Rainfall-Runoff Modelling for Sustainable Water Resource Management in the Louisiana State

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Abstract

Urban watersheds in Louisiana face increasing pressure as urbanization and environmental challenges mount in the 21st century. This study leverages Google Earth Engine (GEE) to model and predict runoff patterns in Louisiana from 2018 to 2023, aiming to improve water resource management. An iterative methodology integrates key data such as soil texture, land use, and daily precipitation, focusing on the Curve Number (CN) approach to represent runoff potential based on land characteristics. The analysis uses the Soil Conservation Service Curve Number (SCS CN) method, factoring in precipitation and antecedent moisture, and visualizes spatial distributions of CN, precipitation, soil, and runoff. Results show an accurate model with an R^2 of 0.964, validated against the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis 5th Generation (ERA5) Land Monthly data. Model performance was further assessed with the receiver operating characteristic (ROC) curve, achieving a high area under the curve (AUC) value of 0.937, underscoring the model's precision in predicting daily runoff. This highlights the role of comprehensive, data-driven approaches in understanding Louisiana's hydrological conditions, emphasizing the importance of soil, land use, and rainfall data in managing water resources and predicting surface runoff within urban watersheds.

1. Introduction

1.1 Louisiana's Urban Watershed

Louisiana's urban watersheds face growing challenges from urbanization, climate change, and water resource management pressures. Known for its rich ecosystems and cultural heritage, Louisiana experiences severe flooding, as seen with Hurricanes Katrina and Harvey, which heightens the need for resilient water management strategies (Diaz et al., 2020). Rapid loss of wetlands and coastal areas further exacerbates flood risks, endangering ecosystems and complicating water management (Antonio et al., 2022). Pollution in urban watersheds endangers both human health and the environment, underscoring the importance of clean water, as emphasized by the Sustainable Development Goal (SDG) 6 (Shehu & Nazim, 2022). Vulnerable communities are particularly impacted, aligning social equity issues with sustainable water resource goals (Guo, 2023). Advanced rainfall-runoff modelling can assess watershed resilience by simulating rainfall and runoff patterns, which helps inform sustainable management approaches that support SDGs on sustainable cities and climate action (Jain et al., 2021; Shen et al., 2019).

1.2 Enhancing Urban Watershed Resilience through Integrated Water Resource Management

Asghari et al. (2023) emphasize the need to assess urban water infrastructure (UWI) resilience, focusing on drainage and stormwater systems to mitigate potential structural and functional failures impacting urban watershed resilience. Their review highlights green infrastructure as a key strategy for enhancing UWI resilience in managing rainfall-runoff (Asghari et al., 2023). Shen et al. (2019) highlight the complexity of flood risk in coastal urban environments, where combined rainfall and storm tide-driven flooding necessitate improved floodplain mapping and mitigation to increase resilience (Shen et al., 2019). Guo (2023) underscores the importance of integrated watershed management within the Mississippi River basin, promoting sustainability and resilience through green infrastructure and preparing for extreme weather, while considering equity and the water-energy-food nexus (Guo, 2023). This research builds on these principles to address Louisiana's unique challenges in urban watershed management through rainfall-runoff modelling, advancing SDGs for clean water, reduced inequalities, climate action, and sustainable land use.

2. Research Methodology

2.1 Study Area- Louisiana State, USA

Louisiana state in the USA has a unique geography and environmental conditions which makes it a prime area for studying urban watershed resilience through rainfall-runoff modelling. Bordered by Texas, Arkansas, Mississippi, and the Gulf of Mexico, and marked by the Mississippi River along its eastern edge, Louisiana is vulnerable to frequent flooding due to its low-lying coastal regions, climate variability, and urbanization (Kesel et al., 2023). These factors, combined with Louisiana's rich ecosystems, cultural importance, and complex water management policies, present a challenging yet comprehensive setting to explore solutions for urban watershed resilience. The state's diverse natural and human interactions offer valuable insights for enhancing watershed resilience strategies.

Figure 1. A Map of Louisiana State (LA) of USA 11. (Klaus, 2023)

2.2 Materials and Data Used

This study utilized Google Earth Engine (GEE) as the primary platform for geospatial data processing and analysis to create a rainfall-runoff model. It incorporates various Earth observation datasets to model runoff in Louisiana state. The key datasets include soil texture information from the OpenLandMap, Copernicus land use/land cover (LULC) data for the specified years (2018 to 2023), Shuttle radar topography mission Digital elevation model (SRTM DEM) and daily precipitation data from the UCSB-CHG/CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) collection. These datasets were integrated to calculate the Curve Number (CN) for each land use and soil class, which is essential for runoff modelling. The datasets and materials used in this study are elaborated in Table 1 with their sources.

Material/data	Source
SRTM DEM	https://developers.google.com/earth-engine/datasets
Copernicus LULC	https://developers.google.com/earth-engine/datasets
Soil Texture Data	https://developers.google.com/earth-engine/datasets
Precipitation data	https://developers.google.com/earth-engine/datasets
GEE code editor	https://code.earthengine.google.com/
ERA-5 data	https://developers.google.com/earth-engine/datasets

Table 1. Materials and Data Used

2.3 Data Processing and Analysis (SCS-CN method)

The SCS (Soil Conservation Service - Curve Number) Curve Number (CN) method was used to estimate the daily surface runoff (Muthu & Santhi, 2015). This method accounts for land cover, soil type, and hydrologic conditions within each sub-basin, giving an initial estimate of the runoff volume based on rainfall depth and retention capacity. A GEE JavaScript code which utilizes an iterative approach of the SCS-CN method to generate runoff values by integrating precipitation and land-specific Curve Number (CN) values, with visualization layers for rainfall and runoff trends was scripted using the code editor. It also includes functionality for exporting mean runoff data to Google Drive for further analysis. During processing, soil data was categorized into hydrologic soil groups (A, B, C, D) as shown in Table 2 and combined with land use data into a composite image. This integration streamlined runoff modelling by incorporating crucial soil and land use variables.

GROUP	Description	Further Description	Minimum Infiltration Rate (mm/hr)
A	Deep sand; deep loess; aggregated silts	San, Loamy sand and sandy loam types of soils. These soils have low runoff potential and high infiltration rates even when thoroughly wetted. They consist chiefly of deep, well to excessively-drained sands or gravels and have a high rate of water transmission	7.6 - 11
B	Shallow loess; sandy loam	Silt, silt loam and loam soils. These soils have a moderate infiltration rate when thoroughly wetted. They consist of moderately deep to deep, moderately well to well-drained soils with moderately fine to moderately coarse textures	3.8 – 7.6
C	Clay loams; shallow sandy loam; soils low in organic content; soils usually high in clay	Sandy clay loam soils. They have low infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes the downward movement of water and soils with moderately fine to fine structure.	1.3 – 3.8
D	Soils swell significantly when wet; heavy plastic clays; and certain saline soils.	Clay loam, silt clay loam, sandy clay, silt clay and clay soils. This group has the highest runoff potential. They have very low infiltration rates when thoroughly wetted and consist chiefly of clay soils with a high swelling potential, soils with a permanent high-water table, soils with a claypan or clay layer at or near the surface and shallow soils over nearly impervious.	0 – 1.3

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Table 2. The hydrologic soil groups (HSG) used for the SCS-CN method (Muthu & Santhi, 2015)

The Curve Number (CN) calculation process, integral to runoff estimation, assigns CN values based on soil group and land use combinations as shown in Table 3, considering both soil absorption capacity and surface properties like vegetation and urbanization (Jain et al., 2021). The study, focused on Louisiana (2018-2023), integrated soil texture data, Copernicus land use data, and CHIRPS precipitation data. Using the SCS-CN method, runoff was calculated with antecedent moisture conditions (AMC) incorporated. Visualizations and a time series chart illustrated the spatial distribution of soil, land use, CN, precipitation, and runoff. The results were exported to Google Drive for further analysis (Shen et al., 2019).

Land-use description (Ia = 0.2S)	Curve Numbers (CN) for Hydrologic Soil Group			
Lawns, open spaces parks, golf courses	**A**	**B**	**C**	**D**
i) Good condition: grass cover on 75% or more of the area	39	61	74	80
ii) Fair condition: grass cover on 50% to 75% of the area	49	69	79	84
iii) Poor condition: grass cover in 50% or less of the area	68	79	86	89
Paved parking lots, roofs, driveways, etc.	98	98	98	98
Streets and Roads:				
Paved with curbs and storm sewers	98	98	98	98
Gravel	76	85	89	91
Dirt	72	82	87	89
Paved with open ditches	83	89	92	93
Commercial and Business areas (85% impervious)	89	92	94	95
Industrial districts (72% impervious)	81	88	91	93
Row houses, townhouses, and residential with lot sizes 500m^2 or less (65% impervious)	77	85	90	92
Residential Average lot size				
1000 m^2 (38% impervious)	61	75	83	87
1350 m^2 (30% impervious)	57	72	81	86
2000 m^2 (25% impervious)	54	70	80	85
4000 m^2 (20% impervious)	51	68	79	84
8000 m^2 (12% impervious)	46	65	77	82

S = potential maximum retention in millimetres; Ia = Initial abstraction.

Table 3. Land Use and Hydrologic Soil Groups (Muthu & Santhi, 2015)

2.4 Delineation of the Watershed in Louisiana state

The catchment delineation process used the SWAT (Soil and Water Assessment Tool) which is a plugin for ArcGIS software to define watershed boundaries for hydrological modelling. The data preparation included gathering digital elevation models (SRTM DEM) as shown in Figure 2, land use/land cover data (Figure 3), and soil maps (Figure 4). Ensuring compatibility with SWAT requirements, the model setup involved configuring SWAT, defining project details, and specifying simulation parameters. Sub-basin delineation was conducted using SWAT tools in ArcGIS software, considering flow accumulation and slope. Outlets were defined for each sub-basin to simulate streamflow at watershed boundaries. Integration of land use and soil data characterizes each sub-basin, and flow routing utilizes DEM for determining flow directions. Reach definition further refined the river network within sub-basins. The output of the catchment delineation (watersheds) as shown in Figure 5 provided insights into hydrological features within Louisiana State, guiding further study or management actions.

2.5 Rainfall-Runoff Modelling

The rainfall-runoff modelling method employed in the code was a fundamental stage in estimating runoff within the study area using Equation 1 and Equation 2. It followed an iterative process wherein the Curve Number (CN) values, obtained from the prior step and representing the combined influence of soil and land use on runoff potential, were utilized to calculate runoff. These calculations were performed by applying the Soil Conservation Service (SCS) CN method to the daily precipitation data derived from the UCSB-CHG/CHIRPS collection (Jain et al., 2021). In this process, the code also takes into account the S-value, which represents the potential maximum retention capacity of the soil. By considering the S-value for each unique combination of soil and land use within the study area, the code was used to generate a comprehensive runoff image collection. This collection serves as the foundation for subsequent analyses, enabling a detailed assessment of how environmental factors, including soil properties, land use patterns, and precipitation, collectively influence and contribute to the overall runoff dynamics in the specified geographic area. In the SCS rainfall-runoff relationship, the total rainfall which comes down is separated into three components:
i) Direct runoff (rainfall excess), Q,
ii) Actual retention, F, and
iii) Initial abstraction, Ia.
The SCS expressed S as a function of CN:

$$CN = \frac{1000}{10+0.0394S} \quad (1)$$

Where CN is a dimensionless number ranging from 0 to 100 obtained from Table 3.

$$Q = \frac{(P-Ia)^2}{(P-Ia)+S},\ P > Ia,\ P \geq Q \quad (2)$$

P = Precipitation in millimetres
Q = Runoff in millimetres
S = Potential maximum retention in millimetres
Ia (Initial abstraction) = 0.2S

2.6 Model Validation

The estimated runoff values were compared to the corresponding locations on Google Earth 2023 images. Evaluating the daily surface runoff of the location, mostly in the southern and coastal region of Louisiana, were found to have high daily runoff values (Figure 7). Thereby, the model's performance was assessed in terms of its classification capability, how closely the model predicted surface runoff with the actual runoff data (ERA5-Land Monthly Averaged by Hour of Day - ECMWF Climate Reanalysis surface runoff data). ERA5-Land is a reanalysis dataset providing a consistent view of the evolution of land variables over several decades at an enhanced resolution compared to ERA5.
ERA5-Land has been produced by replaying the land component of the ECMWF ERA5 climate reanalysis. Reanalysis combines model data with observations from across the world into a globally complete and consistent dataset using the laws of physics. Reanalysis produces data that goes several decades back in time, providing an accurate description of the climate of the past. This dataset includes all 50 variables as available on CDS (Climate Data Store) (Muñoz, 2019). 1000 random points (Figure 9) were generated in ArcGIS software to validate this model. The extract values to points tool in ArcGIS software was used to extract the estimated runoff value from the rainfall-runoff model and the actual runoff value from ERA5

data. A ROC (Receiver Operating Characteristic) curve was plotted for the points using the classify tool in IBM SPSS software, and an AUC (Area under curve) of 0.937 was found for this study (Figure 10), indicating the excellence of the current study (Table 4). Based on this evaluation, the ROC and AUC values show that the current model performed excellently in predicting surface runoff in Louisiana using rainfall.

Accuracy Level	Excellent	Good	Satisfactory	Poor	Failing
AUC Value	0.9 – 1.00	0.80 – 0.90	0.70 – 0.80	0.60 – 0.70	0.50 – 0.60

Table 4. Performance of model based on the AUC values (Rashid & Nurse, 2016)

3. Results and Discussion

the findings from the rainfall-runoff modelling conducted for urban watersheds in Louisiana, focused on the influence of land use, soil classification, and precipitation on runoff patterns between 2018 and 2023. Through the integration of geospatial data from multiple sources, including soil texture, land use, and daily precipitation, the critical insights into the hydrological dynamics of the region were derived. The results highlight the role of Curve Number (CN) values, derived from soil and land use combinations, in estimating runoff potential across varying environmental conditions. The discussion delves into the implications of these findings, evaluating the impact of different land use types and soil groups on runoff, and assessing the accuracy of the model in predicting runoff patterns. Additionally, the results are compared with observed data to validate the model's performance, offering recommendations for improving urban watershed resilience and informing future water resource management strategies in Louisiana.

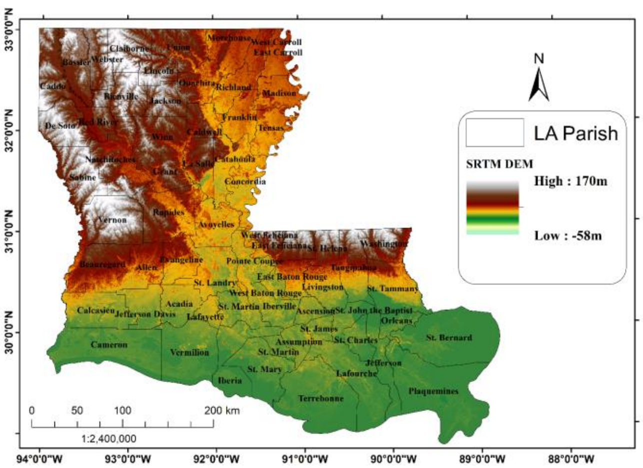

Figure 2. SRTM DEM of Louisiana State

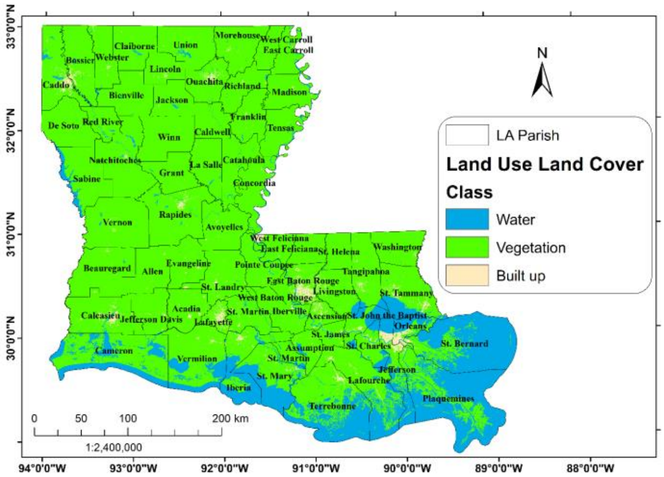

Figure 3. LULC Map of Louisiana State

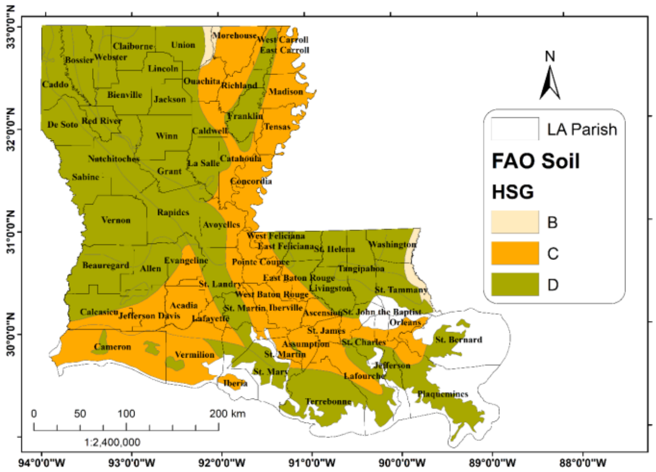

Figure 4. LULC Map of Louisiana State

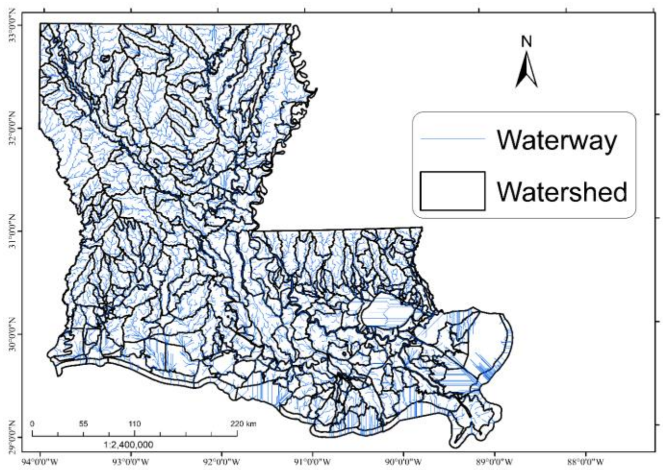

Figure 5. Delineated Watersheds/catchments in the Louisiana State

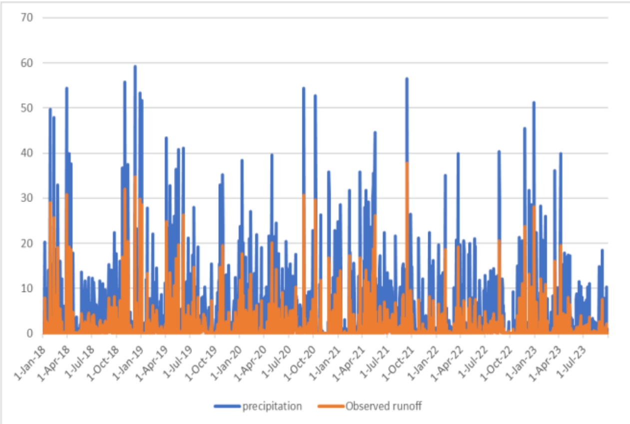

Figure 6. Daily rainfall and runoff in Louisiana State

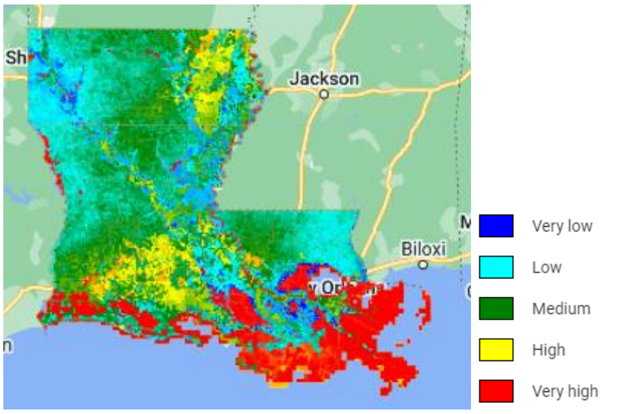

Figure 7. Spatial distribution of Daily runoff in Louisiana State Very Low: 0-0.10 mm, Low: 0.10-0.25 mm, Medium: 0.25-0.50 mm, High: 0.50-1.00 mm, Very High: >1.00 mm

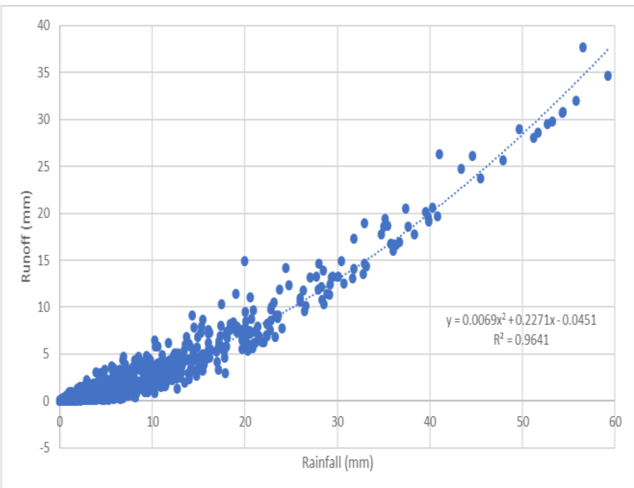

Figure 8. Daily Rainfall-runoff model of Louisiana State

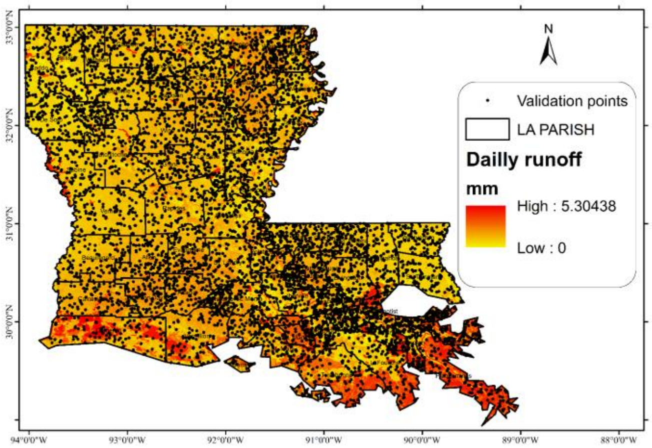

Figure 9. Spatial Distribution of the Validation points for the rainfall-runoff model

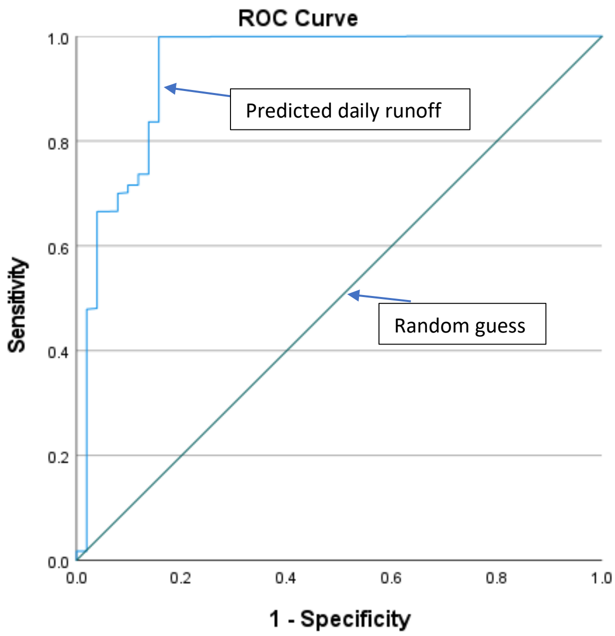

Figure 10. ROC curve for the rainfall-Runoff model

3.1 Potential maximum retention from LULC and Soil data

As shown in Figure 3, the analysis revealed that Water/Permanent water bodies constitute 17% of the total land area in Louisiana State (LA). These areas include natural and artificial water bodies, highlighting the significance of water resources in the region. The presence of permanent water bodies is crucial for biodiversity, supporting aquatic ecosystems, and providing essential resources for various human activities. Shrubs/Herbaceous vegetation / Cropland/Sparse vegetation / Herbaceous wetland / Closed Forest/Open Forest representing Grass cover collectively represent the majority of the region, accounting for 81% of the total land area of LA.

This extensive coverage indicates a diverse range of ecosystems, including natural vegetation, agricultural lands, and various types of forests. The balance between different land cover types within this category suggests a mix of urban and rural landscapes, emphasizing the ecological diversity of LA. Built-up areas, comprising residential, commercial, and industrial developments, account for 2% of the total land area.

While this percentage may seem relatively small, it underscores the importance of sustainable urban planning to ensure efficient land use and minimize environmental impact. Monitoring and managing built-up areas are critical for addressing issues related to urbanization, infrastructure development, and ecological preservation. Furthermore, the observed distribution of LULC classes in LA as shown in Figure 3 reflects the dynamic interactions between natural and anthropogenic factors. The prominence of water bodies highlights the need for conservation efforts and sustainable water resource management. The dominance of diverse vegetation types and croplands signifies the dependence on agriculture and the importance of preserving natural habitats in LA.

The presence of built-up areas, albeit modest, suggests ongoing urbanization and development trends. Local authorities must adopt sustainable urban planning practices to mitigate potential environmental challenges associated with urban expansion. The majority of the State was observed to be covered with HSG D followed by C and B with the least spatial coverage as shown in Figure 4. Figure 7 shows the spatial coverage of daily runoff in Louisiana revealing that the coastal areas have the highest daily runoff with most of the southern part of Louisiana within the High and medium runoff zones.

3.2 Average Daily Rainfall-Runoff Model of Louisiana State

A daily average rainfall-runoff model as shown in Equation 3 and Figure 8 based on the analysis and the model equation is provided as:

$$D_Q = 0.0069 \times P^2 + 0.2271P - 0.0451 \quad (3)$$

Where D_Q = average daily runoff in mm of H_2O and
P = average daily rainfall in mm

Additionally, the coefficient of determination (R^2) for this model is 0.964, indicating a high level of explanatory power. This suggests that the model can explain a significant proportion of the variability observed in daily runoff based on the given rainfall data. A Root Mean Square Error (RMSE) of 0.0002 was obtained which indicates that, on average, the daily runoff predicted by the model deviates from the observed values by approximately 0.0002. The RMSE is a measure of the model's accuracy, with lower values indicating better predictive performance. In this case, a very small RMSE suggests that the model is closely aligned with the observed daily runoff data from ERA-5, reinforcing the reliability of the model in predicting average daily runoff based on the given rainfall.

4. Conclusion

This geospatial modelling study, conducted in Louisiana State using Google Earth Engine, contributes valuable insights into the complex interplay of environmental factors influencing runoff dynamics. The iterative approach employed in the methodology integrates diverse datasets, including soil texture, land use/land cover, and daily precipitation, showcasing the power of GEE for comprehensive environmental assessment. The hydrological analysis, focusing on the period from 2018 to 2023, reveals the significance of water bodies, diverse vegetation types, and croplands in Louisiana. The observed distribution of land use and hydrologic soil groups underscores the dynamic nature of interactions between natural and anthropogenic elements. Notably, the study emphasizes the importance of sustainable urban planning for efficient land use and environmental preservation, particularly in built-up areas.

The calculated Curve Number (CN) values, representing runoff potential, provide a nuanced understanding of specific land parcels. The incorporation of the Soil Conservation Service Curve Number (SCS-CN) method, considering precipitation and antecedent moisture conditions, enhances the accuracy of runoff estimations.

The generated spatial visualizations offer a comprehensive overview of hydrological dynamics, aiding in the assessment of environmental impacts. The rainfall-runoff model derived from the analysis demonstrates robust predictive capabilities, with an impressive coefficient of determination (R^2 = 0.964) and a minimal Root Mean Square Error (RMSE = 0.0002). The high AUC value of 0.937 from the ROC curve achieved in this study reinforces the accuracy and confidence of the Louisiana rainfall-runoff model. These metrics affirm the reliability and accuracy of the model in predicting daily runoff based on rainfall data. The model's performance underscores its potential utility in water resource management and environmental planning.

This study not only enhances our understanding of runoff patterns in Louisiana but also exemplifies the efficacy of geospatial modelling tools in addressing complex environmental challenges. The findings contribute valuable knowledge for informed decision-making in water resource management and underscore the importance of considering diverse environmental variables in hydrological assessments.

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