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Remote Sensing and GIS-Based Morphometric Analysis for Groundwater Prioritization in the Siyom River Basin, Arunachal Pradesh

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Abstract

This study investigates the morphometric characteristics and groundwater suitability of the Siyom River Basin in Arunachal Pradesh, India, employing Remote Sensing (RS) and Geographic Information System (GIS) techniques. Eleven sub-watersheds within the basin were analyzed based on key morphometric parameters including land use/land cover (LULC), slope, drainage density, bifurcation ratio, elongation ratio, and compactness constant, among others. These parameters were integrated into a multi-criteria evaluation framework to identify areas with the highest groundwater potential. Sub-watershed 1 was found to be the most groundwater-deficient, requiring immediate conservation efforts, while sub-watershed 9 exhibited the most favorable conditions for groundwater recharge. The analysis revealed significant spatial variability in groundwater availability, with areas exhibiting high runoff and low infiltration identified as the most vulnerable. The study highlights the importance of site-specific groundwater management strategies that balance the demand for water with ecological and environmental sustainability. The results underscore the effectiveness of combining remote sensing-derived morphometric data with GIS-based analysis to inform groundwater conservation planning. This approach provides a comprehensive decision-making tool for sustainable water resource management in the Siyom River Basin.

Keywords: *Conservation Prioritization, GIS, Groundwater Suitability, Morphometric Analysis, Multi-Criteria Evaluation, Remote Sensing, Siyom River Basin*

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Introduction

A watershed is a natural hydrological unit defined by the flow of runoff from precipitation to a singular discharge point, typically into larger water bodies such as rivers, lakes, or oceans. Watersheds vary greatly in terms of their topographic, climatic, and physical characteristics, all of which influence the flow and storage of water. Proper watershed management is essential for sustaining groundwater resources, which are crucial for human consumption, agriculture, and ecosystem health (Strahler, 1964; Smith, 1950).

Morphometric analysis is a quantitative method used to study the physical characteristics of a watershed's drainage network. Parameters such as stream order, drainage density, slope, bifurcation ratio, and elongation ratio are key to understanding the hydrological dynamics and geomorphological structure of river basins (Strahler, 1964). As noted by Nautiyal (1994), morphometric analysis helps assess runoff potential and erosion risks, which directly influence groundwater recharge and soil conservation. While traditional methods required extensive fieldwork, the integration of Remote Sensing (RS) and Geographic Information System (GIS) technologies has significantly enhanced the efficiency and scope of watershed studies (Magesh et al., 2012).

Remote sensing, particularly through satellite imagery, offers a large-scale, synoptic view of watersheds, making it an invaluable tool for morphometric analysis. Digital Elevation Models (DEMs) derived from satellite data enable the extraction of topographic features such as drainage networks, slope, and elevation contours across vast areas, eliminating the need for on-site surveys (Magesh et al., 2011). Additionally, GIS enables the spatial integration of various thematic layers- land use/land cover (LULC), soil types, and climatic conditions- providing a more comprehensive understanding of watershed characteristics and aiding in groundwater suitability assessments (Ozdemir & Bird, 2009). The integration of RS and GIS technologies has greatly improved the accuracy of hydrological modeling and groundwater resource management (Nag, 1998; Magesh et al., 2012).

The Siyom River Basin, located in Arunachal Pradesh, India, is an important tributary of the Brahmaputra River, known for its ecological sensitivity and diverse geological features (Srinivasa et al., 2004). The basin faces challenges related to groundwater depletion, driven by excessive runoff, deforestation, and unsustainable agricultural practices (Nag, 1998). Indigenous communities, including the Adi and Galo tribes, are heavily dependent on groundwater for agricultural and domestic use. However, groundwater scarcity, compounded by soil erosion and climate change, threatens their livelihoods (Magesh et al., 2012).

In response to these challenges, this study aims to apply RS and GIS-based morphometric analysis to assess the groundwater potential of the Siyom River Basin and prioritize sub-watersheds for conservation interventions. By analyzing key morphometric parameters and integrating them with environmental data, the research seeks to identify areas with the greatest potential for groundwater recharge, as well as those in need of urgent conservation efforts. This research employs a multi-criteria evaluation approach to provide actionable insights for sustainable groundwater management, supporting policymakers and local communities in addressing water scarcity and promoting ecosystem sustainability (Rudraiah et al., 2008; Yadav et al., 2018).

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Study Area

The Siyom River Basin is a crucial tributary of the Brahmaputra River, located in the West Siang District of Arunachal Pradesh, northeastern India. Positioned between 28°10′N to 28°45′N and 94°30′E to 95°15′E, the basin is marked by its unique geography and rich ecological significance (Figure 1). Originating near the Main Central Thrust (MCT) zone, close to the border of Assam and Arunachal Pradesh, the Siyom River flows southeastward and eventually merges with the Brahmaputra River near Pangin. Known for its perennial flow, the river is nourished by monsoonal rainfall and snowmelt, and its drainage pattern ranges from dendritic to sub-dendritic. Some of the river's key tributaries include Yargyap Chu, Saje Chu, and Tato Chu. This region is ecologically sensitive and home to indigenous communities like the Adi and Galo tribes, who have long relied on the river and surrounding forests for their traditional livelihoods.

Geomorphology

The landscape of the Siyom River Basin is shaped by a combination of structural and fluvial processes, giving it a unique character. The region is marked by low to moderately dissected hills and valleys, indicative of both prolonged erosion and tectonic activity. Along the river's course, you'll find a range of fluvial features, such as paleochannels, point bars, terraces, valleys, and channel islands, all pointing to the dynamic nature of sediment transport and river movement. The presence of older floodplains and snow-covered zones highlights the climatic and altitudinal diversity in the region. Additionally, some areas are prone to landslides, typically a result of steep slopes and tectonic shifts, adding another layer of complexity to the basin's geomorphology.

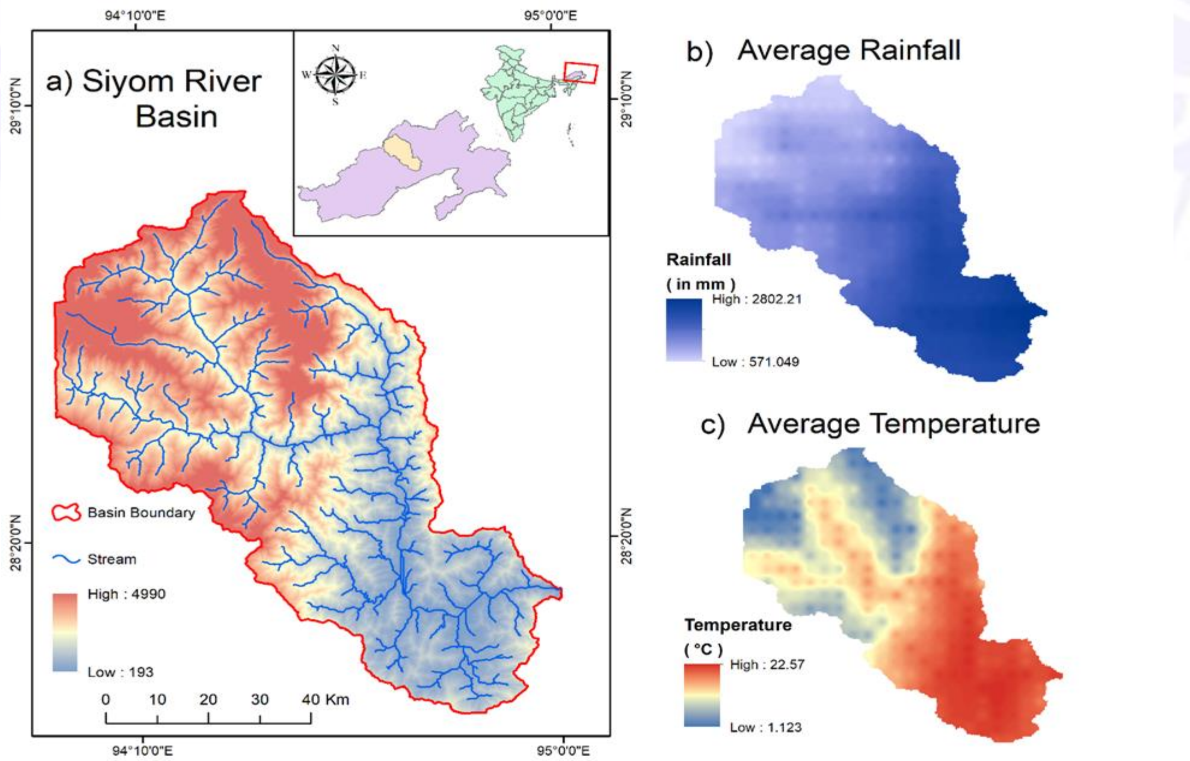

Figure 1: Location of the Study Area. a) Location map of the study area. b) Average Rainfall map of the study area. c) Average Temperature of the study area

Geology

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The geological makeup of the Siyom River Basin is diverse and spans several geological periods, ranging from Paleoproterozoic to Eocene. In the central and eastern parts of the basin, high-grade metamorphic rocks from the Pari Mountain Gneiss and Bomdila Group dominate, while older sedimentary sequences can be found in the Siang Group. Further, Palaeozoic units, such as the Miri and Boleng Groups, reflect past marine sedimentation. To the east, Cretaceous sediments from the Dibang Group and volcanic rocks from the Rotung Volcanics indicate tectonic and volcanic activities that shaped the region during the Himalayan orogeny.

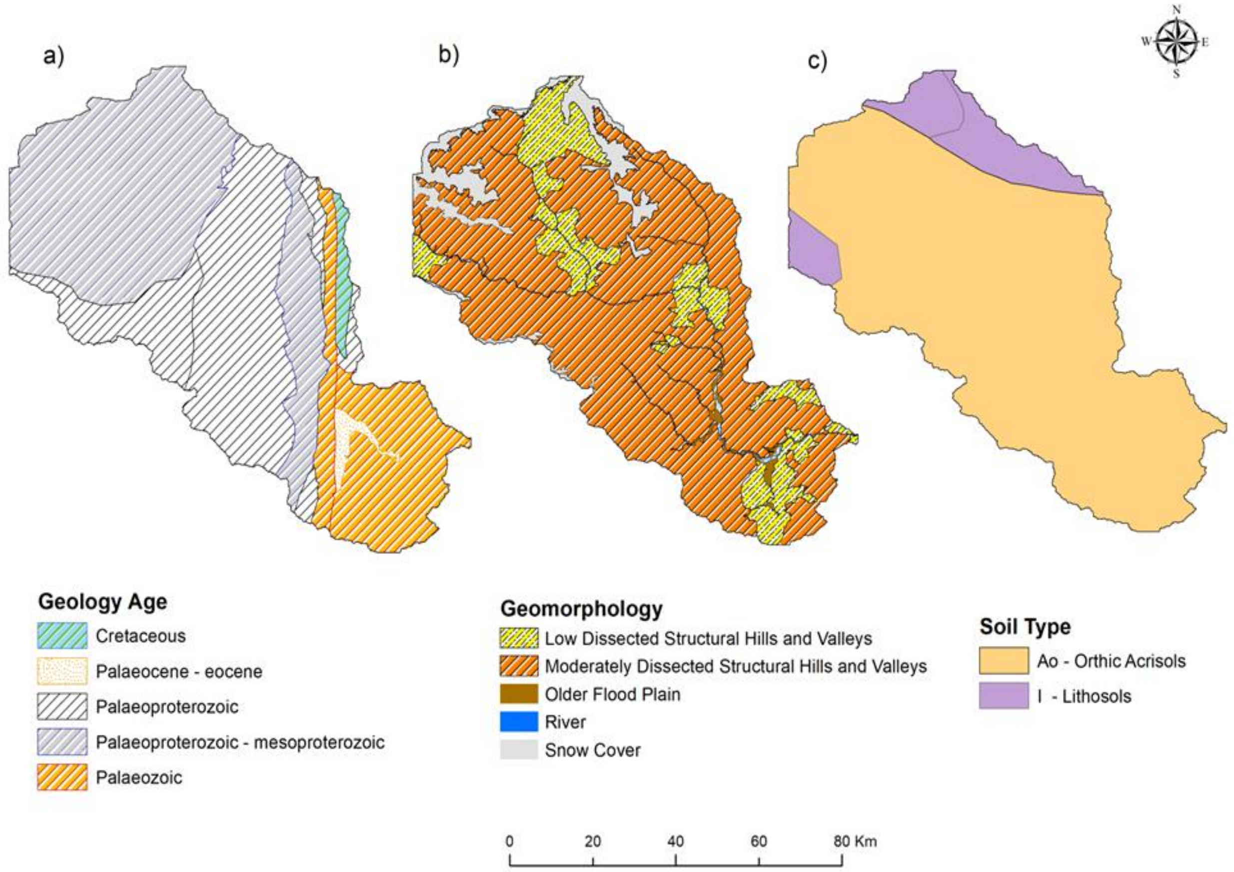

Figure 2: Geology and Geomorphology of the Siyom River Basin. a) Geology age map of the Study area. b) Geomorphology map of the Study area. c) Soil map of the Study area

Climate

The climate in the Siyom Basin is characterized by a mix of humid subtropical and temperate conditions, strongly influenced by the monsoon winds and varying altitudes across the basin. The region, classified under humid mesothermal by Thornthwaite and spanning from Cf (humid subtropical) to Df (cold humid) zones in Trewartha's classification, experiences considerable rainfall throughout the year. Average annual rainfall ranges between 2,000 mm to over 4,000 mm, with the monsoon season (June–September) contributing the majority (80–90%) of this precipitation. July and August usually witness the highest rainfall, which often leads to increased river discharge and sediment load, making these months critical for understanding the basin's hydrological dynamics.

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Land Use and Vegetation

The land use in the Siyom Basin reflects the region's diverse topography and climate. At lower and mid-elevations, the landscape is dominated by dense subtropical evergreen and semi-evergreen forests, while alpine vegetation thrives at higher altitudes. Local agricultural practices are centered around shifting cultivation (jhum), a traditional form of farming that requires the forest to be cleared periodically for cultivation. In valley areas, limited terraced farming is practiced, though human settlements remain relatively sparse. The combination of intensive rainfall, fragile soils, and traditional agricultural practices has led to significant soil erosion, making sustainable land management a challenge. The local communities, primarily engaged in forest-based subsistence activities, face ongoing struggles with soil degradation, further complicating efforts for ecological conservation.

Datasets

For this study, we utilized various geospatial datasets to conduct a detailed morphometric and thematic analysis of the Siyom River Basin. These datasets—covering elevation, climate, geology, geomorphology, and soil—were carefully chosen based on their relevance, spatial resolution, and availability.

Digital Elevation Model (DEM)

The 30-meter resolution SRTM Digital Elevation Model (DEM) was used to create the topographic map of the Siyom River Basin. The DEM was downloaded from the USGS Earth Explorer platform (https://earthexplorer.usgs.gov/), and it provided a reliable foundation for delineating the river basin, mapping the drainage network, and calculating key morphometric parameters.

Climate and Temperature Data

Precipitation and temperature data were sourced from Google Earth Engine (GEE). CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) was used for rainfall data, and TerraClimate provided monthly temperature information. These datasets were processed within GEE for large-scale analysis. Detailed processing scripts can be found in Appendix A.

Geological and Geomorphological Data

We obtained geological and geomorphological maps from the Bhukosh portal (Geological Survey of India), which included details on lithological boundaries and geomorphic features. The data were downloaded in shapefile format, clipped, and reprojected to align with the DEM's spatial reference system, helping to analyze the geological impact on basin morphology.

Soil Data

Soil data were retrieved from the Harmonized World Soil Database (HWSD), provided by the FAO. This global dataset offers valuable information on soil texture and classification, suitable for regional analysis. The soil data were clipped to the Siyom Basin's boundary for integration into the study.

To ensure consistency across all datasets, we standardized everything to the WGS 84 UTM Zone 46N projection

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Table 1: Dataset Used in the Study

Data Type	Description	Source
Digital Elevation Model (DEM)	30-meter resolution SRTM DEM used for basin delineation and morphometric analysis.	USGS Earth Explorer (https://earthexplorer.usgs.gov)
Rainfall Data (CHIRPS)	Climate Hazards Group InfraRed Precipitation data used for annual and seasonal rainfall analysis.	Google Earth Engine (https://developers.google.com/earth-engine/datasets/catalog/UCSB-CHG_CHIRPS_DAILY)
Temperature Data (TerraClimate)	A monthly high-resolution climate dataset used to analyze temperature patterns across the basin.	Google Earth Engine (https://developers.google.com/earth-engine/datasets/catalog/IDAHO_EPSCOR_TERRACLIMATE)
Geological Map	Vector map showing lithological units and major structures in the study area.	Bhukosh – Geological Survey of India (https://bhukosh.gsi.gov.in)
Geomorphological Map	Geomorphological features include structural hills, floodplains, and denudational units.	Bhukosh – Geological Survey of India (https://bhukosh.gsi.gov.in)
Soil Map	A global raster soil dataset used to extract major soil types and their characteristics.	FAO Harmonized World Soil Database (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/hwsd/en/)

Methodology of the Study

An integrated geospatial approach was used to analyze the morphometric characteristics of the Siyom River Basin, combining satellite datasets, open-source platforms, and GIS tools to ensure accuracy and reproducibility.

Morphometric Analysis

Figure 3 outlines the morphometric analysis framework. The SRTM 30-meter resolution DEM was processed in ArcGIS 10.4, starting with reprojection to the WGS 84 UTM Zone 46N coordinate system. Sink-filling removed spurious depressions, and hydrological tools generated flow direction and accumulation layers. These were crucial for delineating the basin boundary and extracting the drainage network. Stream ordering followed Strahler's method for hierarchical classification.

Morphometric parameters were categorized into linear (e.g., stream order, length), areal (e.g., drainage density, form factor), and relief (e.g., basin relief, gradient ratio). All calculations were done using ArcGIS, and statistical analysis was performed in Microsoft Excel. The formulas for these parameters are presented.

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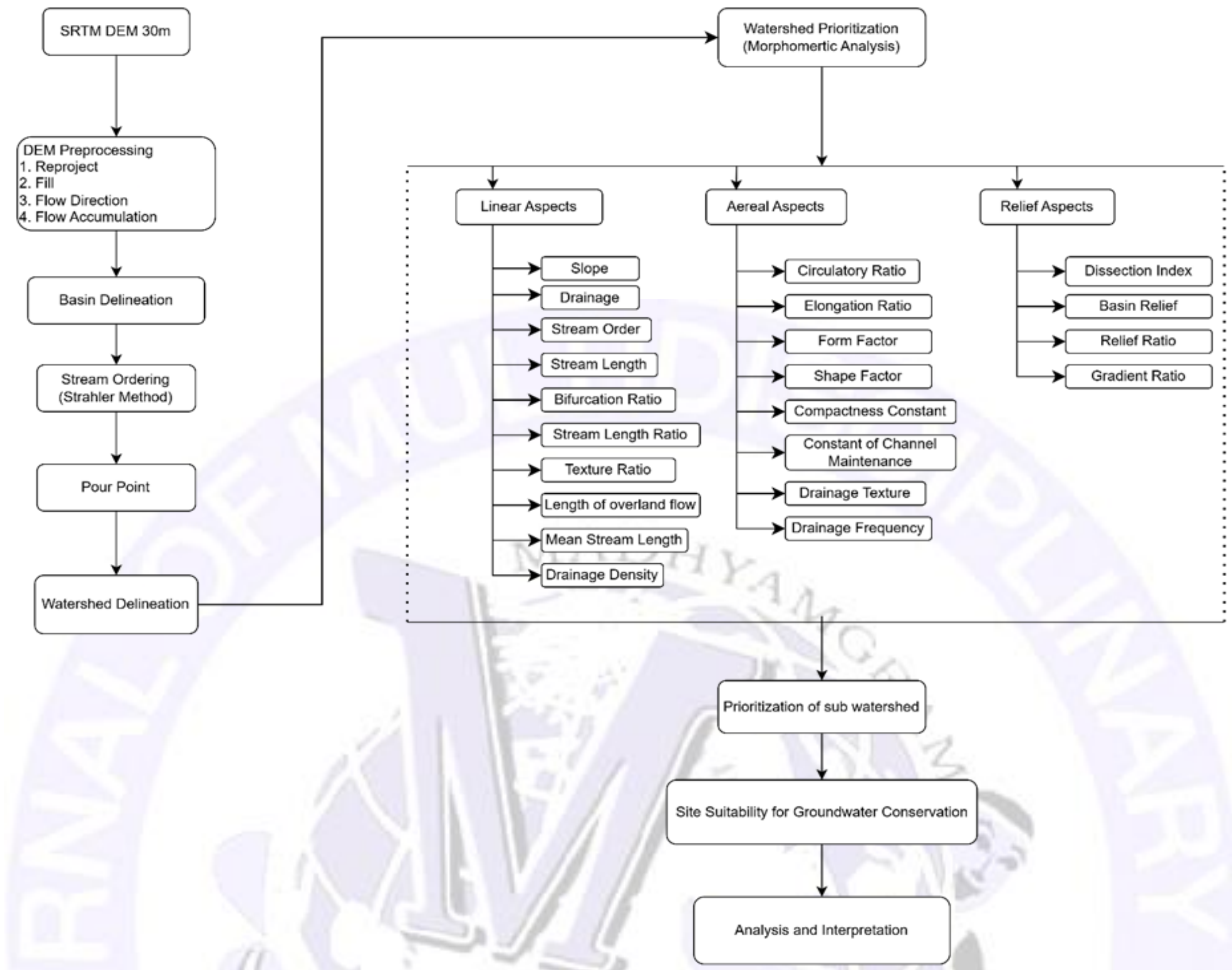

Figure 3: Flowchart of the methodology used

Climatic and Temperature Analysis Using Google Earth Engine (GEE)

Climatic data were analyzed using Google Earth Engine (GEE). CHIRPS data provided rainfall information, and TerraClimate gave temperature data. The area boundary was uploaded, and data were filtered both temporally and spatially to generate mean annual composites, which were exported for GIS analysis.

Sub-Watershed Prioritization

Sub-watersheds were prioritized for soil and water conservation based on eleven morphometric parameters. Each sub-watershed was ranked based on hydrological behavior and erosion susceptibility. Parameters like drainage density and bifurcation ratio were used to identify stable regions, while others (e.g., elongation ratio) indicated favorable hydrological conditions. The final compound factor was the average of all ranks, used to prioritize areas for conservation.

Groundwater Conservation-Suitability Zonation

To identify areas for groundwater conservation, thematic layers (e.g., LULC, slope, drainage density) were resampled to a 30-meter resolution. Each layer was classified into five suitability classes, and weighted sum overlay was used in the ArcGIS software to create a final suitability map for groundwater recharge zones.

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Table 2: Computation of morphometric parameters.

Sl. No.	Parameter	Formula / Definition	Reference
		Estimation of Linear Parameters	
1	Stream Order (μ)	Ranking streams hierarchically	Strahler (1964)
2	Stream Length (Lμ)	Total length of stream segments of a particular order	Horton (1945)
3	Mean Stream Length (L)	$L = \sum L\mu / N\mu$	Strahler (1964)
4	Stream Length Ratio (R_l)	$R_l = L / L(\mu-1)$	Horton (1945)
5	Bifurcation Ratio (R_b)	$R_b = N\mu / N(\mu+1)$	Schumm (1956)
6	Drainage Density (D_d)	$D_d = \sum L\mu / A$	Horton (1932)
7	Texture Ratio	Number of stream segments of all orders per unit perimeter	Horton (1945)
8	Length of Overland Flow (L_o)	$L_o = 1 / (2 \times D_d)$	Horton (1945)
		Estimation of Areal Parameters	
1	Circularity Ratio (R_c)	$R_c = 4\pi A / P^2$	Miller (1953), Strahler (1964)
2	Elongation Ratio (R_e)	$R_e = 1.128 \times \sqrt{(A)} / L$	Schumm (1956)
3	Form Factor (F_f)	$F_f = A / L^2$	Horton (1932, 1945)
4	Compactness Constant (C_c)	Ratio of basin perimeter to circumference of circle of equal area	Horton (1945)
5	Drainage Texture (T)	$T = D_d \times F_s$	Horton (1945)
6	Shape Factor (B_s)	$Bs = L^2 / A$	Horton (1932)
7	Constant of Channel Maintenance (C)	$C = 1 / D_d$	Schumm (1956)
8	Drainage Frequency (Fμ)	$F\mu = N\mu / A$	Horton (1932)
		Estimation of Relief Aspects	
1	Basin Relief (R)	$R = H–h$	Hadley and Schumm (1961)
2	Relief Ratio (R_r)	$R_r = R / L$	Schumm (1956)
3	Gradient Ratio (G_r)	$G_r = (a–b) / L$	Sreedevi et al. (2005)

Groundwater Conservation-Suitability Zonation

To identify areas for groundwater conservation, thematic layers (e.g., LULC, slope, drainage density) were resampled to a 30-meter resolution. Each layer was classified into five suitability classes, and weighted sum overlay was used in the ArcGIS software to create a final suitability map for groundwater recharge zones.

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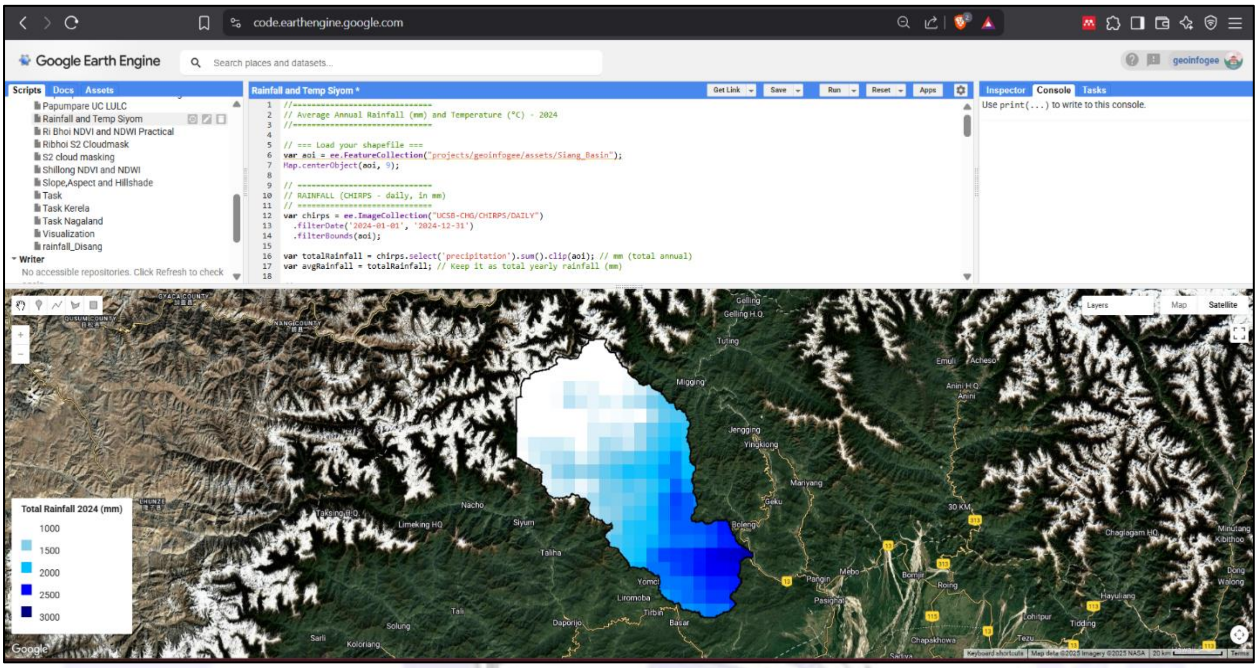

Figure 4: GEE code snippet for rainfall map using CHIRPS

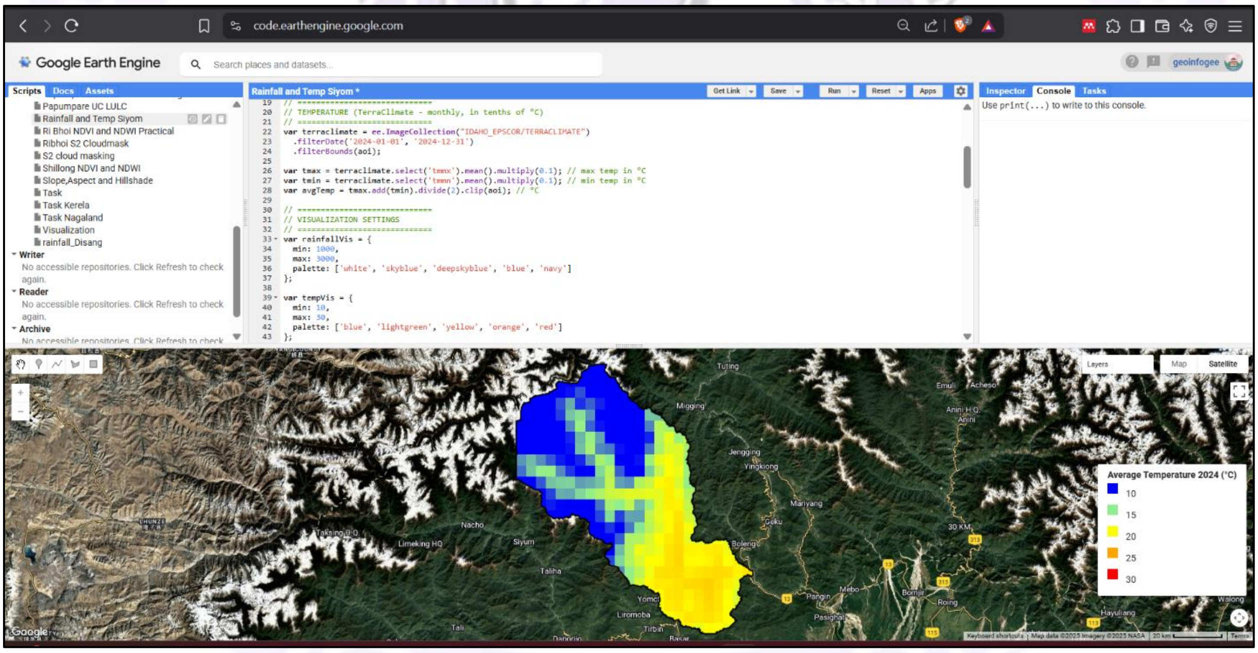

Figure 5: GEE code snippet for temperature map using TerraClimate

Results and Discussion

Linear Morphometric Parameters

Stream Order (μ)

Stream order, classified according to Strahler's (1964) method, is a fundamental morphometric parameter used to characterize the drainage network. In the Siyom River Basin, a fifth-order basin structure was identified, with first-order streams showing the highest frequency, primarily in the hilly terrain. This suggests that the study area is in an early geomorphic stage, with high erosion rates and active landform evolution. The decreasing number of streams with

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increasing order aligns with the general trends observed in other river basins (Strahler, 1964). These findings confirm that stream order classification is a reliable indicator of basin complexity and geomorphic development.

Table 3: Linear Morphometric Parameters

Linear Morphometric Parameters								
Watershed	Stream order (μ)	Stream Length (L_μ)	Mean Stream Length (L)	Stream Length Ratio (R_l)	Bifurcation Ratio (R_b)	Drainage Density (D_d)	Texture Ratio (T)	Length of Overland Flow (L_o)
WS 1	25.00	107.20	30.96	1.36	4.50	0.23	0.22	2.16
WS 2	22.00	94.11	16.09	0.80	2.75	0.28	0.25	1.77
WS 3	31.00	173.05	47.58	1.66	5.00	0.26	0.20	1.92
WS 4	75.00	324.95	45.23	3.18	2.91	0.24	0.33	2.05
WS 5	15.00	51.84	23.01	1.57	3.33	0.26	0.21	1.92
WS 6	23.00	154.14	46.35	1.41	4.25	0.26	0.20	1.89
WS 7	40.00	235.87	79.20	0.43	2.16	0.31	0.24	1.63
WS 8	15.00	85.00	34.47	1.03	3.00	0.26	0.15	1.93
WS 9	13.00	84.46	41.31	33.45	3.00	0.34	0.13	1.45
WS 10	10.00	32.61	15.88	1.07	2.75	0.25	0.19	1.96
WS 11	21.00	89.46	23.26	1.54	2.50	0.30	0.24	1.69

Stream Length ($L\mu$)

Stream length is another essential parameter that reflects the basin's hydrological and geomorphological features. The total stream length for the Siyom River Basin was calculated to be 1,432.68 km, which is consistent with Horton's (1945) principle that stream length increases with decreasing stream order. The highest stream lengths were found in first-order streams, confirming the findings of Horton (1945), who noted that first-order streams typically have greater lengths than higher-order streams. This variability in stream length is attributed to differences in lithology, slope, and elevation, which influence the basin's hydrological behavior and runoff patterns.

Mean Stream Length (L) and Stream Length Ratio (Rl)

The mean stream length for various stream orders showed a general increase with order, as observed in similar studies (Strahler, 1964). The stream length ratio (Rl), however, did not exhibit a consistent trend across sub-watersheds, indicating significant spatial variability. Watershed 9, for example, demonstrated an unusually high Rl value, suggesting abrupt topographic changes or underlying structural controls. This variability in Rl values supports the hypothesis that basin evolution is influenced by complex factors, including slope, lithology, and tectonic activities.

Bifurcation Ratio (R_b)

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The bifurcation ratio, which represents the branching pattern of the basin's drainage network, varied from 2.16 to 5.00, with an average of 3.29. These values indicate a moderately dissected terrain with a predominantly dendritic drainage pattern; characteristic of basins developed under homogeneous lithological conditions. Lower Rb values in some watersheds, such as Watershed 9, suggest that these areas have higher permeability, flatter terrain, and lower erosion potential, making them suitable for groundwater recharge.

Drainage Density (D_d)

The drainage density, which reflects the closeness of stream channels, ranged from 0.23 to 0.34, with an average of 0.27. These low values indicate high permeability, dense vegetation, and gentle slopes, suggesting that the basin is well-suited for groundwater recharge. According to Nautiyal (1994), low drainage density typically correlates with high infiltration rates and minimal surface runoff, making these regions favorable for groundwater conservation.

Texture Ratio

The texture ratio, representing the distribution and spacing of drainage lines, varied from 0.01 to 0.02. These values suggest a coarse to intermediate drainage texture, which is influenced by lithology and vegetation cover. Sub-watersheds with a coarse texture (e.g., Watersheds 1, 3, 4, 6, and 8) are likely to have lower infiltration capacities, making them more susceptible to surface runoff and soil erosion. In contrast, sub-watersheds with intermediate texture (e.g., Watersheds 2, 5, 7, 9, 10, and 11) exhibit relatively higher infiltration rates.

Length of Overland Flow (L_o)

The length of overland flow, calculated as half the reciprocal of drainage density, varied across the sub-watersheds. This parameter influences both hydrological response and the physiographic evolution of the basin. Watersheds with higher Lo values, such as Watershed 9, are characterized by longer flow paths, which favor groundwater recharge by allowing water to infiltrate into the soil.

Estimation of Areal Parameters

Circulatory Ratio (R_c)

The circulatory ratio (R_c), defined as the ratio of the basin area to the area of a circle with the same perimeter, reflects basin shape and runoff potential(Leopold et al., 2020). In this study, R_c values range from 0.31 to 0.57 (Table). Higher values, such as in Watershed 10 (0.57), indicate more circular basins with higher runoff potential, while lower values, like in Watershed 9 (0.31), suggest elongated basins with greater infiltration capacity. Most sub-watersheds exhibit R_c values below 0.50, implying youthful geomorphic stages and favorable conditions for groundwater recharge.

Elongation Ratio (R_e)

The elongation ratio (R_e), defined as the ratio of the diameter of a circle with the same area as the basin to its maximum length, reflects basin shape and hydrological response (Schumm, 1956). Values typically range between 0.6 and 1.0 across diverse climatic and geologic settings. In the present study, R_e varies from 0.53 to 1.55 (Table), indicating a mix of elongated and near-

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circular basins. Lower values suggest steeper slopes and greater structural influence, whereas higher values point to low relief, high infiltration, and reduced runoff potential.

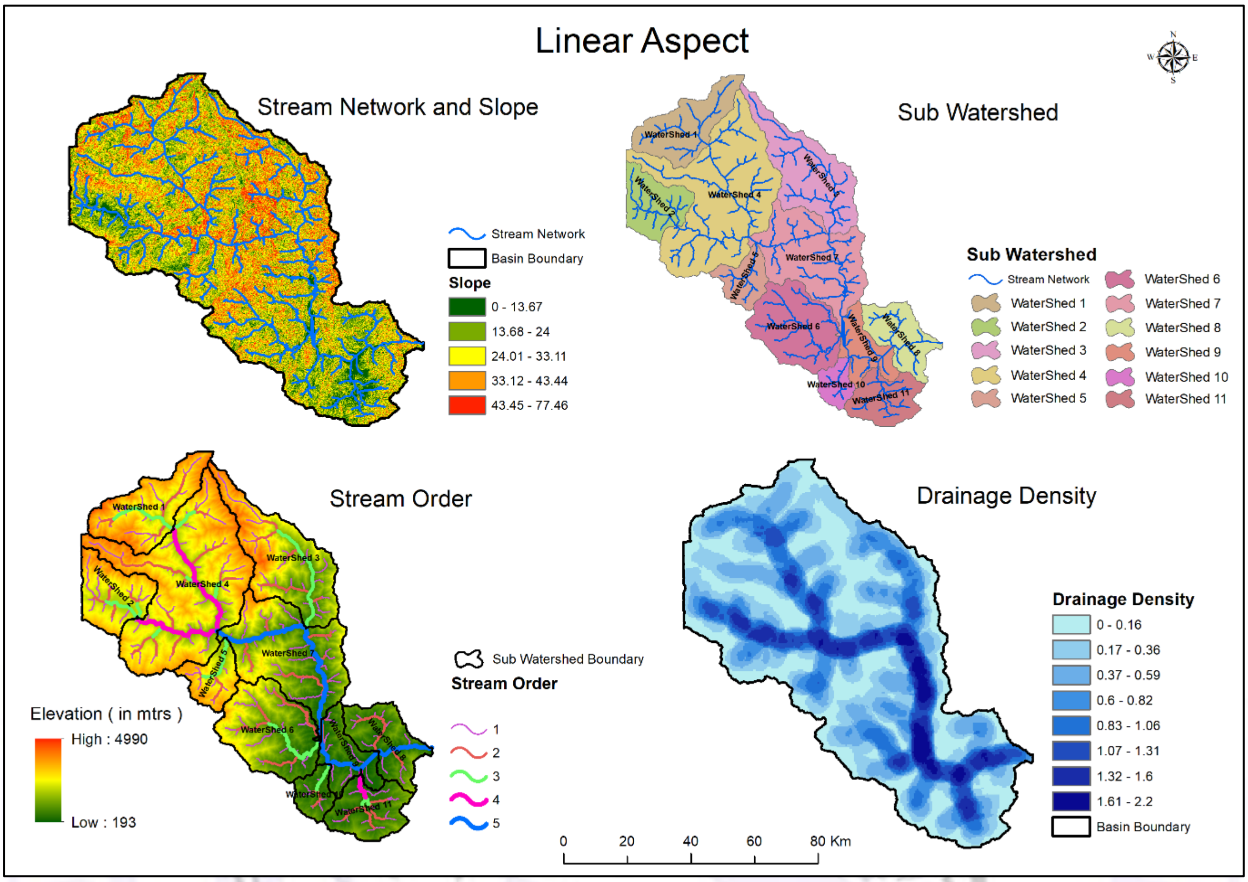

Figure 6: Linear Aspect Parameters of Siyom River Basin

Form Factor (F_f)

Form factor (F_f), as defined by Horton (1932), is the ratio of basin area to the square of its length and reflects the basin's shape and flow characteristics. Values close to 1 indicate circular basins with high peak flows, while lower values signify elongated basins with lower peak discharge and longer flow duration. In the present study, F_f ranges from 0.22 to 1.89 (Table), indicating a predominance of elongated sub-watersheds with gentle peak flows and extended runoff periods. The lowest value was observed in Watershed 3 (0.22), suggesting a highly elongated form.

Compactness Constant (Cc)

The compactness constant (C_c) is defined as the ratio between the perimeter of a drainage basin and the circumference of a circle with an equivalent area (Horton, 1945). It provides a measure of the basin's shape regularity, where a value close to 1.0 indicates a circular basin, while higher values suggest deviation from circularity and greater elongation. In this study, C_c values range from 1.33 to 1.80, indicating that the basins are not compact but moderately elongated. The average value suggests that the watersheds deviate from an ideal circular shape, affecting runoff characteristics and watershed response times. Watershed 4 and Watershed 9, with C_c values of

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1.76 and 1.80, respectively, show greater elongation and perimeter complexity, while Watershed 10, with a value of 1.33, is relatively more compact (Table).

Shape Factor (B_s)

Shape factor (B_s) is defined as the ratio of the square of basin length to its area and is used to assess the shape irregularity of a drainage basin (Yadav et al., 2014). A lower value indicates a more circular basin, while higher values suggest elongation. In this study, B_s values range from 0.53 to 4.51, with an average of 1.65. This indicates that the basins exhibit varying shapes, with some showing elongated forms and others more compact geometry (Table).

Constant of Channel Maintenance (C)

The constant of channel maintenance (C) is defined as the reciprocal of drainage density and was introduced by Schumm (1956) to assess the land area required to sustain a unit length of channel. It serves as an indicator of surface permeability and runoff characteristics. A higher C value implies greater permeability, less surface runoff, and a more stable hydrological regime, whereas a lower C value indicates impermeable surfaces, higher runoff, and more frequent channel formation. In the study, C values range from 2.91 to 4.32, with an average of 3.68 (Table) reflecting moderate to high permeability across the watersheds. Watershed 1, with the highest C value of 4.32, suggests a highly permeable terrain with relatively low surface runoff potential. On the other hand, Watershed 9, having the lowest value of 2.91, indicates a comparatively impermeable surface, potentially leading to higher runoff and channel development.

Drainage Texture (T)

The concept of drainage texture, referring to the relative spacing of drainage lines within a unit area, was first introduced by Smith (1950). It provides insight into the dissection of terrain and the relative influence of lithology, vegetation, infiltration rate, and climatic parameters (Horton, 1945; Smith, 1950). The texture of a drainage basin is influenced by factors such as slope, rainfall intensity, surface permeability, soil type, and vegetation cover. According to Smith, (1950), drainage texture is classified into four categories: coarse (< 4), intermediate (4–10), fine (10–15), and ultra-fine (>15) per km². Vegetation density and geological composition significantly impact the texture by influencing stream frequency and drainage density (Khan et al., 2001). The drainage texture (T) is quantitatively calculated as the product of drainage density (D_d) and stream frequency (F_s). In the Siyom River basin, the calculated values of drainage texture for the 11 sub-watersheds range from 0.01 to 0.02 (Table), indicating an extremely coarse drainage texture. Such low values suggest high permeability, gentle slopes, and dense vegetation cover, which promote greater infiltration and lower surface runoff.

Drainage frequency (F_s)

Drainage frequency is defined as the number of streams per unit area of the basin (Horton, 1932). It reflects the degree of surface runoff and slope steepness, with higher values indicating greater runoff and steeper terrain (Rao 2009; Yadav et al., 2014). In this study, drainage frequency varies among the sub-watersheds, with values ranging from 0.04 to 0.08. Watersheds 5 and 10 exhibit higher frequencies, suggesting more surface runoff, while watershed 6 has the lowest

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frequency, indicating higher permeability and gentler slopes. The average drainage frequency for the basin is approximately 0.05, signifying moderate permeability and soil erosion potential. The detailed data are shown in Table 4.

Table 4: Aereal Morphometric Parameters

Aereal Morphometric Parameters								
Watershed	Circularity Ratio (R_c)	Elongation Ratio (R_e)	Form Factor (F_f)	Compactness Constant (C_c)	Drainage Texture (T)	Shape Factor (B_s)	Constant of Channel Maintenance (C)	Drainage Frequency (F_μ)
WS 1	0.43	1.55	1.89	1.52	0.01	0.53	4.32	0.05
WS 2	0.53	0.88	0.61	1.37	0.02	1.63	3.54	0.07
WS 3	0.35	0.53	0.22	1.70	0.01	4.51	3.83	0.05
WS 4	0.32	1.29	1.32	1.76	0.01	0.76	4.09	0.06
WS 5	0.48	1.04	0.85	1.44	0.02	1.18	3.85	0.08
WS 6	0.54	0.99	0.77	1.36	0.01	1.30	3.78	0.04
WS 7	0.35	0.66	0.34	1.70	0.02	2.91	3.27	0.05
WS 8	0.41	0.81	0.51	1.56	0.01	1.96	3.85	0.05
WS 9	0.31	1.00	0.79	1.80	0.02	1.26	2.91	0.05
WS 10	0.57	1.14	1.01	1.33	0.02	0.99	3.92	0.08
WS 11	0.48	1.04	0.85	1.45	0.02	1.18	3.37	0.07

Estimation of Relief Aspects

Basin Relief (R)

Basin relief represents the vertical difference between a drainage basin's highest and lowest elevations. It is a key morphometric parameter for understanding the denudational status of the landscape and plays a significant role in determining stream gradient, surface runoff, and sediment dynamics. In the present study, basin relief varies from 1,179 m in Watershed 10 to 4,154 m in Watershed 3. The highest elevation within the basin reaches 4,990 m, while the lowest point is recorded at 281 m. These variations suggest a moderately sloping terrain with moderate potential for runoff and erosion. The relief values for each watershed are provided in Table 5.

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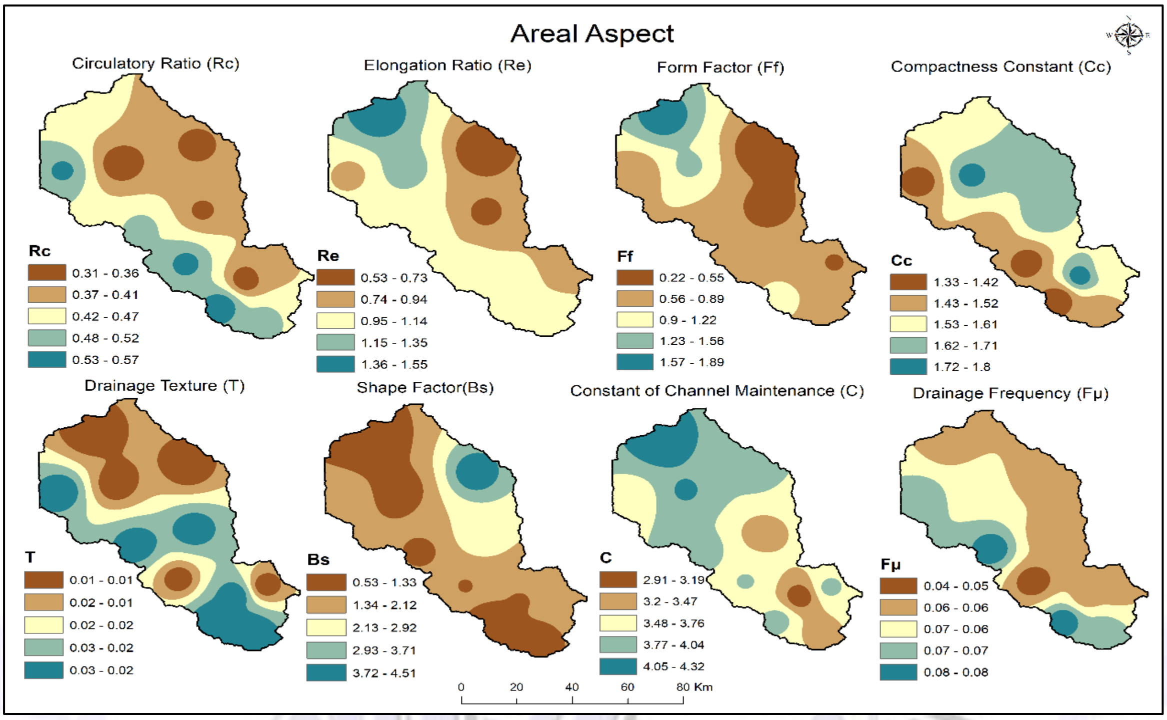

Figure 7: Areal Aspect Parameters of Siyom River Basin

Relief Ratio (R_r)

Relief ratio is the ratio between basin relief and basin length, indicating slope steepness and terrain ruggedness (Avinash et al., 2011). Higher values typically signify hilly or mountainous regions, while lower values suggest gentler slopes or valley areas. In the Siyom River basin, relief ratios vary across sub-watersheds, with higher values (e.g., 0.21) indicating steep terrain, and lower values (e.g., 0.07) reflecting more subdued relief (Table 5). This parameter aids in understanding runoff potential, erosion risk, and land suitability for settlement and agriculture.

Gradient ratio is the ratio of the difference in elevation between the source and mouth of the major stream to the maximum length in the basin. In the Mula river basin, this ratio varies across watersheds, ranging from as low as 1.42 m/km in Watershed 8 to as high as 142.95 m/km in Watershed 5. This variation indicates differences in slope steepness and runoff potential among the sub-basins. Higher gradient ratios suggest steep slopes and greater surface runoff, while lower values indicate gentler slopes with likely higher infiltration and lower runoff (Table 5).

Table 5: Relief Morphometric Parameters

Relief Morphometric Parameters

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	Watershed	Basin Relief (R)	Relief Ratio (R_r)	Gradient Ratio (G_r)
Gradient Ratio (G_r)	WS 1	3.35	0.21	95.03
	WS 2	2.44	0.10	58.70
	WS 3	4.15	0.08	59.00
	WS 4	3.74	0.12	22.11
	WS 5	3.04	0.20	142.95
	WS 6	3.69	0.13	72.66
	WS 7	3.95	0.08	3.33
	WS 8	1.67	0.07	1.42
	WS 9	1.64	0.09	1.65
	WS 10	1.18	0.10	29.47
	WS 11	1.61	0.09	23.61

Note: *The elevation values used for calculating basin relief were originally in meters. Since other morphometric parameters were analyzed in square kilometers or kilometers, the elevation values were converted from meters to kilometers for consistency. Ensuring uniformity in units across all parameters.*

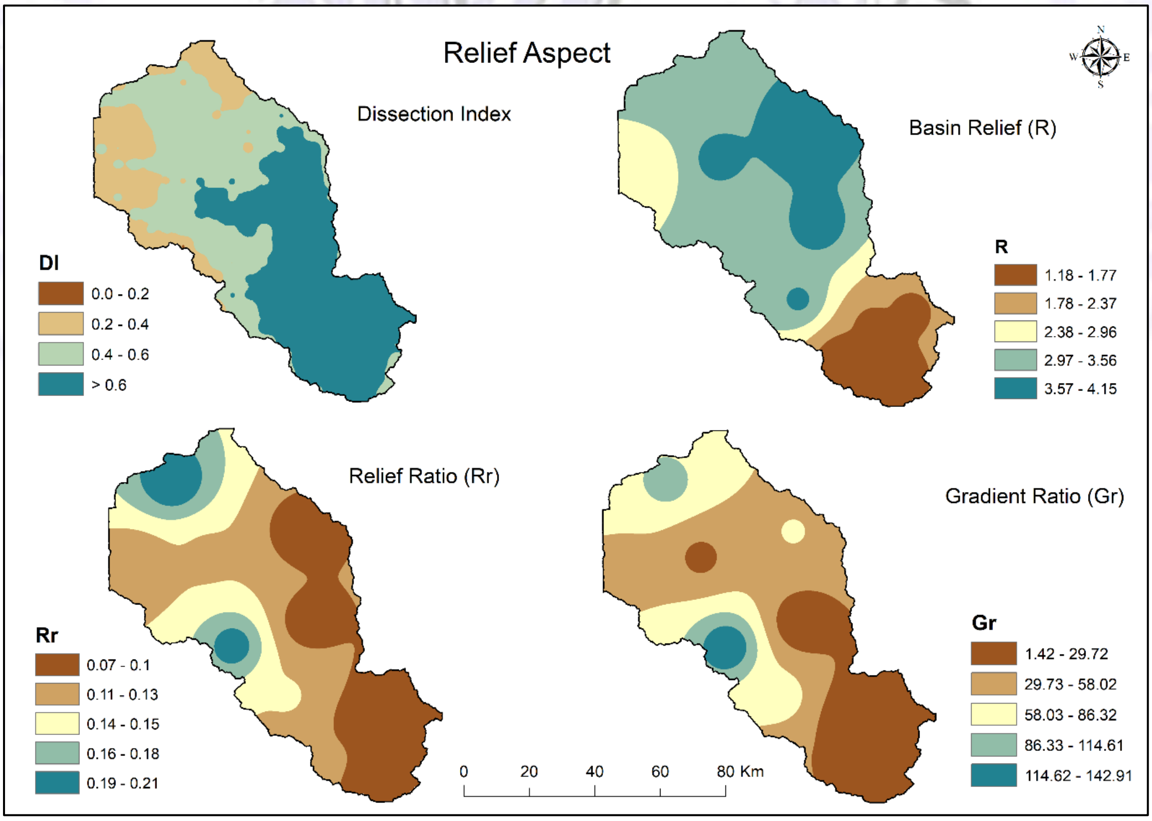

Figure 8: Relief Aspect Map of Siyom River Basin.

Prioritization of Sub-watersheds for Groundwater Potential

The analysis of morphometric parameters plays a crucial role in identifying zones with high groundwater potential and areas susceptible to soil erosion (Yadav et al., 2018).

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In the present study, sub-watersheds of the Siyom River basin were prioritized to determine regions with significant soil erosion risk, allowing targeted conservation efforts over time. Various morphometric parameters such as bifurcation ratio (R_b), drainage density (D_d), stream frequency (F_μ), Length of Overland Flow (L_o), drainage texture (T), Circularity ratio (R_c), Form Factor (F_f), Shape Factor (B_s), Elongation Ratio (R_e)and Compactness Constant (C_c)were calculated for each sub-watershed. Based on the compound factor derived from these parameters, priority rankings were assigned to guide management decisions.

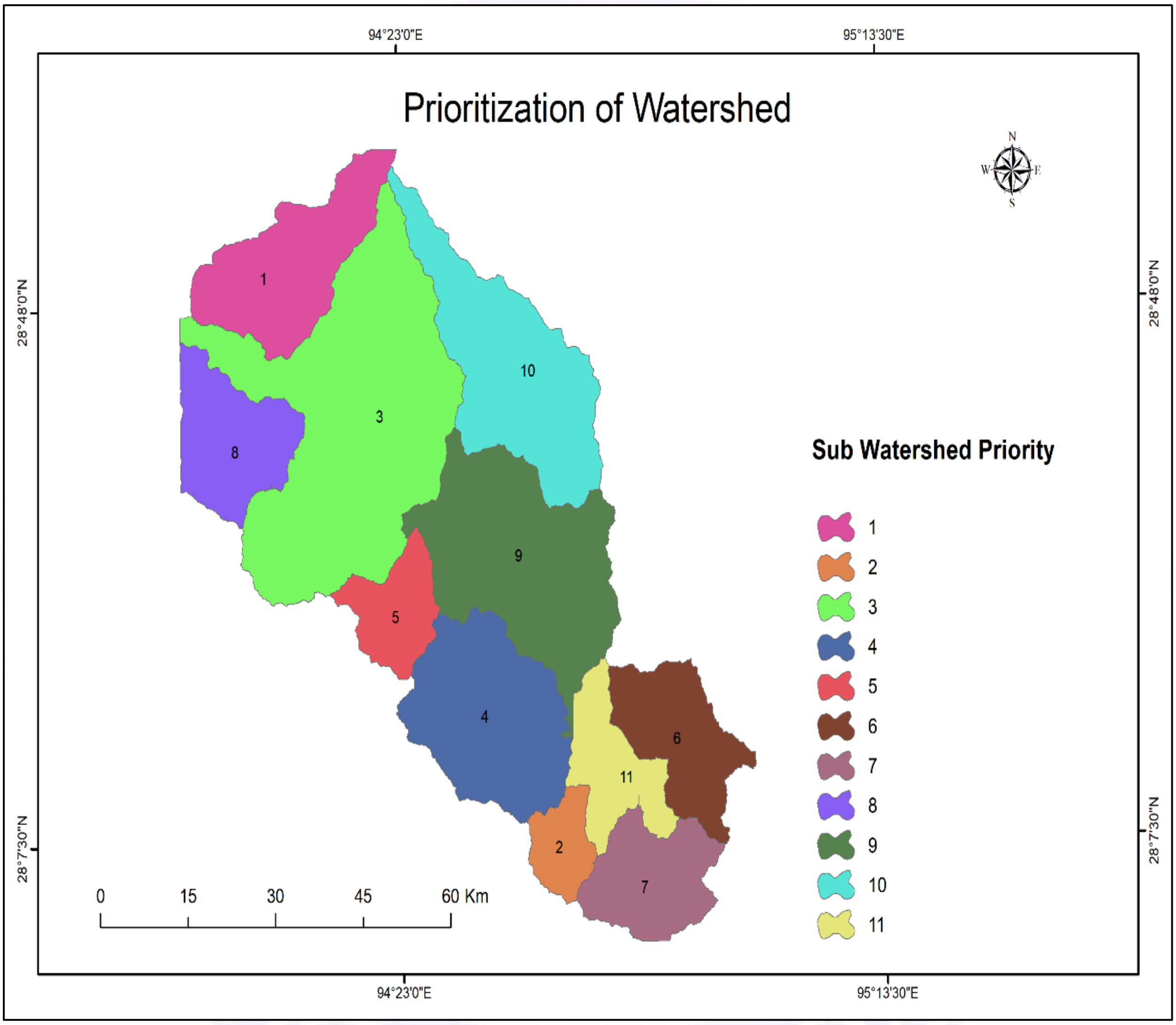

Figure 9: Map showing prioritized sub-watersheds with their ranks.

The results indicate that the morphometric prioritization of the Siyom River sub-watersheds reveals distinct differences in groundwater potential across the basin. Eleven sub-watersheds were ranked. Sub-watershed 1 emerged with the highest priority rank (Rank 1), indicating it is the most groundwater-deficient area due to characteristics like high runoff and low infiltration potential. This zone requires immediate attention for groundwater conservation and recharge interventions. Sub-watersheds 10 and 4 followed with Rank 2 and 3, respectively, also indicating relatively poor groundwater availability and moderate to high erosion risk. In contrast, Sub-watershed 9, which received the lowest priority rank (Rank 11), represents the most

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groundwater-surplus zone. This suggests it has favorable morphometric characteristics such as gentle slopes, lower drainage density, and better potential for water infiltration. Other sub-watersheds, such as WS 6, WS 5, and WS 8, fall under moderate priority zones, indicating a balance between surface runoff and infiltration. Overall, this prioritization helps identify areas requiring focused conservation strategies and supports the sustainable management of groundwater resources within the Siyom River basin.

Table 6: Estimated compound parameter with priority ranking

WS	R_b	D_d	Fμ	L_o	T	R_c	F_f	B_s	R_e	C_c	Compound Factor	Priority Rank
WS 1	4.50	0.23	0.05	2.16	0.01	0.43	1.89	0.53	1.55	1.52	3.70	1
WS 2	2.75	0.28	0.07	1.77	0.02	0.53	0.61	1.63	0.88	1.37	6.55	8
WS 3	5.00	0.26	0.05	1.92	0.01	0.35	0.22	4.51	0.53	1.70	8.00	10
WS 4	2.91	0.24	0.06	2.05	0.01	0.32	1.32	0.76	1.29	1.76	4.70	3
WS 5	3.33	0.26	0.08	1.92	0.02	0.48	0.85	1.18	1.04	1.44	5.70	5
WS 6	4.25	0.26	0.04	1.89	0.01	0.54	0.77	1.30	0.99	1.36	5.00	4
WS 7	2.16	0.31	0.05	1.63	0.02	0.35	0.34	2.91	0.66	1.70	7.70	9
WS 8	3.00	0.26	0.05	1.93	0.01	0.41	0.51	1.96	0.81	1.56	5.95	6
WS 9	3.00	0.34	0.05	1.45	0.02	0.31	0.79	1.26	1.00	1.80	8.05	11
WS 10	2.75	0.25	0.08	1.96	0.02	0.57	1.01	0.99	1.14	1.33	4.15	2
WS 11	2.50	0.30	0.07	1.69	0.02	0.48	0.85	1.18	1.04	1.45	6.50	7

Note: The first priority shows the most deficit area in groundwater water and the last priority indicates a surplus zone of groundwater.

Suitable sites for groundwater conservation

Remote sensing and GIS techniques have proven highly effective in prioritizing river basins and identifying suitable locations for groundwater conservation structures. In this study, parameters such as LULC, slope, dissection index, shape factor, bifurcation ratio, drainage density, drainage frequency, texture ratio, compactness constant, length of overland flow, elongation ratio, form factor, and circulatory ratio were used to compute a weighted sum for delineating conservation-suitable zones. Spatial datasets derived from remote sensing and DEMs were processed within a GIS environment, and a multi-criteria evaluation approach was applied.

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Each watershed was assigned a priority number, with Priority 1 indicating areas of significant groundwater deficit, and Priority 11 denoting surplus zones. A color gradient from blue (low suitability) to red (high suitability) represents physical favorability for recharge. Watersheds 3, 7, and 9, corresponding to Priorities 10, 9, and 11, are identified as highly suitable sites due to favorable characteristics like gentle slopes, permeable soils, and appropriate land use. Although Priority 1 areas face severe deficit, they may lack the physical conditions necessary for effective recharge. Thus, site suitability is influenced not only by groundwater need but also by environmental feasibility, emphasizing the importance of integrating both aspects for sustainable groundwater management. (Figure 10)

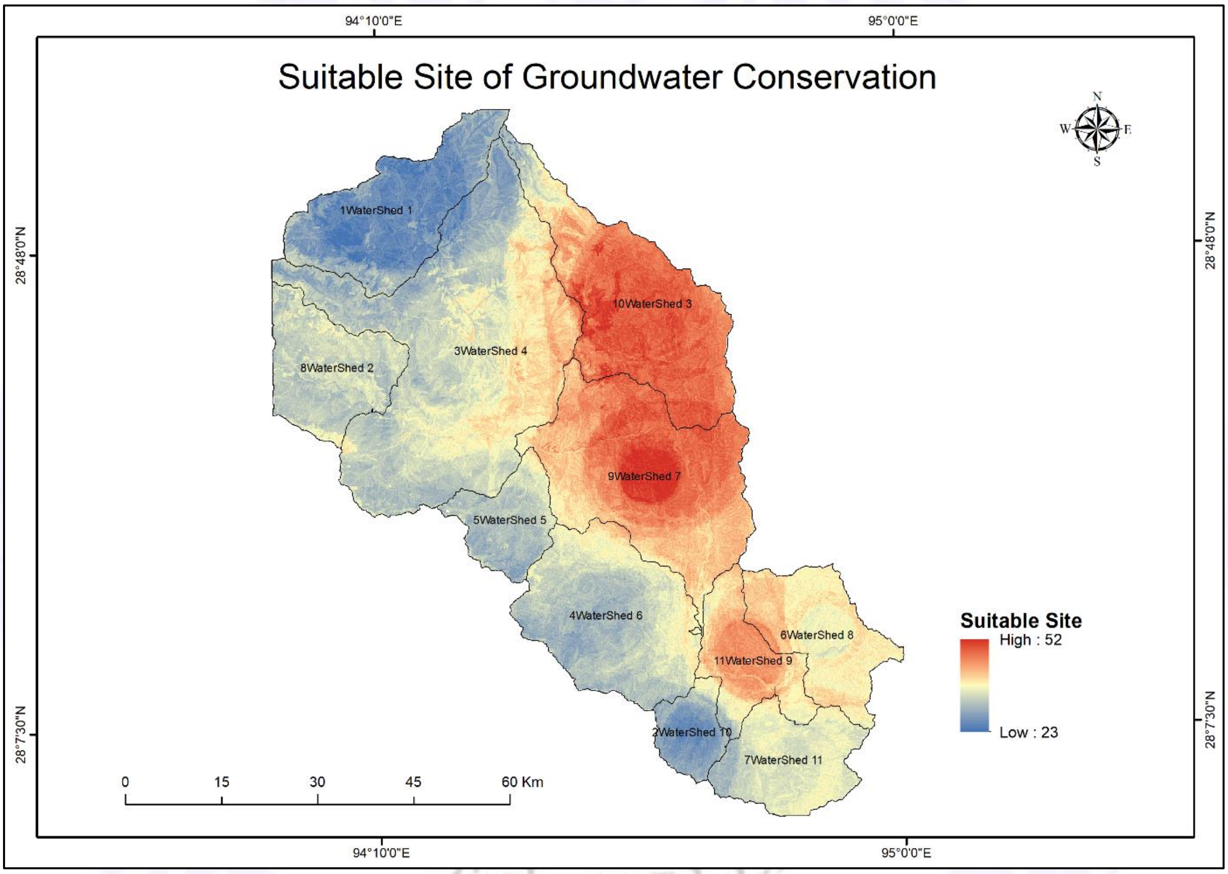

Figure 10: Suitable Locations for Groundwater Recharge Structures.

Conclusion

The morphometric prioritization of the Siyom River sub-watersheds effectively identified areas of groundwater deficit and surplus, enabling targeted groundwater management strategies. Sub-watershed 1, characterized by high runoff and low infiltration, requires immediate intervention of recharge enhancement and conservation. Conversely, sub-watersheds such as 9, with gentle slopes and lower drainage densities, represent promising zones for natural recharge and conservation efforts. The integration of remote sensing-derived morphometric parameters with land use and slope data through GIS-based multi-criteria evaluation proved instrumental in delineating suitable sites for groundwater conservation. This approach ensures that conservation efforts prioritize not only the severity of groundwater scarcity but also the physical feasibility of

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recharge, leading to more sustainable groundwater resource management in the basin. Future work may involve detailed field validation and the implementation of specific conservation structures to improve groundwater availability in identified priority zones.

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