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An Evaluation of the Impact of Urban Growth on Runoff in Abeokuta, Southwestern Nigeria

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Abstract

Abeokuta is one of the urban areas in Nigeria with high cases of runoff fatalities in recent times, indicating the need for a proper understanding of prominent runoff-generating mechanisms, as well as the causative factors. Consequently, this paper, which is focused on flood-prone settlements, is aimed at providing information on the impact of change in urban land use on runoff in the study area. The specific objectives were to determine the change in average runoff in terms of the Soil Conservation Service Curve Number (SCN-CN), and to assess the impact of urban growth on runoff in the area. The SCN-CN was derived from the 30m spatial Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM). At the same time, land cover change was estimated using Landsat TM+ from 2000 and Landsat 8 OLI from 2018. Data were analysed using the Hydrologic Engineering Centre's Hydrologic Modelling System (HEC-HMS) and ArcGIS (version 10.1). The results showed a 14% increase (from 39% in 2000 to 53% in 2018) in urban areas of selected catchments; and a relative increase in average CN from 76.9 units in 2000 to 79.9 units in 2018, suggesting an increase in runoff potential relative to the increase in urban/impermeable space in the catchment. Annual discharge depth increased from 891.84mm to 956.9mm, while peak discharge increased from 161.9m^3/s to 196.2m^3/s. Runoff in the study area tends to exhibit spatial variability that is similar to the pattern exhibited by built-up areas across the study area, suggesting that the development of built-up areas can explain runoff exacerbation in part of the area. The use of SCN-CN and satellite images makes the approach reproducible, and the mixed methods of geographic information system and hydrological model revealed the spatial variability typically hidden in stand-alone hydrological models. The paper recommends further studies with the use of less coarse datasets, as well as the implementation of policies that focus on sustainable urban growth in the region, and other cities.

Keywords: *urban growth, land use/cover change, curve numbers, HEC-HMS*

1. Introduction

Urbanization is a process of urban growth and development (Onanuga et al., 2021). It is associated with population growth and poorly controlled constructed areas, and the distribution of human populations in many countries, particularly in parts of sub-Saharan Africa, Asia, South America, and Eastern Europe (Miller

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et al., 2014). In many developing countries, urbanization is characterized by rapid urban population growth caused by rural-urban migration, and a natural increase in births (UNFPA, 2017). Population increases in urban settlements in many parts of developing countries are fuelled by rural-urban migration, which is often associated with an unequal distribution of economic products and infrastructure, as described in the core-periphery concept (Moore & Owens, 1984; Borgatti & Everett, 2000; Klimczuk & Klimczuk-Kochańska, 2019).

The core-periphery concept describes the disproportions and asymmetric distribution of indices of regional development in a settlement, or regional centre (or core) and periphery. According to Klimczuk & Klimczuk-Kochańska (2019), the periphery is often perceived negatively, and peripheral areas are generally worse equipped with basic amenities than the core, although they (the periphery) may be sources of agricultural structures or natural resources that serve the core. As urbanization progresses, pressure on the core and periphery tends to increase, so that land and water resources are degraded, and vegetated land areas may be replaced by impermeable areas, with negative consequences for land use, livelihoods, land cover, etc.

One of the vulnerable areas in the course of urban growth or development is usually wetlands and catchments, which not only undergo major changes, and in turn often destroy the hydrological characteristics of wetlands and catchment areas (Johnson & Sayre 1973; Paul & Meyer, 2001) that are also becoming sought-after areas for agriculture and residential use. Significant portions of catchments are often converted into impermeable areas, resulting in increased runoff and reduced soil infiltration capacity (Arnold & Gibbons, 1996; Shuster et al., 2005; Chen et al., 2009). Studies have shown that the results from one catchment may not be representative of other catchments due to the tendency of catchments to behave differently. This suggests the need for further research (Blosl et al., 2007). Dudley et al. (2001), for example, reported no historically significant change in peak flows despite a large increase (161%) in impervious surface in a watershed in southern Maine; while Warburton et al. (2012) reported complex and varied contributions of land use change to watershed response to precipitation in their study area.

Despite the need for more research, many developing countries face the problem of the unavailability of accurate information on runoff, and too few recording stations have efficient automatic hydrological monitoring stations installed (Devi & Katpatal, 2016). Most catchments are ungauged, with limited records on daily precipitation and runoff variables. Consequently, techniques that do not require the availability of continuous rainfall and runoff records have become relevant in runoff assessment studies in many developing countries. An important method for predicting and estimating runoff, often referred to as the Soil Conservation Service Curve Number (SCS-CN), has proven useful and accepted worldwide for estimating surface runoff from ungauged basins (Boughton, 1989; Chattopadhyay & Choudhury, 2006; Sindhu et al., 2015). The SCN-CN method is widely used in most hydrological and water quality models due to its robustness and ease of application in different catchments. Therefore, the objectives of the study that led to this paper were to determine runoff coefficients in the study area and to assess the impact of urban growth on runoff in the region. The area is a typical urban settlement in southwestern Nigeria, which has experienced rapid urban growth in recent years due to population growth, and the government's decision to urbanize. However, it is uncertain how large the impact of urban growth is on catchment areas in the region, hence this study.

2. Materials and Methods

2.1 The Study Area

This paper is based on data from a study conducted on a 4th-order catchment of the Ogun River in Abeokuta, Ogun State (7'00'N, 3'5'50'E - 7'30'N, 3'30'E; Figure 1). The study area is characterized by a warm, humid climate zone with the characteristic distinct rainy and dry seasons.

Dry days occur on an average of 130 of the 365 days per year; and the mean annual precipitation, temperature, and potential evaporation average is 1,270mm, 28°C, and 1,100mm, respectively (Akinse & Gbadebo, 2016). The study area is mainly drained by the Ogun and Oyan rivers and their tributaries. Geologically, the study area belongs to the transition zones of southwestern Nigeria, partially underlain by the basement complex (in the northern part) and sedimentary rocks (on the border with the Republic of Benin), and part of the Ise formation of the Abeokuta group in the southeastern part. The section of the basement complex is covered with organic, friable, and reddish sand. The bedrock consists of the ancient gneiss-migmatite series, while the Ise formation of the Abeokuta group consists of conglomerates and grains at the base; and are in turn overlain by coarse to medium-grained loose sand (Akinse & Gbadebo, 2016). Stream flow in the area is strongly influenced by topography, resulting in the formation of overland and slope springs (Orebiyi et al., 2010).

2.2 Data Collection

The data used were the daily precipitation data for the years 2000 and 2018, and the Landsat images for the same years. The Landsat images were Landsat -5 Enhanced Thematic Mapper Plus with a spatial resolution of 30m (ETM+; 02/06/2000; path 191, line 055), and Landsat 8 Operational land images (OLI, 01/20/2020, path 91, line 055); both of which could be downloaded free of charge from the official website of the Global Land Cover Facility (www.glcf. umiacs. umd.edu), hosted by the University of Maryland, USA.

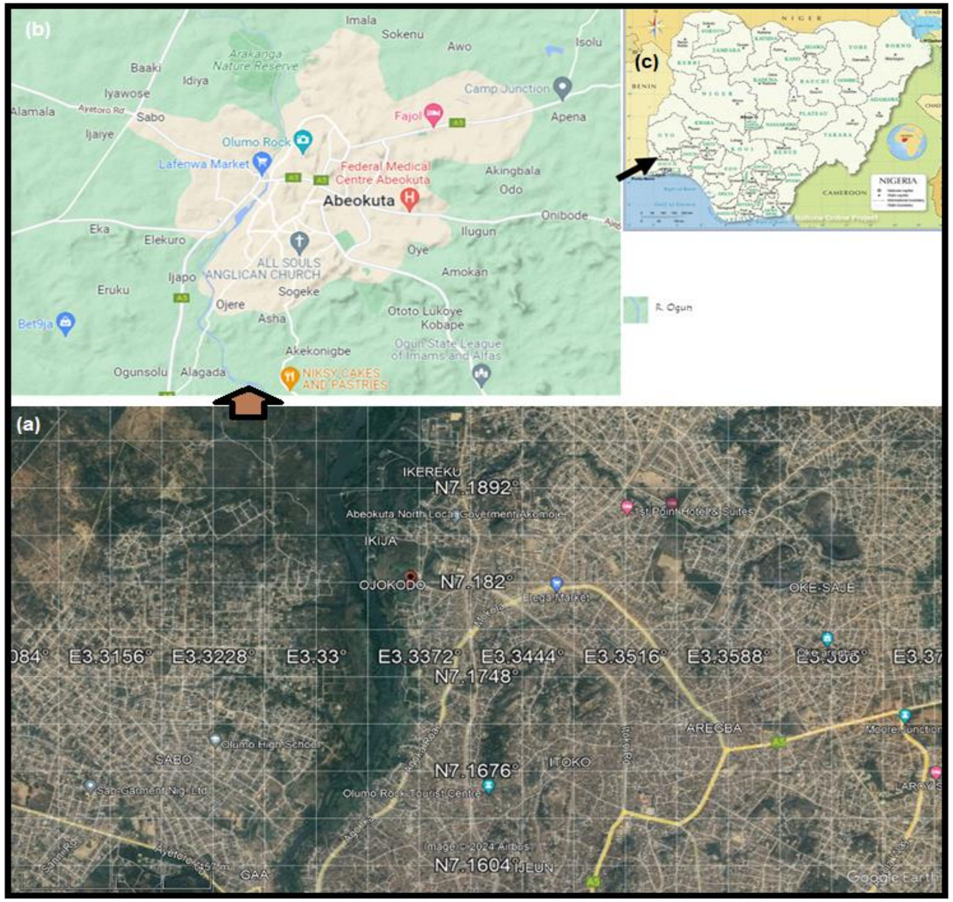

Figure 1: The Study Area, Indicating the Flow Path of River Ogun in Abeokuta (a), and Neighbouring Settlements (b), in Ogun State, Nigeria

The data also included the 30m spatial resolution Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM; SRTM DEM) for the same period, available from the United States Geological Survey website (USGS Earth Explorer, http://earthexplorer.usgs.gov/). For clearer images, all data were collected for the dry season (December–March).

2.3 Data Analysis

The images were rectified, processed, and classified using the supervised classification method with maximum likelihood clustering in ArcMap (version 10.1). Consequently, four land use/cover classes (urban, forest, light vegetation, and water body) were generated. The HEC-HMS, designed to simulate rainfall-runoff processes for drainage basins (Ponce & Hawkins, 1996; Soulis et al., 2009) was adopted for the rainfall-runoff model being an ungauged river at the part of the study area. The Soil Conservation Service Curve Number (SCS-CN), a widely used method to elucidate the rainfall-runoff process, was also used to estimate and predict runoff and runoff depths in the area. Values of SCS-CN or CN can also be used to interpret the effects of land cover changes on runoff yield (Devi & Katpatal, 2016). The CN was estimated using equation 1:

$$P_e = \frac{(P - Ia)^2}{P - Ia + S} \qquad (1)$$

Where

P_e = accumulated precipitation excess at time t;

P = accumulated rainfall depth at time t;

Ia = the initial abstraction (initial loss);

S = potential maximum retention, a measure of the ability of a basin to abstract and retain storm precipitation, until the accumulated rainfall exceeds the initial abstraction, the precipitation excess, and hence the runoff, will be zero.

The maximum retention, S, and basin characteristics are related through CN (equations 2−3; Feldman, 2000)

$$S = \frac{1000 - 10CN}{CN} \qquad (2)$$

$$CN = \frac{1000}{(10 + S)} \qquad (3)$$

The CN values range from 1 to 100, with increasing values suggesting increasing potential for runoff.

In addition, the HEC-HMS model was calibrated with DEM data, slope, flow paths, centre points and reach lengths, and other catchment attributes to delineate the drainage area into different heterogeneous subbasins and extract channel flow characteristics using the HEC-HMS Arc-Hydro extension in ArcGIS (10.1). Regarding precipitation, one-year event data were retrieved from the Tropical Rainfall Measurement Mission (TRMM) archive for a one-year event-based simulation (the May 2−4, 2018 precipitation event was adopted) due to the availability and modelled using the hyetograph method and the gauge option to run the precipitation data. Daily precipitation data was also downloaded from the TRMM archive. To achieve the model, the 'Control Specification Manager' in ArcGIS software (10.1) was used to create control specifications for each of the years under consideration.

3. Results and Discussion

3.1 Land Cover/Use and Corresponding Runoff Coefficients

Figure 2a−b shows the distribution of land cover/use and corresponding CN over the study area for the years 2000 and 2018. In 2000, the built-up or urban area occupied almost 39% (124.6km^2); and this number increased by 40.4% (175.0km^2) in 2018. This suggests that a large part of the forest area was converted into an urban landscape within the study period (Figure 2ai, bi). The CN results indicated a generally increased runoff potential throughout the basin. CN at most parts of the study area, except the northeastern region, was at least 77; and the area with fewer numbers (in the northeastern part of the area) shrank by about 38% by 2018 from what it was in 2000 (Figure 2aii, bii). Between 2000 and 2018, light vegetation and forest area decreased by -92.8% and -5.5%, respectively (Figure 3). The results also showed that the study area had lost most of the forest cover by 2000, and had lost 5.5% of it by 2018. The CN average increased from 76.9 units to 79.9 units between 2000 and 2018.

In general, forest and agricultural areas lost large and significant hectares to urban development, similar to the observations of previous studies (e.g., Oyinloye & Kufoniyi, 2011; Jesuleye et al., 2013; Ibrahim et al., 2016; Usman et al., 2018), which linked the increase in impervious surfaces—and thus increased surface runoff and susceptibility—to nonpoint source pollution to urbanization. When compared at the sub-catchment level, the section in the northeast region (W840) had the lowest runoff potential (CN $\leq$ 43 units). In comparison, the sub-catchment in the built-up area (W1160) had the highest runoff potential (CN = 88.7 units) (Figure 4). Figure 4 also shows that CN increased throughout the sub-basin; although at a lower rate in subbasin W820, which is characterized by lighter vegetation than other land covers/uses. The increased runoff in the developed area is not unexpected as existing studies (e.g., Carlson & Arthur, 2000) have shown that urban areas have higher runoff potential than relatively undisturbed areas. Many reasons—including population increase through births and migration, as well as planned construction with the intention for urbanization—have been mentioned in the literature to explain land conversion (Ahmed & Dinye,2011; Ayele & Tarekegn, 2020).

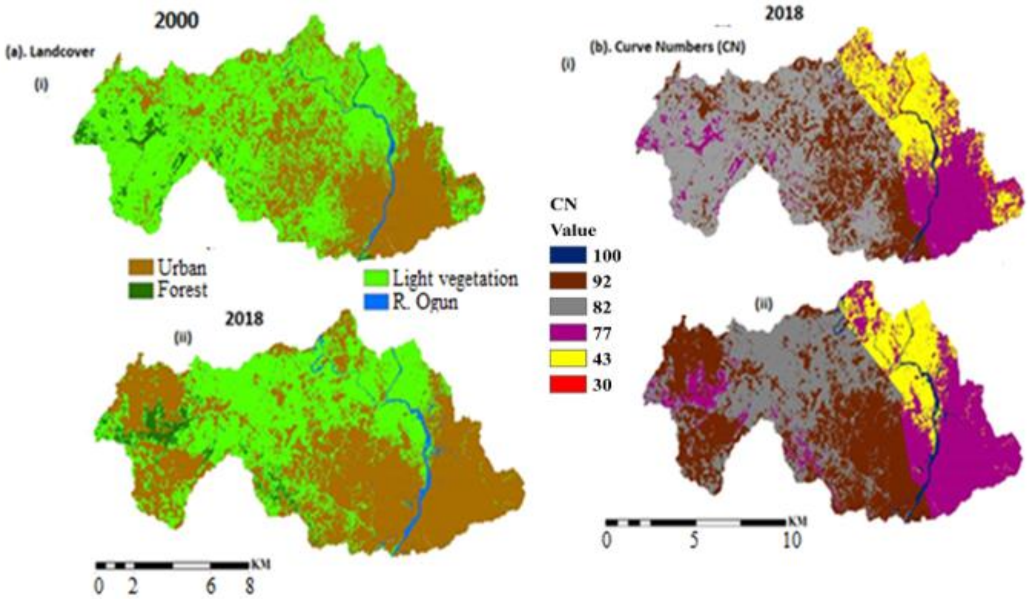

Figure 2: Land Cover/use (ai-ii)- and Corresponding SCN – CN (bi-ii) in 2000 and 2018

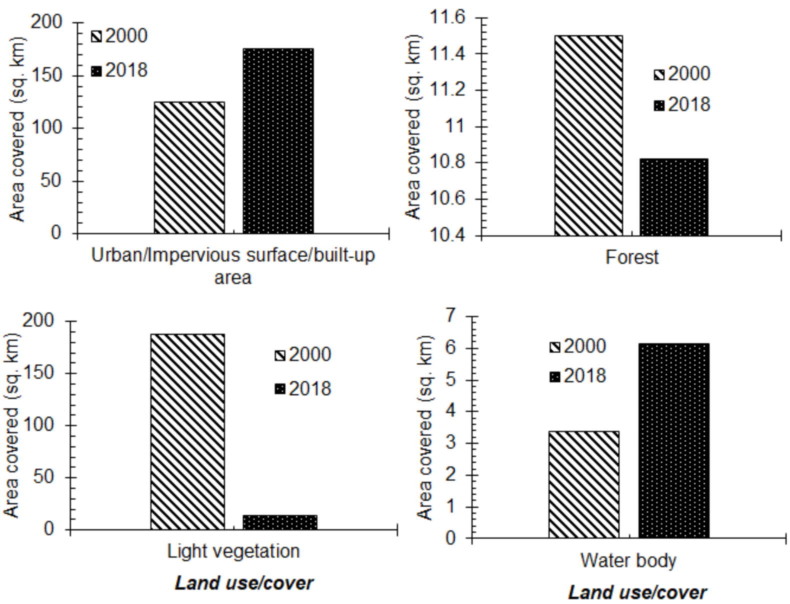

Figure 3: Changes in Land Use/cover in the Study Area (2000 and 2018)

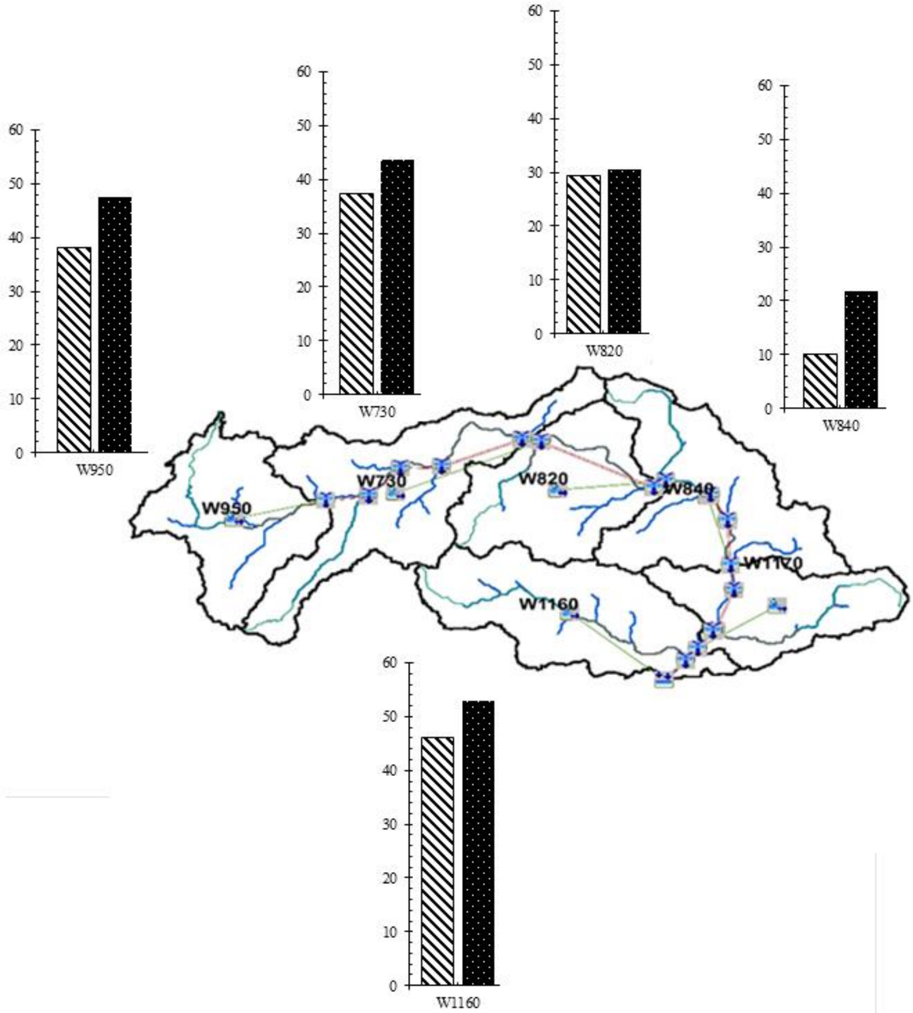

Figure 4: Runoff Depth (mm) in 2000 and 2018 at Different Sub-basins in the Study Area

3.2 Runoff Characteristics

Figure 5 shows the temporal distribution of precipitation and runoff in 2000 and 2018. Mean runoff peaked in July ($420.9m^3s^{-1}$) in 2000 and in May ($287.2m^3s^{-1}$) in 2018. The peak in 2000 was higher than what was reached in 2018. Runoff also appeared to be positively correlated with monthly runoff in both years studied, as both variables fluctuated simultaneously. Existing studies (e.g., Shuster et al., 2005; Singh et al., 2006; Eludoyin et al., 2017) showed that a positive relationship between precipitation and runoff could indicate the importance of overland flow mechanisms (Ologunorisa et al., 2021). Overland flow mechanisms (particularly the infiltration-excess type) are prevalent in various soil and vegetation environments, largely impermeable or loosely vegetated but dry surfaces, riverine wet and vegetated surfaces, and areas characterized by natural or artificial moles or pipes (Beven, 1986; Eludoyin, 2013; Eludoyin et al., 2017). Furthermore, studies (such as Cheng et al., 2009; Sanyal et al., 2014) suggest that the excess of infiltration at any location, except a predetermined one, increases as development and corresponding impermeable layers increase.

In Nigeria, many programmes that have been aimed at improving urban growth and development—such as road construction—have been abandoned in many settlements across the country, causing such areas to be vulnerable to flood, and gully erosion (Aiyewunmi, 2023; Okonkwo et al., 2023). For instance, some studies (e.g., Nyssen et al., 2002; MA & Eburukevwe, 2013; Adediji et al., 2013) have noted that gullies were initiated around abandoned road construction projects, causing significant runoff processes. Adediji et al. (2020) linked the emergence of accelerated gully heads to abandoned road construction sites in a part of Osogbo, Nigeria. Such abandonment or delay in the completion of roads, bridges, etc., are not uncommon sites in the present study area, hence justifying the high tendency for increased runoff observed in this study. The fact that abandonment does not occur in all the sections of the city, and that urban growth does not take place uniformly, could also explain the spatial variations in the runoff occurrence across the study area (Figure 6).

3.3 Changes in Average Runoff Condition

Figure 6 shows the average event-based dynamics of peak discharge in all the sub-basins. All six hydrographs show a progressive increase in peak flow, with the highest peak flows observed in the 2018 land use scenario. The sub-basins with less temporal runoff difference were relatively less disturbed (sub-basin W820) than the sub-basins with obvious temporal runoff differences, suggesting that built-up areas recorded more discharges than the less disturbed regions. An evaluation of land use/land cover changes around the Ogun River basin within the study period has suggested a steeper hydrograph in 2018 than in 2010; a condition that points at increased propensity to floods in a later period (see, e.g., Adelekan, 2011; Oyedepo et al., 2021).

The scenario of increased runoff can explain the now-common incidences of flood disasters in many parts of Abeokuta, particularly in the wet season. Based on the results in Figure 6, the Ogun River basin now responded faster to precipitation than it did in 2010 at all the sub-basins except W820, where the change in the hydrograph was not obvious.

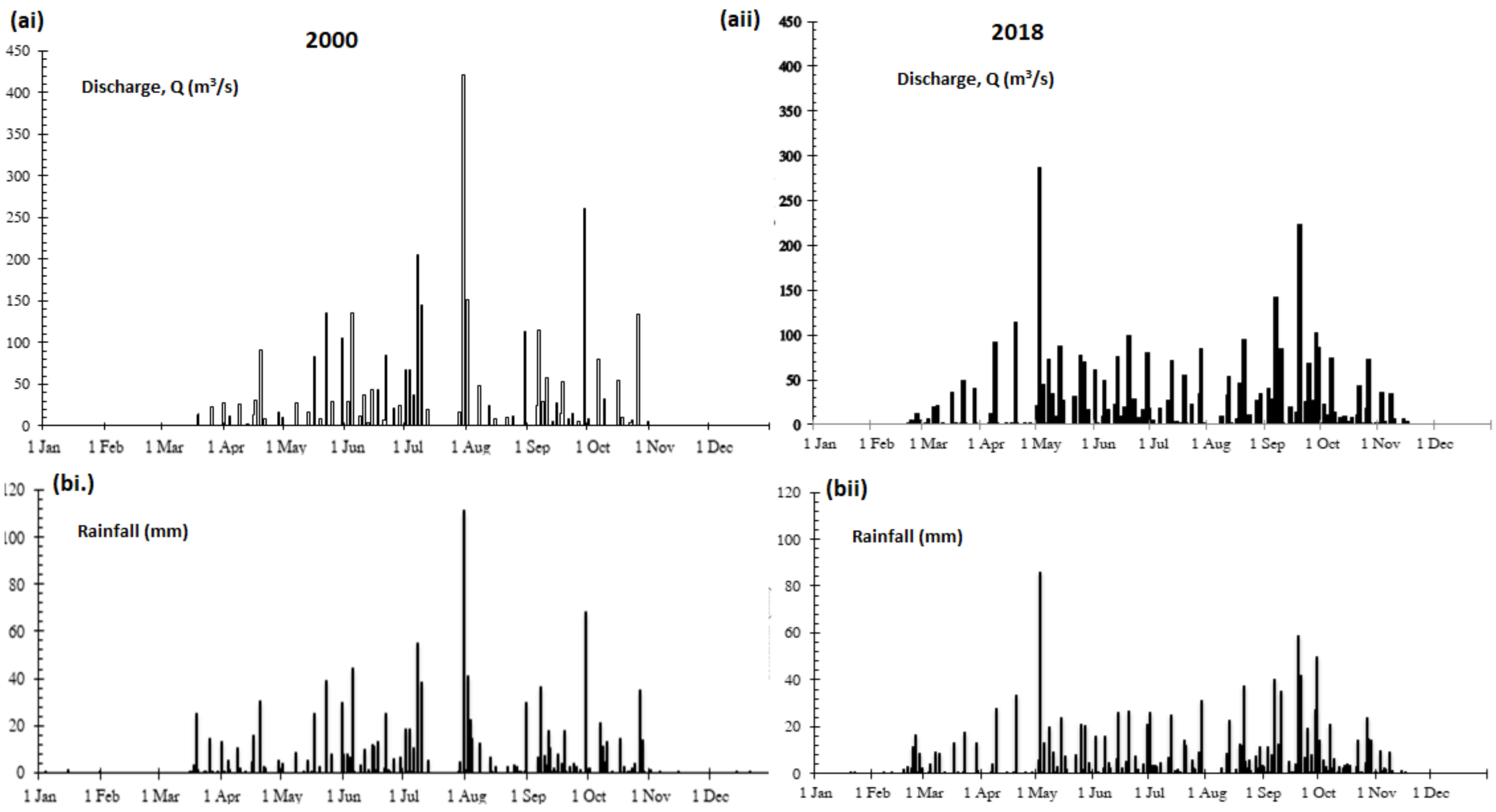

Figure 5: Runoff (Discharge) and Associated Rainfall in the Study Area

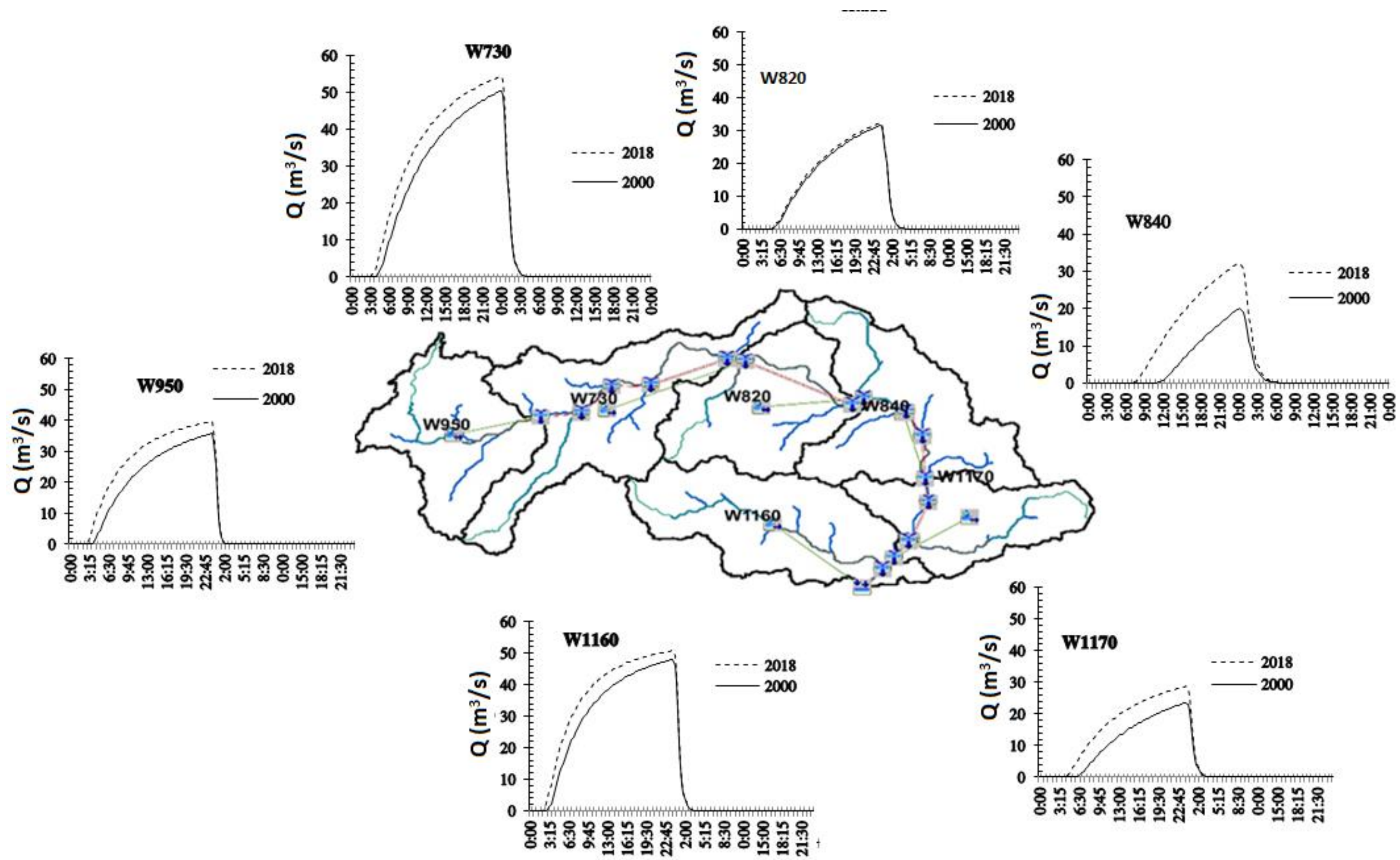

Figure 6: Contrasting Event-based Peak Runoff depth (mm) in 2000 and 2018 at the Sub-basins in the study area

The removal of vegetation and increased imperviousness are important factors that increase runoff response to precipitation, and this implies that more areas experience infiltration-excess overland flow-induced floods, which are more rapid, flashy, and shorter-spanned than saturation-excess flow-induced floods that occur more in vegetated and less impervious areas (Eludoyin, 2013; Neumann et al., 2021; Cao et al., 2023). In many urban areas in Nigeria, flood occurrences are exacerbated by waste dumps that eventually block free water flow along river channels (Asabere et al., 2020; Cao et al., 2020).

Conclusion

This study attempted to examine environmental changes due to the urbanization process, especially in areas within a river basin in a typical medium-to-low-economically developed country. The Nigerian example illustrates the capacity to provide information on the impact of change in urban land use on runoff in a flood-prone area, using sets of open-access remote sensing data (SRTM DEM and Landsat data) that are also available for users that might want to adopt, replicate, or advance the study in data-difficult communities. Study objectives—which included the determination of change in runoff coefficients and assessment of the impact of urban growth on runoff in the area—were achieved using the open access version of Hydrologic Engineering Centre's Hydrologic Modelling System (HEC-HMS), and the ArcGIS (version 10.1), whose cost was subsidized.

The results showed a 14% increase (from 39% in 2000 to 53% in 2018) in urban areas of selected catchments, and a relative non-uniform increase in runoff across the study area; the non-uniformity being due to varying rates of urbanization across the spatial scale. Annual discharge depth increased by 6.9%, and peak discharge increased by 17.5%. Consequently, runoff in the study area tends to exhibit spatial variability that is similar to the pattern exhibited by built-up areas across the study area, suggesting that the development of built-up areas can explain runoff exacerbation in part of the area. The use of SCN-CN and satellite images make the approach reproducible; and the mixed methods of geographic information system and hydrological model revealed the spatial variability typically hidden in stand-alone hydrological models. Finally, we recommend further studies with the use of less coarse datasets, as well as the implementation of policies that focus on sustainable urban growth in the region, and other cities.

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