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Sub-watershed Prioritization for Soil Erosion Potentiality Estimation Based on Integrated Approach of Morphometric Analysis, Hypsometric Analysis and R- Factor: A Study of Pagladiya River Basin

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Abstract
Prioritization of sub-watersheds for the purpose of soil erosion estimation within the Pagladiya watershed has been carried out through three significant approaches—morphometric analysis, hypsometric analysis, and the R factor (RUSLE model). Significantly, the watershed is segmented into 6 small sections of sub-watersheds (Sb-W1 to Sb-W6) using Hydrology tools in ArcGIS. In the morphometric analysis approach, 14 variables are considered to assign priority rankings based on compound values, where Sb-W1, Sb-W2, and Sb-W3 are identified as high-priority sub-watersheds. An inter-correlation matrix is also used to gain a detail understanding of how the morphometric variables are related to each other and how these relationships influence soil erosion. For the R factor (RUSLE model), CRU 2024 rainfall data is utilized to estimate soil erosion due to rainfall. This analysis reveals high priority in Sb-W1 and Sb-W3. Sb-W1, Sb-W4, and Sb-W5 are categorised as high priority based on Hypsometric Integral. Again, by integrating all three approaches Sb-W1 is found as a common high-priority area. Significantly, Sb-W1 followed by Sb-W3 (total area 580.65 km²) are require urgent soil conservation measures, while the remaining sub-watersheds should be regularly monitored to prevent future soil erosion.
Keywords: *Hypsometric Analysis, Morphometric Analysis, Pagladiya Watershed, Prioritization*, *R factor* (*RUSLE model)*

1. INTRODUCTION

Soil is vital for sustained ecosystem function and is essential to life and ecological balance. It supports biogeochemical cycles, crucial for longevity of mankind as well as environmental stability (Dong et al., 2023; Zheng et al., 2022). Currently, one of the major global environmental problems is soil degradation that directly affects hydrological cycle, biodiversity, and carbon retention (Keesstra et al., 2021; Lal, 2004; Thornes, 1985). According to NAAS (2010), soil erosion is a significant threat to India's cultivable land. Based on assessments by ICAR using a harmonized database, about 92.4 million hectares of agricultural land were found to be experiencing soil loss exceeding 10 tonnes per hectare per year. This highlights the alarming scale of land degradation in the country.

Basically, watershed represents an area where movement of surface water occur towards a common discharge point. The water movement along with related exogenic and endogenic processes take place over the course of a watershed reveal valuable insights about the drainage basin such as genesis, evolution, and mechanism etc (Singh et al., 1997). Significantly, statistical analysis for geomorphic variables is fundamental for detail analysing of fluvial geomorphology that provide numerical insights and systematic evaluation of form and functioning of drainage system, forming the basis of its geomorphological characterization (Strahler, 1964).

Prioritization of watershed is a long-term effective conservation tool for geopedological and hydrological assets (Mir et al., 2021). In this process, fluvial geomorphology insights a systematic framework of landforms formed through fluvial mechanism (Barman et al., 2021). Moreover, Sub-watersheds prioritization plays a significant role in detail analysis of morphometric behaviour of each basin segment by supporting strategic resource allocation to ensure the management efforts are mainly for priority areas (Haing et al., 2008; Javed et al., 2011; Brooks et al., 2006; Strahler, 1957). The integration of advanced technological tools such as Remote sensing, GIS etc. with spatial data helps in determine absolute location of high-priority site for initiating soil and water conservation (Gupta et al., 1997; Kumar et al., 2008; Chowdary et al., 2009; Makwana & Tiwari, 2016).

The study of Pagladiya watershed emphasises on the prioritization of sub-watersheds using geospatial techniques depending on morphometric variables for the necessary monitoring and soil conservation strategies. Significantly, this study includes soil erosion assessment for systematically evaluate and identify areas in Pagladiya basin that are highly prone to degradation. It associated with delineation the watershed and sub-watersheds of Pagladiya river along with the computation of basic measures (area, basin length) for sub-watershed prioritization that helps in identifying the subwatershed at high risk of soil erosion. Lastly, to find out the sub-watersheds needed for soil loss control based on Morphometric Analysis, R factor (RUSLE Model), Hypsometric Analysis.

2. DESCRIPTION OF THE STUDY AREA

Pagladiya is a transboundary river network passing through two nations Bhutan and India with the extension of 91° 25′ E to 91° 27′ E longitude and 25° 15′ N to 26° 59′ N latitude. It originates in the Lhozhag region of southern Bhutan (2548 meters), and by flowing across Bhutan over steep slopes it enters in India covering two districts Baksa and Nalbari and joining the Brahmaputra River near Lowpara village. Significantly, Pagladiya is a perennial river but due to less rainfall and snowmelt reduced flow seen in winter. The watershed is characterised with diverse land use including water bodies (31.56%), dense vegetation (24.2%), trees (17.54%), agriculture (14.59%), bare ground (7.71%), and built-up areas (4.39%) (Figure 3). Slopes vary from 0° to 72.68°, with the steepest in the north and gentler slopes in the south (Figure 2). Elevation ranges from 18 to 2,548 meters (Figure 2). Main FAO soil types include Ao, Be, Nd, and Rd (Figure 2). As part of north-eastern region (Assam) of India it is characterised with sub-tropical climate where temperatures range from 10° C to 35° C that gradually increasing moving from north to south direction, with August being the hottest and January the coolest (Figure 2). The NDVI map of Pagladiya watershed indicates that the north-western part of the watershed is densely forested, while reduced vegetation due to agriculture, grasslands, and seasonal dryness are found in the central and southern parts (Figure 2).

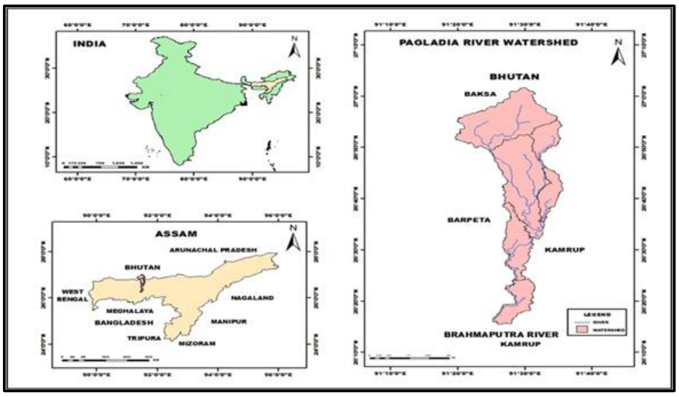
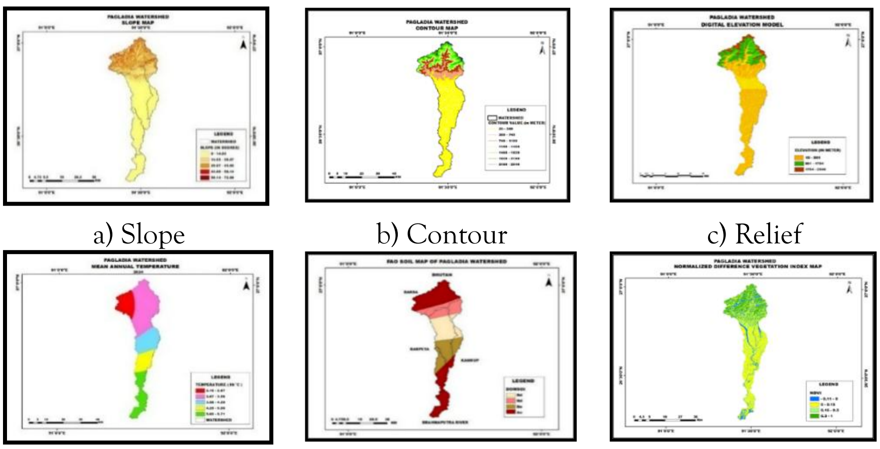


Figure 1: Geographical location of the study area



a) Slope b) Contour c) Relief

d) Mean Annual Temperature e) Soil f) Vegetation

Figure 2: Maps of Geographical aspects within Pagladiya Watershed

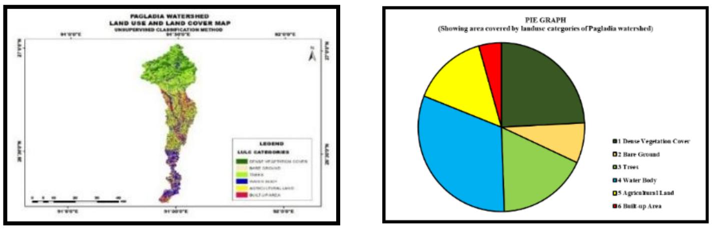


Figure 3: Land use and Landcover map and related Pie-Graph of Pagladiya basin

3. METHODOLOGY

3.1: Methods

Integration of advanced technologies including remote sensing and GIS with morphometric variable help in demarcation, ranking and prioritization of sub-watersheds of Pagladiya watershed. In this process the primary databases included SRTM DEM (30 meters resolution) is mainly used for its all-weather durability (Kabite and Gessesse, 2018), along with Landsat 8 imagery from January 2024. Significantly, the whole data are reprojected into a common coordinate system and processed using ArcGIS 10.8. The ArcGIS Hydrology tool is used for delineation of sub-watershed boundaries that beginning with DEM pre-processing using the fill tool, followed by flow direction and accumulation tools. A stream network is generated and ordered using the Strahler method, identifying pour points to define six sub-watersheds (Sb-W1 to Sb-W6).

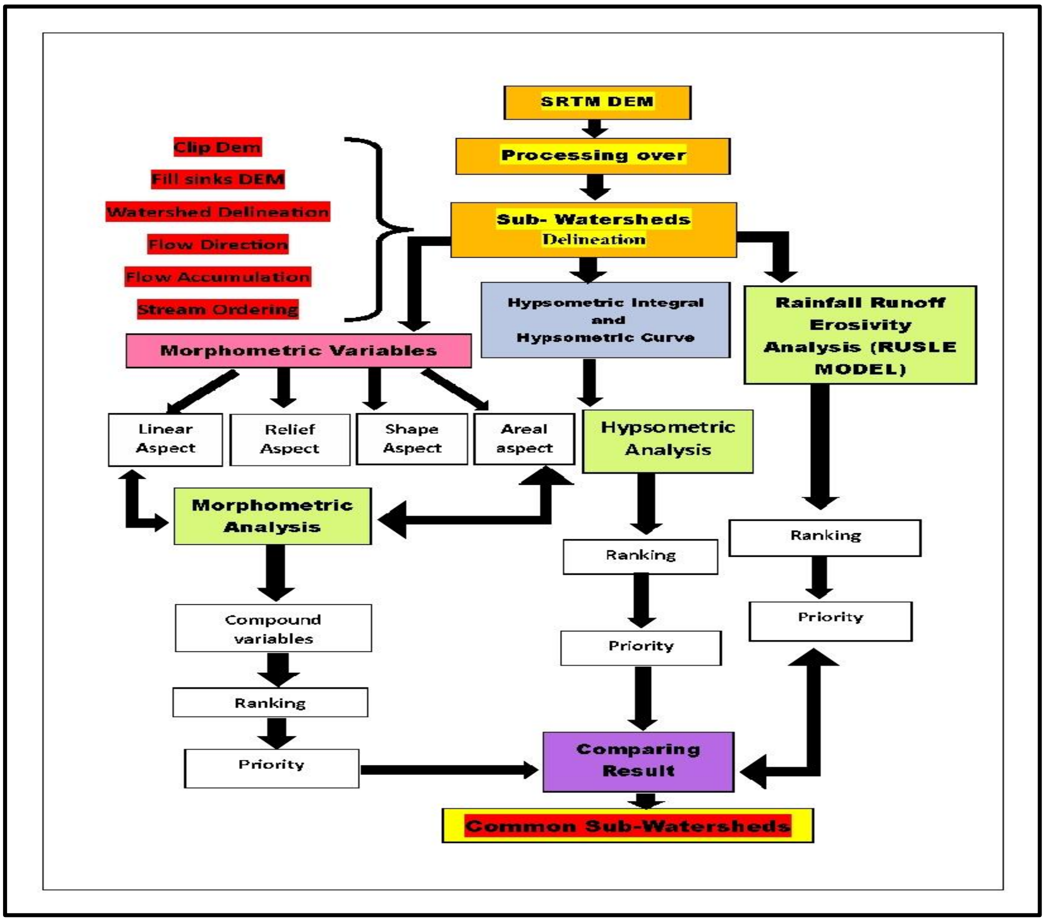


Figure 4: Flow chart showing the Methodology

Morphometric analysis is performed using standard formulas (Horton, Strahler, Schumm) grouped under linear, areal, shape, and relief variables and the R-factor (RUSLE model) with 2024 Climatic Research Unit (CRU) rainfall data.

Table 1: Sources and Data type

Data Type	Source	Purposes
Watershed boundary	Global Watersheds (HydroSHEDS)	Delineation of the Pagladiya watershed
Soil data	FAO (DSMW)	For generating Soil map of Pagladiya watershed
Elevation (DEM)	SRTM (Shuttle Radar Topography Mission) USGS Earth Explorer	Used for deriving slope, elevation, stream network, and morphometric indices
Satellite Imagery	Landsat 8, USGS Earth Explorer	Land use/landcover (LULC) classification with 30m spatial resolution
Rainfall data	Climate Research Unit (CRU) Gridded Datasets (2024)	Supports climate characterization of the Watershed
Temperature data	Climate Research Unit (CRU) Gridded Datasets (2014)	Supports climate characterization of the Watershed

3.2: Segmentation of Watershed and assessment of drainage network

In this study, firstly the small grid pieces of DEM of that study area are merged and aligned to a uniform spatial reference framework (WGS 1984 UTM Zone 46N). After that, for the segmentation of Watershed, ArcGIS Hydrology tool is used for its remarkable accuracy combined with time efficiency (Wondimu & Mamo, 2014; Fenta et al., 2017), with the first step of fill the DEM to eliminate sinks, followed by the calculation of flow direction using the D8 algorithm and flow direction map has been generated. Again, flow accumulation map is also prepared to identify areas of concentrated surface runoff (Figure 6). A threshold value is applied through the Stream definition tool to create a stream grid, highlighting cells with enough accumulated flow to represent streams (Figure 6). Using the Stream Segmentation tool, the grid is divided and then converted into a polyline stream network. Finally, six sub-watersheds are delineated, and the resulting raster catchment areas are converted into vector polygons to clearly define sub-watershed boundaries (Figure 5).

Figure 5: Sub-Watersheds of Pagladiya Watershed

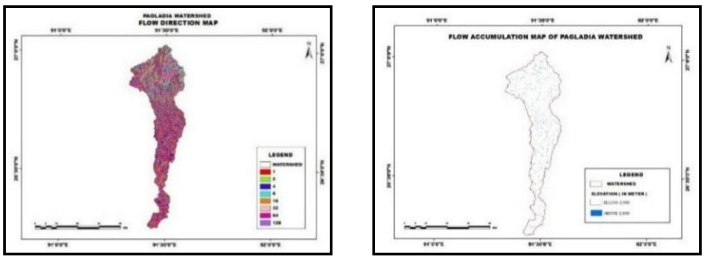


Figure 6: Flow Direction and Flow Accumulation maps of Pagladiya Watershed

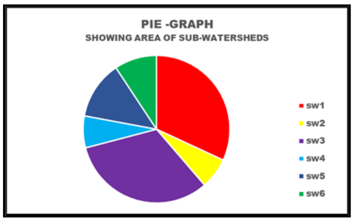
3.3: Quantification of Morphometric Variables

3.3.1: Morphometric Analysis

Morphometric analysis of streams is a significant tool for sustainable watershed management and conservation (Gajbhiye et al., 2014). In this process, all the morphometric variables of Pagladiya watershed are arranged into four groups: linear variable, shape variable, areal variable, and relief variable. By using standard quantitative formulas, the variables are calculated (Table 3).

Table 2: Computation of Morphometric variables

Variables	Sb-W1	Sb-W2	Sb-W3	Sb-W4	Sb-W5	Sb-W6
Area (in sq.km)	288.46	61.48	292.19	63.18	115.42	84.49
Minimum Elevation, h (in meter)	177	160	45	49	24	26
Maximum Elevation, H (in meter)	2548	2350	1501	135	88	89
Perimeter (in km)	92.14	41.06	118.72	58.38	86.49	58.97



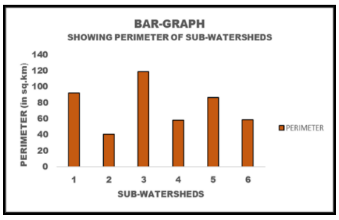


Figure 7: Pie- Graph (showing area) and Bar-Graph (showing perimeter) of Pagladiya Watershed

Table 3: Quantitative formulas of selected Morphometric Variables

Sl No	Morphometric Variables	Symbol	Formulas	Units	References
	Linear Morphometric Variables				
1	Stream Order	U	Hierarchical Ranking		Strahler, 1964
2	Stream Number	Nu	Nu=N1+N2+.......+Nn		Horton, 1945
3	Stream Length	Lu	Lu= L1+L2+........Ln	km	Horton, 1945
4	Mean Stream Length	Lm	Lm= Lu/Nu	km	Strahler, 1964
5	Stream Length Ratio	Rl	Rl=Lu/L(u+1)		Horton, 1945
6	Bifurcation Ratio	Rb	Rb=Nu/N(u+1)		Horton, 1945
	Shape Morphometric Variables				
7	Form Factor	Ff	$Ff=A/Lb^2$		Horton, 1932
8	Circulatory Ratio	Rc	$Rc=4\pi A/P^2$		Miller, 1953
9	Compactness Coefficient	Cc	$Cc=P/\{2(\pi A)^{1/2}\}$		Gravelius, 1941
	Aerial Morphometric Variables				
10	Stream Frequency	Fs	Fs=Nu/A	$1/km^2$	Horton, 1945
11	Drainage Texture	Dt	Dt=Nu/P	1/km	Horton, 1945
12	Drainage Density	Dd	Dd=Lu/A	km/km^2	Horton, 1932
13	Infiltration Number	If	If=Dd×Fs	$1/km^3$	Faniram, 1968
14	Length of Overland Flow	Lo	Lo=1(2×Dd)	km	Horton, 1945
15	Constant of Channel Maintenance	C	C=1/Dd	km	Schumm, 1956
	Relief Morphometric Variables				
16	Basin Relief	R	R=H-h		Schumm, 1956
17	Relief Ratio	Rr	Rr=(H-h)/Lb		Schumm, 1956
18	Ruggedness Number	Rn	Rn=Dd×(H-h)		Schumm, 1956
19	Dissection Index	Din	Din=(H-h)/H		Gravelius, 1941

3.3.2: Hypsometric Analysis

Hypsometric analysis is an essential aspect based on elevation relative to area, helps in determine the youth, mature, and old stages of topographic evolution within a watershed (Strahler, 1954). This involves generating a hypsometric curve, which plots relative elevation against relative area. Hypsometric Integral (HI) indicates the total area beneath hypsometric curve (Schumm, 1956).

3.3.3: R-factor (RUSLE Model)

R factor is related to determine the latent ability of precipitation responsible for soil erosion (Wu et al., 2018). Researchers use the RUSLE model along with advanced techniques to assess both large- and small-scale regional variations in long-term average soil loss (Onori et al., 2006). In this study, the R-factor is quantified using CRU precipitation data of the year 2024. The study spatially interpolated the rainfall data using the IDW tool in ArcGIS at resolution of 30 meters. It then prepared the final rainfall erosivity map by following the equation given by Morgan et al (1984).

R = 38.5 + 0.35P (Eq 1)

Where, R = rainfall erosivity factor in mm ha^{-1} $year^{-1}$, P = mean annual rainfall in mm

4. RESULTS

4.1: Linear Morphometric analysis

The linear morphometric analysis is prior for description of the one-dimensional characteristics of watershed. Stream Order, Stream Number, Stream Length, Mean Stream Length, Stream Length Ratio, and Bifurcation Ratio are included in the linear morphometric analysis. Table 4 showing the computed values.

Table 4: Variables of Linear Aspect

Variables	Sb-W1	Sb-W2	Sb-W3	Sb-W4	Sb-W5	Sb-W6
Stream Orders(U)	4	2	4	2	2	2
Total Number of Streams (∑Nu)	56	9	55	10	22	20
Nu1	44	8	42	8	18	18
Nu2	9	1	9	2	4	2
Nu3	2		3			
Nu4	1		1			
Total Stream Length (∑Lu)	151.49	38.48	201.68	33.26	54.67	32.95
Lu1	76.58	22.91	115.01	19.02	33.05	21.45
Lu2	41.23	15.57	35.74	14.24	21.62	11.5
Lu3	31.69		45.67			
Lu4	1.99		5.26			
Mean Stream Length (∑Lm)	2.7	4.27	3.66	3.32	2.48	1.64
Lm1	1.74	2.86	2.73	2.37	1.83	1.19
Lm2	4.58	15.57	3.97	7.12	5.4	5.75
Lm3	15.84		15.22			
Lm4	1.99		5.26			
Mean Stream Length Ratio (∑Rl)	2.06	5.44	1.9	3	2.95	4.83
Rl (2/1)	2.63	5.44	1.45	3	2.95	4.83
Rl (3/2)	3.45		3.83			
Rl (4/3)	0.12		0.34			
Rl (5/4)						
Mean Bifurcation Ratio (∑Rb)	3.79	8	3.55	4	4.5	9
Rb	4.88	8	4.66	4	4.5	9
Rb	4.5		3			
Rb	2		3			
Rb						

Stream order indicates stream's rank within a drainage basin by combining the low order streams that form the high order stream (Strahler, 1964). The stream orders are delineated in the study by using Strahler method, where Sb-W1 and Sb-W3 have the highest number of stream order but Sb-W2, Sb-W4, Sb-W5, Sb-W6 have lowest number of stream orders (2nd Order Streams) (Figure 8). Sb-W1 and Sb-W3 with higher number of stream orders (4th order streams) indicate how that stream flow is more substantial in these sub-watersheds compared to the rest (Kabite and Gessesse, 2018).

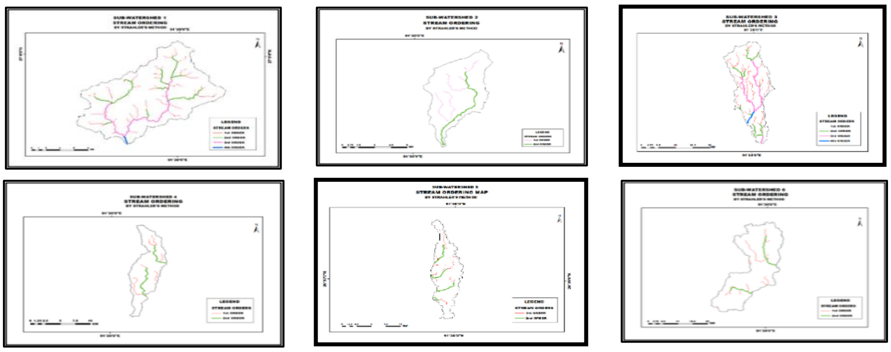


Figure 8: Stream Ordering of Sub-Watersheds in Pagladiya watershed

Stream number indicates cumulative stream segments within a watershed. In Pagladiya watershed, stream number ranges from 9 (Sb-W2) to 56 (Sb-W1) (Figure 13). This relationship highlights how stream number gradually decreases with increasing stream order, indicating a contrary correlation (Horton, 1945) (Figure 9).

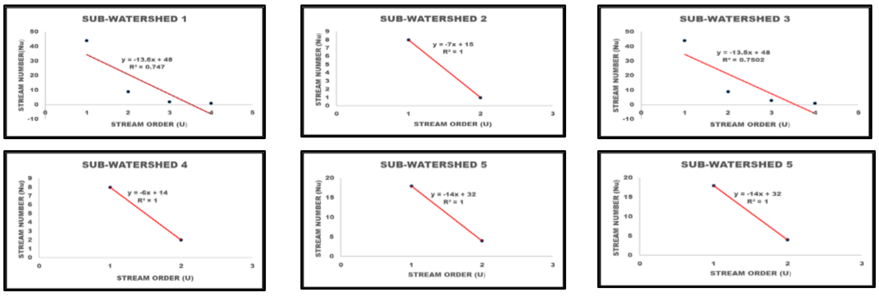


Figure 9: Inverse pattern relative to Stream Number and Stream Order

Stream length represents aggregate linear distance between the stream's origin and its outlet. Significantly, Sb-W3 has the highest stream length (201.68 km) followed by Sb-W1 (151.49 km) and Sb-W4 (33.26 km) is characterised with lowest stream length (Figure 13), which corresponds with Horton's (1945) rule of contrary relationship relative to stream length and stream orders where stream length decreases with higher stream orders (Figure 10). According to Wondimu and Mamo (2014), variation in slope in stream orders might be responsible for this.

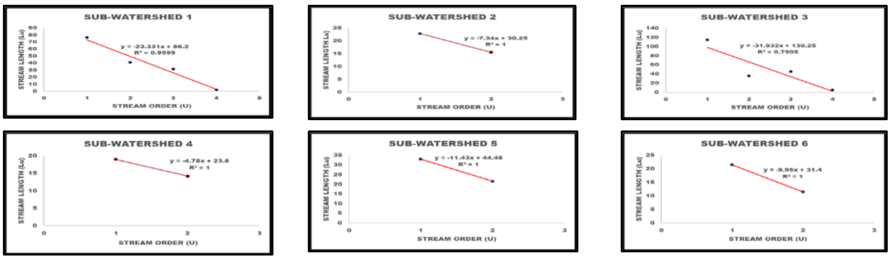


Figure 10: Inverse pattern relative to Stream Order and Stream Length

In Pagladiya watershed, the average stream length varies between 1.64 km (Sb-W6) to 4.27 km (Sb-W2) (Figure 13). SbW2 (5.44) is characterised with highest mean stream length ratio and Sb-W3 (1.90) has the lowest mean stream length ratio (Figure 13). According to Horton (1945), a Bifurcation Ratio varies between 3.0 to 5.0 is observed in less distorted geological structural basins. The lower Bifurcation ratio represents a flat terrain, while higher Bifurcation ratio indicates a mountainous terrain (Farhan, 2017). As a result, Extensive erosion and sediment transportation are caused by the high degree of structural disturbance in Sb-W6, while Sb-W3 is characterized by a nearly flat surface and lower structural disruption (Figure 13).

4.2: Shape Morphometric Variables

Shape Morphometric variables are essential for asserting the water flow rate into stream (Fenta et al., 2017). It includes circulatory ratio, compactness coefficient, and form factor. Table 5 is representing the calculated values of these variables. The compactness coefficient is observed between 0.05 (Sb-W3) to 0.14 (Sb-W4) (Figure13).

Table 5: Calculated variables of Shape Aspects

Variables	Sb-W1	Sb-W2	Sb-W3	Sb-W4	Sb-W5	Sb-W6
Circulatory Ratio (Rc)	0.42	0.45	0.26	0.23	0.19	0.3
Compactness Coefficient (Cc)	0.1	0.1	0.05	0.14	0.11	0.11
Form Factor (Ff)	0.28	0.18	0.19	0.7	0.62	0.8

In a basin, more elongated basin shapes are indicated by lower form factor and circulatory ratio values, while higher values correspond to circular shape (Miller, 1953; Schumm, 1956; and Strahler, 1964). Significantly, a circular basin shape is characterised with low compactness coefficient, whereas an elongated shape indicating high value. Circular basins are typically associated with higher runoff, lower infiltration, and greater erosion risk (Patel et al., 2013).

4.3: Aerial Morphometric Variables

The degree of landscape dissection is determined by areal morphometric variables, which are used to provide information about the infiltration potential of the terrain (Farhan, 2017; Meshram & Sharma, 2017). Variables such as stream frequency, drainage texture, drainage density, infiltration number, length of overland flow, and constant of channel maintenance are included in this analysis. Their calculated quantitative values are presented in Table 6.

Table 6: Computed variables of Aerial Aspects

Variables	Sb-W1	Sb-W2	Sb-W3	Sb-W4	Sb-W5	Sb-W6
Stream Frequency (Fs)	0.19	0.14	0.18	0.15	0.19	0.23
Drainage Texture (Dt)	0.6	0.21	0.46	0.17	0.25	0.33
Drainage Density (Dd)	0.52	0.62	0.69	0.51	0.47	0.38
Infiltration Number (If)	0.098	0.086	0.124	0.076	0.089	0.087
Length of Overland Flow (Lo)	0.96	0.8	0.72	0.98	1.06	1.31
Constant of Channel Maintenance (C)	1.92	1.61	1.44	1.96	2.12	2.63

From the distribution, the highest Stream frequency is observed in Sb-W6 (0.23 km^2) and lowest stream frequency is found in Sb-W2 (0.14 km^2) (Figure 13). Notably, lower stream frequency in a sub-watershed is associated with the presence of more permeable surface materials relative to other sub-watersheds (Dubey et al., 2015). Again, the highest drainage density is found in Sb-W3 (0.69 km/km^2) and lowest drainage density is found in Sb-W6 (0.38 km/km^2) (Figure 13). In this context, a minimum drainage density demonstrates material permeability, reduced surface runoff, and increased infiltration capacity (Nautiyal, 1994) (Figure 11) showing the drainage density of all the sub-watersheds of Pagladiya watershed separately. The Drainage Texture in Pagladiya watershed varies between 0.60 km/km^2 (Sb-W1) to 0.17 km/km^2 (Sb-W4) (Figure 13). According to Smith's classification scheme (1950), lower drainage texture is characterized by a coarse texture, whereas higher drainage texture is associated with a moderate texture. In terms of the infiltration number, Sb-W3 (0.124 km^2) is identified with the highest value, indicating low infiltration capacity, while Sb-W4 (0.076 km^2) has the lowest value, indicating high infiltration capacity (Figure 13). Infiltration number and infiltration capacity both are inversely related (Strahler, 1964). Whole sub-watersheds of the Pagladiya watershed exhibit high length of overland flow. Significantly, drainage basins with higher length of overland flow generally possess greater infiltration capacity against those with a shorter overland flow length (Chandrashekar et al., 2015). The constant of Channel maintenance in Pagladiya watershed lies between 1.44 km (Sb-W3) to 2.63 km (Sb-W6) (Figure 13). The Constant of Channel Maintenance with high value leads to reduced surface discharge and heightened surface intake (Sreedevi et al., 2013).

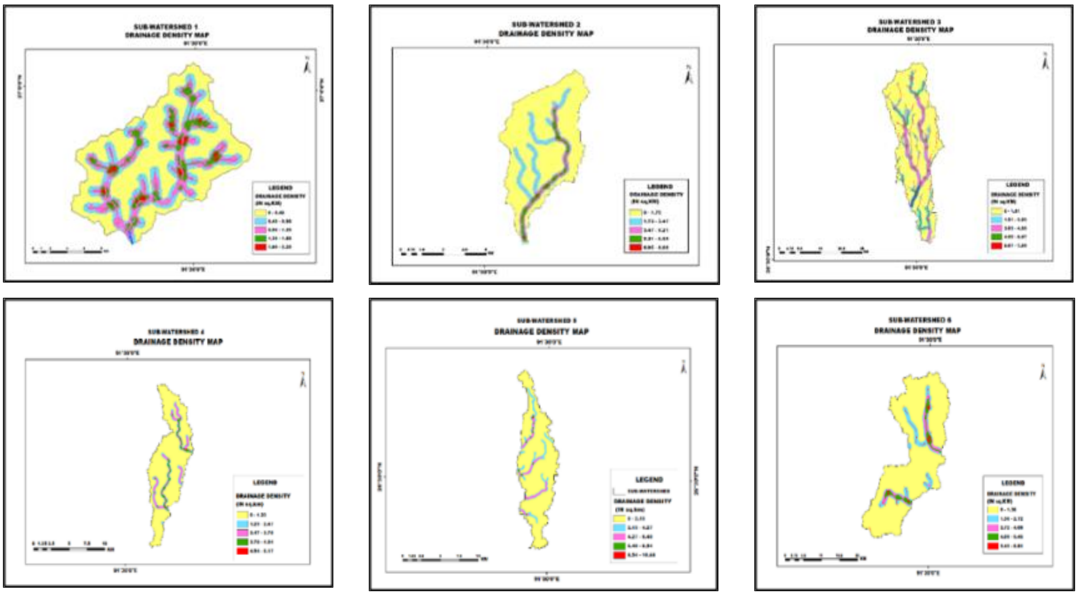


Figure 11: Drainage Density across sub-watersheds within Pagladiya Watershed

4.4: Relief Morphometric Variables

Relief morphometric variables are essential for drainage network analysis as it provides critical insights into surface flow direction (Gudu Tufa, 2018), erosion vulnerability (Fenta et al., 2017), unstable terrain conditions (Rekha et al., 2011), and internal structural configuration (Dubey et al., 2015). These variables include basin relief, relief ratio, ruggedness number, and dissection index. Table 7 representing computed data of these variables.

Table 7: Computed variables of Relief Aspects

Variables	Sb-W1	Sb-W2	Sb-W3	Sb-W4	Sb-W5	Sb-W6
Basin Relief (R)	2.43	2.19	1.45	0.08	0.064	0.063
Relief Ratio (Rr)	0.07	0.11	0.03	0.009	0.004	0.007
Ruggedness Number (Rn)	1.26	1.35	1.004	0.043	0.03	0.023
Dissection Index (Din)	0.95	0.93	0.97	0.63	0.72	0.7
Hypsometric integral (HI)	0.46	0.43	0.33	0.46	0.49	0.43

In the Pagladiya watershed, the basin relief extends between 2.43 km (Sb-W1) to 0.063 km (Sb-W6) (Figure 13). Again, the Relief ratio lies between 0.004 (Sb-W5) to 0.11 (Sb-W2) (Figure 13). A high relief ratio in Sb-W2 is considered indicative of a greater vulnerable to erosion (Magesh et al., 2011). The ruggedness number has been recorded to range from 0.023 in Sb-W6 to 1.35 in Sb-W2 (Figure 13). Significantly, the Sb-W6 with lower ruggedness number is characterised with more unstable and complex leads to high level of persistent soil degradation (Wondimu and Mamo, 2014). The Dissection Index in Pagladiya watershed lies between 0.63 (Sb-W4) to 0.97 (Sb-W3) (Figure 13). The Sb-W4 is characterised with flat terrain, while Sb-W3 results in high-gradient (Pal et al., 2012). Again, the hypsometric integral values lie between 0.33 (Sb-W3) to 0.49 (Sb-W5). Therefore, HI value indicates mature stage of development of the Pagladiya watershed (Strahler, 1954) (Figure 12). Sb-W3 with the HI value of 0.33 refers 33% of its landmass is remain at present, while, Sb-W5 with HI value 0.49 refers 49% of its landmass is remain till now. Therefore, Sb-W5 exhibits a relatively higher proneness to erosion.

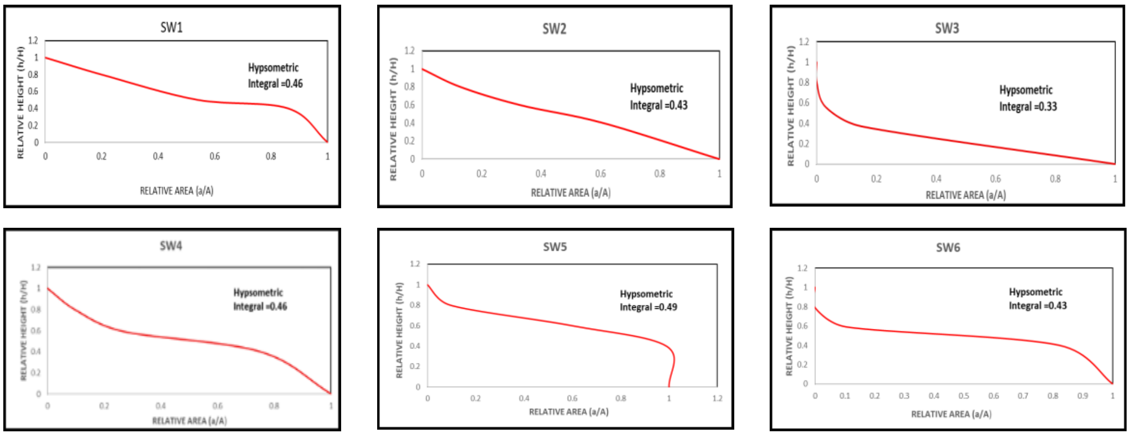


Figure 12: Determination of Hypsometric Integral for Sub-Watersheds of Pagladiya Basin

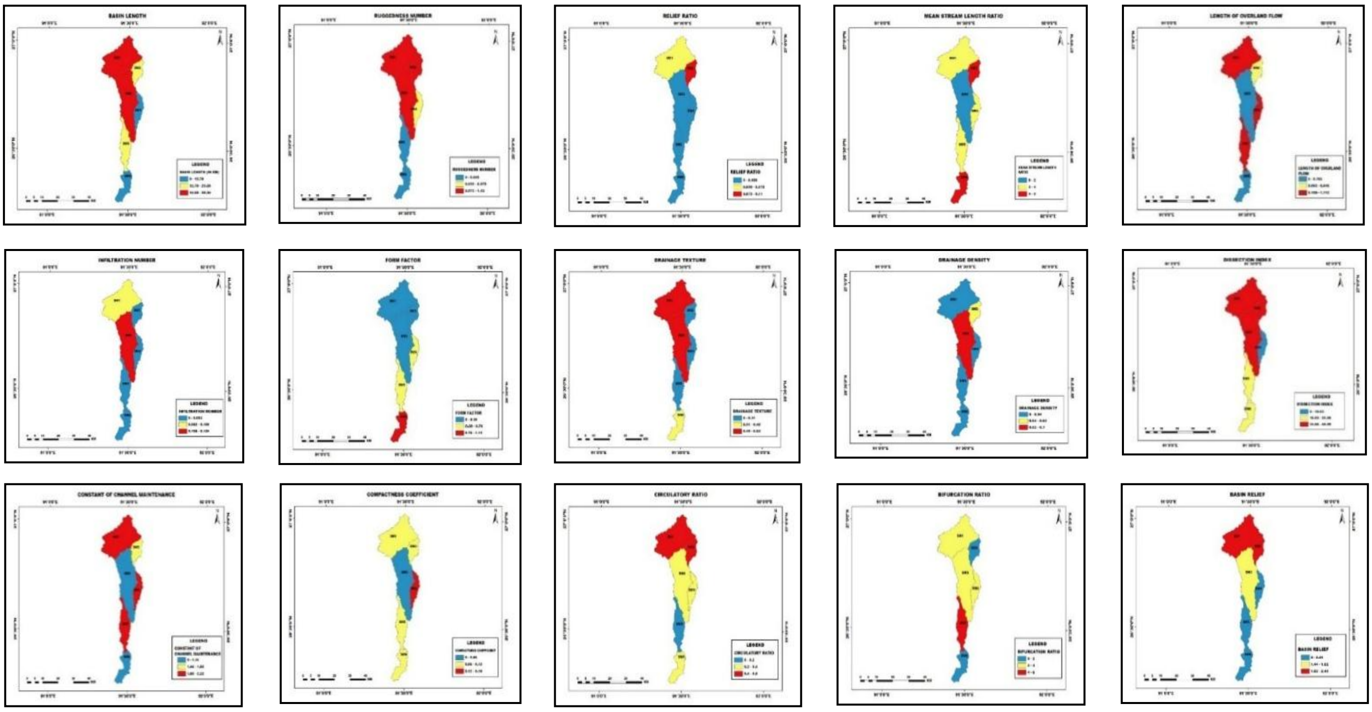


Figure 13: Maps showing Morphometric variables of sub-zones in Pagladia Basin

4.5: Sub-Watershed Prioritization for determination of soil erosion

4.5.1: Morphometric Analysis

Considering their expected impact on soil loss, 14 morphometric variables are considered, comprising stream frequency (Fs), bifurcation ratio (Rb), drainage density (Dd), drainage texture (Dt), infiltration number (If), length of overland flow (Lo), constant of channel maintenance (C), circulatory ratio (Rc), compactness coefficient (Cc), form factor (Ff), relief ratio (Rr), ruggedness number (Rn), dissection index (Din), and hypsometric integral (HI). These variables are used in the evaluation process to establish the erosion-sensitivity based ranking of the sub-watersheds (Table 8).

After the variables are assigned ranks, the compound value for each sub-watershed is calculated by summing all the ranks and dividing total by 14 (the number of variables). The resulting values lies between 2.5 (Sb-W3) to 4.14 (Sb-W6) (Table 8). After calculating the compound variable values, the study ranks the sub-watersheds based on those values. Sub-watersheds with the minimum compound value are assigned as Rank 1, followed by Rank 2 for the next lowest values, and so on. This study classifies sub-watersheds with compound values ranging from 2.5 to 3 (Sb-W1, Sb-W2, and Sb-W3) as high priority. Sub-watersheds with values between 3 and 3.5 (Sb-W5) are placed in the medium priority category, while those with values above 3.5 (Sb-W4 and Sb-W6) are categorized as low priority. This classification shows the highest-priority sub-watersheds are highly prone to intense runoff, elevated peak flow, and severe soil erosion (Figure 8).

Table 8: Primary classification by priority, computation of compound variables, ranking, and prioritization for soil erosion estimation

Variables	Sb-W1	Sb-W2	Sb-W3	Sb-W4	Sb-W5	Sb-W6
Rb	5	2	6	4	3	1
Ff	3	1	2	5	4	6
Rc	5	6	3	2	1	4
Cc	3	3	4	1	2	2
Fs	2	5	3	4	2	1
If	2	5	1	6	3	4
Dd	3	2	1	4	5	6
Dt	1	5	2	6	4	3
C	3	2	1	4	5	6
Lo	3	2	1	4	5	6
Rr	2	1	3	4	6	5
Rn	2	1	3	5	4	6
Din	2	3	1	6	4	5
HI	2	3	4	2	1	3
Sum of Ranking (x)	38	41	35	57	49	58
Total number of variables (y)	14	14	14	14	14	14
Compound Variables (x/y)	2.71	2.92	2.5	4.07	3.5	4.14
Ranking	**2**	**3**	**1**	**5**	**4**	**6**
Final Priority	**High**	**High**	**High**	**Low**	**Medium**	**Low**

Table 9: Assessment of inter-correlation matrix of morphometric variables influencing soil erosion

	Rb	Ff	Rc	Cc	Fs	If	Dd	Dt	C	Lo	Rr	Rn	Din	HI
Rb	1													
Ff	-0.35	1												
Rc	-0.41	-0.47	1											
Cc	0.41	-0.76	0.41	1										
Fs	0.24	-0.68	0.41	0.13	1									
If	-0.52	0.28	0.21	-0.75	0.41	1								
Dd	-0.66	0.88	-0.35	-0.76	-0.68	0.35	1							
Dt	-0.24	0.07	0	-0.69	0.6	0.90	0.15	1						
C	-0.66	0.88	-0.35	-0.76	-0.68	0.35	1	0.15	1					
Lo	-0.66	0.88	-0.35	-0.76	-0.68	0.35	1	0.15	1	1				
Rr	-0.12	0.78	-0.79	-0.52	-0.82	-0.14	0.78	-0.16	0.78	0.78	1			
Rn	-0.18	0.97	-0.52	-0.63	-0.73	0.12	0.78	-0.08	0.78	0.78	0.79	1		
Din	-0.52	0.79	-0.25	-0.98	-0.16	0.79	0.78	0.65	0.78	0.78	0.45	0.66	1	
HI	0.27	-0.40	0.61	0.73	0.13	-0.38	-0.61	-0.55	-0.61	-0.61	-0.61	-0.27	-0.61	1

Observing the inter correlation matrix in Table 9, we have found that, there is a strong negative correlation of compactness coefficient with form factor and circulatory ratio, which indicates that more circular basins are characterised with less soil erosion risk. The high positive association of Drainage Density with stream frequency and strong negative correlation with Circulatory ratio and compactness coefficient determines drainage basin characterised with dense stream networks are usually more elongated and less prone to erosion. Again, the very strong negative correlation of compactness coefficient with dissection index leads to irregular and more prone to erosion. The stream frequency demonstrates a positive association with Infiltration number indicating denser drainage results in the reduction of infiltration and high erosional vulnerability. Moreover, there is a positive linkage of Relief Ratio and Ruggedness number with stream frequency and drainage density results in rugged basin with high steep gradient that are more prone to erosion. Hypsometric Integral has a negative correlation with drainage density and Dissection Index and positive relation with Circulatory Ratio and Compactness Coefficient indicating youth stage of a basin characterised with lower surface erosion. Bifurcation Ratio is showing a negative association with most of the variables but associated with localized soil erosion due to surrounding geological condition.

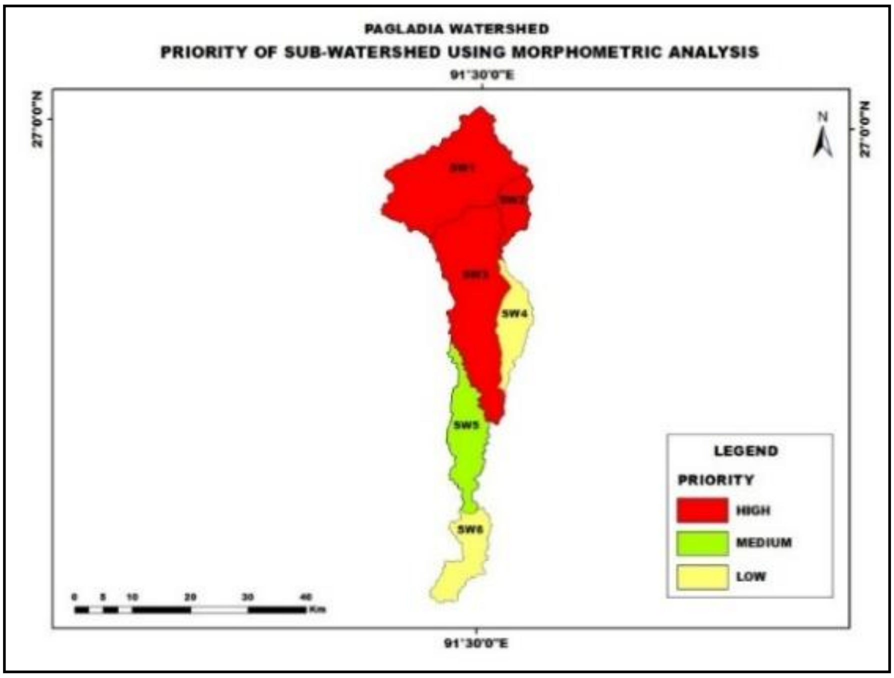


Figure 14: Soil erosion Priority map of Sub-Watersheds of Pagladiya Watershed using Morphometric Analysis

4.5.2: Hypsometric Analysis

The Hypsometric curve, which plots relative elevation against relative area, is apply for compute the Hypsometric Integral (HI) and based on that Hypsometric analysis is done. In the Pagladiya watershed, the HI values vary between 0.33 (Sb-W3) to 0.49 (Sb-W5), indicating that the sub-watersheds are in a mature stage of geomorphic evolution (Strahler, 1954). We categorize sub-watersheds with HI values below 3.5 as low priority (e.g., Sb-W3) less prone to soil erosion. Sub-watersheds with HI values ranging from 3.5 to 4 were classified as medium priority (Sb-W6 and Sb-W2), while those with HI values above 4 are identified as high priority (Sb-W1, Sb-W4, and Sb-W5), results in actively eroding landscape (Table 10).

Table 10: Sub-Watershed Prioritization Using Hypsometric Integral Values

Variables	Sb-W1	Sb-W2	Sb-W3	Sb-W4	Sb-W5	Sb-W6
Hypsometric Integral	0.46	0.43	0.33	0.46	0.49	0.43
Ranking	2	3	4	2	1	3
Priority	**High**	**Medium**	low	**High**	**High**	**Medium**

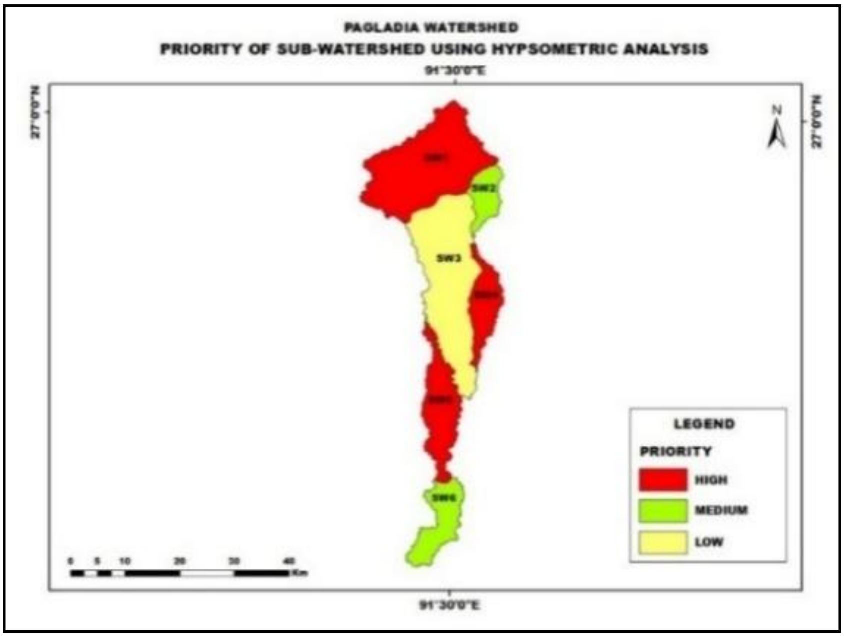


Figure 15: Soil erosion Priority map of Sub-Watersheds of Pagladiya Watershed using Hypsometric Analysis

4.5.3: R-factor (RUSLE model)

Considering the average R-factor values, the sub-watersheds are grouped under different priority divisions. For this classification, the average values obtained from the R-factor map are used (Figure 16). It is noticeable that the highest rainfall runoff erosivity found in Sb-W1 (1122.25 MJ mm ha $^{-1}$ h $^{-1}$ yr $^{-1}$) and Sb-W3 comes second (1105.5 MJ mm ha $^{-1}$ h ^{1} yr $^{-1}$) and so on (Table 12). Significantly, three priority classes have been categorised according to the mean R factor values, such as high priority (above 1100 MJ mm ha $^{-1}$ h $^{-1}$ yr $^{-1}$), medium priority (1080-1100 MJ mm ha $^{-1}$ h $^{-1}$ yr $^{-1}$), and low priority (below 1080 MJ mm ha $^{-1}$ h $^{-1}$ yr $^{-1}$). Moreover, among 6, 2 sub-watersheds (Sb-W1 and Sb-W3) are categorised under high priority (580.65 km^2), 2 sub-watersheds (Sb-W2 and Sb-W5) fall under medium priority (176.97 km$^{2)}$, and 2 sub-watersheds (Sb-W4 and Sb-W6) are categorised under low priority (147.67 km^2) (Table 11).

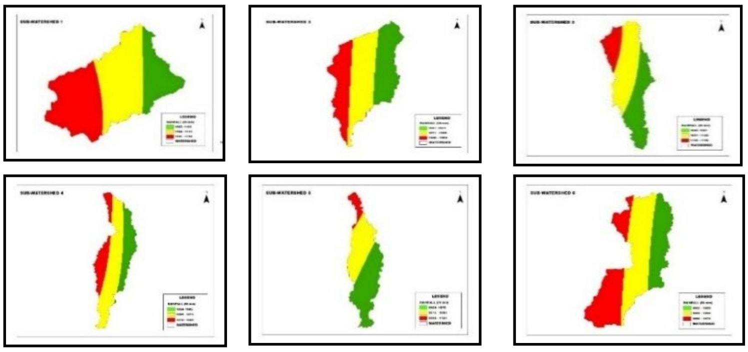


Figure 16: R factor rainfall runoff erosivity maps (RUSLE Model) of all Sub-Watersheds of Pagladiya Watershed

Table 11: Sub-Watersheds Prioritization based on R (Rainfall-runoff erosivity) factor

Variables	Sb-W1	Sb-W2	Sb-W3	Sb-W4	Sb-W5	Sb-W6
Mean value of Rainfall-runoff erosivity factor (MJ mm ha $^{-1}$ h $^{-1}$ yr $^{-1)}$	1122.25	1078	1105.5	1069	1082.25	1062.5
Area (in Km^2)	288.46	61.48	292.19	63.18	115.49	84.49
Ranking	**1**	**4**	**2**	**5**	**3**	**6**
Priority	**High**	**Medium**	**High**	**Low**	**Medium**	**Low**

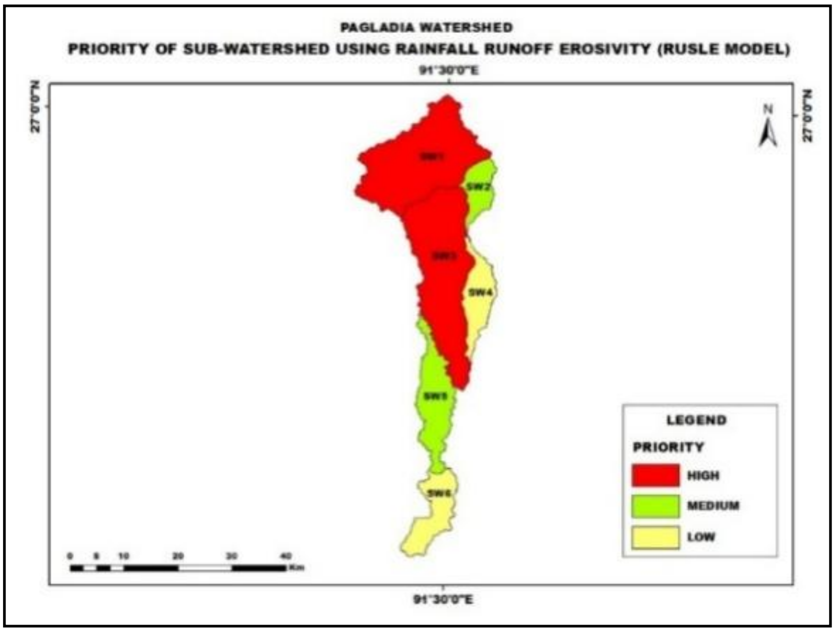


Figure 17: Soil erosion Priority map of Sub-Watersheds of Pagladiya Watershed using R- factor (RUSLE Model)

The land quality decline through erosional activity within Pagladiya watershed creates challenges to sustainability and productivity by effecting related economic activities including agriculture, irrigation, as well as biodiversity, human lives etc. By grouping the Pagladiya watershed into 6 sub-watersheds and prioritized them through an aggregated analysis of rainfall runoff erosivity (RUSLE, R-factor), hypsometric analysis, and morphometric analysis offer in-depth insight of erosion susceptibility over different zones. Again, it is noticeable that one approach can't provide the complete information about the watershed. Significantly, R factor analysis indicates the soil erosion due to factor like rainfall, Hypsometric Integral showing the geomorphic maturity of the basin, and Morphometric analysis determines the internal topographic pattern. Therefore, integrating all these three approaches provides a multi-dimensional understanding about soil erosion in the Pagladiya watershed along with sustainable soil erosion control strategies.

Table 12: Interconnected relationships among Morphometric analysis, Hypsometric analysis and Rainfall runoff erosivity analysis

Sub-Watersheds	Morphometric Analysis	Hypsometric Analysis	R-factor (RUSLE model)
Sb-W1	High	High	High
Sb-W2	High	Medium	Medium
Sb-W3	High	Low	High
Sb-W4	Low	High	Low
Sb-W5	Medium	High	Medium
Sb-W6	Low	Medium	Low

From Table 12, it is clear that Sb-W1 is characterised with high values across all three analyses (morphometric, hypsometric integral, and R factor) indicating it is extremely vulnerable to soil loss and needs urgent management strategies with top priority for soil conservation. Again, Sb-W2 with high morphometric values and medium hypsometric and R-factor values has moderate erosion risk, mainly due to its terrain structure. It requires moderate priority in management planning. Sb-W3 with high both in morphometric and R-factor and low hypsometric value is indicating that though the topography may have matured but erosive forces are still strong so it is also at high risk of soil erosion and needs priority intervention.

Sb-W4, having low morphometric and R-factor value and high hypsometric integral value is characterised with mature stage of development. Although the current erosion risk is low, future vulnerability may increase so it requires periodic monitoring. Moreover, Sb-W5 with medium morphometric and R-factor values, and high hypsometric index, suggesting moderate erosion risk with potential for future development so it is assigned in moderate priority in management policies. Lastly, Sb-W6 having low values across all the three approaches are indicating minimal risk of soil erosion presently can be assigned as low priority for intervention. Therefore, from the above discussions it is clear that by balancing the influences of external forces (rainfall), internal landscape features (slope, relief), and evolutionary status (topography), planners and policymakers can design more accurate and site-specific interventions for the Pagladiya watershed management.

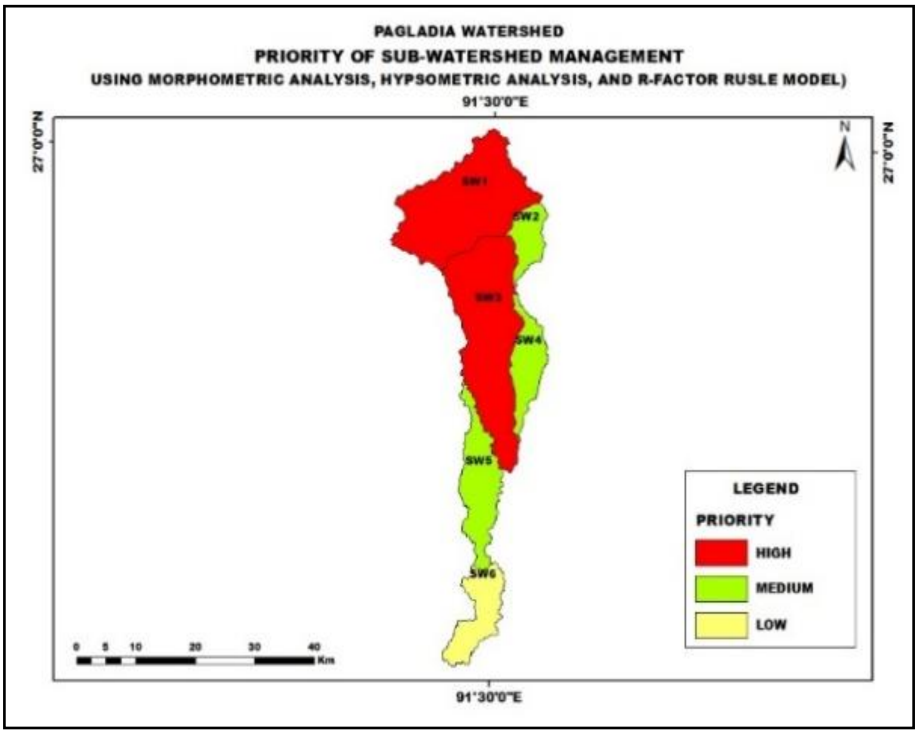


Figure 18: Soil erosion Priority map of Sub-Watersheds within Pagladiya Watershed using Morphometric Analysis, Hypsometric Analysis and R- factor (RUSLE model)

5. CONCLUSION

To determine the extent of soil erosion within Pagladiya watershed, it is categorized into six sub-watersheds and three approaches including morphometric analysis, hypsometric analysis, and the R-factor along with GIS and remote sensing techniques. Fourteen morphometric variables, CRU rainfall data for the year 2024, and hypsometric integral values are calculated and scientifically analysed based on which related maps are generated using ArcGIS 10.8. Considering morphometric analysis, Sb-W1, Sb-W2, and Sb-W3 are grouped as high-priority sub-watersheds. Hypsometric analysis indicates Sb-W1, Sb-W4, and Sb-W5 as high priority, while the R-factor-based analysis shows Sb-W1 and Sb-W3 as high priority. Among all methods, Sb-W1 consistently ranked as the highest priority area followed by Sb-W3. Therefore, these sub-watersheds require urgent and suitable conservation measures along with frequent monitoring for protecting those areas from land degradation.

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