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Application of Geospatial Technology in Watershed Delineation and Extraction of Hydrologic Characteristics in Opa Catchment, Southwestern Nigeria

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Authors' contributions

This work was carried out in collaboration between all authors. Author MO designed the study, wrote the framework and wrote the first draft of the manuscript. Author AK managed the literature searches and analyses of the study performed the geospatial analysis. Authors II, SF, IL and AA were involved in the field work and data preparation. All authors read and approved the final manuscript.

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ABSTRACT

This study explored the opportunity offered by geospatial technology to delineate the watershed draining surface water into Opa River, Southwest Nigeria and its tributaries using a selected outlet downstream of Opa reservoir and then carried out extraction of hydrologic characteristics of the

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watershed. The automated delineation procedure of ArcHydro extension of ArcGIS software was used. The watershed delineated has coverage of 197.21 km^2 and 17 sub-watersheds. Hydrologic Engineering Centre-Geospatial Hydrologic Modelling Extension (HEC-GeoHMS) was used to extract the hydrologic characteristic of the sub-watershed such as area, basin slope, river slope, centroid elevation and longest flow length. The division of the catchment into sub-watersheds enables matching the characteristics of each unit with soil and and land use characteristics thereby making watershed management at micro scale easier.

Keywords: Automated; delineation; land use; hydrologic; watershed.

1. INTRODUCTION

Sustainable management of land and water resources is important in order to continuously derive the benefits of these resources on earth. There is a paradigm shift towards managing these resources at the watershed scale. Watersheds as spatial units are usually considered as critical functional and ecological management units [1] and are important in management policy formulation and implementation. To obtain the areas that are drained to a common outlet, which is defined as the watershed, delineation is done. Watershed delineation has been done for long using the traditional method of visual interpretation of topographic maps. This method, referred to as 'manual delineation', is tedious and time consuming [2]. However, recent advancement in geospatial technology makes it easier with several readily available methods for automated watershed delineation using digital data [3]. In Nigeria, despite ongoing research efforts on watershed management, there remains a need for small watersheds delineation and development of hydrologic characteristics of the watersheds. There seems to be a gap in the available information about micro watersheds for use in regional and national decision making process and planning.

This observation is also true with to the southwestern part of Nigeria. Although there are studies on the water and forest resources as well as urbanization in the area [4-8], most of them were not done at the micro-watershed scale. Watershed management is a problem in many catchment in Nigeria due to the huge cost of physical delineation, inadequate data and dearth of expertise. There is need to delineate and characterize watershed for water resources management at micro and macro scale in order to achieve sustainable development objectives.

This study therefore aimed at delineating the micro watershed of Opa River, extracting its hydrologic characteristics as well as soil characteristics using digital elevation data, soil map with minimal cost and Geospatial technology for effective water resources planning.

1.1 The Study Area

The study was conducted in Opa watershed, which is a sub-unit of Ogun Osun River Basin, southwestern Nigeria, located between latitude 7º26'56''N to 7º35'5''N and longitude 4º24'53''E to 4º39'13''E. It cut across the boundaries of four local governments – Atakunmosa West, Ife Central and Ife East and Ife North. The area is located in the cocoa belt of Nigeria. The climate of the study area belongs to the Moist Tropical Climates according to Köppen Global Climate Classification System [9]. They are known for their high temperatures year round and for their large amount of year round rain [10,11]. The geology of the area includes granite gneiss and schist epidiorite. The soil of the catchment is Alfisols with Ferruginous Tropical overlay in most cases. The soil belongs to Egbeda and Iwo Asssociation and OxicTropudalf series by the USDA system and it was derived from granite and gneiss parent materials [12]. The natural or climax vegetation of the area is lowland tropical rainforest. However, the natural vegetation of the area has now been reduced to secondary forest or replaced by perennial and annual crops (7-Mengistu and Salami, 2007). The main river in the catchment is Opa which has many tributaries such as Obudu, Esinmirin, Ominrin, Ogbe, Okun, and Mokuro (see Fig. 1).

2. MATERIALS AND METHODS

The materials and methods employed in this research are described below and is divided into five stages. This stages are namely; data acquisition, data preparation, terrain pre-processing, watershed processing and hydrological characterisation.

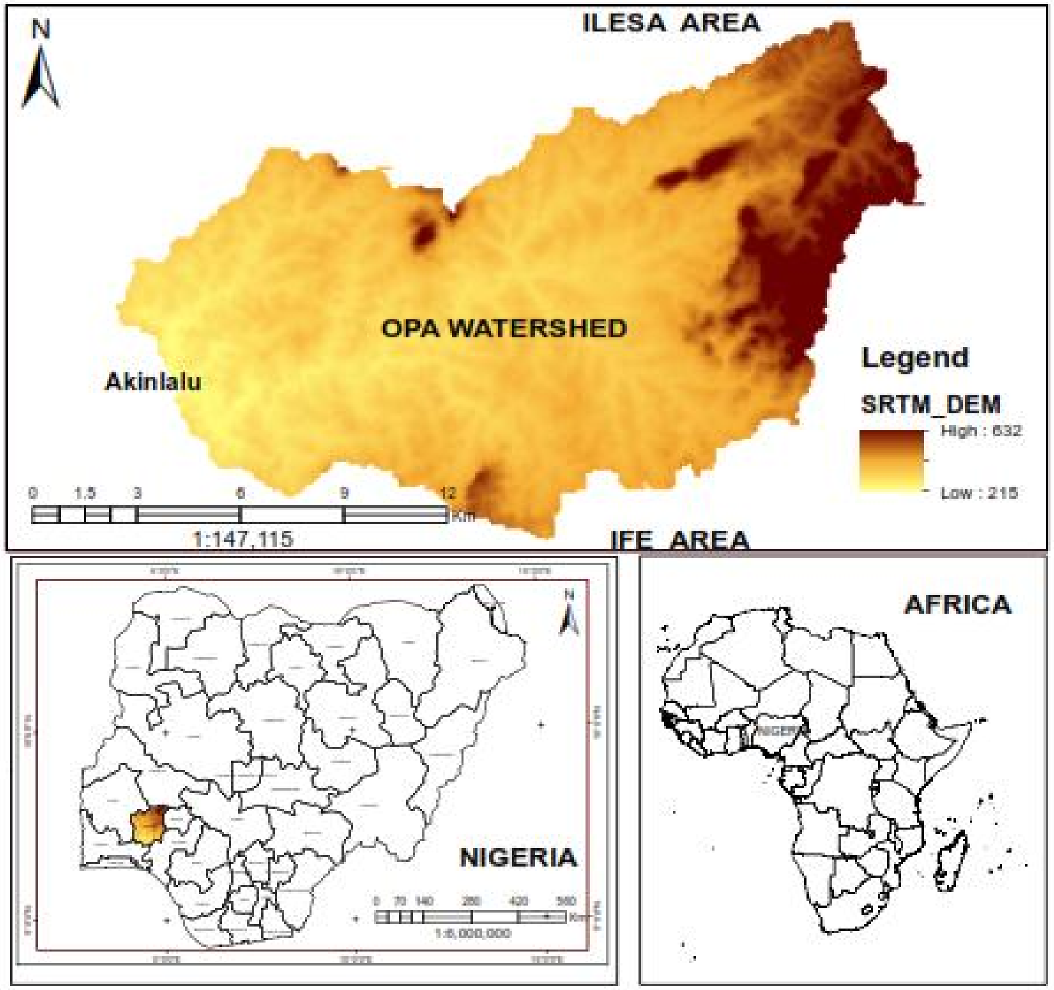

Fig. 1. The study area
(Source: Author's Field Work)

2.1 Description of Data/Sources

The primary data used for this study is the 2010 Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) of 1 arc-second (approximately 30 m) resolution. It is an elevation data obtained on a near-global scale to generate the most complete high-resolution digital topographic database of Earth. The Shuttle Radar Topography Mission (SRTM) was a collaboration effort between the National Aeronautics and Space Administration (NASA) and the National Imagery and Mapping Agency (NIMA) [13]. The secondary data used includes topographic maps (sheets Ilesha 243SW, Iwo 242SE, Apomu 262NE and Ondo 263NW) covering Ile-Ife and environs at scale 1:50000 and the soil map of southwestern Nigeria (1: 200000) obtained from the department of Soil Science and Land Management, Obafemi Awolowo University. IKONOS imagery of 2009 with 1m resolution obtained from Regional Centre for Training in Aerospace Surveys (RECTAS), Ile-Ife was used as a base map to appraise the type of land use in the watershed.

2.2 Data Preparation and Geodatabase Creation

The topographic maps and the soil map were scanned and imported into the ArcGIS 10.0 software environment. The maps were then georeferenced, resampled and the submap of the study area (547.16 km^2) was extracted. The stream network of the area was digitized and incorporated into the database created. The soil associations of the area were digitized and assigned hydrologic soil groups based on their properties. These maps were all brought to the UTM projection system (UTM Zone 31N). Also, the orthorectified SRTM digital elevation model (DEM) of the study area was clipped and stored in the database.

2.3 Terrain Pre-processing

The watershed boundary was delineated to determine the contributing areas to a selected outlet or pour point downstream. The Arc Hydro tool of ArcGIS 10.0 was used to process the DEM. ArcMap was opened and a new empty map was created. It was saved and named. The DEM raster data and the digitized stream layer were then added to the project for processing and the map document was saved again. The steps taken for automated boundary delineation is summarized in Fig. 2. DEM reconditioning was done using the AGREE algorithm in order to resolve the problem of undesirable competing flow paths within watersheds [3]. Fill Sinks tool was selected to obtain a depressionless DEM. Flow direction tool was selected to obtain the flow direction grid. The values in the cells of the flow direction grid indicate the direction of the steepest descent from that cell. The Flow Accumulation tool was selected to obtain the flow accumulation grid that contains the accumulated number of cells upstream of a cell, for each cell in the input grid. Other automated steps were stream definition, stream segmentation, catchment grid delineation, catchment polygon processing, drainage line processing, adjoint catchment processing and drainage point processing. After these pre-processing steps was the final stage of watershed processing.

2.4 Watershed Processing

The Arc Hydro toolbar also provides an extensive set of tools for delineating watersheds and sub-watersheds. To delineate the watershed boundary of the study area, batch watershed delineation function of the Arc Hydro was used. This function delineates the watershed upstream of each point in an input Batch Point feature class. In the ArcMap, the map display was arranged so that Fac, Catchment and Drainage Line datasets were visible in order to locate the outlet of the watershed. An outlet point was created using the batch point icon, on the flow accumulation path indicated by Fac grid where the flow leaves the study area. *Batch Watershed Delineation* tool was selected on the *Watershed Processing* menu. In the dialog box, the appropriate input data were confirmed - Fdr was the input to Flow Direction Grid, Str to Stream Grid, Catchment to Catchment, Adjoint Catchment to Adjoint Catchment, and Batch Point to Batch Point. For output, the Watershed Point was Watershed Point, and Watershed was Watershed. Watershed Point and Watershed were default names that can be overwritten. Smaller sub-basins were then merged to reduce their number for better analysis.using basin merge tools.

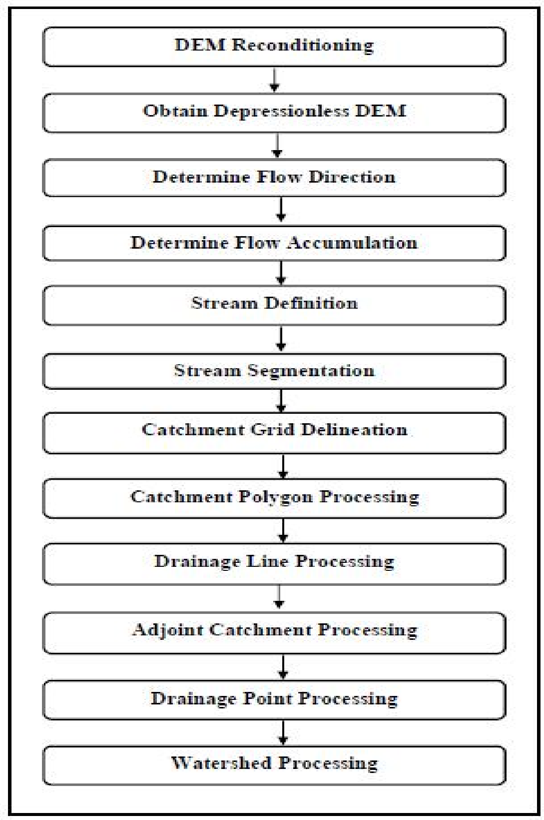

Fig. 2. Steps in automated watershed boundary delineation

2.5 Extraction of Watershed Characteristics

The basin characteristics that are required for water resources management in the study area were extracted using Hydrologic Engineering Centre-Geospatial Hydrologic Modelling Extension (HEC-GeoHMS) of ArcGIS 10.0. A new project was opened in ArcMap and the HEC-GeoHMS extension was activated. The new project was saved and named. All the raster and

Table 1. SCS Hydrologic Soil Groups (HSGs) and infiltration (loss) rates

Soil group	Description	Range of loss rates (in/hr)
A	Deep sand, deep loess, aggregated silts (Highly Drained Soil)	0.30-0.45
B	Shallow loess, sandy loam (Well Drained Soil)	0.15-0.30
C	Clay loams, shallow sandy loam, soils low in organic content, and soils usually high in clay (Moderately drained soil)	0.05-0.15
D	Soils that swell significantly when wet, heavy plastic clays, and certain saline soils (Poorly drained soil)	0.00-0.05

(Source: SCS, 1986; Skaggs and Khaleel, 1982)

vector dataset generated during watershed delineation were made available in addition to the Slope Grid which was created using the Arc Hydro. In the Arc Hydro tools, Slope was selected under Terrain Preprocessing menu. DEM data was confirmed as the input in the dialog box and the slope type was percent_rise. The resulting output was a slope grid. The basin characteristics menu in the HEC-GeoHMS Project View provide tools for extracting physical characteristics of streams and sub-basins into attribute tables. The following characteristics were extracted: river length, river slope, basin slope, longest flow path, basin centroid and basin centroidal elevation.

2.6 Hydrologic Soil Characterization

The soil associations of the watershed were digitized from the soil map and Hydrologic Soil Groups (HSGs) were assigned to each association based on the physical properties of the soils as described in Table 1. The vector layer of the delineated watershed was then used to clip out the digitized soil map thereby producing the soil map of the watershed.

3. RESULTS AND DISCUSSION

The results and subsequent discussion of the research is presented below with tables, figures and maps for illustration.

3.1 Watershed Extents and Description

The delineated watershed covers an area of 197.21 km^2 out of the sub-mapped area 547.16 km^2 while the remaining areas belong to other sub-watersheds of Ogun-Osun river basin. The watershed is a dendritic type which 17 sub-watersheds after processing (Fig. 3) which were named SW1 to SW17 for identification purposes during analysis. The watershed has a man-made Opa reservoir which is about 0.5 km^2 in surface area and a length of 1.8 km. This reservoir receives all the surface runoff from the upper part of the watershed, while the streams draining the southern parts of the watershed joins the main Opa river at the outlet of the watershed at Akinlalu, a town close to Ile-Ife. Each sub-watershed has a unique shape, slope and area. Table 2 showed the area and the slope of the sub-basins.

The time taken to achieve this watershed delineation using geospatial technology method as well as by other authors [14-16], are minimal compared to manual delineation. The same applies to the ease of repeatability of the process. It was also noted that while raster dataset (e.g. SRTM DEM) can be easily acquired and processed digitally to achieve watershed delineation, it is difficult to handle raster manually. However, the accuracy of DEM used is very important in watershed delineation.

3.2 Watershed Hydrologic Characteristics

The slope of the watershed is very important in its management and resources planning. The slope is steep in the upper part and gentle towards the lower part of the watershed as observed in Table 2. The values of basin slope in percentage is higher for sub-watersheds SW15 (8.05%), SW2 (4.43%) and SW8 (3.56%). As observed from the IKONOS imagery in Fig. 4, greater parts of these steep sub-watersheds are vegetated and this is very important factor that is considered for maintaining water quality and flood control. Delineated drainage network from the DEM is very similar to the available drainage extracted from topographic map of the study area. Studies [17-18] have shown that spatial resolution of DEM is vital in getting accurate drainage network. The SRTM DEM used in this study supports this finding.

The longest flow length of the streams is very important in quantifying the volume of available surface water, the carrying capacity of the stream channels and the urban floodplain extent as well as its vulnerability. Since the flow length is a function of the area of sub-watershed, the largest sub-watershed SW10 has the longest flow length of 13.17 m while the smallest sub-watershed, SW11 has the longest flow length of 3.17 m. The steams that pass through urban sub-watershed in this study area are very useful to the urban populations who use it for activities such as agriculture, domestic washing, fishing, and car washing. However, they also constitute a great flood hazard to the floodplain dwellers especially during overbank flow due to excessive precipitation and shallow stream bed. Sub-watersheds with higher slope such as SW15 (5.57%) and SW5 (2.34%) requires management options different from sub-watershed with lower slopes such as SW7 (0.89%) and SW9 (0.99%). Managing, stream length, slope, flow direction, depth and bank conditions are very important in watershed management.

3.3 Watershed Soil Characteristics

The soils of Opa watershed belongs to three soil associations - Egbeda, Itagunmodi and Iwo. Fig. 5 showed the distribution of these soil associations in the catchment. Iwo soil association (57%) is widely distributed in the watershed spreading from the northeast region to the southwest and interlocked with Egbeda soil association (36%). Itagunmodi soil association (7%) is present in the mountainous region of the eastern part of the watershed. The soil associations have correlation to their parents materials in the basement complex [19]. On the basis of Hydrologic Soil Group (HSG), Iwo soil association has properties that belong to class B while Egbeda and Itagunmodi soils belong to class C. HSG B to which Iwo soil association belongs has moderately low runoff potential when thoroughly wet as water transmission through the soil is unimpeded. HSG C to which Egbeda and Itagunmodi soil association belong have moderately high runoff potential when thoroughly wet as water transmission through the soil is somewhat restricted. The overall runoff potential in the urban sub-catchments is high due to the presence of the HSG C in the mountainous regions and the increased imperviousness due to settlements [20].

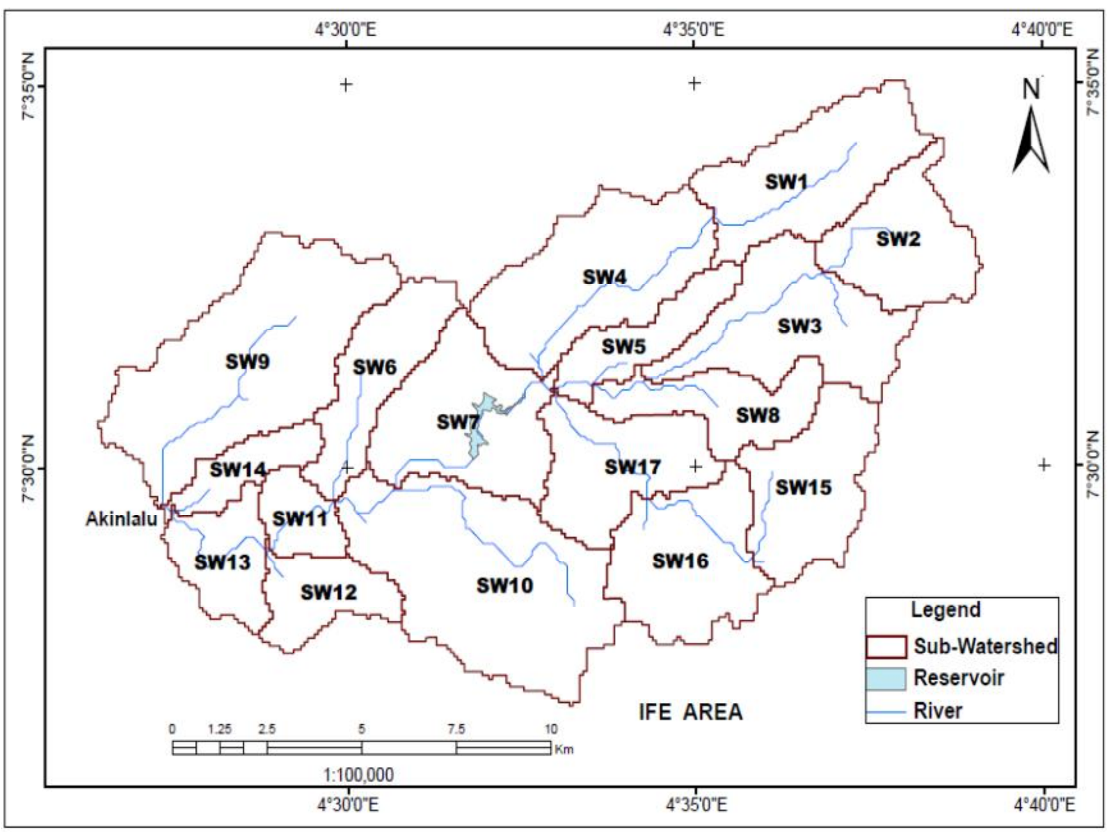

Fig. 3. The delineated watershed with 17 sub-watersheds

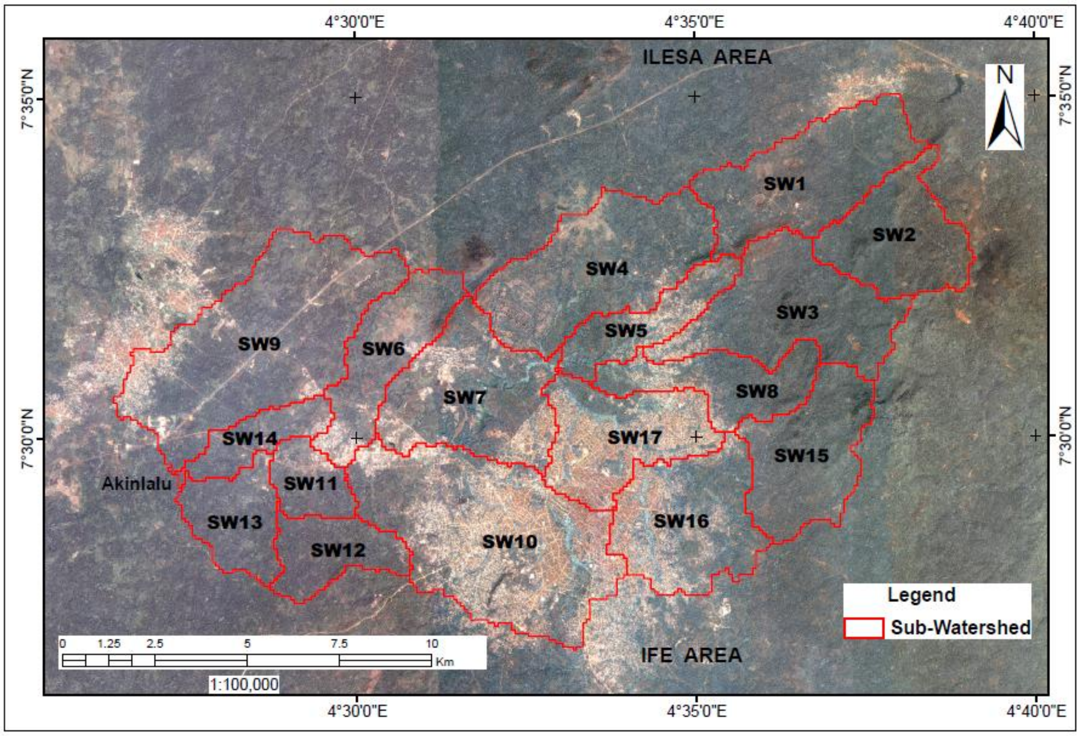

Fig. 4. The delineated watershed over the high resolution IKONOS imagery of 2009

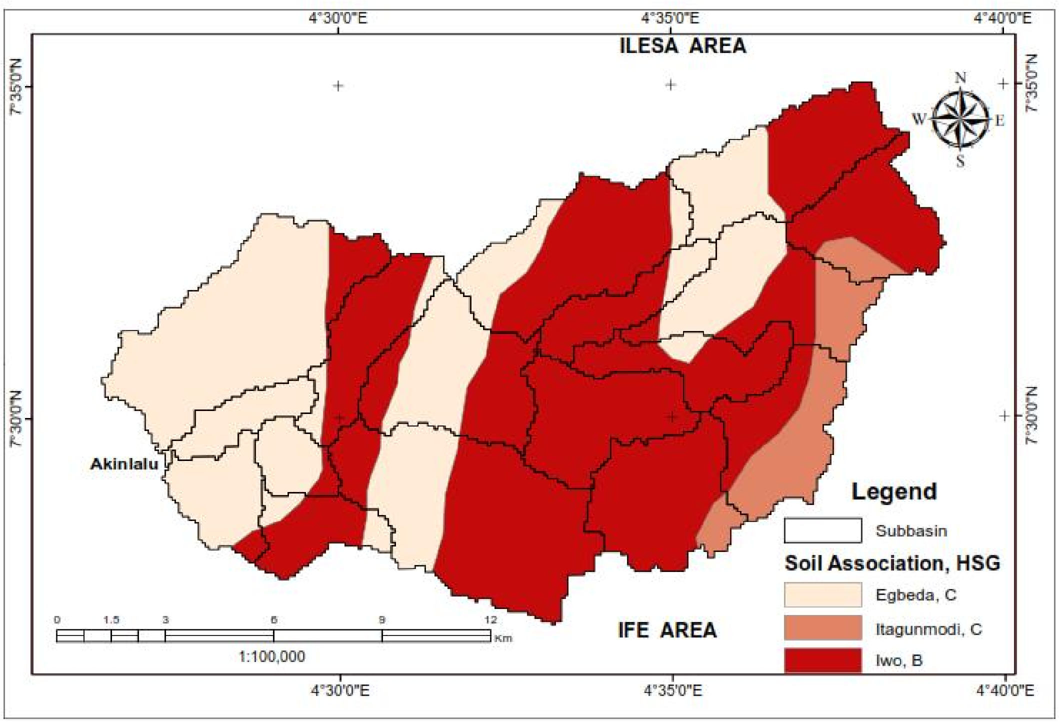

Fig. 5. Soil associations and Hydrologic Soil Groups (HSGs) in the watershed

Table 2. Hydrologic characteristics of the watershed

Sub-basin ID	Sub-basin area (km^2)	Longest flow length (m)	Elevation upslope (m)	Elevation downslope (m)	River slope (%)	Basin slope (%)
SW1	13.91	7.30	453.00	250.00	2.78	2.64
SW2	10.03	6.30	424.00	302.00	1.94	4.43
SW3	14.39	10.23	440.00	230.00	2.05	3.40
SW4	16.75	7.50	303.00	219.00	1.12	1.44
SW5	5.90	6.55	371.00	218.00	2.34	3.55
SW6	8.87	7.52	383.00	212.00	2.28	1.88
SW7	14.37	7.54	279.00	212.00	0.89	1.01
SW8	7.80	8.48	421.00	226.00	2.30	3.56
SW9	24.58	10.07	290.00	190.00	0.99	2.47
SW10	25.50	13.17	351.00	212.00	1.06	3.07
SW11	3.78	3.17	254.00	205.00	1.54	3.90
SW12	5.80	4.87	279.00	205.00	1.52	2.22
SW13	6.32	5.11	262.00	190.00	1.41	1.84
SW14	4.22	5.24	265.00	190.00	1.43	1.71
SW15	11.17	6.52	618.00	255.00	5.57	8.05
SW16	12.81	5.27	305.00	235.00	1.33	2.00
SW17	11.01	6.22	326.00	218.00	1.74	1.27

4. CONCLUSION

The statistical analysis revealed that the proportion of the watershed delineated is 48% of the digital elevation model utilized for this research. The remaining areas are drained by neighbouring sub watersheds in the study area. This study has demonstrated that the recent advancement in geospatial technology provide powerful tools for watershed boundary delineation and extraction of hydrologic characteristics for sustainable watershed management. The difficulties encountered using manual catchment delineation is now eliminated by using digital elevation models captured through remote sensing in a GIS environment by automated algorithms. Division of large watershed into sub-watershed enhances the ability to identify watershed units with peculiar characteristics and manage it accordingly. This will enable river basin authorities to deploy staff to areas that need management attention without much difficulty. This study also gives information about the physical characteristics of the watershed. This is very important in urban planning, resources allocation and flood control. The findings of this study highlight the need for capacity building in geospatial technology and a comprehensive assessment of Nigeria's watersheds beyond the regional large basins in order to sustainably manage the country's abundant land and water resources. However, it should be noted that while automated watershed delineation has advantages such as time and cost savings, repeatability, it also have some disadvantages such as unavailability or high cost of high resolution data which produces the most accurate results.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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