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RESEARCH ARTICLE

Watershed delineation and hydrological response unit (HRU) analysis of the Banas River Basin using the SWAT model

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Abstract

The present study aims to delineate the Banas River Basin of south-eastern Rajasthan, India, to generate hydrological response units (HRUs) using the Soil and Water Assessment Tool (SWAT) in a geographic information system (GIS) environment. The objective of the research is to develop a reliable spatial framework that represents basin heterogeneity for future hydrological simulation and water resource planning in a semi-arid region. Watershed delineation was carried out using the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model, while land use/land cover, soil and slope layers were integrated through the ArcSWAT interface to derive HRUs. Threshold values of 20 % for land use, 10 % for soil and 10 % for slope were applied to balance spatial detail and computational efficiency. The analysis resulted in the delineation of 33 sub-basins and 580 HRUs, reflecting significant spatial variability within the basin. Agricultural land was found to be the dominant land use (approximately 55 %), followed by forest and pasture areas, while silt loam soils and gentle slopes (0–10 %) prevailed across large portions of the basin. These physiographic characteristics indicate moderate runoff potential with localised erosion risk. The outcomes of this study provide a robust spatial foundation for hydrological modelling, soil and water conservation planning and assessment of land-use and climate change impacts in the Banas River Basin.

Keywords: hydrological response unit; remote sensing; SWAT; water resources; watershed delineation

Introduction

A river basin is the land area drained by a river and its tributaries, encompassing all surface runoff that flows into a common outlet. It represents a fundamental hydrological unit for water resource planning and management. River basins consist of interconnected streams and creeks that transfer water from the land surface to the main river channel, playing a vital role in shaping regional ecosystems, supporting biodiversity and sustaining human livelihoods. Climate change, land use transitions and anthropogenic pressures have significantly altered hydrological processes and degraded many river basins worldwide, including those in semi-arid regions such as Rajasthan, India.

Effective river basin management integrates multidisciplinary efforts to enhance water quantity and quality, protect ecological health, improve socio-economic conditions and optimise land use practices (1). It involves stakeholder engagement, adaptive planning and scientific modelling to ensure sustainable development and resource conservation. In this context, hydrological models are essential tools that enable researchers and planners to simulate, analyse and predict the behaviour of complex watershed systems under varying environmental and land management scenarios.

The Soil and Water Assessment Tool (SWAT) are a robust, physically based, semi-distributed watershed model developed to predict the long-term impacts of land use, soil properties, topography, climate and management practices on water and sediment yield at the basin scale (2). The Soil and Water Assessment Tool (SWAT) divides watersheds into sub-basins and further into hydrological response units (HRUs), which are unique combinations of land use, soil type and slope class (3, 4). The integrated use of remote sensing and geographic information systems (GIS) enables the delineation of HRUs and analysis of their hydrological responses based on physiographic parameters in Indian basins. The utility of SWAT in evaluating the effects of climate variability, land use changes and spatial resolution on streamflow and watershed hydrology has been analysed by previous researchers (5, 6). The application of remote sensing and GIS in delineating HRUs and analysing their hydrological responses based on physiographic parameters in Indian basins has also been previously studied (7). The Banas River Basin, a tributary of the Chambal River, serves as a critical water resource for south-eastern Rajasthan. However, limited research has been conducted on hydrological modelling in this basin, particularly in its hilly regions. The basin's diverse terrain and land use patterns make it an appropriate choice for spatially detailed hydrological analysis using the SWAT model.

Therefore, the objective of the present study is to delineate the Banas River Basin and perform HRU analysis using the SWAT model, with the aid of high-resolution spatial datasets and GIS tools. The outcomes of this study are expected to support water resource planning, soil conservation strategies and future hydrological simulations under different land and climate scenarios.

Materials and Methods

The Banas River Basin is selected for the present study, located in the eastern region of Rajasthan, India. Geographically, the basin lies between 24°10′ N to 27°20′ N latitude and 73°40′ E to 77°15′ E longitude. The Banas River originates in the Khamnor Hills of the Aravalli Range in Rajsamand District at an elevation of approximately 576 m above mean sea level.

The river flows in a north-easterly direction for a length of about 512 km, passing through the districts of Rajsamand, Udaipur, Bhilwara, Chittorgarh, Ajmer, Tonk, Jaipur, Dausa, Sawai Madhopur and Karauli, before ultimately joining the Chambal River, a tributary of the Yamuna River. The total catchment area of the Banas River Basin is about 45833 sq km, making it one of the major ephemeral river basins in Rajasthan.

The basin exhibits varied topographical features, with steep slopes and rugged terrain in the upper reaches, transitioning to nearly flat plains in the lower regions. The region experiences a semi-arid climate, with most of the rainfall occurring during the monsoon season (June to September), contributing significantly to surface runoff and groundwater recharge.

The location of the Banas River Basin is shown in Fig. 1. The spatial datasets used in this study include Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission, soil maps from the FAO Digital Soil Map and land use/land cover (LULC) data from the BHUVAN Land Cover Database. The list and sources of input data required for watershed delineation and HRU analysis are detailed in Table 1.

Delineation of the study area

The delineation of the Banas River Basin was carried out using ArcGIS 10.3 integrated with the ArcSWAT interface, which provides robust tools for watershed and sub-basin delineation. The DEM, obtained from the Shuttle Radar Topographic Mission (SRTM) with a resolution of 30 m, served as the primary input for capturing the topographical features essential for accurate delineation. In addition to the DEM, survey of India topographic sheets were utilised to validate the spatial accuracy of river networks, drainage lines and elevation contours.

The delineation process involved importing the DEM into the ArcSWAT tool to generate flow direction and accumulation grids, followed by the identification of stream networks and watershed boundaries. The delineated watershed was then divided into multiple sub-basins based on hydrological and terrain characteristics. The resulting outputs were stored in the project's source folder and converted into GeoTIFF format when required for further GIS processing.

Stream network creation

The creation of the stream network is a critical step in defining the drainage pattern and flow pathways within the basin. In ArcSWAT, this was achieved by setting a threshold value for stream definition, which determines the minimum drainage area required to initiate a stream. The threshold can be defined in terms of area units (e.g., hectares or square km) or by the number of raster cells contributing to the flow.

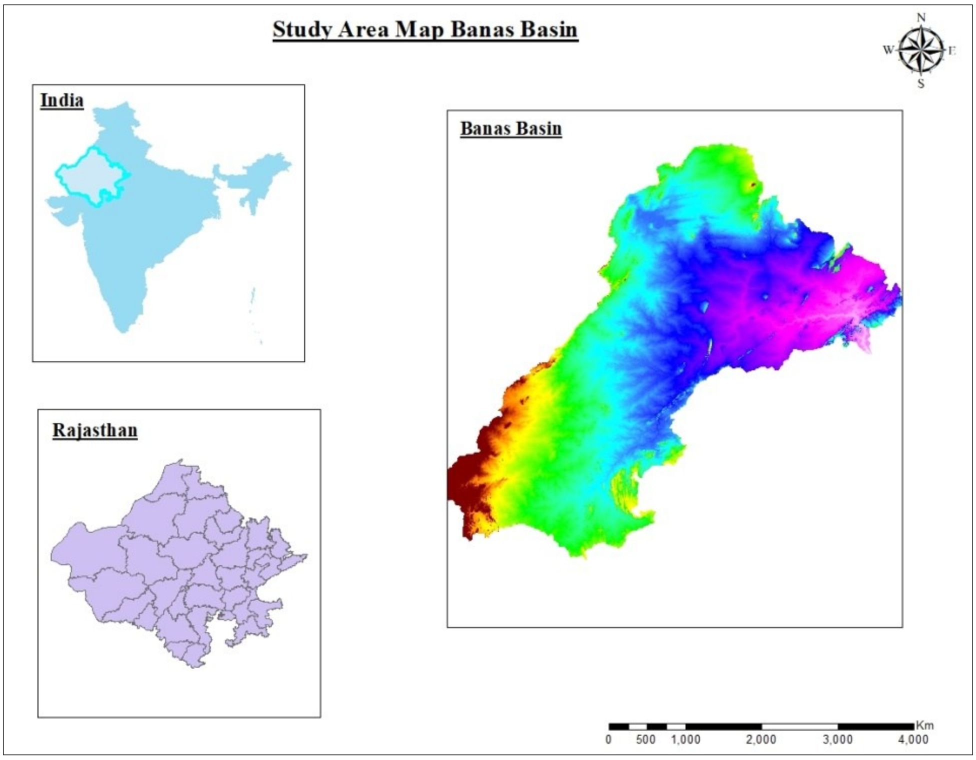

Fig. 1. Map of the study area.

Table 1. Details about the data required for the study

Sl. No.	Data type	Source	Resolution	Data parameter
1	Topography map	Unites State Geological Survey ((USGS)	30M	Digital elevation model (DEM)
2	Soil map	FAO (Digital Soil Map of the World)	1: 500000	Soil classification
3	Land use/ land cover map	BHUVAN Land Cover Database	30M	Land use classification

To represent key hydrological features such as inlets, outlets, reservoirs and point sources, the "Draw Inlets/Outlets" tool within ArcSWAT was used. These points were carefully positioned to align precisely with the generated stream network. The snapping threshold was adjusted to ensure that all manually placed points were accurately recorded as part of the stream segment, thereby maintaining the integrity of the hydrological model structure.

This detailed delineation and stream network development form the foundational step for further HRU analysis and hydrological simulation using the SWAT model.

Adding inlets and outlets

In the ArcSWAT interface, inlets and outlets are added to the watershed by selecting points from the inlets/outlets file. Users can choose either an inlet or outlet, which then highlights in yellow on the map and the total count of selected points is displayed at the bottom left of the main window. To verify the accuracy of these points, the "Review Snapped" option is used, which displays all inlets and outlets that lie within the specified snapping threshold distance to the nearest stream segment.

Once the inlets and outlets are confirmed, the river basins are generated by clicking the "Create Watershed" button. This process takes a few minutes, depending on the size and complexity of the basin, resulting in the automatic delineation of watersheds corresponding to each inlet/outlet.

Merging sub-basins

The SWAT model allows for the merging of smaller sub-basins, which helps to avoid an excessive number of small, fragmented sub-basins that can complicate the analysis. Sub-basins can be individually selected and combined using the merge function. After selection, the sub-basins turn yellow to indicate they have been chosen.

Following the merging process, the new combined sub-basin is saved and the model automatically updates the numbering and attributes of the sub-basins. This step finalises the basin delineation process by producing a manageable number of sub-basins suitable for HRU analysis and subsequent SWAT simulations.

Results and Discussion

Delineation of the Banas River Basin

The Banas River Basin was delineated using the DEM and processed through the ArcSWAT interface integrated with ArcGIS 10.3. The DEM facilitated accurate extraction of terrain characteristics and stream networks. The stream definition threshold was set to appropriately segment the watershed into meaningful hydrological units.

Upon delineation, the basin was subdivided into 580 HRUs and 33 sub-basins, which represent unique hydrologic zones used for further analysis and modelling. These sub-basins form the primary spatial units for runoff estimation, sediment routing and water balance simulations.

HRUs were derived by overlaying land use/land cover (LULC), soil and slope data within each sub-basin. These HRUs represent unique combinations of physical and geographical features.

Land use/land cover (LULC) map

The LULC map of Banas River Basin, year 2024, derived from the BHUVAN Land Cover Database was reclassified using SWAT's USGS-compatible LULC classification system. The LULC raster was clipped to the sub-basin boundary and reclassified into SWAT-readable land use codes. The selected thresholds (20 % LULC, 10 % soil, 10 % slope) were adopted to balance spatial detail and computational efficiency, consistent with previous SWAT-based watershed studies. Lower thresholds increase HRU numbers substantially without significant improvement in hydrological response, while higher thresholds may oversimplify basin heterogeneity. A brief sensitivity consideration indicates that reducing thresholds below these values leads to excessive HRU fragmentation. The LULC Map of the Banas River Basin is shown in Fig. 2 and the SWAT-compatible classification of land use types is shown in Table 2.

The analysis revealed that the agricultural land (AGRL) is the dominant land use class in the Banas River Basin, covering approximately 25200 km^2 (around 55 % of the total basin area). In contrast, the wetland–non-forest (WETN) class covered the smallest area, approximately 150 km^2, accounting for less than 0.5 % of the basin. Other major land use classes include deciduous forest (FRSD), which covered about 7800 km^2 (17 %), urban or built-up areas

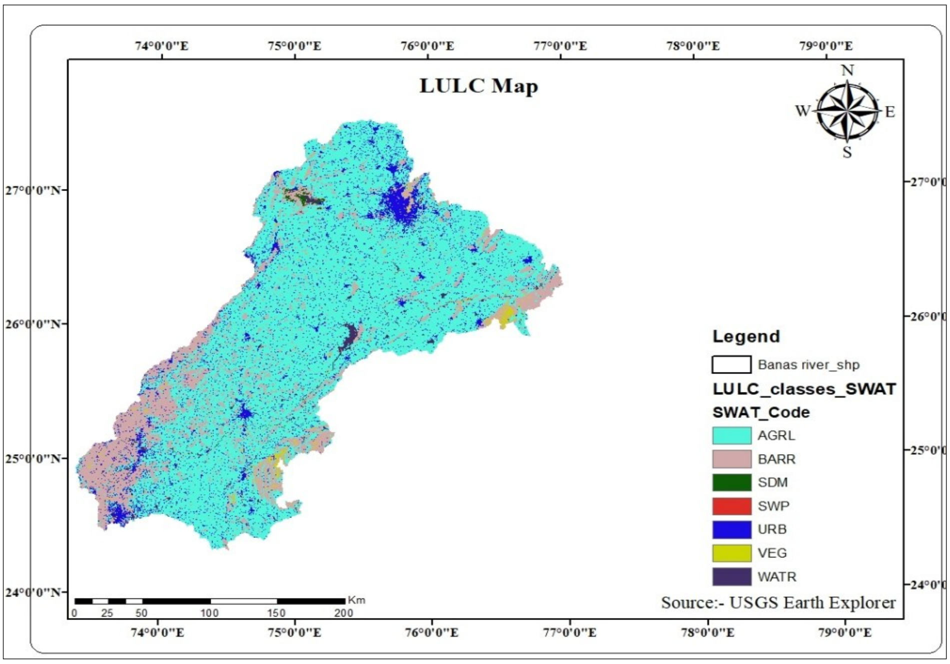

Fig. 2. Land use/land cover map of the Banas River Basin 2024.

Table 2. Soil and Water Assessment Tool-compatible land use/land cover classification for Banas River Basin

S. No.	Land Use	SWAT Code
1	Forest-mixed	FRST
2	Agriculture	AGRL
3	Wetlands-forested	WETF
4	Barren	BARR
5	Urban	URBN
6	Range-grasses	RNGE
7	Pasture	PAST
8	Mines	SWRN
9	Water bodies	WATR
10	Wetland-non-forest	WETN

(URLD) with around 3200 km^2 (7 %) and pastureland (PAST) with approximately 6000 km^2 (13 %). The remaining area comprises scrublands, water bodies and barren lands.

Soil map

The FAO Digital Soil Map was imported and converted into raster format for compatibility with SWAT for the year 2024. The soil classes were reclassified into SWAT-readable codes as per soil texture and group. The spatial distribution of soil classes in the Banas River Basin is shown in Fig. 3 and the reclassified soil groups used in the SWAT model are summarised in Table 3.

Among the classified soils, silt loam dominated the basin with an area of approximately 18200 km^2, while loam soils covered 11500 km^2.

Slope map

Slope is a vital topographic factor that governs surface runoff and erosion. The slope map was generated from the DEM and categorised into 5 slope classes using SWAT's default classification system. The slope map of the Banas River Basin is shown in Fig. 4 and the slope classes used in the analysis are presented in Table 4.

Table 3. Soil and Water Assessment Tool-compatible soil classification

Sl. No.	Soil type	SWAT code
1	Silt Loam	Xh12-2a-6673
2	Loam	I-Be-Lc-b-3716
3	Loam	Be74-2a-3674

The gentle slope (0–10 %) category covered the largest portion of the basin, with approximately 7790 sq km, while the moderately steep (30–40 %) slope class occupied the smallest area of about 0.9 sq km.

Hydrological response units generation and spatial distribution

After processing and reclassification of LULC, soil and slope layers, the HRUs were generated by applying thresholds of 20 % for LULC,10 % for soil and 10 % (The thresholds of 20 % for LULC and 10 % for soil and slope were selected to retain dominant hydrological characteristics of the basin while avoiding excessive HRU fragmentation and unnecessary computational complexity, as commonly practiced in SWAT-based watershed studies.) for slope, which helps reduce redundancy and computational load. The HRU map of the Banas River Basin is shown in Fig. 5.

The total number of HRUs generated was 580 and 33 sub-basins, which reflects the spatial heterogeneity of the basin and serves as the foundation for accurate simulation of hydrological processes.

The HRU analysis allows for targeted identification of areas vulnerable to runoff, soil erosion, or needing intervention. It plays a key role in designing conservation strategies and assessing the impacts of land management scenarios on the basin's hydrological response.

The HRU analysis of the Banas River Basin highlights the significant influence of land use, soil type and topography on basin-scale hydrological behaviour. The generation of 580 HRUs across 33 sub-basins reflects the spatial heterogeneity of the basin and demonstrates the suitability of the SWAT framework for semi-arid river basins.

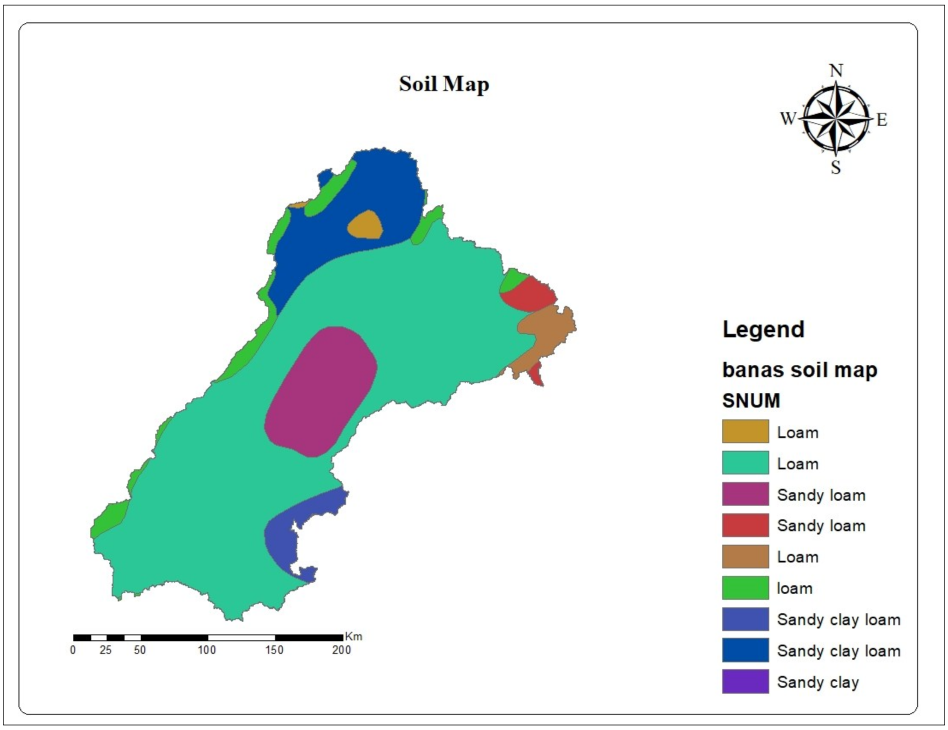

Fig. 3. Soil map of the Banas River Basin.

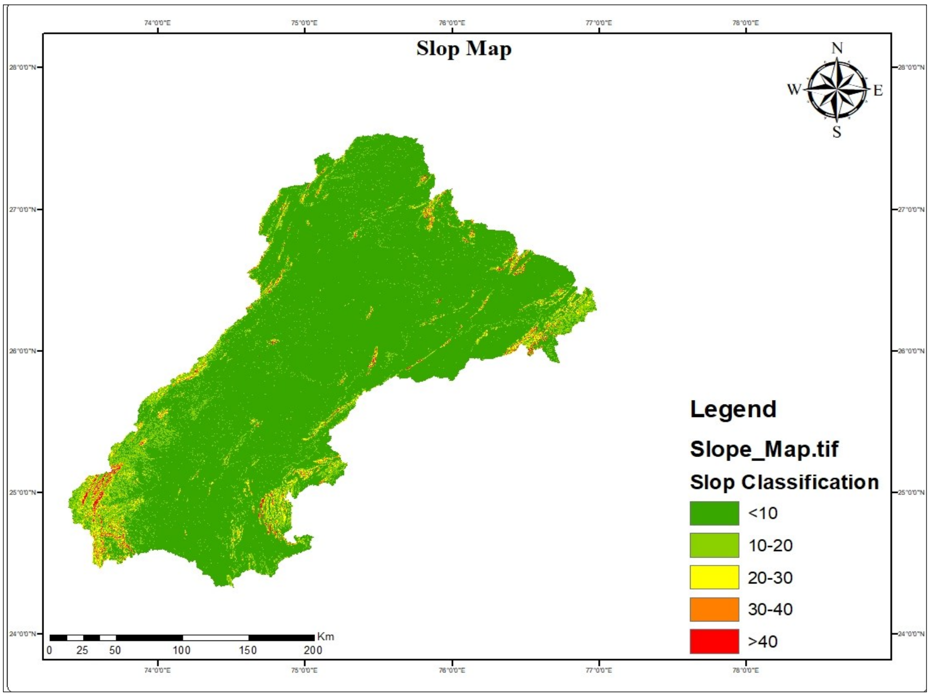

Fig. 4. Slope map of the Banas River Basin.

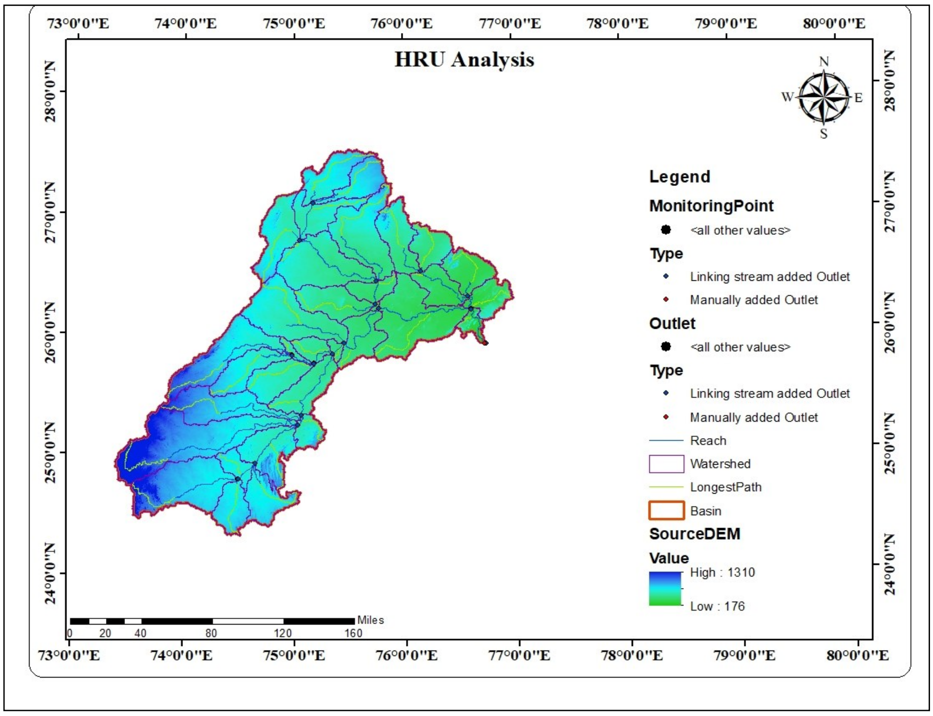

Fig. 5. Hydrological Response Unit map of the Banas River Basin.

Table 4. Slope classification

Sl. No.	Slope (%)	Category
1	0 – 10 %	Gentle
2	10 – 20 %	Moderately gentle
3	20 – 30 %	Steep
4	30 – 40 %	Moderately steep
5	> 40 %	Very steep

Influence of land use/land cover on hydrological response

The dominance of agricultural land (≈ 55 %) across the basin has important hydrological implications. Agricultural areas, particularly in semi-arid regions, are often associated with increased surface runoff and sediment yield due to periodic soil disturbance, reduced vegetative cover during fallow periods and irrigation-induced soil compaction. Similar findings have been reported by previous researchers, who observed that agricultural dominance significantly alters runoff generation and sediment transport in SWAT-simulated basins (2, 4). In the Banas River Basin, the extensive agricultural coverage suggests that hydrological responses are likely to be highly sensitive to land management practices, emphasising the importance of HRU-based modelling for identifying priority areas for soil and water conservation.

Role of soil characteristics in runoff and infiltration

The prevalence of silt loam soils across large parts of the basin plays a key role in governing infiltration and runoff processes. Silt loam soils generally exhibit moderate infiltration capacity and water-holding potential; however, under intense monsoonal rainfall, these soils can become susceptible to surface sealing and erosion. Previous SWAT-based studies have demonstrated that very low thresholds significantly increase the number of HRUs without proportionate improvement in hydrological accuracy, whereas higher thresholds may oversimplify watershed heterogeneity (4, 8). Previous studies using SWAT have highlighted that basins dominated by silt loam soils tend to show moderate runoff coefficients but elevated erosion risk under improper land management (9, 6). In the context of the Banas River Basin, the interaction between silt loam soils and intensive agricultural land use, increases the likelihood of localised erosion hotspots, which can be effectively captured through HRU-level analysis.

Effect of slope on hydrological processes

Slope is a critical topographic factor controlling runoff velocity and erosion potential. The dominance of gentle slopes (0–10 %) across the basin indicates relatively lower runoff velocities and higher opportunities for infiltration under natural conditions. Similar slope-dominated hydrological behaviour has been reported in other semi-arid Indian basins, where gentle slopes contribute to groundwater recharge while still generating surface runoff during high-intensity rainfall events (7). However, when gentle slopes coincide with agricultural land and silt loam soils, the hydrological response becomes strongly dependent on rainfall intensity and land management practices, reinforcing the need for spatially explicit HRU-based assessment.

Justification of HRU threshold selection

The application of threshold values of 20 % for land use, 10 % for soil and 10 % for slope was aimed at reducing excessive HRU fragmentation while preserving dominant physiographic characteristics of the basin. The selected thresholds in this study resulted in an optimal number of HRUs (580), ensuring computational efficiency while maintaining meaningful representation of land–soil–slope interactions, which is essential for subsequent hydrological simulations.

Implications for watershed management and future modelling

The HRU framework developed in this study provides a scientifically robust basis for simulating hydrological processes such as runoff generation, sediment transport and water balance at sub-basin and HRU levels. Comparable studies have shown that accurate HRU delineation significantly improves the reliability of SWAT-based scenario analysis, including land-use change and climate variability assessments (9, 10). The spatial discretisation of HRU allows the model to capture heterogeneity in watershed characteristics and improves the accuracy of hydrological simulations (11). For the Banas River Basin, the present HRU configuration can support targeted soil and water conservation planning, identification of erosion-prone zones and evaluation of sustainable land management practices, particularly in agriculturally dominated regions.

Beyond supporting soil and water conservation planning, the results of this study have direct practical relevance for farmers, planners and water management stakeholders. For farmers, the HRU-based spatial framework can assist in identifying suitable areas for crop planning, irrigation scheduling and adoption of site-specific land management practices, thereby improving water-use efficiency and reducing production risks under variable rainfall conditions. The information on land–soil–slope interaction can also guide the selection of crops and conservation practices tailored to local field conditions.

For watershed managers and policymakers, the delineated sub-basins and HRUs provide a scientific basis for prioritising watershed interventions, planning irrigation infrastructure and optimising allocation of water resources. The results can support decision-making related to groundwater recharge enhancement, drought mitigation and sustainable agricultural development in the basin. Additionally, the spatial database developed through this study can serve as a baseline for evaluating the impacts of future land-use change, agricultural intensification and climate variability.

The HRU configuration established in this research forms a robust foundation for future hydrological simulations, including runoff, sediment yield and water balance assessments using SWAT. Although the study is limited by the resolution of available soil data and the absence of hydrological calibration, these limitations can be addressed in future research using high-resolution datasets and long-term observed hydro-meteorological data. Overall, the study contributes valuable spatial insights that support integrated river basin management, climate-resilient agriculture and sustainable water resource planning in the Banas River Basin.

Conclusion

The present study successfully delineated the Banas River Basin into 33 sub-basins and 580 HRUs using the SWAT model by integrating topography, land use/land cover, soil and slope datasets. The dominance of agricultural land (approximately 55 %), widespread silt loam soils and the prevalence of gentle slopes (0–10 %) indicate moderate runoff potential with spatially variable erosion risk across the basin. These findings highlight the importance of spatially explicit watershed characterisation in semi-arid river basins.

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Authors' contributions

AK conceived and designed the study, carried out watershed delineation, HRU analysis and the preparation of LULC, soil and slope maps and drafted the manuscript. RC assisted with statistical analysis and interpretation of the results, supervised the study, critically reviewed the manuscript for intellectual content and approved the final version. Both authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process: The authors declare that Artificial Intelligence (AI) tools were utilised only for language editing and grammar improvement during manuscript preparation. No AI tools were used for data analysis, interpretation of results, scientific originality, or drawing conclusions. The tools used include OpenAI for language refinement and formatting.

All research ideas, methodology, results and conclusions are original and generated by the authors. The authors take full responsibility for the integrity and accuracy of the content presented in this manuscript.

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