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SURFACE RUNOFF ESTIMATION AT THE DENSU RIVER BASIN USING GEOGRAPHIC INFORMATION SYSTEM (GIS) AND REMOTE SENSING (RS)

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Abstract. Accurate estimation of runoff depth and volume is essential for effective watershed management. Runoff, resulting from rainfall, is influenced by numerous factors, including soil type, vegetation, land use patterns, and rainfall characteristics. The Densu River Basin, located in the Greater Accra region of Ghana, has experienced flooding incidents, partly attributed to changes in land use and land cover. To address these challenges and facilitate proper flood management, drainage network design, hydropower generation, and other applications, this study aims to estimate surface runoff depth in the Densu River Basin, Ghana. The Natural Resources Conservation Services Curve Number (NRCS-CN) method, combined with Geographic Information System (GIS) and Remote Sensing (RS), is employed for runoff depth estimation. The research involves supervised classification of Landsat images from 2001, 2011, and 2022 to determine land use patterns, calculate grass cover percentages, identify hydrologic soil categories, extract rainfall intensity data, compute maximum soil storage, and estimate runoff depths for 10 year, 25 year, and 50 year return periods. The study reveals a significant increase in direct surface runoff depth, from 138.29 mm to 144.70 mm, for soil type D (Clay loam), the dominant soil type in the basin, during the 10 year return period, attributed to changes in land use and climate within the basin. The findings from this study hold valuable insights for mitigating environmental hazards in the area and improving water resource management.

Keywords: surface runoff depth, supervised classification, hydrologic, rainfall intensity, soil storage.

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1. Introduction

Accurate estimation of runoff depth and volume is a critical component of effective watershed management (Rajbanshi, 2016). Runoff, generated by rainfall events, is profoundly influenced by various factors, encompassing soil composition, vegetation cover, land use patterns, as well as the intensity, duration, and distribution of precipitation. Precise knowledge of the resources within a watershed region is indispensable for sustainable economic and social development (World Bank, 2022). Effective watershed management entails a multitude of responsibilities, including flood control, the construction of irrigation and drainage networks, hydropower generation, and other crucial functions. Marui and Food and Agriculture Organization of the United Nations (1988) emphasize the intricate interplay of factors, including rainfall characteristics, in shaping runoff patterns. Beyond rainfall attributes, basin-specific factors further contribute to the overall volume of surface runoff (Marui & Food and Agriculture Organization of the United Nations, 1988).

Various hydrological models, such as lumped models, physically dispersed models, five empirical models, and statistical models, can evaluate the availability of water resources. Distributed hydrological models, for instance, are able to geographically simulate water balance using a variety of soils, land uses, terrain, and climate variables (Singh et al., 2011). SWAT (Soil and Water Assessment tools) (Arnold et al., 1998), has been investigated in a variety of climatic contexts across the globe, from humid and tropical areas to arid (Rafiei Emam et al., 2015; Perrin et al., 2012; Nguyen & Kappas, 2015; Alansi et al., 2009). It may also replicate both local and huge water resources. For instance, Schuol et al. (2008) assessed the amount of water present in eleven United Nations (2020). In a regional area of Vietnam, Phuong et al. (2014) looked at soil erosion and surface runoff. Heavy rainfall causes soil erosion, surface runoff, and flooding in tropical and humid areas (Xu et al., 2013; Cerdà et al., 1998). Numerous researchers have examined how variations in climate impact hydrological processes, water quality, and soil erosion. The tropical region of Ghana is vulnerable to surface runoff and soil erosion. The majority of vegetated regions have recently been turned into agricultural fields and developed, especially in the Densu River Basin, causing surface runoff and soil erosion (Ofosu et al., 2020). Severe socioeconomic strain has led to natural disasters including flooding and soil degradation in the Basin. Lack of data and sophisticated tools to analyse this issue is one of the biggest problems facing policymakers in this field. Therefore, there is a need to analyse the spatial changes in the surface runoff within the Densu River Basin for early flood and erosion control. Based on the aforementioned research needs, this study employs GIS and RS to derive the surface runoff depth in the Densu River Basin using the Natural Resources Conservation Services Curve Number (NRCS-CN) method.

Several runoff models have shown that surface runoff is dependent on the surface infiltration and rainfall pattern. This is as a result of changes in LULC patterns that have increased the impervious surfaces in a particular area. The Densu River Basin (DRB) in Ghana is rapidly urbanizing as a result of population growth (Ofosu et al., 2020). This would affect the ecology of the DRB. The pattern of precipitation changes drastically, and the amount of water running off into the stream networks increases. The DRB has not seen a lot of surface runoff study, but according to Jeong et al. (2010) findings, "rainfall-generated runoff is dependent on the strength, duration, and distribution of rainfall events." Other catchment-specific factors, in addition to the characteristics of the rainfall, have a direct influence on how much runoff occurs. The surface runoff in an ungauged river catchment can be estimated using a number of methods, including the Artificial Neural Network (ANN), the Soil Conservation Service-Curve Number (SCS-CN) Model, the Geomorphological Instantaneous Unit Hydrograph (GIUH), and others. One of these approaches that is often used is the SCS-CN, also referred to as the Natural Resource Conservation Service Curve Number (NRCS-CN) methodology. The classic SCS-CN approach for runoff estimation is a labour and error intensive process. Thus, the NRCS-CN paradigm is rapidly incorporating GIS and remote sensing technology (Gnanachandrasamy et al., 2022). GIS and RS techniques have been employed by numerous scholars from across the world to precisely calculate curve numbers. Gajbhiye and Mishra (2012) claimed that a large portion of the input data required by the SCS-CN methodology might be generated utilizing incredibly trustworthy methods like remote sensing and GIS. The SCS-CN, which is based on RS and GIS, can be used to predict runoff from river basins with comparable geo-hydrological characteristics, according to Ahmad and Verma's (2015) research.

The NRCS-CN or SCS-CN model was utilized for this inquiry because it is an empirical, straightforward model with few data needs and clearly stated assumptions that can be used to anticipate runoff for a specific rainfall event (Ponce & Hawkins, 1996). One CN parameter includes all of the important factors that affect runoff production, including soil type, land use and treatment, surface condition, and soil moisture condition (Ponce & Hawkins, 1996). Mishra and Singh (2003) provided a summary of the SCS-CN uses in storm water modelling for particular rainfall events, long-term hydrologic simulation, projecting infiltration and rainfall-excess rates, and simulating sediment yield and transit of urban pollutants. The SCS-CN model has been used to compute runoff in numerous hydrological and ecological models, including CREAMS (Knisel, 1980), ANSWERS (Beasley et al., 1980), AGNPS (Young et al., 1989), EPIC (Sharpley & Williams, 1990), and SWAT (Neitsch et al., 2005). In industrialized nations, it is now a common practice to evaluate a watershed's conditions using advanced techniques like GIS and remote sensing (RS). Ghana requires researchers who can use this approach to enhance watershed management and planning because it is a developing nation.

With rising urbanization in Ghana, Densu is one of the country's watersheds. Anthropogenic activities have occasionally caused the runoff in the watershed to grow dramatically (Gnanachandrasamy et al., 2022). A technique to estimate runoff in the watershed at a broad scale without using any conventional methods which are exceedingly laborious and time-consuming is needed to detect this accretion and its effects on the watershed. Water resource management needs to be successful when there is accurate estimation of surface runoff that comes from rainfall. Surface runoff is responsible for flooding in a watershed. Part of DRB, which is part of the Greater Accra region, has experienced flooding (Ofosu et al., 2020). Changes in land use and land cover have an impact on the depth of surface runoff in the basin. The pattern of land use in the basin affects surface runoff. For the long-term management of soil and water resources, hydrological modelling of the water cycle in places vulnerable to extreme events and natural hazards (such as flooding and droughts) is essential. Watersheds in the DRB have lately experienced changes in their hydrological behaviour due to anthropogenic influences. Examples of this include soil erosion, increased surface runoff, and floods in the Densu Basin. Since there is no comprehensive framework in place to mitigate environmental hazards in this region, methods to estimate the depth of surface runoff in the Densu Basin are required for proper management of flooding, design of drainage and irrigation networks, hydropower generation, and many other things. This study calculates the Basin's surface runoff from 2001 to 2022.

2. Study area

The DRB is the subject of the investigation. The area was picked because of the ongoing destruction of the vegetation brought on by recurrent urbanization. Farming is the primary socioeconomic activity in the area and is impacted by climate change. In order to evaluate changes between 2000 and 2022, the study uses the NRCS-CN model, which evaluates surface runoff under various moisture levels. The

Densu River Basin is situated in the southeast of Ghana, between latitudes 500 45 and 600 15 and longitudes 100 30 to 100 45. Its catchment area is bordered to the east and north by the Odaw and Volta River basins, to the northwest by the Birim, and to the west by the Ayensu and Okurudu. The Densu River's map is shown in Figure 1.

3. Resources and methods used

3.1. Resources

The materials used for this study are elaborated in Table 1 with their sources

Table 1. Materials used with their source for this study

Data	Source
Landsat images	U.S. Geological Survey (2000)
SRTM DEM	U.S. Geological Survey (2000)
Shapefile of Administrative Boundary	Hijmans et al. (2004)
Metrological stations and IDF curve for Ghana	Ghana Meteorological Agency (2004)
Google earth Pro	Google (2004)
QGIS 3.16.3 software	QGIS (2002)
ArcGIS 10.4	Esri (1969)

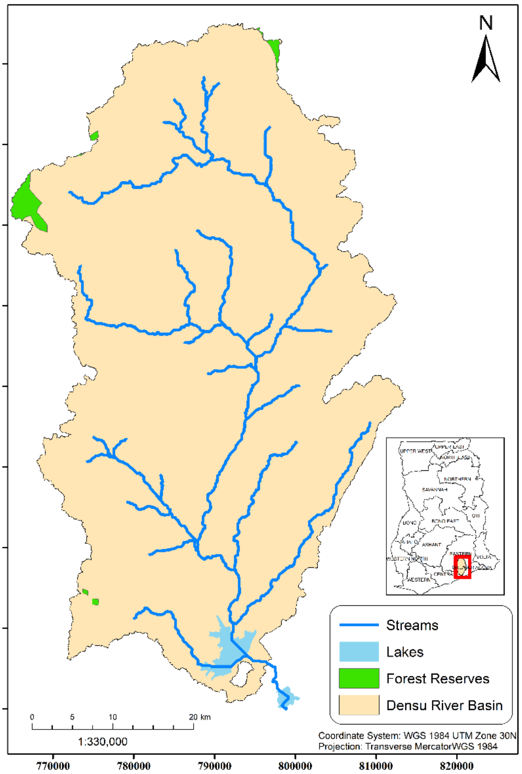


Figure 1. A map of Densu River Basin

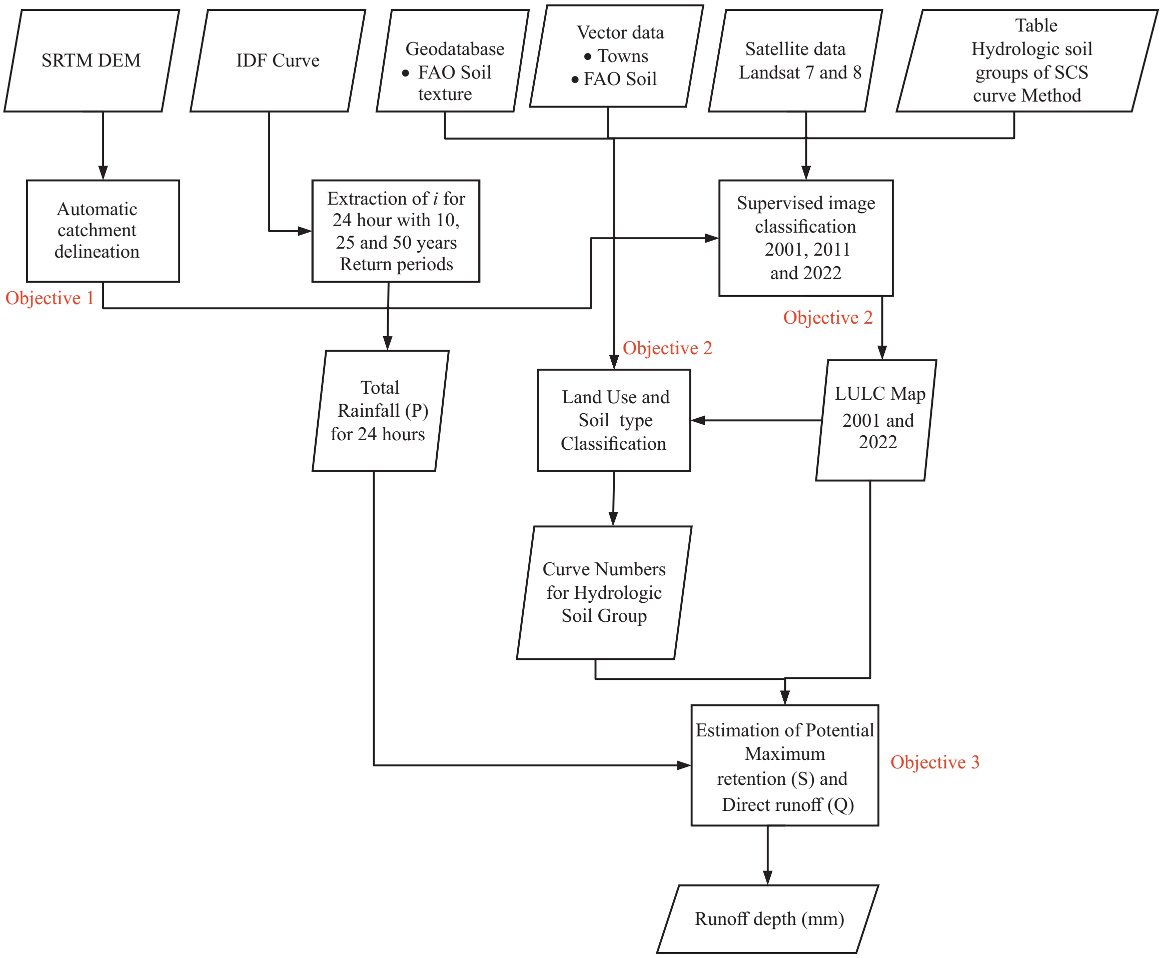


Figure 2. Conceptual framework of the study

3.2. Methods

Landsat photos from 2001, 2011, and 2022 underwent supervised classification to produce a description of the land use in the Densu River Basin. The percentage of grass cover within the Basin was computed from the classified image. The Hydrologic soil categories found in the Densu River watershed were identified using the SWAT FAO soil geodatabase. The Curve number for normal moisture conditions for 2001, 2011 and 2022 was calculated using Table 1 (ARC II). In order to calculate the total 24-hour rainfall (P) for the 10 year, 25 year, and 50 year return periods, the rainfall intensity was derived from the intensity-duration frequency (IDF) curve for the nearest metrological station (Accra) to the Densu River Basin. The systematic framework of these processes is shown in Figure 2. The methods are elaborated in details for this study in this chapter.

3.2.1. Automatic catchment delineation in Arc SWAT for ArcGIS 10.4

The SRTM DEM obtained from earth explorer was used to perform a catchment delineation for the Densu River. During this process, the outlet location of the Densu River to the sea was used to aid the SWAT software to delineate the catchment area. All the streams within the basin were extracted automatically by the software.

3.2.2. Determination of hydrologic soil groups in the Densu River Basin

The Soil shapefile obtained from FAO; eight (8) different FAO soil classes were identified within the Densu River Basin. These soils have a unique soil number (SNUM) assigned to them. These SNUM were used to determine the hydrologic soil group for the FAO soil classes, using the SWAT 2012 Geodatabase with FAO soil classes.

3.2.3. Supervised image classification for LULC

A supervised classification was done for three Landsat datasets (2001, 2011 and 2022) obtained from earth explorer. The images were pre-processed in QGIS 3.16.3 using the Semi-automatic classification plugin (SCP) to remove atmospheric and radiometric errors. The Pre-processed images were used to form a false colour composite (NIR, Red and Green) for 2001, 2010 and 2022. Three classes were considered for this study:

1. Pervious (Grass lands, Forest, croplands and other vegetations).
2. Impervious (Settlements and Bare lands or Built-up areas).
3. Water (Hydrologic features).

A total of 120 ground truth data was collected from google earth of which 70% (84 samples) was used for classification and 30% (36) was used to validate the classified images as shown in Table 3. The random forest algorithm with 500 trees was used for the supervised classification in QGIS 3.16.3.

3.2.4. Estimation of surface runoff depth in the Densu River Basin

The LULC and hydrologic soil group for the Densu River Basin was used to extract the Curve Number (CN) 2001, 2011 and 2022 conditions. The IDF curve for Accra metrological station was used to extract a 24hr rainfall for a return period of 10, 25 and 50 yrs. The maximum soil storage (S) was computed for 2001, 2011 and 2022 using Equation (1). Knowing the rainfall, P and maximum storage S, for 2001, 2011 and 2022, the runoff depth (Q) was computed for 2001, 2011 and 2022 using Equation (2).

$$S = \left(\frac{100}{CN} - 10\right)\left(\frac{1}{0.0394}\right); \tag{1}$$

$$Q = \left(\frac{P - 0.2S}{P + 0.8S}\right), P > 0.2S. \tag{2}$$

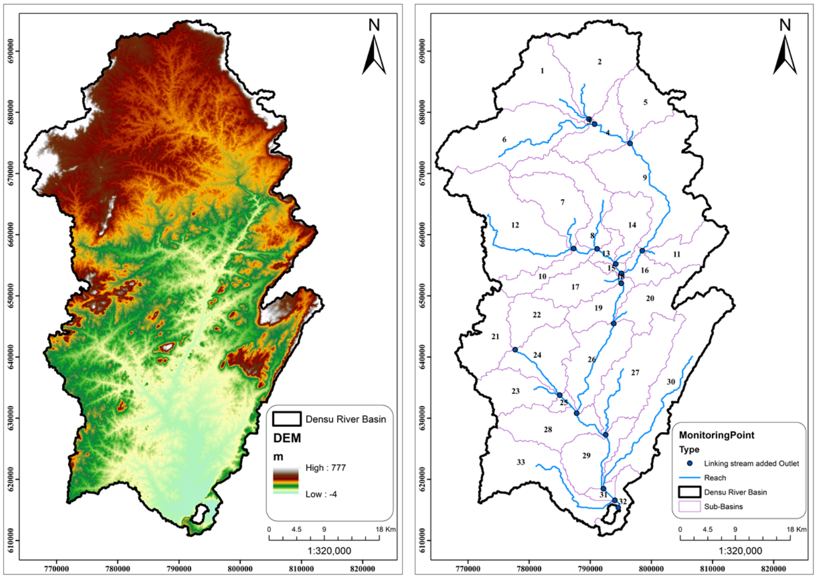


Figure 3. Automatic catchment delineation from DEM

4. Results

4.1. Delineation of the catchment area for the Densu River Basin

The Densu River Basin has a total area of 255,174.10 km^2, thirty-three sub basins, thirty-three exits, and a total stream length of 282.164 km, as shown in Figure 3, according to the results of the watershed delineation of the Densu River.

4.2. The land use and the hydrologic soil groups in the Densu Basin

The result obtained from the supervised classification of the Landsat images for 2001, 2011 and 2022 within the Densu River Basin showed that, 90%, 82% and 51% of the area within the basin were pervious with 9%, 17% and 48% impervious areas respectively as shown in Figures 4 and 5.

4.3. Hydrologic soil group for the soil types in the Densu River Basin

An observation from the eight (8) soil classes identified within the Densu River Basin with FAO SNUM showed that, there are two hydrologic soil classes that is C and D within the basin as shown in Table 2 and Figure 6.

Table 2. Hydrologic soil group from FAO soil in SWAT Geodatabase

SNUM	FAO SOIL	Soil group
1046	Ao1-ab	D
1229	I-Bd-Nd-b	C
1051	Ao11-b	D
1323	I-b	C
1052	Ao13	D
1052	Ao13	D
1017	Af1-1/2a	C
1727	Vc5-3a	D

4.4. Estimating the change in surface runoff depth in the DRB from 2001 to 2022

The results obtained from the estimation of runoff depth for 10, 25 and 50 year return periods shown in Fig-

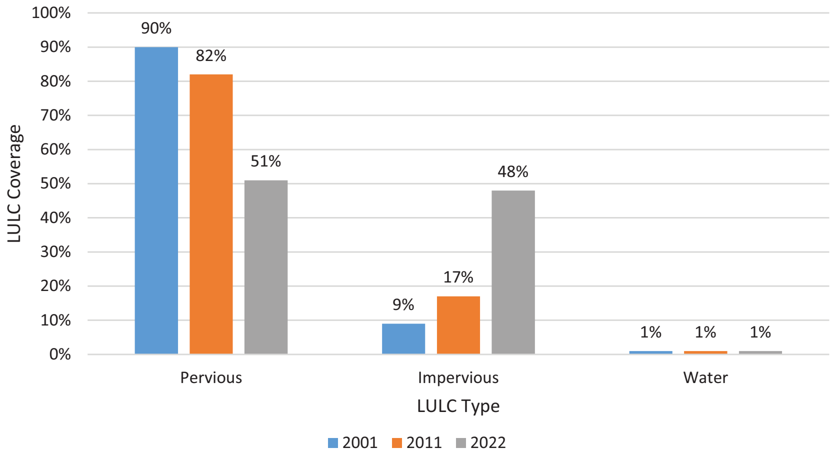
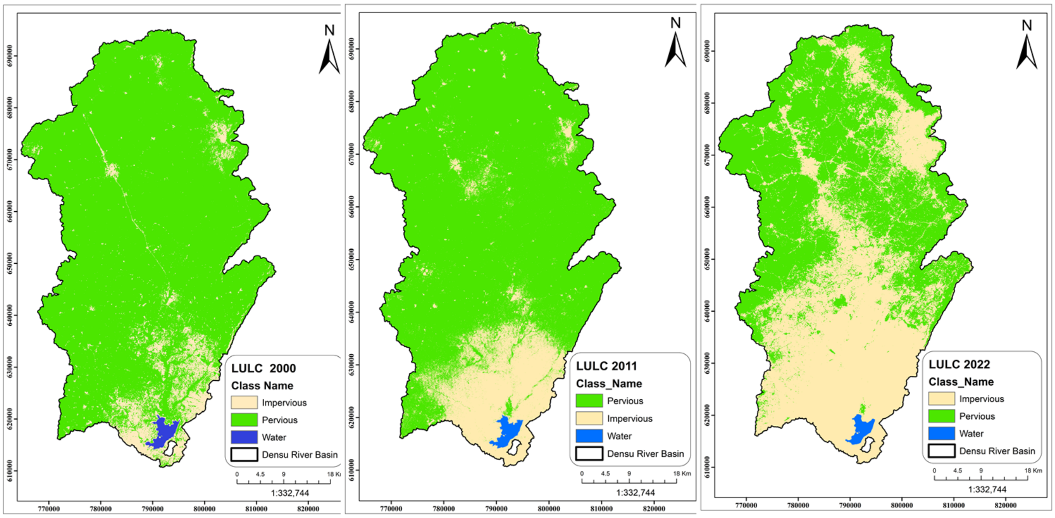


Figure 4. Land use in the Densu River Basin



a) b) c)

Figure 5. Spatial distribution of LULC coverage within the Densu River Basin for: a – 2001; b – 2011; c – 2022

ures 8, 9 and 10 respectively were obtained from the estimation of the maximum retention (S) for the two identified hydrologic soil groups in the DRB also shown in Figure 7 for 2001, 2011 and 2022.

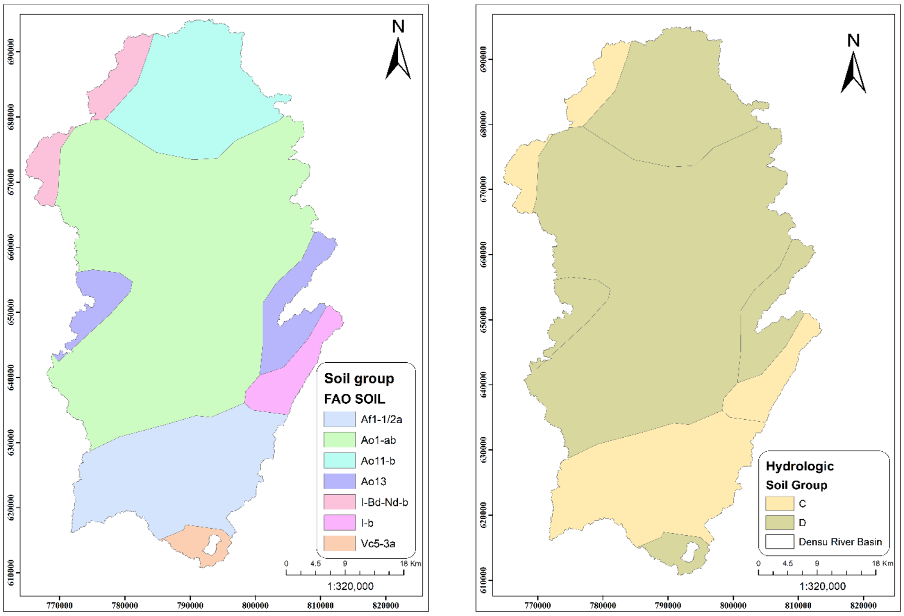


Figure 6. Hydrologic soil group from FAO soil

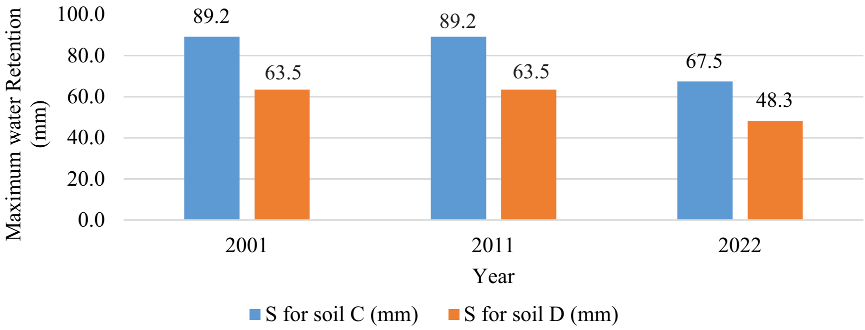


Figure 7. Maximum water retention from 2001 to 2022 in the Densu River Basin

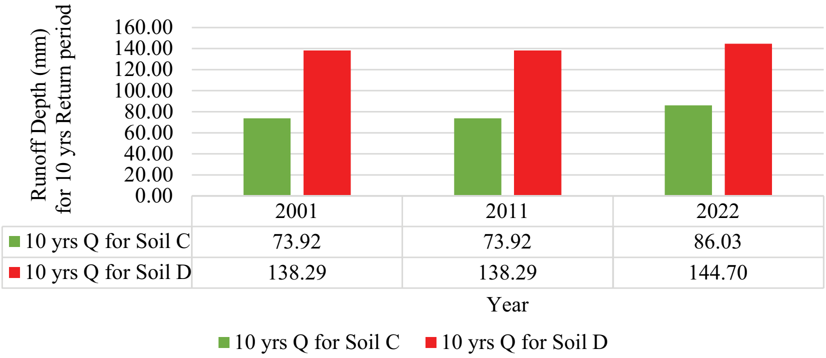


Figure 8. Runoff depth for 10 years return period within the Densu River Basin 2001–2022

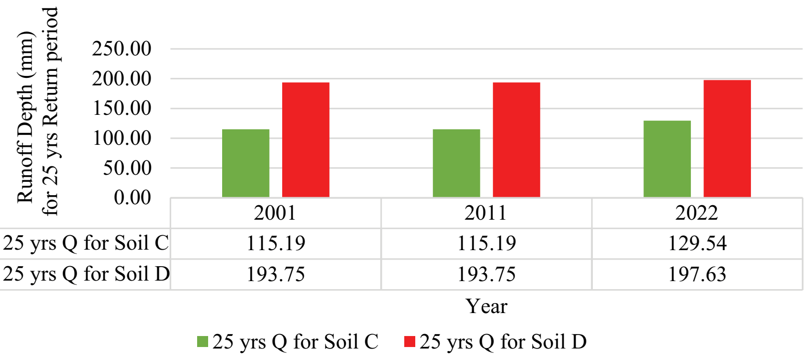


Figure 9. Runoff depth for 25 years return period within the Densu River Basin 2001–2022

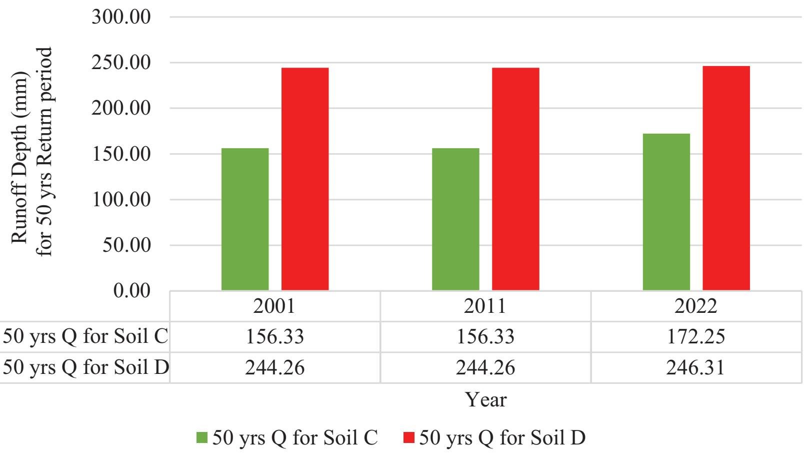


Figure 10. Runoff depth for 50 years return period within the Densu River Basin 2001–2022

Table 3. Accuracy assessment of supervised classification

2001	Pervious	Impervious	Water	Total	User accuracy
Pervious	87	3	0	90	97%
Impervious	1	9	0	10	90%
Water	0	0	10	10	100%
Total	88	12	10	110	
Producer accuracy	99%	75%	100%		
Kappa	0.888889				
Overall accuracy	96%				
2011	Pervious	Impervious	Water	Total	User Accuracy
Pervious	81	1	0	82	99%
Impervious	1	16	0	17	94%
Water	0	0	10	10	100%
Total	82	17	10	109	
Producer accuracy	99%	94%	100%		
Kappa	0.954279				
Overall accuracy	98%				
2022	Pervious	Impervious	Water	Total	User accuracy
Pervious	50	1	0	51	98%
Impervious	2	46	0	48	96%
Water	0	0	10	10	100%
Total	52	47	10	109	
Producer accuracy	96%	98%	100%		
Kappa	0.952423				
Overall accuracy	97%				

End of Table 3

5. Discussion

5.1. Delineation of the catchment area for the Densu River Basin

The Densu River Basin covered a total area of 2551742.10 km^2 with thirty-three (33) sub basins with thirty-three (33) outlets and a total stream length of 282.164 km. This shows how big the basin is. The delineation of the basin would have been difficult using traditional methods. The use of GIS and RS was very effective in dealing with a large catchment like Densu.33 sub basins have been contributing runoff to the main river within the basin. All these basins have their soil types and LULC that influence the hydrologic behaviour of the basin. Watershed management agencies can utilise this result on the catchment characteristics to plan and manage the Densu basin. Although the Channels that were delineated depicts the flow paths in the basin but not to accuracy because of the resolution of the SRTM DEM used in this study.

5.2. The land use and the hydrologic soil groups in the Densu Basin

In 2011, the pervious surfaces within the basin have decreased to 82% with an increase in the impervious surfaces to 17%. In 2022, the Pervious areas have decreased to 51% and the Impervious areas have increased to 48% as shown in Figures 4 and 5. This shows how urbanisation is increasing in the Densu River Basin. All the years recorded no change in the water coverage. Anthropogenic activities within the basin which has been causing the increase in urbanisation within the catchment has become the major agent of deforestation and vegetation cover decrease over the years. The two main hydrologic soil groups (C and D) identified within the Basin are the soil group with low infiltration rate with soil group D which appeared to be the dominant soil group in the basin (Figure 6) is noted to have a very high runoff potential (Table 2). A good policy to monitor the LULC within the basin would be an early preventive measure to avoid flooding in the future. The FAO soil database was found to be very useful in this study to classify the soil into their respective Hydrologic group.

5.3. The changes in surface runoff depth in the Densu River Basin from 2001 to 2022

An observation from the hydrologic soil group and land use description derived from the supervised classification showed that, the land use in 2001 and 2011 were in a good condition since the grass cover (Pervious areas) is more than 75%. In 2022, the condition of land use changed to a fair condition since the grass cover (Pervious) within the basin is within 50% and 75% as shown in Figure 4. This is attributed to the increase in urbanisation within the basin. It was observed that, hydrologic soil group C retained water more than soil group D from 2001 to 2022 within the Densu River Basin as shown in Figure 7. The higher the CN of the soil, the lower the maximum retention of the soil. Furthermore, an observation from the direct runoff depth for a normal soil condition (ARC II) showed that, the runoff depth of the Hydrologic soil groups has been increasing from 2001 to 2022 with soil group D with the highest runoff depth for 10 years return period. This same trend was observed for 25 and 50 years return periods as shown in Figures 8, 9 and 10 respectively. However, inference from these changes in runoff depth from 2001 to 2022 confirms the fact that LULC change has a major impact on the retention capability within the basin. Remote sensing and GIS have made the analysis of the changes in runoff depth from 2001 very easy. Nevertheless, limitations on the resolution of the satellite images used for this analysis would give different outcomes on results but same conclusion on the catchment dynamics.

6. Conclusions and recommendations

The findings shed light on many critical aspects of the hydrological behavior and changes within the Densu River Basin, emphasizing the value of Geographic Information System (GIS) and Remote Sensing (RS) technologies in improving how we understand complex catchment dynamics. The key conclusions drawn from the analysis of catchment characteristics, land use and hydrologic soil groups, and changes in surface runoff depth from 2001 to 2022 are:

The Densu River Basin, covering a vast expanse of approximately 2,551,742.10 km^2, comprises thirty-three subbasins, each contributing runoff to the main river within the basin. The delineation of such an extensive catchment area would have been a formidable challenge using traditional methods alone. However, the integration of GIS and RS proved highly effective in this task. These sub-basins exhibit diverse soil types and land use/land cover (LULC) characteristics that significantly influence the hydrologic behavior of the basin. This comprehensive understanding of the catchment's characteristics provides valuable insights for watershed management agencies in their planning and management efforts. While the delineated channels represent flow paths within the basin, it's important to acknowledge that the resolution of the SRTM DEM used in this study may introduce some limitations in accuracy.

Land use and hydrologic soil groups

A significant trend observed in the Densu River Basin is the rapid increase in urbanization, marked by a decrease in pervious surfaces and a simultaneous rise in impervious areas. In 2011, pervious surfaces comprised 82% of the basin, but by 2022, this had reduced to 51%, with impervious areas expanding to 48%. This urbanization trend is a major driver of deforestation and vegetation cover reduction within the basin. The dominant hydrologic soil group within the catchment is group D, characterized by a low infiltration rate and a high runoff potential. Monitoring land use and LULC changes within the basin emerges as a crucial policy recommendation to mitigate potential flooding in the future. The use of the FAO soil database proved instrumental in classifying soils into their respective hydrologic groups.

Changes in surface runoff depth

Analysis of surface runoff depth over the period from 2001 to 2022 revealed noteworthy shifts in land use and hydrologic soil group dynamics. In 2001 and 2011, the land use exhibited a favorable condition, with grass cover (pervious areas) exceeding 75%. However, by 2022, the land use condition had deteriorated to a fair state, with pervious cover ranging from 50% to 75%. This decline in grass cover can be attributed to the escalating urbanization within the basin. Hydrologic soil group C was observed to retain water more effectively than group D throughout this period.

Furthermore, an investigation into the direct runoff depth for a normal soil condition (ARC II) unveiled a concerning trend. Runoff depth for hydrologic soil group D displayed the highest values for the 10 year return period, a pattern consistent with the 25 year and 50 year return periods. These findings underscore the impact of land use and land cover changes on the retention capability of the basin. The analysis of changes in runoff depth from 2001 to 2022 confirms that LULC change plays a pivotal role in the hydrological dynamics of the catchment. The integration of remote sensing and GIS technologies facilitated the assessment of these changes, although it is essential to acknowledge potential limitations arising from the resolution of the satellite images used.

Recommendations

Based on the findings of this study, several recommendations emerge:

- Monitoring and Managing Urbanization: Given the rapid urbanization within the Densu River Basin, it is imperative for local authorities and watershed management agencies to implement effective monitoring and management strategies to mitigate the adverse effects of urbanization on surface runoff and flooding.
- Land Use Planning: The study underscores the importance of robust land use planning and policies that prioritize the preservation of pervious surfaces, especially grass cover, to maintain the basin's retention capabilities.
- Data Resolution Enhancement: Future research in this area should consider using higher-resolution satellite images and more advanced remote sensing techniques to improve the accuracy of results, particularly in areas where fine-scale details are crucial.
- Integrated Watershed Management: Watershed management agencies should consider an integrated approach that leverages GIS, RS, and hydrological modeling to better understand and address hydrologic challenges within the Densu River Basin.
- Long-Term Monitoring: Continuous monitoring of land use, hydrologic soil groups, and surface runoff depth is essential for tracking changes and implementing adaptive management strategies over time.

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