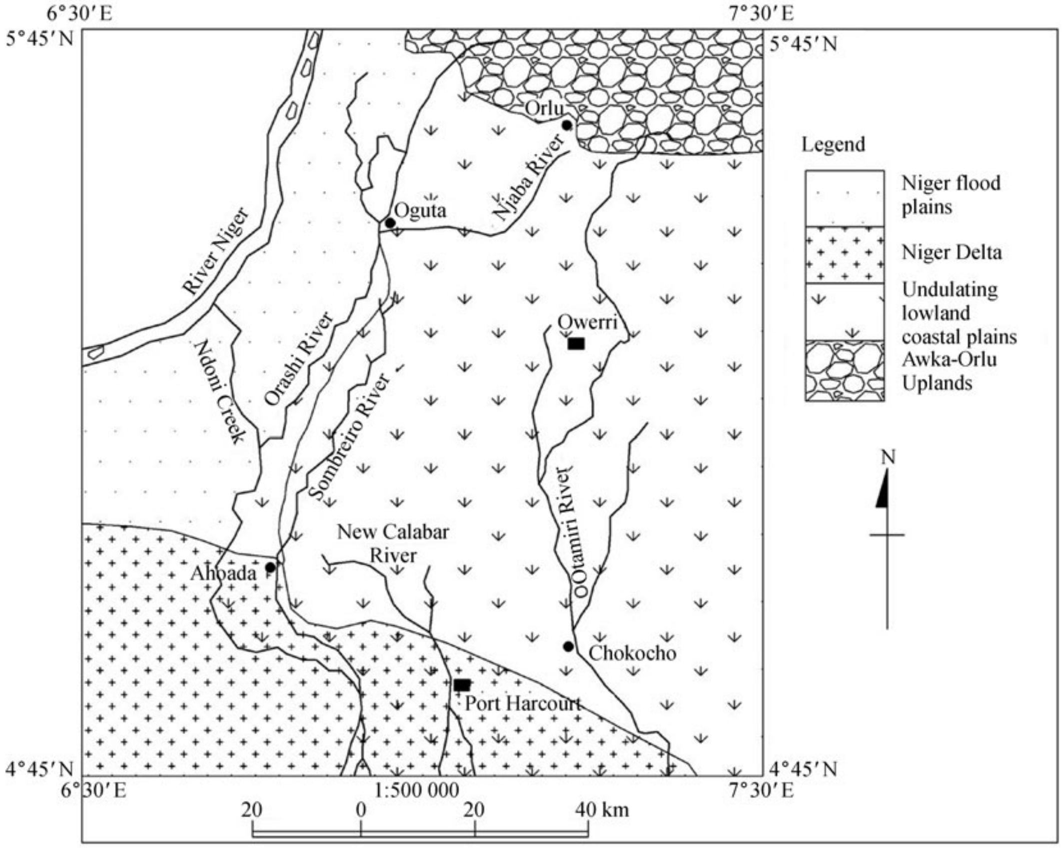

Fig. 2 Aspects of the geomorphology of the study area

species. It is mainly fresh water swamp with a greater range and density of plant species when compared with the saline lowland rainforests. This area is also noted for its climax ecosystem communities and high biomass productivity levels (Igbozurike, 1975). The general floristic composition of the study area is mature evergreen forests interspersed with grassy plains and isolated strands of thicket and bush. To the west and south-west of the study area, massive fresh water swamp basins exist and two of the studied catchments (Sombreiro and New Calabar) take their rise from such swamps.

3 Materials and methods

Four major rivers flow through the study area. The Orashi (Ulasi) and Otamiri have their source in the Awka-Orlu Uplands while the Sombreiro and New Calabar (Kalabari) rivers take their rise in the swamp basins at the southern tip of the study area from a maze of effluents and ephemeral streams crossing the homogeneously flat land (Fig. 1).

Catchments were delimited using 1:50,000 and 1:100,000 topographical maps of Nigeria, the Degema NE, Ahoada S.E., maps, and sheets 312 (Okigwe), 321 (Aba), 311 (Aboh), and 320 (Ahoada). Some of the sheets carry no contour lines and were supplemented with details obtained from some large scale sheets published for private use by the Shell Petroleum Development Company of Nigeria.

Catchment delimitation was done using the blue line method described in Gardener (1990) and Eze and Efiong (2010), while the Horton (1945), Miller (1953), Schumm (1956), Strahler (1952), and Morisawa (1968) methods were used for morphometric analysis (see Table 1). Maximum relief (Highest elevation (H_{max})), was read from the topographic map as the highest contour elevation of the ridge forming the boundary of the basin. Minimum Relief (lowest elevation (H_{min})), was the elevation at the gauging station which was taken as the contour value at the point of gauging. The relief ratio (R_r), as suggested by Schumm (1956), was defined as the total relief of the catchment (elevation difference between the lowest and the highest points in the basin) and the longest dimension of the basin parallel to the principal drainage line. Drainage density was measured as the length of stream channel per unit area of drainage basin. Stream frequency which describes how often one finds a stream segment in a unit area of basin space was calculated as the ratio of total number of streams to the basin area. Drainage intensity (I_d), was obtained as the product of drainage density (D_d),

Table 1 Description of measured morphometric parameters

No.	Measured parameters	Meaning/Derivation
1	H_{max}	Highest contour elevation of the ridge forming the boundary of the basin
2	H_{min}	Elevation at the gauging station (contour value at gauging point)
3	R_r (Schumm, 1956)	(H_{max} − H_{min})/maximum basin length
3	Mean length of Streams (Schumm,1956)	Total length of Streams/No. of streams
4	D_d (Schumm, 1956)	Length of stream channel per unit area of drainage basin. $D_d = L_\mu/A_\mu$
5	F_s (Morisawa, 1968)	Total stream length/basin area (A)
6	I_d	$D_d \times F_s$
7	R_c (Miller, 1953)	Ratio of basin area to the area of a circle having the same perimeter as the basin
8	E_r (Schumm, 1956)	Diameter of a circle of the same area as the basin to maximum basin length
9	Lemniscate ratio (k) (Chorley et al., 1957)	The basin length^2/A^4
10	F_f (Horton, 1945)	A/Length of the basin^2
11	C_c	Perimeter of the basin divided by circumference of equivalent circular area
12	L_o	Reciprocal of two times the drainage density
13	Axial width	Maximum width of the basin
14	Axial length	Maximum length of the basin
15	Order of basin or stream segment (Horton, 1945)	μ
16	Number of streams of order 'μ' (Horton, 1945)	N_μ
17	Stream length (Horton, 1945)	$L_\mu/L_\mu + 1$
18	Bifurcation ratio (R_u) (Horton, 1945; Strahler, 1952)	$N_\mu/N_\mu + 1$
19	Ruggedness number (Horton, 1945; Strahler, 1952)	(H_{max} –H_{min}) × D_d
20	Relative relief (Horton, 1945; Strahler, 1952)	(H_{max} –H_{min})/Basin perimeter

and stream frequency (F_s). Circularity ratio (R_c) was taken as the ratio of basin area to the area of a circle having the same perimeter as the basin. Elongation ratio (E_r) was the ratio of the diameter of a circle of the same area as the basin to maximum basin length. The form factor (F_f) was defined by the area of the basin divided by the square of axial length of the basin. The compaction coefficient (C_c) was defined as the perimeter of the basin divided by circumference of equivalent circular area. The length of overland flow (L_o) was taken as the reciprocal of two times the drainage density. Axial width was taken as the maximum width of the basin while the axial length was taken as the maximum length of the basin (Eze and Efiong, 2010).

4 Results and discussion

4.1 Catchment description

A summary of catchment characteristics of the studied basins are shown in Table 2. A catchment mouth for the upper Orashi River system was placed at the gauging station in Oguta, west of the Oguta Lake (Fig. 3). This was in order to avoid the distortion in measurement and analysis that any location farther south would inevitably create because of the link of a distributary channel from the River Niger system into the Orashi just south of Oguta. Besides, there are no direct open channel links in the Orashi system between Ozubulu and Oguta after which the

Table 2 Topographical characteristics of catchments

Characteristics	Orashi	Otamiri	Sombreiro	New Calabar
Area/km^2	1,473.0	2,287.5	484.0	208.0
Basin perimeter/km	140.6	212.5	81.48	52.65
Basin length/km	46.54	85.75	39.6	19.3
Max. basin relief/m	269.4	213	10.7	34
Relative relief	0.002	0.001	0.0001	0.0006
Catchment order	5	4	3	2
Drainage density	0.36	0.35	0.18	0.18

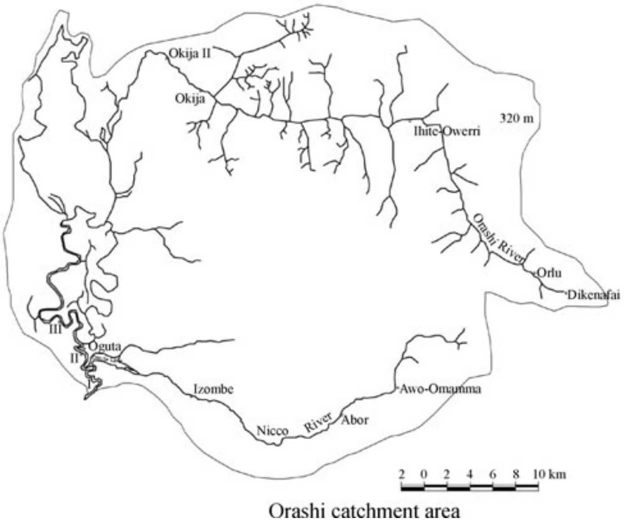

Fig. 3 The Orashi catchment area

Orashi meanders through the Niger flood plain (Fig. 2). Designating the catchment mouth at Oguta also means that the Njaba river system, which enters the Orashi system through the Oguta Lake, is regarded as a sub-system of the Orashi River. The catchment area from the designated mouth at Oguta south of the lake is 1,473 km^2 (Table 2). This catchment encloses a basin of the fifth order over an area with a heterogeneous geologic formation (Fig. 2) including sediments of Miocene to Recent age.

For the Otamiri system, the catchment mouth was at Chokocho, a location just below which the Otamiri joins the Imo River system (Fig. 4). The designated catchment is a basin of the fourth order with an area of 2,287.5 km^2 (Table 2). The entire catchment drains the gently rolling topography of the Coastal Plain Sands. The Sombreiro has an extremely flat catchment with an area of 484 km^2 and is a third order basin from its catchment mouth at Ahoada (Fig. 5). The New Calabar River is a second order basin occupying an area of 208 km^2 (Table 2) from its designated catchment mouth at Choba (Fig. 6).

4.2 Catchment characteristics

4.2.1 Linear aspects

The Horton (1945) catchment classification using channel segments and stream ordering systems was adopted. Table 3 provides figures on the number of stream segments (N_u) and bifurcation ratios (R_b) in the four catchments. The mean bifurcation ratios, as determined from Table 3 below,

Fig. 4 The Otamiri catchment area

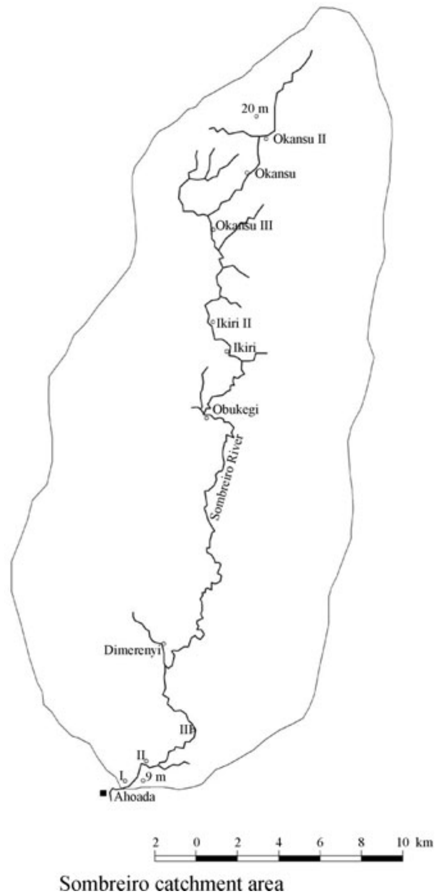

Fig. 5 The Sombreiro catchment area

Fig. 6 The New Calabar catchment area

Table 3 Stream segments and bifurcation ratios in catchments

Stream order	Orashi		Otamiri		Sombreiro		New Calabar	
	N_u	R_b	N_u	R_b	N_u	R_b	N_u	R_b
1	269		28		13		4	
2	69	3.89	8	3.5	3	4.3	1	4
3	20	3.45	2	4.0	1	3		
4	4	5.0	1	2.0				
5	1	4.00						

are 4.08 for Orashi, 3.17 for Otamiri, 3.65 for Sombeiri, and 4.0 for the New Calabar River. This is consistent with Strahler's (1975) observation that "*values of bifurcation ratio between 3 and 5 are characteristics of natural stream systems*." The Hortonian postulation of an orderly development of drainage basins has been previously subjected to empirical verifications (Wong, 1963, Ebisemiju, 1976; 1979) with varied results.

Horton's first law represented by Eq. (1) below was tried out on the four catchments and the results, computed from a plot of number of stream segments (N_n) against order (U), were compared with map analysis of blue lines in each catchment. Figure 7 is a plot of the logarithms of all four catchments with regression analysis results for each of the catchments:

$$D_d = L/A, \tag{1}$$

where, D_d = Drainage density; L/A = Length of stream per unit area.

If the law of stream numbers (Horton, 1945) is a good fit for these catchments, the mean bifurcation ratio derived from map analysis therefore should be same as the antilog of obtained regression coefficients. The antilog values derived from the plots are 3.63 for Sombreiro, 4.07 for the Orashi, 3.16 for the Otamiri, and 3.98 for the New Calabar River. These are remarkably close to the observed values (Tables 4–7).

Horton's second law represented in quantitative terms by Eq. (2) below was also tested.

$$D_d = L_u R_b^{(k-1)} \times P^k - 1, \tag{2}$$

where, u is stream order; k is order of trunk segment; R_b is bifurcation ratio; R_L is length ratio; L is mean length and $P = R_L / R_b$.

The same kind of relationship seen above between stream number and order seems to exist between stream length and order. However, computations from Eq. (2) showed obvious differences from figures obtained from map measurements. Values of average stream length for higher-order stream segments in the Orashi, Otamiri, and Sombreiro systems are shorter than they should be if the law of stream lengths is valid. Morisawa (1968) explains this discrepancy as a result of the Strahler method of ordering. Horton considered the length of a higher-order

Table 4 Observed and computed stream segments and stream length for Orashi catchment

Stream order	Number of streams		Length of stream segments/km			
	By Topo Map	By equation $N_u = r_b(k-u)$	By Topo Map	Mean stream length (L_u)	Cumulative (L_u)	By equation $L_u = L_1^{(u-1)}$
1	269	277.1	200.9	0.743	o.743	0.743
2	69	67.9	151.5	2.19	2.933	4.07
3	20	16.65	79.5	3.97	6.903	22.31
4	4	4.08	19.8	4.99	11.893	122.27
5	1	1	79.4	79.4	91.293	670.05

R_b = 4.08 (R_b = 4.07 from regression analysis) R_1 = 5.48 (R_1 = 3.02 from regression analysis)

Table 5 Observed and computed stream segments and stream length for the Otamiri catchment

Stream order	Number of streams		Length of stream segments/km			
	By Topo Map	By equation $N_u = r_b(k-u)$	By Topo Map	Mean stream length (L_u)	Cumulative (L_u)	By equation $L_u = L_1 R_1^{(u-1)}$
1	28	31.8	142.5	5.09	5.09	5.09
2	8	10.05	302.5	37.81	42.9	21.58
3	2	3.17	156.25	78.12	121.02	91.5
4	1	1	193.75	193.75	314.77	387.98
R_b = 3.17 (R_b = 3.16 from regression analysis)			R_1 = 4.24 (R_1 = 3.8 from regression analysis)			

Table 6 Observed and computed stream segments and stream length for Sombreiro catchment

Stream order	Number of streams		Length of stream segments/km			
	By Topo Map	By equation $N_u = r_b(k-u)$	By Topo Map	Mean stream length (L_u)	Cumulative (L_u)	By equation $L_u = L_1 R_1^{(u-1)}$
1	13	13.3	30.2	2.32	2.32	2.32
2	3	3.65	9.55	3.18	5.5	19.02
3	1	1	47.85	47.85	53.35	155.00
R_b = 3.65 (R_b = 3.63 from regression analysis)			R_1 = 8.2 (R_1 = 4.79 from regression analysis)			

Table 7 Observed and computed stream segments and stream length for New Calabar catchment

Stream order	Number of streams		Length of stream segments/km			
	By Topo Map	By equation $N_u = r_b(k-u)$	By Topo Map	Mean stream length (L_u)	Cumulative (L_u)	By equation $L_u = L_1 R_1^{(u-1)}$
1	4	4	20.6	5.15	5.15	5.15
2	1	1	17.1	17.1	22.25	17.1
R_b = 4.00			R_1 = 3.32			

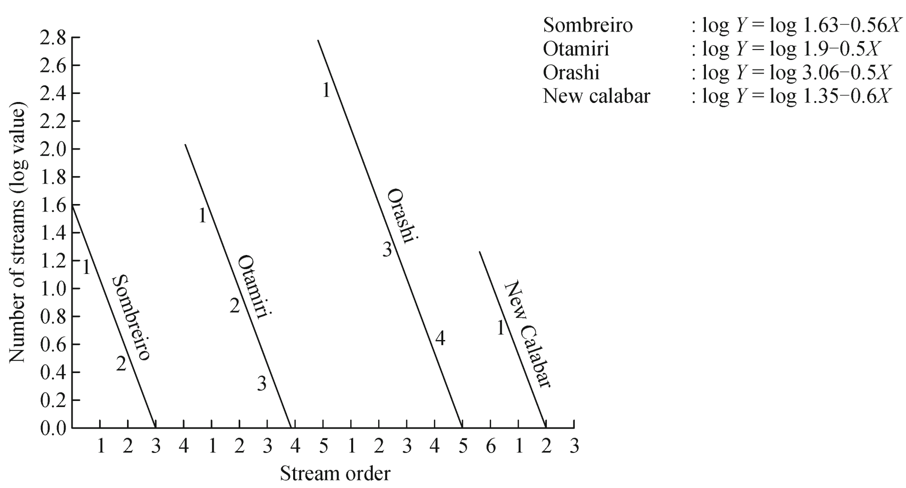

Fig. 7 Number of streams (log) against stream order

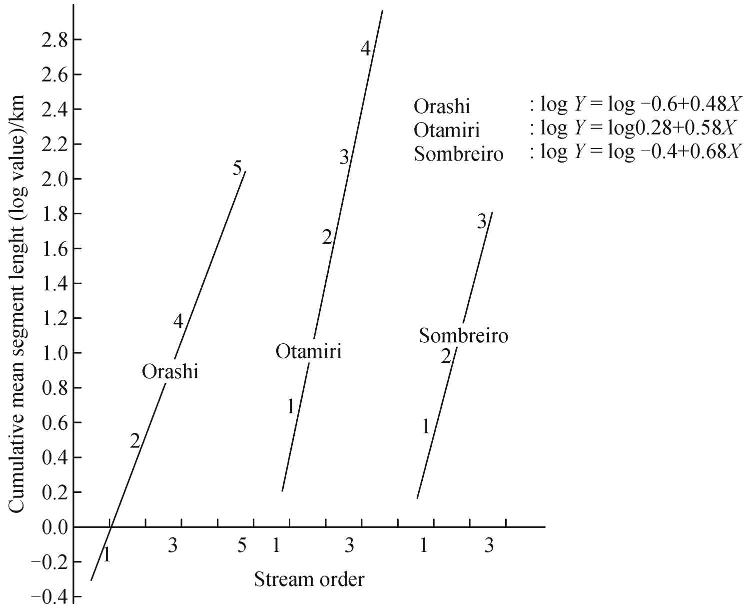

Fig. 8 Cumulative mean stream length (log) against stream order

stream to extend from the head in a fingertip tributary to its mouth, whereas the Strahler method breaks a stream up into segments. This makes higher-order segments shorter than those from which the Hortonian law was derived (Morisawa, 1968).

In the plot of the mean stream length against order, the Strahler method was used (Fig. 8). The cumulative mean length in log value was plotted against order for only three of the catchments. No meaningful analysis could be done on the fourth, the New Calabar River, because it is a second order stream at the designated catchment mouth.

While the length ratio (R_l) which is the antilog of the regression coefficient was 3.02 for the Orashi, 3.8 for Otamiri, and 4.79 for the Sombreiro, map-derived values included 5.48, 4.24, and 8.2 for each of the three catchments, respectively.

Further significant difference is noted when the Horton equation for stream length is computed with these data. The disparities are rather wide as to call into question the validity of the Hortonian generalization for catchments in the study area.

Observed and computed stream segments and lengths are presented below. Table 4 shows that the blue-line channel network from topographical maps conforms to Horton's law of stream numbers. A close fit can be observed between the number of streams derived from the equation with that counted from the map, for such order except perhaps for the third order.

The Orashi has a fine drainage network, particularly in the north-west corner. This area is underlain by the impervious Imo clay shales which naturally sustains higher run-off, hence a finer drainage network. Ebisemiju's (1976) work in a contiguous environment (Udi-Awgu Cuesta) also yielded similar results. The Orashi catchment therefore does not conform to the Horton's law of stream length. Wide variations were observed in the mean length of stream segments measured from the map compared with that derived by Horton's equation. The first two orders have fairly close values, but the last three higher-orders have very disparate mean length values. This is in line with earlier findings (Morisawa, 1968; Ebisemiju, 1976). Morisawa (1968) attributes this discrepancy to the Strahler method of ordering.

Horton also attempted to calculate the drainage density of a catchment based on a combination of Eqs. (1) and (2):

$$D_{\mathrm{d}} = L_{\mathrm{u}} R_{\mathrm{b}}^{(k-1)} / AxP^{k} - 1/P - 1. \tag{3}$$

When this equation was applied to the Orashi catchment, a value of 1.37 was obtained which was far greater than the map derived value of 0.36. This large difference is again traceable to the disparate length ratio obtained for the Orashi from Horton's equation of mean stream length. When the mean length ratio obtained from the regression coefficient was substituted, the drainage density value shrank to 0.42. This value is the most probable of the two since most of the catchment is bare, lacking any stream network because of the highly porous nature of the underlying material.

In the Otamiri system, a close fit exists between the number of streams from the blue line network and that derived from the Horton's equation although the law of mean stream length was inapplicable. The catchment is quite short and covered by very permeable sandy sedimentary sequences. Equation (3) was also applied to this catchment, and a drainage density of 0.46 was obtained. A drainage density of 0.35 was obtained from the topographical sheets, therefore, the same general conclusions reached from the Orashi catchment analysis applies to this catchment. Horton's postulate on stream length is therefore inapplicable to this catchment.

The Sombreiro catchment (Fig. 5) has a close fit with Horton's law of stream numbers just as the other two catchments discussed above have. But the law of mean stream length is inapplicable. A test of Eq. (3) for the catchment has also yielded non-conformal results. Calculation yields a drainage density value of 0.53 — a value way off the map derived value of 0.18. As consistent with the other two catchments however, a closer value of 0.26 is obtained when the substitute length ratio is used.

No real morphometric analysis was done on the New Calabar catchment. It is a second order stream and no meaningful analysis or tests can be done as all results are predictable. We therefore cannot say if the New Calabar River conforms to Horton's generalization or not. The major handicap against a rigorous test of its morphometry is that it is a second order stream from its designated catchment, as well as from the information presented as the blue line in the Nigeria 1:50,000 topographic sheets.

4.2.2 Channel lengths and erodibility constants

The constant of channel maintenance is that area necessary to develop and maintain the drainage channel. This constant is obtained from the slope of the regression of total stream length with average basin area. This constant is also a measure of the erodibility of the land surface of a catchment, and is approximately the reciprocal of drainage density of a catchment. A catchment with a high erodibility constant is more likely to be stable as the sediment supply area is wider than an area with a small constant. Small constants with active streams may encourage gullying as a result. Channel constants for the catchments were found to be 2.78, for the Orashi, 2.86 for the Otamiri, and 5.55 for both the Sombreiro and New Calabar catchments.

Channel lengths for the catchments range from 19.3 km for the New Calabar to 85.75 km for the Otamiri, while the Orashi and Sombreiro have 46.6 km and 42.3 km, respectively. The channel perimeter values are 52.5 km for the New Calabar catchment, 140.6 km for the Orashi, and 212.5 km and 81.48 km for the Otamiri and the Sombreiro systems, respectively.

These therefore imply that, for instance, the New Calabar and Sombreiro catchments have about 5.55 km^2 of catchment surface to maintain each kilometres of channel length. This is considerably more than the 2.78 km^2 and 2.86 km^2 available for the maintenance of each kilometre of channel length in Orashi and Otamiri systems, respectively. Therefore these latter two catchments have more erodible land surface than the Sombreiro and New Calabar catchments. This is a major factor in explaining the presence of gullying in the drainage basins of the Orashi and Otamiri rivers, especially the Orashi system in its Njaba sub-basin (Faniran and Jeje, 1983).

4.2.3 Stream frequency

Stream frequency is the number of channels per unit describing dissection in a catchment per unit area (Morisawa 1968). Stream frequency measurements include 0.25 for the Orashi system, 0.02, for the Otamiri, 0.035 and 0.02 for the Sombreiro and New Calabar systems, respectively. Earlier studies (Schumm, 1956, 1977; Strahler, 1957; Morisawa, 1968) state that stream frequency and drainage density, as well as constants of channel maintenance are strongly influenced by climate and the physiographic characteristics of the catchment. Therefore, a basin underlain by clay or shale formations has a higher drainage density and stream frequency than those underlain by porous, sandy materials. This affects stream run-off, contaminant transport, and soil and groundwater infiltration/percolation rates. Stream quality, fish habitat proliferation, and groundwater recharge and quality are therefore intricately tied to stream frequency and its factors.

The Orashi catchment has a higher value of drainage density and stream frequency primarily because a substantial part of its northern sector is underlain by the impervious Imo clay-shale group. It therefore seems that the general conclusions reached from other studies (Schumm, 1956, 1977; Strahler, 1957; Morisawa, 1968) are applicable to this particular catchment in relation to its linear characteristics.

The length of overland flow is a measure of stream spacing or extent of dissection, and is approximately half of the reciprocal of the drainage density if the average channel slope is less than half of average ground slope. The Orashi has a value of 1.39, the Otamiri 1.43, and the Sombreiro and New Calabar with 2.8. This indicates a low degree of dissection, and a relatively longer mean horizontal length of the flow path from the divide to the stream especially in the Sombreiro and New Calabar catchments.

Summing up, it is apparent that two broad subdivisions can be made among the catchments as regards their linear characteristics. The Orashi and Otamiri make up one group, and the New Calabar and Sombreiro make up the other. Each pair has similar morphometric properties and contrast rather vividly with the other pair. The Sombreiro-New Calabar system will therefore present less recharge and contaminant transport problems than the Orashi-Otamiri systems.

4.2.4 Basin area and shape

Schumm (1956) also proposed a law of basin areas in the manner of Horton's equation of drainage composition. This law could not be tested in the catchments under study as some of the topographical maps used for catchment delineation carried no contour lines. However, basin shape measures such as form factor, circularity ratio, elongation ratio, and lemniscate ratio were applied to the studied catchments. These measures essentially are comparisons of the basin area and length, with the area of a circle having the same perimeter and diameter, respectively.

Catchment Form Factor (F) is derived by the following:

$$F = A/L^2, \tag{4}$$

where A is drainage area and L is basin length.

The F values for the catchments include 0.68, 0.3, 0.31, and 0.6 for the Orashi, Otamiri, Sombreiro, and New Calabar rivers, respectively, while basin Circularity ratios (C_r) are 0.94, 0.64, 0.92, and 0.95, respectively. Elongation ratios (E_r) range from 0.93, 0.63, 0.59, and 0.84. The relatively higher values of the Orashi and New Calabar catchments attest to their more circular shape as can been seen from Figs. 3 and 6.

The lemniscate ratio (Chorley et al., 1957) was applied to the catchments and the following results obtained: 0.37 for Orashi, 0.80 for Otamiri, 0.81 for Sombreiro, and 0.45 for the New Calabar. This indeed is a more meaningful test of basin shape as the Otamiri and Sombreiro catchments (Figs. 4 and 5) have a greater semblance with the lemniscate loop (Gregory and Walling, 1973) than do the Orashi and New Calabar catchments (Figs. 3 and 6).

A look at the various measures of basin shape and their values indicates that the Otamiri and Sombreiro catchments are very much alike (Table 8). The Orashi and New Calabar catchments can be seen to have some similarities too. However, since basin shape profoundly influences catchment processes, especially hydrologic and sedimentologic processes (Schumm, 1977), the striking similarities noticed between processes in the Otamiri and Sombreiro during the study are strongly indicative of the catchment shape as a common underlying factor. The hydrologic and sedimentologic characteristics of the catchments have been discussed elsewhere in more detail.

4.2.5 Basin relief

It is not very easy to adequately express the slope and relief of a basin or catchment because "one is often attempting to express three dimensional variations in a very simple index" (Gregory and Walling, 1973). Nevertheless, these simple and complex indices are still in use and are frequently employed to express the relief aspects of basins. Moreover significant correlations have been noted between various relief measures and other morphometric parameters of the drainage basin (Doornkamp and King, 1971), implying that the varied parameters of a drainage system are strongly associated with each other.

The maximum basin relief recorded in any of the four catchments is 269.4 m in the Orashi, with the Sombreiro recording the lowest value is of 10.7 m. The Otamiri catchment has a value of 213 m, and the New Calabar is 34 m. The maximum basin relief (H_{max}) for the catchments showed strongly significant correlation between relief ratio and maximum basin relief (Table 2). Strahler (1958) suggested two combined indices, (i) ruggedness number and (ii) geometry number, in order to derive dimensionless measures that are representative of all the aspects of basin relief. Ruggedness number is a product of drainage density and maximum basin relief. The Sombreiro has the lowest value while the Orashi has the highest (Table 8).

Geometry number as relief measure is more representative when considering catchment ruggedness. The 1.08 value of the Orashi suggests it is way off the ideal equilibrium; therefore the basin is undergoing an active down wearing of its catchment surface through fluvial erosion. Empirical evidences of this were noted during the field work in the catchment especially in the Osu Obodo-Ihiala-Mgbidi-Umuaka-Orlu axis of the basin. By contrast the Sombreiro and New Calabar catchments seem to have 'planed-out' beyond this ideal equilibrium value of 0.5. Both basins have measures much below this value — 0.026 for Sombreiro and 0.07 for New Calabar.

As adjacent catchments lying wholly within the broad Niger Delta lowlands, their low value is fairly rational. Theoretically these two catchments should, by virtue of

Table 8 Catchments shape and relief measures.

Basin measure	Orashi	Otamiri	Sombreiro	New Calabar
Form factor	0.68	0.3	0.31	0.6
Circularity ratio	0.94	0.64	0.91	0.95
Elongation ratio	0.93	0.63	0.63	0.84
Lemniscate ratio	0.37	0.80	0.81	0.45
Drainage density	0.36	0.35	0.18	0.18
Relief ratio	0.006	0.0025	0.00027	0.0006
Ruggedness number	96.98	74.55	1.93	6.12
Geometry number	1.08	0.83	0.03	0.07

their low values of geometry number, be predominated by depositional activities. That there would be no erosional activity is a geomorphological heresy however, as field observation strongly indicates that these rivers have relatively stable land surface areas and channel perimeters.

Notably, the Otamiri catchment is the only catchment to compare favorably with the ideal profile or equilibrium. It has a geometry number of 0.83. This may be because of its extensive nature — from the Awka-Orlu Uplands to the low plains of the Niger Delta. The catchment thus combines elements of ruggedness and ‘instability’ in the upper sections with the plane-like profile of the coastal plain/lowland areas. This combination evens out any possible extreme values for the catchment. Although elements of gullying noticed in the upper parts of the basin around Nekede and Ihiagwa could be attributed more to anthropogenic disturbances mainly from sand mining which affects the sedimentologic stability of the basin in these areas.

5 Summary and conclusions

Morisawa (1976) has noted that a great deal of inconsistencies exist in the application of the laws of fluvial dynamics to basins; also the relationships which exist between basinal attributes such as relief or shape can also be variedly expressed (Gregory and Walling, 1973). It is therefore unrealistic to dissect the drainage basin system arbitrarily into components since every river is in a dynamic relationship with its basin area from head to mouth (Morisawa, 1968; Schumm, 1977).

A coefficient of correlation was therefore applied to the various catchments using the Student’s *t*-test and a correlation coefficient of 0.88 was obtained implying that there was less than 1% chance that observed morphology in the basins occurred by chance. Thus, in all certainty, an interrelationship exists between basin area and the longest stream length in catchments found in the study area.

Relief ratio was found to be strongly related to relative relief ($r = 0.98$), a relationship significant at a 0.01 level. A significant relationship (using least squared method) also exists ($r = 0.95$) between drainage densities and relief ratios of the four catchments.

Other significant relationships (ά 0.05 and 0.01) for all the four catchments, the variable nature of the trunk order streams notwithstanding, include that between drainage density and stream frequency; stream frequency and relief ratio; ruggedness number and relief ratio; and basin area and total stream length.

Notable among all relationships above is that between area and longest stream length. The power function obtained from our calculations confirm Strahler’s (1957) postulate about the geometrical similarity of drainage basins which states that if all catchments are geometrically similar, regardless of area, the exponent, n, would be 0.5 (Haggett and Chorley, 1969). This is the same value obtained for the four catchments suggesting geometrical similarity between the four catchments, from the smallest (New Calabar) to the largest (Otamiri).

We also conclude that morphologically, two of the catchments studied — Sombreiro and New Calabar — are depositional landforms, while the other two — Orashi and Otamiri — are predominantly erosional landforms as established in Ofomata (1975, 1983) and Dangana (1980). The basic morphologic characteristics typical of each of these landforms were found in the catchments, including slope wash, channel runoff, sediment transfer and chemical eluviation.

Horton’s (1945) law explaining the linear aspects of drainage basins provides only marginal explanations for the observed topographic networks in all four catchments, while the law of stream numbers was verified empirically in all four basins, but this is not particularly significant because the facts can be derived mathematically from concepts of elementary combinatorial analysis (Melton, 1959).

No adequate verification was provided for the other laws of basin morphometry due primarily to the peculiar topography of the study area being shallow in relief.

On the basis of other linear parameters of drainage basins, however, the Orashi and Otamiri catchments compare favorably, and contrast vividly with the more southerly catchments — Sombreiro and New Calabar. When area and shape topographic characteristics are examined, juxtaposition in affinity between the catchments can be seen. Otamiri and Sombreiro catchments have much in common. The Orashi and New Calabar also possess some similarities, but marked differences in areal and shape properties, unlike the results obtained from the elongated Sombreiro and Otamiri catchments.

Relief measures also show the variable nature of the topographic characteristics. All four catchments have variable relief characteristics although similitude is between Orashi and Otamiri on the one hand and New Calabar and Sombreiro on the other.

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