Effectiveness of Spatially Distributed Rainfall-Runoff Modeling Using GIS

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Abstract

The assessment of surface runoff is a superficial, complex, and sensitive topic, and its changes amidst the challenges of climate change, which this region is not immune to. Especially in the Kurdistan region and throughout Iraq, due to the lack of ground monitoring stations for flow rates, and if they exist, they are old and outdated. The present investigation seeks to evaluate the outflow and the rainfall-runoff process for the Jundian sub-basin. A GIS environment has been employed to alter spatial information in the form of slope, soil type, land cover diagrams, and the runoff coefficient (RC) as a crucial component for the investigation. For obtaining ongoing precipitation data, inverse distance weighted (IDW) extrapolation was performed. The runoff coefficient ranged from low to high (0.12 to 1.00). The highest runoff was observed during 2014 at (23.34 m^3/s). During 2009 (12.06 m^3/s), the least was produced in the watershed. Random Forest Regression achieved the highest R^2 (0.862), lowest RMSE (1.927 m^3/s), and highest NSE (0.862), excelling all other models used to relate the ratio between actual and predicted runoff. The study confirms the importance of GIS in storing and processing surface runoff. This is a good step towards investing in water resources, setting future strategies, and opening new horizons for decision-makers.

Keywords: soil type, land cover, GIS, runoff coefficient, slope.

1 Introduction

The application of the unit hydrograph model is limited in rainfall-runoff computation since the precipitation itself is spatially distributed, as is the development of excess precipitation(Olivera and Maidment, 1999). One of the primary challenges in groundwater development strategies, hydrologic modeling, and water harvesting is having accurate rainfall and runoff records(Trivedi et al., 2018;Al-Ghobari et al., 2020). Since rain is one of the most important water sources for water sustainability, effective rain harvesting is essential (Oweis et al., 1999;Aladenola and Adeboye, 2010;Qi et al., 2019;Babu et al., 2024;Lepcha et al., 2024;Subramanian et al., 2024;Ssekyanzi et al., 2024).Surface runoff volumes, which are obtained by multiplying rain by a runoff coefficient, are a function of slope, land urbanization, storm volume, and the soil characteristics (Chahine, 1992;De Smedt et al., 2000;Hundecha and Bárdossy, 2004;Pechlivanidis et al., 2011;Deshmukh et al., 2013;Sitterson et al., 2018;Sundarapandi et al., 2024).The GIS has a significant impact in developing hydrological models as the data on soil, land cover, rainfall, and other hydrological parameters can be derived and aggregated from various sources using their features, including map overlay and analysis(Colosimo and Mendicino, 1996;Coskun and Musaoglu, 2004;Jain et al., 2004;Bahremand, 2006;Skaugen and Onof, 2014;Thakur et al., 2017;Tuna and Aytaç, 2024;Muhammed and Aziz, 2025). Numerous investigations have been conducted on modeling rainfall-runoff using the popular curve number developed by the USDA Natural Resources Conservation Service(Usda, 1986). They employed soil textures, land cover maps, and hydrologic conditions in the GIS environment among them (Zakaria et al., 2013;Jaber et al., 2017;Khalil, 2017;Al-Juaidi, 2018;Muneer et al., 2020;Goodarzi et al., 2022;Ibrahim et al., 2022;Kara and Baykurt, 2022;Alataway, 2023;Oleiwi et al., 2023)

The primary purpose of the task at hand is to assess the effectiveness and practicability of traditional techniques in conjunction with GIS-based spatially distributed rainfall-runoff models. Furthermore, to successfully manage, process, and evaluate enormous, geographically separated datasets (such as rainfall, land use/land cover, and soil data) necessary to build distributed models via GIS features. This work stands out due to the ability of GIS to apply the geographical diversity present in raw data and watershed features, which are crucial for improved representation of hydrological events. GIS significantly increases the accuracy and efficacy of the model as compared to traditional lumped or mean-areal rainfall methods. The current investigation focuses on modeling rainfall-runoff for the Jundian watershed, is located in the northeast of Erbil in Iraq, where the area experiences a mountainous climate due to its high altitude, with warm summers and cold and snowy winters. To execute this research, meteorological data from 2000-2024, runoff coefficient (RC), digital elevation model (DEM), land cover description, slope of the topography, and soil map were simulated using the ArcGIS calculator tool to process and analyze the spatial data.

2 Methodology

2.1 Area and sources of data

The Jundian watershed is found from latitudes 36° 45′ 44.2″ N and 36° 22′ 54.2″ N and longitudes 45° 03′ 55.4″ E and 44° 35′ 23.6″ E as demonstrated in Fig. 1. It has an area of 1166.5 km², and extends from 641.5 and 3562 meters above mean sea level.

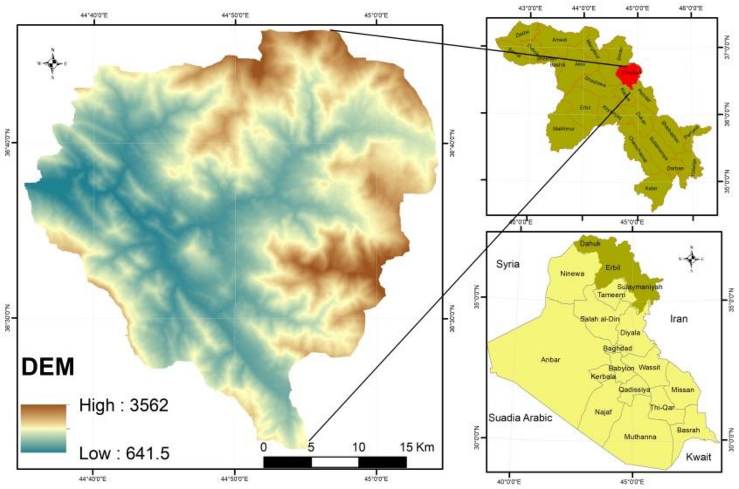

Fig. 1 The study area's layout and elevation map

In the study, Sentinel-2 imagery (10 meters resolution)for the year 2023 was used to generate land cover interpretation employing unsupervised classification criteria in Idrisi Selva 17.0 .Arc Map software was installed to determine the researched area's slope from a DEM at a resolution of thirty meters. The investigation relies on 24 years of cautiously recorded rainfall data from three gauged stations and they do not exist within the watershed. Spatially distributed rainfall data at a 30-meter scale was achieved through (IDW) approximation. Accurate stream flow simulation is crucial for rainfall runoff modeling because of missing data; 10 years of actual discharge ground measurement were used. Furthermore, the virtual soil texture of the research area is produced by the Food and Agriculture Organization (FAO)(Buringh, 1960;Batjes, 1997). However, the existing models face several significant limitations, primarily related to the quality of data, as almost the entire basins in the area are not occupied by discharge measurements.

2.2 Estimation of Runoff Coefficient (RC)

As indicated by Chow et al. (1998), the amount of precipitation that turns into runoff from rain is known as the runoff coefficient (RC). For this purpose, GIS will be used to combine the vector coverage of soil, land cover and land use classification, and slope of the area into one map. Land use and land cover have several impacts on the hydrological cycle, such as floods, droughts, and runoff (Maidment, 1996). In this study, it is considered using the linear relationship given in Equation 1 (Liu and De Smedt, 2004):

$$C = C_O + (1 - C_O)\frac{S}{S+S_O} \qquad (1)$$

In which:

(C) is standing for the possible runoff coefficients for a topography slope (S) in percent, S_0(%) represents the constant surface slope for various land use and soil type, and (C_0) is the runoff coefficient for the close to zero slopes related to the values listed in the first row of each land use category(Liu and De Smedt, 2004). Both S_0

and C_0 metrics are given in Table 1and Table 2(Liu, 2004).The information in Table 2 was extracted from sources previously published (Chow et al., 1998;Beven, 2012).

Table 1: Slope t S_0 (%) for many land cover and soils required to estimate runoff coefficient(Liu, 2004)

Land use	Sand	Loamy Sand	Sandy Loam	Loam	Silt Loam	Silt	Sandy Clay Loam	Clay Loam	Silty Clay Loam	Sandy Clay	Silty Clay	Clay
Forest	0.68	0.65	0.62	0.59	0.56	0.53	0.5	0.47	0.44	0.41	0.38	0.35
Grass	0.58	0.551	0.522	0.493	0.464	0.435	0.405	0.376	0.347	0.318	0.289	0.26
Crop	0.5	0.471	0.442	0.413	0.384	0.355	0.325	0.296	0.267	0.238	0.209	0.18
Bare soil	0.42	0.393	0.365	0.338	0.311	0.284	0.256	0.229	0.202	0.175	0.147	0.12

Table 2: Runoff Coefficient values of close to zero slopes, different land use, and soil types(Liu, 2004)

Land use	Slope (%)	Sand	Loamy Sand	Sandy Loam	Loam	Silt Loam	Silt	Sandy clay Loam	Clay Loam	Silty clay Loam	Sandy Clay	Silty Clay	Clay
Forest	<1.5	0.03	0.07	0.10	0.13	0.17	0.20	0.23	0.27	0.30	0.33	0.37	0.40
	0.5–5	0.07	0.11	0.14	0.17	0.21	0.24	0.27	0.31	0.34	0.37	0.41	0.44
	5–10	0.13	0.17	0.20	0.23	0.27	0.30	0.33	0.37	0.40	0.43	0.47	0.50
	>10	0.25	0.29	0.32	0.35	0.39	0.42	0.45	0.49	0.52	0.55	0.59	0.62
Grass	<0.5	0.13	0.17	0.20	0.23	0.27	0.30	0.33	0.37	0.40	0.43	0.47	0.50
	0.5–5	0.17	0.21	0.24	0 27	0.31	0.34	0.37	0.41	0.44	0.47	0.51	0.54
	5–10	0.23	0.27	0.30	0.33	0.37	0.40	0.43	0.47	0.50	0.53	0.57	0.60
	>10	0.35	0.39	0.42	0.45	0.49	0.52	0.55	0.59	0.62	0.65	0.69	0.72
Crop	<0.5	0.23	0.27	0.30	0.33	0.37	0.40	0.43	0.47	0.50	0.53	0.57	0.60
	0.5–5	0.27	0.31	0.34	0.37	0.41	0.44	0.47	0.51	0.54	0.57	0.61	0.64
	5–10	0.33	0.37	0.40	0.43	0.47	0.50	0.53	0.57	0.60	0.63	0.67	0.70
	>10	0.45	0.49	0.52	0.55	0.59	0.62	0.65	0.69	0.72	0.75	0.79	0.82
Bare soil	<0.5	0.33	0.37	0.40	0.43	0.47	0.50	0.53	0.57	0.60	0.63	0.67	0.70
	0.5–5	0.37	0.41	0.44	0.47	0.51	0.54	0.57	0.61	0.64	0.67	0.71	0.74
	5–10	0.43	0.47	0.50	0.53	0.57	0.60	0.63	0.67	0.70	0.73	0.77	0.80
	>10	0.55	0.59	0.62	0.65	0.69	0.72	0.75	0.79	0.82	0.85	0.89	0.92
IMP		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

2.3 Runoff-Rainfall relationship

The majority of KRI's watersheds lack long-term observed discharge data, although all of them have rainfall data accessible for a far longer time frame. Therefore, to have a discharge event with a long duration, rainfall must be converted to runoff by multiplying it by the runoff coefficient.

The evaluation of rainfall-runoff model performance is indeed crucial in catchments for grasping hydrological events and for improving the precision of the models (Firouzi and Sharifi, 2015;Revilla-Romero et al., 2015). Multiple models, to select the proper goodness-of-fit criteria: (log-linear random forest, support vector (SVR), polynomial (2nd order), and gamma GLM (generalized linear model)) regression were examined in the current paper. The R-squared (R^2), the root mean squared error (RMSE), and Nash-Sutcliffe Efficiency (NSE), also known as the (model predictive capacity vs. mean), were used for assessing each. Runoff coefficient (RC) and depth runoff depth estimated using Arc Map 10.4 (Raster calculator tool to overlay and compute values). Eventually, rainfall-runoff correlation analysis was performed using R-language version 4.4.1 to assess the relationships between models and the layout of the graph.

Results and Discussion

2.4 Description of Slope

Usually, larger slopes promote the runoff coefficient as they generate greater flow with lower drainage. The area of this research is rugged with high slope variations, as shown in Fig.2. The basin slope values fluctuate between 0% to438.6%, it had seven grades: (flat, gently, moderately, strongly, moderately steep, steep, and very steep) slopes.

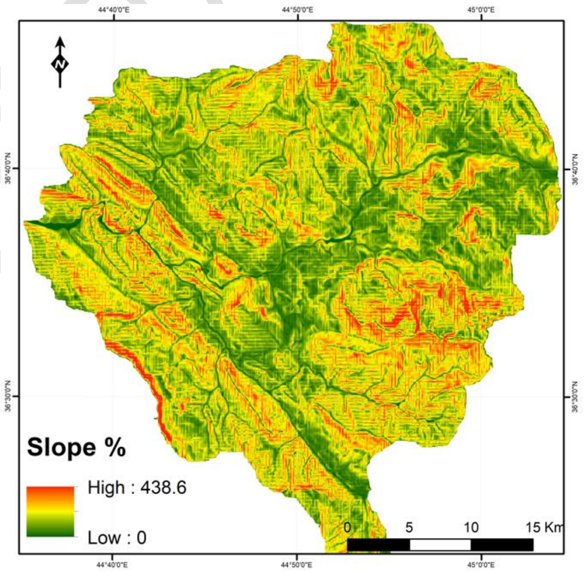

Fig. 2 Slope map of Jundian sub-basin

2.5 Soil texture

The soil analysis shows gravelly loam to sandy loam (42%), loamy sand (11.2%), and sandy clay loam (46.3 %). The first and second types have well-drained soils with low runoff potential and high water permeability, while the third group is poorly drained soils with rough textures and weak absorption rates (Cronshey, 1986;Ammar et al., 2016;Singhai et al., 2019). This illustrates that a good portion of the research area is suitable for runoff and water retention, and can be used properly in the exploitation of water resources. The soil texture is depicted in Fig.3.

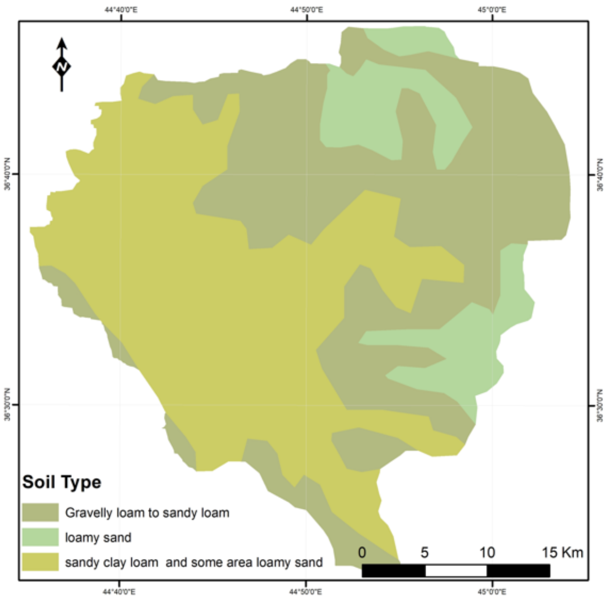

Fig. 3 Features of the Junian sub-basin's soil

2.6 Land use and land cover (LULC)

The watersheds' LULC map which is a motivating factor in this work was classified into six categories: bare land, build-up, crop, grass, forest, and water covering 30.1 %, 3.6%, 24.4 %,36.9%,4.8% , and 0.2% of the entire area ,respectively (Fig.4). Cropland and urban areas have heavy runoff, but grass and forests lower surface runoff rates.

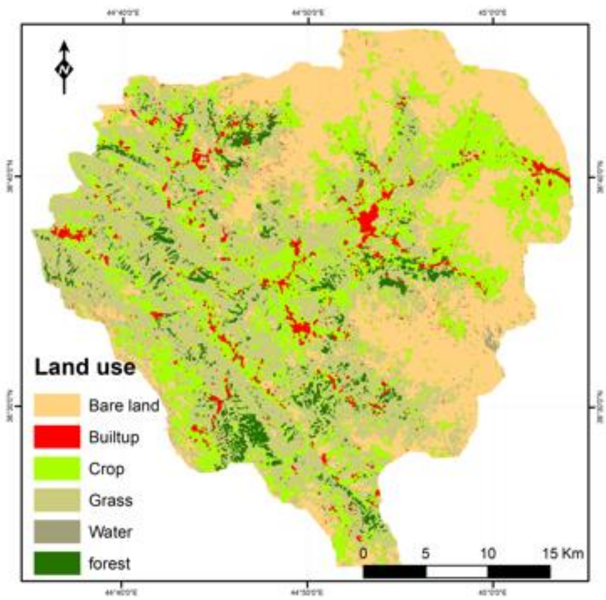

Fig. 4 Characteristics of the land cover map for the Jundian sub-basin

2.7 Runoff coefficient(RC)

As demonstrated in Fig.5, the results show that the Jundian water has a low to high runoff coefficient were varying from 12% to 100%, were in lands covered by bare and built-up are low and high for lands occupied by grass and forest.

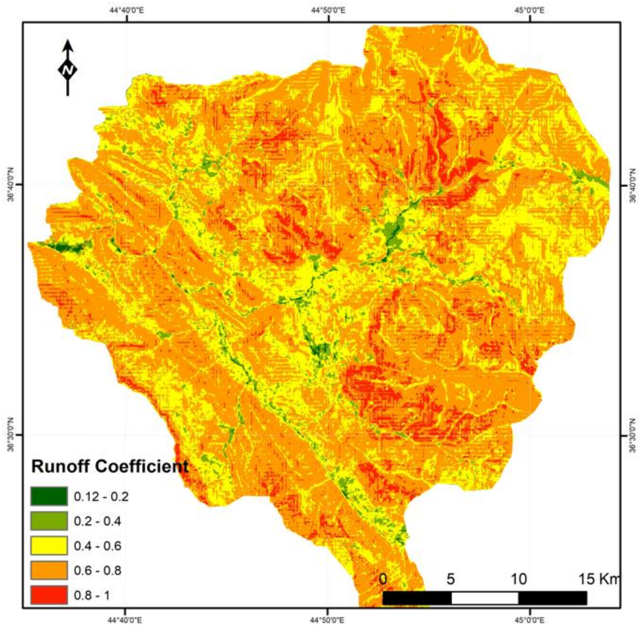

Fig. 5 Runoff coefficient (RC) in the basin

2.8 Rainfall and Runoff depth

The study finds that employing GIS techniques to map the rainfall's spatial distribution at the sub-basin is highly successful. Fig.6 shows the average distribution of rainfall for years 2000- 2024 and was varied from 690.3 to 779.9 mm.

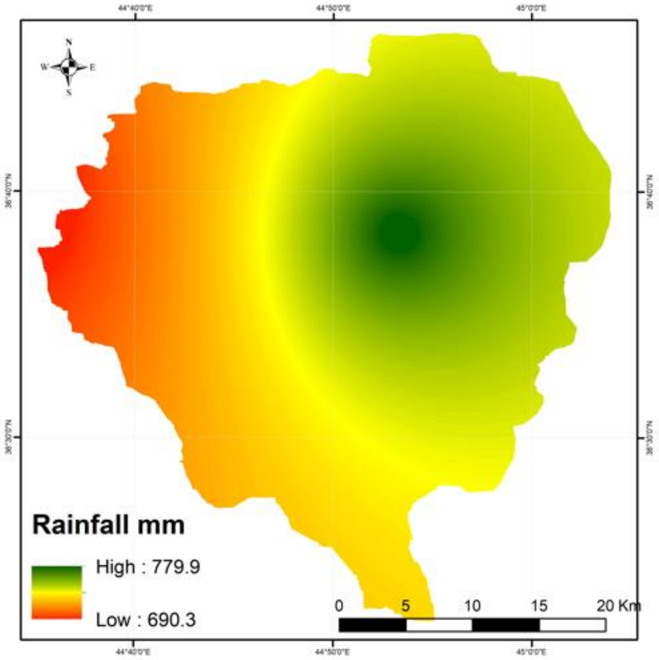

Fig. 6 Spatial rainfall distribution within the investigation area

With the ArcGIS calculator tool, the annual runoff depth is estimated by combining the runoff coefficient and the annual precipitation excess, as illustrated in Fig.7. The runoff depths changed from 690.5 mm as maximum to 74.7 mm as minimum. According to rainfall statistics, the watershed's maximum runoff, 23.34 cubic meters per second (m^3/s), was recorded in 2014. The least discharge, however, was recorded in 2009 at12.06 m^3/s.

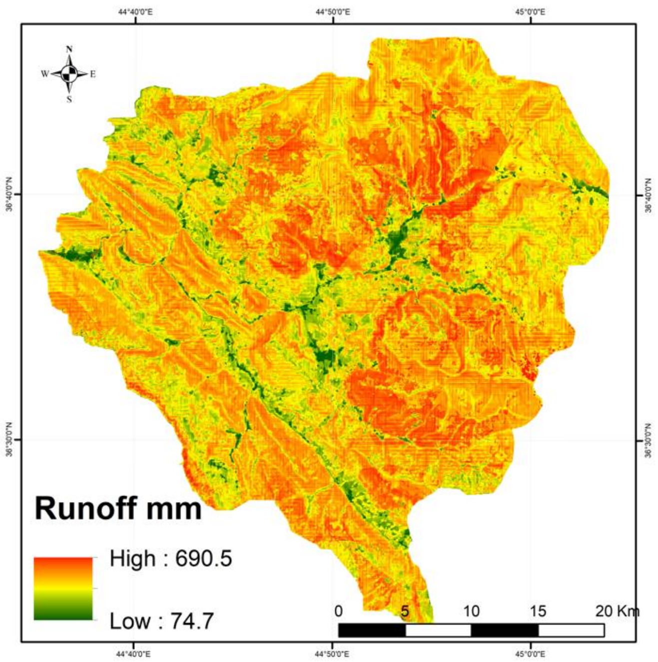

Fig. 7 Runoff depth in the Jundian sub-basin

2.9 Runoff- Rainfall Correlation Analysis

The performance of the correlation analysis in the present study are achieved with statistical indicators R^2 and NSE as featured in Table 3 and Fig.8, using five different models, as the observed runoff at the outlet of the basin was limited only for ten years (2011-2021) due to a lack of data. The findings using the Random Forest model achieved the highest R^2 (0.862), lowest RMSE (1.927 m^3/s), and highest NSE (0.862).

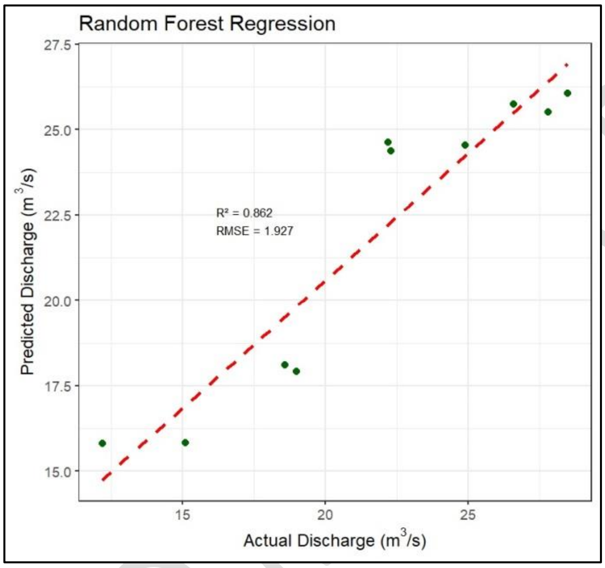

Fig. 8 Model Evaluations for Jundian watershed

Table 3 Model Evaluation for Jundian watershed

Model	R^2	RMSE (m^3/s)	NSE
Log-Linear Regression	0.849	2.269	0.809
Gamma GLM	0.785	2.403	0.785
Polynomial Regression	0.820	2.202	0.820
Support Vector Regression	0.770	2.485	0.770
Random Forest	**0.862**	**1.927**	**0.862**

3 Conclusions

The most valuable outcomes of the current research are summarized below:

- In this work it has been demonstrated the role of GIS in extracting the DEM, slope, land cover, soil data, facilitating estimation of a spatially distributed map of runoff coefficient (RC), and effectively producing the surface water.

- Dominant soil types that were digitized: gravelly loam to sandy loam (42%), loamy sand (11.2%), and sandy clay loam (46.3 %). Furthermore, six different classes of land cover were recognized: bare land (30.1 %), built-up (3.6) %, crop (24.4%), grass (36.9%), forest (4.8%), and water (0.2%).

- The watershed produced a runoff coefficient from 12% to very high 84%. Rainfall distributions for years 2000- 2024 vary from 690.3 to 779.9 mm. In 2014, the watershed's discharge reached its maximum at 23.34m³/s. However, because of the lower rainfall in 2009, the runoff was the lowest, measuring 12.06 m³/s. The study's findings showed that the Jundian sub-basin is significant for storing runoff and could be very important for managing water resources.
- Despite limited data with the 86.2% correlation between observed and computed runoff forecasting accuracy is remarkable. The study underlines the necessity it is to having reliable precipitation data, hydrological soil categorizations, and land use cover data in order to improve the model's validity.

Supplementary Information Not contained extra information

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Data Availability Data can be obtained upon request from the author.

Declarations

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

Ethical Approval Not applicable.

Consent to Participate the study's author consented to take part.

Consent to Publish the author consented to publish the findings of this study in this journal.

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