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Impact of Urbanization on surface runoff using Remote Sensing and GIS technology: a case study of Lusaka District

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ABSTRACT

Accurately assessing the hydrological impact of urbanization on surface runoff is crucial for resilient urban planning and effective water resource management. The objective of this study was to evaluate the effects of urbanization on surface runoff using Geographic Information System (GIS), Remote Sensing, and the Soil Conservation Services Curve Number (SCS CN) model. The research was conducted in Lusaka District, Zambia and involved classifying land use/land cover maps derived from Landsat TM/EMT+ imagery for the years 1984, 1994, 2004, 2013, and 2020, employing an integrated approach of remote sensing and GIS techniques. Four distinct land use classes; built-up area, vegetation, water body, and barren land, were defined. The supervised classification technique, specifically maximum likelihood pixel-based classification, was used to select training sites for each land use class by identifying representative ground features using different spectral band combinations. The resulting land use/land cover maps exhibited an overall accuracy ranging from 93.22% to 99.19%. The study further analyzed surface runoff using the SCS CN model to investigate variations in surface runoff corresponding to changes in land use. The SCS CN model considers various factors such as soil type, precipitation data, land use, soil moisture conditions, and the size and shape of the watershed. The findings revealed a notable increase in the percentage of urban areas from 28.7% in 1984 to 68.7% in 2020. The SCS CN model demonstrated an associated increase in surface runoff, with a minimum recorded runoff of 385.02 mm in 1994 and a maximum of 1082.59 mm in 2020. These results indicate a clear correlation between urbanization and heightened surface runoff. Continued monitoring and assessment of land use changes using high-resolution satellite imagery are recommended for better understanding urbanization dynamics.

Keywords: Land use / land cover (**LULC**), Soil Conservation Services Curve Number (**SCS-CN**), Geographical Information System (**GIS**), Hydrological Soil Group (**HSG**), Runoff.

INTRODUCTION

In recent decades, the growth of urban population in developing countries has led to increased urbanization, posing significant environmental and ecological challenges (Yang et al., 2003). It is crucial for urban planning and decision makers in land/water management to accurately map land use and land cover (LULC) changes in urban areas and evaluate their impact on surface runoff and river quality. Patil et al. (2008) highlighted that as population density and development continue to rise, the increased presence of impervious surfaces leads to challenges in managing stormwater runoff at both local and global scales. Estimating surface runoff is a critical hydrological variable for water resource applications, with the occurrence and quantity of runoff influenced by rainfall intensity, duration, and distribution. Sindhu et al. (2013) employed the SCS CN model to examine the variations in surface runoff potential based on different LULC and soil conditions.

Therefore, the objective of this study was to evaluate the impact of urbanization on surface runoff in Lusaka district by utilizing Geographic Information System (GIS) and remote sensing techniques, along with the SCS CN model. The significance of this study will help in mapping the areas in Lusaka District which may be affected by flooding due to rapid urbanization. The first section of this paper reviews the literature related to the research topic and thereafter the methodology used will be highlighted. After the methodology, the next section centers on data analysis and discussions. The last part of this research paper focuses on the conclusion and recommendations based on the data analysis and discussions.

LITERATURE REVIEW

Urbanization has become a prominent global phenomenon that profoundly affects land cover and hydrological processes in urban areas (Huang et al, 2023). The expansion of built-up areas and the rapid growth of urban populations have resulted in an increase in impervious surfaces, such as roads, buildings, and pavements, leading to changes in the hydrological cycle and subsequent alterations in surface runoff patterns (Benedict and McMahon, 2006).

Remote Sensing and Geographic Information System (GIS) technologies have emerged as powerful tools for studying land cover changes and their impact on hydrological processes (Herold et al., 2003; Liu et al., 2014). These technologies provide valuable means to analyze and monitor the spatial distribution of land cover types, quantify land use changes, and assess their influence on surface runoff.

Satellite imagery from platforms such as Landsat, have been widely used in land cover mapping and monitoring land use changes over time (Lu and Weng, 2007). There are also various classification techniques such as supervised maximum likelihood, support vector machines, and random forest, that have been employed to accurately classify land cover types and assess their changes in urban areas (Huang et al., 2002; Jokar Arsanjani et al., 2013; Ma et al., 2019).

These techniques enable researchers to analyze the conversion of natural surfaces to impervious surfaces and quantify the extent to which urbanization has impacted surface runoff.

The Soil Conservation Service Curve Number (SCS CN) model is a widely used method for estimating surface runoff based on land cover characteristics, soil properties, and rainfall data (Mishra et al., 2009). This model has been extensively applied in assessing the impact of urbanization on surface runoff and flood risk (Arnold and Gibbons, 1996; Wang et al., 2001; Yang et al., 2003). By incorporating information on land cover changes obtained through Remote Sensing and GIS, the SCS CN model allows for the assessment of the relationship between urbanization and surface runoff.

Studies have demonstrated that urbanization has a significant impact on surface runoff patterns. The conversion of natural surfaces to impervious surfaces in urban areas disrupts the natural hydrological cycle, resulting in increased peak flows and flood risks (Douglas et al., 2005). The loss of natural vegetation and soil permeability reduces the infiltration capacity, leading to a higher proportion of rainfall becoming surface runoff (Liu et al., 2014).

METHODOLOGY

This section gives a description of the area where the study was carried out, the methods used as well as how the data was processed.

Project Background

Lusaka is located in Lusaka province and is the capital city of Zambia. Its central geographical coordinates are 15° 24′ 24” S and 28° 17′ 13” E as shown in Figure 1.

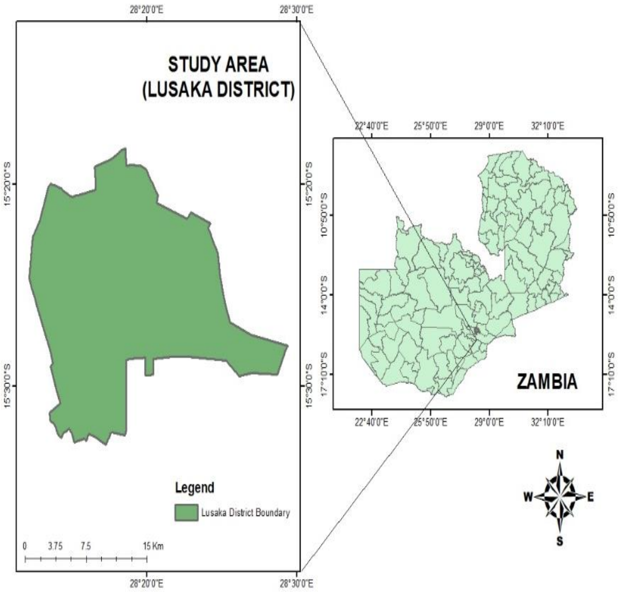

Figure 1: Study Area (Lusaka District)

Lusaka, with an administrative area spanning approximately 412 km², is experiencing rapid growth and is recognized as one of the fastest growing cities in southern Africa (Simwanda and Murayama, 2017). It serves as the political, cultural, and economic hub of the country, housing the central government and attracting numerous institutional, commercial, and industrial activities. With a population of approximately 2 million inhabitants, Lusaka holds a dominant position within Zambia's urban system (Simwanda and Murayama, 2017). The Central Statistical Office report of 2010 found that 79% of the urban population resides within Lusaka district, while the remaining population is distributed among other districts within Lusaka province.

Material and methods

The methodology chosen for this study was based on a case study in Lusaka, Lusaka Province, Zambia. The steps taken to carry out the research are shown in the flow chart in Figure 2

Land Use /Land cover Classification

In this study the first step was to obtain the satellite data as shown in Figure 2 methodology flow chat. We used a supervised maximum likelihood pixel-based classification technique to process Landsat 5, 7, and 8 satellite imagery. The second step was the classification of land use/ land cover for Lusaka District as shown in Figure 2. The processing was conducted using the ArcGIS software. For each Landsat imagery, a band composite file was generated, and a delineated boundary shape file for Lusaka district was used to mask the study area within the band composite layer. To aid in identifying different land use types, a false color composite band was applied to the masked study area for each respective Landsat image.

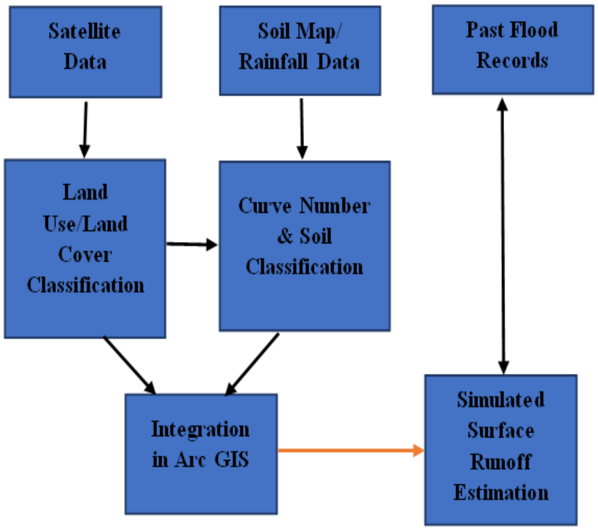

Figure 2: Methodology flow chart

To create accurate training samples for classification, representative features on the ground were identified using different spectral band combinations. Training sample sites were selected for each of the four land use classes; namely built-up area, barren land, vegetation, and water body. The number of training sample sites varied from 10 to 30 for each land use class, aiming to improve the classification accuracy. However, due to the complex and heterogeneous nature of the study area, some misclassifications were observed among the land use classes. These misclassifications were mainly caused by spectral confusions. To mitigate these errors, the maps were reclassified and it was ensured that each map had error matrix accuracy above 90%, as recommended by Simwanda and Murayama (2017). This process helped improve the overall accuracy of each land use classification.

It is important to note that the classification accuracy could be affected by factors such as image quality, training sample selection, and classification algorithms (Halubanza, 2022). Therefore, necessary precautions were taken and recommended practices to minimize errors and enhance the reliability of the land use classifications.

Accuracy Assessment

To evaluate the accuracy of the classified maps, we employed the error matrix accuracy assessment method for the study area. In this process, 30 to 100 points for each land use class were randomly selected, ensuring that the point selection was unbiased. These random points served as true ground data for accuracy assessment. To obtain ground data for time periods from 1984, 1994, 2004, 2013, and 2020, Google Earth's historical imagery feature was utilized.

The overall accuracy levels for each of the classified maps were as follows: 97.169% for 1984, 99.19% for 1994, 98.41% for 2004, 93.22% for 2013, and 97.328% for 2020. These accuracy levels represent the agreement between the classified maps and the true ground data. A higher accuracy percentage indicates a better agreement between the classified land use categories and the actual land cover on the ground.

It is important to note that accuracy assessments are crucial to determine the reliability and validity of the classified maps. The use of random points and the inclusion of ground data from multiple time periods enhance the robustness of the accuracy assessment process. By considering a range of historical maps, we were able to account for temporal changes in land use and obtain a comprehensive evaluation of the classified maps' accuracy.

Surface Runoff analysis (SCS CN Model)

The SCS curve number model is an efficient method for determining the approximate amount of rainfall event in a specific area (Handbook of Hydrology., 1972). The SCS curve number method is based on the water balance equation 1 and on two (2) hypotheses: (1) The ratio of actual direct runoff to the potential runoff is equal to the ratio of the infiltration to the potential infiltration and (2) the amount of initial abstraction is some fraction of the potential infiltration (Handbook of Hydrology., 1972).

This was the third and fourth step as shown in our methodology flow chat. Equation 1, 2 3 and 4 was used for computing potential maximum retention, actual direct runoff weighted curve number and initial abstraction respectively.

$$\boldsymbol{S = (25400 \div CN) - 254}$$ Equation1

$$\boldsymbol{Q = (P - 0.2S)^2 \div (P + 0.8S)},$$

$$where\ P > Ia\ otherwise\ Q = 0$$

Equation 2

$$CN = \left(\varepsilon\ (NCi \times Ai)\right) \div A$$ Equation 3

$$I_a = 0.2S$$ Equation 4

Where;

CN = Weighted curve Number

CNi = Curve number from 1 to any no. N

Ai = Area with Curve number

A = Total area of water shed

Q = actual direct runoff (mm)

P = Total storm rainfall cumulative (mm)

I_a = Initial abstraction

S = Potential Maximum Retention

Soil Classification

Soils are classified into four hydrological classes A, B, C and D based on infiltration, slope and other characteristics.

From the soil map analyzed, Lusaka district soils are classified as clay to sandy clay loam which fell under hydrological soil group C as shown in Table 1

Table 1: USDA-SCS Hydrologic Soil Group

Hydrological Soil	Type of Soil	Runoff Potential	Final Infiltration Rate (mm/hr)	Remarks
Group A	Deep, well-drained sands and gravels	Low	>7.5	High rate of water transmission
Group B	Moderately deep, well-drained with moderately fine to coarse textures	Moderate	3.8-7.5	Moderate rate of water transmission
Group C	Clay looms, shallow sandy loam, soils with moderately fine to fine texture	Moderately high	1.3-3.8	Moderate rate of water transmission
Group D	Clay soils that swell significantly when wet, heavy plastic and soils with a permanent high water table	High	<1.3	Low rate of water transmission

Antecedent moisture condition

Antecedent moisture condition (AMC) refers to the moisture content present in the soil at the beginning of the rainfall event under consideration. AMC-I soils are dry, AMC -II average conditions, AMC – III sufficient rainfall has occurred within 5 days. This study chose AMC -II to simulate runoff flow on average conditions which is a fifth step in our methodology flow chat (Handbook of Hydrology., 1972).

Land cover condition

The land cover condition describes surface conditions of the Lusaka watershed as follows: poor having less than 50% ground cover, fair 50% ground cover and heavy for more than 50% ground cover. In this study, fair ground cover conditions were selected for the model analysis.

Rainfall Data

Table 2 shows the rainfall data for 1984, 1994, 2004, 2013 and 2020 obtained from the Zambia Meteorological Department as one of the inputs in our simulation of surface runoff estimations.

Table 2: Rainfall Data

Time Period	Rainfall Received(mm)
1984	759.99
1994	564.92
2004	848.11
2013	729.5
2020	1147.77

RESULTS

Land use / Land cover classification

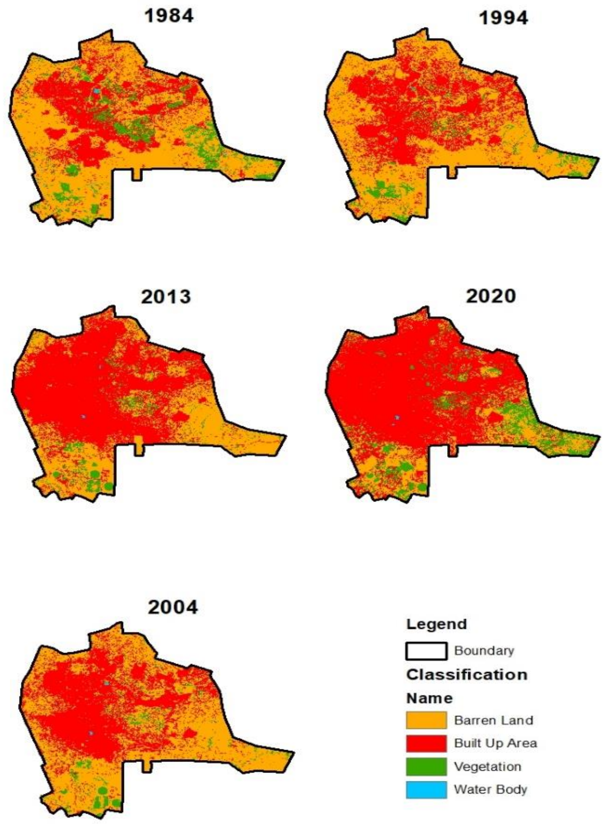

Figure 3: Land use / Land cover classification (1984, 1994, 2004, 2013 & 2020).

Figure 3 shows the classified maps for 1984, 1994, 2004, 2013 and 2020 which were generated using GIS and Remote sensing techniques.

Land use/Land cover Trends (1984-2020)

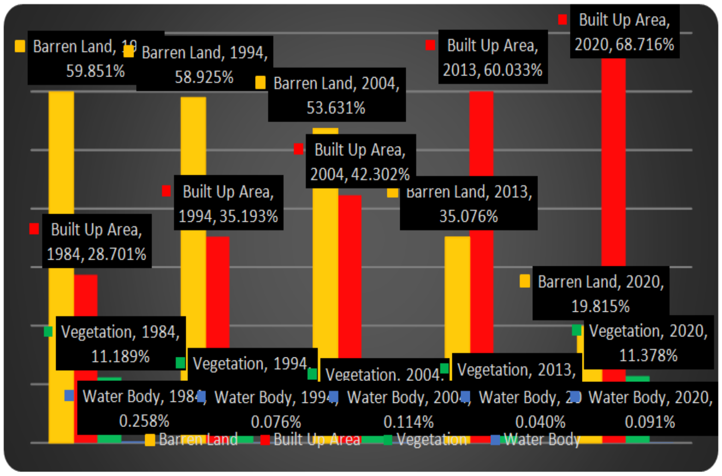

Figure 4: Land use / Land cover trend analysis (1984, 1994, 2004, 2013 & 2020)

Figure 4 illustrates the changes in the percentage of the four land use classes (built-up area, barren land, vegetation, and water body) for the years 1984, 1994, 2013, and 2020. The analysis revealed significant transformations in land use patterns over this time period.

The findings indicate a substantial increase in the percentage of urban areas (built-up area) from 28.701% in 1984 to 35.193% in 1994, further escalating to 42.302% in 2004, 60.033% in 2013, and reaching 68.716% in 2020. This upward trend highlights the rapid urbanization and expansion of built-up areas in the study area.

Conversely, barren land exhibited a notable decline from 59.851% in 1984 to 19.815% in 2020. This significant decrease indicates the conversion of barren land to other land use categories, primarily driven by urbanization and land development activities.

Calculations of weighted curve numbers

Table 3 shows the calculation of weighted curve numbers for the four (4) different land use classes (built up area, water body, vegetation and barren land) for 1984, 1994, 2004, 2013 and 2020. This analysis was based on the CN attributed to each land use class which was obtained from the Hydrologic soil cover complexes manual. Additional determining criteria used included AMC-II and fair ground cover conditions.

Table 3: Calculation of weighted curve numbers

No.	Land use Class	HSG	CN	Area (km²)	% Area	Area * CN	Weighted CN
				1984			
1	Built Up Area	C	94	120.16	28.701	27042.37	84.742
2	Water Body	C	100	1.081	0.258	38.11325	
3	Vegetation	C	86	46.845	11.189	4096.507	
4	Barren Land	C	80	250.572	59.851	6636.497	
				1994			
1	Built Up Area	C	94	147.335	35.193	13849.57	85.289
2	Water Body	C	100	0.319	0.076	31.902	
3	Vegetation	C	86	24.305	5.806	2090.265	
4	Barren Land	C	80	246.691	58.925	19735.31	
				2004			
1	Built Up Area	C	94	177.097	42.302	16647.12	86.181
2	Water Body	C	100	0.478	0.114	47.85	
3	Vegetation	C	86	16.55	3.953	1423.302	
4	Barren Land	C	80	224.526	53.631	17962.1	
				2013			
1	Built Up Area	C	94	251.332	60.033	23625.26	88.704
2	Water Body	C	100	0.168	0.04	16.83	
3	Vegetation	C	86	20.307	4.851	1746.476	
4	Barren Land	C	80	146.85	35.076	11748.06	
				2020			
1	Built Up Area	C	94	287.684	68.716	27042.37	90.321
2	Water Body	C	100	0.381	0.091	38.113	
3	Vegetation	C	86	47.6338	11.378	4096.507	
4	Barren Land	C	80	82.956	19.815	6636.497	

Table 4 shows the simulated runoff (mm) generated from the SCS CN model corresponding to the amount of rainfall (mm) received and the percentage of surface runoff generated. The results generated from the model were graphically represented in Figure 5.

Table 4: Annual Rainfall and SCS CN Model Runoff simulation

Year	CN	S(mm)	Ia(mm)	P(mm)	Q(mm)	%Runoff
1984	84.742	45.733	9.146	623.2	571.491	91.703%
1994	85.289	43.811	8.762	433.5	385.023	88.817%
2004	86.181	40.728	8.145	1138.8	1091.343	95.833%
2013	88.704	32.345	6.469	785.6	748.075	95.223%
2020	90.321	27.219	5.443	1114.6	1082.590	97.128%

Rainfall data and simulated runoff

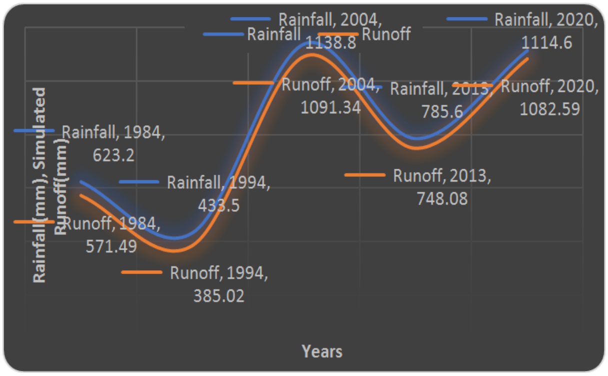

Figure 5: Rainfall data and simulated runoff

Figure 5 above shows the rainfall recorded and the simulated runoff observed for each respective time period. The peak runoff points recorded from the runoff simulation model were compared to past records of flood events (2005, 2009, 2017 & 2020) in the district which corresponded to the observed results from the SCS CN model.

DISCUSSION

The results obtained from the study provide valuable insights into the impact of urbanization on surface runoff in Lusaka District. The classification of land use/land cover maps using remote sensing and GIS techniques revealed a significant increase in the percentage of urban areas (built-up area class) from 28.7% in 1984 to 68.7% in 2020. This finding indicates rapid urban expansion and highlights the ongoing process of urbanization in the district.

The SCS CN model simulations demonstrated a corresponding increase in surface runoff over the study period. The minimum recorded runoff of 385.02 mm in 1994 increased to a maximum of 1082.59 mm in 2020. These findings indicate a substantial increase in surface runoff as urban areas expand. The correlation between urbanization and increased surface runoff is consistent with previous research findings (Patil et al., 2008; Sindhu et al., 2013). The expansion of impervious surfaces in urban areas leads to reduced infiltration capacity and increased runoff generation, contributing to higher surface runoff volumes.

The high overall accuracy of the land use/land cover maps, ranging from 93.22% to 99.19%, reflects the effectiveness of the supervised classification technique used in this study. Accurate land cover classification is crucial for reliable surface runoff simulations and provides a foundation for urban planning and water resource management decisions.

The integration of remote sensing, GIS, and the SCS CN model offers a comprehensive approach to assess the hydrological impacts of urbanization. By considering various factors such as soil type, precipitation data, and land use characteristics, the SCS CN model provides insights into the variations in surface runoff associated with different land cover types. This information is essential for understanding the hydrological dynamics of urban areas and can guide the development of effective strategies for stormwater management and flood control.

The findings of this study have important implications for urban planning and water resource management in Lusaka District. The significant increase in urban areas and the corresponding rise in surface runoff emphasize the need for sustainable and resilient urban development practices. Future urban planning initiatives should prioritize the implementation of green infrastructure strategies to mitigate the adverse effects of increased surface runoff. These may include the incorporation of green spaces, permeable pavements, and other stormwater management techniques that promote infiltration and reduce runoff volume (Ahern, 2007; Benedict & McMahon, 2006).

Continued monitoring and assessment of land use/land cover changes in urban areas is recommended for a better understanding of urbanization dynamics and their hydrological implications. Regular updates of land use maps using high-resolution satellite imagery can provide valuable data for urban planners and decision-makers. Additionally, the integration of more detailed information, such as soil properties and vegetation cover, can enhance the accuracy of surface runoff simulations and improve the effectiveness of urban planning strategies.

CONCLUSION AND RECOMMENDATIONS

The results obtained from the simulated runoff model (SCS CN Model) showed correlation of increased surface runoff to increased urbanization which also corresponded to observed ground flood data in the district. A minimum of 385.023 mm simulated runoff with a percentage runoff of 88.817% was recorded in 1994 which sequentially increased by 8.3% to 97.128% in 2020 with a runoff record of 1082.590 mm.

In conclusion, this study utilized Remote Sensing and GIS technology to assess the impact of urbanization on surface runoff in Lusaka District. The findings from the simulated runoff model (SCS CN Model) demonstrated a clear relationship between urbanization and increased surface runoff, which aligned with the observed ground flood data in the district.

The analysis revealed a significant increase in simulated runoff over the study period. In 1994, a minimum of 385.023 mm of simulated runoff, accounting for 88.817% of total precipitation, was recorded. This percentage of runoff progressively rose by

8.3% to 97.128% in 2020, accompanied by an increase in the runoff volume to 1082.590 mm.

These results highlight the influence of urbanization on hydrological processes, specifically surface runoff, and the subsequent implications for flood management in Lusaka District. As urban areas expand, the increase in impervious surfaces leads to reduced natural infiltration, resulting in a higher proportion of rainfall becoming surface runoff.

Based on the findings, the following are the recommendations:

1. Integrated urban planning: It is crucial to incorporate comprehensive urban planning strategies that consider water management aspects. This includes the integration of green infrastructure, such as permeable pavements, green spaces, and retention ponds, to enhance natural infiltration and reduce surface runoff (Ahern, 2007; Benedict and McMahon, 2006).

2. Sustainable land use practices: Promoting sustainable land use practices, such as preserving natural areas, implementing green roofs, and encouraging vegetation cover, can help mitigate the effects of urbanization on surface runoff. These practices enhance infiltration and reduce runoff volumes (Benedict and McMahon, 2006; Liu et al., 2014).

3. Continuous monitoring and modeling: Regular monitoring of land use changes, surface runoff, and flood patterns using Remote Sensing and GIS technologies is essential. This data can be utilized to improve modeling techniques and assess the effectiveness of mitigation measures, facilitating informed decision-making (Brown and Farrelly, 2009; Maidment et al., 2016).

4. By adopting these recommendations, stakeholders including urban planners, policymakers, and water management authorities can work towards sustainable urban development while mitigating the adverse impacts of urbanization on surface runoff and flood risk in Lusaka District. This will contribute to the overall resilience and sustainability of the urban environment.

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