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ORIGINAL RESEARCH
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Spatial Hydrological Analysis on storm water harvesting investigation for sustainable water resources management strategy

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ABSTRACT

The water issue has become a frontier of public debate globally due to public awareness of sustainable development. Nigeria's water resources are under serious threat from inadequate catchment management that includes widespread pollution from indiscriminate waste disposal. Stormwater is now recognized as a valuable resource rather than a nuisance, especially in large urban centers. Growing demand for water has exerted pressure on groundwater via dug well and boreholes scattered virtually in every dwelling in Nigeria. This challenge motivated this investigation of the feasibility of harvesting stormwater for due purposes of supplementing water supply and flash flood management. This study aims at quantification of harvestable stormwater and identification of potential capturing sites using Spatial Hydrological Analysis of GIS model and Synthetic Hydrograph. The result indicated total harvestable stormwater for 24-hr rainfall of 161.3 Mm³ and three available capturing sites of eight depressions identified. This volume is a good incentive to incorporate storm harvesting in overall water resources sustainable management.

KEYWORDS

water harvesting, spatial hydrology, runoff, watersheds, hydrograph

1. INTRODUCTION

Without any doubt, water is a versatile substance that covers 75 percent of the earth's surface. However, the amount available for human use is very limited. Ninety-seven percent of the world's water is contained in the oceans not readily usable while only 2.5% is fresh water. However, the most accessible freshwater found in a river system, reservoirs, and lakes is just 0.26% of total freshwater on earth [1]. Precipitation, the key source of freshwater has an annual flow that is fifty times the stock held in reservoirs, rivers, and lakes [2]. The implementation of effective healthcare policies and poverty alleviation are through the accessibility of adequate potable water [3], hence making it a cornerstone in public health [4]. Water also plays a vital role in political and international relations already having led to regional hydropolitics in the last 3 decades such as illustrated in [5–9]. The combination of increased world population, urbanization, industrialization, environmental degradation, and climate change have limited the accessibility and adequacy of renewable water resources in all regions of the world and the severity only varies. Rainwater harvesting is a promising and sustainable

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renewable resource for surface and underground water at different scale levels and scope. The chronological development of stormwater harvesting is available in [10] and [11].

The challenge of achieving Africa's water security is contingent on the hydrological variability and its extremes [12]. The existing urban water management in most cities has been challenged by climate change, urbanization, and environmental degradation, hence the need to find a more sustainable solution. There is evidence that Nigeria is drifting into water crises considering the shrinking lakes, disappearing of rivers, environmental pollution that is becoming obvious [13]. Nigeria is suffering from water poverty which is conditioned according to [14] on the inability of the citizenry to access or be able to afford the cost of sustainable potable water at all times due to non-utility-improved water sources [15]. In Nigeria, water will likely be a source of conflict as other countries sharing rivers will fight for access to these resources in the next 25 years, especially if the population of Nigeria rises from 140 million in 2006 to 254.7 million in 2025 as predicted [16]. Okeola et. al. [17] discussed water conflicts issues. Therefore, Nigeria needs structural and non-structural strategies to supplement Nigeria's finite renewable water resources which cannot support ever-increasing demand.

The purpose of urban stormwater management in the 1980s was to dispose of storm water quickly into receiving water bodies [18, 19]. Many studies have shown the use of harvesting stormwater as an effective structural approach to ease pressure on renewable resources or as part of strategies to reduce the vulnerability of urban settings to flash floods as part of holistic water resources management [20, 21]. In order to reduce potable water demand and overcome capacity challenges stormwater can become a valuable resource for usage on a fit-for-purpose requirement [22, 23]. The integration of stormwater management has received strong consideration even in affluent countries. In France, 15% of the population have a rainwater harvesting system due to factors such as the 2008 law on rainwater harvesting, incentive mechanisms to foster the practice, and the increasingly "green" sensitivities of various stakeholders [24]. There is the American Rainwater Catchment Systems Association (ARCSA) that caters to over 3,000 members who either owned, installed, or have observed rainwater harvesting in the field [25]. Yet, it is traditionally rural communities in Africa and Asia who depend on rainwater harvesting. In this study, the authors will adhere to the usage: "storm water harvesting (SWH)" which has the same meaning as "runoff water harvesting" or "rainwater harvesting" adopted by other authors.

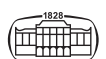
2. LITERATURE REVIEW

Miller [26] came up with a system definition after aggregating nine different definitions: "A system is a group of elements, either physical or non-physical in nature, that exhibit a set of interrelationships among themselves and interact together towards one or more goals, objectives or

ends". Application of a "system concept" gives insights into the systemic and methodological basis of stormwater harvesting. SWH systems are made up of [27]: (1) catchment, (2) storage facility, and (3) target. In order to create a water buffer in a catchment to reduce seasonal variation in rainfall and drought vulnerability, potential stormwater storage zones are established for the construction of harvesting structures in a planned and systematic manner [28]. The actualization focuses on the selection of suitable harvesting sites and methodological tools that are employed to do that. In the former, the biophysical and socioeconomic are two criteria largely considered. These include rainfall, slope, land use, and rivers network. While in the latter, key considerations are the distances of the site to settlement, stream, road, and the cost. The type of storage is cost influenced and can be check dam, ponds, percolation tanks and terracing.

The UN's Food and Agriculture Organization (FAO) [27] gave guidelines to select SHW potential sites that are very comprehensive yet. It incorporates wider ranges parameters and various socioeconomic criteria that are associated with local farmers. The challenge of water security albeit the climate change debacle, urbanization, increase in population, and environmental pollution are the precursor to the increased studies in SWH as a sustainable approach to address water scarcity. This sustained interest is adduced to advancement in computer technology in the area of remote sensing (RS), which is a precursor to various approaches to stormwater harvesting. In one of the available reviews of the subject, [27] categorized the methodological approach with accompanied strategies in the identification of feasible capturing sites in the past 30 years. They are four groups [29]: (i) GIS/RS, (ii) hydrological modeling (HM) with GIS/RS, (iii) multi-criteria decision analysis (MCDA) integrated with HM and GIS/RS, and (iv) MCDA integrated with a GIS.

In the identification of suitable dam locations for rainwater harvesting in Iraq's Western Desert, [30] developed a model using ModelBuilder in ArcGIS. This model utilized biophysical factors that included stream order slope, soil texture, land use, runoff depth, and slope to develop a suitability map for SWH locations. They confirmed GIS veracity as a tool to integrate a variety of information in identifying suitable sites for rainwater harvesting dams. The authors concluded that "ArcGIS was a flexible, time-saving, and cost-effective tool for screening large areas for their suitability of RWH intervention". Similar studies were reported in [31]. There are several methods to confirm suitable sites for SWH but not on the performance assessment of existing SWH infrastructure. Adham et al. [32] addressed this gap using a methodological framework that is scientifically based in evaluating the performance of existing SWH infrastructure in Iraq. The outcome of the approach showed sites with low, moderate, and high suitability scores respectively. However, their result was disturbing because only two sites have high suitability scores. We (the authors) believe the result showed all the existing SWH facilities are working at a very low designed capacity. It is imperative to



carry out a scientific study in identifying potential harvesting sites before embarking on infrastructure construction.

In Iraq's Maysan province, [33] selected optimum sites for harvesting using GIS-based Multi-Criteria Evaluation. In doing this, the authors selected a Fuzzy membership that was used for standardization of the criteria in a Fuzzy Gamma overlay and then generated a combination of multi-layers in the ArcGIS interface. The authors then generated seven criteria layers (the Normalized Difference Vegetation Index (NDVI), roads, slope, evaporation, precipitation, soil type, and stream order) for identification of SWH catchment. They finally developed a potential rainwater harvesting catchment map to aid the water resources management of the region. Other similar studies are [28, 32, 34].

Several authors [35–37] considered biophysical factors of rainfall, drainage, soil types, slope, and land usage as the important parameters to identify SWH sites. Others such as [38], from their study, found mean annual rainfall as the most significant factor in selecting suitable sites for SWH. We agree because the whole exercise is about securing another water source to augment the limited renewable water resources sustainably. However, in Nigeria, capturing rainwater from the rooftop in the urban and rural settings has been practiced since prior independence till to date. Many studies are focusing on the quantification of rainfall volume and storage capacity [39–45], quality assessment of rooftop rainwater [46–49] and the socioeconomic component of the practice [50].

Ohiambe et al. [51] gave one of the most extensive studies on SWH in both scale and scope in Nigeria. The perennial water scarcity in Abuja, the Nigeria capital appears to have motivated the authors to investigate the rainwater harvesting potential of the city targeted in the year 2046. The GIS and Multi-Criteria Evaluation (MCE) are the methodological tools of assessment. The significant criteria are prioritized with Analytical Hierarchy Process (AHP) which gave; rainfall 55.9%, LULC 26.3%, slope 12.2%, and soil 5.7% respectively. With GIS, they produced potential sites map for harvesting with categorization into moderate (10.7), good (34.4), and excellent (54.9) respectively. They confirmed from their investigation that Abuja will have at least 5.8 billion liters of harvestable rainfall per year which is a 14.8% increase compared to the 2016 estimation. This assertion was contingent on increased rainfall from 1,170 to 1,470 mm in 2016 to 1,230–1,910 mm in 2,046, bare surfaces from urbanization, and an increase in population. There are other location-specific studies on SWH in the country for example, [52, 53].

The continuous water shortages, urbanization, and annual flash flood motivated the current study for SWH in Ilorin metropolitan, Kwara state administrative capital, Nigeria. It is the first to the best knowledge of the authors. Despite abundant water resources, the city still faces the challenge of meeting water demand while several volumes of water are annually wasted through storm runoff. Stormwater has also become a threat to life and property in several populated areas (eg. Central Post-office, Offa Garage Motor Park, Unity Road). The groundwater is experiencing pressure from dug wells and boreholes virtually in every

dwelling. There is a need to strategize an effective way of capturing and reusing stormwater to reduce pressure on water resources, recharge aquifers and provide a measure for urban water runoff management to safeguard life and properties.

3. METHODOLOGICAL FRAMEWORK

3.1. Study area

The Kwara state administrative capital, Ilorin in north-central Nigeria (Fig. 1a) is the case study. The republic of Nigeria is located in the west of the African continent (Fig. 1a). Ilorin comprises four merged local government areas (LGAs) (Fig. 1b): Ilorin West, East, South, and Asa on latitude $80^{\circ} 24'N$ and $80^{\circ} 36'N$ and longitude $40^{\circ} 10'E$ and $40^{\circ} 36'E$ with a total area of 2056.3 km^2 . The north-central Nigeria that habited Ilorin is intertwined within the sparsely populated middle belt and the densely populated south-western of Nigeria. The climate has a significant dry season from November to May. The annual rainfall is 1200 mm and relative humidity in the wet season is 75–80% and the dry season is 65%. From November to May, the sun shines between 6.5 and 7.7 h daily. The geology consists of Precambrian basement complex rock. River Asa, which flows in a south-north direction, drained the catchment.

3.2. Conceptual approach

The approach adopted involves desk and field works. The desk work includes analysis of surface water hydrology and spatial hydrological analysis. The fieldwork entails a reconnaissance survey, identifying the drainage outlet potential stormwater capturing sites. The data sourced from administrative map, and rainfall data. Twenty-nine years of rainfall data ranging from 1983 to 2011 were obtained from Nigeria Meteorological Agency. The major analytical tools include Google Earth, ArcGIS, and Global Positioning System (GPS). The ArcGIS desktop 9.3 was utilized for the spatial analysis from which watershed characterization was determined. The Shuttle Radar Topographical Mission (SRTM) archive is the source of DEM used in the study. The assessment of hydrologically based indices from digital terrain analysis is done with Digital Elevation Model (DEM). The drainage outlet's location on the ground surface was achieved with GPS using coordinates generated by ArcGIS. The determination of the drainage structure of the catchment was done with the DEM cell-wise elevation information. This involves the filling of depressions, flow direction, and flow accumulation datasets. The D8 (eight flow direction matrix) is the approach commonly adopted in deriving drainage networks from raster DEM data. The D8 model is used to the identified flow direction. That is the streamflow to a neighboring cell in a straight or diagonally steeper cell. The flow direction of a cell is the direction water will flow out of the cell. However, a synthetic unit hydrograph was used in the computation of peak flow discharge and reservoir storage capacity.



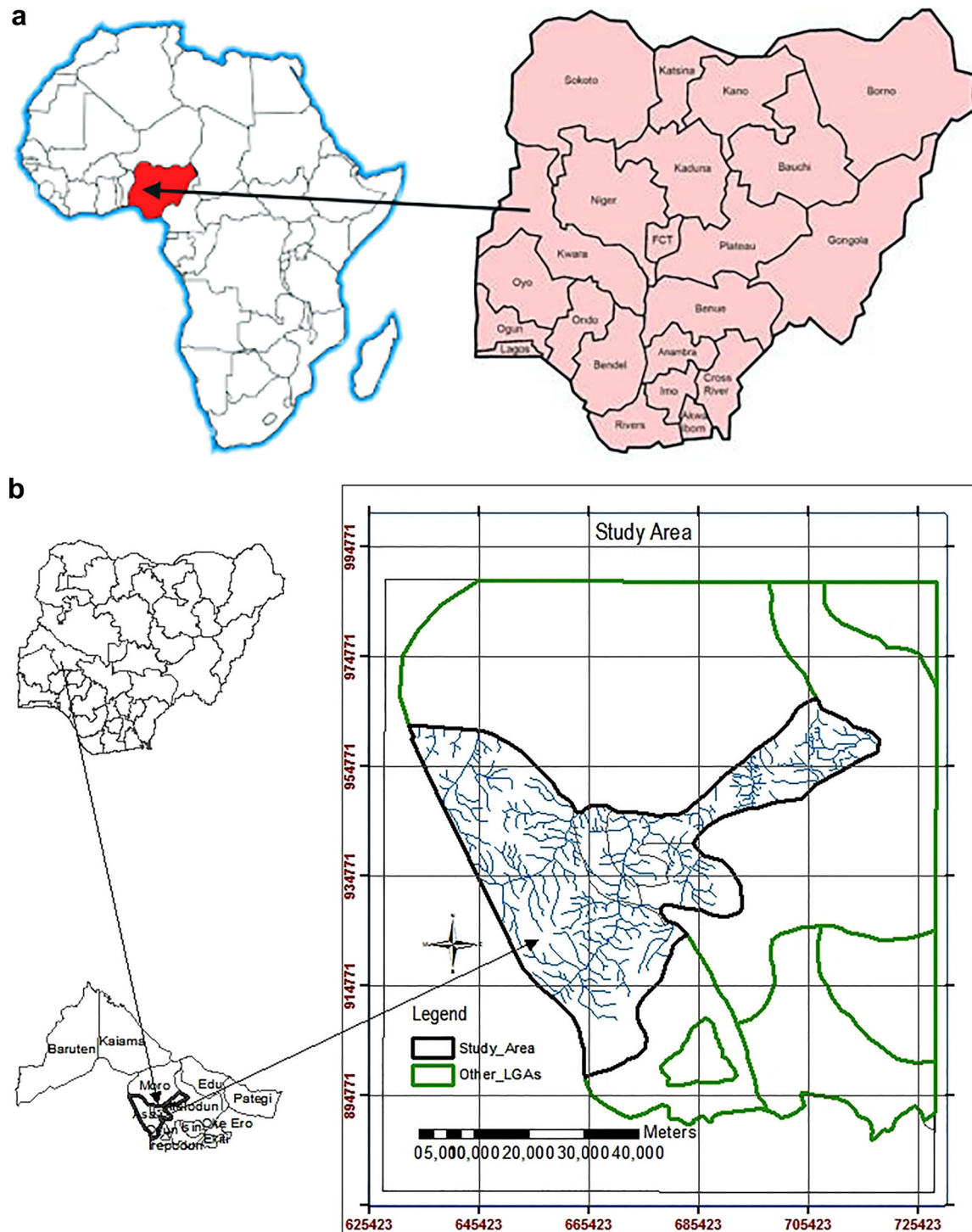


Fig. 1. a) Map of Africa showing Nigeria (red) while Nigeria indicated Kwara among the 31 states; b) Map of the merged LGAs study area

3.3. Hydrological framework

3.3.1. Unit hydrograph. A unit hydrograph is an approach commonly applied to develop storm hydrographs from actual watershed rainfall. The method is contingent on assumptions that the same unit hydrograph shape applies to all catchments but only differs in scale [54]. In predicting the basin's response to design storm events, unit hydrographs are produced for gauged watersheds from historical records. In

this study, there was no available streamflow data to develop hydrographs. Hence, a synthetic unit hydrograph for ten sub-watersheds was developed using Snyder's method with the following parameters:

$$T_L = C_t (L \times L_{ca})^{0.3} \quad (1)$$

$$T_d = \frac{T_L}{5.5} \quad (2)$$

$$T_{LA} = T_L + 0.25(T_{da} - T_d) \quad (3)$$

where:

T_L = lag time (hr),

C_t = empirical coefficient of the lag factor,

L = length along main channel from outlet to divide (Km) (miles),

L_{ca} = length along the main channel from outlet to a point opposite the watershed centroid (Km) (miles),

T_d = duration of rain excess (hr),

T_{LA} = alternative unit hydrograph duration (hr).

However, the T_b is a fraction of the time lag:

$$T_b = 3 + \frac{T_L}{8} \quad (4)$$

$$q_p = \frac{640AC_p}{T_L} \quad (5)$$

where:

q_p = peak flow discharge ($ft^3 s^{-1}$),

C_p = the peak flow factor (0.5–0.70),

A = drainage area (square miles).

Design storm hydrographs for average annual rainfall data were developed through convolution. Hydrograph convolution is the procedure for establishing a storm hydrograph from a multi-period of rainfall excess [55] and mathematically expressed in Equation (6).

$$Q_n = R_1 U_n + R_2 U_{n-1} + R_3 U_{n-2} \quad (6)$$

where:

U_n = the unit hydrograph ordinates,

P_n = incremental rainfall excess.

Equation (6) is the equation for discrete convolution adopted in the computation of direct runoff Q_n . The summation of areas under storm hydrograph curves is equal to the runoff volume in the study area computed by segmenting the graph into several trapezoidal shapes using Equation (7).

$$Q = \sum \frac{(A+B)*C}{2} \quad (7)$$

where A = first discharge ($m^3 s^{-1}$), B = second discharge ($m^3 s^{-1}$), C = time (sec).

3.3.2. Forecast of rainfall for return period (R_T) using Gumbel extreme type 1 distribution model. The R_T with period T (yrs) was described by the Gumbel distribution model as in Equation (8).

$$R_T = R_{av} + \sigma(0.48y - 0.45) \quad (8)$$

where σ = standard deviation.

$$\sigma = \sqrt{\frac{\sum (x - \bar{x})^2}{n}} \quad (9)$$

$$y = -\ln(-\ln(1 - P)) \quad (10)$$

$$P = \frac{1}{T} \quad (11)$$

R_{av} = 24-hr average rainfall depth,

R_T = T-yr, 24-hr rainfall depth.

3.3.3. Runoff curve number. The empirical USDA-SCS-CN model is widely employed in watershed run-off estimation for the simplicity and efficiency attributes [56–58]. The model only requires precipitation, land cover, and hydrologic soil group parameters. Therefore, the CN, a function of the above parameter is employed with rainfall data for estimation of the study watershed surface runoff capacity. The maximum retention(S) is calculated from the CN value, which does not consider rainfall intensity. However, the estimated runoff depth (Re) is computed from Equation (13) [59]:

$$Q_d = \frac{(P^{**} - I_a)^2}{(P^{**} + 0.8S)} \quad (12)$$

Q_d = Runoff depth estimation in mm,

$Q_d = 0$ for $P^{**} \leq I_a$, P^{**} = Depth of rainfall depth in mm;

$I_a = 0.2S$

S = Potential maximum retention after runoff begins (mm) given by:

$$S = 25.4 \left(\left(\frac{1000}{CN} \right) - 10 \right) \quad (13)$$

Note that CN is a dimensionless curve number, $0 \leq CN \leq 100$.

4. RESULTS AND DISCUSSION

This study utilized the versatility of GIS to determine watershed characterization, boundary, areal coverage, and volumetric capacity of runoff. The study also utilized twenty-nine years of rainfall data from 1983 to 2011 to forecast rainfall of 25yrs return period determined by peak average annual rainfall depth. The outcome was utilized in computing storm hydrograph through convolution.

4.1. Catchment characteristics

The watershed coverage with its stream network is shown in Fig. 2 and the highest point above mean sea level is 550 m while the lowest point elevation of 147 m is depicted in Fig. 3, thus revealing variation in the elevation of the catchment. The projected DEM was hydrologically corrected by filling the sinks. The flow direction tool in the “ArcHydro tool” extension of ArcMap® 9.3 determined the flow direction and accumulation. The resulting map obtained was then used for the evaluation of the slope map. A running iterative process of the cell was carried out to determine flow direction based on the D8 model.



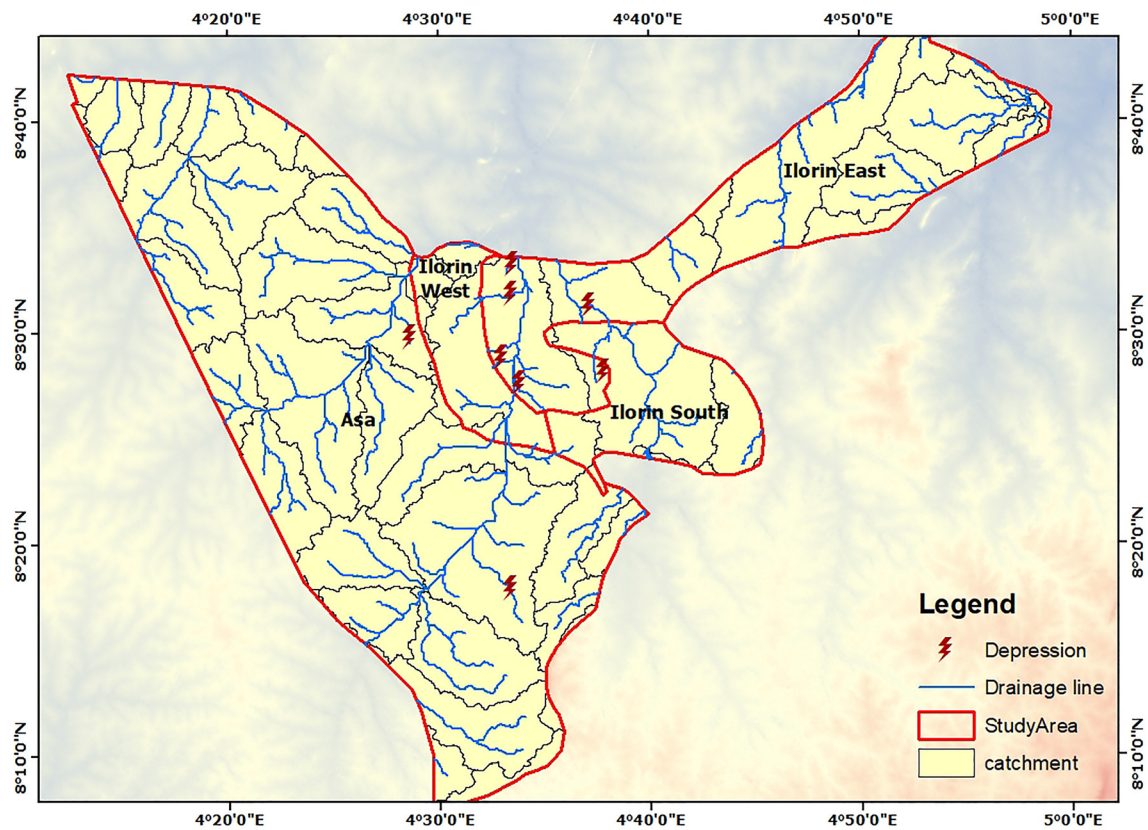


Fig. 2. The merged LGAs' watershed and streams

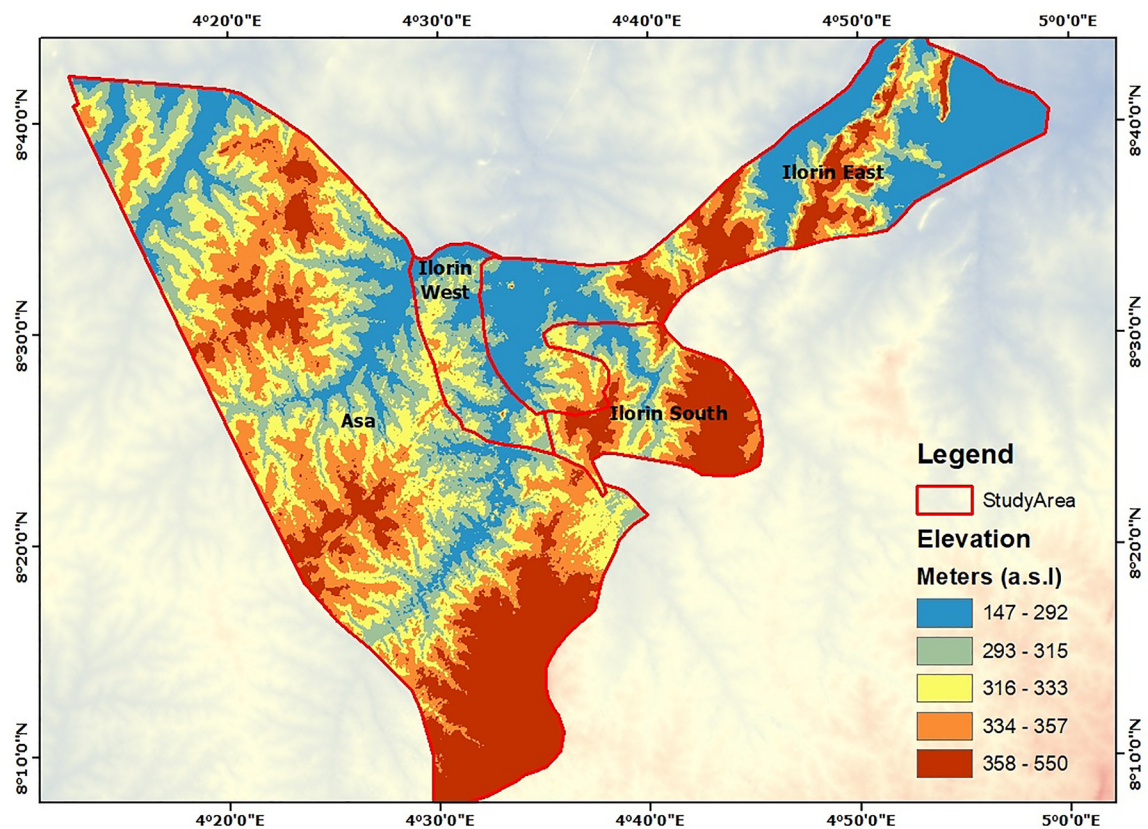


Fig. 3. The study area DEM layer



Table 1. The watershed excess rainfall estimation

Time (hr)	Precipitation Ratio ($P^*/24$)	Precipitation P^* (mm)	Cumulative Rainfall Excess Q_d (mm)	Incremental Rainfall Excess (mm)	Incremental Rainfall Excess (cm)
0	0.0000	$0.0000 < l_a$	0.0000	0.0000	
3	0.0350	$3.5679 < l_a$	0.0000	0.0000	
6	0.0800	$8.1552 < l_a$	0.0000	0.0000	
9	0.1470	$14.9852 < l_a$	0.0000	0.0000	
12	0.6630	67.5862	13.5706	13.5706	1.3571
15	0.8540	87.0568	24.4753	10.9047	1.0905
18	0.9210	93.8867	28.7370	4.2617	0.4262
21	0.9650	98.3721	31.6388	2.9018	0.2902
24	1.0000	101.9400	34.0007	2.3619	0.2362

Table 2. Watershed characteristics

Catchment	A (km^2)	L (km)	L_c (km)	T_L (hours)	T_r (hours)
1	36.2	7.3	4.6	4.6	0.8 (1)
2	26.6	5	3.1	3.6	0.7 (2)
3	196.8	15	11	7.4	1.3 (3)
4	445.3	26.2	11.8	8.94	1.62 (4)
5	575.3	41.8	21	12.22	2.2 (5)
6	210	13	22	8.73	1.58 (6)
7	28.3	5.1	2.5	3.43	0.62 (7)
8	59.68	9.8	5.3	5.23	0.95 (8)
9	60.2	9.9	4.6	5.03	0.91 (9)
10	95.95	16.7	7.5	6.81	1.24 (10)

L_c (km): Length of stream from centroid to outlet; L (km): Length of main stream

4.2. 24-hr, 25-yr rainfall depth return period using Gumbel model distribution

From Equations (9) to (12), 24-hr, 25-yr rainfall depth was established for average rainfall depth. The statistical analysis of rainfall yielded average and standard deviation values of 54.21 and 43.95 mm respectively. The 25 years rainfall return period was 101.94 mm with a probability of exceedance of 0.04. The rainfall excess was obtained

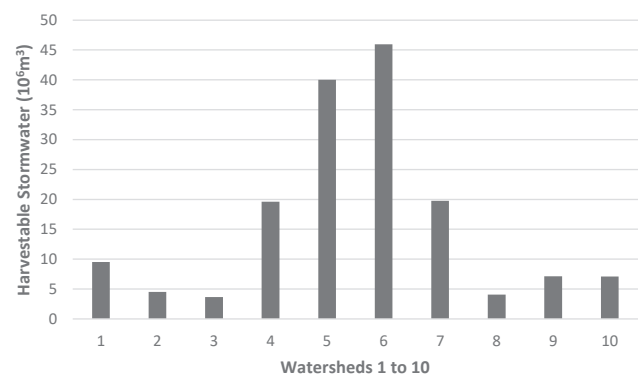


Fig. 5. Amount of harvestable stormwater

from the forecasted rainfall of 25yrs return period using Equation (13) (Table 1).

4.3. Storm hydrograph development

The study area was delineated into ten watersheds and their centroid was determined. Each watershed's characteristics such as area, main streams length from its centroid to the outlet needed to obtain unit hydrograph ordinates generated with ArcGIS are indicated in Table 2. The watersheds correspond to the catchments of Rivers Asa, Moro, and Oli.

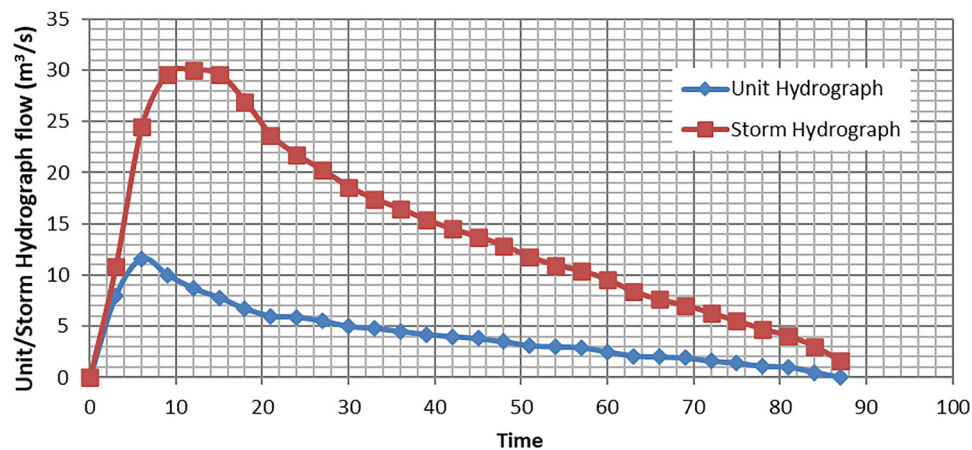


Fig. 4. A plot of 1hr-unit and 25-yr, 24-hr storm hydrograph for watershed 1

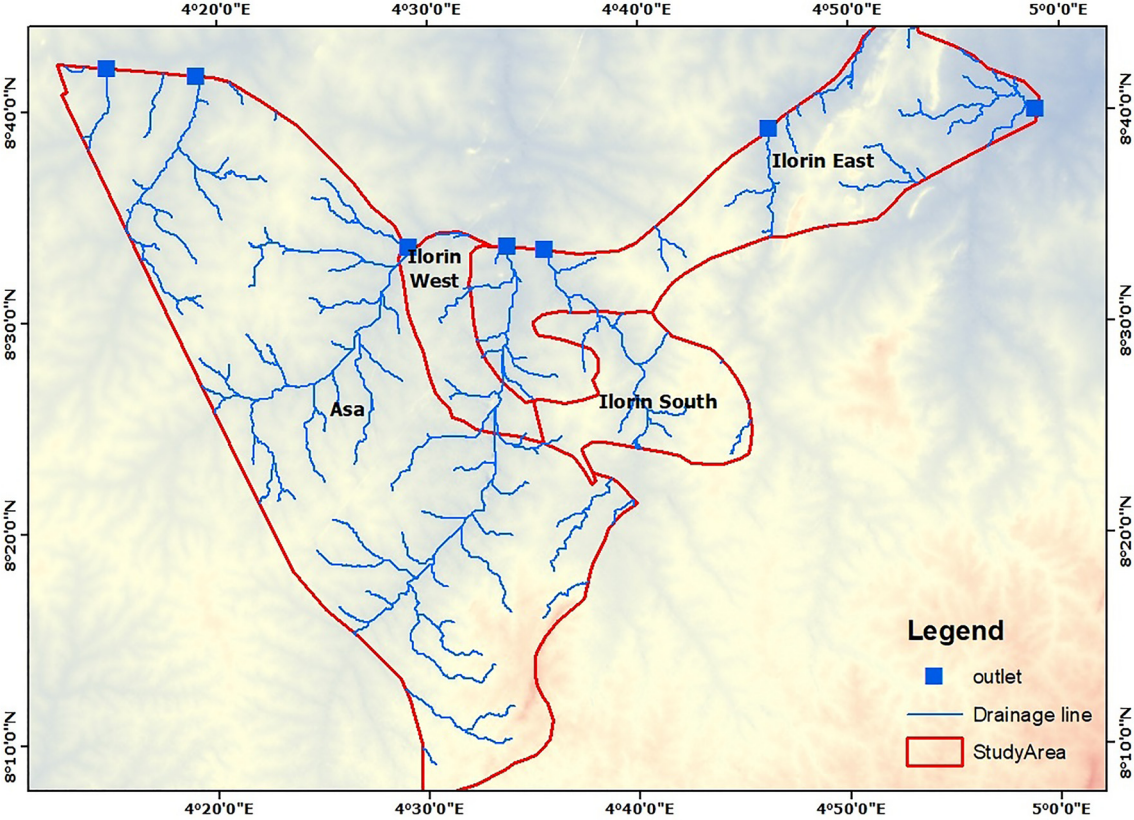


Fig. 6. Outlets through which stormwater escapes from Ilorin

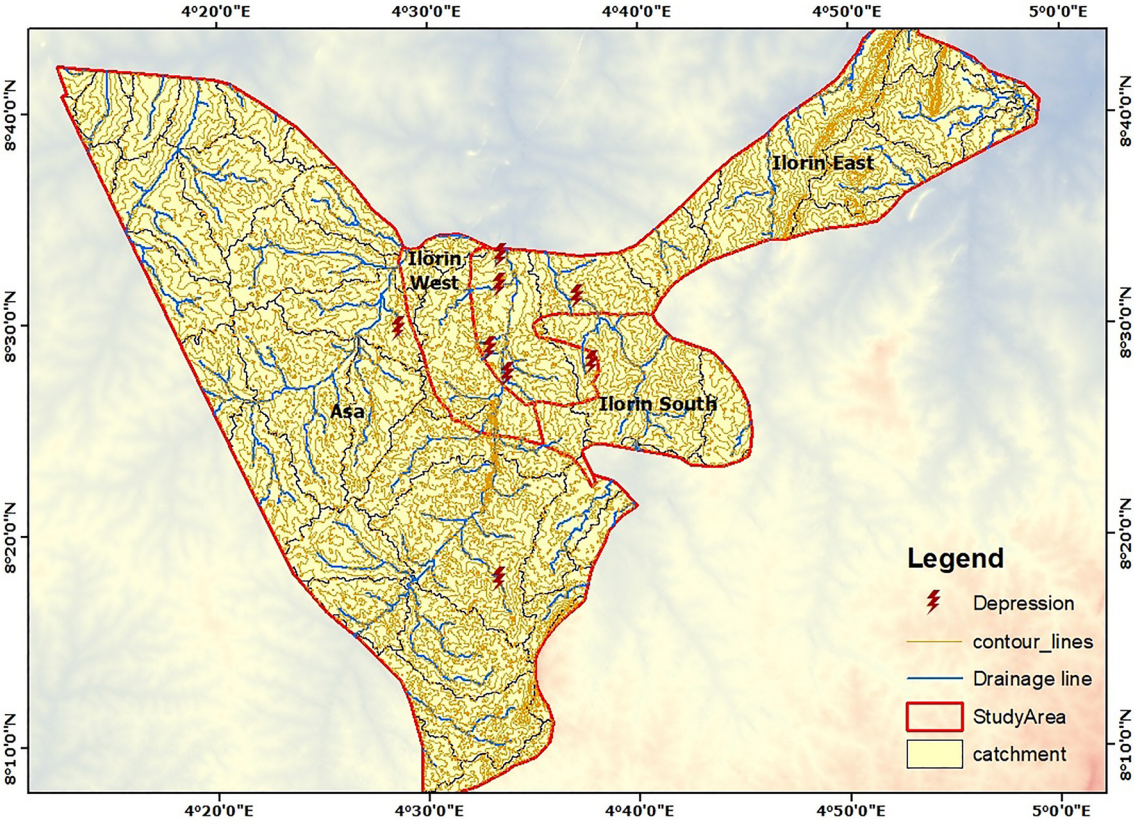


Fig. 7. Contour, depressions, and watersheds of the study area



Table 3. Descriptions of depressions

Depression	Coordinates		Location	Condition
	Longitude °E	Latitude °N		
1	4.467	8.503	Afon	Available
2	4.567	8.476	Onikanga	Built-up
3	4.610	8.530	Sango	Built-up
4	4.623	8.485	Tanke	Built-up
5	4.550	8.490	Edun	Built-up
7	4.570	8.550	Shao	Available
8	4.530	8.320	Asa	Available

The hydrograph method was chosen as a result of the large surface area of the Catchments. Equation (1) is used for the computation of storm runoff for the ten-watersheds using Microsoft Excel. Thereafter, a storm hydrograph curve was established for catchment 1 (Fig. 4) and repeated for the remaining catchments. The results showed that peak flows were obtained at $12 \text{ m}^3 \text{ s}^{-1}$ and $30 \text{ m}^3 \text{ s}^{-1}$ for unit and storm hydrographs respectively.

4.4. Stormwater volume and capturing site locations

Figure 5 indicated harvestable stormwater volume for each watershed from the stormwater hydrograph. The slope map derived from the DEM was used to determine seven outlets through which runoff escapes from Ilorin (Fig. 6). The contours generated from the DEM were employed in identifying eight retention ponds shown in Fig. 7, which are the depressions that could serve as the potential stormwater capturing sites.

The coordinates of each identified depression were generated from ArcGIS as presented in Table 3. The coordinates were used in locating the depressions on the earth's surface on GE imageries.

The derived potential runoff volume and topography were considered in the location of optimal sites for runoff harvesting. The GIS approach reduces the aerial extent of a catchment by identifying potential specific sites for runoff harvesting and which are thus confirmed on the field. Out of the eight obtained potential retention ponds, depressions 2, 3, 4, and 5 were developed residential areas confirmed with the GPS. However, depressions 1, 7, and 8 are available and suitable as harvesting sites. Depression 6 was annulled for it was found along the existing river channel. The huge amount of storm volume computed with the three available depressions makes stormwater management feasible.

5. CONCLUSION

For an average 24-hr rainfall depth in Ilorin, 161.3 Mm^3 of water is virtually wasted through runoff. This huge volume if harvested will offer a potential alternative supply for non-drinking purposes and also serve as a means of mitigating flooding and pollution in natural waterways. The locations and sizes of the available depressions are advantageous to stormwater management in Ilorin in terms of supporting

topography, holding capacity, and less vulnerability to flooding. The urban runoff water harvesting system, though a new phenomenon at a large scale in Nigeria, can serve all the non-potable water demands. It can be integrated into the city planning to reduce the frequent flooding thereby improving the street landscape, greener environment, and reducing water shortage by providing an alternative water supply for non-potable usage. The Ilorin metropolitan needs to start utilizing the stormwater runoff that is available in a sustainable manner for non-potable uses in a green environment and vegetable irrigation during the dry season, in addition to the usage in mitigating damages from flash water during the peak rainfall period. This study has confirmed three depressions for locating optimal sites for stormwater harvesting and storage. This can now clear the way for civil works design and cost implications. The huge amount of stormwater volume computed with the three available depressions makes stormwater harvesting in the Ilorin metropolis feasible.

Conflict of interest: The corresponding author states that there is no conflict of interest on behalf of all authors.

Author contributions:

1. Concept: OGO
2. Methodology framework: OGO, LTS
3. Field Work: OGO, LTS, Undergraduate Student's mentees
4. Data acquisition: LTS, Undergraduate Student's mentees
5. Analysis/Findings/Interpretation: LTS, TAS, OGO
6. Manuscript: LTS, OGO
7. Manuscript Final Oversight: WAS

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