REPORT ON

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

Submitted to

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Submitted by

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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 Shipra river, located in Nainital 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-basin prioritization in the Shipra 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 Shipra 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 behavior 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 Shipra river basin

The Shipra river is a significant river system in the Nainital 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 Kosi river.

Geographical location and extent

The Shipra river basin lies within the latitudinal range of approximately 29°23'20'' to 29°26'40''N and the longitudinal range of 79°29'10'' to 79°31'41''E. The region covers an area of around 33 km², with elevations varying from 1000 meters to over 2408 meters above mean sea level, contributing to diverse climatic and hydrological characteristics (Figure 1a).

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 1463 mm to 1829 mm, heavily influencing the river's flow regime.

Topography and land use

The terrain of the Shipra river basin is predominantly mountainous, interspersed with valleys and plains, elevation ranges between 1000 meters and 2408 meters amsl. Current Land use (LANDSAT, Dec-2024) in the region comprises: Based on the satellite image, the 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 Nainital as the nearest urban center.

Soil

The study area is mainly governed by the loamy soil and sandy loam (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.

Slope

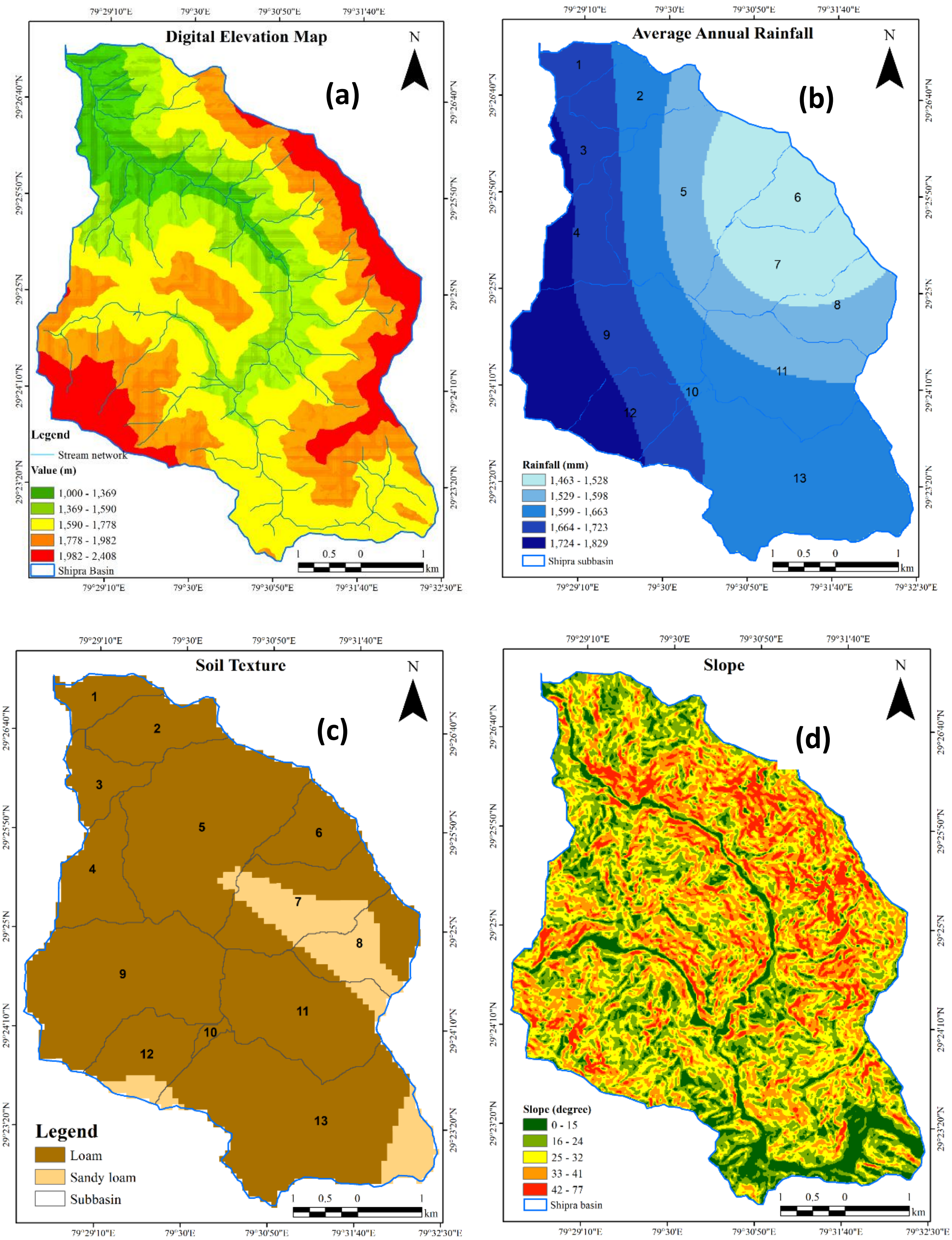
The slope variation in the Shipra river basin, ranging from 15° to 77°, highlights the highly diverse and rugged terrain of the area (Figure 1d). Such steep slopes significantly influence the river's hydrological and geomorphological processes. Slopes exceeding 45° suggest a propensity for rapid surface runoff, as water infiltration is minimal in such steep areas. This results in higher streamflow and increased velocity, which can enhance the river's erosive power. Furthermore, steep slopes are prone to soil erosion during rainfall, contributing to a substantial sediment load in the river. The gentler slopes, around 15°, may allow for some infiltration and act as transition zones for sediment deposition.

Hydrology

The Shipra 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.

Geology

The geology (Figure 1f) of the Shipra River basin, predominantly consisting of quartzite (90%) and phyllite (10%), plays a significant role in shaping the region's hydrological behavior. Quartzite, being a hard and dense rock, exhibits low permeability, limiting groundwater infiltration and encouraging surface runoff during rainfall events. This characteristic contributes to higher streamflow and faster water movement, especially on the steeper slopes, which can lead to increased erosion and sediment transport. The phyllite, being a softer and more easily weathered rock, has slightly higher permeability compared to quartzite, allowing for some water infiltration, particularly in less steep areas. However, the overall impact of quartzite on the hydrological system is dominant, restricting the infiltration capacity and enhancing surface runoff. Together, the geology of the region creates a hydrological system where surface runoff predominates, resulting in increased discharge, faster water flow, and potential for higher erosion rates in the river system. This interaction between geology and hydrology also influences groundwater recharge, sediment transport, and streamflow dynamics throughout the watershed.



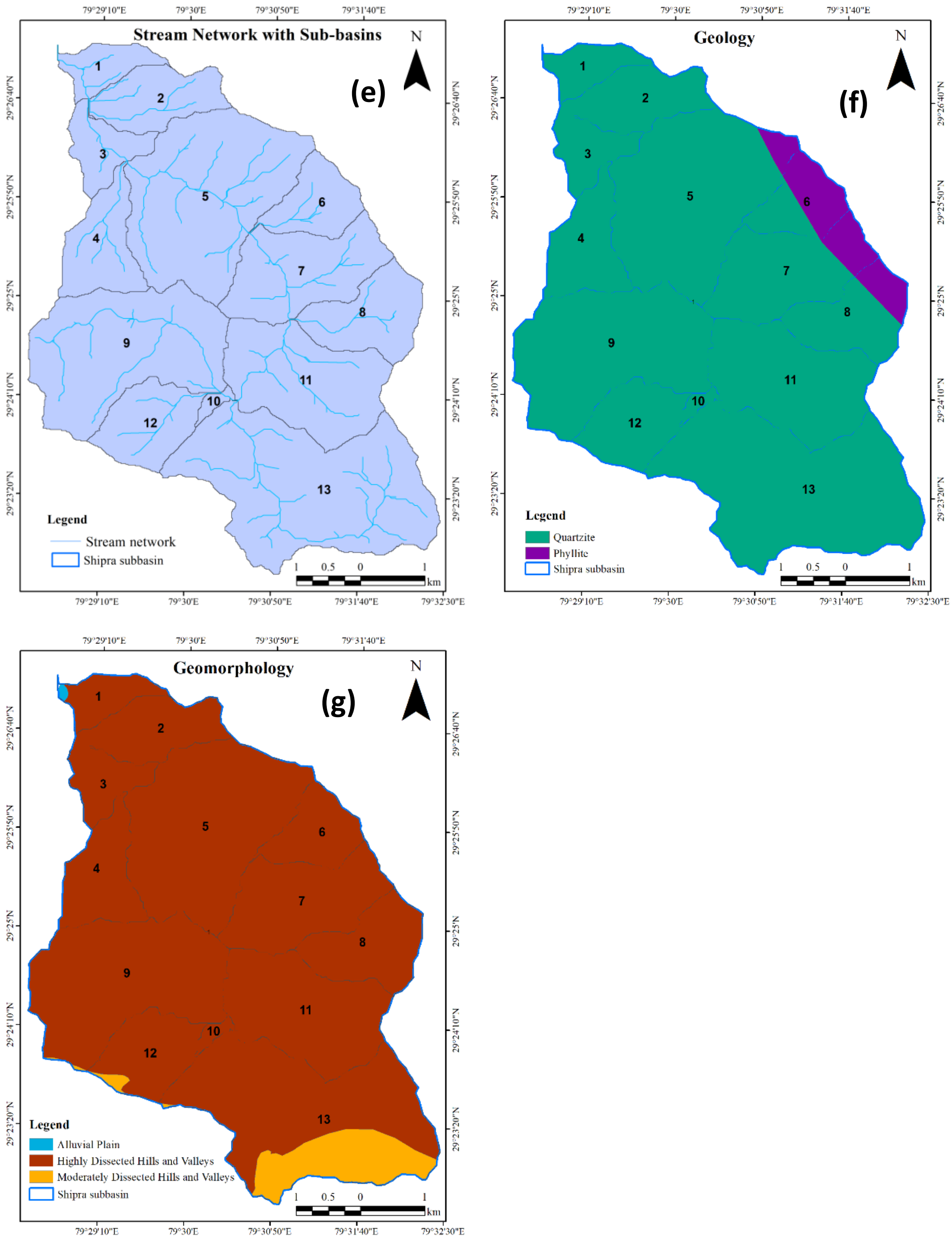


Figure 1. DEM (1a), rainfall (1b), soil (1c), slope (1d), sub-basins (1e), geology (1f) and geomorphology (1g) of the Shipra River basin

Geomorphology

The geomorphology (Figure 1g) of the Shipra River basin is predominantly shaped by 95% highly dissected valleys and hills, with a smaller portion of 4% moderately dissected hills and valleys, and a minor area of alluvial plains. The dominance of highly dissected valleys and hills suggests a steep and rugged terrain, which leads to rapid surface runoff and faster streamflow, resulting in significant erosion and sediment transport within the river system. The moderately dissected hills and valleys contribute to a more variable runoff pattern, with some areas allowing for increased infiltration while others experience accelerated surface runoff. The alluvial plains, though minimal, provide areas for sediment deposition and groundwater recharge, promoting slower runoff and more infiltration. The combination of these landforms creates a dynamic hydrological environment, with rapid water movement and erosion in the steep areas, and areas of groundwater recharge and sediment retention in the alluvial plains.

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 Mahargaon village is the high population density (802462.26 person/km2) and Josiya Dhuna village is the lowest population density (259.56 person/km^2).

Table 1 Demographic profile of the Shipra River basin

Village Name	**Total Population**	**Area (sq.km)**	**Population Density (**person/km^2)
Padli	0.27	440.00	1644.48
Mahargaon	0.0029	2295.00	802462.26
Hartapa	0.49	596.00	1218.32
Sirodi	0.61	290.00	476.57
Josiya Dhuna	0.24	63.00	259.56
Dhuna	0.01	41.00	4887.38
Niglat Talla	0.58	280.00	479.16
Bhowali Gaon	0.53	483.00	906.19
Niglat Malla	1.30	593.00	456.54
Kuleti	0.32	26.00	80.12
Bhowali Senitorium	0.53	719.00	1364.29
Shyamkhet	0.58	881.00	1527.11
Bhawanipur	0.62	87.00	141.20
Kalahpeera	0.33	549.00	1670.01
Lvesaal	0.68	1029.00	1507.81
Bhowali (urban)	0.83	6309.00	7583.64
Nagri Gaon	0.04	1493.00	35629.45

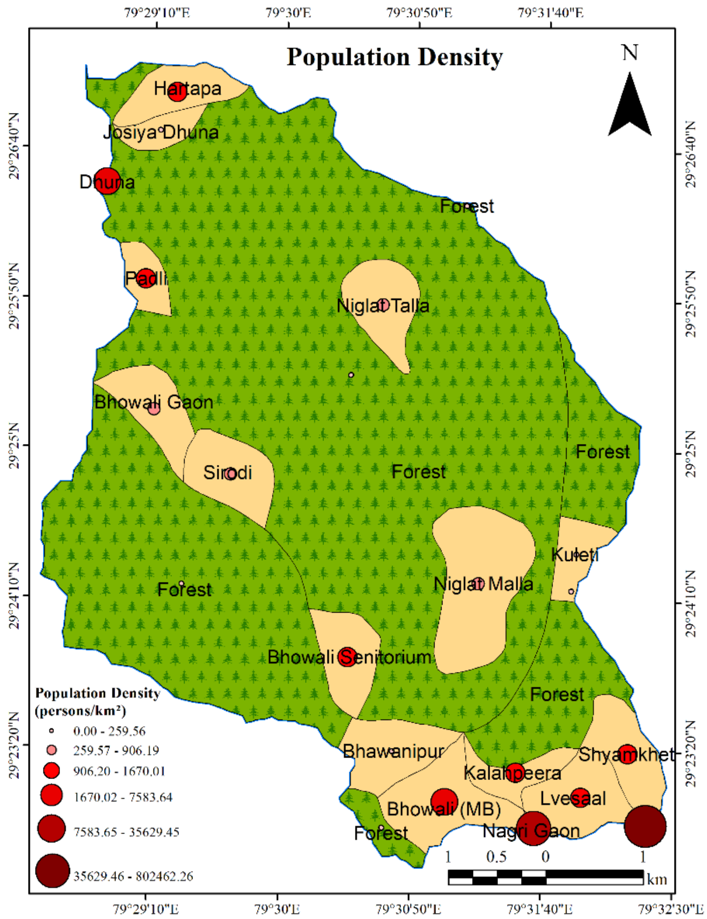


Figure 2. Population density of the Shipra River basin

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 Shipra River basin in Nainital. 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	15.87	20.52	19.23	18.10	+2.23
Cultivated	2.36	1.83	4.94	6.30	+3.94
Open Forest Cover	14.95	10.63	8.18	7.47	-7.48
Settlement	0.56	1.15	1.41	1.73	+1.17

Dense forest cover

The decrease in dense forest cover from 1995 to 2015 indicates deforestation, likely driven by agricultural expansion and urban development. However, the slight increase observed in 2024 suggests that reforestation initiatives or conservation efforts may have been implemented successfully in recent years, reflecting a positive shift toward forest regeneration.

Cultivated land

The steady increase in agricultural land from 1995 to 2024 indicates significant land-use changes. This expansion could be attributed to population growth and the rising demand for food production, leading to the conversion of forested and other land types into agricultural fields.

Open forest cover

The decline in open forest cover from 1995 to 2024 highlights a consistent trend of degradation, potentially caused by encroachment for agriculture or urban development. This significant reduction suggests the need for targeted restoration programs to address the loss of these critical forest ecosystems.

Settlement area

The increase in built-up areas from 1995 to 2024 reflects urban expansion, likely driven by population growth and infrastructure development. This trend underscores the growing demand for urban spaces and the associated impact on natural and agricultural land.

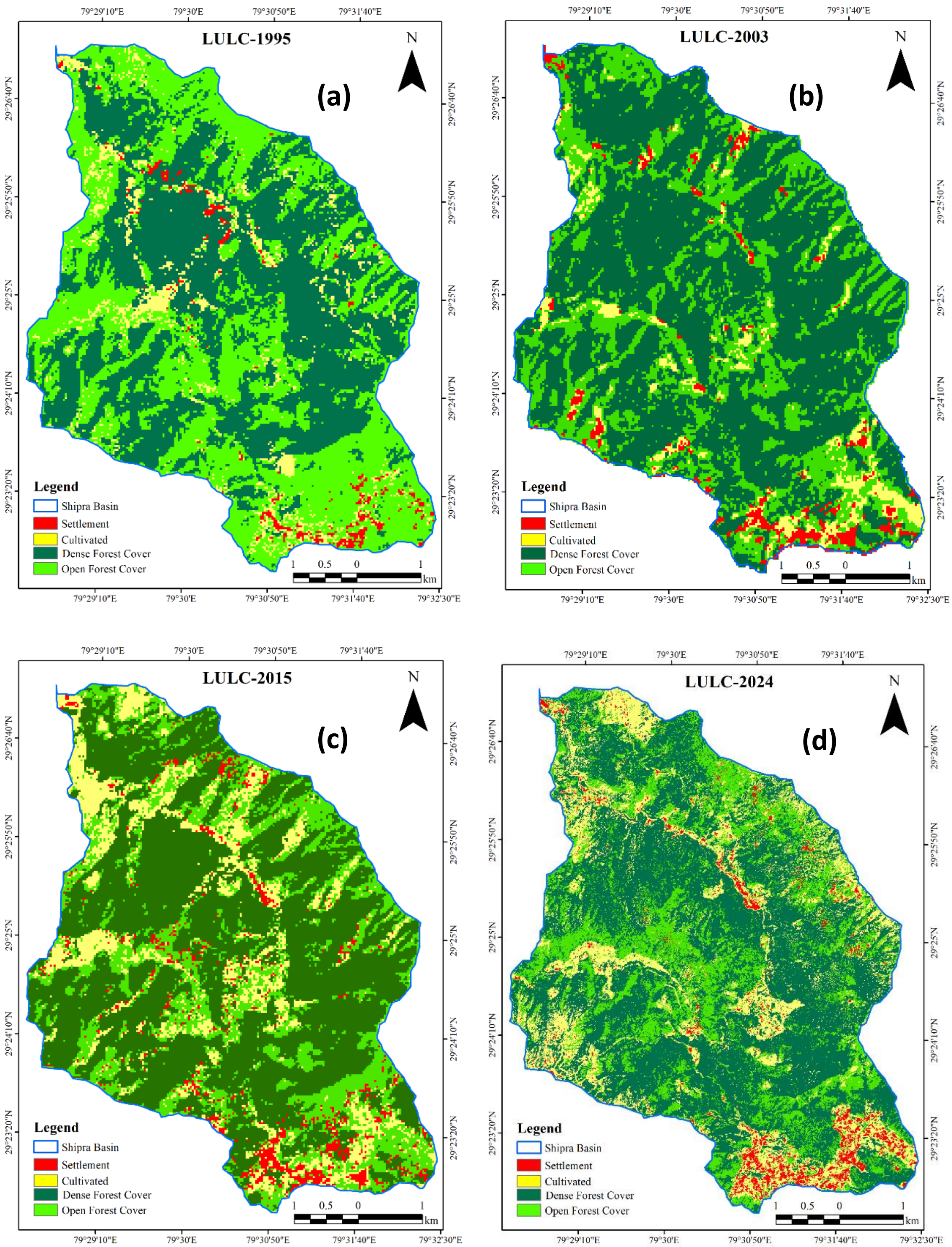


Figure 3. Temporal Dynamics of LULC for 1995 (3a), 2003 (3b), 2015 (3c), and 2024 (3d).

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 Shipra River basin have been discussed accordingly (Table 3).

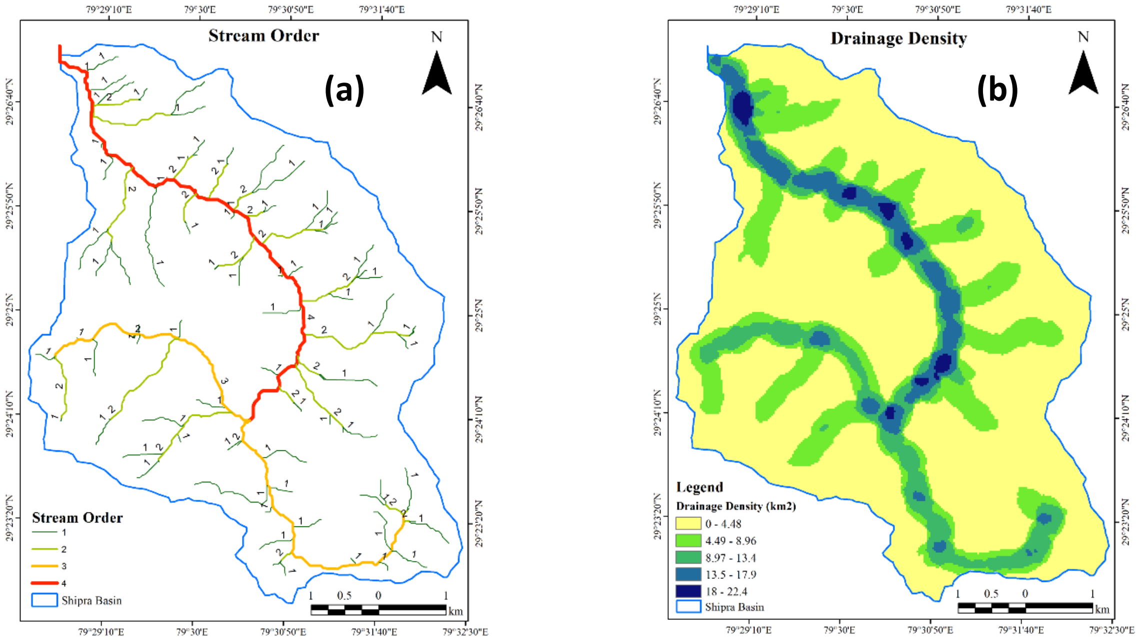


Figure 4. Stream order (4a) and drainage density (4b) of the Shipra River basin

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) and bifurcation ratio (Rb) as discussed below:

Stream order (U)

The stream order of the Shipra 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 132 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 (Figure. 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, Shipra has been identified as a 4^{th} 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.

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)

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 67.75 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 Shipra River is 132, 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 5. The lowest bifurcation ratio is observed in sub-basin 10, with a value of 1. On the other hand, the highest bifurcation ratio is recorded in sub-basin 12, with a value of 5.00. 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 bifurcation ratio values for Shipra River sub-basins are represented in Table 5.

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

Sub-basins	Stream Order (U)	I Order	II Order	III Order	IV Order	Total
Sub Basin 1	No of Stream (Nu)	3			1	
	Stream Length (LU) (km)	1.25			1.17	2.42
Sub Basin 2	No of Stream (Nu)	5	2	1		
	Stream Length (LU) (km)	2.28	2.13	0.03		4.44
Sub Basin 3	No of Stream (Nu)	2			1	
	Stream Length (LU) (km)	0.56			1.32	1.89
Sub Basin 4	No of Stream (Nu)	3	1			
	Stream Length (LU) (km)	2.12	1.29			3.41
Sub Basin 5	No of Stream (Nu)	18	6		1	
	Stream Length (LU) (km)	5.73	3.12		2.54	11.38
Sub Basin 6	No of Stream (Nu)	4	1			
	Stream Length (LU) (km)	1.52	1.06			2.58
Sub Basin 7	No of Stream (Nu)	8	2		1	

	Stream Length (LU) (km)	2.68	1.04		1.67	5.39
Sub Basin 8	No of Stream (Nu)	4	1			
	Stream Length (LU) (km)	1.26	1.76			3.02
Sub Basin 9	No of Stream (Nu)	15	4	1		
	Stream Length (LU) (km)	2.72	2.82	3.60		9.15
Sub Basin 10	No of Stream (Nu)			1		
	Stream Length (LU) (km)			0.31		0.31
Sub Basin 11	No of Stream (Nu)	10	3		1	
	Stream Length (LU) (km)	2.48	1.99		1.77	6.25
Sub Basin 12	No of Stream (Nu)	5	1			
	Stream Length (LU) (km)	1.92	1.50			3.42
Sub Basin 13	No of Stream (Nu)	20	5	1		
	Stream Length (LU) (km)	8.58	0.82	4.70		14.10

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 0.82 km to 1.4 km across the Sub-basins. Sub-basin 3 exhibit the shortest overland flow length of 0.82 km, suggesting steeper slopes and quicker runoff towards the drainage network. In contrast, sub-basin 1 has the highest overland flow length of 1.48 km, indicative of gentler slopes and slower water movement, allowing for greater infiltration and delayed runoff.

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 Shipra 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) of the Sub-basins varies between 1.78 km/km² and 2.96 km/km², reflecting a range of hydrological and geomorphological characteristics. Sub-basin 11 exhibits the lowest Dd of 1.78 km/km², suggesting widely spaced streams, indicative of permeable soils and higher infiltration potential. In contrast, sub-basin 1 has the highest Dd of 2.96 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 0.36 to 1.89, indicating different levels of stream frequency and drainage network development. Sub-basin 10 exhibits the lowest drainage texture of 0.36, 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 5 has the highest drainage texture of 1.89, 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 Shipra River sub basins. Sub-basin 10 has the smallest basin length of 0.78 km, reflecting its compact and narrow morphology. In contrast, Sub-basin 13 has the largest basin length of 3.73 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 Shipra 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	0.82	6.90	4	2.42	1.81	3.00	2.96	0.58	4.90	0.43	1.48	0.25	0.22	1.68	0.69	0.38
2	1.58	7.30	8	4.44	2.23	2.25	2.80	1.10	5.06	0.68	1.40	0.32	0.37	1.34	0.89	0.40
3	0.99	6.40	3	1.89	1.56	2.00	1.91	0.47	3.03	0.31	0.95	0.41	0.30	1.42	0.55	0.35
4	1.62	7.88	4	3.41	2.37	3.00	2.10	0.51	2.46	0.38	1.05	0.29	0.33	1.36	0.85	0.36
5	5.68	13.25	25	11.38	2.94	1.50	2.00	1.89	4.40	1.36	1.00	0.66	0.41	0.81	1.07	0.36
6	1.28	6.93	5	2.58	1.83	4.00	2.02	0.72	3.91	0.58	1.01	0.38	0.33	1.35	0.93	0.51
7	2.79	10.05	11	5.39	2.29	2.00	1.93	1.09	3.94	0.80	0.97	0.53	0.35	1.02	0.98	0.43
8	1.83	8.00	5	3.02	2.13	4.00	1.65	0.63	2.73	0.50	0.82	0.41	0.36	1.21	0.89	0.42
9	5.04	13.00	20	9.15	3.13	3.90	1.81	1.54	3.97	1.15	0.91	0.52	0.37	0.89	0.89	0.29
10	0.14	2.78	1	0.31	0.78	1.00	2.14	0.36	6.98	0.36	1.07	0.23	0.23	2.64	0.34	0.43
11	3.51	10.45	14	6.25	2.81	1.66	1.78	1.34	3.99	0.96	0.89	0.44	0.40	1.01	0.75	0.27
12	1.63	7.35	6	3.42	2.21	5.00	2.10	0.82	3.68	0.68	1.05	0.33	0.38	1.31	0.82	0.37
13	6.83	17.00	26	14.10	3.73	4.50	2.06	1.53	3.80	1.18	1.03	0.49	0.30	0.83	0.61	0.16

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 2.46 in Sub-basin 4 to 6.98 in Sub-basin 10. Sub-basin 4 exhibits the lowest stream frequency, indicating a sparse drainage network, likely due to gentle slopes, high infiltration, or permeable soils. Conversely, Sub-basin 10 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 0.31 in Sub-basin 3 to 1.36 in Sub-basin 5. Sub-basin 5 has the highest texture ratio of 1.36, 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), a measure of the shape of a basin calculated as the ratio of basin area to the square of basin length, ranges from 0.23 in Sub-basin 10 to 0.66 in Sub-basin 5. A higher form factor, such as in sub-basin 5, indicates a near-circular basin shape, which typically results in a shorter lag time for peak discharge during rainfall events. Conversely, sub-basin 10, 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 0.22 in sub-basins 1 to 0.41 in sub-basin 5. A low circularity ratio, such as those observed in Sub-basins 1, indicates an elongated basin shape, which typically results in longer travel times for runoff. In contrast, sub-basin 5, 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 0.81 in sub-basin 5 to 2.64 in sub-basin 10. A low elongation ratio, like in sub-basin 5, indicates a highly elongated, narrow basin, which can result in longer surface flow paths and delayed runoff. In contrast, sub-basin 10, 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 5, with a difference of 1069 meters between the highest point at 2232 meters and the lowest point at 1163 meters. On the other hand, sub-basin 10 has the lowest relief of just 341 meters, signifying a relatively flat or gently sloping area (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-basins with higher relief ratios, such as sub-basin-6 (0.5087) and sub-basin-10 (0.4344), indicate steeper slopes and more pronounced elevation changes. These areas are likely to experience faster runoff, higher streamflow velocities, and increased erosion potential. In contrast, Sub-basins with lower relief ratios, such as sub-basin-13 (0.1640) and sub-basin-11 (0.2657), represent gentler slopes with less dramatic elevation differences, which may promote slower runoff and higher infiltration rates.

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:

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw})_i \quad (2)$$

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 Shipra River. The HRUs were defined using the multiple land use/soil/slope technique, with land use (10%), soil (15%), and slope (15%) thresholds, creating 189 HRUs for the Shipra River basin.

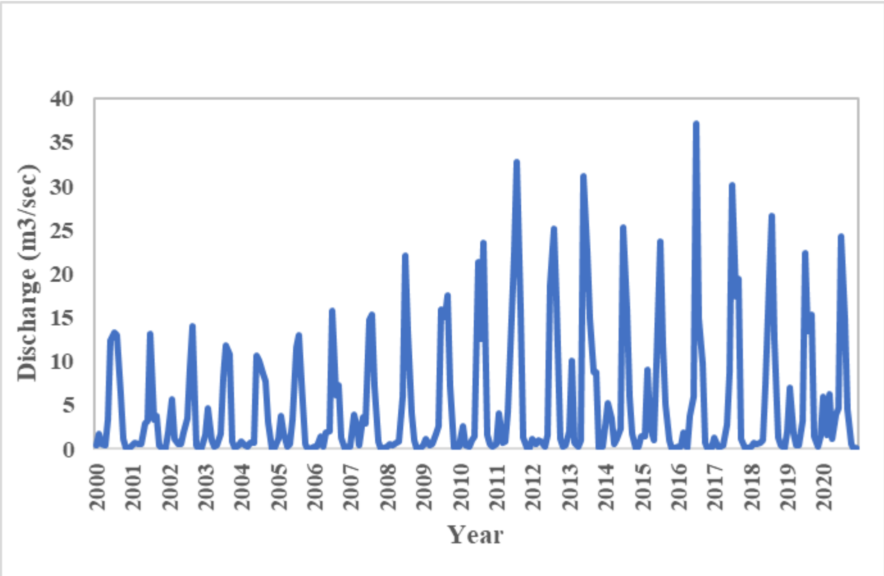


Figure 5. Annual simulated discharge of the Shipra River basin from 2000 to 2020

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. 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.

Period 1: 1995–2003 (Baseline discharge): During the first period, streamflow discharge was relatively lower across all Sub-basins. For example, Sub-basin 1 had a discharge of 8.54 m^3/s, while sub-basin 3 and Sub-basin 5 recorded 7.95 m^3/s and 7.29 m^3/s, respectively. Sub-basins with lower flow, such as sub-basin 2 (0.40 m^3/s) and sub-basin 6 (0.33 m^3/s), indicate minimal land cover changes or largely natural vegetation. The overall streamflow in this period reflects a baseline condition with limited urbanization or other significant anthropogenic impacts.

Period 2: 2003–2015 (Increase in discharge): Streamflow discharge increased noticeably in this period, with significant rises observed in high-flow sub-basins. For instance, sub-basin 1's discharge rose to 11.12 m^3/s, while sub-basin 3 and Sub-basin 5 increased to 10.34 m^3/s and 9.49 m^3/s, respectively. Smaller Sub-basins, such as sub-basin 2 and sub-basin 6, also showed moderate increases, reaching 0.52 m^3/s and 0.42 m^3/s, respectively. These trends suggest intensified LULC changes, likely driven by urban expansion, deforestation, or agricultural development, leading to enhanced surface runoff and reduced infiltration.

Period 3: 2015–2020 (Continued increase in discharge): The third period exhibits the highest streamflow discharges, with all Sub-basins showing continued increases. Sub-basin 1 reached 13.36 m^3/s, and sub-basin 3 and sub-basin 5 rose to 12.42 m^3/s and 11.39 m^3/s, respectively. Smaller sub-basins like sub-basin 2 and Sub-basin 6 increased further to 0.62 m^3/s and 0.51 m^3/s, respectively. The increases are consistent across the board, suggesting intensified human activities, including urban sprawl and land-use conversions, exacerbating surface runoff and altering the hydrological regime.

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	8.54	11.12	13.36
2	0.40	0.52	0.62
3	7.95	10.34	12.42
4	0.41	0.53	0.64
5	7.29	9.49	11.39
6	0.33	0.42	0.51
7	5.53	7.19	8.63
8	0.49	0.62	0.74
9	1.27	1.66	2.00
10	1.71	2.25	2.70
11	4.29	5.62	6.77
13	0.41	0.54	0.65
12	1.70	2.22	2.69

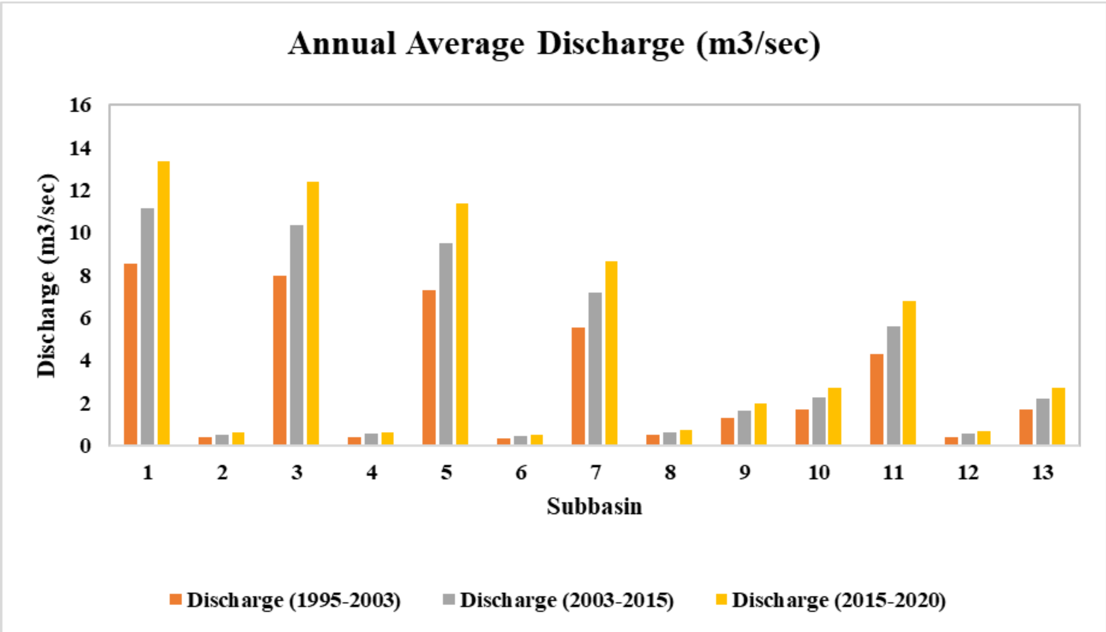


Figure 6. LULC impacts on discharge for 1995–2003, 2003–2015, and 2015–2024

8. Prioritization of Shipra 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 (<5.42), Medium priority (>5.42-<6.57), and Low priority (>6.57) (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.

High priority sub-basins

Sub-basins 1, 2, 6, and 10 falls under the high-priority category, with compound factor values of 4.273, 4.909, 5.273, and 4.636, respectively (Figure 7). These Sub-basins exhibit conditions that demand immediate attention for resource conservation and sustainable management due to their relatively lower compound factor values, indicating higher vulnerability or criticality.

Medium priority sub-basins

Sub-basins 4, 7, 12, and 13 are classified as medium priority, with compound factor values of 6.091, 6.545, 5.818, and 6.455, respectively (Figure 7). These areas exhibit moderate levels of concern and should be monitored closely, with targeted interventions to prevent them from shifting to high-priority status.

Low priority sub-basins

Sub-basins 3, 5, 8, 9, and 11 are categorized as low priority (Figure 7), with compound factor values ranging from 6.909 to 7.727. These Sub-basins currently show less critical conditions but still require periodic monitoring to ensure that they remain stable and do not degrade over time.

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 (<5.83), Medium Priority (>5.83-<7.91), and Low Priority (>7.91) (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.

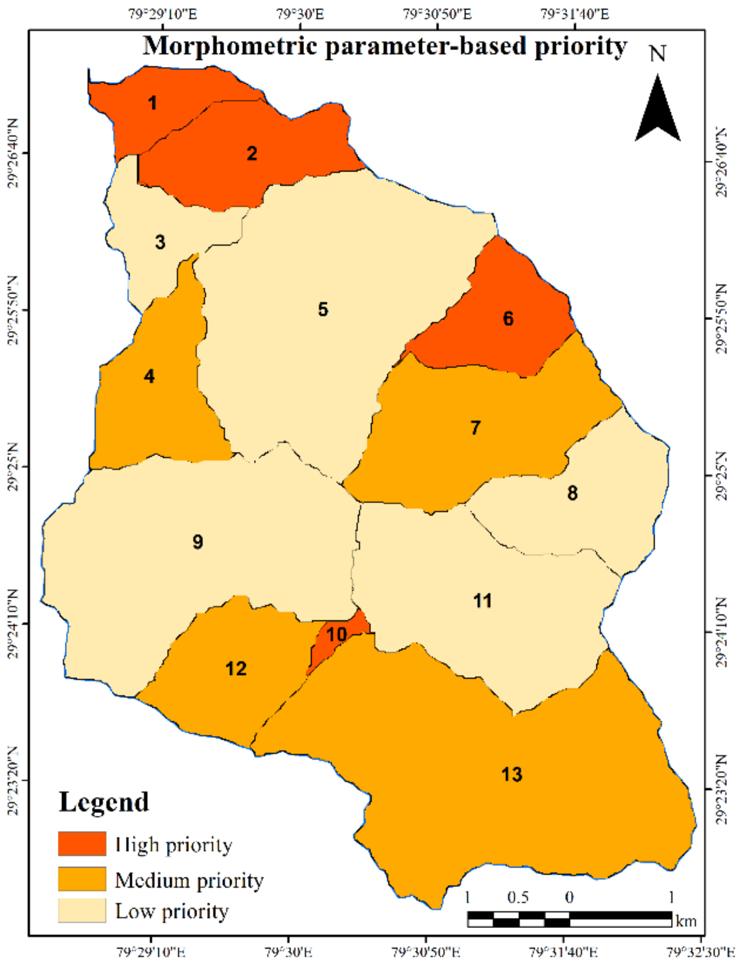


Figure 7. Prioritization based on morphometric parameter analysis

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	5	1	10	3	1	4	2	2	12	1	6	4.27	High
2	6	2	5	2	2	7	4	6	8	7	5	4.91	High
3	7	9	12	9	4	1	7	3	11	3	10	6.91	Low
4	5	4	11	11	3	3	3	4	10	4	9	6.09	Medium
5	9	7	1	4	4	12	12	13	1	10	8	7.36	Low
6	3	6	8	6	4	6	6	5	9	4	1	5.27	High
7	7	8	6	6	4	8	11	9	5	5	3	6.55	Medium
8	3	12	9	10	6	5	7	8	6	6	4	6.91	Low
9	4	10	2	5	5	10	10	11	3	7	11	7.09	Low
10	10	3	13	1	3	2	1	1	13	2	2	4.64	High
11	8	11	4	5	5	9	8	10	4	9	12	7.73	Low
12	1	4	7	8	3	7	5	7	7	8	7	5.82	Medium
13	2	5	3	7	4	11	9	12	2	3	13	6.45	Medium

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

Sub-basins	Dense forest cover	Rank	Open forest cover	Rank	Cultivated	Rank	Settlement	Rank	Compound Factor	Priority
1	0.278	2	0.181	2	0.31	6	0.043	5	3.75	High
2	0.950	5	0.305	4	0.32	7	0.014	10	6.50	Medium
3	0.346	3	0.199	3	0.41	8	0.036	7	5.25	High
4	1.033	6	0.391	8	0.20	2	0.007	12	7.00	Medium
5	3.261	12	1.544	11	0.79	11	0.108	2	9.00	Low
6	0.639	4	0.350	6	0.27	4	0.026	8	5.50	High
7	1.648	9	0.618	9	0.44	9	0.102	3	7.50	Medium
8	1.165	8	0.358	7	0.29	5	0.024	9	7.25	Medium
9	2.173	10	1.592	12	1.22	12	0.085	4	9.50	Low
10	0.090	1	0.031	1	0.02	1	0.004	13	4.00	High
11	2.213	11	0.696	10	0.56	10	0.040	6	9.25	Low
12	1.079	7	0.319	5	0.22	3	0.010	11	6.50	Medium
13	3.267	13	1.637	13	1.28	13	0.647	1	10.00	Low

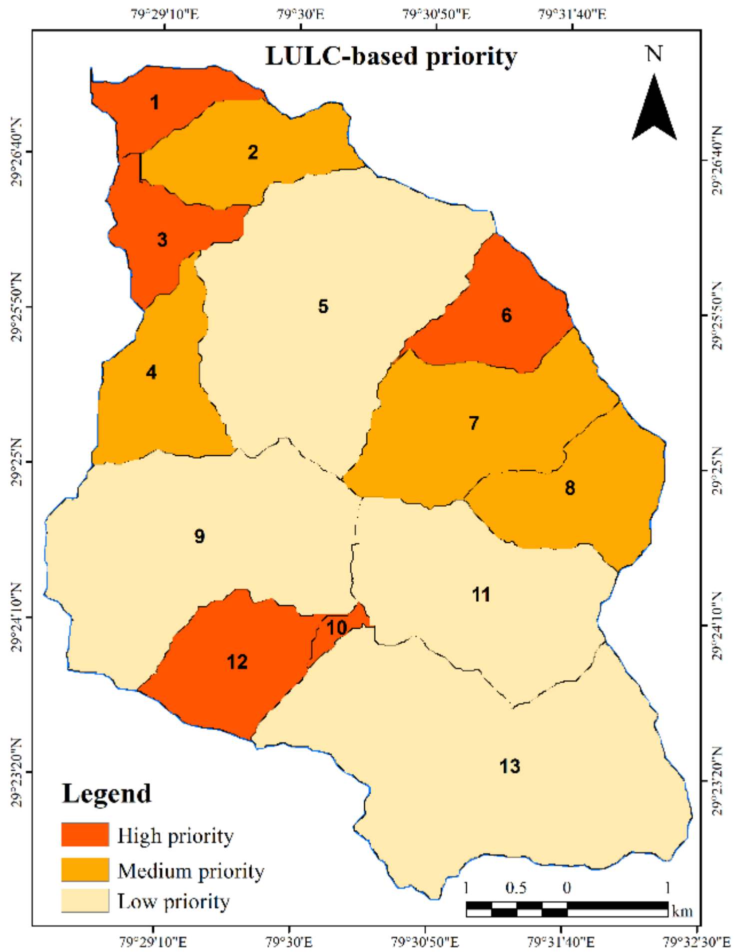


Figure 8. Prioritization based on LULC analysis

High priority Sub-basins

Sub-basins 1, 3, 6, and 10 are classified as high priority (Figure 8), with compound factor values of 3.75, 5.25, 5.5, and 4, respectively. These Sub-basins demonstrate critical LULC conditions that require immediate intervention to mitigate potential degradation and support sustainable development.

Medium priority Sub-basins

Sub-basins 2, 4, 7, 8, and 12 falls into the medium priority category (Figure 8), with compound factor values of 6.5, 7, 7.5, 7.25, and 6.5, respectively. These sub-basins exhibit moderate vulnerability and demand focused management to address specific LULC-related challenges and prevent further deterioration.

Low priority Sub-basins

Sub-basins 5, 9, 11, and 13 are categorized as low priority (Figure 8), with compound factor values of 9, 9.5, 9.25, and 10, respectively. These sub-basins currently reflect relatively stable LULC conditions but still require regular monitoring to ensure that these conditions are maintained.

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 (<5.50), medium priority (>5.50-<6.99), and low priority (>6.99) (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.

High Priority Sub-basins

Sub-basins 1, 6, and 10 falls under the high-priority category, with mean compound factor values of 4.01, 5.39, and 4.32, respectively (Figure 9). These sub-basins require immediate intervention due to critical morphometric and LULC conditions that suggest higher vulnerability to environmental and hydrological stresses.

Medium priority Sub-basins

Sub-basins 2, 3, and 4 are classified as medium priority, with mean compound factor values of 5.70, 6.08, and 6.55, respectively (Figure 9). These areas display moderate vulnerability, necessitating targeted management efforts to prevent further degradation and ensure sustainable use of resources.

Low priority Sub-basins

Sub-basins 5, 7, 8, 9, 11, 12, and 13 are categorized as low priority (Figure 9), with mean compound factor values ranging from 7.02 to 8.49. These sub-basins currently exhibit relatively stable conditions but still require periodic monitoring to maintain their status and address emerging risks.

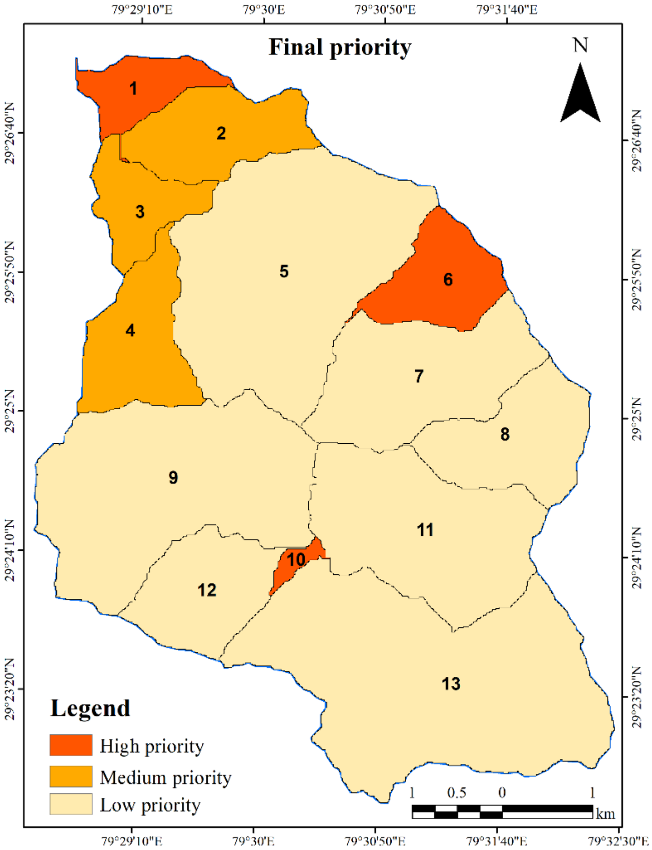


Figure 9. Prioritization based on morphometric parameter and LULC analysis

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	4.27	3.75	4.01	High
2	4.91	6.5	5.70	Medium
3	6.91	5.25	6.08	Medium
4	6.09	7	6.55	Medium
5	7.36	9	8.18	Low
6	5.27	5.5	5.39	High
7	6.55	7.5	7.02	Low
8	6.91	7.25	7.08	Low
9	7.09	9.5	8.30	Low
10	4.64	4	4.32	High
11	7.73	9.25	8.49	Low

12	5.82	6.5	6.16	Low
13	6.45	10	8.23	Low

9. Conclusions and recommendations

The prioritization of sub-basins reveals distinct vulnerability levels. Sub-basins 5, 7, 8, 8, 11, 12, and 8, classified as low priority, exhibit high stability and require minimal intervention, focusing primarily on monitoring. Sub-basin 2, 3 and 4, in the medium priority zone, shows moderate stability, requiring sustainable management to prevent degradation.

Sub-basins 1, 6 and 10 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 Shipra River basin, ensuring effective river rejuvenation.

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