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GEOSPATIAL RAINFALL–RUNOFF MODELLING AND HYDROLOGICAL ASSESSMENT OF AN UNGAUGED ARID MOUNTAIN CATCHMENT USING GIS AND HEC-HMS

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Abstract: Reliable hydrological information is essential for sustainable water-resource planning in arid and semi-arid environments where rainfall is highly variable and hydrometric networks are sparse. The present study evaluates rainfall–runoff processes within the ungauged Deh Desvi catchment located in the Khirthar National Range of Sindh Province, Pakistan. An integrated framework combining Geographic Information Systems (GIS), Remote Sensing, Digital Elevation Models (DEMs), spatial rainfall interpolation, and Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) was employed to quantify runoff generation and hydrological response. A 30 m Advanced Land Observing Satellite (ALOS) DEM was used for watershed delineation and extraction of hydrological parameters, while precipitation data from the Pakistan Meteorological Department were utilized to simulate runoff during a major monsoon event occurring from 8–10 September 2025. The study catchment covers approximately 818.5 km² and represents a typical arid mountainous watershed characterized by steep slopes, sparse vegetation cover, ephemeral drainage networks, and limited infiltration capacity. Hydrological modelling using the Soil Conservation Service Curve Number method indicated that a total rainfall of 116 mm generated 63.97 mm of effective rainfall and produced a peak discharge of 189.5 $m^3 s^{-1}$. Approximately 55% of total precipitation was transformed into direct runoff. Hydrograph analysis demonstrated a rapid rise and recession response typical of flashy arid watersheds. Results further revealed that catchment topography, antecedent soil moisture, and rainfall intensity exert significant control over runoff generation. The findings demonstrate the applicability of GIS-integrated hydrological modelling for ungauged arid catchments and provide a scientific basis for rainwater harvesting, flood mitigation, groundwater recharge enhancement, and climate-resilient watershed management in the Khirthar mountain region. The study contributes toward addressing hydrological information gaps in data-scarce environments and supports sustainable water-resource development under changing climatic conditions.

Keywords: GIS, HEC-HMS, ungauged catchment, rainfall–runoff modelling, rainwater harvesting.

Introduction

Freshwater scarcity has emerged as one of the most critical environmental challenges affecting arid and semi-arid regions worldwide. Population growth, climate variability, increasing water demand, and land degradation have intensified pressure on already limited water resources (Wheater *et al.,* 2007). In arid mountainous environments, rainfall events are infrequent but often intense, producing flash floods and substantial runoff losses that remain largely unutilized (Dingman, 2015).

Recent studies have shown that climate change is intensifying hydrological extremes in arid and semi-arid environments, resulting in increased rainfall variability, flash floods, prolonged droughts, and uncertainty in water availability (IPCC, 2023; Mahmood *et al.,* 2024). Consequently, accurate rainfall–runoff assessment has become increasingly important for climate-resilient water resources planning and sustainable watershed management (UNESCO, 2024).

Hydrological modelling provides an effective means for understanding rainfall–runoff relationships, particularly in ungauged basins where field measurements are unavailable (Sivapalan *et al.,* 2003). The integration of Geographic Information Systems (GIS), Remote Sensing, and physically based hydrological models has significantly improved watershed analysis and runoff estimation in ungauged and data-scarce watersheds worldwide (Maidment, 1993; Chow *et al.,* 1988). High-resolution Digital Elevation Models facilitate accurate characterization of drainage networks, flow pathways, catchment morphology, and runoff generation mechanisms (Ahmad *et al.,* 2019). Recent applications of TGIS-integrated HEC-HMS and SWAT models have demonstrated high reliability for runoff prediction, flood assessment, and rainwater harvesting planning in arid regions (Soomro *et al.,* 2022; Khan *et al.,* 2023; Alharbi *et al.,* 2024).

Pakistan faces severe water stress, with arid and semi-arid regions covering a substantial portion of the country. The

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Khirthar mountain system located in Sindh Province receives highly variable monsoonal rainfall and supports agriculture through hill-torrent runoff, rainwater harvesting, and groundwater extraction (Mirjat *et al.*, 2011). Despite considerable runoff potential, limited hydrological monitoring has restricted the development of scientifically designed water-harvesting interventions.

Previous investigations have highlighted the importance of hill-torrent management and rainwater harvesting in the Kohistan and Khirthar regions (PARC, 2010; Mirjat *et al.*, 2011; Memon *et al.*, 2020). However, detailed runoff quantification using integrated GIS and HEC-HMS modelling remains limited. Therefore, the present study aims to quantify rainfall–runoff processes within the Deh Desvi catchment and assess its water-harvesting potential using modern geospatial techniques.

Materials and Methods

Study Area

The study area, Deh Desvi, is a sub-catchment within the arid mountainous region, situated in the Khirthar National Range of Sindh Province, Pakistan. Geographically, it extends between latitudes 25°34′1.18″ N and 25°14′43.74″ N and longitudes 67°36′14.99″ E and 67°56′33.76″ E, covering an approximate area of 818.5 km² (Fig. 1). The terrain is predominantly hilly and rugged, consisting of steep slopes and barren ridges with high relief and a well-developed dendritic drainage network formed by ephemeral torrents that converge into their respective catchments before draining downstream.

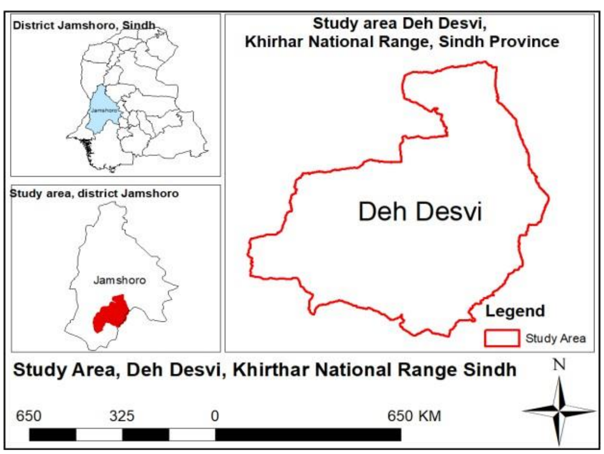

Fig. 1 Study area.

The soil type of the study area is the sandy loam, and could moderate infiltration capacity (often belonging to Hydrologic Soil Group C). The land cover might be cultivated agricultural land or a moderately vegetated area**.** A significant portion of rainfall becomes surface runoff**,** while some portion infiltrates into the soil. A CN value of 80 indicates a moderate-to-high runoff potential**.** The HEC-HMS rainfall–runoff model, the selected Curve Number (CN) of 80 is consistent with the hydrological response characteristics of sandy loam soils and is typically associated with the corresponding Hydrologic Soil Group (HSG) under average antecedent moisture conditions.

Land Use for Cultivated agricultural land, mixed rangeland, or sparsely vegetated catchment, and average hydrologic condition**s** have been selected (neither heavily compacted nor very permeable). For example, in the study area, where land is mostly barren to semi-cultivated**,** with moderate infiltration and high runoff during flash floods**,** a CN value between 75 and 85 is quite realistic.

Rainfall Data

The primary data collected through real-time survey during the monsoon. Existing situation was recorded by taking pictures. The secondary precipitation dataset was collected from the Pakistan Meteorological Department. Rainfall data from September 8 to 10, 2025**,** were recorded and used to analyze the rainfall–runoff relationship over the study area. Except for the reporting period from January to September 7, 2025**,** no rainfall was recorded in the study area.

Table 1. Rainfall data year 2025.

Date	Precipitation (mm)
08.09.25	32.00
09.09.25	45.00
10.09.25	39.00

Digital Elevation Model (DEM)

The Advanced Land Observing Satellite (ALOS) Digital Elevation Model (DEM) with a spatial resolution of 30 meters was utilized. The DEM data were processed and analyzed using Geographic Information System (GIS) tools to support the estimation of rainfall-runoff potential and to identify suitable sites for rainwater-harvesting structures.

Watershed Delineation and Spatial Analysis

Spatial watershed parameters derived in ArcGIS 10.5.1 from a 30 m resolution ALOS DEM. The analysis included watershed boundary delineation, sink filling, flow direction/accumulation, stream-network extraction, and topographic derivatives (slope, aspect, contours). The study-area polygon for the Deh Desvi catchment (within the Khirthar National Range, Sindh Province) was digitized in Google Earth Pro, converted via “KML to Layer”, and used to clip all datasets.

High-resolution DEM-based watershed extraction has been widely recognized as an effective approach for hydrological parameterization and runoff simulation, particularly in ungauged basins where conventional field measurements are unavailable (Tarekegn *et al.*, 2022; Ahmed *et al*., 2023).

DEM Pre-Processing and Flow Analysis

The DEM is projected into the UTM coordinate system. Sinks and depressions were filled (“Fill” tool), then the DEM was clipped to the watershed boundary. Flow direction was computed on the filled DEM, and flow accumulation was derived. A threshold of flow-accumulation cells is applied to delineate the stream network. Using the outlet point identified via field/topographic inspection, the "Watershed" tool delineated the contributing area, which was converted to a polygon for parameter extraction. Slope, aspect, and 10 m-interval contour maps generated from the hydrologically corrected DEM to characterize terrain controls on runoff and flow concentration.

Lag Time Estimation

Lag time (the interval between the centroid of rainfall and hydrograph peak) estimated using the empirical SCS lag equation (USDA 1972; Sultan *et al.*, 2022) given by:

$$TL = \frac{(L^{0.8}) \times (S+1)^{0.7}}{1900 x\, Y^{0.5}}$$

$$S = \frac{25400}{\mathrm{CN}} - 254$$

Where:

- TL = Lag time (hours)
- L = Hydraulic length of the watershed (m) — measured as the flow path from the most distant point to the outlet using the "Flow Length" tool in ArcGIS.
- S = Potential maximum retention (mm), estimated from the curve number (CN) using the relationship
- Y = Average slope of the watershed (%)

The hydraulic length was derived using the "Flow Length" tool in ArcGIS, and the average slope from the slope map via the "Zonal Statistics" tool. This relationship has been widely applied for small to medium-sized catchments (McCuen, 1989; Maidment, 1993; Sultan *et al.*, 2022).

Spatial Precipitation Mapping

Rainfall data obtained from the Pakistan Meteorological Department (PMD) was processed in ArcGIS 10.5.1. The data, initially in tabular (.xls) format, were georeferenced by assigning coordinates to each station. Spatial interpolation was carried out using the Kriging method in the Geo-statistical Analyst tool, which models spatial dependence through variogram analysis and provides statistically optimal rainfall estimates (Ahmad *et al.*, 2019; Zaman *et al.*, 2020), producing a continuous raster of total precipitation 08-11 September 2025.

The resulting precipitation raster clipped to (a) the Sindh Province boundary and (b) the Deh Desvi (Thana Bula Khan) watershed using the "Extract by Mask" tool. The outputs were classified into rainfall ranges (mm) and visualized with color gradients representing spatial variability.

Hydrological Modelling in HEC-HMS

Using HEC-HMS version 4.x (USACE, 2000; USACE, 2002), a rainfall-runoff simulation was carried out for the period 8–17 September 2025. Watershed parameters (area, slope, flow length, lag time, CN) extracted from GIS analysis were imported into HEC-HMS. The basin model included sub-basins, reaches, junctions, and an outlet node. Losses estimated through the SCS Curve Number method:

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

Where Q is the direct runoff (mm), P is the total precipitation (mm), Ia is the initial abstraction (mm), and S is the potential maximum retention (mm). The initial abstraction related to S by the equation:

$$Ia = 0.2S$$

S is defined as:

$$S = \frac{25400}{\mathrm{CN}} - 254$$

Where CN is the Curve Number, a dimensionless value (80) representing soil type, land cover, and antecedent moisture conditions.

$$Q_p = \frac{0.208 \times A \times P_e}{T_p}$$

Where Qp is the peak discharge (m^3/s), A is the catchment area (km^2), Pe is the effective rainfall (cm), and Tp is the time to peak (hours). The time to peak is computed as:

$$T_p = T_L + \frac{D}{2}$$

Where TL is the basin lag time (hours) and D is the duration of effective rainfall (hours).

Base Flow Estimation – Exponential Recession Method

Base flow, representing groundwater contribution to total flow, is estimated using the exponential recession equation:

$$Q_t = Q_0 \times K^{\frac{(t)}{(\Delta t)}}$$

Where Q_t is the base flow at time t, Q_0 is the initial base flow (m^3/s), K is the recession constant (typically 0.90–0.98), and Δt is the time step. In this study, base flow was almost zero, consistent with the semi-arid conditions of the catchment.

Simulation and Output and Hydrogeological Analysis

The model ran with daily time-steps from 08 - 17 September2025. Outputs included precipitation input, infiltration losses, effective rainfall, direct runoff, base flow, and hydrographs to analyze the catchment response to rainfall. The detailed flowchart of methodology is as under remote sending/GIS modeling.

Table 2. Estimation of lag time.

Dam	Catchment Area (mile^2)	u/s Elevation (ft)	d/s Elevation (ft)	Length of Channel (ft)	Slope (%)	CN	S	Lag Time (hrs)	Lag Time (min)
Stream Channel-1	316.04	775	304	150474.74	0.31	80	2.50	31.35	1,881

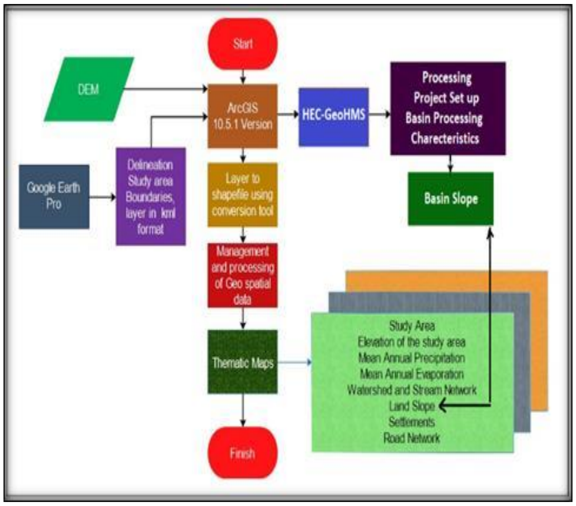

Fig. 2 Flow chart methodology remote sensing modeling.

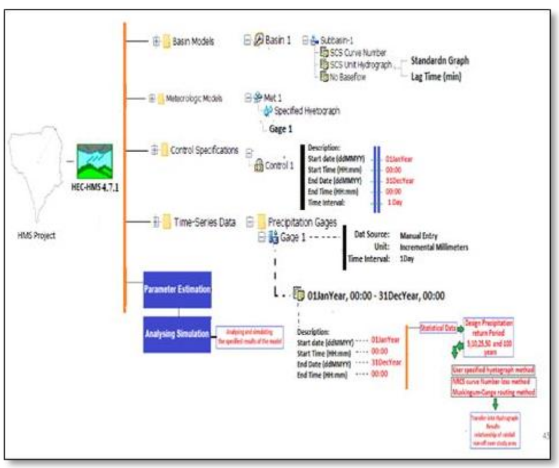

Fig. 3 Flow chart methodology of hydrological methodology.

Results and Discussion

Spatial Precipitation Map of Sindh Province

The spatial map reveals clear rainfall variability across Sindh, increasing from north to south. Northern districts (Jacobabad, Sukkur, Larkana, Khairpur) received low rainfall of 10–40 mm, while central areas (Dadu, Sakrand, Padidan) showed moderate values of 70–90 mm. The southern and southeastern regions (Thatta, Badin, Karachi, Mithi) experienced the highest precipitation, exceeding 130 mm and reaching up to 160 mm. This gradient reflects the province's climatic pattern, enhanced coastal monsoonal influence, and moisture convergence from the Arabian Sea, contrasting with the semi-arid north.

Hydrologically, higher rainfall in the south indicates better groundwater recharge and surface water potential, whereas northern areas remain water-stressed. The results agree with previous studies showing a similar north–south rainfall gradient in Sindh (Chaudhry & Rasul, 2017; Memon *et al.*, 2021). Kriging interpolation proved reliable for capturing spatial rainfall variability, consistent with findings by Ahmad *et al*. (2019) and Zaman *et al*. (2020), though accuracy depends on station density. The map provides a valuable spatial overview for regional water resource management and rainfall–runoff analysis up to September, 2025.

Spatial Precipitation Map of Deh Desvi (Thana Bula Khan)

Precipitation in Deh Desvi ranged from 103 mm in the north to 116 mm in the south, showing a southward increase influenced by topography and monsoonal flow. The southern sector's higher rainfall enhances runoff and recharge potential, vital for rainwater harvesting in this semi-arid catchment.

The rainfall pattern reflects regional monsoonal trends and supports hydrological assessments for water management and climate adaptation. Similar GIS-based analyses have effectively represented localized rainfall variation in arid regions (Ahmad *et al.*, 2019; Memon *et al.*, 2021). The map thus offers precise spatial insight into early-September 2025 rainfall dynamics in Thana Bula Khan.

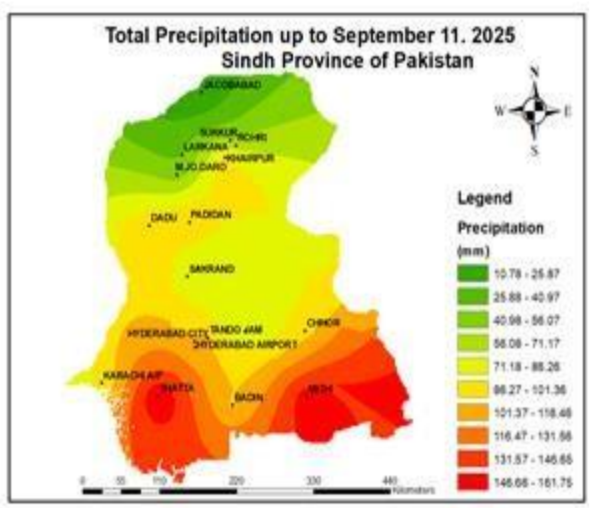

Fig. 4 Spatial precipitation map of Sindh Province.

Table 3. Hydrological model output interpretation (HEC-HMS simulation: 8–17 Sept 2025).

Date	Precipitation (mm)	Loss (Infiltration / initial abstraction) (mm)	Excess (mm)	Direct Flow/Runoff (m^3/s)	Base Flow (m^3/s)	Total Flow/Runoff (m^3/s)
08.09.25	32.00	27.50	4.50	10.20	0.00	10.20
09.09.25	45.00	17.15	27.85	80.70	0.00	80.70
10.09.25	39.00	7.38	31.62	189.50	0.00	189.50
11.09.25	0.00	0.00	0.00	182.00	0.00	182.00
12.09.25	0.00	0.00	0.00	85.80	0.00	85.80
13.09.25	0.00	0.00	0.00	34.90	0.00	34.90
14.09.25	0.00	0.00	0.00	14.10	0.00	14.10
15.09.25	0.00	0.00	0.00	5.70	0.00	5.70
16.09.25	0.00	0.00	0.00	2.30	0.00	2.30
17.09.25	0.00	0.00	0.00	0.70	0.00	0.70
Total	116.00	52.03	63.97	605.90	0.00	605.90

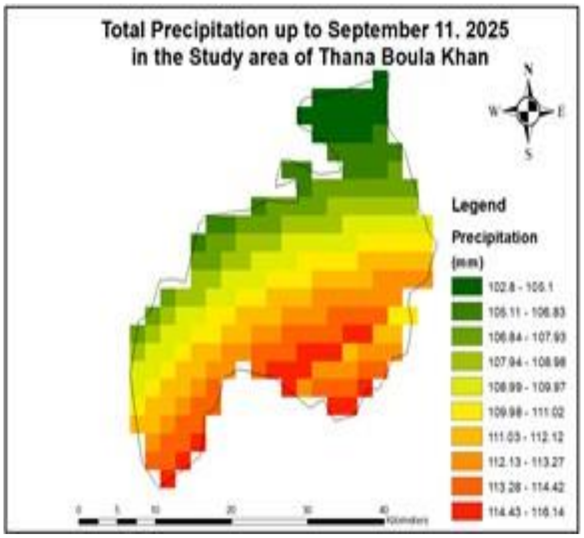

Fig. 5 Spatial precipitation map of Deh Desvi (Thana Bula Khan).

Hydrological Model Output Interpretation (HEC-HMS Simulation, Year 2025

Table 3 represents the HEC-HMS model simulation, showing a 10-day rainfall-runoff event, reflecting how precipitation transformed into surface flow under arid watershed conditions of the Deh Desvi (Khirthar National Range). The output of the model shows total Precipitation received 116.0 mm, total Infiltration 52.03 mm, total Effective Rainfall (Excess) 63.97 mm, and total Simulated Runoff (Flow) 605.9 m³/s was recorded.

Such runoff estimation patterns are consistent with arid hydrological responses where infiltration rapidly decreases after initial rainfall events (Chow *et al.,* 1988; Maidment, 1993).

Runoff Response and Catchment Behavior

The HEC-HMS simulation revealed a strong hydrological response of the Deh Desvi watershed to the monsoonal rainfall event of 8–10 September 2025. The runoff response was primarily influenced by steep topography, sparse vegetation cover, limited soil-water storage capacity, and antecedent moisture conditions.

On 8 September 2025, 32 mm of rainfall generated 4.5 mm of effective rainfall and a discharge of 10.2 $m^3 s^{-1}$. High infiltration losses (27.5 mm) reflected the dry antecedent soil conditions, resulting in low runoff efficiency of approximately 14% (Dingman, 2015).

On 9 September 2025, rainfall increased to 45 mm, producing 27.85 mm of effective rainfall and a discharge of 80.7 $m^3 s^{-1}$. Reduced infiltration losses (17.15 mm) indicated increasing soil saturation and enhanced runoff generation (Beven & Kirkby, 1979).

The highest hydrological response occurred on 10 September 2025, when 39 mm of rainfall produced 31.62 mm of effective rainfall and a peak discharge of 189.5 $m^3 s^{-1}$. The substantial reduction in infiltration losses (7.38 mm) suggests the dominance of saturation-excess runoff conditions, where a large proportion of rainfall was converted directly into surface flow (Pilgrim *et al.*, 1988; Ponce, 1989).

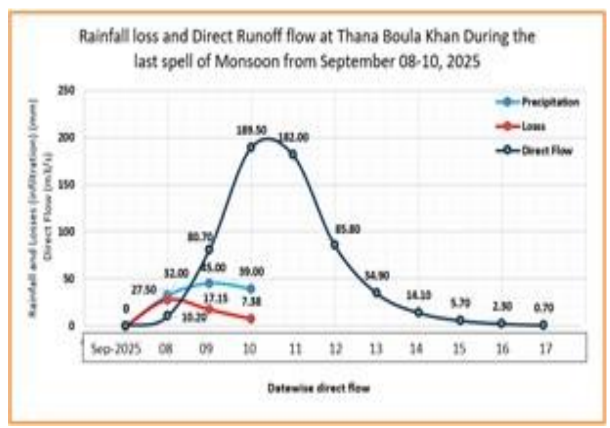

Fig. 6 Hydrographical representation of the rainfall runoff relationship over the study area.

Although no rainfall occurred on 11 September 2025, discharge remained high at 182 $m^3 s^{-1}$, indicating delayed runoff routing and watershed storage effects. Subsequently, from 12 to 17 September 2025, discharge gradually declined from 85.8 $m^3 s^{-1}$ to 0.7 $m^3 s^{-1}$, representing the recession phase of the hydrograph. The absence of measurable baseflow confirms the ephemeral nature of the watershed and its limited groundwater contribution (Wheater *et al.*, 2007). Overall, the event sequence demonstrates a transition from infiltration-dominated conditions to runoff-dominated processes, followed by rapid recession. These findings indicate that runoff generation in the Deh Desvi watershed is strongly controlled by rainfall intensity, antecedent moisture conditions, and watershed morphology (Maidment, 1993; Wheater *et al.*, 2007).

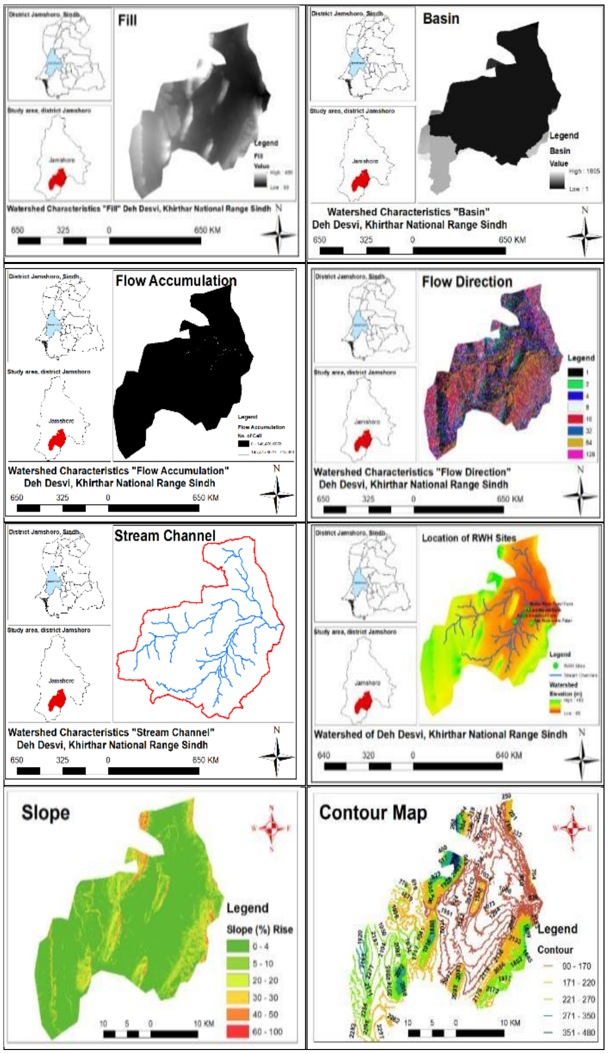

Fig. 7 Watershed characterizes of the study area

Spatial Maps of Watershed Characteristics

The hydrological response observed in the Deh Desvi watershed is characteristic of arid and semi-arid mountainous catchments, where intense rainfall events produce rapid runoff and short-duration flood peaks. The estimated peak discharge of 189.5 $m^3 s^{-1}$ demonstrates the substantial runoff-generating potential of the watershed despite relatively short rainfall duration. Similar hydrological behavior has been reported in hill-torrent watersheds of Pakistan and other arid regions, where steep slopes and limited vegetation promote rapid conversion of rainfall into surface runoff (Mirjat *et al.*, 2011; Soomro *et al.*, 2022; Alharbi *et al.*, 2024).The hydrological modeling framework developed in this study has broader applicability beyond the Deh Desvi catchment and provides a practical approach for sustainable watershed management in ungauged arid and semi-arid regions.

The integration of remote sensing, GIS, and HEC-HMS can support long-term watershed planning by identifying runoff potential, prioritizing rainwater harvesting sites, enhancing groundwater recharge, and improving flood risk management under changing climatic conditions. Such geospatially based hydrological assessments are increasingly recognized as essential tools for climate change adaptation and integrated water resources management, particularly in data-scarce watersheds where conventional hydrological observations are limited (UNESCO, 2024; WMO, 2024).

These findings may therefore assist planners and policymakers in developing resilient water resource strategies for similar environments.
The study confirms that GIS-derived watershed characteristics and HEC-HMS modelling provide reliable tools for hydrological assessment in ungauged and data-scarce environments. The identified runoff potential highlights significant opportunities for rainwater harvesting, groundwater recharge, and flood mitigation through strategically located check dams, recharge ponds, and detention structures.

Furthermore, projected increases in rainfall variability and extreme precipitation under climate change scenarios may intensify flash-flood risks in the Khirthar mountain region (IPCC, 2023). Therefore, integrating geospatial technologies with climate-resilient watershed management and rainwater harvesting strategies will be essential for enhancing water security and supporting sustainable development in arid regions of Pakistan.

Conclusion

The study area was spread over 818.5 km^2, received short-duration rainfall for three days and recorded 116 mm, while the average annual rainfall of the study area is 150-250 mm. The peak Discharge (PQ): 189.5 m^3/s. (10.09.2025), while the average flow is 60.59 m^3/s. The study successfully demonstrated that integrated GIS and HEC-HMS hydrological modelling is a powerful tool for quantifying rainfall–runoff potential in data-scarce, semi-arid mountainous catchments. The Deh Desvi watershed exhibits effective hydrological responses to monsoon rainfall, with significant scope for rainwater harvesting and watershed development.

The watershed of the study area could be promoted with the different rainwater harvesting infrastructures i.e., control, diversion, inlet, storage for groundwater recharge, spillway structures, based on the monitoring system for tracking by rainfall runoff data log, for the utilization runoff collection accordingly for the sustainable agriculture in the study area. The application of such advanced modeling frameworks supports evidence-based water management**,** soil conservation**,** and policy planning in Pakistan's arid regions.

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