RESEARCH ARTICLE

Erosion Risk Assessment for Prioritization of Soil and Water Conservation Measures in the Semi-Arid Region: A Remote Sensing and GIS-Based Approach

Ashish Koradia[1] · **Jayantilal N. Patel**[2]

Abstract

Erosion risk assessment is essential for implementing effective soil and water conservation (SWC) measures, presenting complex challenges, especially in data-scarce semi-arid regions of India. This study addresses these challenges by applying a comprehensive approach to prioritize intervention areas, thus enhancing erosion management efficiency in the Devgadh Baria Watershed (DBW) in Gujarat, India. The primary objective is to systematically prioritize sub-watersheds (SWs) through geomorphometric and LULC analyses and propose appropriate SWC measures for high-priority areas. Utilizing remote sensing (RS) and geographical information systems (GIS) techniques, the study delineates SWs and assesses their vulnerability using seven distinct morphometric parameters and LULC classes, including agricultural land, forest, wasteland, and built-up areas. The combined analysis integrates these parameters to produce compound values for all 30 SWs, resulting in a refined priority ranking. SW26, initially very high priority in morphometric analysis due to steep slopes and minimal drainage density, shifted to medium priority in the combined analysis, reflecting effective agricultural management practices that reduce erosion. Conversely, SW7 remained a very high priority across both analyses, indicating consistent high erosion risk due to a significant built-up area and limited forest cover. SW30 shifted from high to medium priority, influenced by balanced agricultural activities and lower slopes. SWs 6 and 24 transitioned from very high to medium priority, while SW22 remained high, supported by moderate forest cover and beneficial soil types mitigating erosion. This research underscores the scientific importance of integrating morphometric and LULC analyses for precise SW prioritization. The combined approach enhances erosion risk assessments and supports targeted SWC strategies, crucial for effective watershed management in semi-arid regions. The findings provide actionable insights that align with global sustainability goals, contributing to improved soil conservation and water resource management.

Keywords Watershed prioritization · Geomorphometry · LULC · RS and GIS · SWC

Introduction

India supports 18% of the world's population on 2.42% of the global land area with only 4% of the world's freshwater. However, the demand for land and water resources has dramatically increased because of rapid industrialization and population growth (Sabale et al., 2023). This directly impacts the country's efforts to achieve SDGs, especially those dealing with food and water security (SDG 6: Clean Water and Sanitation and SDG 2: Zero Hunger). Soil erosion and land degradation are among the most serious issues. Beyond just causing topsoil loss, soil erosion has a major negative impact on soil fertility and water-holding capacity, which ultimately affects agricultural productivity

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(Abiye, 2022). It impacts roughly 175 million hectares or 53% of India's total land area (Raj et al., 2023). Deforestation, human activity, and natural cycles are the leading causes of this degradation and a major factor in India's unstable food and water security (Wassie, 2020). Water erosion threatens about 113.3 million hectares in India, resulting in an approximate annual loss of 5334 metric tons of soil (Kumar & Sahu, 2020).

In addition to that, in India, 194.4 million people suffer from malnutrition, and 15.2% of the country's population is undernourished. It is evident how urgent it is to address these land and water management concerns for water and food security (WHO, 2019). Also, climate change worsens these problems by increasing the frequency and severity of weather events like storms, droughts, and heavy rainfall, which increase soil degradation for a particular region. Water scarcity is another critical consequence, impacting ecosystem health and agricultural productivity. In India, sustainable development relies on managing water effectively due to its frequent scarcity and unequal distribution. The National Institution for Transforming India (NITI) Aayog report estimates that 600 million Indians experience high to extreme water stress and that this causes nearly 200,000 deaths annually as a result of insufficient access to clean water (NITI Aayog, 2019). Moreover, 37.6% of India's geographical area is semi-arid. About one-third of India's geographical area is affected by droughts, including 39% of cultivable land and 29% of the population (RS, 2007). The semi-arid regions are the most vulnerable regions in India due to low and erratic rainfall, extreme temperatures, and intense solar radiation. These regions have low groundwater tables, low rainfall, and high water runoff, which leads to lower water and food security. Therefore, it is important to address the semi-arid region of India to increase water availability by setting watersheds as the top conservation priority for the preservation and sustainable production of natural resources. Achieving the SDGs for food and water security depends on a watershed-level strategy. Which is essential for sustainable land and water management (Eekhout et al., 2018; Ofori et al., 2021).

The accurate assessment of a watershed's hydrological behaviour is crucial for developing effective management plans. However, the main problem with semi-arid regions is that most of the basins are either ungauged or sufficient data are not available for hydrological modelling (Shekar & Mathew, 2023). This situation poses challenges for water-related studies in semi-arid regions. Various approaches to watershed prioritization have been developed, ranging from simple analytical models to process-oriented, physical-based models. Both analytical and process-oriented models are information-driven and nuanced, making them challenging (Shekar et al., 2023). To overcome these challenges, many researchers have adopted the geomorphometric approach for watershed prioritization (Singh et al., 2021; Sarkar et al., 2022; Khan & ElKashout, 2023). This approach requires less data and is more effective in determining suitable SWC measures (Sutradhar & Mondal, 2023). Results from watershed morphometric analysis can serve as a strategic tool in water management, soil erosion sustainability, and watershed prioritization (Khanday & Javed, 2016; Malik et al., 2019; Dali et al., 2023).

While SWC are key focuses in watershed management, addressing the entire area simultaneously is impractical. However, it is very difficult to identify erosion-prone patches under the whole watershed. Therefore, the basin is divided into smaller units, such as sub-watersheds (SWs) or micro-watersheds, based on the drainage system (Meshram & Sharma, 2017; Suthar et al., 2022). Quantitative morphometric analysis of SWs is a valuable tool, providing insights into the hydrological nature of the exposed rocks within the watershed. This process involves evaluating morphometric parameters and prioritizing them based on their relationship with soil erosion to identify the areas that are most at risk. Implementing soil conservation measures in these prioritized watersheds can reduce soil erosion and increase the availability of water resources, directly contributing to food and water security (Farhan et al., 2016). Most researchers have studied the morphometric parameters of watersheds using RS and GIS approaches (Mishra et al., 2018; Kadam et al., 2019; Pande et al., 2021; Salunke & Wayal, 2023). However, very few studies have considered land use land cover (LULC), soil, and slope data to propose SWC measures, particularly for the semi-arid region of India (Aher et al., 2014; Makwana & Tiwari, 2016; Halder et al., 2021).

Therefore, this study focuses on the data-scarce, drought-vulnerable, and erosion-prone semi-arid region of India, where the development of RS and GIS technologies has revolutionized morphometric and LULC analysis, watershed prioritization and proposing the SWC measures. This research aims to help efficiently allocate resources to support climate change mitigation, improve water availability, reduce soil erosion, promote sustainable land management, and preserve ecosystems by prioritizing SWs and proposing the SWC measures area based on LULC, soil and Slope data for high priority areas. The results will provide decision-makers and stakeholders with insightful information on managing watersheds, safeguarding natural resources, fostering long-term sustainability and addressing critical aspects of water and food security, particularly in the semi-arid regions of India.

Methodology

Study Area

This study is focused on the Devgadh Baria, a semi-arid agricultural watershed, which is situated in the Dahod district of eastern Gujarat, India (Fig. 1). The area of this watershed is 794.97 km^2 and further classified into 30 different SWs (Fig. 2). The study area has minimum and maximum elevations above mean sea level of 150 and 671 m, respectively. Water availability and conservation are major and pressing concerns in the region due to its semi-arid location and mix of forest and agricultural land with significant altitude variations. The majority of farmers in this watershed are classified as marginal or small farmers due to the average land holding being less than 2 ha (Behera, 2015). This semi-arid watershed, which receives 785 mm of rain on average. The different variety of crops, including castor, cotton, sugarcane, potato, rapeseed, mustard, pigeon pea, sorghum, groundnut, ragi, soybean, and pearl millets are cultivated in this watershed. During field visits, it was observed that this watershed has poor soil and water harvesting conditions, which suggests a significant opportunity to improve water availability for agriculture (see field visit photographs, Fig. S1). Enhancing these conditions could greatly boost the watershed's agricultural potential. Additionally, Makwana and Tiwari (2016) highlighted that watersheds in semi-arid regions often face similar issues, indicating a considerable potential for improving water availability for agriculture. Addressing these challenges could substantially increase the watershed's agricultural productivity.

Pre-Processing of Data Set

This study conducts a detailed analysis of the Devgadh Baria Watershed (DBW), focusing on key parameters such as soil type, land use, and slope, which play crucial roles in watershed prioritization and proposing effective soil and water conservation (SWC) measures. The slope map was prepared from the Shuttle Radar Topography Mission (SRTM) DEM data of 30 m resolution using ArcMap software. The slope analysis revealed a wide range of slope variations within the watershed, ranging from 0 to 98%, with a significant area (over 70%) of the watershed having slopes between 0 and 15% (Fig. 2). This information will help to identify areas prone to erosion and inform the selection of appropriate conservation measures based on the slope intensity.

The soil map of the study area was extracted from the India soil map prepared by the National Bureau of Soil Survey and Land Use Planning NBSS-LUP, Nagpur. The study found that clayey soil comprises the majority (52.95%), followed closely by loam soil (47.05%) (Fig. 2). This distribution is significant as different soil types have varying water retention and infiltration capacities, directly impacting the
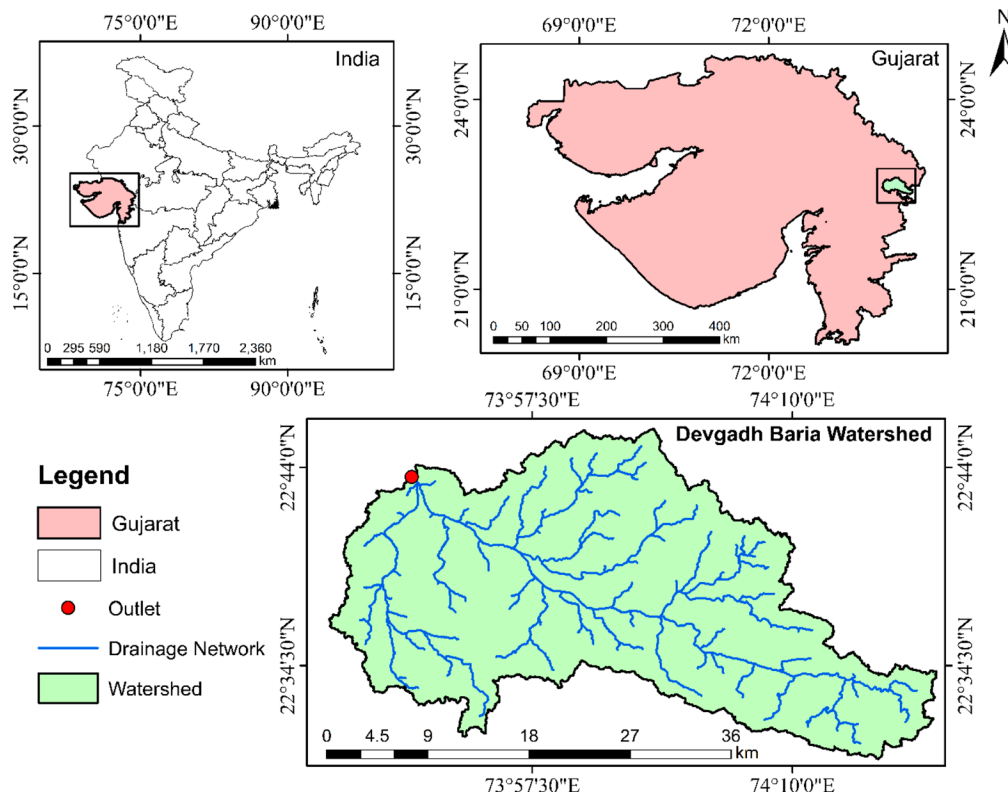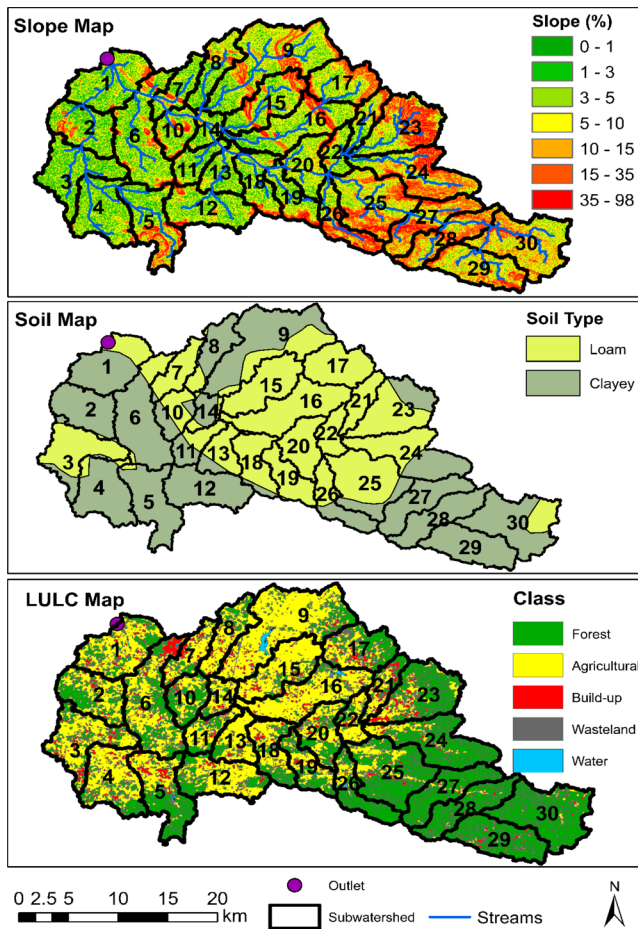

Fig. 1 The study area map of the Devgadh Baria watershed

Fig. 2 Slope, soil and LULC map of the study area

Table 1 Different geomorphometric parameters of watershed

Aspects	Morphometric parameter	Formula	Reference
Linear aspects	Stream order (N_u)	Hierarchical rank	Strahler (1952)
	Total Stream length (L_u)	Length of the stream	Horton (1945)
	Mean stream length (L_{sm}).	$L_{sm}=L_u/N_u$	Horton (1945).
	Length of overland flow (L_g)	$L_g=1/2D_d$	Horton (1945)
Aerial aspects	Drainage density (D_d)	$D_d=L_u/A$	Horton (1932)
	Stream frequency (F_s)	$F_s=N/A$	Horton (1945)
	Circulatory ratio (R_c)	$R_c=4\pi A/P^2$	Miller (1953)
	Elongation ratio (R_e)	$R_e=(2/L_b)\times(A/\pi)^{0.5}$	Schumm (1956)
	Form factor (R_f)	$R_f=A/(L_b)^2$	Horton (1932)
	Watershed shape factor (W_s)	$W_s=L_{sm}/D_c$	Wu et al. (1964)
	Compactness coefficient (C_c)	$C_c=0.2821\times P/A^{0.5}$	Strahler (1964)
	Unity shape factor (R_u)	$R_u = L_b/A^{0.5}$	Horton (1945)
Relief aspects	Total relief (H)	$H = h_2-h_1$	Hadley and Schumm (1961)
	Relief ratio (R_h)	$R_h = H/L_b$	Schumm (1956)
	Relative relief (R_{hp})	$R_{hp} = H/P$	Melton (1957)

watershed's hydrological characteristics. Understanding the soil composition will allow for tailoring conservation strategies that address specific soil vulnerabilities and enhance overall soil health and productivity. The Land Use and Land Cover (LULC) map of the study area was extracted from Sentinel-2 data with a 10 m resolution for the year 2022 using the Google Earth Engine (GEE) platform (Karra et al., 2021). The data source can be accessed at GOOGLE_DYNAMICWORLD_V1. The watershed is predominantly covered by agricultural (46.40%) and forest (46.69%) areas (Fig. 2). This distribution highlights the importance of sustainable land management practices to preserve soil fertility, prevent erosion, and maintain biodiversity. By integrating land use data into the analysis, areas where conservation efforts can have the greatest impact on preserving soil and water resources can be identified.

Prioritization of Sub-Watershed for SWC Measures

This study used the Geospatial Hydrologic Modeling Extension (HEC-GeoHMS) toolkit in the ArcMap software to extract morphometric parameters from DEM. Further,

morphometric analysis was performed on measured parameters and classified into three aspects: linear, aerial, and relief. The details of morphometric parameters and their formula are shown in Table 1. After estimating the geomorphometric parameters, this study employed a procedure suggested by Kandpal et al. (2017) to prioritize the SWs. Subsequently, rankings were assigned to guide future SWC interventions.

For prioritization of the sub-watershed (SW), the DBW is divided into 30 SWs. This study focused on seven morphometric parameters for the prioritization of watersheds due to their significant impact on erosion processes in semi-arid regions. As Makwana and Tiwari (2016) suggested, these parameters include elongation ratio, compactness coefficient, drainage density, form factor, circularity ratio, length of overland flow, and unity shape factor. Linear parameters such as drainage density and length of overland flow directly relate to erodibility; higher values indicate higher erodibility. On the other hand, shape parameters like elongation ratio, compactness coefficient, circularity ratio, unity shape factor, and form factor have an inverse relationship with erodibility; lower values of these parameters indicate higher

erodibility (Makwana & Tiwari, 2016). By concentrating on these specific parameters, this study will develop a more targeted and efficient prioritization approach for watershed management in the DBW. Further, the prioritization ranking process involves the evaluation of each individual parameter. The ranking values for both the linear and shape parameters of the aerial aspect of each SW are cumulatively aggregated across all 30 SWs, yielding a compound parameter value. Based on the average value of compound parameters, the SW with a lower value of compound parameters was prioritized first, the next higher value was assigned as a second priority, and so on. The LULC data prioritised SWs based on agricultural land, forest, wasteland, and built-up area. Details of the priority classes according to different compound parameter values for morphometric and LULC analysis are provided in Table S1. Following separate prioritizations through morphometric and LULC analyses, a combined compound parameter was calculated, and the integrated priority rank and class were determined. Additionally, LULC, soil, and slope data were used to propose SWC measures. The detailed methodology of this study is illustrated in Fig. 3.

Results and Discussion

Prioritization of Sub Watersheds Using Morphometric Analysis

For the prioritization of the sub-watersheds (SWs), the DBW is divided into 30 SWs, and their morphometric parameter values are shown in Table S2. This study focused on seven morphometric parameters for the prioritization of watersheds due to their significant impact on erosion processes in semi-arid regions. Prioritization ranking is shown in Table 2. SW number 26, with a compound parameter value of 7.286, receives the highest priority (one), indicating the need for initiating water conservation work in this watershed. Conversely, SW number 4 holds the least priority (thirty) with a compound parameter value of 23. Furthermore, the SWs were reclassified into five priority classes: very high, high, medium, low, and very low, based on their compound parameter ranks (Fig. 4). This classification is beneficial as it provides a systematic approach to prioritize conservation efforts, enabling targeted interventions in areas with the highest need first. By focusing on high-priority
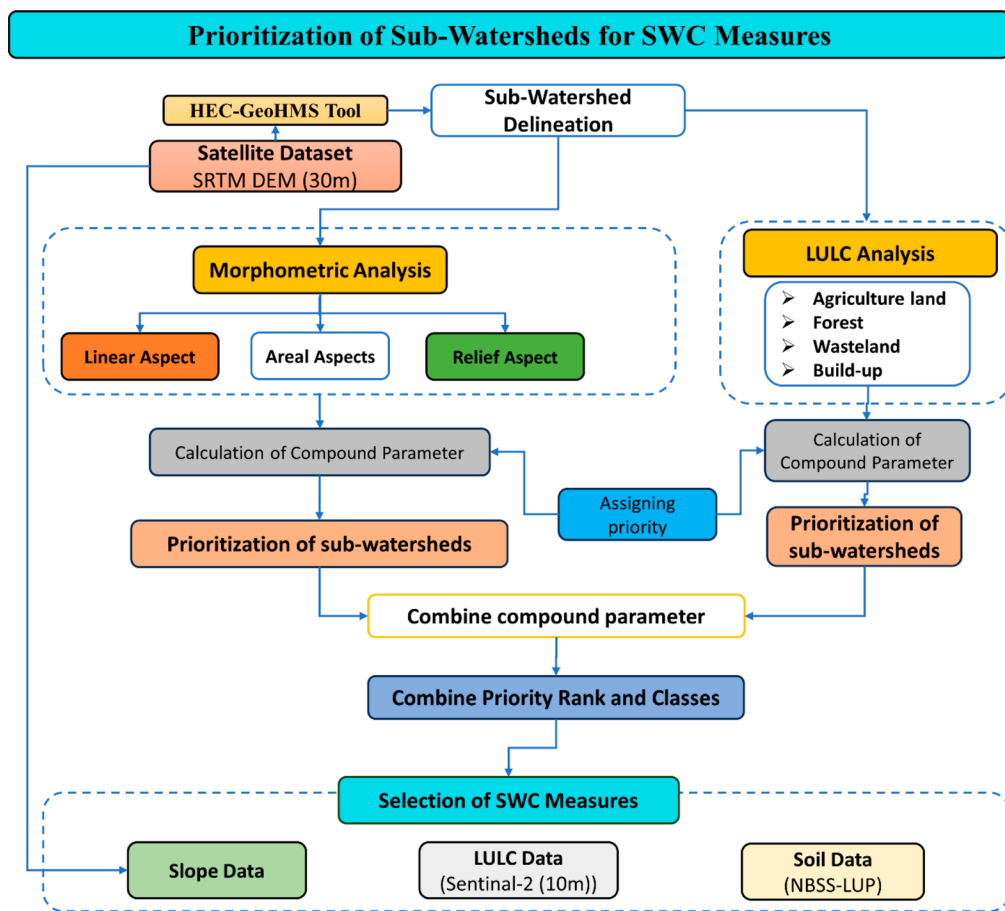

Fig. 3 The methodology for watershed prioritization for SWC measures

**Table 2** The sub-watershed priority calculation under morphometric analysis

SW No.	Individual priority rank							Compound parameters	Priority rank	Priority class
	R_e	C_c	D_d	R_f	R_c	L_g	R_u			
26	7	5	10	7	1	16	5	7.28	1	Very High
6	5	14	8	5	16	9	3	8.57	2	Very High
7	8	2	1	8	8	11	22	8.57	3	Very High
14	4	4	5	4	13	22	14	9.42	4	Very High
24	10	8	11	10	2	1	26	9.71	5	Very High
22	18	7	2	18	22	7	1	10.71	6	High
25	3	16	9	3	14	8	23	10.85	7	High
8	13	12	19	13	9	3	10	11.28	8	High
30	12	3	12	12	10	14	16	11.28	9	High
1	16	10	14	16	3	12	12	11.85	10	High
15	1	15	25	1	21	30	2	13.57	11	Medium
5	26	1	16	26	5	10	17	14.42	12	Medium
23	27	9	3	27	12	19	6	14.71	13	Medium
20	2	27	20	2	20	28	8	15.28	14	Medium
9	23	22	7	23	7	2	27	15.85	15	Medium
10	6	11	24	6	24	23	18	16.00	16	Low
17	19	13	22	19	4	5	30	16.00	17	Low
3	9	25	26	9	6	27	11	16.14	18	Low
12	14	23	4	14	19	15	28	16.71	19	Low
19	30	19	15	30	23	4	4	17.85	20	Low
28	17	6	27	17	25	26	9	18.14	21	Low
13	21	18	21	21	30	6	21	19.71	22	Low
21	22	24	23	22	11	24	15	20.14	23	Very Low
11	15	20	28	15	27	20	19	20.57	24	Very Low
18	28	30	6	28	18	21	13	20.57	25	Very Low
2	24	17	13	24	26	17	29	21.42	26	Very Low
27	11	28	29	11	29	18	24	21.42	27	Very Low
16	20	21	30	20	15	25	20	21.57	28	Very Low
29	29	26	17	29	17	13	25	22.28	29	Very Low
4	25	29	18	25	28	29	7	23.00	30	Very Low

SWs, resources can be utilized more efficiently, improving SWC outcomes in the DBW.

Prioritization of Sub Watersheds Using LULC Analysis

Land use encompasses how humans and their ecosystems utilize land, emphasizing its central role in economic activities. In contrast, land cover describes the physical attributes of the Earth's surface, including man-made structures, natural vegetation, soils, rocks, water bodies, and other features resulting from land transformation. The prioritization of SWs relies on data from Sentinel-2 imagery, with a resolution of 10 m for LULC. Key LULC categories, such as agricultural land, forests, wastelands, and built-up areas, were evaluated to rank SWs (Table 3). Built-up areas received the highest rank when their extent was maximal. Conversely, the lowest rank for built-up areas was assigned to those with minimal extents, while agricultural land, forests, and wastelands followed an ascending rank order based on minimal

extent. SWs were then grouped into five priority levels like very high, high, medium, low, and very low, based on their Compound Parameter (Cp) values. Table 3 illustrates the prioritization of SWs in the DBW using LULC analysis. The SW7 emerged as the highest priority due to its substantial built-up area (2.29 km²) and minimal wasteland and forest cover, which significantly increase erosion risks through enhanced runoff and soil disturbance. Conversely, SW1, with extensive agricultural land (21.09 km²) and notable forest cover (9.48 km²), was ranked lower in priority as these factors contribute to soil stabilization and reduced erosion potential. Sub-watersheds SW6 and SW24, despite having significant built-up areas, were also classified as lower priority due to their extensive forest cover (17.29 km² and 29.66 km², respectively), which effectively mitigates erosion. SW21 and SW22 saw increased prioritization due to their limited forest cover and relatively high built-up areas, which exacerbate erosion risks. The SWs prioritization map using LULC analysis is presented in Fig. 5. Overall, the LULC analysis highlights how built-up areas

Fig. 4 Sub-watershed prioritization using morphometric analysis

Sub-Watershed Prioritization Map under the Morphometric Analysis

Priority Class
- Very Low
- Low
- Medium
- High
- Very High
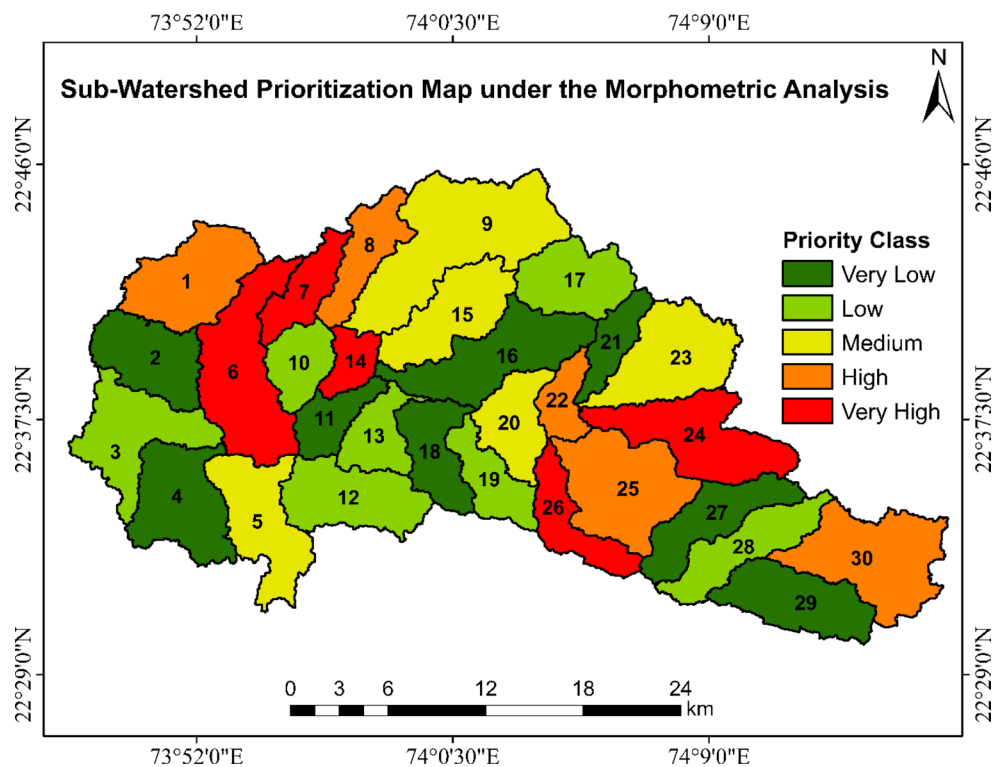
and limited forest cover elevate erosion risks, while well-managed agricultural lands and substantial forest cover reduce these risks, influencing the prioritization of SWs for SWC measures.

Prioritization of Sub Watersheds Using Combine Morphometric and LULC Analysis

To identify SWs that are consistently prioritized across different analyses, a comparison was made between the outcomes of morphometric analysis and LULC analysis. This comparative approach revealed that both methods highlighted the same four SWs as common priorities: SW7 for very high priority, SW22 for high priority, SW20 for medium priority, and SW12 for low priority (Table 4). The combined analysis of morphometric and LULC data, supplemented by an understanding of soil types, revealed nuanced changes in the prioritization of SWs. In particular, the presence of extensive agricultural land and its interaction with soil types significantly influenced erosion potential and priority classifications. The SWs prioritization map using LULC analysis is presented in Fig. 6. Sub-watersheds with substantial agricultural areas, such as SW1 (21.09 km²) and SW9 (47.66 km²), generally experienced a reduction in priority when considering both morphometric and LULC factors. This decrease reflects the effective land management practices associated with large-scale agriculture, such as terracing, contour plowing, and cover cropping, which reduce erosion by stabilizing soil and enhancing water

infiltration. SW1, which was initially high priority based on morphometric parameters alone, was reclassified to medium priority in the combined analysis due to the mitigating effects of its agricultural management practices and forest cover (9.48 km²) (Fig. 6). Similarly, SW9 maintained its low priority in the combined analysis, despite its extensive agricultural land, because these practices effectively reduce runoff and soil loss.

The influence of soil types provided further insights into these changes. SW16, with significant loamy soil (36.70 km²), exhibited low erosion potential, which is consistent with loamy soils' high infiltration capacity and balanced texture that support agricultural activities and reduce surface runoff. Consequently, SW16's prioritization decreased, reflecting the lower erosion risk associated with well-managed agricultural areas on loamy soils. Conversely, SW24, with substantial clayey soils (16.20 km²) and forest cover (29.66 km²), showed a reclassification from medium to low priority (Table 4). Clayey soils, typically more prone to surface runoff due to their low permeability, have their erosion risks effectively mitigated by extensive forest cover, stabilising the soil and reducing erosion. The integrated analysis recognized the protective role of forest cover, resulting in a lower priority classification for SW24. SW7, with smaller agricultural (9.85 km²) and forest areas (3.18 km²) but higher clayey soil content (0.99 km²), shifted from medium to high priority. This reclassification underscores the limited erosion control provided by minimal forest cover and the increased erosion risks posed by clayey

Table 3 Sub-watershed prioritization using LULC analysis

SW No.	LULC ((Area in km^2) and rank)				Compound parameters	Priority rank	Priority class
	Agricultural land	Wasteland	Build-up	Forest			
1	(21.09) 26	(0.58) 28	(2.15) 10	(9.48) 16	20.00	30	Low
2	(13.72) 22	(0.04) 10	(1.25) 16	(10.90) 19	16.75	19	Low
3	(20.78) 25	(0.07) 16	(3.24) 3	(8.09) 15	14.75	11	Medium
4	(20.24) 24	(0.04) 11	(2.14) 11	(9.49) 17	15.75	14	Medium
5	(11.20) 18	(0.14) 23	(2.30) 7	(17.15) 22	17.5	23	Low
6	(21.62) 27	(0.22) 26	(4.37) 1	(17.29) 23	19.25	28	Low
7	(9.85) 15	(0.00) 1	(2.29) 8	(3.18) 4	7	1	Very High
8	(13.52) 21	(0.08) 19	(1.47) 12	(3.87) 6	14.5	9	Medium
9	(47.66) 30	(0.92) 29	(3.02) 4	(7.52) 12	18.75	26	Low
10	(7.00) 9	(0.10) 20	(0.59) 26	(8.06) 14	17.25	22	Low
11	(7.66) 11	(0.03) 7	(0.81) 23	(4.67) 9	12.5	4	Medium
12	(18.41) 23	(0.03) 8	(1.17) 18	(10.04) 18	16.75	20	Low
13	(12.22) 20	(0.03) 9	(0.65) 25	(2.66) 3	14.25	8	Medium
14	(6.96) 8	(0.11) 22	(0.76) 24	(1.92) 1	13.75	6	Medium
15	(23.26) 28	(0.17) 24	(1.45) 13	(3.54) 5	17.5	24	Low
16	(29.29) 29	(0.19) 25	(2.66) 5	(4.12) 7	16.5	18	Low
17	(9.91) 16	(1.16) 30	(2.29) 9	(11.52) 20	18.75	27	Low
18	(11.38) 19	(0.06) 13	(1.06) 19	(7.32) 10	15.25	13	Medium
19	(8.03) 13	(0.07) 17	(0.96) 21	(7.81) 13	16	16	Medium
20	(10.84) 17	(0.07) 18	(1.18) 17	(7.51) 11	15.75	15	Medium
21	(5.64) 6	(0.06) 14	(2.47) 6	(4.38) 8	8.5	2	Very High
22	(7.50) 10	(0.04) 12	(0.88) 22	(2.59) 2	11.5	3	High
23	(8.85) 14	(0.23) 27	(3.55) 2	(22.20) 24	16.75	21	Low
24	(5.77) 7	(0.01) 5	(1.41) 14	(29.66) 28	13.5	5	Medium
25	(8.01) 12	(0.06) 15	(1.31) 15	(30.86) 29	17.75	25	Low
26	(3.58) 5	(0.10) 21	(0.25) 30	(14.32) 21	19.25	29	Low
27	(1.20) 3	(0.00) 2	(0.32) 28	(22.84) 25	14.5	10	Medium
28	(0.81) 1	(0.00) 3	(0.28) 29	(23.04) 26	14.75	12	Medium
29	(0.90) 2	(0.01) 6	(1.03) 20	(26.27) 27	13.75	7	Medium
30	(1.90) 4	(0.00) 4	(0.58) 27	(38.81) 30	16.25	17	Low

soils and less extensive agricultural management. Similarly, SW12, which combined substantial agricultural land (18.41 km²) with clayey soils (29.65 km²), was classified as a higher priority in the combined analysis due to the compounding effects of clayey soils on erosion dynamics despite agricultural practices. The combined analysis effectively integrated morphometric, LULC, and soil characteristics to refine sub-watershed prioritization. Large agricultural areas, typically associated with effective land management practices, generally resulted in lower erosion risks and reduced priority classifications. However, the interplay between land use and soil types, particularly the mitigating effects of loamy soils and forest cover versus the challenges posed by clayey soils, played a critical role in determining the final priority rankings. This comprehensive approach emphasizes the importance of tailored SWC strategies that reflect the specific conditions of each sub-watershed for effective and sustainable watershed management.

Selection of Soil and Water Conservation Measures

The prioritization SWs into very high, high, medium, and low priority classes, based on combined morphometric and LULC analyses, informs tailored SWC measures. This prioritization is further refined by considering specific soil characteristics, essential for designing effective erosion control strategies. Detailed LULC and soil data are presented in Table S3, guiding the proposed measures.

The SW7, classified as a very high priority, has significant built-up areas, minimal forest cover, and clayey soils prone to erosion. Immediate measures such as contour farming and conservation tillage to manage water flow and minimize soil disturbance. Also, installing loose boulder structures and checking dams will dissipate runoff energy and control sediment deposition. Terracing is advised for any steep slopes, while increasing vegetative cover and

Fig. 5 The sub-watershed prioritization map using LULC analysis
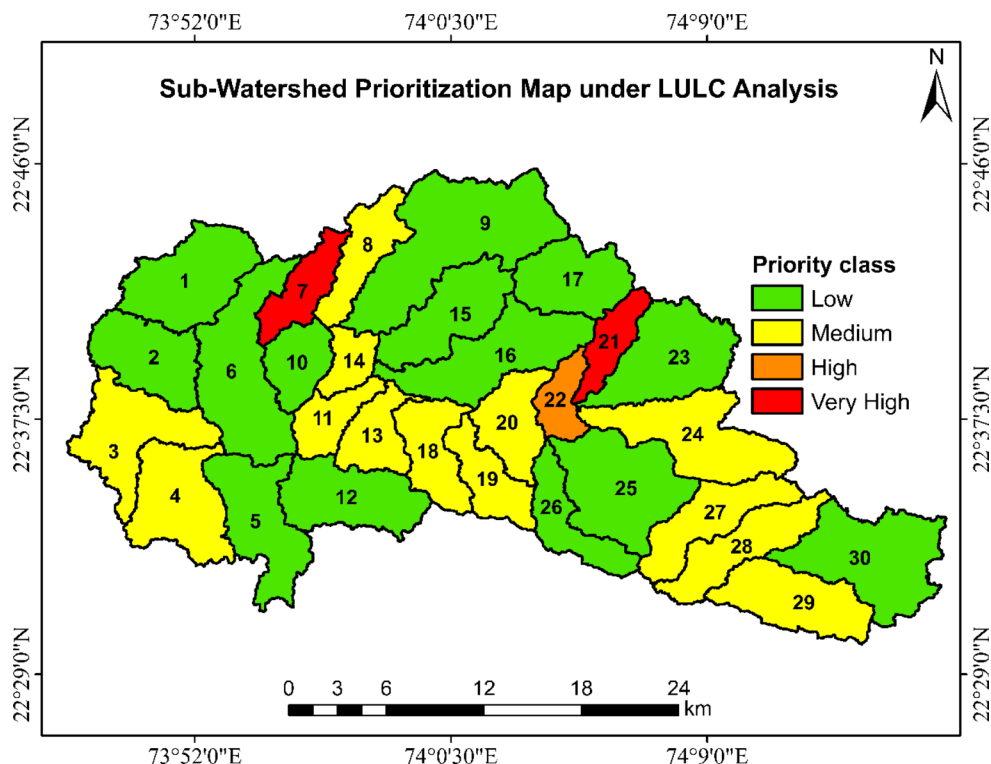
implementing rainwater harvesting systems will stabilize soil and manage runoff from built-up areas effectively. For SW14, SW22, and SW24, which are identified as high priority, SWC measures should address their steep slopes and varied soil types. SW14 and SW22 have loamy soils that, while having good infiltration rates, still require erosion control on slopes. Recommended interventions include bench terraces, check dams and tree plantations. These measures help manage slope steepness, control runoff, and enhance soil stability, crucial for loamy soils. SW24, with a mix of loamy and clayey soils, benefits tree plantations and check dams to manage runoff and enhance groundwater recharge, mitigating erosion risks.

SWs with a medium priority, such as SWs 1, 3, 5, 6, 8, 20, 21, 23, 25, 26, and 30, require balanced SWC measures considering their moderate erosion risks and soil characteristics. SW1 and SW6 have extensive agricultural land and forest cover on loamy soils, making contour bunding, strip cropping, and mulching suitable. These practices help manage water flow and enhance soil moisture retention, particularly important for loamy soils that balance infiltration and runoff. SW25 and SW26, with more clayey soils, benefit from measures like percolation tanks and strip cropping, which improve water infiltration and reduce surface runoff on clayey soils. SWs such as SW2, 4, 9, 10, 11, 12, 13, 16, 17, 18, 19, 27, 28, and 29, classified as low priority, have effective land management or favorable geomorphometric features that naturally mitigate erosion risks. For these areas, maintaining agricultural best practices like crop rotation, cover cropping, and level bunding is essential. These measures help sustain soil structure, enhance nutrient cycling, and provide ongoing erosion control, particularly beneficial for maintaining the fertility of loamy soils and managing runoff on clayey soils.

The proposed SWC measures are tailored to each SW's specific LULC characteristics and soil types, addressing their combined priority classification. Immediate and intensive interventions are crucial for very high and high-priority SWs with high erosion risks, particularly on clayey soils, while medium and low-priority SWs benefit from ongoing balanced conservation practices that consider their soil properties. This integrated approach ensures effective soil and water conservation, enhancing the resilience and sustainability of the watershed.

Conclusions

The morphometric and LULC analysis determined using RS and GIS methodologies provided researchers with a thorough understanding of the catchment's development and its response to hydrologic conditions. This understanding enables more effective natural resource management strategies in the Devgadh Baria Watershed DBW. The analysis
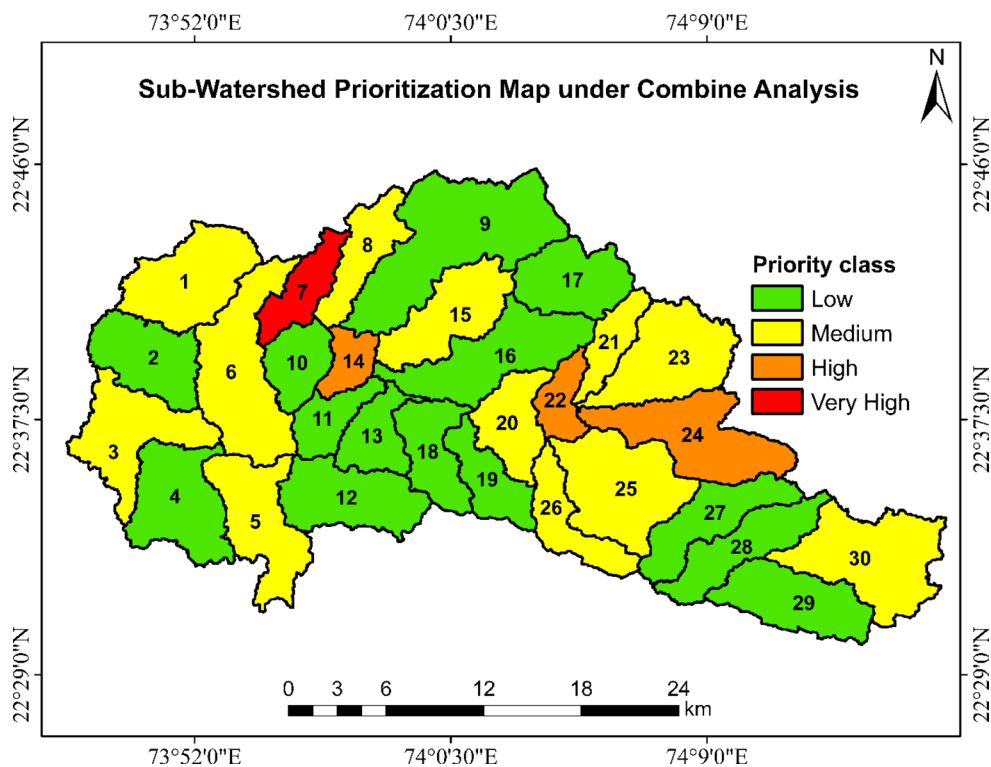
Table 4 The SW priority rank and class based on morphometric, LULC and combined assessment

Sub watershed no.	Morphometric analysis			LULC analysis			Common priority	Combine	
	Compound parameters	Priority rank	Priority class	Compound parameters	Priority rank	Priority class		Priority rank	Priority class
1	11.86	10	High	20.00	30.00	Low	No	15	Medium
2	21.43	26	Very Low	16.75	19.00	Low	No	29	Low
3	16.14	18	Low	14.75	11.00	Medium	No	11	Medium
4	23.00	30	Very Low	15.75	14.00	Medium	No	30	Low
5	14.43	12	Medium	17.50	23.00	Low	No	16	Medium
6	8.57	2	Very High	19.25	28.00	Low	No	8	Medium
7	8.57	3	Very High	7.00	1.00	Very High	Very High	1	Very High
8	11.29	8	High	14.50	9.00	Medium	No	5	Medium
9	15.86	15	Medium	18.75	26.00	Low	No	23	Low
10	16.00	16	Medium	17.25	22.00	Low	No	19	Low
11	20.57	24	Very Low	12.50	4.00	Medium	No	18	Low
12	16.71	19	Low	16.75	20.00	Low	Low	20	Low
13	19.71	22	Low	14.25	8.00	Medium	No	22	Low
14	9.43	4	Very High	13.75	6.00	Medium	No	3	High
15	13.57	11	Medium	17.50	24.00	Low	No	13	Medium
16	21.57	28	Very Low	16.50	18.00	Low	No	28	Low
17	16.00	17	Medium	18.75	27.00	Low	No	24	Low
18	20.57	25	Very Low	15.25	13.00	Medium	No	25	Low
19	17.86	20	Low	16.00	16.00	Medium	No	21	Low
20	15.29	14	Medium	15.75	15.00	Medium	Medium	12	Medium
21	20.14	23	Very Low	8.50	2.00	Very High	No	10	Medium
22	10.71	6	High	11.50	3.00	High	High	2	High
23	14.71	13	Medium	16.75	21.00	Low	No	14	Medium
24	9.71	5	Very High	13.50	5.00	Medium	No	4	High
25	10.86	7	High	17.75	25.00	Low	No	9	Medium
26	7.29	1	Very High	19.25	29.00	Low	No	6	Medium
27	21.43	27	Very Low	14.50	10.00	Medium	No	26	Low
28	18.14	21	Low	14.75	12.00	Medium	No	17	Low
29	22.29	29	Very Low	13.75	7.00	Medium	No	27	Low
30	11.29	9	High	16.25	17.00	Low	No	7	Medium

identified SWs 7, 14, 22, and 24 as having a higher susceptibility to soil erosion, necessitating prioritized conservation efforts. This targeted approach aims to mitigate soil erosion and prevent further land degradation by implementing tailored SWC measures based on their geomorphometric, LULC, and soil characteristics. The combined prioritization framework effectively integrates geomorphometric assessment with LULC, soil, and slope parameters, providing a robust basis for selecting appropriate SWC measures. By identifying conservation strategies such as bench terraces, check dams, contour farming, and tree plantation tailored to the specific conditions of each SW, we can enhance water management, improve soil stability, and promote sustainable land use practices. This integrated approach not only protects soil health and water resources but also increases the resilience and sustainability of the watershed ecosystem, particularly in the semi-arid and hilly terrain of the DBW.

Given the watershed's rainfed condition and limited irrigation resources, the research highlights the critical potential for implementing SWC strategies to improve water availability and support the UN Sustainable Development Goals related to food and water security. These strategies enhance the watershed's resilience to environmental hazards such as droughts and floods, contributing to overall regional well-being. Future research should focus on refining these approaches, incorporating high-resolution DEM and LULC data, and expanding the analysis to include climate data, land cover changes, and socio-economic factors. This continued development will further enhance our understanding of watershed dynamics and improve the effectiveness of conservation efforts, providing valuable insights for policymakers, land managers, and conservationists in developing adaptive and efficient strategies for sustainable watershed management.

Fig. 6 Sub-watershed priority map under combined analysis

Declarations

Originality of Study Our research focuses on the erosion risk assessment for implementing soil and water conservation measures in semi-arid regions of India. We acknowledge the inherent challenges in this field and elaborate on how these challenges are overcome through the application of remote sensing and GIS-based morphometric analysis. We would like to reassure you that the originality of our study is clearly emphasized both in the abstract and in detail within the introduction section of the manuscript. In the abstract, we provide a concise overview of the unique contribution our study makes to the existing literature, highlighting the innovative use of remote sensing and GIS-based morphometric analysis in addressing challenges associated with erosion risk assessment in semi-arid regions. Furthermore, in the introduction section, we delve into a comprehensive discussion, presenting the context, background, and specific aspects of our research that set it apart from previous works. We explicitly outline the distinctive methodology employed and the novel insights gained through our study. We are confident that our manuscript adds valuable insights to the field.

Conflict of Interest The authors declare no conflict of interest.

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