REPORT ON

PRIORITIZATION OF SUB-BASINS OF THE GAUDI RIVER BASIN FOR DEVELOPMENT OF RIVER REJUVENATION PLAN

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Watershed Management Directorate,
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Submitted by

Indian Institute of Technology Roorkee,
Roorkee (Uttarakhand) – 247667

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Prioritization of sub-basins of the Gaudi river basin for development of river rejuvenation plan

1. Background

Water resources are among the most critical natural assets for sustaining life and supporting economic activities. River basins play a significant role in regulating hydrological processes, providing freshwater for domestic, agricultural, industrial, and ecological needs. Understanding the dynamics of streamflow in river basins is crucial for effective water resource management, particularly in regions experiencing pressures from population growth, urbanization, and climate variability.

The Gaudi river, located in Champawat district of Uttarakhand is vital water bodies supporting diverse ecosystems and human settlements. This river are not only lifelines for the local population but also hold cultural, economic, and environmental significance. However, these basins face challenges due to changes in rainfall patterns, land use/land cover (LU/LC) modifications, and human interventions.

Hydrological behaviors in river basins are governed by various factors, including rainfall distribution, morphometric characteristics (e.g., basin shape, slope, and drainage density), LU/LC changes (e.g., urbanization, deforestation, agricultural expansion), and soil properties. Identifying trends and patterns in streamflow dynamics and understanding the role of these governing factors is essential for sustainable water management and for mitigating potential risks like flooding, droughts, and water scarcity.

Moreover, prioritizing sub-basins based on hydrological sensitivity and societal importance is critical for informed decision-making. The inclusion of schemes like the Jal Jeevan Mission (JJM), aimed at ensuring adequate domestic water supply, underscores the need for integrating societal considerations into hydrological planning. This study seeks to assess the streamflow dynamics, evaluate the governing factors, and establish a framework for sub-basins prioritization in the Gaudi river basin, contributing to the broader goal of sustainable water resource management.

2. Objectives

i. To assess streamflow dynamics in selected river basins, including the Gaudi river, by analyzing the observed /estimated streamflow data to identify trends and patterns over time.

ii. To assess the role of governing factors (Rainfall Pattern, Morphometry, LU/LC, Soil Types etc.) on the hydrological behaviour of the selected river basins and their sub-basins

iii. To prioritize the sub-basins on the basis of land use / land cover changes and morphometric characteristics and establish a framework for their prioritization considering the societal importance (population residing in the sub-basin and the JJM schemes for providing their domestic water requirements).

3. Characteristics of the Gaudi River basin

The Gaudi river is a significant river system in the Champawat district of Uttarakhand, India. Originating from the southern slopes of the middle Himalayan ranges, the river flows through a terrain characterized by steep gradients, dense forests, and rural settlements before merging with the Sharda River.

3.1.Geographical location and extent

The Gaudi River basin lies within the latitudinal range of approximately 29°16'40’’N to 29°20' 50’’N and the longitudinal range of 80°5' to 80°7'30’’E. The region covers an area of around 22 km², with elevations varying from 1512 meters to over 2118 meters above mean sea level, contributing to diverse climatic and hydrological characteristics (Figure 1a).

3.2.Climatic conditions

The region experiences a subtropical to temperate climate, with significant monsoonal rainfall from June to September. Based on 37 years rainfall data (1983-2020), the average annual rainfall ranges from 1264 mm to 1270mm, heavily influencing the river's flow regime

3.3.Topography and lulc

The terrain of the Gaudi River basin is predominantly mountainous, interspersed with valleys and plains, elevation ranges between 1512 meters and 2118 meters amsl. Current Land use (LANDSAT, Dec-2024) in the region comprises: Based on the satellite image, the current land-use and land cover were categorized into 4 classes (Table 2). The current land-use and land cover map are shown in Figure 3d.

Open and dense forests: Accounting for a significant portion, dominated by pine and oak species. *Agricultural lands:* Found mainly in the valleys and terraced slopes, supporting subsistence farming. *Settlements:* Small villages and towns, with Champawat as the nearest urban center.

3.4.Soil

The study area is mainly governed by the loamy soil (Figure 1c). The soil texture map of the basin has been downloaded from the site of IIT Delhi (http://gisserver.civil.iitd.ac.in/grbmp). The availability of water is the main characteristic of loamy soil. It is good for wheat and paddy cultivation being mixture of sand, silt, clay and organic matters.

3.5.Slope

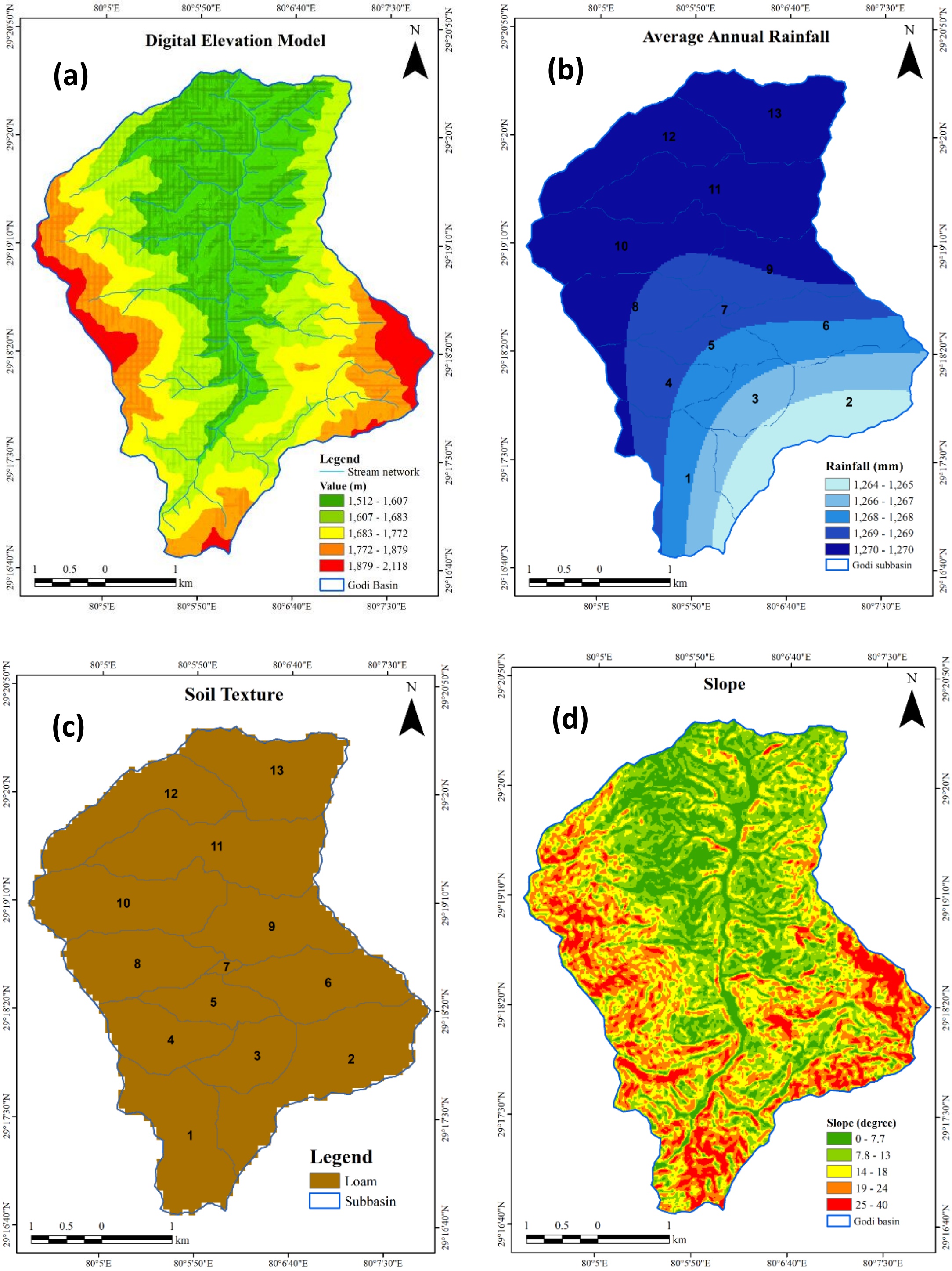
The slope of the basin plays a crucial role in determining the flow dynamics and the rate of runoff within the river system. In this particular basin, the slope varies significantly, ranging from 7.7 degrees to 40 degrees (Figure 1d). A slope of 7.7 degrees indicates relatively gentle terrain, where water flow may be slower, allowing for greater infiltration and less erosion. In contrast, a slope of 40 degrees represents steep terrain, which can lead to faster runoff, increased erosion, and a higher likelihood of flash floods during intense rainfall events. The variation in slope across the basin can also affect soil erosion rates, sediment transport, and the overall hydrological behavior of the area. Steeper slopes may result in quicker drainage, while gentler slopes allow for more prolonged water retention and groundwater recharge.

3.6.Hydrology

The Gaudi River plays a vital role in the hydrology of the region, serving as a critical water source for irrigation, domestic use, and supporting local biodiversity (Figure 1e). The river exhibits a perennial flow pattern, with seasonal variations influenced by monsoonal rainfall and snowmelt from the higher altitudes.

3.7.Geology

The geology (Figure 1f) of the basin is primarily composed of granite and gneiss, two types of metamorphic rocks that play a significant role in shaping the region's hydrological characteristics. Granite, an igneous rock, is typically hard, impermeable, and resistant to weathering, which means that areas with significant granite outcrops may have lower infiltration rates, resulting in higher surface runoff during rainfall events. On the other hand, gneiss, a metamorphic rock formed from the alteration of granite or other rocks under high pressure and temperature, can exhibit a foliated texture, which may influence water flow patterns differently depending on the degree of weathering and fracturing. The combination of these two rock types can create varied drainage patterns across the basin, with granite areas generally contributing to rapid surface runoff, while gneissic regions, which may have more fractured zones, could allow for some groundwater storage and slower runoff.


(a)
Digital Elevation Model
Legend
Stream network
Value (m)
1,512 - 1,607
1,607 - 1,683
1,683 - 1,772
1,772 - 1,879
1,879 - 2,118
Godi Basin
(b)
Average Annual Rainfall
Rainfall (mm)
1,264 - 1,265
1,266 - 1,267
1,268 - 1,268
1,269 - 1,269
1,270 - 1,270
Godi subbasin
(c)
Soil Texture
Legend
Loam
Subbasin
(d)
Slope
Slope (degree)
0 - 7.7
7.8 - 13
14 - 18
19 - 24
25 - 40
Godi basin
N
km
80°5'E
80°5'50"E
80°6'40"E
80°7'30"E
29°20'50"N
29°20'N
29°19'10"N
29°18'20"N
29°17'30"N
29°16'40"N

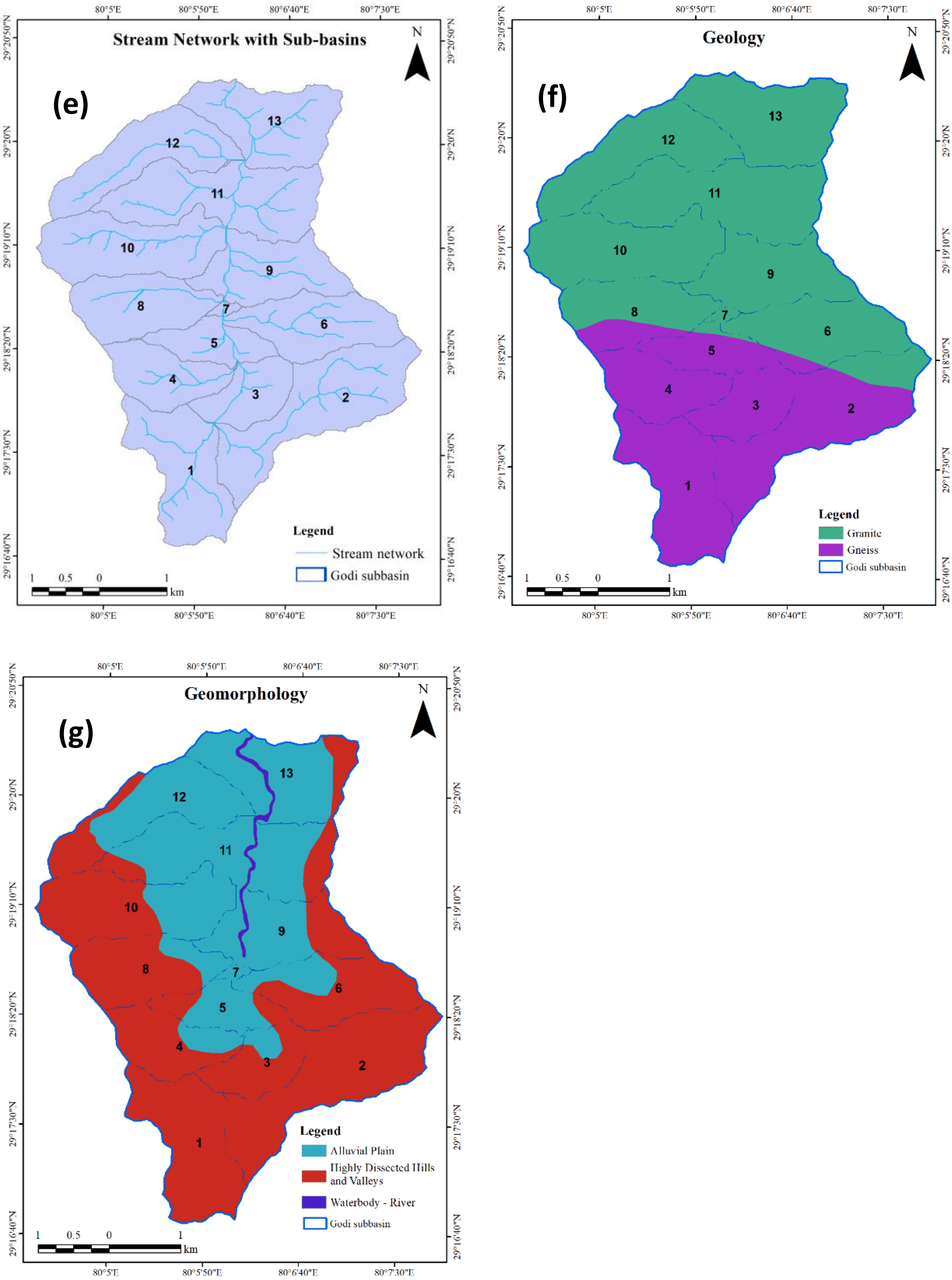


Figure 1. DEM (1a), rainfall (1b), soil (1c), slope (1d), sub-basins (1e), geology (1f) and geomorphology (1g) of the Gaudi River basin

3.8.Geomorphology

The geomorphology (Figure 1g) of the basin is characterized by a combination of alluvial plains and highly dissected hills and valleys, creating a diverse landscape with distinct hydrological implications. The alluvial plains, typically formed by the deposition of sediment carried by rivers and streams, provide flat, fertile areas that are often more prone to flooding during periods of high rainfall. These plains act as natural floodplains where sediment accumulation results in soil that is generally well-drained and conducive to agriculture. In contrast, the highly dissected hills and valleys are indicative of areas that have undergone significant erosion, leading to steep, rugged terrain with sharp ridges and deep valleys. These areas are subject to rapid runoff during rainfall events, which can increase the risk of soil erosion, landslides, and flash floods. The interplay between the gentle slopes of the alluvial plains and the steep, erosion-prone hills and valleys creates a complex drainage network within the basin.

3.9. *Demographic scenario*

According to the 2011 census report of GOI (Government of India), the population and density of the villages within the basin are as presented in Table 1. As per the 2011 census, it is observed that Dungra Saithi village is the high population density (33635.85 person/km^2) and Danthi village is the lowest population density (6.15 person/km^2).

Table 1 Demographic profile of the Gaudi River basin

Village Name	Total Population	Area (sq.km)	Population Density (person/km^2)
Dungra Saithi	517	0.02	33635.85
Punaithi	1150	0.19	6199.83
Nadhan	618	0.17	3731.67
Latauli	568	0.16	3541.01
Khark Karki	2147	0.81	2655.06
Dhakna Badola	551	0.25	2228.59
Chhira Pani	80	0.04	1876.90
Madli Talli	547	0.30	1811.33
Majgaon	363	0.26	1384.11
Chowkni Bora	493	0.41	1205.20
Shaktipur	650	0.65	998.76
Palsau	630	0.65	964.08
Danda Bisht	383	0.41	932.41
Lamkaniya	100	0.11	913.25
Tyarkunda	222	0.29	768.96
Kanalgaon	746	1.30	572.06
Mudiyani	1083	1.89	572.00
Saidula Bora	193	0.34	567.07
Jup Patua	511	0.98	521.26
Kaflang	250	0.49	507.58
Naad Bora	157	0.41	379.72
Dudh Pokhara	193	0.62	312.16
Chaura Sethi	289	0.95	305.67

Kuteli	202	0.70	287.16
Bajrikot	671	2.42	277.54
Lista	47	0.20	231.44
Rakri Phulara	208	1.09	190.29
Chaniya	68	0.45	152.06
Chayura Khark Khet	73	0.51	143.26
Chowkni Pandey	60	0.48	124.80
Pawait	72	0.68	106.37
Danthi	6	0.98	6.15
Reserve Forest Range Ranikhet	0	1.20	0.00

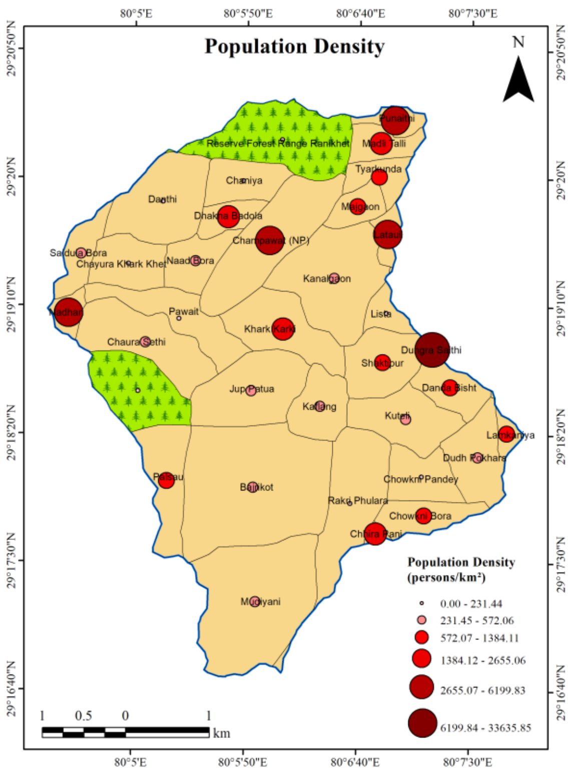


Figure 2. Population density of the Gaudi River basin

4. Land use and land cover (LULC) change detection analysis

The LULC change detection analysis utilized four satellite images from different time periods: 1995, 2003, 2015 (LANDSAT), and 2024 (SENTINEL). These images were analyzed to assess changes in the land use and land cover (LULC) of the Gaudi River basin in Champawat. The analysis focused on four primary LULC classes: Dense Forest Cover, Cultivated Land, Open Forest Cover, and Settlement Area (Table 2). The images were processed to detect changes in the spatial extent of these classes over the years, which were then quantified and compared.

Table 2 LULC dynamics across four time periods (1995, 2003, 2015, 2024)

Class name	1995	2003	2015	2024	Change (1995-2024)
	Area (sq.km)	Area (sq.km)	Area (sq.km)	Area (sq.km)	
Dense Forest Cover	11.66	10.80	10.72	12.20	+0.54
Cultivated	7.95	9.71	7.88	6.88	-1.07
Open Forest Cover	2.33	0.78	1.92	1.39	-0.94
Settlement	0.47	1.10	1.89	1.93	+1.46

Dense forest cover

The decrease from 1995 to 2015 is likely due to deforestation for agricultural and urban expansion. However, the increase in 2024 suggests reforestation or conservation efforts, highlighting that efforts to protect and regenerate forest areas may have been successful in the last few years.

Cultivated land

There was an increase in cultivated land from 1995 to 2003, indicating agricultural intensification. However, the decrease by 2024 could be due to urban sprawl, land degradation, or a shift toward forest conservation or other land uses.

Open forest cover

The significant decrease from 1995 to 2003 is attributed to land conversion for agriculture and settlements. While there was some recovery in 2015, the open forest area did not fully recover, suggesting that some land has been permanently lost due to urbanization and agricultural activities.

Settlement area

The consistent increase in settlement areas reflects a trend of urbanization driven by population growth and the expansion of infrastructure. The increase from 1995 to 2024 shows the ongoing rural-to-urban migration and the growing demand for land for housing and commercial purposes.

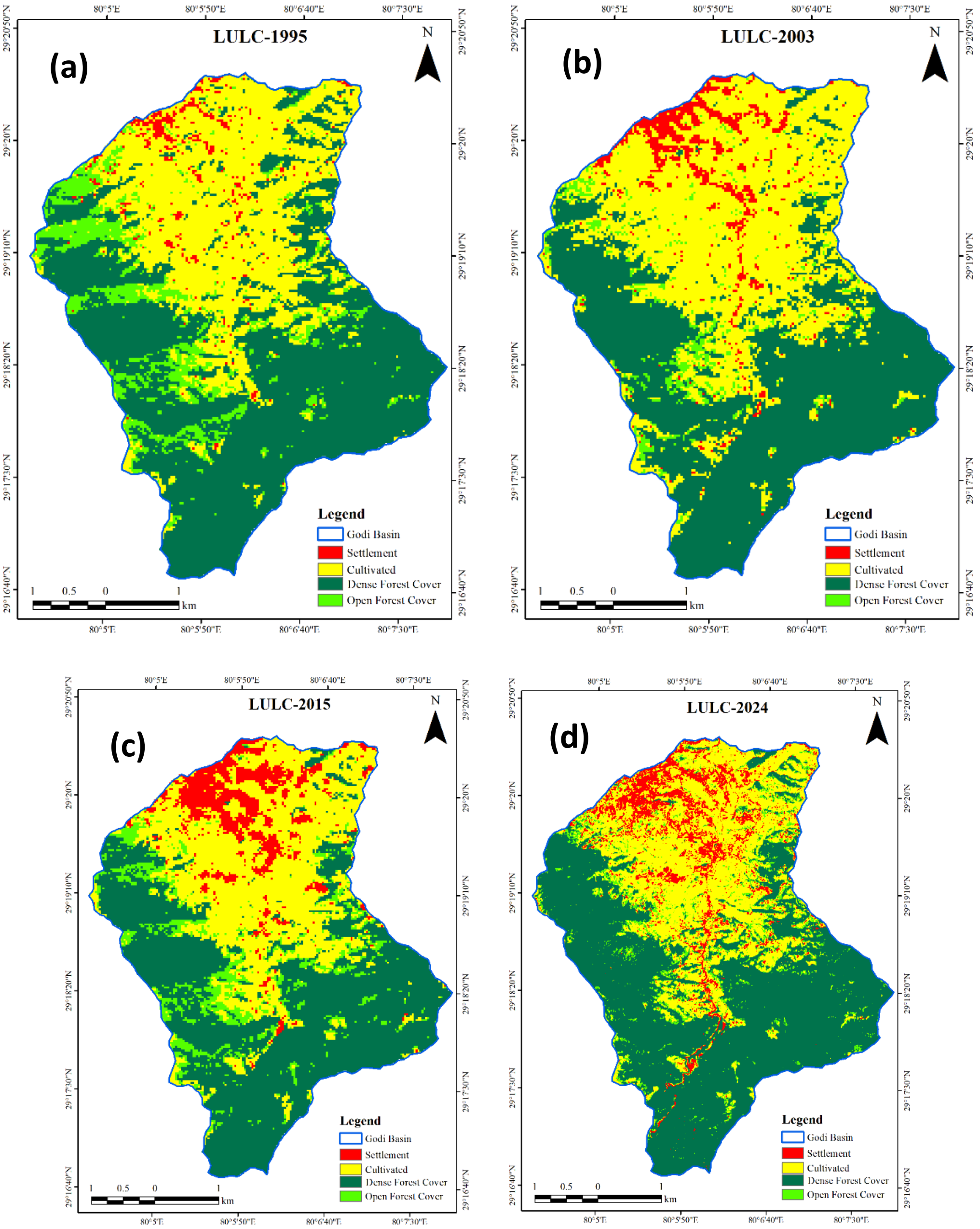


Figure 3. Temporal Dynamics of LULC for 1995 (3a), 2003 (3b), 2015 (3c), and 2024 (3d)

5. Morphometric analysis

Morphometric analysis explains the quantitative characteristics of a river basin or a hydrological unit. This is the most scientific method used to evaluate the lands produced by the fluvial system in a basin (Clarke 1966). There are three aspects used in morphometric parameter analysis viz., linear aspect (one dimensional), areal aspect (two dimensional) and relief aspect (three dimensional). The various quantitative morphometric parameters of the Gaudi River basin have been discussed accordingly. Various standard mathematical formulas as presented in Table 3.

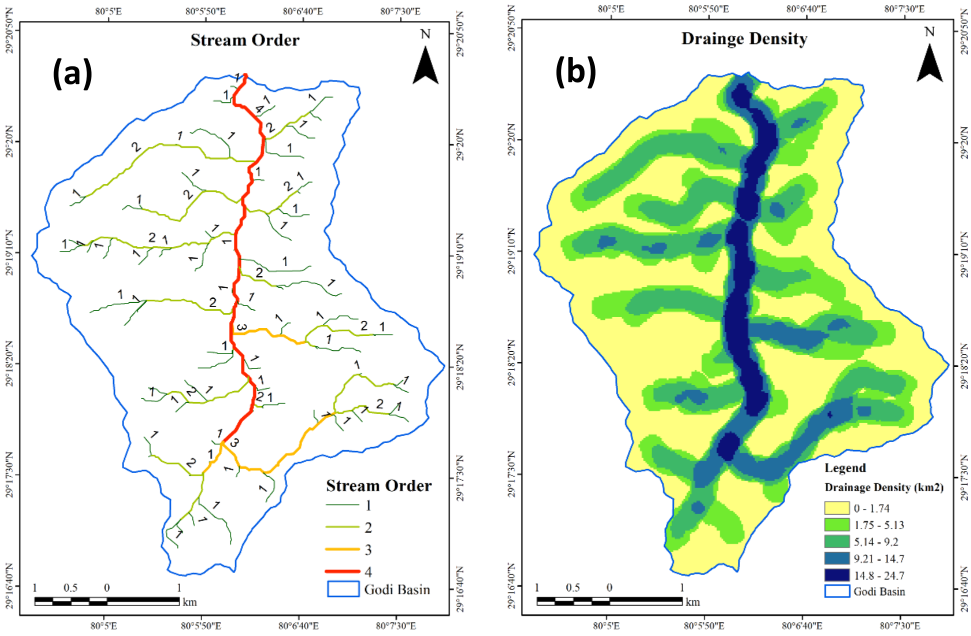


Figure 4. Stream order (4a) and drainage density (4b) of the Gaudi River basin

Table 3 Morphometric parameters and standard mathematical formula

S. no.	Morphometric parameters	Formula	References
1	Stream Order (u)	Ranking hierarchically.	Strahler (1964)
2	Stream Length (Lu)	Length of the stream	Horton (1945)
3	Stream Length Ratio (R_1)	R_1 = Nu/ Nu–1 Nu=the mean length of the stream of a given order Nu–1= the mean length of the streams of the next smaller order	Horton (1945)
4	Stream number (Nu)	Total no of stream segment of each order	Horton (1945)
5	Bifurcation Ratio (Rb)	Rb = Nu /Nu + 1 Nu = total no. of stream segments of order 'u' Nu + 1 = number of segments of the next higher order	Schumn (1956)
6	Length of overland flow (Lo)	Lo=2/Dd Dd= drainage density of basin	Horton (1945)
7	Basin Length (Lb)	Lb=1.312XA $^{0.568}$; Lb= length of basin (km) A= area of the basin (sq.km)	Horton (1945)
8	Stream Frequency (Fs)	Fs = ΣNu/ A ΣNu= total number of stream segments of all orders. A= area of the river basin (sq.km)	Horton (1932)
9	Drainage Density (Dd)	Dd = ΣLu/ A ΣLu = total stream length of all orders A = area of the river basin(sq.km)	Horton (1945)
10	Drainage Texture (Dt)	T = Nu/P Nu= total number of all order streams P = perimeter of basin.	Horton (1945)
11	Texture Ratio (Rt)	T=N1/A; Nu= total no of stream of first order, A= perimeter of basin.	Horton (1945)
12	Form Factor (Rf)	Rf=A/L2; A= area of basin (sq.km), L= length of Basin (km)	Horton (1932)
13	Shape Factor (Bs)	Bs=L^2/A; L= length of basin (km), A= area of the river basin (sq.km)	Horton (1945)
14	Circulatory Ratio (Rc)	Rc =4A/ P^2; A= area of the river basin (sq.km), P= perimeter (km)	Miller (1953)
15	Elongation Ratio (Re)	Re= D/L=1.128/A/L D= diameter of a circle of the same area (A) as the basin. A = area of the basin (sq.km), L= basin length (Km)	Schumm (1956)
16	Basin relief (Bh)	Bh=H/H-h; H= maximum height (m) h= minimum height (m)	Strahler (1952)
17	Relief Ratio (Rh)	Rh=Bh/Lb; Bh= basin relief Lb= basin length (km)	Schumn (1956)

5.1.Linear aspects

Linear aspect provides information about the one-dimensional parameters of a river basin like: stream order (U), stream length (Lu), stream number (Nu), bifurcation ratio (Rb) and Length of overland flow (Lo) as discussed below:

Stream order (U)

The stream order of the Gaudi River is based on the Strahler (1964) stream ordering system. The variation in the orders and length of the tributaries of the basin is largely dependent on the geological conditions of the region. Based on the ALOS PALSAR DEM (12.5), a total of 97 streams were identified in this basin. The drainage pattern was found to be dendritic in type; wherein the main feature of this system is the irregular branching of the river tributary (Fig.

4a). The stream order increases from the upstream of the river to the downstream on the basis of regional geomorphology. According to the stream order system, Gaudi has been identified as a 4th order river system. Stream order is changing according to the sub-basins. The detailed information of stream order of various sub-basins is represented in Table 4.

Stream length (Lu)

The stream length was quantified according to the second law of Horton (1945). The study basin's total stream length was found to be 49.98 km. In first-order streams of the basin, the total stream segments had maximum length, which kept on decreasing as the stream order increased. Sub-basin wise details of stream along with the length of sub-basins are represented in Table 4.

Stream number (Nu)

Stream number is the total number of stream segments belonging to different stream order. It is inversely proportional to the sequence of streams. The total number of streams in the Gaudi River is 97, which progressively decreases as the stream order increases. It was observed that the number of 1st order streams was maximum in higher elevation areas whereas it was lower in plain areas. Sub-basin wise stream numbers are presented in Table 4.

Bifurcation ratio (Rb)

Bifurcation ratio (Rb) is a non-dimensional factor that represents the ratio between the number of streams of any given order and the number in next higher order (Schumn 1956). A bifurcation ratio, indicates whether or not the geological structure controls the drainage pattern of a basin (Strahler 1957). Higher values indicate mostly hilly areas with more flood potential whereas lower values indicate the possibility of flat terrain, high permeability and higher penetration thus leading to more groundwater. Sub-basin wise, mean bifurcation ratio values range from 1 to 9. The lowest bifurcation ratio is observed in Sub-basin 7, with a value of 1. On the other hand, the highest bifurcation ratio is recorded in sub-basin 10, with a value of 9.00. The bifurcation ratio values show the structure of the drainage network in each sub-basin, with a higher value indicating a more branching and regular drainage pattern, while a lower value suggests a more complex or irregular network. The mean bifurcation ratio values for Gaudi River sub-basins are represented in Table 5.

Table 4 Stream order, number and length of the Gaudi River sub-basins

Sub-basins	Stream Order (U)	I Order	II Order	III Order	IV Order	Total
Sub Basin 1	No of Stream (Nu)	9	2	1		
	Stream Length (LU) (km)	2.46	1.60	0.55		4.61
Sub Basin 2	No of Stream (Nu)	10.00	2.00	1.00		
	Stream Length (LU) (km)	2.35	2.13	2.18		6.67
Sub Basin 3	No of Stream (Nu)	4.00	1.00		1.00	
	Stream Length (LU) (km)	0.67	0.15		1.11	1.92
Sub Basin 4	No of Stream (Nu)	4.00	1.00			
	Stream Length (LU) (km)	1.40	1.36			2.75
Sub Basin 5	No of Stream (Nu)	3.00	1.00		1.00	
	Stream Length (LU) (km)	1.38	0.04		0.87	2.29
Sub Basin 6	No of Stream (Nu)	6.00	2.00	1.00		
	Stream Length (LU) (km)	1.86	1.27	1.26		4.40
Sub Basin 7	No of Stream (Nu)				1.00	
	Stream Length (LU) (km)				0.20	0.20
Sub Basin 8	No of Stream (Nu)	3.00	1.00			
	Stream Length (LU) (km)	1.51	1.35			2.87
Sub Basin 9	No of Stream (Nu)	5.00	1.00		1.00	
	Stream Length (LU) (km)	2.62	0.64		1.09	4.35
Sub Basin 10	No of Stream (Nu)	9.00	1.00			
	Stream Length (LU) (km)	2.47	2.34			4.81
Sub Basin 11	No of Stream (Nu)	8.00	2.00		1.00	
	Stream Length (LU) (km)	2.36	2.63		1.17	6.17
Sub Basin 12	No of Stream (Nu)	4.00	1.00			
	Stream Length (LU) (km)	1.23	2.77			4.00
Sub Basin 13	No of Stream (Nu)	7.00	1.00		1.00	
	Stream Length (LU) (km)	2.67	0.77		1.51	4.95
						49.98

Length of overland flow (Lo)

The length of overland flow (Lo), a crucial parameter influencing the time water takes to reach the stream channels, varies from 0.9 km to 1.4 km across the sub-basins. Sub-basins 3 and 8 exhibit the shortest overland flow length of 0.9 km, suggesting steeper slopes and quicker runoff towards the drainage network. In contrast, sub-basin 7 has the highest overland flow length of 1.4 km, indicative of gentler slopes and slower water movement, allowing for greater infiltration and delayed runoff.

5.2.Areal aspects

Areal aspect represents two dimensional properties of a river basin. The Perimeter (P) and basin area (A) are two important parameters in the quantitative areal morphology. Hydrologically areal aspects are very important due to the size of storm hydrograph viz., magnitudes, peak and the surface runoff are directly influenced by the perimeter. An inverse relation exists between the size of the basin and the maximum flood discharge per unit area (Chorley et al. 1957). In the Gaudi River, following areal aspect features were observed - Drainage density (Dd), Drainage Texture (Dt), Stream Frequency (Fs), Circulatory Ratio (Rc), Elongation Ratio (Re), Form Factor (Rf) and Texture Ratio (Rt) are calculated and discussed accordingly.

Drainage density (Dd)

The drainage density (Dd) (Figure 4b) of the sub-basins varies between 1.9 km/km² and 2.8 km/km², reflecting a range of hydrological and geomorphological characteristics. Sub-basin 3 exhibits the lowest Dd of 1.9 km/km², suggesting widely spaced streams, indicative of permeable soils and higher infiltration potential. In contrast, sub-basin 7 has the highest Dd of 2.8 km/km², indicating a dense stream network typically associated with impermeable surfaces, steep slopes, and higher runoff potential. These variations in drainage density highlight the diverse response of sub-basins to rainfall events and their capacity for groundwater recharge. The values of Dd for various sub-basins are presented in Table 5.

Drainage texture (Dt)

The drainage texture (Dt) across the sub-basins varies from 0.50 to 1.27, indicating different levels of stream frequency and drainage network development. Sub-basin 12 exhibits the lowest drainage texture of 0.50, suggesting a relatively coarse drainage network with fewer stream channels per unit area, often associated with permeable soils, gentle slopes, and lower surface runoff. In contrast, Sub-basin 1 has the highest drainage texture of 1.27, reflecting a fine drainage network with higher stream frequency, typically found in areas with impermeable soils, steeper slopes, and higher susceptibility to erosion. The values of Dt for various sub-basins are presented in Table 5.

Basin length (Lb)

According to Horton (1945), basin length has been calculated of the Gaudi River sub-basins (Table 5). Sub-basin 7 has the smallest basin length of 0.29 km, reflecting its compact and narrow morphology. In contrast, sub-basin 2 has the largest basin length of 3.26 km, indicative of an elongated basin shape that influences its drainage pattern and water flow dynamics.

Table 5 Computed values of morphometric parameters of the Gaudi sub-basins

Sub basin	Area (sq.km)	Perimeter (km)	No of Stream (N1)	Stream Length (N1) (km)	Length of Sub Basin (Lb)_km	Mean bifurcation ration (Rb)	Drainage Density	Drainage Texture (Dt)	Stream Frequency (Fu)	Texture ratio (T)	Length of Overland Flow (Lo)	Form Factor (Rf)	Circularity ratio (Rc)	Elongation ratio (Re)	Basin relief (bh)	Relief ratio (Rh)
1	2.15	9.48	12	4.61	1.91	3.25	2.14	1.27	5.59	0.95	1.07	0.59	0.30	1.06	0.39	0.20
2	2.87	12.33	13	6.67	3.26	3.50	2.32	1.05	4.53	0.81	1.16	0.27	0.24	1.20	0.54	0.17
3	1.02	5.55	6	1.92	1.02	2.00	1.89	1.08	5.88	0.72	0.94	0.98	0.42	1.13	0.23	0.22
4	1.26	6.78	5	2.75	2.06	4.00	2.19	0.74	3.97	0.59	1.09	0.30	0.34	1.44	0.42	0.20
5	0.88	6.43	5	2.29	0.88	1.50	2.60	0.78	5.68	0.47	1.30	1.13	0.27	1.13	0.37	0.42
6	1.77	8.15	9	4.40	2.74	2.50	2.48	1.10	5.08	0.74	1.24	0.24	0.33	1.40	0.54	0.20
7	0.07	1.88	1	0.20	0.29	1.00	2.82	0.53	13.82	**0.53**	1.41	0.88	0.26	2.25	0.06	0.22
8	1.65	7.08	4	2.87	2.30	3.00	1.74	0.57	2.43	0.42	0.87	0.31	0.41	1.33	0.44	0.19
9	1.72	9.00	7	4.35	2.14	2.50	2.53	0.78	4.07	0.56	1.26	0.38	0.27	1.26	0.35	0.16
10	2.25	9.20	10	4.81	2.85	9.00	2.14	1.09	4.44	0.98	1.07	0.28	0.33	1.27	0.43	0.15
11	2.71	11.58	11	6.17	2.44	2.00	2.28	0.95	4.06	0.69	1.14	0.45	0.25	1.07	0.24	0.10
12	1.97	9.93	5	4.00	2.96	4.00	2.03	0.50	2.54	0.40	1.02	0.22	0.25	1.38	0.34	0.11
13	2.09	9.30	9	4.95	1.24	3.50	2.37	0.97	4.31	0.75	1.18	1.37	0.30	0.87	0.16	0.13

Stream frequency (Fs)

The stream frequency (Fu) (Table 5), representing the number of streams per unit area, varies significantly across the sub-basins, ranging from 2.43 in sub-basin 8 to 13.82 in sub-basin 7. sub-basin 8 exhibits the lowest stream frequency, indicating a sparse drainage network, likely due to gentle slopes, high infiltration, or permeable soils. Conversely, sub-basin 7 shows the highest stream frequency, reflecting a dense and intricate drainage network. This is characteristic of steep terrain, low infiltration rates, and possibly impermeable geological formations.

Texture ratio (Rt)

The texture ratio (T) (Table 5), which measures the ratio of stream frequency to basin perimeter, varies from 0.00 in Sub-basin 7 to 0.98 in sub-basin 10. Sub-basin 7, with a texture ratio of 0.00, reflects an absence of well-defined drainage patterns, likely due to flat terrain or minimal stream development. In contrast, sub-basin 10 has the highest texture ratio of 0.98, indicating a relatively fine drainage texture typically associated with steeper slopes and higher runoff potential. The moderate values observed in most sub-basins suggest a balanced interplay of geomorphic and hydrological factors.

Form factor (Rf)

The form factor (Rf) (Table 5), a measure of the shape of a basin calculated as the ratio of basin area to the square of basin length, ranges from 0.22 in sub-basin 12 to 1.37 in sub-basin 13. A higher form factor, such as in Sub-basin 13, indicates a near-circular basin shape, which typically results in a shorter lag time for peak discharge during rainfall events. Conversely, sub-basin 12, with the lowest form factor, suggests an elongated basin, leading to prolonged runoff duration.

Circulatory ratio (Rc)

The circularity ratio (Rc) (Table 5), which compares the perimeter of a basin to the perimeter of a circle with the same area, ranges from 0.25 in Sub-basins 11 and 12 to 0.42 in sub-basin 3. A low circularity ratio, such as those observed in sub-basins 11 and 12, indicates an elongated basin shape, which typically results in longer travel times for runoff. In contrast, sub-basin 3, with the highest circularity ratio, suggests a more compact and near-circular shape, which is associated with quicker hydrological responses and faster runoff.

Elongation Ratio (Re)

The elongation ratio (Re) (Table 5), which measures the shape of a basin in terms of its elongation, ranges from 0.87 in Sub-basin 13 to 2.25 in sub-basin 7. A low elongation ratio, like in sub-basin 13, indicates a highly elongated, narrow basin, which can result in longer surface flow paths and delayed runoff. In contrast, Sub-basin 7, with the highest elongation ratio, suggests a basin with a more circular shape, which is typically associated with a faster runoff response and shorter lag times.

Relief aspects

Relief aspects are the three-dimensional properties of the basin. Calculated relief aspects such as basin relief (Bh) and Relief ratio (Rh) of the basin are discussed accordingly:

Basin relief (Bh)

The highest relief is observed in Sub-basin 6, with a difference of 544 meters between the highest point at 2095 meters and the lowest point at 1551 meters. Sub-basin 2 also has a considerable relief of 539 meters, indicating a relatively rugged terrain. On the other hand, sub-basin 7 has the lowest relief of just 64 meters, signifying a relatively flat or gently sloping area. Other sub-basins, such as sub-basin 1 and sub-basin 4, also exhibit moderate relief differences of 389 meters and 419 meters, respectively (Table 5).

Relief ratio (Rh)

The relief ratio (Table 5), which indicates the steepness of a basin and is calculated as the ratio of the basin's relief to its length, varies across the sub-basins. Sub-basin 5 exhibits the highest relief ratio of 0.4154, which suggests a relatively steep terrain and rapid runoff potential. In contrast, Sub-basin 11 has the lowest relief ratio of 0.0987, indicating a more gently sloping or flat terrain with slower runoff characteristics. The remaining sub-basins have moderate relief ratios, with sub-basin 3 (0.2214) and sub-basin 7 (0.2229) showing higher ratios, reflecting regions with moderately steep slopes that influence surface water movement.

6. Hydrologic modelling with SWAT: setup and simulation

SWAT is a physical-based and semi-distributed hydrological model that processes, combines, and analyses spatially input data using GIS technology (Arnold et al. 1998; Srinivasan et al. 1998). This model divides a watershed into multiple sub-watersheds or sub-basins, further subdivided into hydrologic response units (HRUs) based on land use, soil type, and slope (Maliehe & Mulungu, 2017). The model predicts the hydrology for each HRU using the water balance equation below:

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw})_i \quad (1)$$

Where: SWt is the ultimate level of moisture in the soil (mm), SW_0 is the initial soil moisture content (mm). Rday is the quantity of rainfall on a given day i (mm). Qsurf is the amount of runoff that occurs at the surface on day i (mm), and Wseep is the quantity of water that enters the vadose zone from the soil profile on day i, (mm). Qgw is the amount of return flow that occurs on day i, (mm). Ea is the quantity of evapotranspiration that takes place on day i (mm), and t is the duration of time (days).

Table 6 Details of data used for SWAT model simulation

Data type	Source and Resolution	Year	Purpose
Land Use/Land Cover	SENTINEL (10m)	2024	Current LULC mapping
Digital Elevation Model (DEM)	ALOS PALSAR (12.5m)	Latest available	Watershed delineation and slope analysis
Soil Data	Downloaded from IIT Delhi website (30m)	Latest available	Soil classification for hydrological processes
Climate Data	CHIRPS and CHIRTS (0.05°×0.05°)	1995-2024	Precipitation and temperature

The SWAT model for this watershed was developed using the same model equations and the spatial (DEM, land use, and soil maps) temporal data a (weather data) data. Details of the dataset used in this study are summarized in Table 6. A threshold drainage area of 100 hectares (ha) was used to identify all the sub-watersheds and outlets of the Gaudi River. The HRUs were defined using the multiple land use/soil/slope technique, with land use (10%), soil (15%), and slope (15%) thresholds, creating 204 HRUs for the Gaudi River. Figure 5 presents the simulated discharge of the basin based on the SWAT model.

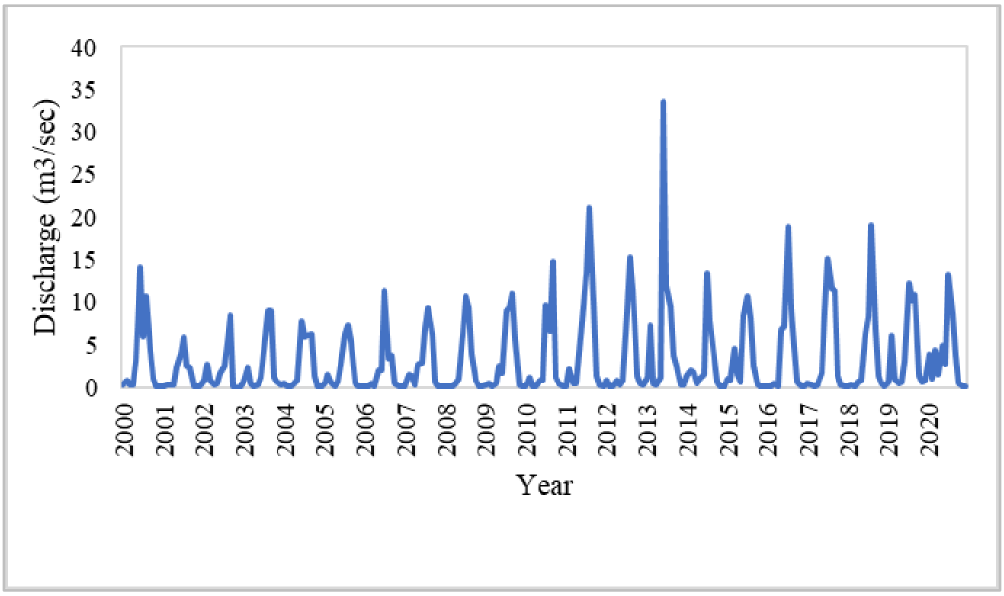


Figure 5. Annual simulated discharge of the Gaudi River basin from 2000 to 2020

7. Impact of LULC changes on streamflow dynamics

The impact of land use/land cover (LULC) changes on streamflow dynamics is reflected in the results provided below. Over the periods from 1995-2003, 2003-2015, and 2015-2020, discharge values have shown a noticeable increase in most sub-basins (Figure 6). These changes in streamflow are attributed to the transformation of land cover, including urbanization, agricultural development, and changes in vegetation, all of which have affected streamflow (Table 7).

Period 1: 1995–2003 (Baseline discharge): During the period 1995–2003, the discharge values across the sub-basins represent the baseline streamflow conditions under the land use/land cover (LULC) scenario of 1995. The results indicate moderate discharge values, reflecting relatively stable hydrological conditions with balanced water retention and runoff. Sub-basin 2 (4.48 m^3/sec) and Sub-basin 3 (3.69 m^3/sec), exhibit higher discharge values, while Sub-basin 6 (0.33 m^3/sec) and Sub-basin 8 (0.36 m^3/sec), show lower discharge. This period serves as a reference point for understanding the impacts of subsequent LULC changes.

Period 2: 2003–2015 (Increase in discharge): From 2003 to 2015, significant increases in discharge values are observed across most sub-basins, correlating with LULC changes, including urbanization and agricultural expansion. Sub-basin 2, for instance, experiences an increase from 4.48 m^3/sec (1995–2003) to 6.14 m^3/sec, reflecting intensified runoff due to reduced vegetation cover and increased impervious surfaces. Similarly, sub-basin 1 shows a notable rise from 0.38 m^3/sec to 0.78 m^3/sec, emphasizing the impact of land transformation on smaller basins. This period marks a critical shift in streamflow dynamics, with LULC changes amplifying surface runoff and altering the hydrological balance.

Period 3: 2015–2020 (Continued increase in discharge): The period 2015–2020 reveals a further increase in discharge values, underscoring the cumulative effects of sustained LULC changes. Sub-basin 2 continues to exhibit the highest discharge, increasing from 6.14 m^3/sec (2003–2015) to 8.09 m^3/sec, while Sub-basin 3 rises from 4.81 m^3/sec to 5.84 m^3/sec. Sub-basin 6 (0.52 m^3/sec) and sub-basin 8 (0.57 m^3/sec), also show incremental changes. These results highlight an acceleration in surface runoff likely driven by urban sprawl, agricultural intensification, and reduced natural vegetation. The increasing discharge trends indicate heightened flood risks and the potential for altered water availability in the region.

Table 7 Impact of LULC change on stream flow

Sub basin	Discharge (m^3/sec) (1995-2003)	Discharge (m^3/sec) (2003-2015)	Discharge (m^3/sec) (2015-2020)
1	0.38	0.78	1.33
2	4.48	6.14	8.09
3	3.69	4.81	5.84
4	0.45	0.59	0.71
5	2.71	3.51	4.26
6	0.33	0.43	0.52
7	2.03	2.63	3.19
8	0.36	0.47	0.57
9	1.66	2.15	2.60
10	0.25	0.33	0.40
11	1.23	1.59	1.93
13	0.58	0.75	0.92
12	0.44	0.57	0.69

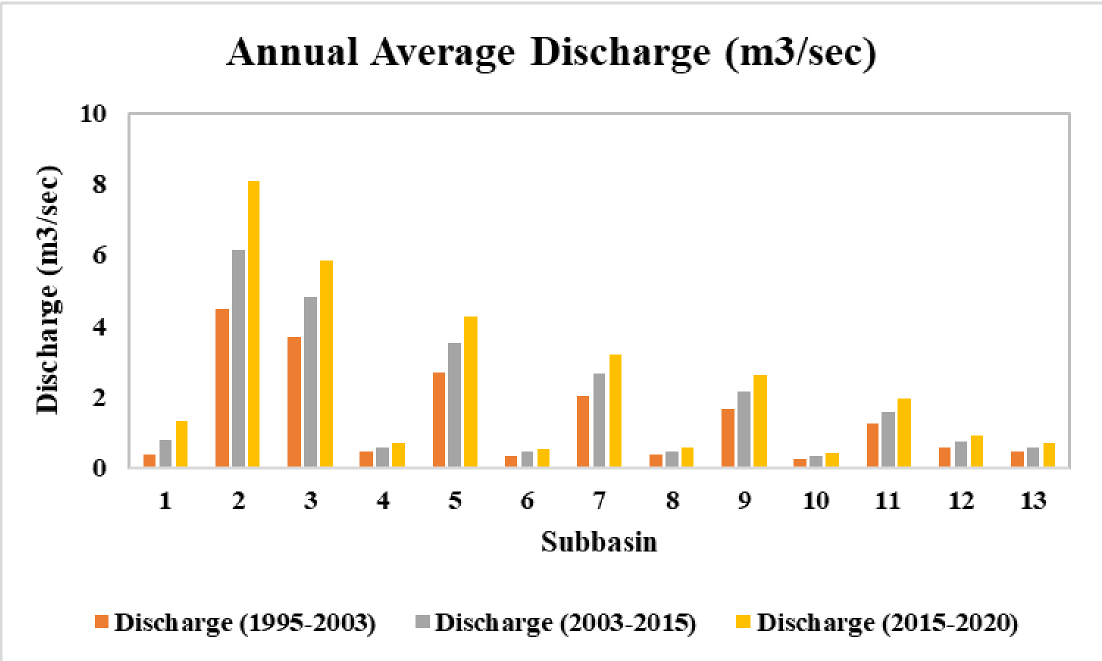


Figure 6. LULC impacts on discharge for 1995–2003, 2003–2015, and 2015–2024

8. Prioritization of Gaudi sub-basins

8.1. Based on morphometric parameter analysis

In the context of morphometric parameter-based prioritization of sub-basins, the compound factor (CF) value serves as a critical tool for classifying the sub-basins into different priority zones. The prioritization process is grounded in the understanding that morphometric parameters—such as linear, areal and relief are indicative of the hydrological characteristics and vulnerability of each sub-basin. Based on the compound factor value, the sub-basins are divided into three distinct priority zones: High priority (<5.73), Medium priority (>5.73-<6.46), and Low priority (>6.46) (Table 8). These zones are determined through an analysis of the compound factor values, which integrate the various morphometric attributes that influence the watershed's ecological stability and susceptibility to degradation (Figure 7).

The high priority zone (Figure 7) is defined for sub-basins with a compound factor value greater than 6.75, indicating regions that are ecologically or hydrologically sensitive and require immediate attention for conservation or restoration. These sub-basins typically exhibit features such as high erosion potential, steep slopes, or a lack of vegetation cover, which necessitate prompt intervention. The High Priority category identifies sub-basins that are more vulnerable to soil erosion, floods, or other hydrological stresses. Sub-basins 3, 5, 6, and 7 are classified into this category, with compound factor values of 6.55, 5.09, 5.00, and 5.00, respectively. These values reflect areas in need of urgent watershed management practices to prevent further degradation and improve water retention and soil quality.

The medium priority zone (Figure 7) is designated for sub-basins with compound factor values between 5.00 and 6.75. These sub-basins have moderate morphometric characteristics that suggest they are stable but may still require interventions to optimize their ecological and hydrological functions. While these areas are not as critical as the high-priority zones, they still exhibit characteristics that warrant ongoing monitoring and some degree of management. Sub-basins 1, 4, 9, 10, 11, and 12 falls under this category, with compound factor values ranging from 5.00 to 7.18. Although these sub-basins are more stable, they may still face challenges such as localized erosion, moderate flooding, or unsustainable land use, which require proactive land management strategies.

The low priority zone (Figure 7) is assigned to sub-basins with compound factor values higher than 7.18, indicating relatively stable morphometric conditions with lower vulnerability to degradation. These sub-basins are typically less susceptible to severe erosion or hydrological stresses and can function well with minimal intervention. Sub-basins 2 and 13, with compound factor values of 5.27 and 6.91, fall into this zone, reflecting regions where the existing ecological and hydrological conditions are more stable, though continued monitoring may still be necessary to ensure the maintenance of these conditions.

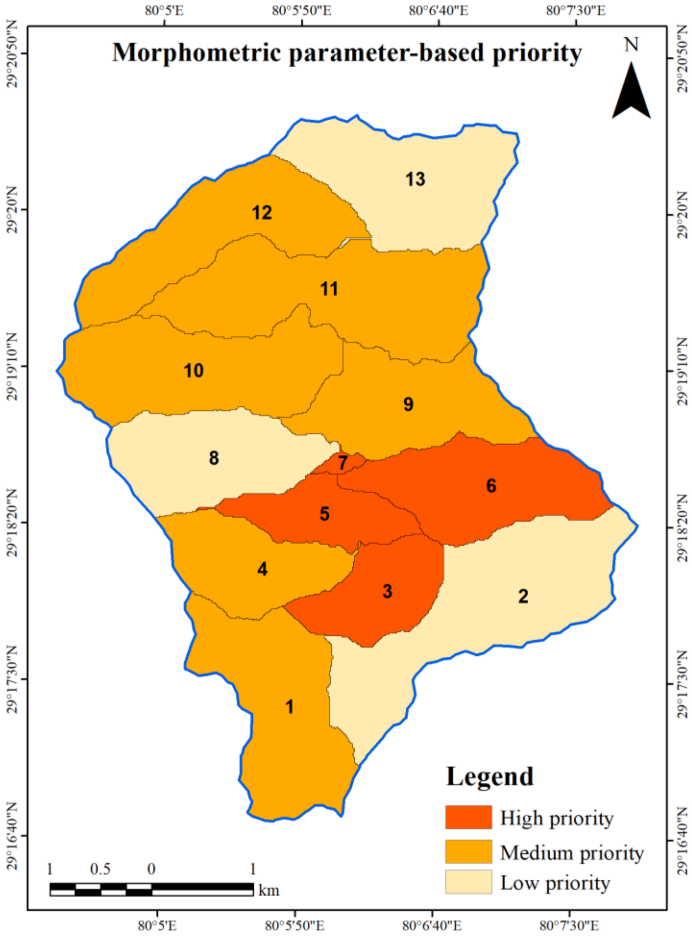


Figure 7. Prioritization based on morphometric parameter analysis

Table 8 Sub-basins priorities and ranks based on morphometric parameters

Sub-basins	Rank of Linear Parameter					Rank of Areal Parameter					Rank of Relief Parameter	Compound factor value	Priority
	Mean Rb	Dd	Dt	Fu	Lo	T	Rf	Bs	Re	Rc	Rh		
1	4	7	1	4	4	12	9	11	2	5	4	5.73	Medium
2	3	5	5	6	3	11	3	8	5	1	8	5.27	Low
3	7	9	4	2	6	8	11	9	4	9	3	6.55	High
4	2	6	9	10	4	6	5	2	11	7	5	6.09	Medium
5	8	2	8	3	2	3	12	9	4	4	1	5.09	High
6	6	3	2	5	3	9	2	3	10	6	6	5.00	High
7	9	1	11	1	1	4	10	1	12	3	2	5.00	High
8	5	10	10	12	6	2	6	5	8	8	7	7.18	Low
9	6	3	8	9	2	5	7	7	6	4	9	6.00	Medium
10	1	7	3	7	4	13	4	6	7	6	10	6.18	Medium
11	7	5	7	9	4	7	8	10	3	2	13	6.82	Medium
12	2	8	12	11	5	1	1	4	9	2	12	6.09	Medium
13	3	4	6	8	3	10	13	12	1	5	11	6.91	Low

8.2.Based on LULC analysis

The prioritization of sub-basins based on Land Use/Land Cover (LULC) analysis provides valuable insights into their ecological stability and vulnerability. Based on the compound factor values, sub-basins are categorized into three priority zones: High Priority (<6.75), Medium Priority (>6.75-<8.25), and Low Priority (>8.25) (Table 9). Each of these zones reflects the degree of vulnerability or stability of the sub-basin, guiding resource managers in decision-making and intervention planning.

High priority zones

Sub-basins with lower compound factor values are classified into the high priority zone (Figure 8), indicating areas that are ecologically or hydrologically vulnerable. These sub-basins typically exhibit features such as degraded land cover, high erosion potential, or unstable hydrological conditions, which necessitate urgent attention. Interventions in these zones may include afforestation, soil conservation, and restoration of natural vegetation to prevent further degradation and improve watershed management.

In the study, sub-basin 5, with a compound factor value of 6.00, sub-basin 9 (5.50), sub-basin 10 (6.50), sub-basin 11 (5.50), sub-basin 12 (5.25), and sub-basin 13 (5.25) are classified under the high priority zone. These sub-basins exhibit vulnerable conditions that require immediate restoration measures. The relatively low compound factor values signal that these areas may face challenges such as soil erosion, deforestation, or habitat loss, making them the highest priority for intervention.

Medium priority zones

Sub-basins with moderate compound factor values fall into the medium priority zone (Figure 8). These areas are relatively stable but still have the potential to face degradation if not properly managed. They require moderate attention, including monitoring, sustainable land management practices, and ecological interventions to prevent any decline in their condition. The medium priority classification indicates that while immediate intervention is not required, these areas should not be neglected.

In this case, sub-basin 1 (8.00), sub-basin 3 (7.50), sub-basin 4 (8.75), sub-basin 7 (6.75), and sub-basin 8 (7.25) are categorized as medium priority. These sub-basins show moderate ecological health and are not as vulnerable as those in the high priority zone, but they may still experience localized issues such as soil erosion, water quality degradation, or unsustainable agricultural practices. Management efforts in these zones should focus on maintaining the current balance while mitigating any emerging threats.

Low priority zones

Sub-basins with higher compound factor values are classified into the low priority zone (Figure 8). These sub-basins are considered ecologically stable, with less vulnerability to land degradation or hydrological instability. Typically, they exhibit favourable land cover and well-maintained ecosystems. While these sub-basins require minimal intervention, they should still be regularly monitored to ensure long-term sustainability and to address any emerging issues that may arise in the future.

Sub-basin 2 (9.75) and sub-basin 6 (9.00) fall under the low priority category. These areas are characterized by relatively better land use and land cover conditions, indicating a lower level of degradation and greater ecological stability. As a result, they require minimal management efforts, with a primary focus on ensuring that their current status is preserved through routine monitoring.

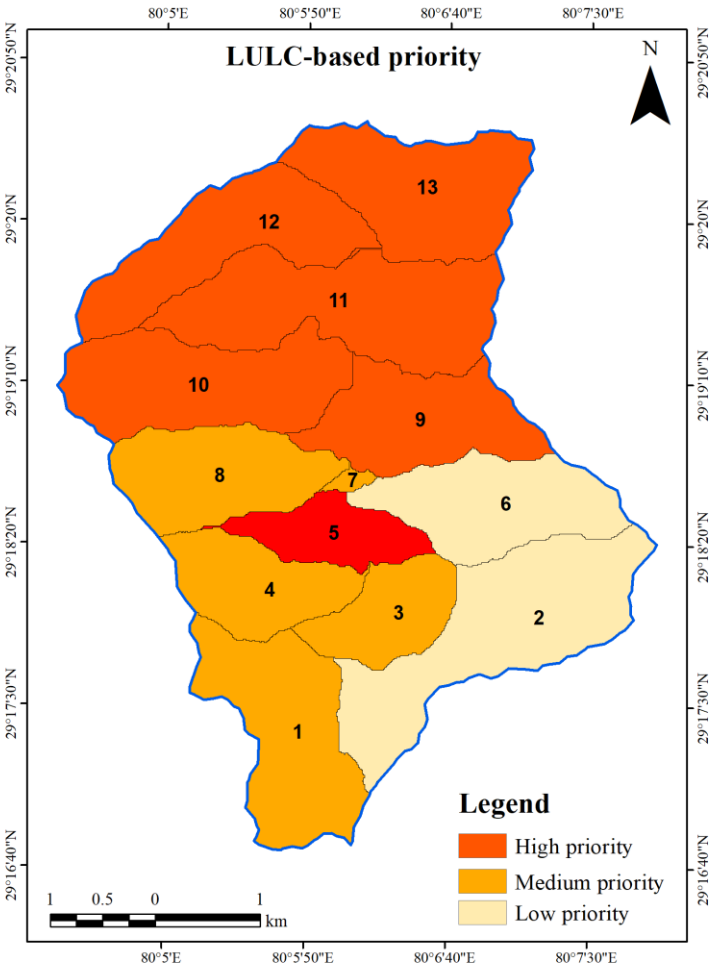


Figure 8. Prioritization based on LULC analysis

Table 9 Sub-basins priorities and ranks based on land use–land cover

Sub-basins	Dense forest cover	Rank	Settlement	Rank	Cultivated	Rank	Open forest cover	Ran k	Compound factor	Priority
1	1.86	12	0.05	7	0.12	4	0.10	9	8.00	Medium
2	2.70	13	0.00	13	0.08	3	0.09	10	9.75	Low
3	0.89	7	0.03	9	0.07	2	0.03	12	7.50	Medium
4	1.03	8	0.01	11	0.15	5	0.09	11	8.75	Medium
5	0.40	4	0.07	6	0.30	8	0.11	6	6.00	High
6	1.36	11	0.02	10	0.28	7	0.11	8	9.00	Low
7	0.01	1	0.01	12	0.04	1	0.01	13	6.75	Medium
8	1.23	10	0.04	8	0.25	6	0.13	5	7.25	Medium
9	0.50	6	0.15	4	0.85	11	0.21	1	5.50	High
10	1.15	9	0.13	5	0.81	9	0.17	3	6.50	High
11	0.45	5	0.41	2	1.66	13	0.19	2	5.50	High
12	0.33	3	0.68	1	0.84	10	0.11	7	5.25	High
13	0.23	2	0.36	3	1.33	12	0.16	4	5.25	High

8.3.Final Integrated Prioritization with Morphometric Parameters and LULC

The final prioritization of sub-basins has been established by combining the analysis of morphometric parameters and Land Use/Land Cover (LULC) data. The mean compound factor values for each sub-basin were calculated, and based on these values, sub-basins were assigned to one of three priority zones: high priority (<6.21), medium priority (>6.21-<6.86), and low priority (>6.86) (Table 10). This combined approach considers both the physical characteristics of the sub-basins and the current land use conditions, providing a more comprehensive assessment of each sub-basin's vulnerability and management needs.

Low priority zones

Sub-basins with higher mean compound factor values indicate greater ecological stability and less vulnerability to degradation. These sub-basins are categorized into the low priority zone, meaning they are more resilient and require minimal intervention. The priority here is to monitor these areas and ensure their ecological balance is maintained.

Sub-basin 1 (6.86), sub-basin 2 (7.51), sub-basin 3 (7.02), sub-basin 4 (7.42), sub-basin 6 (7.00), and sub-basin 8 (7.22) fall into the low priority zone (Figure 9). These sub-basins exhibit relatively stable land use and land cover characteristics, suggesting that they are less prone to soil erosion, flooding, or other environmental stressors. While they may still benefit from monitoring, they do not require urgent intervention.

Medium priority zones

The medium priority zone is assigned to sub-basins with moderate compound factor values, indicating areas that are relatively stable but may still face challenges if not properly managed. These sub-basins require ongoing attention, with a focus on sustainable land management practices to preserve their ecological health.

Sub-basin 10 (6.34) is classified into the medium priority zone (Figure 9). With a moderate compound factor value, this sub-basin is relatively stable but should be monitored to prevent potential degradation. It may require localized interventions to enhance land cover and maintain watershed health.

High priority zones

Sub-basins with lower mean compound factor values are categorized into the high priority zone (Figure 9), reflecting areas that are more vulnerable and require immediate attention. These sub-basins may experience land degradation, erosion, or other environmental threats that necessitate urgent conservation and restoration measures.

Sub-basin 5 (5.55), sub-basin 7 (5.88), sub-basin 9 (5.75), sub-basin 11 (6.16), sub-basin 12 (5.67), and sub-basin 13 (6.08) fall under the high priority zone. These sub-basins require immediate interventions such as reforestation, soil conservation, or other measures aimed at restoring their ecological balance. Their lower compound factor values indicate that these areas are more vulnerable to environmental stress, making them a high priority for restoration efforts.

Table 10 Final priority of sub-basins based on Morphometry and LULC

Sub-basins	Compound factor value of morphometric parameters	Compound factor value of LULC	Mean compound	Final priority
1	5.73	8	6.86	Low
2	5.27	9.75	7.51	Low
3	6.55	7.5	7.02	Low
4	6.09	8.75	7.42	Low
5	5.09	6	5.55	High
6	5.00	9	7.00	Low
7	5.00	6.75	5.88	High
8	7.18	7.25	7.22	Low
9	6.00	5.5	5.75	High
10	6.18	6.5	6.34	Medium
11	6.82	5.5	6.16	High
12	6.09	5.25	5.67	High
13	6.91	5.25	6.08	High

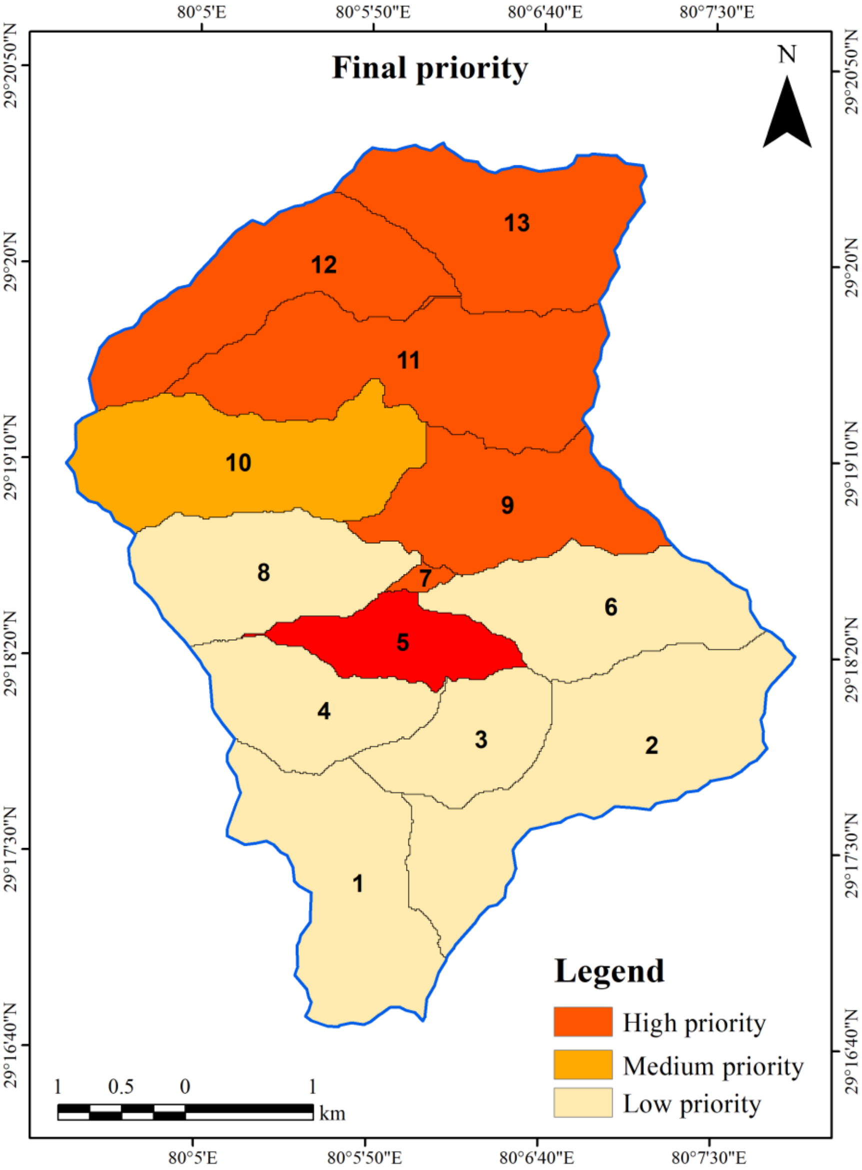


Figure 9. Prioritization based on morphometric parameter and LULC analysis

9. Conclusions and recommendations

The prioritization of sub-basins reveals distinct vulnerability levels. Sub-basins 1, 2, 3, 4, 6, and 8, classified as low priority zones, exhibit high stability and require minimal intervention, focusing primarily on monitoring. Sub-basin 10, in the medium priority zone, shows moderate stability, requiring sustainable management to prevent degradation.

Sub-basins 5, 7, 9, 11, 12, and 13 falls into the high priority zone, indicating significant vulnerability to degradation and requiring urgent conservation efforts like reforestation and soil conservation. This prioritization highlights the need for tailored management to ensure sustainable watershed health.

Key Recommendations:

Gabion Check Dams – To control erosion, reduce flow velocity, and enhance groundwater recharge, especially in steep terrains.

Contour Trenches & Staggered Trenches – To slow runoff, prevent soil loss, and improve water retention on sloping lands.

Spring-Shed Management – To protect and rejuvenate natural springs, ensuring sustained baseflow in river systems.

Vegetative Measures & Bioengineering – To stabilize slopes, prevent landslides, and enhance groundwater infiltration using afforestation and grass strips.

These nature-based solutions will contribute to long-term hydrological stability and ecological sustainability in the Gaudi River basin, ensuring effective river rejuvenation.

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