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Developing a scalable framework for accurate flood forecasting in arid regions: A case study of the Jerash Basin, Jordan

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ABSTRACT

This study addresses the need for accurate hydrological data in arid and semi-arid regions by estimating runoff volume in the Jerash Basin, Jordan, using advanced geographic information systems (GIS) and the soil conservation service curve number (SCS-CN) method. The primary goal is to enhance flood risk assessment and support sustainable water resource management in the Jerash Basin by providing accurate hydrological data. The research integrates high-resolution digital elevation models (DEMs) and spatial data to analyze soil and land use characteristics, applying the SCS-CN method within a GIS environment to estimate runoff volume, drainage density, and concentration time. Findings reveal a general CN of 87.83, indicating high runoff potential, a drainage density of 12.60 km/km², and a concentration-time of approximately 222.48 minutes, suggesting a high susceptibility to flooding due to the short transit distance of runoff. The low relief ratio of 0.035 further highlights the basin's limited dissection and drainage capacity. These results demonstrate that accurate runoff estimation using high-quality digital data sources can significantly improve flood risk assessment and water resource planning in arid and semi-arid regions. A limitation of the study is its reliance on static data, which may not fully capture dynamic hydrological processes, and the findings are specific to the Jerash Basin, requiring adaptation for application in other regions. The practical value of this research lies in its scalable framework for flood risk assessment and water resource management in arid and semi-arid regions, informing decision-making processes related to infrastructure development, flood mitigation, and sustainable water resource planning. The originality of this study lies in its innovative application of GIS and SCS-CN methods in the Jerash Basin, a region with limited hydrological records, offering new insights into flood risk and water resource management. By applying these well-established tools in a data-scarce context, this research provides significant value for sustainable water resource planning and flood mitigation in arid and semi-arid regions.

Keywords: digital elevation model, soil conservation service, curve number method, Jerash, Jordan.

INTRODUCTION

Jordan is considered the second poorest country in terms of water resources, with an extremely critical water situation affecting life sectors. The rates of water consumption far exceed the rates of natural recharge, and according to official figures, the per capita consumption of water is approximately 100 m³ per year, compared to about 4,000 m³ to 5,000 m³ in developed countries (The National Water Strategy, 2016–2025). The reasons behind that include rapid population growth, an increased number of refugees, and political unrest surrounding the Jordan River, all of which have significantly raised water demands (Al-Addous et al., 2023).

Jordan's water supplies come from both traditional and unconventional sources, such as rainfall, surface water, groundwater, and treated wastewater. However, the country faces severe water scarcity, with the eastern region receiving approximately 600 million cubic meters of rainfall annually (Salman et al., 2018; Moneer and Elewa, 2024). The Jerash Basin, covering 405.78 km² in Jordan, is characterized by unique hydrological, morphological, and geographical features that play a role in water resource management. This region faces significant challenges due to limited hydrological data and frequent extreme weather events, such as flash floods, which have become more prevalent in recent years. This has increased the need for accurate runoff estimation to support sustainable water resource planning and flood risk management.

While the curve number (CN) method and GIS technology have been widely used in hydrological studies globally, their application in the Jerash Basin remains limited. Previous studies in Jordan have primarily focused on traditional methods, which often lack the precision required for modern hydrological assessments (Ibrahim and Shatnawi, 2022; Shatnawi and Ibrahim, 2022; Sulistyowati et al., 2018). This study addresses this gap by integrating high-resolution digital elevation models and spatial data to provide a more precise alternative to traditional methods. (Shatnawi and Ibrahim, 2022; Al-Raggad et al., 2021).

The research aims to derive key hydrological parameters, including curve numbers, drainage density, and concentration time, which are critical for accurate flood risk assessment and water resource management. These parameters were selected because they directly influence the basin's runoff behavior, flood susceptibility, and water retention capacity, enabling precise estimation of runoff volume and supporting sustainable water resource planning in arid regions. The originality of this study lies in its innovative application of GIS and SCS-CN methods in the Jerash Basin, a region with limited hydrological records, offering new insights into flood risk and water resource management. By applying these well-established tools in a data-scarce context, this research provides significant value for sustainable water resource planning and flood mitigation in arid and semi-arid regions

The primary goal of this study is to estimate the runoff volume in the Jerash Basin using advanced GIS and CN methods, thereby enhancing our understanding of the basin's hydrological characteristics. The expected scientific value of this study lies in its potential to provide a scalable framework for similar arid and semi-arid regions, contributing to the broader field of hydrological sciences.

MATERIALS AND METHODS

Study design

The researchers employed a quantitative analytical approach incorporating mathematical equations, statistical analysis, model development, and an inductive methodology.

Study area

Jerash City is situated in the northern part of the Hashemite Kingdom of Jordan, positioned between latitudes 32°16′37″N and latitudes 35°54′20″E. Jerash is considered one of the areas famous for its clay soil, which is part of the Kurnub Group from the early Cretaceous period. The total area of the study area was 405.78 km^2.

Data used

Satellite data from 2022 was obtained from the US Geological Survey website, based on the World Geodetic System (WGS 1984 UTM-Zone 37N), with a DEM spatial resolution of up to 30 meters. The analysis was conducted using ArcGIS v10 and ArcHydro Tools.

METHODOLOGY

Overview of GIS and SCS-CN method

The use of GIS and RS techniques is an important means of assessing surface runoff resulting from precipitation because water resource specialists are constantly faced with the challenge of estimating direct runoff due to the lack of available hydrological records for small, or sometimes even large, basins (Ibrahim et al., 2024). Thus, the CN method is a widely accepted tool in water resource assessment, as it responds to four important elements in the water basin: soil texture, land use, surface conditions, and initial moisture conditions, in addition to its growth and prevalence of use. The United States Department of Agriculture created CN Tables and found that minimum CN values indicate low runoff, whereas CN values close to 100 indicate heavy runoff (Ibrahim et al., 2022).

Methodology for runoff estimation

The main goals of this study is estimate the runoff volume using GIS and CN methods to analyze and characterize natural data related to soil and land use in the Jerash Basin. GIS techniques provide more accurate elevation mapping and hydrological flow assessments. Therefore, the study area may be considered a successful alternative to the traditional method based on paper maps. As well as it highlights the efficiency and effectiveness of specialized software in deriving and processing spatial data and digital elevation models to extract the hydrological characteristics of the study area. The methodology relies on the soil conservation service – curve number (SCS-CN) method, GIS, and RS to perform the necessary hydrological analyses for the region. A soil texture map was utilized to identify the hydrological groups of soil types, along with a land-use map, and these were merged within the GIS environment to extract the CN for the study area. Several hydrological analyses were conducted, including sink filling, flow direction, flow accumulation, and stream orders with their respective numbers and lengths. This information was used to determine morphometric properties such as the relief ratio and river bifurcation ratio.

Soil and land use map analysis

The spatial analysis of hydrological characteristics plays a crucial role in shaping the surface runoff process, as it reflects the climatic conditions of drainage basins. The key hydrological characteristics of the study area are outlined below.

Soil map

The soil types in the Jerash area were analyzed, as shown in Figure 1. The study identified three main soil types: clay soil, covering 166.49 km² (41.03% of the total area); silty clay soil, which is the most dominant, spanning 186.05 km² (45.85%); and silty clay loam, the least prevalent, occupying 53.24 km² (13.12%).

The soil type and its classification in km² are presented in Table 1, indicating that Hydrological Group D dominates the entire study area, covering 405.78 km². This means that the soil of the study area is a thick clay layer covered with a shallow layer of fine silt or a bare rock layer, and this indicates that the depth of flow is high.

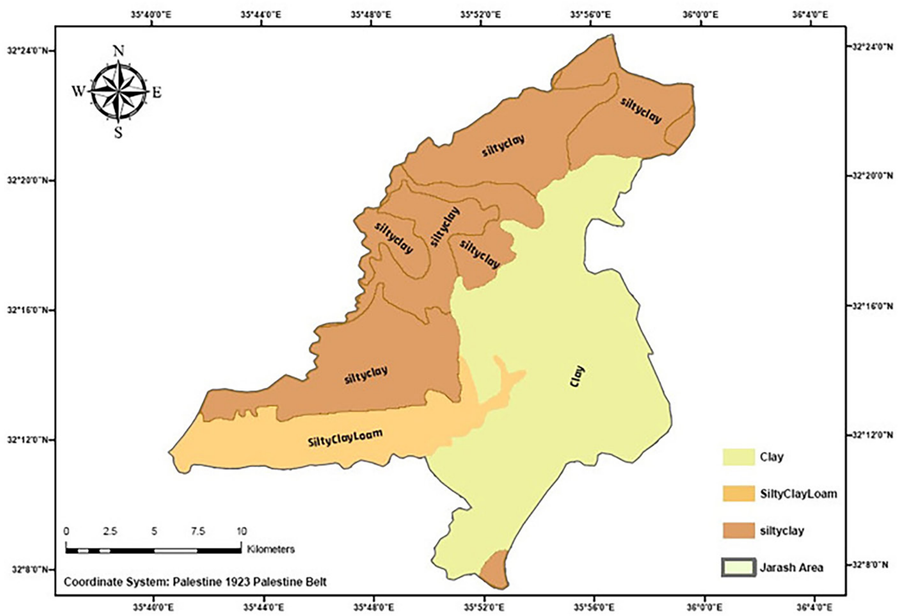

Figure 1. Soil map of the study area

Table 1. Hydrological group, soil type for study area

No.	Soil texture	Hydrologic group	Area (km²)	Area (%)
1	Clay	D	166.49	41.03
2	Silty clay	D	186.05	45.85
3	Silty clay loam	D	53.24	13.12
			Sum = 405.78	100

Land use analysis

The researchers identified six land use categories within the 405.78 km² study area in Jerash. Unirrigated land is the most extensive, covering 249 km² (61.36%), while water bodies occupy the smallest portion at 1.04 km² (0.25%). Built-up areas span 36.6 km² (9.01%), and forests cover 57.6 km² (14.19%). Additionally, irrigated land accounts for 37.2 km² (9.16%), as illustrated in Figure 2.

Curve number values

The curve number (CN) for the Jerash area was derived using land use and soil type maps through a union operation within the GIS environment, as shown in Figure 3. The CN values ranged from 77 in highly permeable areas to 97 in less permeable regions, indicating a tendency for surface runoff, as all values exceed the average threshold of 50. The basin's overall CN average was 87.83, while the Wadi Al-Arab

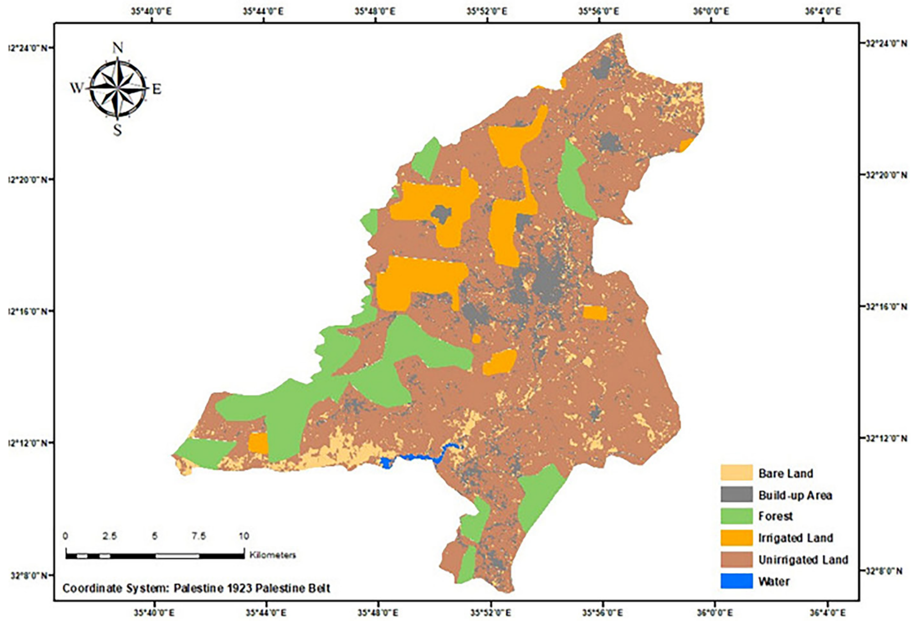

Figure 2. Landuse map of the study area

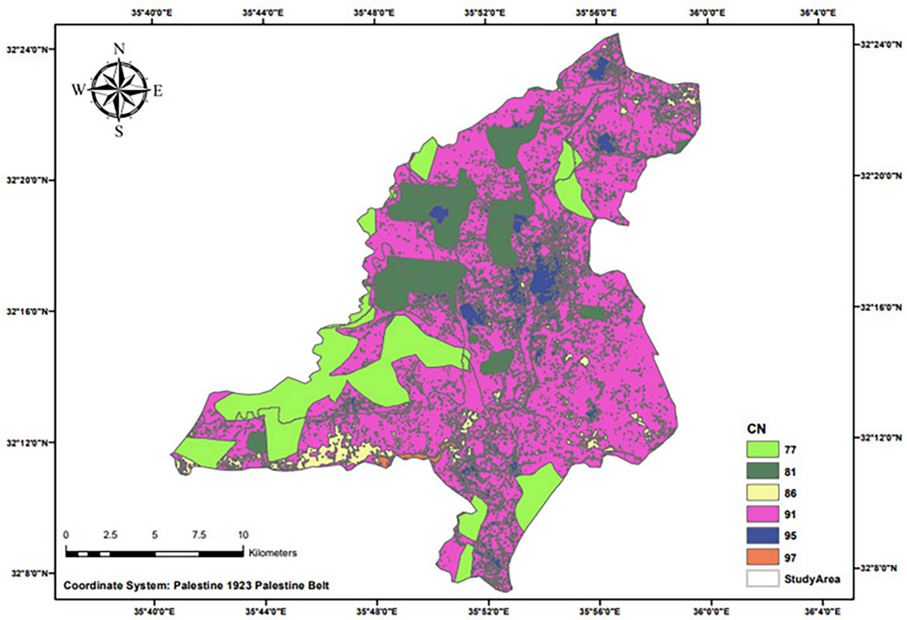

Figure 3. Distribution of CN values in the study area

Dam area had a *CN* value of 86.5, with a range between 70 and 97 (Alharahsheh et al., 2024). These findings confirm the basin's propensity to generate runoff.

Calculation of potential maximum retention (*S*)

The parameter *S*, representing the potential maximum retention, depends on the soil–vegetation–land use complex of the catchment and the antecedent soil moisture condition in the catchment just before the commencement of the rainfall event (Meißl et al., 2023). For convenience in practical application, the SCS of the USA, in 1969, expressed *S* (in mm) in terms of a dimensionless parameter, *CN* (the Curve Number), as:

$$S = \left(\frac{25400}{CN}\right) - 254 \tag{1}$$

where: *CN* – curve number, *S* – potential maximum retention

By applying the (*S*) equation to the study area, the potential maximum retention values after runoff were determined. The lowest value (7.9) suggests minimal soil capacity to retain water on the surface. This indicates that the amount of water flowing on the surface has increased, and the maximum result (75.9) shows that the soil has great potential for water conservation. A map showing the distribution of *S* factor values in the research area is shown in Figure 4.

Calculation of the initial loss coefficient (*Ia*)

The initial loss coefficient (*Ia*) is one-fifth of the (*S*) value, representing the portion of precipitation lost before surface runoff begins. This includes losses due to evaporation, interception by vegetation, water retention in surface depressions, and infiltration. The equation was formulated by the SCS in the USA in 1969 as follows.

$$Ia = 0.25 \times S \tag{2}$$

where: *Ia* refers to initial loss before runoff; *S* means the potential maximum retention

The values of (*Ia*) were calculated using formula 2, as presented in Table 2, showing the areas covered by these values and their percentage relative to the study area. Low (*Ia*) values, such as 1.97, suggest minimal rainwater loss before surface runoff begins, resulting in faster runoff. In contrast, high (*Ia*) values, such as 18.97, indicate significant rainwater loss, leading to a reduction in surface runoff.

Runoff depth

The runoff depth is determined by the intensity and duration of precipitation, as well as how the rainstorm interacts with soil permeability and land cover properties. Consequently, the depth of runoff accumulating on the surface varies. If we assume that rainstorms

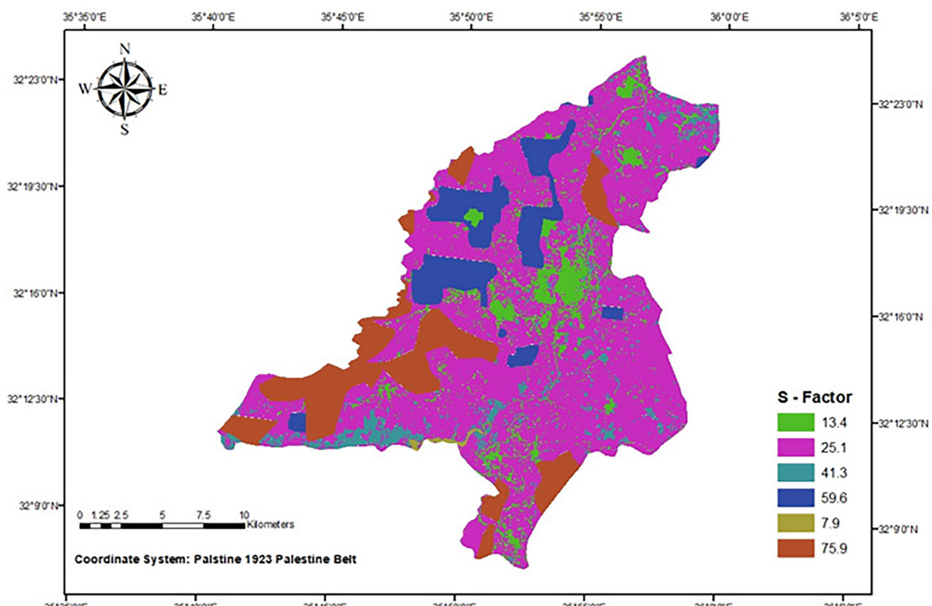

Figure 4. Potential maximum retention map (*S*)

Table 2. Represents (*S*) and (*Ia*) values and the percentage of these values relative to study area

Landuse + hydrologic group	(CN)	(km^2)	S Factor
Bare land D	86	24.07	5.93
Build-up area D	95	36.6	9.01
Forest D	77	57.6	14.19
Irrigated land D	81	37.2	9.16
Unirrigated land D	91	249	61.36
Water D	97	1.04	0.25
		Sum = 405.78	99.9%

are uniform across the entire area, CN will be the variable factor governing the variation in runoff depth in the research region. The runoff depth for the study area was estimated based on the arithmetic average of annual rainstorms between 2013 and 2023, annual precipitation varied significantly, peaking at 430.71 mm in 2020 and dropping to 101.55 mm in 2017. Several years experienced moderate rainfall, with totals ranging from 236.69 mm to 330.72 mm. Recent years (2021–2023) showed a declining trend, with 2023 recording the second-lowest total (206.70 mm), highlighting ongoing rainfall variability.. This estimation was derived from the components of land cover and soil hydrology, represented by CN, in addition to the amounts of rainfall received in the study area.

As mentioned previously, the runoff depth (*Q*) can be calculated by the SCS curve number method which is developed by SCS in 1969. It is now known as the natural resources conservation service (NRCS), the equation as follows:

$$Q = \frac{(P-Ia)^2)}{(p-Ia)+S} \tag{3}$$

where: *Q* is the runoff depth (mm), *P* is the precipitation (mm), *S* is the potential maximum retention.

Runoff volume

One of the crucial hydrological computations is the runoff volume, which represents the total of the surface runoff to the study region. The runoff depth computations are used to estimate the runoff volume for the study area. The following formula can be used to express the runoff volume:

$$V = \frac{Q \times A}{1000} \tag{4}$$

where: *V* – runoff volume (m^3), *Q* – runoff depth (mm), *A* – study area (m^2), 1000: conversion coefficient from (mm) to (m).

The runoff volume for the study area was calculated based on the runoff depth formula. The data indicate significant variations in runoff depth (*Q*) and runoff volume (*V*) across different years. Runoff volume varied significantly across years, influenced by precipitation levels. The highest runoff occurred in 2018 (4,556.90 m^3) with 35.13 mm of rainfall, while the lowest was in 2017 (726.35 m^3) with 10.73 mm. Notable years include 2020 (3,830.56 m^3) and 2016 (2,394.10 m^3), reflecting moderate runoff levels. Recent years (2021–2023) showed a declining trend, with 2023 recording only 941.41 m^3

RESULTS AND DISCUSSION

Hydrology analysis

The use of DEM processing capabilities has been instrumental in the hydrological investigation of the Jerash region. These features facilitate the identification of downstream sites for each circulation, the delineation of sub-basins, and the creation of a waterway network. To calculate the relief ratio, the methodology involves addressing anomalous elevation values (sink filling), which range from 1229 meters above sea level to 2 meters, as shown in Figure 5a. The optimal threshold value for retrieving the drainage network is determined by stream ordering. After testing, a threshold value of one was found to be the most suitable for the area under examination (Ozulu and Gökgöz, 2018).

Using the Strahler method, the streams in the region were classified into eight orders, totaling 477,621 streams. The first order consists of 337,523 streams (70.6%), characterized by a higher number and length of streams. The second order contains 90,927 streams (19.04%), followed by the third order with 27,724 streams (5.80%), the fourth order with 11,071 streams (2.32%), the fifth order with 5,671 streams (1.19%), the sixth

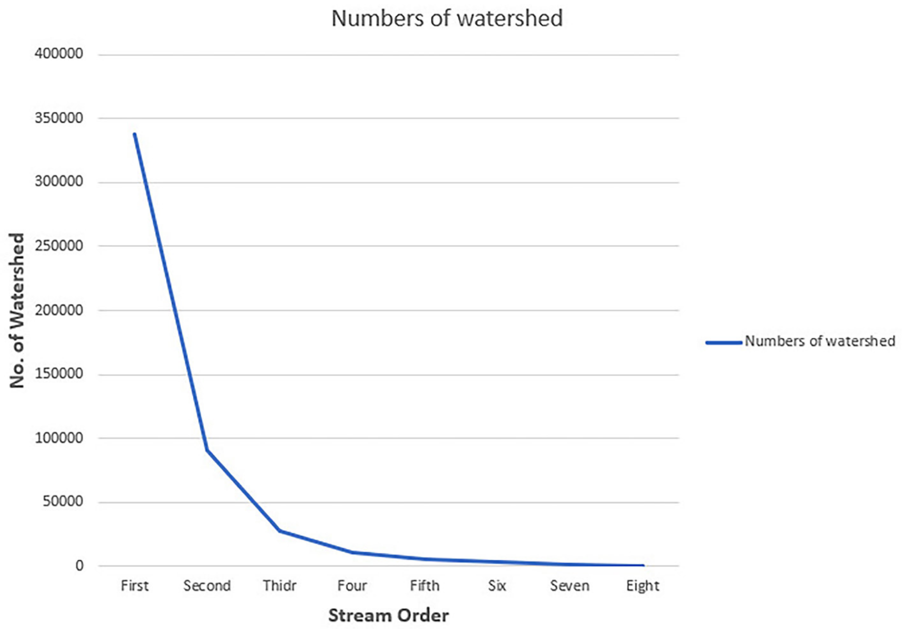

Figure 5. Hydrology analysis maps: a) map of fill, b) map of flow direction, c) map of flow accumulation, d) map of stream order

order with 3,379 streams (0.71%), the seventh order with 1,057 streams (0.22%), and the eighth order with 269 streams (0.056%), which are typically shorter and fewer in number. These classifications offer key insights into the region's hydrological structure and flow hierarchy (Figure 5d). The next step involves determining the drift route—the movement of water from one cell to neighboring cells. The results indicated that the southwest direction (cost 8) was the most common, with flow directions represented by different colors: eastward flow (value 1, light blue), westward flow (value 16, medium blue), and northeastward flow (value 128, dark blue) Figure 5b. The flow accumulation tool calculates the number of contributing cells for each cell based on the streams, which flow toward the southwest in the Jerash area, as shown in Figure 5c.

The study area contains a total of 477,621 stream orders, with first-order streams being the most dominant, accounting for 70.6% (337,523 streams). Second-order streams follow with 19.04% (90,927 streams), while third- and fourth-order streams make up 5.80% (27,724) and 2.32% (11,071), respectively. Higher-order streams are less frequent, with fifth-order at 1.19% (5,671), sixth-order at 0.71% (3,379), and seventh-order at 0.22% (1,057). The rarest are eighth-order streams, constituting only 0.056% (269). These results highlight the dominance of lower-order streams in the study area.

These findings demonstrate that accurate hydrological modeling using high-resolution DEMs and GIS techniques can significantly improve flood risk assessment and water resource management in the Jerash Basin, supporting sustainable development in arid and semi-arid regions.

Morphometric analysis

River bifurcation ratio

It is defined as the ratio of the number of streams in a given order to the number of streams in the next order (Mishra et al., 2023). Since it regulates the basin's drainage rate and may be used to predict the likelihood of flooding, the bifurcation ratio is considered one of the key factors influencing the hydrological features of the basin (Mishra et al., 2023). According to a previous study, the geology of the basin is considered homogeneous if the bifurcation ratio falls between 2 and 5 (Anya and Bhuiyan, 2024). A low bifurcation ratio indicates a high drainage density.

To calculate the river bifurcation ratio, the number of streams in two successive orders must first be extracted and then multiplied. Table 3 shows the river orders, the number of streams for each of the eight orders, and the bifurcation ratio for the study area. The following is how this ratio is measured:

$$RBR = \frac{\text{No.of watersheds in one order}}{\text{No.of watersheds in the next}} \quad (5)$$

where: RBR – river bifurcation ratio.

Table 3. preparation of streams for different orders in the study area by their bifurcation ratio and general bifurcation rate

Streams order	Streams in each order	Bifurcation ratio	Streams in two consecutive orders	River bifurcation ratio × streams in two consecutive orders	Bifurcation rate
First	337523	3.71	428450	1589549.5	$\frac{2142885.42}{617450} = 3.47$
Second	90927	3.28	118651	389175.28	
Third	27724	2.50	38795	96987.5	
Four	11071	1.95	16742	32646.9	
Fifth	5671	1.68	9050	15204	
six	3379	3.19	4436	14150.84	
Seven	1057	3.9	1326	5171.4	
Eight	269	–	–	–	
SUM	477621	–	617450	2142885.42	

Drainage density

It is defined as the total length of all the streams to the entire area of the basin. The period of concentration decreases when the drainage density is low because surface runoff duration increases (Taloor et al., 2024). This is how it is measured:

$$DD = \frac{Swl}{Dba} \tag{6}$$

where: *DD* refers to drainage density, Swl means the sum of watercourse lengths of all drainages in whole basin ranks (m), *Dba* – drainage basin area (m^2).

Table 4 shows the lengths of streams for each of the eight orders, the area of the study area, and the calculation of the drainage density of the study area. A high value of drainage density of Jerash area (12.60) indicates the severity of the region's influence on erosion factors meaning that its texture is fabric (fine grain) if it is more than 10 based on Smith's division, the particle size of the Jerash soil was studied by (AlFukaha et al., 2024) using mechanical and hydrometer methods, the soil's nominal mean D50 value was 0.00302 mm, which means the study area consists of clayey soil. This proves that the grain size of the study area is fine grain.

Relief ratio

It indicates the range of the relief of the basin according to its length. The value of the relief ratio is related to the geological conditions of the basin, climate, slope, area, and relief characteristics (Raja Shekar and Mathew, 2024). The relief ratio increases if the area of the basin is small and the shape of the basin is circular, the equation was extracted by Schumm, (1956) as follows (Schumm, 1956):

$$RR = \frac{Dhl}{L} \tag{7}$$

where: *RR* – relief ratio, *Dhl* – the difference between the highest and lowest level in the drainage basin (m), *L* – length of the drainage basin (m).

After applying the equation, Table 5 shows the result of the relief ratio of the study area which is 0.0351.

Table 4. The drainage density of the study area

Stream order	Length of streams in each order (km)	Area (km²)	Drainage density
First	2426.31	405.78	$\frac{5115.07}{405.78} = 12.60$
Second	1278.84		
Third	662.3		
Four	256.92		
Fifth	258.6		
Six	132.4		
Seven	97.1		
Eight	2.6		
SUM	5115.07		

Table 5. Represents the calculation of relief ratio and concentration time (in min) of study basin

Highest height (m)	Lowest height (m)	Length of basin (m)	Relief ratio	Concentration time
1229	2	34911.51	$\frac{(1229-2)}{34911.51} = 0.0351$	222.48

Calculation of concentration time

Is the time required for runoff to move from the farthest point hydraulically in the watershed to the outlet. The farthest point hydraulically is the point that needs the longest travel time to the outlet of the watershed (Michailidi et al., 2018). It depends on slope, CN, and hydraulic length. Table 5 shows the result of the concentration time (in min) of the study area which is 222.48 min. The following equation is used for computing the time of concentration (in hours):

$$tc = 0.01947 \times \left(\frac{L^3}{\Delta H}\right)^{0.385} \quad (8)$$

where: tc is the time of concentration (hours), L is the length of the mainstream (m), ΔH is the average slope of the basin.

These morphometric analyses highlight the basin's susceptibility to flooding and its limited drainage capacity, emphasizing the need for accurate hydrological modeling to support flood risk assessment and sustainable water resource management in the Jerash Basin.

CONCLUSIONS

This study provides a detailed hydrological analysis of the Jerash Basin by integrating the SCS-CN method with GIS, revealing significant findings about the region's runoff potential and hydrodynamics. The calculated CN of 87.83 highlights the basin's high susceptibility to runoff, while metrics such as drainage density, concentration time, and relief ratio further emphasize its vulnerability to flooding under specific rainfall conditions.

A key contribution of this study lies in its innovative application of high-resolution digital data and modern GIS techniques, which allowed for a more precise evaluation of hydrological and geomorphological features compared to previous research. By classifying the basin's streams into eight orders and analyzing bifurcation ratios, the study revealed a unique hydrological structure that reflects both the homogeneous geology and high drainage density of the region. These findings fill a critical knowledge gap in understanding flood dynamics in arid environments, providing a refined methodology for runoff estimation and flood risk assessment.

Moreover, the study demonstrates the value of integrating hydrological models with GIS for practical applications in water resource management and urban planning. It opens new prospects for utilizing advanced remote sensing technologies and morphometric analyses in similar arid and semi-arid regions, offering a robust framework for future research on the impact of climate variability and land use changes on hydrological systems.

These findings can guide future efforts to mitigate flood risk in the region by informing infrastructure development and water management policies. We recommend further research that incorporates real-time data from advanced remote sensing technologies in other countries to improve the accuracy of runoff prediction models. Future studies should also investigate the impact of climate variability on hydrological behavior in different basins. Additionally, we suggest utilizing GIS technology and digital elevation models for natural studies on the morphometric features of drainage basins, particularly in the Arab region and Jordan. For quantitative measurements, it is crucial to rely on highly accurate digital data sources, as their precision significantly affects results and map displays using modern technologies like GIS.

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