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Article · July 2019

DOI: 10.1080/15715124.2019.1640226

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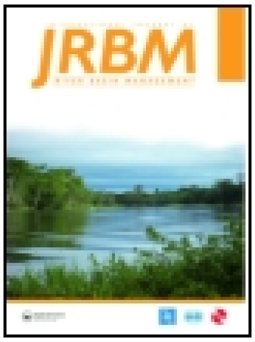

International Journal of River Basin Management

ISSN: 1571-5124 (Print) 1814-2060 (Online) Journal homepage: https://www.tandfonline.com/loi/trbm20

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To cite this article: Adebayo Oluwole Eludoyin & Adedayo Oreoluwa Adewole (2019): A remote sensing-based evaluation of an ungauged drainage basin in Southwestern Nigeria, International Journal of River Basin Management, DOI: 10.1080/15715124.2019.1640226

To link to this article: https://doi.org/10.1080/15715124.2019.1640226

Accepted author version posted online: 22 Jul 2019.
Published online: 26 Aug 2019.

INTL. J. RIVER BASIN MANAGEMENT
https://doi.org/10.1080/15715124.2019.1640226

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RESEARCH PAPER

A remote sensing-based evaluation of an ungauged drainage basin in Southwestern Nigeria

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ABSTRACT

Paucity of scientific information about many river basins in developing countries, especially in sub-Saharan Africa, has been linked to poor datasets and expensive monitoring technology. This study assessed the capability of freely available Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Shuttle Radar Topography Mission (SRTM) Digital Elevation Models (DEMs) and Landsat imageries to provide management decision support on river basins in the region. Main objectives are to examine landuse/landcover change over the Opa river basin in Ife area in southwest Nigeria, characterize the basin morphometrically and compare the morphometric characteristics from different sensors and resolutions. Results showed that the ecosystem of the river basin is vulnerable to urban intrusion and disturbance from human activities as urban population increases. Also, analysis of the DEMs allowed the drainage basin to be delineated into relatively homogenous and manageable sizes that can ease management, organization and evaluation of their eco-hydrological systems. The study concluded that complementary use of SRTM and ASTER DEMs with Landsat imageries that are freely available spatial data for researchers, is capable of providing useful decision support system for management of river basins in the region, to a level of uncertainty occasioned by sensors' characteristics.

ARTICLE HISTORY
Received 16 October 2018
Accepted 23 June 2019

KEYWORDS
Ungauged river basins; remote sensing; morphological analysis of basins; developing countries

1. Introduction

Recent studies (Marcus and Fondstad 2010, Entwistle *et al.* 2018) have argued in favour of the capability of remote sensing and geographical information system to revolutionize the understanding of geomorphological form and process. Remote sensing is typically defined as the art, science and technology involved in the observation and collection of location-referenced information on a particular scene on the earth, with the use of devices that do not come in contact with the scene. Marcus and Fonstad (2010) reported an increase in the use of remotely sensed data in fluvial geomorphology, especially in the area of data acquisition and processing. In general, remote sensing is known to enhance monitoring, prediction, and management of geomorphological events, processes and forms.

An important aspect of fluvial geomorphology is morphometric analysis or topographical expression of river basins, whose understanding is known to aid estimation of the dynamic characteristics of basins, as well as basin prioritization for soil and water conservation and control of soil erosion and resources management (Hajam *et al.* 2013, Khare *et al.* 2014, Srivastava *et al.* 2014, Ohal 2015). A river basin is characterized by a defined and unambiguous unit area with a topographic, hydraulic and hydrological unity; and are therefore identifiable planning regions (Faniran 1974, Doornkamp 1982). Understanding drainage basin morphometry is a requirement for runoff modelling, geotechnical investigation, identification of water recharge sites and groundwater prospect mapping (Gardiner and Park 1978, Fenta *et al.* 2017). Mapping the characteristics of river basins also provide information that is capable of facilitating planning and development of the basins (Salau 1986). Salau (1986) argued that a comprehensive evaluation of the attributes of river basins is required for their management, and that the idea of river basin planning and management is underlain by the principle of the integrated complexity of the hydrological and the socio-economic attributes of the basin. Drainage basins' geomorphological analysis is legalized in Europe, under the Water Framework Directive (Kallis and Butler 2001), and as such river basin projects and catchment restoration programmes often require results of geomorphological analysis (Wharton and Gilvear 2007, Langat *et al.* 2019). This (basin legalization) is however not the case for most developing countries, especially in sub-Saharan Africa.

Furthermore, evaluation of studies across decades (e.g. Beven *et al.* 1984, Tetzlaff *et al.* 2008, Kendall and McDonnell 2006, Sheriff 2016, Eludoyin *et al.* 2017a) reveals different levels of concerns of methodologies for evaluating morphology and biogeochemical cycle in the river basins; for the purposes of pollution control, water management and seeking understanding of the effects of landuse changes in hydrological basins. The general consensus is that the river basins are difficult to conceptualize (Tetzlaff *et al.* 2008), and this formed the basis for the declaration of the Prediction in Ungauged Basins (PUB) science programme (2003–2012) that urged a rethink about the different ways in which the form and function of river basin systems are conceptualized (Sivapalan *et al.* 2003).

Existing studies have shown that major river basin development projects in tropical Africa have been criticized on environmental, social and economic grounds, often because the specific attributes of the drainage basins were not adequately inventorized, and as such, management plans appeared alien to the locality (Adams 1985). For example,

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Scudder (1996) had argued that river basin development throughout Africa failed to account for floodplains and indigenous activities within the basins. The case is not different for Nigeria in the sub-Saharan African region, where in most cases, information is scarce on the drainage basins, despite knowledge that adequate analysis of the forms and other attributes of the river basins in the region can be a strategy for rural development (Salau 1986, Eze and Effiong 2010, Amangabara 2015, Oruonye *et al.* 2016). Predictions of changes in a basin's ecosystem are also important for planning and improvement in the standard of living and human welfare within the basin area (Salau 1986).

A major reason for the poor information on river basins in Nigeria is the limitation posed by non-availability of relevant datasets. A review of existing studies on the Nigerian drainage basins showed that except for the efforts of international organizations (including the World Bank Group) on River Niger and Lake Chad, information on smaller, but not less important, river basins in the region is scanty and uncoordinated. This is probably because majority of the existing studies have attempted to characterize drainage morphometric attributes, basically from 2-dimensional (2-D) topographic maps, field surveys and other 2-D optical imageries, that have been associated with discrepancies and inaccurate information on some river basins across Nigeria (Eze and Effiong 2010, Amangabara 2015, Ashaolu 2016, Oruonye *et al.* 2016). Contemporary studies, elsewhere, have shown that imageries showing Digital Elevation Models (DEMs), 2.5-D to 3-D, imageries provide more precise and accurate morphometric characterization of the basin.

The present study area, Opa river basin, is a sub-basin of the larger Ogun-Osun river basin that is directly under the management of the Ogun-Osun River Basin Development Agency in Nigeria. The basin is impounded at a section to create the 116 km^2 Opa Reservoir, in 1980 within Obafemi Awolowo University campus, where it provides potable water for at least 644,375 people (based on 2015 records). Human population around the drainage basin is currently around a million of both rural and urban dwellers (based on projection from National Population Commission (2006)'s records). Water from the basin is also used for laboratory, domestic and agricultural uses (Akinbuwa and Adeniyi 1996, Babatimehin *et al.* 2019).

Although analyses involving DEMs such as Shuttle Radar Topography Mission (SRTM) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) abound in studies involving many technologically advanced countries (e.g. Sujatha *et al.* 2015), information on their relevance to regions in sub-Saharan Africa is substantially limited. Many studies from the Nigerian environment have focused mainly on the drainage basin morphometry from the angle of landuse/landcover change from Landsat imageries (e.g. Adediji 2005, Ajibade *et al.* 2010, Udoka *et al.* 2016). Orunonye *et al.* (2015), for instance, rather than documenting quantitative morphology of Lamurde river basin in Jalingo in northern Nigeria, were only able to appraise the basin's water resources potential due to what they referred to as 'lack of reliable hydrological data'. Also, Eze and Effiong (2010) characterized the morphology of Calabar river basin from topographical maps and Landsat imageries, producing very coarse and relief-deficient information. In general, conclusions from 2D evaluation of drainage basins are reported in literature as inadequate.

Consequently, this study aimed at elucidating drainage morphometric characteristics and landuse/cover dynamics over a typical basin area from freely available remotely sensed DEMs – STRM and ASTER, and Landsat imageries, respectively. This is with the view of demonstrating how the freely available datasets can be used in the Nigerian environment. Specific objectives are to examine landuse/landcover change over the Opa river basin in Ife area, characterize the basin morphometrically and compare the morphometric characteristics from different sensors within the scope (1986–2016) of the available data.

2. Study area

Opa river basin is a tributary of River Shasha (one of the main tributaries of River Osun) located within latitudes 7°26′56″ – 7° 35′5″ N and longitudes 4°24′53″ – 4°39′13″E. Important streams in the basin include Amuta, Obubu and Esinmirin streams, which transverse different landuse systems in the area (Eludoyin *et al.* 2004, Akinbuwa and Adeniyi 1996, Eludoyin 2014) (Figure 1). The basin covers four local government areas (Atakumosa west, Ife central, Ife east and Ife north local government areas). An important impoundment in the basin is the Opa Dam that was established to supply water for use in Obafemi Awolowo University, Ile-Ife and adjoining communities since 1978 (Adediji 2005). The Reservoir catchment occupies about 68 km^2 area, with a maximum capacity of 675,000 m^3 and is characterized by 1.01–4.99 m depth level and a 25 m (width) by 55 m (length) spillway; with seasonal fluctuations (Adediji 2005, Adesakin *et al.* 2017).

Dominant climate, classified as Koppen's *Af* climatic type (after Koppen 1936), is characterized by heavy rainfall and tropical rainforest. Both wet are dry seasons are experienced in the area; wet season starts from April and extends till October while the dry season starts in November and ends in March. Mean annual rainfall varies as 206–232 cm over the study area. Mean maximum temperature ranges between 28.8°C in February and 33.84°C in August while mean minimum temperature values range between 25.81°C in March and 23°C in August. Average annual wind speed varies between 4.0 and 6.2 ms^{-1}, and peaked between July and August. Wind direction is often southwesterly in the wet season and northeasterly in the dry season (Information on climate is based on records of meteorological data from the stations in the University) The native tropical rainforest vegetation, characterized by multiple canopies and Lianas (Adediji 2005) have been converted to secondary forest, consisting of perennial and annual crops due to intensive agricultural practices over the area (Mengistu and Salami 2007). Analysis of the landcover change in the study period (1986–2016) showed that about 23.8% of the native vegetation may have been converted to built-up, agricultural lands and bare surfaces. It also showed that built-up area has increased from 5% of the total surface area in 1986–18% of the total surface area in 2016. Report from ground-truthing tour indicated that occupants of lands within the basin are predominantly farmers who construct their farmsteads, camps and hamlets close to their farmlands. Dominant soils are the Alfisols soil series with tropical ferruginous overlay, as common to areas that are associated with Basement Complex rocks. The soil belongs to Egbeda and Iwo association and *Oxic Tropudalf* series. Geology are primarily granites, undifferentiated

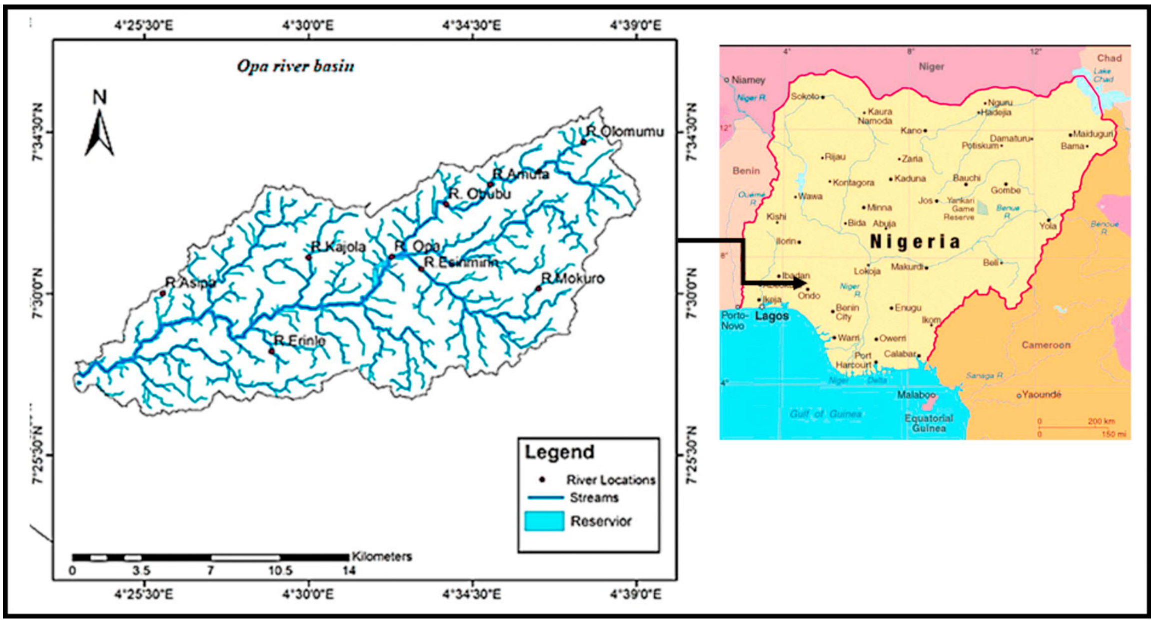

Figure 1. Study area, Opa river basin in southwestern Nigeria.

schist-gneisses, pegmatilized schists, pegmatites and epidiorite (Adediji 2005).

3. Materials and methods

3.1. Data

Studies (e.g. Alho *et al.* 2009, Entwistle *et al.* 2018) have argued that fluvial processes and forms have been widely explained using different hydrological and hydraulic models that require digital terrain models (DTMs) or DEMs. The DTMs or DEMs have also been acquired using different approaches, including global positioning system, airborne surveys and satellite remote sensors, whose preference is often dictated by availability and consideration for accuracy (Bates 2004, Alho *et al.* 2009). Entwistle *et al.* (2018) reviewed the development in DEM acquisitions from remote sensing, and identified the importance of the very high resolution and well considerably accurate remote sensing data but studies which focus on sub-Saharan Africa and some developing countries (e.g. Bastiaanssen *et al.* 2000, Forkuor and Maathuis 2012, Eludoyin *et al.* 2019) indicated that such high-resolution imageries, despite their usefulness, are very expensive. They also noted that embarking on a remote sensing mission may require a huge budget for researchers in developing countries.

Consequently, the data used in this study were considered for their availability to encourage its replication for other basins with appreciable success. Data used were DEMs that were extracted from available satellite data (ASTER Global DEM of 15 m and 30 m resolution and SRTM of 30 m resolution). According to Musa *et al.* (2015), SRTM, which was flown in February 2000, covers about 85% of the Earth's surface, and was obtained through Synthetic Aperture Radar interferometry of C-band signals. SRTM is available in 30 and 90 m spatial resolutions, with a vertical accuracy of about 3.7 m and greater gentle slopes than on steep slopes (Syvitski *et al.* 2012, Jarihani *et al.* 2015). ASTER Global DEM was released to the public on July 2009, after it was launched onboard NASA's Terra spacecraft in December 1999. Both ASTER and SRTM data were downloaded from the United States of America's Geological Surveys' site (USGS Earth Explorer, http://earthexplorer.usgs.gov/). In addition, freely available Landsat data (TM, ETM+ and OLI/TIR) for 1986, 1999, 2002 and 2016, in the dry season period (December – March) were used to evaluate land cover changes for the listed period. Landsat imageries were downloaded from the Landsat archive section of the USGS (https://landsat.usgs.gov). In addition, the available 1:50,000 topographical map covering Ife-Osu-Ilesa region was obtained from the Department of Geography in the University (Obafemi Awolowo University).

3.2. Data processing

First, each of the imageries was georeferenced in ArcGIS (10.4 version), which was preferred because it is relevant and available. ArcGIS has been made available for researchers in higher institutions in Nigeria by ESRI at subsidized rate in the last few years (Vaidya *et al.* 2013, Khare *et al.* 2014). The topographical map, complemented with coordinates (x,y,z) of selected prominent landmark features that were obtained through the use of a handheld global positioning system (Garmin eTrex 10 model with 3 m precision), was used for georeferencing of the imageries. The essence of performing a georeferencing task on the imageries is to improve their quality and provide enough localization of the imageries as advised in remote sensing literature.

3.2.1. DEM extraction and analysis

The DEMs were extracted from each of the SRTM and ASTER datasets following the tutorials provided by Trent University Library Maps, Data and Government Information Centre (MaDGIC 2014). Following the tutorials, a work environment was created and the DEMs were input through ArcMap. The analysis was achieved with the 'Raster analysis' option (in Spatial analyst extension) of the *Hydrology toolbox* of ArcGIS. First, the *Fill* option in the toolbox was used to improve the quality (sink) of the DEMs. the *Fill* operation assigns values to raster cells within flow path that hitherto did not have an associated drainage value based on defined interpolation procedure. Subsequently, flow direction and accumulation were extracted, using relevant operation tool in the 'toolbox' (MaDGIC 2014). Relevant morphometric parameters (Table 1) were extracted from each DEM, following the procedure described by Parmenter and Melcher (2012). Average statistics for selected parameters were also organized following relative homogeneous neighbourhood principle; that areas with high likelihood of homogeneity are grouped together and in contrast to more heterogeneous areas.

Furthermore, the Landsat imageries, after they had been georeferenced to ensure local compatibility with the coordinate systems of the study area, were corrected for inherent radiometric errors. The imageries were then classified into different landuse/cover areas using supervised classification approach. Studies have shown that supervised classification allows guidance of training pixels, and it returns a more accurate result than the unsupervised classification approach (Iqbal and Sajjad 2014, Ibitoye *et al.* 2016). Accuracy of the classification operation was assessed with confusion matrix analysis, and the results indicated at least 62% level of accuracy. Landcovers, especially rock surfaces and other impervious layers (bare surface) that were difficult to be classified were merged to improve the classification accuracy to 75% before imageries were further analysed.

Table 1. Selected parameters for this study, their formulae and sources of theoretical information.

S/No	Morphometric parameters	Calculation formulae	Reference
1.	Stream order	Hierarchical rank	Strahler (1964)
2.	Stream length (L_u)	The length of the stream	Horton (1945)
3.	Mean stream length (L_{sm})	$L_{sm} = L_u/N_u$ L_u = total stream length of order u N_u = total number of stream segments of order u	Strahler (1964)
4	Stream length ratio (R_L)	$R_l = L_u/(L_u - 1)$ L_u = total stream length of order u $(L_u - 1)$ = total stream length of next lower order	Horton (1945)
5	Stream frequency (F_s)	$F_s = N_u/A$ N_u = total number of stream segments of order u A = Area of the basin	Horton (1932)
6	Drainage density (D_d)	$D_d = L_u/A$ L_u = total stream length of all orders A = Area of the basin	Horton (1932)
7	Drainage texture (R_t)	$R_t = N_u/P$ N_u = total number of streams of all orders P = perimeter of the basin	Horton (1945)
8	Bifurcation ratio (R_b)	$R_b = N_u/(N_u + 1)$ N_u = total number of stream segments of order u $(N_u + 1)$ = number of segments of next higher order	Schumm (1956)
9	Form factor (R_f)	$R_f = A/L_b^2$ A = area of the basin L_b^2 = square of the basin length	Horton (1932)
10	Elongation ratio (R_e)	$R_e = 2\sqrt{(A/\pi)}/L_b$ A = area of the basin π- = 3.14 L_b = basin length	Schumm (1956)
11	Circularity ratio (R_c)	$R_c = 4\ \pi\ (A/P^2)$ A = area of the basin π- = 3.14 P = perimeter of the basin	Miller (1953)
12	Relief ratio (R_h)	$R_h = H/L_b$ H = total relief of the basin L_b = basin length	Schumm (1956)
13	Length of overlandflow (L_o)	$L_o = 1/(2D)$ D = drainage density of the basin	Horton (1945)

4. Statistical analysis

For management purpose, relatively homogenous parts of the entire drainage basins were classified as sub-basins with the ArcGIS software. Each sub-basin was subsequently analysed for selected hydrological parameters, and relationship among them (sub-basins) was assessed using cluster analysis while the level of contributions of each the selected parameters was assessed with principal component analysis (PCA). Foster *et al.* (2005) noted that the structure of the relationship between elements or between construct can be analysed by PCA, and that a hierarchical cluster analysis can be used to obtain a tree-like structure of how the elements or constructs cluster. Statistical analyses were obtained with standard statistical packages, basically 'PAlentological STatistics' (PAST) and SPSS (IBM 21 version).

5. Results

5.1. Hydrological characteristics of Opa drainage basin

5.1.1. Relief and stream order

Except for few steep slopes identified around the north-eastern part and other dotted regions around Opa drainage basin, elevation ranges between 186 and 647 m; with most basin area within 0–15% slope range (Figure 2(a–b)). Areas with high altitudes (eastern region) including Itagunmodi and Ijesaland (above 399.3 m) are regions whose valleys are known for gold mining (see Adeoye 2016, Eludoyin *et al.* 2017b for information on gold mining in the area). Four hundred and fifteen (consisting of 331, 68, 13, 2 and one of 1st, 2nd, 3rd, 4th and th – order streams, respectively) streams were identified, based on Strahler stream ordering principle (Strahler 1964) from the SRTM data whereas analysis of the ASTER Global DEM revealed 475 (375, 78, 20, 3 and one for 1st, 2nd, 3rd, 4th and 5th – order streams, respectively). The difference in the result of the stream ordering from the two DEMs indicated that the ASTER Global DEM revealed more streams (44 of 1st order, 10 of 2nd order, 7 of 3rd order and one of 2nd order) than the SRTM DEM for the basin, and this may have significant implications for planning a drainage basin. Nonetheless, both DEMs showed the drainage pattern as dendritic, and therefore indicate relatively homogeneous texture and insignificant level of structural control by its geology as suggested by studies (e.g. Wandre and Rank 2013, Gebre *et al.* 2015).

5.1.2. Drainage density and landcover change

In terms of drainage density, the drainage basin is characterized by 0–2.89 km of stream length per unit area, with five relatively heterogenous sub-regions within the basins (Figure 3). Since Gregory and Walling (1973) noted that drainage density is related to basin's physiographic characteristics as well as the input and output of the drainage basin system, it may be argued that the Opa river basin can be planned based on the categorization for further research. In general, most parts of the basin exhibited between less than 2 km per unit

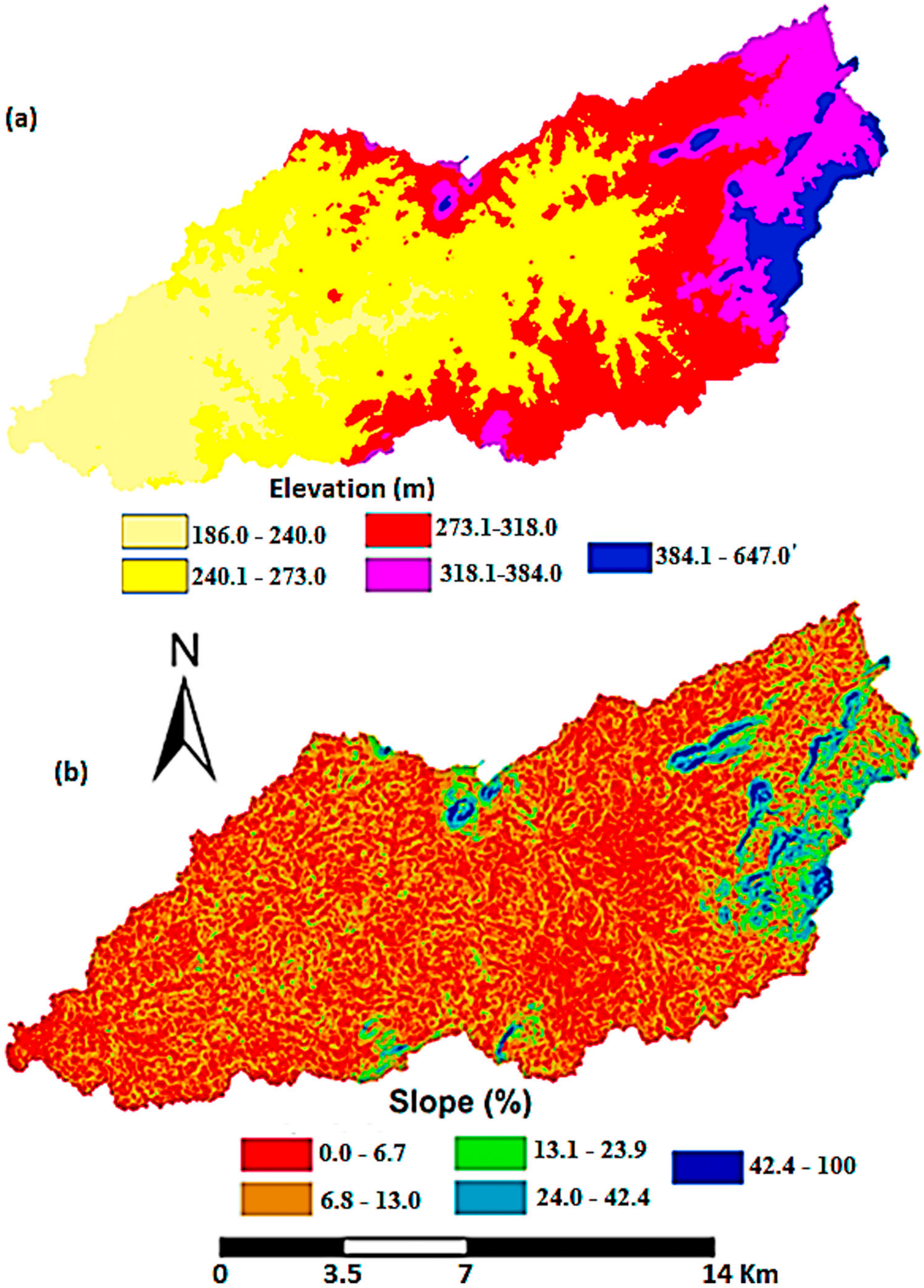

Figure 2. Slope and elevation patterns in Opa river basin in southwestern Nigeria.

area of drainage density, and are therefore considered low when compared with results from results in some other studies (e.g. Kant *et al.* 2015). Low drainage density suggests the dominance of permeable subsurface material and good vegetation cover that often results in increased infiltration capacity. Drainage characteristics in the study area are typical of basins in the tropical vegetation but land cover change analysis showed increased farmlands and built-up areas over selected periods with resultant levels of increased rocky/exposed land (Figure 4). From 1999 to 2016, built-up areas have increased, even in areas that were previously (before 1999) classified as farmland, and will increase further at the expense of the natural forest (Table 2). The result suggests the need for further monitoring of the drainage basin, especially given the rate of landcover/landuse change; and unless the hydrological monitoring techniques are improved, dynamic planning of the drainage basin may be ineffective. Also, the result of the stream length ratio that varied from 0.66 to 66.81, depicts significant heterogeneity that is may be associated with different land cover and characteristics over the drainage basin.

5.1.3. Basin attributes' dimensions

Total length of the streams in the basin ranges from 0.1–65.6 km. Sub-basins within the urban section of the drainage basin are characterized by shorter streams (less than 25 m) than those in the rural areas; and longer stream was in relatively higher elevations than those occupied by shorter streams. By inference, relief and urbanization are main influencers of stream lengths in the area. In addition, the result of the classification of the basin's mean stream frequency indicated a ratio (greater than 1.45). Pandey *et al.* (2007) classified basin with above 1.45 stream frequency ratio as that, which is covered by 'agricultural land and

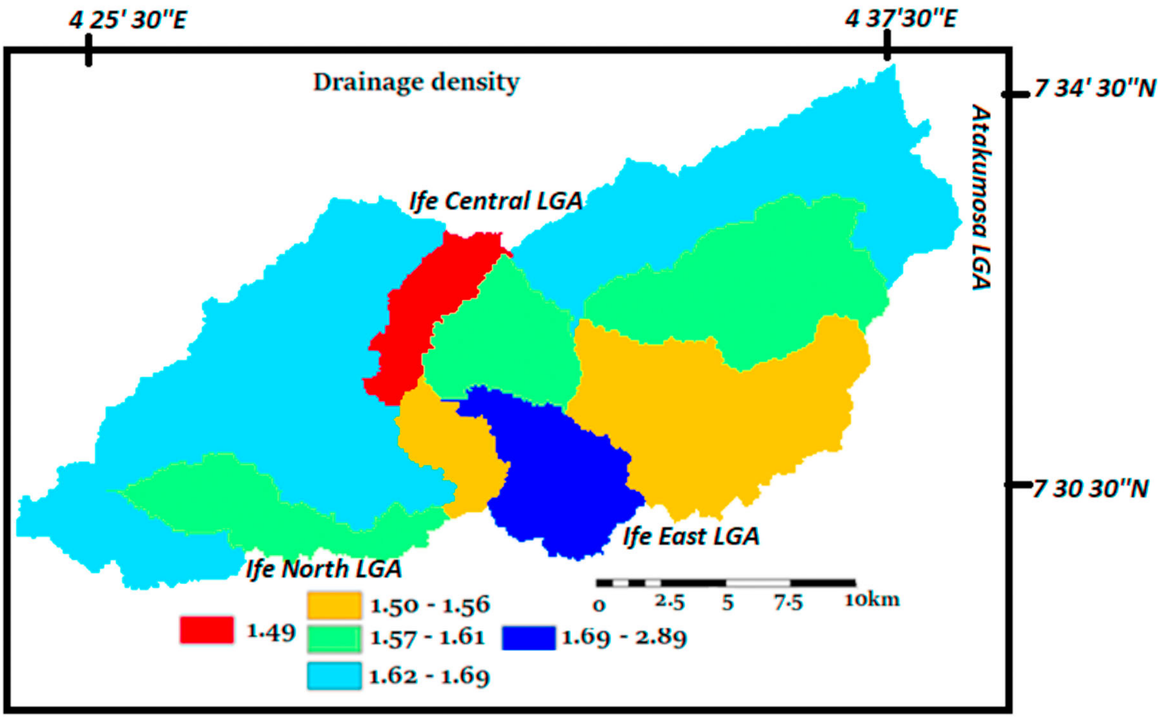

Figure 3. Average drainage density distribution in Opa river basin, southwestern Nigeria.

built-up area'. Forest cover only extends to less than 15% of the total basin area. Results of both stream length and frequency suggest significant anthropogenic activities within the basin (Figure 5(a–d)). Plate 1 which contains some terrestrial images of parts of the drainage basin, provides evidence of farming activities within the drainage basin while evidence of urban development within the basin had been illustrated in Figure 4. Both of anthropological activities reflect population intrusion into the basin.

5.1.4. Elongation ratio, overland flow, bifurcation ratio and stream length ratio

Elongation ratio in the basin varied between 0.47 and 0.81, and are therefore within the range described by Strahler (1964) to be 'associated with high relief and steep ground slope'. Chopra *et al.* (2005) described basins with such range of elongation ratio to vary between being 'less elongated and close to oval shape'. The results were further supported by the form factor, which ranged 0.10–0.52. Hortonian observations and many of the

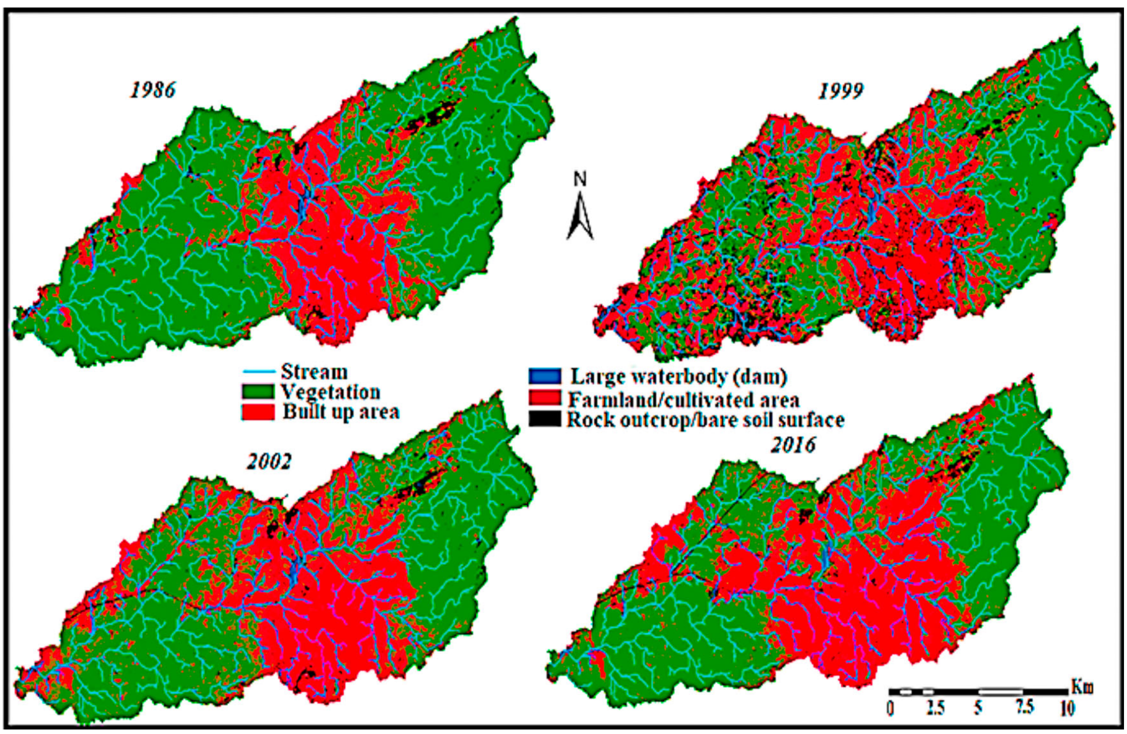

Figure 4. Landcover change over Opa river basin in southwest Nigeria between 1986 and 2016.

Table 2. Change in extent of area covered by selected landcover (in sq. km).

Year	Vegetation	Built-up	Waterbody	Farmlands	Rock outcrop/Bare surface
1986	158.1	11.8	0.32	59.6	4.73
1999	119.19	7.77	0.42	88.9	18.2
2002	123.93	25.48	0.36	79.93	4.78
2016	120.5	42.8	0.35	63.86	7.05
Trend	$2541.5 - 1.2x$	$-2164.2 + 1.1x$	$-1.1 + 0.01x$	$-99.0 + 0.09x$	$-43.5 - 0.03x$
R^2	0.64	0.72	0.05	0.01	0.03

Note: $x = n$th, where 1986 is the 1st.

derivatives(of the observations) have argued that basins with form factor greater than 0.38 are likely to experience larger peak flows of shorter duration, than basins with lower factor (Chopra *et al.* 2005). Circulatory ratio is generally low, ranging from 0.1 to 0.36; indicating low channel storage and high sediment yield–delivery (Figure 6(a–d)). Nigam *et al.* (2017) also argued that low circulatory ratio may also indicate moderate -to- low relief, whose drainage system seems to be less influenced by structural disturbances.

In addition, analysis of overland flow showed three distinct sub-basins (0.75–0.80, 0.81–0.85 and 0.86–1.45 km) that reflect different influence of dominant overland flow mechanism (Figure 6(c)). Sub-basin with less than 0.85 km overland flow suggests a slower hydrologic response to precipitation than sub-catchment with greater than 0.85 km; sub-catchment the urban areas also tend to exhibit more rapid response than the parts. By inference, urban and farming activities may have altered the runoff mechanism in the catchment. Rather than the dominance of saturation-excess overland flow expected in the humid region, the influence of imperviousness and vegetation removal created by urban development and probably farming activities in the drainage basin have nurtured the prevalence of an infiltration-excess overland flow that is typical of rocky, largely impermeable and poorly vegetated surfaces (Church 1997).

In terms of the bifurcation ratio, four categories were obtained; sub-basins where mining activities have been reported exhibited greatest values of bifurcation ratio (5.35–7.91) (Figure 5(c)). The large values at the sub-basin suggest geological disruptions at the mining activities, with a tendency for significant implication on the catchment's processes and health (Strahler 1964).

5.2. Sub-basins delineation and their characteristics

The mean, coefficient of variations and range values of the 12 generated sub-basins are provided in Table 3. Greater level of variations, suggesting heterogeneity, occurred among the sub-basins; in terms of the total and mean stream lengths (51.9% and 65%, respectively), basin area (52.5%) and stream number (47%) than observed with other parameters. By implication, the sub-basins more distinguished in the drainage basin by the factors of their area, length and number of streams, rather than geology-related forms. Table 2 had shown that except stream frequency, texture ratio and elongation ratio, all other morphometry parameters were positively skewed.

The results of the PCA, whose components 1 and 2 explained 56.1% (36% and 20.1%, respectively) of the total variations in the differences among the sub-basins showed four (A-D) distinct groups; two (C and D) of whose eigenvalues, being less than 0.5, did not contribute significantly to the total differences in the sub-basins (Figure 7). Subsequently, based on the result of the hierarchical clustering of the sub-basins, five groups emerged (Figure 8). The

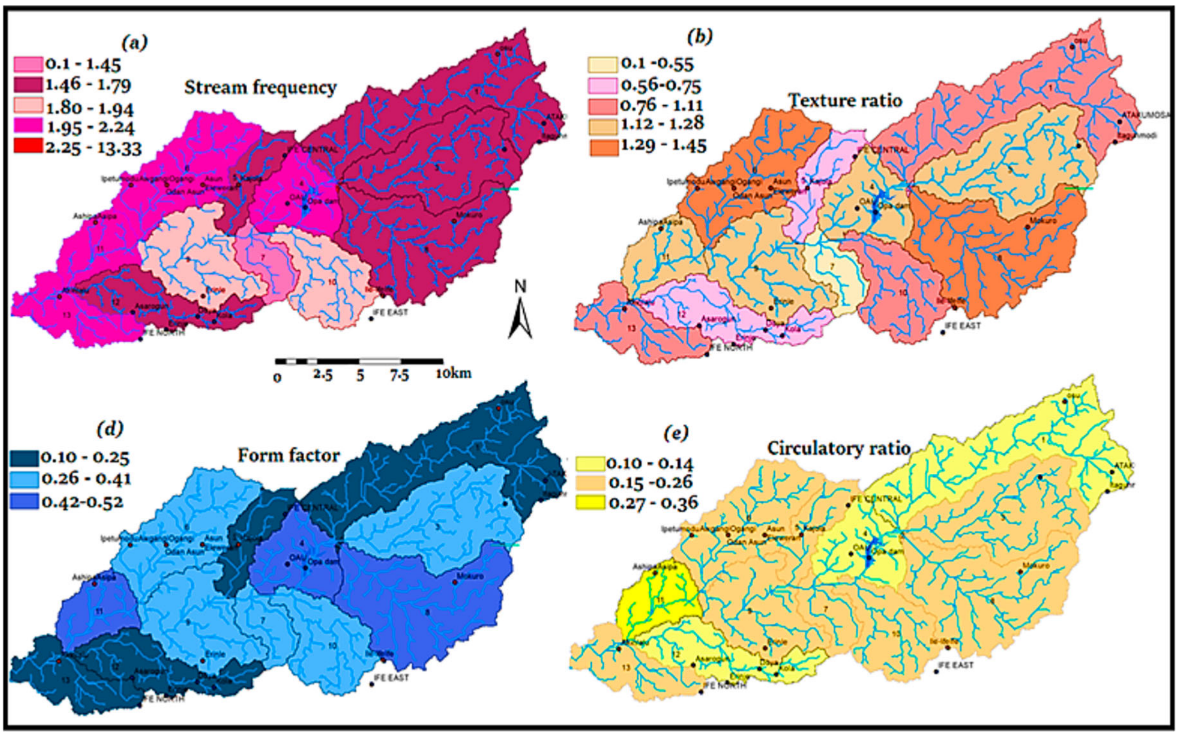

Figure 5. Stream frequency, texture ratio, form factor and circulatory ratio of Opa river basin in southwestern Nigeria.

Plate 1. Dumping of refuse on streams and connecting runoff channels and farming activities are evidences of man's influence on the drainage basins.

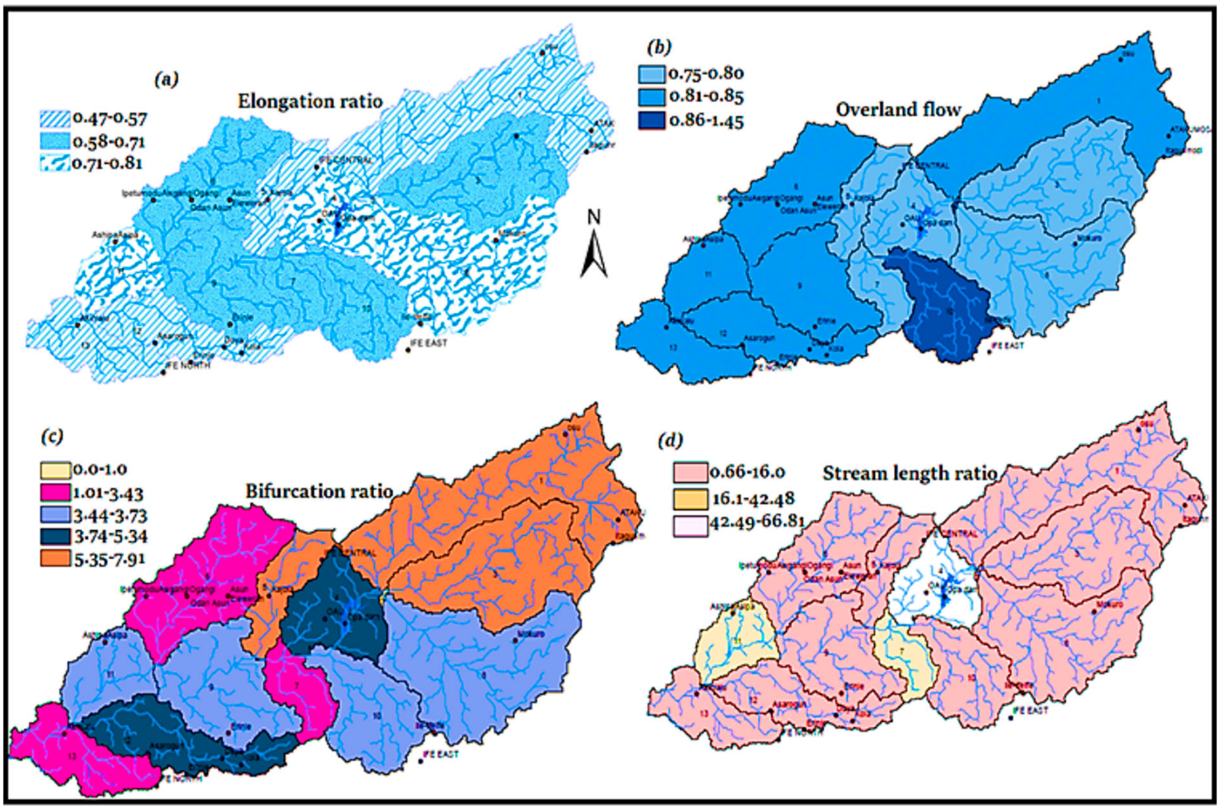

Figure 6. Elongation, overland, bifurcation and stream length ratios of Opa river basin in southwestern Nigeria.

Table 3. Some statistical characteristics of selected morphometric parameters at the 12 delineated sub-basins of Opa river basin in southwestern Nigeria.

Morphometric parameters	Mean	SD	Coeff. Variation (%)	Min	Max	Skewness
Basin length (m)	7.59	2.44	32.2	4.53	13.14	0.91
Basin area (sq.km)	19.48	10.23	52.5	7.60	39.40	0.85
Perimeter (m)	32.30	11.12	34.4	19.44	58.52	1.13
Drainage density (m)	1.72	0.37	21.7	1.49	2.89	3.31
Stream frequency	1.86	0.22	11.8	1.45	2.24	−0.09
Texture ratio	1.08	0.29	27.3	0.55	1.45	−0.58
Form factor	0.34	0.11	31.1	0.17	0.52	−0.07
Circulatory ratio	0.22	0.07	29.2	0.13	0.36	0.29
Elongation ratio	0.65	0.10	16.0	0.47	0.81	−0.32
Length of overland flow (m)	0.86	0.19	21.8	0.75	1.45	3.32
Mean stream length (m)	2.91	1.89	65.0	1.46	7.61	1.74
Total stream length (m)	33.25	17.25	51.9	11.79	65.57	0.50
Bifurcation ratio	4.61	1.68	36.5	2.37	7.91	0.76
Stream number	35.75	17.15	48.0	11.00	65.00	0.46

range of morphometric parameters of each of the groups (Table 4) suggests a non-significant mutual exclusiveness, indicating relative uniformity in among sub-basins.

5.3. Comparison of basin characteristics from imageries of different sensors and resolutions

Table 5 compares selected relief features (elevation, aspect and slope) around the basin from DEMs, as delineated from SRTM and ASTER imageries (Figure 9 is a sample from elevation for visual appreciation), respectively. While the extracted means and variability in elevation and aspect appear not-significantly different with SRTM and ASTER Global DEMS, results for slope show an overestimation of the mean but underestimation of variability in ASTER (30 m) DEM compared to ASTER (15 m) and SRTM. Evaluation of the visual differences suggests that the variations in the values may have occurred due to radiometric alterations by atmospheric noises. Ahmed *et al.* (2010) noted that differences in the size of pixels of DEMs (ASTER and SRTM) can

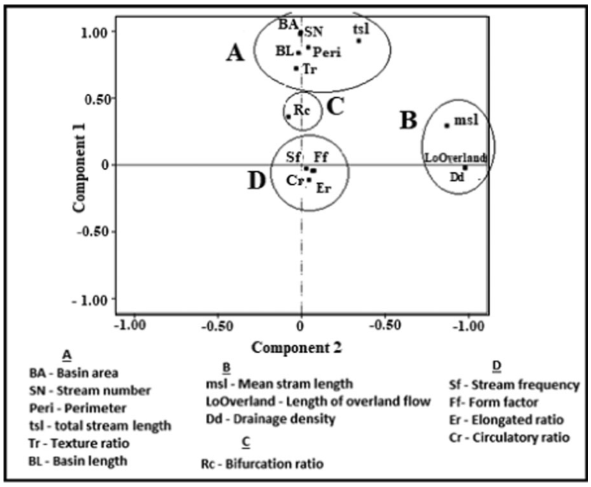

Figure 7. Results of PCA of selected morphometric parameters in the study area.

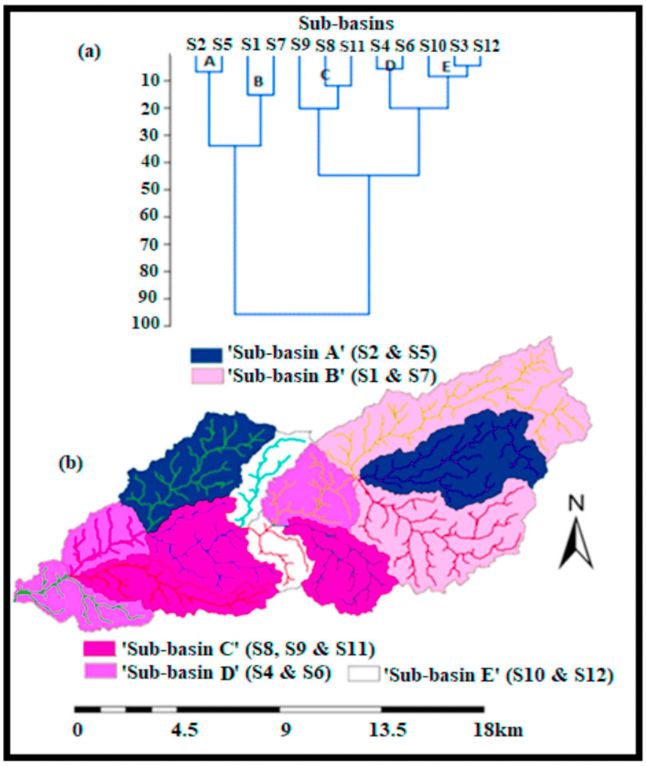

Figure 8. Delineated regions from hierarchical clustering of sub-basins (S1–S12) and the corresponding location in Opa river basin, southwestern Nigeria.

Table 5. Comparison of means and variability extracted from the ASTER and SRTM data.

Datasets	Parameters	Min (m)	Max (m)	Mean (m)	St. Dev (m)	Coeff. Variation (%)
SRTM	Elevation	186.0	649.0	276.9	48.85	17.6
30 m	Slope	0.0	2244.5	218.2	177.08	81.1
	Aspect	−1.0	360.0	189.2	103.08	54.5
ASTER	Elevation	163.0	638.0	270.3	48.4	17.9
30 m	Slope	0.0	2655.8	375.9	226.25	60.2
	Aspect	−1.0	360.0	184.5	103.74	56.2
ASTER	Elevation	181.0	638.0	272.5	48.12	17.7
15 m	Slope	0.0	2660.9	291.7	235.4	80.7
	Aspect	−1.0	360.0	171.3	110.75	64.6

be a source of their variations, and this can cause a difference in the values of extracted hydrological parameters. It is not therefore surprising that the 15 m resolution ASTER DEM reveals the upper and lower boundaries of classes (0–6% and 37–100%) more than the 30 m resolution ASTER DEM, based on known fact that resolution is an important determinant of the instantaneous field of view (IFOV) of any sensor to capture information about an earth-referenced image. In general, comparison of the values that were derived from the computed values of selected morphometric parameters from the DEMs indicated more discrepancies among sensors (ASTER with SRTM) than between sensors (ASTER 15 m vs ASTER 30 m) (Table 6).

6. Discussion

The objectives of this study were to examine landuse/landcover change over the Opa river basin in Ife area, characterize the basin morphometrically and compare the morphometric characteristics from different sensors and resolutions. The results showed that built-up areas and farmlands have increased in the study area by 262.71% and 7.15%, respectively, at the expense of vegetation cover that has reduced by 23.78% within the study period of 1986–2016. The changes observed in the landuse/landcover in this period are, however, not unexpected as studies over different settlements within the drainage basin have at different period indicated increase in population and consequent pressure on the natural landscape of the area (Ajala and Olayiwola 2013, Iqbal and Sajjad 2014, Ibitoye *et al.* 2016). In general, studies have shown that urbanization is a major factor that influences drainage basins, globally; causing changes in hydrologic regime (Thanapakpawin *et al.* 2007), discharge, water quality (Hundecha and Bardossy 2004) and

Table 4. Result of the cluster analysis for the sub-basins.

Morphometric parameters	Cluster A S2, S5	Cluster B S1, S7	Cluster C S8, S9, S11	Cluster D S4, S6	Cluster E S3, S10, S12
Basin length (m)	8.56–9.62	4.5–6.3	6.45–9.56	8.9–13.1	4.9–7.07
Basin Area (sq.km)	23.7–28.6	7.6–9.2	15.8–20.6	34.7–39.4	10.7–14.27
Perimeter (km)	33.7–37.4	19.9–23.9	29.5–39.2	42.64–58.5	19.4–27.6
Drainage density	1.60–1.68	1.49–1.55	1.61–2.89	1.56–1.66	1.59–1.69
Stream frequency	1.68–2.07	1.45–1.75	1.77–1.94	1.65–1.79	2.03–2.24
Texture ratio	1.28–1.45	0.55–0.67	0.75–1.23	1.11–1.45	0.9–1.23
Form factor	0.32–0.33	0.23–0.37	0.17–0.41	0.23–0.44	0.25–0.52
Circulatory ratio	0.26	0.2–0.24	0.14–0.26	0.14–0.24	0.13–0.36
Elongation ratio	0.64–0.65	0.54–0.69	0.47–0.71	0.54–0.75	0.57–0.81
Length of overlandflow (m)	0.8–0.84	0.75–0.78	0.82–1.45	0.78–0.83	0.8–0.85
Mean stream length (m)	1.8–4.32	1.83–2.95	1.67–7.6	2.44–5.3	1.46–1.86
Total Stream length (m)	39.78–45.57	11.79–13.7	25.4–47.53	54.1–65.57	18.2–22.6
Bifurcation ratio	3.43–6.61	3.33–6.5	3.58–5.34	3.62–7.91	2.37–5.2
Stream number	48–49	11–16	28–39	62–65	24–29

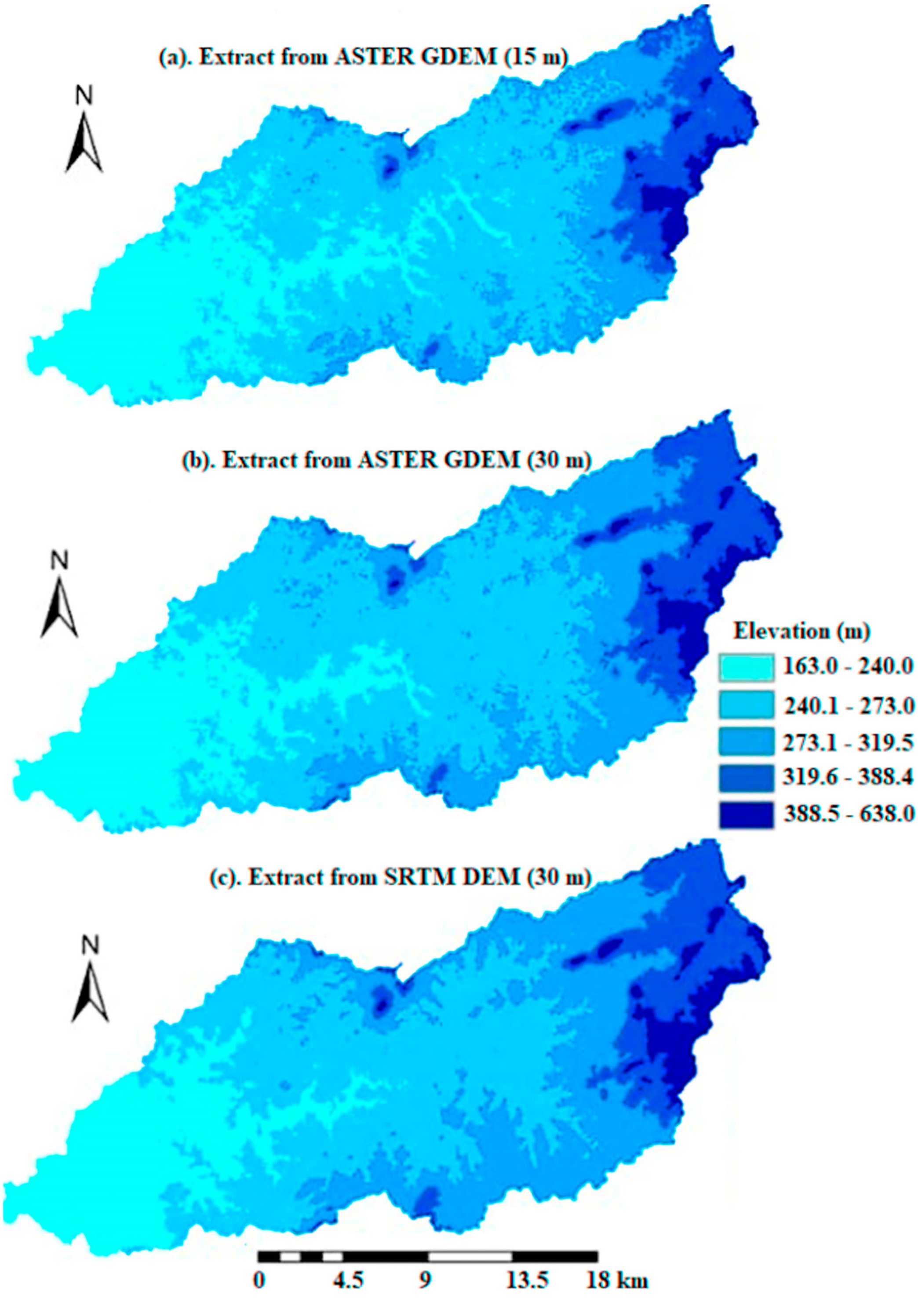

Figure 9. Comparison of classified elevation of the Opa river basin from the selected DEMs.

water balance (Bosch and Hewlett 1982, Costa *et al.* 2003) in basins. Also, the increase in farming activities have been linked with an increasing number of solids (both dissolved and suspended) in streams. In the study area, previous studies, including those reported by Ogunkoya (2012) and Adediji (2005) showed evidence of siltation of the Opa dam, and this may be linked to anthropogenic changes of the natural vegetation due to farming and urban development, through which streamflow-influencing impervious surfaces and sediments are generated in the area. Walling (2017) expressed the need for extensive monitoring of sediments yield, especially as they accumulate to exhibit substantial environmental effects in a drainage basin over many years and this will be required for further study in the study area. Attempts of an extensive investigation of the influence of landuse changes on the basin or sub-basins in the area will also require instrumentation that is presently lacking, and probably a clearer and more detailed high-resolution imageries as the result of the analysis of one of the Landsat imageries (Landsat ETM of 1999) showed radiometric distortion associated with noise and cloud cover that affected the ability to distinguish some land features in this study, especially the farmlands, bare surfaces and rock outcrops.

Furthermore, analysis of the DEMs classified the river basin as belonging to a 5th Order class, with about 480 tributaries over the 236 km^2 area. The hierarchical ordering of the basin is same with Adediji and Jeje (2004) as a 5th order basin. Given the bifurcation ratio, it can be argued that the geology of the

Table 6. Comparative mean values of selected parameters from ASTER 15 m, SRTM 30 m and ASTER 30 m.

Morphometric parameters	SRTM DEM (30 m)	ASTER DEM (30 m)	ASTER DEM (15 m)
Drainage density	1.6	1.68	1.67
Stream frequency	1.76	1.91	1.89
Drainage texture	2.82	3.21	3.16
Circularity ratio	0.45	0.36	0.40
Elongation ratio	0.58	0.55	0.55
Form factor	0.27	0.30	0.24
Length of overlandflow	0.32	0.30	0.30
Compactness constant	1.51	1.67	1.57
Number of streams	415	480	477
Mean Bifurcation ratio	4.65	4.55	4.60
Total length of streams (km)	378.14	421.02	422.37
Mean length of streams (km)	0.91	0.88	0.89
Mean Stream length ratio	0.46	0.65	0.63

drainage basin has not been significantly affected by structural disturbances, based on the interpretation of bifurcation ratio by Schumm (1956). Also, based on the relationship of bifurcation ratio with risk of flooding as interpreted by Chorley (1962), the sub-basin around Ipetumodu and Akinlalu with bifurcation ratio of 1.01–3.43, are considered vulnerable to flooding. The different vulnerability status of different section of the basin indicates the need for clear sub-basin scale management plan for the entire basin. Furthermore, the average drainage density and stream frequency of 1.6 and 1.85 km, respectively, shows the dominance of gentle-to-moderate slope and permeable bedrock over the drainage basin (Gregory and Walling 1973). The basin is also elongated (based on the 0.4 unit of circularity ratio), suggesting a longer duration of high flow, and vulnerability to erosion (Kant *et al.* 2015). With drainage texture of less than 4 km, the Opa drainage basin is considered as ‘coarse’ or one where headwater streams are not uniformly distributed across identifiable sub-basins (Prakash *et al.* 2016).

Considering its dendritic pattern, no significantly contrasting lithological characteristics of the basin area’s geology is inferred (Fenta *et al.* 2017). Previous studies have shown that the Opa drainage basin is characterized by essentially metamorphic rocks that include fine-grained biotite gneiss and schists, quartzite and quartz-schist rocks around the slopes and ridges, and the soils are characterized by mostly the well-drained Egbeda series soil, known as Alfisols, which is a fertile soil in the region (Smyth and Montgomery 1962, Eludoyin *et al.* 2004). The fertile soil also probably promoted the use of the drainage for agricultural purposes. The characteristics of the Opa drainage basin appears to be typical of River Lamurde basin in Taraba State, Nigeria (Oruonye *et al.* 2016) and Calabar River basin in Calabar, Nigeria (Eze and Effiong 2010) among others that are characterized by elongated shape, coarse drainage texture and areas prone to flooding. The studied drainage basin is also characteristically different from Qusseir and Abu Dabbab basins in Egypt that were reported to be oval in shape (Ghany 2015) and Milli basin of Raichur district in India with a circular basin shape (Polisgowdar *et al.* 2013). Elongated basins are generally characterized by longer lag times and low peak discharges as the water drains from the furthest reaches of the basin to the channel whereas in the circular basins, all points on the basin are equidistant from the channel, leading to shorter lag and higher peak discharge. Subsequently, there is a need for the management of the Opa drainage basin at sub-basin levels for comparative advantage consideration of varying drained distances and peak discharges of the streams.

Furthermore, the results of the comparison of the morphometric analysis of the drainage basin from 30 and 15 m resolution DEMs from ASTER sensor produced fewer contrasting results than what obtained from different sensors (but same resolutions)’ analysis of 30 m ASTER and 30 m SRTM. Except for none availability of product of the same sensor, the results showed that it is better to adopt the same product of a particular sensor rather than imageries of different sensor. Studies which have compared ASTER and SRTM argued that differences may occur due to variations in their mission specifications (Nikolakopoulos *et al.* 2006). Nikolakopoulos *et al.* (2006) argued that whereas SRTM elevation data are unedited, and contained occasional voids, or gaps, where the terrain lay in the radar beam’s shadow or in areas of extremely low radar backscatter, such as sea, dams, lakes and virtually any water-covered surface, ASTER imageries can be influenced by weather conditions during the stereo-imagery acquisition. Subsequently, it is argued that it may be necessary to compare the datasets from both sources before they are used complementarily as such provide information on the level of uncertainty in their description of DEMs of a location. In general, although the use of remotely sensed data provides an immensurable advantage for assessing changes in a river basin, differences in resolution and product sensor are important factors that may influence the results.

7. Conclusion

The study showed that SRTM and ASTER DEMs with Landsat imageries, which are freely available spatial data for researchers in sub-Saharan Africa, are capable of providing useful decision support system for management of river basins in the region. Opa river basin in southwestern Nigeria, as typical of many river basins in developing countries, is not protected from urban intrusion and disturbance from human activities as urban population increases. Also, analysis of the freely available DEMs allowed the drainage basin to be delineated into relatively homogenous and manageable sizes that can ease management, organization and evaluation of their eco-hydrological systems. In all, the study concluded that the available DEMs can be used complementarily for the effective decision-making process for drainage basin management for the basin. Efforts are on to replicate the study on another important drainage basin in different climatic condition in the region, such that effective comparison will be made with the applicability of the available DEMs and other relevant products of satellite missions in sub-Saharan Africa.

Acknowledgement

The authors acknowledge the contribution of Dr. A. Muibi and Mr. Samuel Samson of the Cooperative Information Network (COPINE) at Obafemi Awolowo University, Ile-Ife, Nigeria who assisted in satellite data analysis. We also thank Mrs Rukayat Yetunde Olayiwola of Department of Geography, Obafemi Awolowo University, for assisting in fieldwork activities. The comments of anonymous reviewers helped to raise the quality of the manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors.

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