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Assessment of Runoff Potential for Disaster Risk Reduction Using Geospatial Technology in Opa Watershed, Southwestern Nigeria

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Abstract

Flood prediction is very important in land and water resources management. Many flood disasters could be mitigated with adequate preparedness especially in urban watershed. This study assessed the runoff potential of Opa watershed in Southwest Nigeria using remote sensing and the Soil Conservation Service or SCS curve number (CN) techniques. The 2007 NigSat image of the year 2007 was classified into different land cover classes and combined with its hydrological soil groups to determine the curve number of each sub-watershed. The sub-watershed with low curve number is considered to have lower runoff potential while the one with higher curve number is considered to have higher runoff potential. The CN was also used to estimate the potential maximum retention, (S) and potential runoff, (Q) for each sub-watershed using a rainfall event of 2-year return period in the watershed. The weighted runoff was used to determine sub-watersheds with highest and lowest runoff potential. The study showed that urban sub-watershed 9 with average CN value of 85.93 has highest weighted runoff potential (5.53 mm) while the vegetated sub-watershed 10 with average CN value of 69.46 has the lowest weighted runoff potential (0.34 mm). The study concluded that using available geospatial technology and appropriate hydrologic assessment techniques constitute an effective flood prediction method for disaster risk reduction and sustainable urban watershed management.

***Keywords**: runoff, watershed, potential, curve number*

1. Introduction

Flooding is one of the greatest natural risks facing many areas along the river banks in the world today and addressing the risks associated with these river systems involves evaluating its three main components: the hazard, the probability that a flood reaches a certain threshold and the vulnerability (Camarasa-Belmonte and Soriano-García, 2012). A watershed is the area covering all the land that contributes runoff water to a common outlet. Accurate information on runoff in most Nigeria's watersheds is very scarce. However, watershed management programme for natural resources conservation and development requires adequate information about runoff potential. Recent advances in remote sensing and Geographic Information System (GIS) contribute to combination of various data for use in hydrological applications.

In urban watershed, runoff potential usually increases with change in land use due to increase in impervious surface cover. According to Leopold (1968), among all land use changes affecting the hydrology of an area, urbanization is by far the most forceful. The effects of surface imperviousness on the hydrology are changes in peak flow characteristics, total runoff, stream water quality and ecology (Sung and Li, 2010; Suriya and Mudgal, 2012). Surface imperviousness is often used as an overall indicator of the health status of urbanized watersheds and it has also been identified as one of the key factors in the occurrence of flash floods (Canters *et al*., 2006)

The climate change, which was projected to exacerbate the risks of disasters (ISDR, 2008) include flooding, is affecting several countries today and the impact is more severe in areas of greater vulnerability. Approaches toward the management of climate change impacts have to consider the reduction of human vulnerability under changing levels of risk. A key challenge and opportunity therefore lies in building a bridge between current disaster risk management efforts aimed at reducing vulnerabilities to extreme events and efforts to promote climate change adaptation (Few *et al*., 2006; Olorunfemi, 2008).

One of the effective methods of vulnerability reduction in urban watersheds is flood modelling and prediction. Quantification of the spatial distribution of impervious surfaces is very important in flood modeling and flood prediction (Sleavin *et al*., 2000). Direct and indirect methods are available for impervious surface mapping meant for runoff estimation, many of which rely on existing land-use data sets (Sleavin *et al*., 2000). Direct method is preferred at a more spatially detailed level but it is time consuming and tedious, and is most suitable for a small area. The indirect approach, which is less expensive but efficient alternative, is to develop a model that estimates the degree of imperviousness inside pixels of medium-resolution images. The NRCS-Curve Number (CN) method is a suitable model for determining the runoff potential of the watershed based on the percentage impervious surface that is estimated from land cover analysis and soil type, and was selected for this study. The CN method was used because it is a simple and widely applied approach for determining direct runoff volumes from a precipitation event especially for small ungauged watersheds (Ponce and Hawkins, 1996; Garen and Moore, 2005). The CN method was developed by the USDA Natural Resources Conservation Service, which was formerly called the Soil Conservation Service (USDA-SCS, 1985; SCS, 1986). With the recent advancement in geospatial technologies, flood modelling and prediction can now easily be accomplished using appropriate data sets.

The aim of this study is to evaluate the problem of flooding and flood vulnerability in Opa catchment in Southwest Nigeria, using a combination of digital terrain modelling and hydrologic simulations to predict flooding potential in order to reduce flood risk in the study area. The main objective of is to assesses the runoff potential of the watershed using remote sensing and the SCS curve number (CN) techniques.

2. Materials and methods

2.1. Study Area

The study was conducted in Opa watershed which cuts across the boundaries of four local governments – Atakunmosa West, Ife Central, Ife East and Ife North (Fig. 1), Southwestern Nigeria. The watershed derives its name from Opa River, which is the longest stream that flows from Northeast towards the Southwest direction. The river is of third order and the tributaries form a dendritic type with high drainage density. The watershed has an area of 225 km^2 which extends from latitude 7º26'56''N to 7º35'5''N and longitude 4º24'53''E to 4º39'13''E. The climate of the study area belongs to the moist tropical climates according to Köppen Global Climate Classification System (Kottek *et al.*, 2006). This area is known for high temperatures year round and for large amount of year round rain (Garnier, 1967). Rainfall is heavy in all months with average annual value of 1348 mm (Climate-Data, 2014). The driest month is January with rainfall value of 9 mm. Most precipitation falls in September, with an average of 213 mm. The average annual temperature in Ile-Ife is 26.1 °C (Climate-Data, 2014). The geology of the area is classified as basement complex. According to Rahaman (1976), the area is underlain by granite gneiss and schist epidiorite. The soil of the catchment is Alfisols with ferruginous tropical overlay in most cases. The soil is classified at association level into Egbeda, Itagunmodi and Iwo associations (Smyth and Montgomery, 1962) and as OxicTropudalf by the USDA system and it was derived from granite and gneiss parent materials (Ojanuga, 1975).

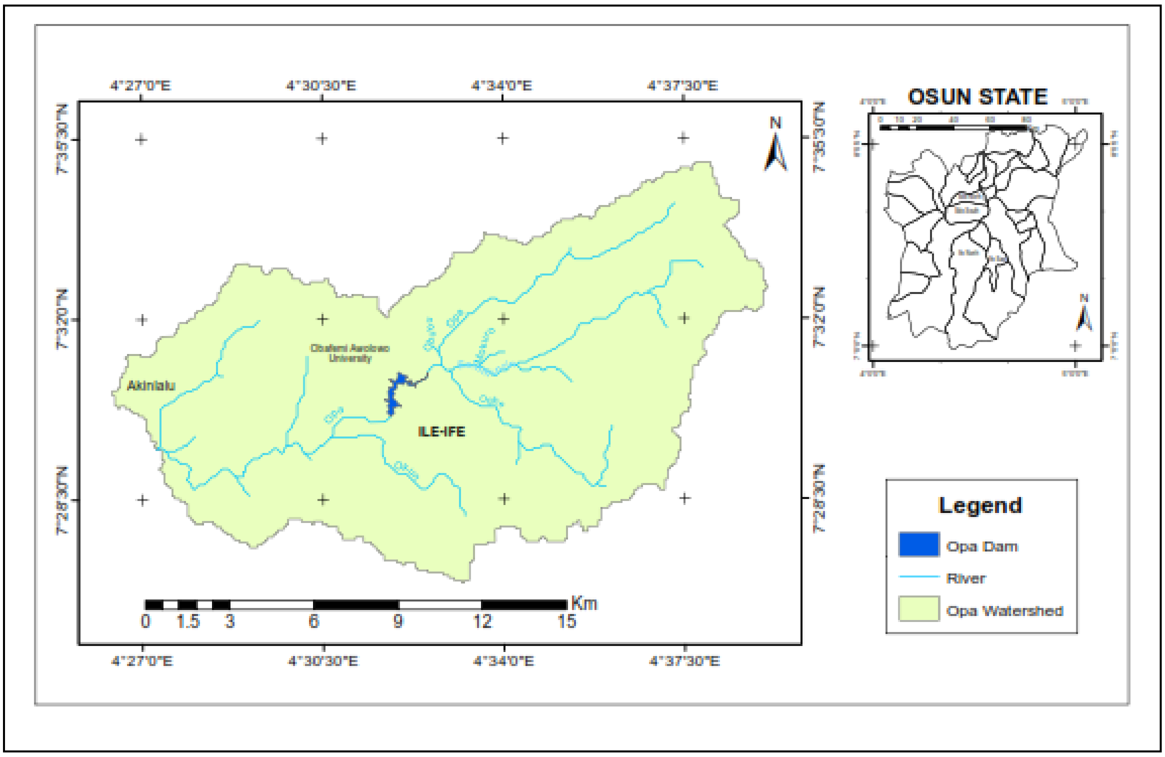

Figure 1: Location of the watershed in Osun State, Nigeria.

2.2. Data Sources

Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) of 30 m resolution acquired from the global land cover facility (http://glcf.umiacs.umd.edu) was used for watershed boundary delineation as well as the creation of sub-watersheds and stream network. NIGSAT image of 2007 (32 m resolution) obtained from Regional Centre for Training in Aerospace Surveys (RECTAS), Obafemi Awolowo University, Nigeria was used to generate the land cover map. The Soil map of Central Western Nigeria obtained from the Department of Soil Science and Land Management, Obafemi Awolowo University was used to generate the watershed soil associations and hydrological soil groups (HSGs). The rainfall data obtained from the Institute of Ecology and Environmental Studies, Obafemi Awolowo University was used to generate rainfall events of different return periods from which the smallest return frequency of 2-year was selected for the CN model. ArcGIS 10.0 software was used for creating, managing, and generating different data layers and maps.

2.3. Watershed Boundary Delineation

The boundary of Opa watershed was delineated using automated method of ArcHydro extension in the Arc GIS. It involved terrain pre-processing and watershed processing. SRTM DEM was used to delineate watershed, sub-watersheds and stream network. The process involved using the ArcHydro tool to iteratively run in-built algorithms to generate different raster and vector layers from the DEM. The preceding layer serves as input for the next process until the final process. The layers generated during the process include: depressionless DEM, flow direction, flow accumulation, stream definition, stream segmentation, catchment grid, catchment polygon, drainage line, adjoint catchment, drainage point and finally, the watershed boundary.

2.4. Generating Hydrologic Soil Groups (HSGs), Land Cover and CN Maps

The Soil map of Central Western Nigeria obtained from the Department of Soil Science and Land Management, Obafemi Awolowo University was scanned, geo-referenced and resampled to 30 m spatial resolution. The map was then digitized to obtain soil associations in the area. After clipping the map with the watershed boundary layer, the three types of soil documented in the watershed were Egbeda, Itagunmodi and Iwo soil associations. Based on the documented characteristics of the soils (Smyth and Montgomery, 1962; Skaggs and Khaleel, 1982; SCS, 1986), Iwo soil association correspond to hydrological soil group HSG B, Egbeda and Itagunmodi correspond to HSG C and were appropriately assigned (Table 1).

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

Soil Group	Description	Range of Loss Rates (cm/hr)
A	Deep sand, deep loess, aggregated silts	0.76-1.14
B	Shallow loess, sandy loam	0.38-0.76
C	Clay loams, shallow sandy loam, soils low in organic content, and soils usually high in clay	0.13-0.38
D	Soils that swell significantly when wet, heavy plastic clays, and certain saline soils	0.00-0.13

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

The NIGSAT 2007 satellite imagery was resampled to 30m spatial resolution, subset to the boundary of the watershed and classified using maximum likelihood supervised classification algorithm of IDRISI Selva software. Four land cover classes obtained after the analysis were: Vegetated Area, Bare and Cultivated Land, Settlement and Water Body. The land cover layer was vectorized and exported to ArcGIS 10.0 where it was reclassified for subsequent merging with shape file of soil. Each land cover type was assigned an estimated curve number value based on hydrologic soil group of the sub-watersheds using documented runoff curve number table (SCS, 1986). CN values range from 100 (for water body) to approximately 30 for permeable soils with high infiltration rates. A Curve Number (CN) grid was generated from GIS analysis of merging land cover and hydrologic soil group shapefiles.

2.5. Estimating Runoff Depth using CN Model

From the CN map, average CN for each sub-watershed was estimated and the maximum potential retention, (S) was calculated using equation 1 (USACE, 2000). The maximum retention, (S) and watershed characteristics are related through an intermediate parameter, the curve number (CN) as:

$$S = \frac{25400}{CN} - 254 \qquad [1]$$

From analysis of results from many experimental watersheds, the SCS developed an empirical relationship between initial abstraction (I_a) from the rainfall event (USACE, 2000).

$$I_a = 0.2S \qquad [2]$$

The potential runoff for a rainfall frequency of 2-yr (77 mm) rainfall event was estimated using SCS-CN model in equation 3 (USACE, 2000).

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad [3]$$

Where Q = runoff depth (mm); P = rainfall (mm); I_a = the initial abstraction (initial loss); and S = potential maximum retention. The weighted runoff depth was estimated for the watershed by multiplying the area of each sub-watershed with its runoff depth value and divided by the total area of the watershed (equation 4).

$$\overline{Q} = \frac{\sum Q_i A_i}{A} \quad [4]$$

Where $\bar{Q}$ is the weighted runoff depth of the watershed, Q_i is runoff depth for each sub-watershed (mm), A_i is the area of each sub-watershed (km^2), and A is the watershed area (km^2).

3. Results

3.1. Hydrological Soil Groups

The watershed contains Iwo soil association which corresponds to hydrological soil group HSG B, Egbeda and Itagunmodi soil associations which correspond to HSG C. The hydrologic soil group map generated in GIS environment for the watershed is shown in Fig. 2. Group B soil has a moderately low runoff potential due to moderate infiltration rates (0.38-0.76 cm/h) and group C with soils having moderately high runoff potential due to low infiltration rates (0.13-0.38 cm/h) (USDA-SCS, 1993). The greater percentage of the catchment is covered by Iwo soil association, HGS-B (57%) with 112 km^2 followed by Egbeda soil association, HGS-C (36%) and Itagunmodi soil association, HGS-C (7%) with 72 km^2 and 13 km^2 extents respectively (Fig. 2).

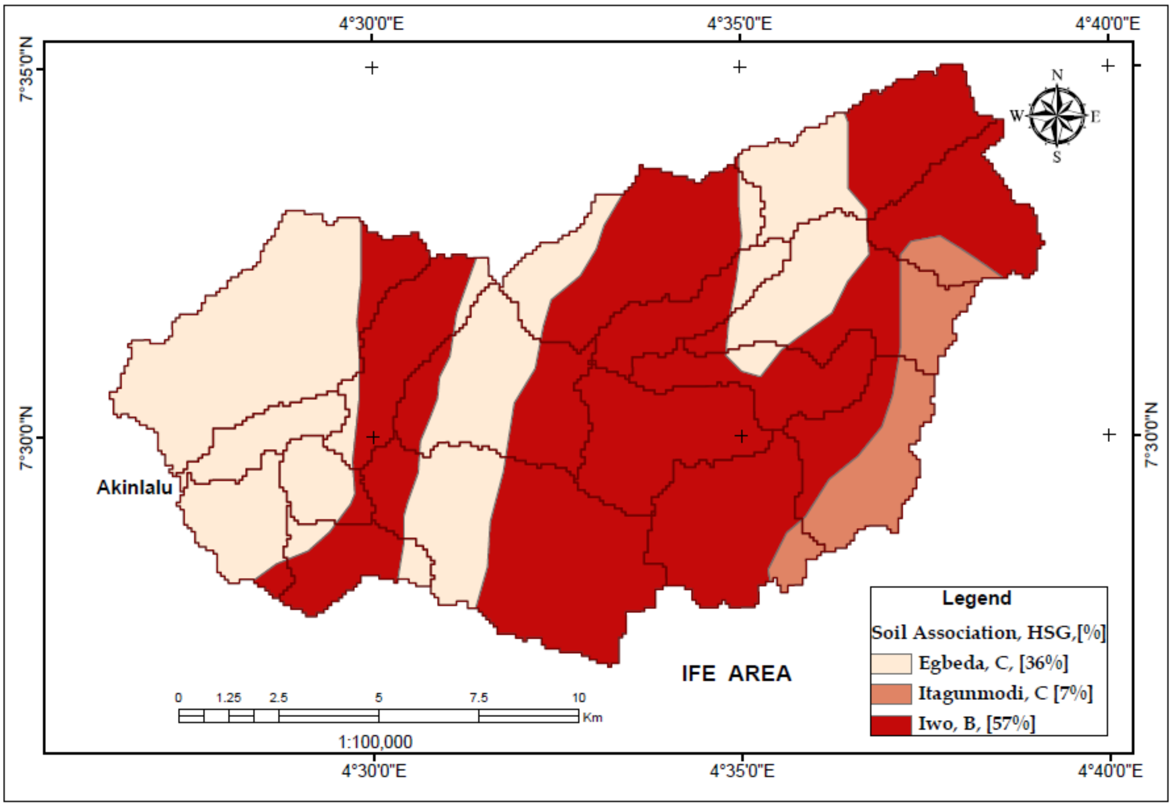

Figure 2: Soil Associations and Hydrologic Soil Groups (HSGs) in the catchment.

3.2. SCS Curve Number (CN) Values

Geographic Information System (GIS) analyses of the land cover and hydrologic soil group shapefiles produced the Curve Number (CN) grid of the catchment shown in Fig. 3. The range of the CN is between 71 and 87. The areas with higher values (sub-watersheds 4, 9 and 16) exist in the urban areas of the watershed and they represent the areas with high runoff potential and low infiltration rate. The areas with lower values (sub-watersheds 4, 9 and 16) exist in the areas with high vegetal cover and they represent the areas with low runoff potential and higher infiltration rate.

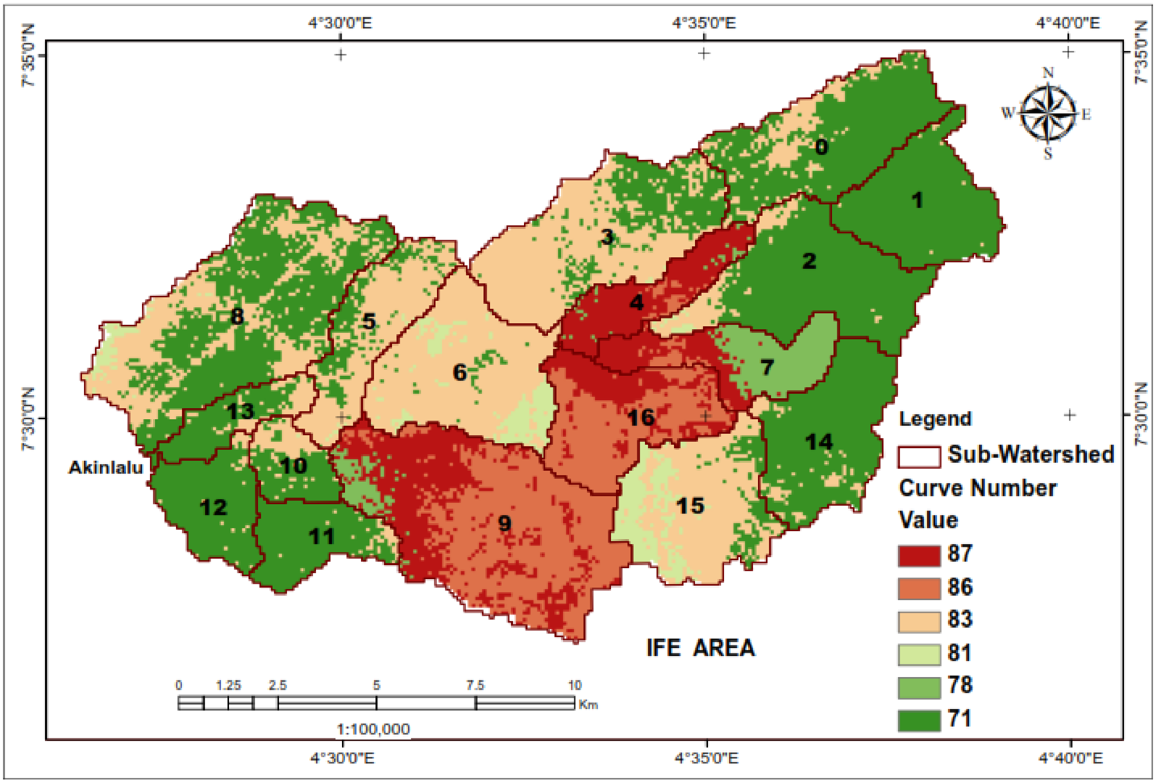

Figure 3: SCS Curve Number for Opa Watershed.

3.3. Estimated Runoff Depth for 2-year Return Period Rainfall Event (77 mm)

The result of potential maximum retention, (S), initial abstraction, (I_a) and potential runoff, (Q) for each sub-watershed using a rainfall event of 2-year return period in the watershed is shown in Table 1. The weighted runoff, ($\bar{Q}$) was used to determine sub-watersheds with highest and lowest runoff potential. The result showed that the weighted runoff, ($\bar{Q}$) ranged between 0.34 and 5.53 mm. The result showed that urban sub-watershed 9 with average CN value of 85.93 has highest weighted runoff potential (5.53 mm) while the vegetated sub-watershed 10 with average CN value of 69.46 has the lowest weighted runoff potential (0.34 mm).

Table 2: Runoff Potential in Opa Watershed

Sub-Watershed	Area (km^2)	SCS Curve Number (CN)	Potential Max Retention, S (mm)	Initial Abstraction, I_a (mm)	Runoff Potential, Q (mm)	Weighted Runoff Potential, $\overline{Q}$ (mm)
0	13.91	73.46	91.77	18.35	22.87	1.61
1	10.03	76.25	79.11	15.82	26.68	1.36
2	14.39	72.71	95.33	19.07	21.90	1.60
3	16.75	79.43	65.78	13.16	31.45	2.67
4	5.9	86.44	39.85	7.97	43.77	1.31
5	8.87	79.9	63.90	12.78	32.19	1.45
6	14.37	82.41	54.22	10.84	36.36	2.65
7	7.8	81.91	56.10	11.22	35.50	1.40
8	24.58	75.84	80.92	16.18	26.10	3.25
9	25.5	85.93	41.59	8.32	42.78	5.53
10	3.78	69.46	111.68	22.34	17.96	0.34
11	5.8	71.91	99.22	19.84	20.89	0.61
12	6.32	71.64	100.55	20.11	20.56	0.66
13	4.22	74.01	89.20	17.84	23.59	0.50
14	11.17	72.03	98.63	19.73	21.04	1.19
15	12.81	81.07	59.31	11.86	34.09	2.21
16	11.01	86.33	40.22	8.04	43.55	2.43

4. Discussion

The use of digital elevation model in watershed boundary delineation is considered efficient for watershed management and acceptable in a moderate terrain like the present study area. Alarcon and O'Hara (2006) compared the SRTM elevation data used in this study to National Elevation Data (NED) used in the United States. They found that SRTM elevation data produced optimum delineation results comparable to delineation achieved using NED when areas and sub-basin perimeters are compared and that SRTM delineation provides overland plane slope values up to 35 times higher than those provided by the NED delineation. The hydrologic soil groups B and C found in the watershed are fairly drained soils that reduce the susceptibility of the watershed to flooding due to moderate precipitation but not to a prolonged and high intensity precipitation. The land cover types influence the watershed vulnerability as areas where there are substantial vegetal covers allows runoff infiltration more than areas with impervious layers due to urbanization (Canters *et al.,* 2006). With the high runoff potential observed in the urban sub-watersheds, further urban expansion towards the vegetated areas, which are mainly on higher elevation will expose the settlement downstream to higher level of flood risk. Contrarily, further afforestation efforts in the vegetated areas and expansion of channels downstream for quick discharge of runoff out of the watershed are potential mitigation strategies against the flood hazard risk. Sustainable watershed management involves knowledge about runoff potential, geospatial technology, hydrological models, meteorological models, as well as understanding other extraneous factors (Montz and Gruntfest, 2002).

5. Conclusions

This study concluded that runoff potential is very high in the sub-watershed with higher impervious surface due to urbanization while the sub-watersheds with more vegetal cover have lower runoff potential. The use of geospatial technology enhances watershed delineation as well as manipulation of various datasets to produce meaningful spatial and non-spatial information for environmental management. Curve Number method is very useful in hydrologic assessment for flood prediction at sub-watershed scale and sustainable urban watershed management. If the government adopts the use of geospatial technology and flood prediction method such as Curve Number at the local government scale and formulates policy in its regard, it will aid flood disaster risk reduction in Nigeria.

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