Bima Journal of Science and Technology, Vol. 8(1B) Apr, 2024 ISSN: 2536-6041

DOI: 10.56892/bima.v8i1.628

Hydraulic Evaluation of Urban Drainage System for Flash Floods in Abeokuta, Nigeria

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ABSTRACT

Flash floods are rapid-onset floods typically caused by intense rainfall over a short period, often exacerbated by factors like urbanization and deforestation. This study presents a hydraulic evaluation of the urban drainage system in Olorunsogo, Abeokuta, Ogun State, focused on assessing its capacity and efficiency. Measurements of the width, depth, and length of the drains were conducted to determine their total volume. The system's adequacy was evaluated using a drain ratio, which compares the drain volume to the catchment area's runoff volume, expressing the system's capacity to manage runoff. The study found that the total volume is estimated at 46,094.09 m^3. The drainage system could only accommodate a limited portion of runoff generated over time. Within one hour, it could handle 32.06%, increasing to 64.13% after two hours, and reaching 96.2% in three hours. However, a significant volume of runoff, up to 737,505.44 m^3, would still overwhelm the system in heavy rainfall events lasting over three hours, leading to potential flooding. The study highlights the limitations of the urban drainage system in Olorunsogo, Abeokuta, Ogun State, in managing runoff, particularly during heavy rainfall events. Appropriate recommendation such as implementing floodplain evacuation and a 200 m setback limit, demolishing buildings in high-risk areas, and redesigning the drainage system for improved flash flood management were given for practical adaptation.

Keywords: Flash flood, Drainage system, Capacity, Runoff, Efficiency

INTRODUCTION

Flooding in urban areas of Nigeria has become a recurrent concern, often attributed to inadequate drainage systems, poor urban planning, and climatic changes (Ajibade *et al*., 2013). During a flood, streams and channels are unable to convey the amount of water that has been generated through the runoff process. Sometimes water is unable to escape downstream due to high water levels in receiving streams. Consequently there is an overspill of water over the river banks (Sobowale and Oyedepo, 2013). Urban drainage systems are critical infrastructures that influence the livability and sustainability of urban environments. The effectiveness of these systems is pivotal in managing storm water, reducing flooding risks, and ensuring environmental protection (Zhou, 2014). In many developing countries, including Nigeria, urban drainage systems are often inadequately planned and maintained, leading to recurrent flooding issues (Adelekan, 2010). Urban areas are expanding rapidly, leading to the replacement of natural landscapes with extensive impervious surfaces due to urban development (Smith, 2017). These impervious surfaces can impact local streams and alter flooding patterns (Johnson *et al*., 2021).

The stormwater drainage systems in urban areas are typically designed to efficiently collect and channel excess surface runoff to prevent urban flooding (Gouri and Srinivas 2015). However, many of these drainage networks experience reduced functionality and capacity over time due to factors such as degradation, inappropriate design, insufficient maintenance, sedimentation, increased roughness of materials, and structural deterioration. Urban development and climate change further compound these challenges (Torres, 2006). In the absence of effective surface-water drainage, frequent flooding can lead to various problems: infrastructure damage, including roads, buildings, and goods, incurring significant costs; contamination of runoff with human waste from latrines, septic tanks, and sewers during floods, which spreads throughout the affected areas; and the creation of stagnant ponds that become breeding grounds for mosquitoes, contributing to the spread of diseases like malaria (Negin *et al*., 2016).

Floods in Nigeria, triggered by urbanization, are not a recent development. The beginning of the wet season in 2007 brought about extraordinary flood disasters in numerous urban and rural areas across the nation, catching both residents and government off guard (Adelekan, 2010). On July 26, 2007, the citizens of Abeokuta, capital of Ogun State in southwestern Nigeria, experienced a flood of exceptional severity, considered by many as the most severe in the city's recent memory (Adelekan, 2010). Lack of surface-water drainage and frequent flooding creates many problems in the urban settlement. The flood damages infrastructures such as roads, houses etc. The situation in Olorunsogo area of Abeokuta, Nigeria, exemplifies the challenges faced in such urban settings, where rapid urbanization, poor infrastructural planning, and climatic variations converge to exacerbate flooding risks (Oyebande and Odunuga, 2012). This paper aimed at conducting a hydraulic evaluation of the urban drainage systems in the Olorunsogo area of Abeokuta Nigeria, in order to determine the flood vulnerability in the area.

MATERIALS AND METHODS

Study Area

The study area is Olorunsogo in Abeokuta. Abeokuta is the capital city of Ogun State, and shares boundary with Lagos and Oyo states. It is situated in the sub-humid tropical zone of southwestern Nigeria. This catchment is marked by a tropical climate, distinctly divided into wet and dry seasons. The wet season occurs under the influence of a moist tropical maritime air mass from the Atlantic Ocean, while the dry season is driven by a tropical continental air mass originating from the Sahara desert. The region is noted for its bimodal rainfall distribution, with the heaviest rainfall occurring from April to July, followed by a lesser rainy period from August to October. In Abeokuta and its surroundings, the average annual rainfall is about 1238 mm, and the temperature typically averages 27.1°C. The elevation in the Olorunsogo area varies between 63 and 101 meters.

Data Requirement and Analysis

The data required for this research include: Rainfall data of the area, geometric properties of the drains (such as width, depth, and length of both natural and artificial drainage), the topographical map, and runoff (volume).

Topographical Map

The topographical map was used to show the flow direction of natural drainage and also to indicate the various elevation and water bodies of the study area. The map was also use to delineate the catchment area.

Catchment Size (Area)

The size of the catchment was determined using satellite map in conjunction with the topographic of the entire catchment. By using the add polygon, the area studied was marked out after which the area was obtained. The co-ordinates and topographical map were obtained using the Google Earth Pro software. The area of each land use features were calculated.

Geometric Properties of Drainage structures in the Study Area

The geometric attributes of the drainage system (both natural and artificial) such as the width, depth and length of the drainage were determined. The width and depth of both the natural and artificial drainage were measured using a measuring tape in cm. Different points of the drainage were measured and the average of the data given was used to calculate the maximum of runoff the drain can accommodate without flooding.

Rainfall Data of the Study Area

Daily precipitation records covering an 18-year period (2001-2018) for Abeokuta metrological station were acquired from the Nigeria Meteorological Agency (NIMET) in Oshodi, Lagos State. These precipitation records were then subjected to trend analysis using Microsoft Excel. The average rainfalls for each year were determined. The rainfall data were also used in estimating the catchment runoff. Values of discharge and velocity are obtained for varying volume of runoff in the drainage.

Estimating runoff from rainfall data for the Study Area

Runoff was calculated using HYDROWAT software. The software runs using the CN (curve number) method, and was developed using python for the encoding.

NRCS Curve Number (CN) Model

In the CN method, the volume of runoff (Q) relies on various factors, such as precipitation amount (P), potential maximum soil retention (S), and initial abstraction (Ia). Through analysis of natural rainfall and runoff data, the Soil Conservation Service (SCS) found that runoff does not commence immediately upon the onset of rainfall but rather after a certain threshold of rainfall has been reached as stated in United State department of Agriculture (USDA, 2004). Equations (1) and (2) were used to calculate the runoff volume, Q:

$$Q = \frac{(P-Ia)}{(P-Ia)+S} \qquad (1)$$

And,

$$I_a = 0.2S \qquad (2)$$

Where, Q = runoff volume; P = Amount of rainfall S = Maximum soil retention

I_a = Initial Abstraction

(USDA, 2004)

In calculating the composite curve number, the percentage of each land features was multiplied by their respective curve number and then divided by 100. The runoff result for 18 years (2001-2018) was analyzed using Excel spreadsheet and the average runoff for each year was determined.

Estimating the Amount of Runoff the Drains Can Accommodate (Volume)

After the geometric properties were obtained, it was used in estimating the total volume of runoff the drains can accommodate in terms of volume using Equation (3)

Volume = Length × Depth × Width (3)

RESULTS

The results of the topographic map, geometric characteristics of the drainage (natural and artificial), rainfall data analysis and the runoff were presented below.

Topographical Map

The topographical map generated was use to delineate the expanse of land contributing runoff to the study area. The delineated watershed was discovered to be 4,803,518.87 m^2. The elevation of the catchment area range from 65 – 140 m and the landforms includes rivers, road, bridge, forest cover and residential areas. The topographical map through the vector lines showed that, runoff generated in the catchment flows toward the outlet in the southwest direction. Elevation transect of the catchment length is presented in the Figure 1, starting from Asero at an elevation of 130 m above sea level and slopes towards River Iran-ala with an elevation of 64 m which is approximately 3,091 m from Asero. From the bridge toward Iyana-mortuary, the elevation was 64.75 m.

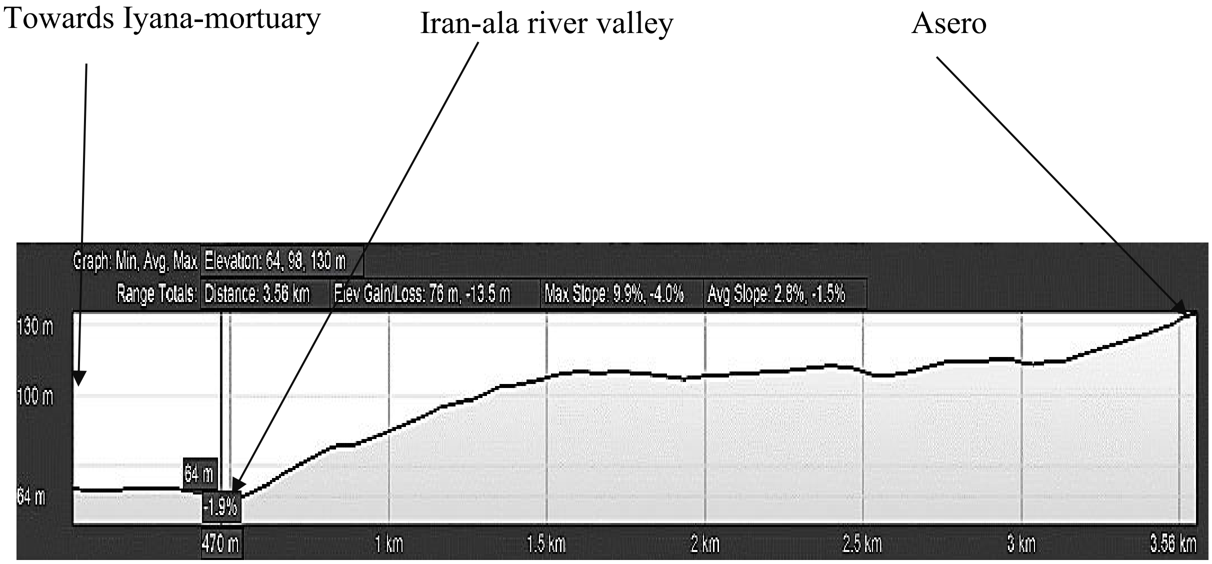

Figure 1: Elevation transect of the study area

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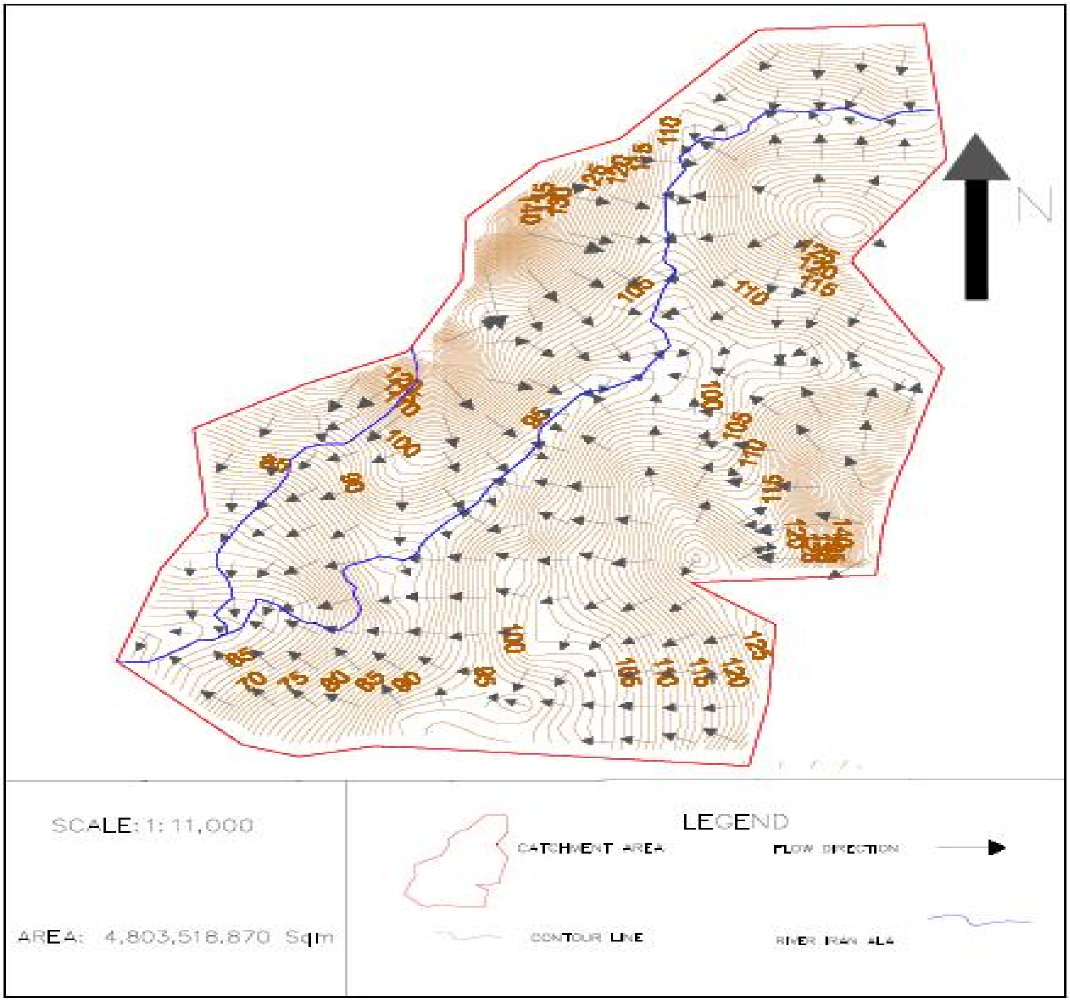

Figure 2: Topographical map of Olorunsogo catchment

The land use in the study area consisted of the following categories: Residential, which encompasses around 4,803,518.870 m^2, constituting 84% of the total land use. Additionally, paved roads, streets, dirt roads, open spaces (including lawns, parks, and cemeteries), and woodland or forested areas occupy 114,552 m^2 (2%), 257,344.5 m^2 (5%), 180,216 m^2 (4%), and 221,462 m^2 (5%) of the land use, respectively.

Geometric Properties of the Drains

The width, depth and area of the natural and artificial drains from the study area were presented in Table 1. Table 2 presented the total volume in m^3 for both natural and artificial drains.

Table 1 showed the width, depth and area of the drains in the study area at different sampling points. The average area of the natural drain is 80,273 and 17,594.4 m^2 for natural drain one and natural drain two respectively. The average area of artificial drain one and two are 10,019 and 9,151.4 m^2 respectively. The total volume of both natural and artificial drains is 46,094.06 m^3 which is shown in table 2.

Table 1: Natural and Artificial Drains

Coordinates	Width (cm)	Depth (cm)	Area (cm^2)
Natural Drain One			
$7^{0}9.266^{1}$N, $3^{0}22.137^{1}$E	500	34.6	17,300.0
$7^{0}9.276^{1}$N, $3^{0}22.134^{1}$E	880	23.6	20,768.0
$7^{0}9.268^{1}$N, $3^{0}22.130^{1}$E	635	20.9	13.271.5
$7^{0}9.408^{1}$N, $3^{0}22.246^{1}$E	250	180	45,000.0
$7^{0}9.129^{1}$N, $3^{0}21.890^{1}$E	1034	295	305,030.0
Average			80,273.9
Natural Drain Two			
$7^{0}9.546^{1}$N, $3^{0}22.050^{1}$E	185	170	31,450.0
$7^{0}9.471^{1}$N, $3^{0}21.980^{1}$E	135	70.0	9,450.0
$7^{0}9.219^{1}$N, $3^{0}22.806^{1}$E	550	31.9	17,545.0
$7^{0}9.227^{1}$N, $3^{0}21.808^{1}$E	530	30.5	16,165.0
$7^{0}9.214^{1}$N, $3^{0}21.810^{1}$E	510	26.2	13,362.0
Average			17,594.4
Artificial Drain One			
$7^{0}9.474^{1}$N, $3^{0}22.101^{1}$E	102	101	10,302.0
$7^{0}9.436^{1}$N, $3^{0}22.078^{1}$E	102	100	10,200.0
$7^{0}9.198^{1}$N, $3^{0}21.935^{1}$E	100	104	10,400.0
$7^{0}9.151^{1}$N, $3^{0}21.907^{1}$E	98	96	9,408.0
$7^{0}9.091^{1}$N, $3^{0}21.871^{1}$E	103	95	9,785.0
Average			10,019.0
Artificial Drain Two			
$7^{0}9.470^{1}$N, $3^{0}22.118^{1}$E	99	81	8,019.0
$7^{0}9.405^{1}$N, $3^{0}22.077^{1}$E	98	93	9,114.0
$7^{0}9.194^{1}$N, $3^{0}21.950^{1}$E	95	95	9,025.0
$7^{0}9.130^{1}$N, $3^{0}21.912^{1}$E	100	100	10000.0
$7^{0}9.061^{1}$N, $3^{0}21.871^{1}$E	98	98	9,604.0
Average			9,151.4

Table 2: Total volume of drains in Olorunsogo catchment

	Area (m^2)	Average length (m)	Volume (m^3)
Artificial Drain One	1.0019	4,311.70	4,319.90
Artificial Drain Two	0.91514	4,332.95	3,965.26
Natural Drain One	8.02739	4,368.81	35,070.10
Natural Drain Two	1.75944	1,556.63	2,738.80
Total			46,094.06

Rainfall Trend of the Study Area

The mean annual precipitation over an 18-year period (2001 – 2018) is presented in Figure 3. The data showed that in 2001, the mean annual precipitation was 846.9 mm, which then steadily increased in 2002 and 2003, reaching 1251.9 and 1470.2 mm, respectively. In 2004, there was a notable decrease to 1155.3 mm, which further declined to 874.1 mm in 2005. The average annual precipitation slightly rose in 2006, followed by a significant jump to 1596.9 mm in 2007. The following years, 2008 and 2009, saw a decrease to similar values of 1343.5 and 1350 mm, respectively, before soaring to the highest level for the study period in 2010, at 1625.4 mm. A sharp decrease was observed from 2011 to 2013, with a minor increase in 2012 (1364.2 mm), followed by a rise to 1533.5 mm in 2014. The year 2015 experienced a marked decline in mean annual precipitation, dropping to 948.3 mm, but it increased again to 1451.6 mm in 2016. The years 2017 and 2018 then saw reductions to 1068.3 and 1147 mm, respectively.

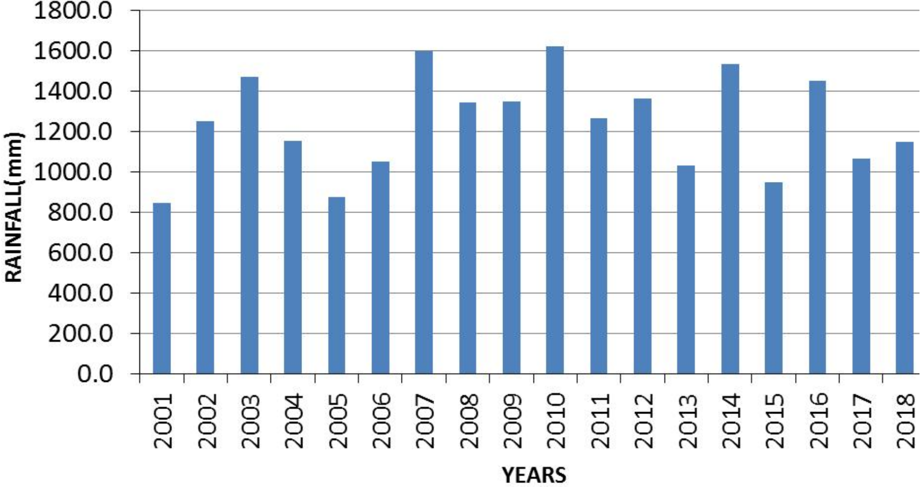

Figure 3: Mean yearly rainfall in Abeokuta (2001 – 2018)

There was a low mean monthly precipitation value as shown in Figure 4 for the month of November to February which signal the period of dry season with a value range of 2.4 to 23.7 mm in the study area. The month of March and April showed an improved monthly precipitation values of 73.2 and 124.7 mm respectively. The mean monthly precipitation in May to October showed a steady precipitation with a value range of 190.5 to 198.1 mm except for a slight decrease in August and October with a value of 81.3 and 136.6 mm respectively.

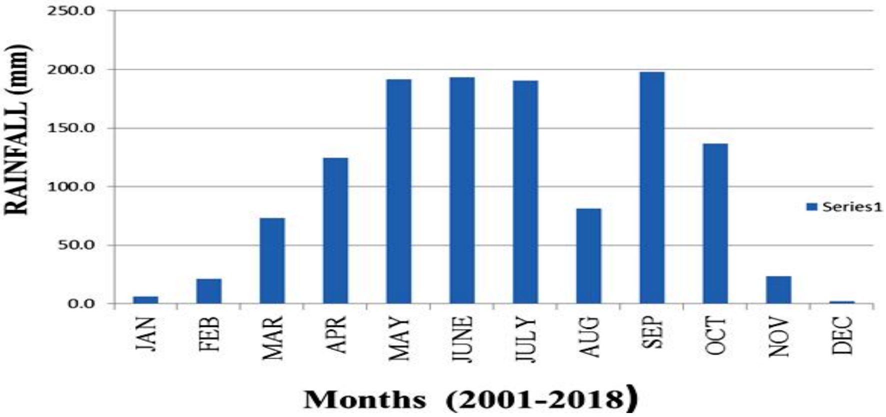

Figure 4: Mean monthly rainfall in Abeokuta (2001 – 2018)

Results from Runoff Estimation

The catchment exhibited no runoff occurrences in January and December. A pattern of increasing monthly mean runoff was evident from February to May, followed by a gradual decline from June through August. A subsequent rise in September and a decrease from October to November were observed. The direct runoff peaked in September, recording 660,951 m^3, while the lowest was in February, at 15,370 m^3. This data provided a comprehensive understanding of runoff variability and trends in the catchment as shown in Figures 5 to 7.

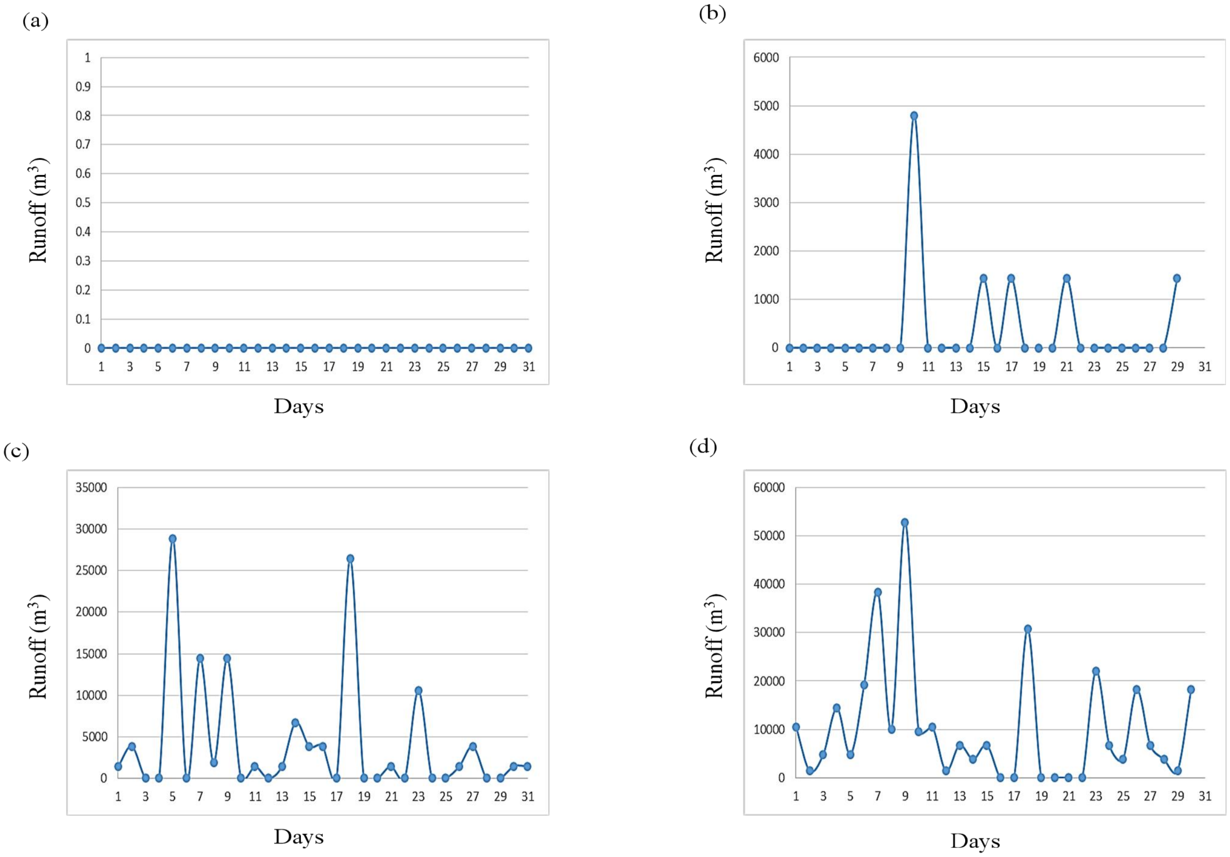

Figure 5: Daily mean runoff for the months of (a) January (b) February (c) March (d) April

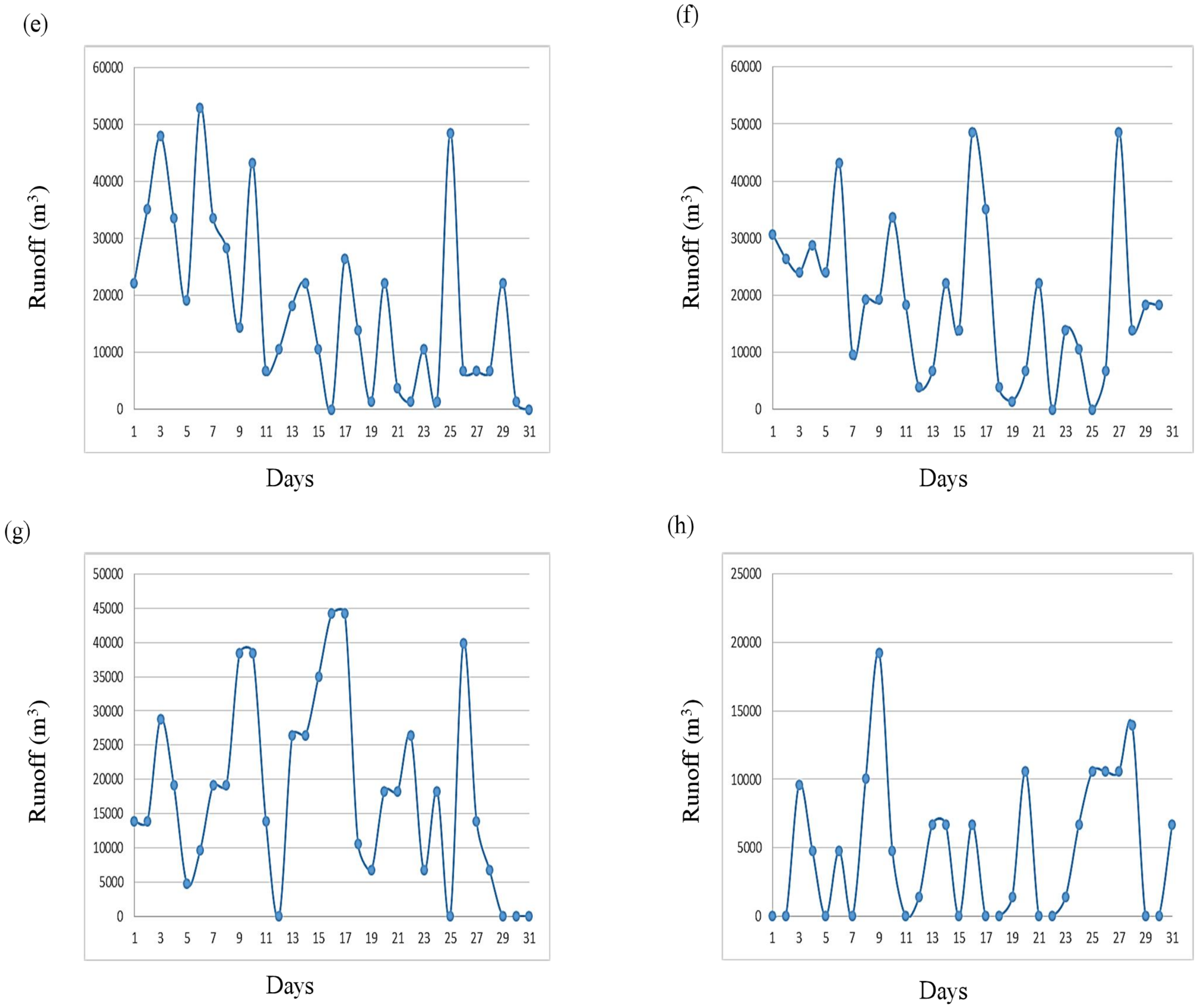

Figure 6: Daily mean runoff for the months of (e) May (f) June (g) July (h) August

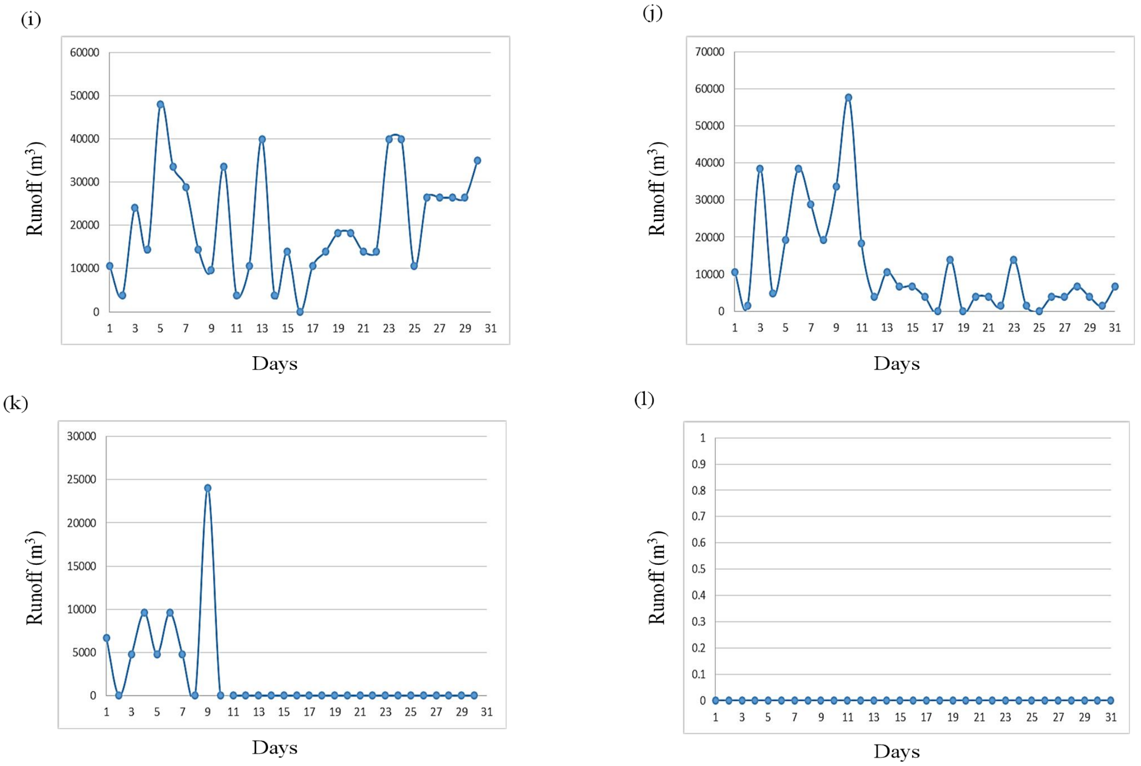

Figure 7: Daily mean runoff for the months of (i) September (j) October (k) November (l) December

CONCLUSION

The hydraulic evaluation of the urban drainage system in Olorunsogo, Abeokuta, Ogun State, focused on assessing its capacity and efficiency. Measurements of the width, depth, and length of the drains were conducted to determine their total volume, estimated at 46,094.09 m^3. The system's adequacy was evaluated using a drain ratio, which compares the drain volume to the catchment area's runoff volume, expressing the system's capacity to manage runoff. The study found that the drainage system could only accommodate a limited portion of runoff generated over time. Within one hour, it could handle 32.06%, increasing to 64.13% after two hours, and reaching 96.2% in three hours. However, a significant volume of runoff, up to 737,505.44 m^3, would still overwhelm the system in heavy rainfall events lasting over three hours, leading to potential flooding. It is recommended that, evacuating the floodplain and enforcing a 200 m setback limit around it. This measure aims to mitigate life and property losses annually and provide space for water flow during flash floods. Additionally, demolishing buildings at risky locations, like the downstream confluence of Iran ala and the ephemeral stream, is advised to prevent loss of life and property. Finally, redesigning the drainage system to better manage flash floods is recommended for long-term effectiveness and safety.

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