Geospatial and Earth System Science
An International Triannual Scientific Journal

e-ISSN: 3139-549X	Vol. 1	No. 1	Page Nos. 19 - 30	June 2026

Original Research Paper https://www.maned.org/journals **Open Access Journal**

Hypsometric Analysis of Terrain Evolution and Erosional Stages of the Thamirabarani River Basin Using GIS and Remote Sensing

Snegan S[1]*, Ilamathi P.R[2], V. Emayavaramban[3]

[1]*Department of Geography, University of Madras, Guindy Campus, Chennai - 600025, Tamil Nadu, India

[2, 3] Department of Geography, School of Earth and Atmospheric Sciences, Madurai Kamaraj University, Madurai, Tamil Nadu 624021, India

*Corresponding author: Snegan S; sneganshankar73@gmail.com

Abbreviation: GESS
Website: www.maned.org/journals

Received: 20-01-2026
Revised: 27-03-2026
Accepted: 07-04-2026

Key Words:

Hypsometric Analysis; Hypsometric Integral; Terrain Evolution; Erosion Dynamics; GIS; Remote Sensing; Thamirabarani River Basin; Watershed Management

ABSTRACT

Hypsometric analysis provides an effective quantitative approach for understanding geomorphic evolution and erosion dynamics of river basins. The present study evaluates the terrain characteristics and erosional stages of the Thamirabarani River Basin, Tamil Nadu, India, using Remote Sensing (RS) and Geographic Information System (GIS) techniques. A 30 m resolution Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) was utilized to delineate the watershed and its sub-basins, extract drainage networks, and derive elevation parameters. Hypsometric curves were generated based on the relationship between relative area and relative elevation, while the hypsometric integral (HI) was computed using standard empirical methods. The results indicate that the Thamirabarani River Basin exhibits an HI value of 0.47, corresponding to a mature stage of geomorphic development. The S-shaped hypsometric curve further confirms a balanced state between erosion and deposition processes, suggesting moderate landscape dissection and progressive stabilization. Spatial analysis reveals that higher elevations in the Western Ghats are less affected by erosion, whereas low-lying regions are more vulnerable due to increased runoff and anthropogenic influences. The study highlights the significant role of geological structure, climatic conditions, and human activities in controlling erosion processes and terrain evolution. The findings emphasize the need for targeted watershed management strategies, including soil and water conservation measures, to mitigate erosion and enhance sustainability. The integration of GIS-based analysis with hypsometric techniques provides a robust framework for assessing watershed conditions and can be applied to similar river basins for effective environmental planning and management.

INTRODUCTION

Water resources constitute a fundamental component of environmental sustainability and socio-economic development, particularly in regions experiencing rapid population growth, agricultural expansion, and industrialization. Increasing pressure on water resources has intensified the need for scientific assessment of watershed characteristics to support effective planning and management. In this context, drainage basin analysis provides critical insights into hydrological behavior, erosion dynamics, and landscape evolution. Morphometric and geomorphological investigations of river basins are therefore essential for understanding terrain development and for implementing sustainable watershed management strategies. Among various geomorphic techniques, hypsometric analysis has emerged as a robust quantitative approach for evaluating the evolutionary stage of landscapes. Originally introduced to examine the relationship between elevation and area within a drainage basin, hypsometry offers a simplified yet powerful representation of complex topographic structures. The hypsometric curve, which expresses the distribution of land area at different elevations, and the hypsometric integral (HI), a dimensionless parameter, are widely used to interpret erosional status and geomorphic maturity of river basins. These indices enable comparison across basins of varying sizes and physiographic settings, making them particularly valuable in regional and comparative geomorphological studies (Strahler, 1952; Schumm, 1956).

Theoretical and empirical studies have demonstrated that the shape of the hypsometric curve and the magnitude of the hypsometric integral are controlled by the interplay of tectonic activity, lithology, climate, and denudational processes. Convex hypsometric curves with high HI values typically indicate youthful landscapes characterized by minimal erosion and active uplift, whereas concave curves with low HI values represent older, highly eroded terrains approaching peneplanation. Intermediate S-shaped curves correspond to mature stages, where erosion and deposition processes are relatively balanced. Thus, hypsometric analysis serves as an effective tool for assessing the equilibrium state of landscapes and for identifying areas vulnerable to erosion and geomorphic instability (Weissel et al., 1994; Hurtrez et al., 1999).

In recent decades, the integration of Remote Sensing (RS) and Geographic Information Systems (GIS) has significantly enhanced the accuracy and efficiency of hypsometric analysis. High-resolution Digital Elevation Models (DEMs), such as those derived from SRTM, ASTER, and ALOS missions, enable automated extraction of elevation data, watershed boundaries, and drainage networks. GIS-based analytical tools facilitate the generation of hypsometric curves and computation of hypsometric integrals with improved precision, thereby allowing detailed spatial analysis of terrain evolution. This technological advancement has broadened the application of hypsometric methods in geomorphology, hydrology, and environmental management (Girish et al., 2014; Abdo, 2020).

Despite the extensive application of hypsometric analysis in different physiographic regions, limited studies have focused on river basins of southern Tamil Nadu, particularly the Thamirabarani River Basin, which exhibits diverse geomorphological and geological characteristics. Originating from the Western Ghats and draining into the Gulf of Mannar, the basin represents a complex terrain influenced by structural controls, climatic variability, and anthropogenic activities. Understanding its erosional status and geomorphic evolution is crucial for sustainable land and water resource management in the region.

In this context, the present study aims to perform a comprehensive hypsometric analysis of the Thamirabarani River Basin using geospatial techniques. The study seeks to evaluate the relationship between elevation and area, determine the erosional stages of the basin, and analyze the influence of geomorphological and environmental factors on its terrain evolution. By integrating GIS-based analysis with hypsometric principles, the study contributes to a better understanding of watershed dynamics and provides a scientific basis for resource planning and conservation.

STUDY AREA

The Thamirabarani River Basin is located in the southern part of Tamil Nadu, India, extending between latitudes 8°26′45″N to 9°12′00″N and longitudes 77°09′00″E to 78°08′30″E. The basin covers an area of approximately 5,717 km² and spans predominantly across the districts of Tirunelveli and Thoothukudi. Originating from the eastern slopes of the Western Ghats, specifically the Agasthyamalai hills at an elevation of about 1869 m, the river flows eastward and ultimately drains into the Gulf of Mannar near Palayakayal. The basin is bounded by the Vaippar River Basin to the north, the Nambiyar and Kodaiyar basins to the south, the Western Ghats to the west, and the Gulf of Mannar to the east.

The Thamirabarani River system exhibits a well-developed dendritic drainage pattern, characteristic of homogeneous lithological conditions and moderate structural control. The basin comprises several major tributaries, including the Servalar, Manimuthar, Gadana Nadhi, Pachaiyar, and Chittar rivers, which collectively contribute to the hydrological complexity of the system. The total basin length is approximately 126 km, with a variable width ranging between 20 and 85 km. The drainage network reflects an integrated fluvial system shaped by both structural influences and long-term denudational processes.

Physiographically, the basin displays significant variation, ranging from steep mountainous terrains in the Western Ghats to gently sloping plains and coastal lowlands in the eastern region. This pronounced elevation gradient plays a critical role in controlling runoff, erosion, and sediment transport processes. The upper reaches are characterized by rugged topography and high relief, whereas the lower reaches consist of alluvial plains, floodplains, and fluvial landforms such as meanders and oxbow lakes, indicating progressive geomorphic evolution.

Geologically, the western part of the basin is dominated by Precambrian crystalline rocks, while the eastern region comprises sedimentary formations of Tertiary and Quaternary age. This lithological contrast significantly influences drainage characteristics, erosion susceptibility, and soil formation processes. The basin supports a variety of soil types, including lateritic soils in upland regions, alluvial soils in riverine tracts, black cotton soils in selected pockets, and sandy soils in coastal areas. These soil variations directly affect infiltration rates, runoff generation, and agricultural productivity (Gopinath et al., 2015).

Climatically, the basin experiences a tropical monsoon regime, receiving an average annual rainfall of approximately 985 mm, primarily during the southwest and northeast monsoon seasons. Temperature conditions remain relatively high throughout the year, with mean maximum temperatures around 32°C and minimum temperatures near 25°C. The seasonal variability in rainfall plays a crucial role in influencing hydrological responses, erosion rates, and sediment yield within the basin (Ritter et al., 2002).

The vegetation cover in the basin ranges from dense tropical evergreen forests in the Western Ghats to scrublands and agricultural fields in the plains. Forested regions contribute significantly to slope stability and soil conservation, while agricultural lands dominate the lower reaches, supporting crops such as paddy, sugarcane, and groundnut. However, increasing anthropogenic interventions, including deforestation, agricultural intensification, and urban expansion, have altered natural land use patterns, thereby influencing erosion dynamics and hydrological processes (Mohammed I. Khattab et al., 2023).

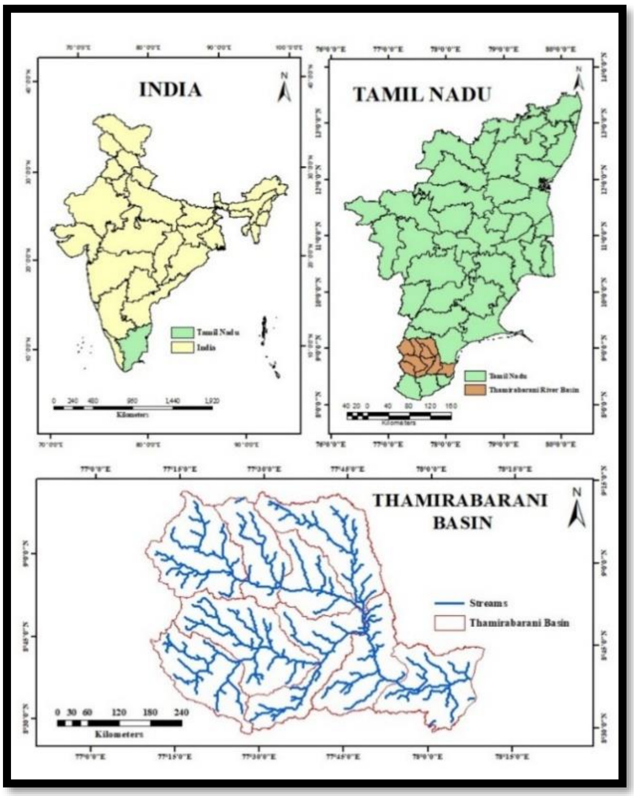

Fig 1 - Study Area map of Thamirabarani Basin

METHODOLOGY

Data Sources and Pre-processing

The present study employs geospatial techniques integrating Remote Sensing (RS) and Geographic Information Systems (GIS) for conducting hypsometric analysis of the Thamirabarani River Basin. A 30 m resolution Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) was obtained from the United States Geological Survey (USGS) Earth Explorer and Open Topography platforms. The SRTM DEM is widely used for hydrological and geomorphological studies due to its reliable spatial resolution and global coverage (Farr et al., 2007).

The downloaded DEM tiles were mosaicked and pre-processed to remove data inconsistencies. Sink filling was performed to eliminate spurious depressions, ensuring hydrological correctness of the terrain. Subsequently, the processed DEM was used as the primary input for watershed delineation and terrain analysis.

Watershed Delineation and Drainage Extraction

Watershed boundaries and drainage networks were delineated using hydrological tools available in the Spatial Analyst module of ArcGIS software (ArcGIS Pro 3.o). The standard workflow involved:

- Generation of flow direction and flow accumulation grids, identification of stream networks based on threshold values, extraction of drainage lines and delineation of the Thamirabarani watershed and its seven sub-watersheds

Additionally, river and basin datasets were cross-validated using HydroSHEDS data to improve spatial accuracy. The extracted watershed boundaries were then used to clip the DEM using the Extract by Mask tool for further analysis.

Elevation Analysis and Data Preparation

The elevation data of the basin was reclassified into 32 equal intervals to facilitate hypsometric analysis. Zonal statistics were computed for each elevation class to obtain minimum, maximum, and mean elevation values. The corresponding area for each elevation interval was calculated and tabulated.

The relative elevation and relative area values were derived and used for constructing hypsometric curves. This process was carried out using GIS and spreadsheet-based computation for cumulative area estimation.

Hypsometric Analysis

Hypsometric analysis is a quantitative method used to describe the distribution of elevation within a drainage basin and to assess its geomorphic development. It establishes a relationship between the relative area and relative elevation of a watershed in a dimensionless form (Strahler, 1952).

Hypsometric Integral (HI)

The hypsometric integral (HI) represents the proportion of the original landmass remaining after erosion and is used as an indicator of the stage of landscape evolution. It was calculated using the empirical relationship proposed by Pike and Wilson (1971):

$$HI = \frac{E_{mean} - E_{min}}{E_{max} - E_{min}}$$

Where:

- E_{mean}= Mean elevation of the basin
- E_{min}= Minimum elevation
- E_{max}= Maximum elevation

Based on HI values, the stages of geomorphic development were classified as:

- Young stage: HI ≥ 0.60
- Mature stage: 0.30 ≤ HI ≤ 0.60
- Old (Monadnock) stage: HI ≤ 0.30

These classifications help in understanding erosion intensity and landscape stability (Strahler, 1952; Pike & Wilson, 1971).

Hypsometric Curve (HC)

The hypsometric curve represents the relationship between relative area and relative elevation of a basin and is plotted using:

- Relative area (a/A)on the x-axis
- Relative height (h/H)on the y-axis

Where:

- a= Area above a given contour
- A= Total basin area
- h= Elevation difference from base level
- H= Maximum basin relief

The shape of the hypsometric curve provides insights into the erosional stage of the basin:

- Convex curve → Youthful stage (low erosion)
- S-shaped curve → Mature stage (moderate erosion)
- Concave curve → Old stage (high erosion)

The hypsometric curves for the Thamirabarani Basin and its sub-basins were generated following the method proposed by Strahler (1952), enabling interpretation of geomorphic evolution and denudation processes.

GIS-Based Workflow Integration

The entire analysis was performed using ArcGIS environment, integrating DEM processing, hydrological modeling, and statistical computation. The workflow ensures reproducibility and accuracy in deriving geomorphic parameters. The combination of DEM-based analysis and hypsometric techniques provides a robust framework for evaluating terrain evolution and erosion dynamics (Daniel Asfaw et al., 2019).

RESULTS AND DISCUSSION

Terrain Characteristics and Elevation Analysis

The Digital Elevation Model (DEM) of the Thamirabarani River Basin provides significant insights into its geomorphological and hydrological characteristics.

The elevation across the basin shows considerable spatial variation, with higher elevations concentrated in the northwestern region corresponding to the Western Ghats, and lower elevations gradually extending towards the southeastern coastal plains. The high-relief mountainous terrain is primarily associated with tectonic uplift and resistant lithological formations, which limit erosion compared to low-lying regions (Padala Raja Shekar et al., 2022).

In contrast, the southeastern part of the basin is characterized by low elevation and gentle slopes, making it more vulnerable to erosion due to increased surface runoff. Areas below 500 m elevation, as indicated in the DEM, represent critical zones for soil erosion and sediment transport. These regions are further influenced by anthropogenic activities such as agriculture, deforestation, and urbanization, which accelerate land degradation processes.

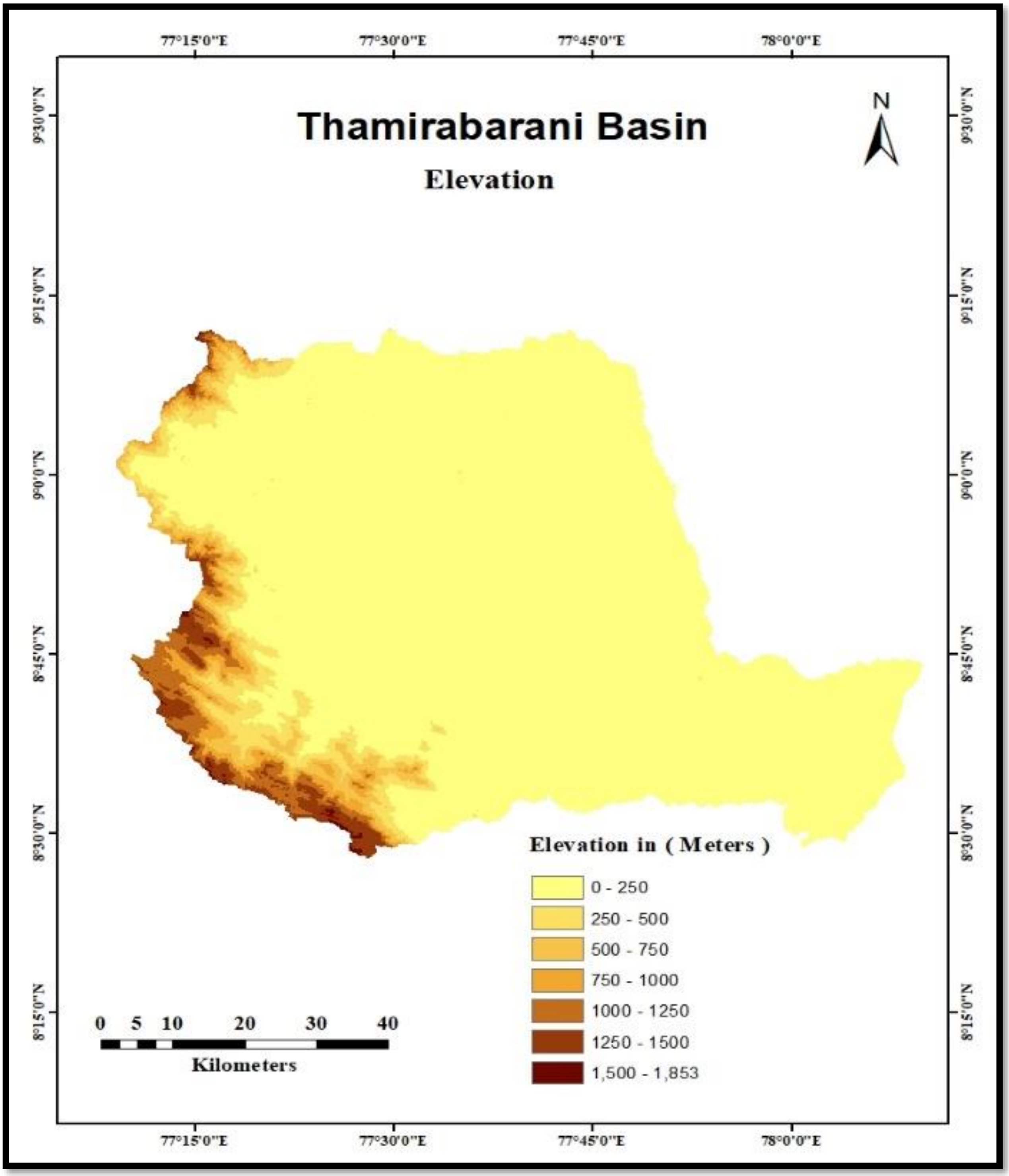

Fig 2 - *DEM Map for Thamirabarani basin*

Topographic Characteristics from Contour Analysis

The contour map (as shown in Fig.3) derived from the DEM provides a detailed representation of the basin's relief and terrain variability.

The contour intervals illustrate elevation ranges from near sea level to over 1750 m, indicating a highly varied topography (Arora Aman et al., 2018). Closely spaced contours in the upper basin signify steep slopes and rugged terrain, whereas widely spaced contours in the lower basin indicate relatively flat areas.

This variation in slope directly influences hydrological processes such as infiltration, runoff, and sediment transport. Steeper slopes enhance runoff velocity and erosion intensity, while flatter terrains promote deposition and groundwater recharge. Such spatial variability plays a crucial role in watershed management and land-use planning.

Drainage Network and Stream Order Analysis

The drainage network of the Thamirabarani Basin exhibits a hierarchical structure based on Strahler's stream ordering system (as shown in Fig.4), reflecting the basin's hydrological organization.

The basin is dominated by first-order and second-order streams originating from the Western Ghats, which progressively merge to form higher-order streams. Major tributaries such as Manimuthar, Gadana Nadhi, and Chittar contribute significantly to the basin's discharge.

The presence of higher-order streams indicates a well-developed drainage system with efficient water conveyance. This hierarchical structure supports diverse hydrological functions and plays a vital role in sediment transport, flood regulation, and ecological sustainability.

Hypsometric Analysis

The hypsometric analysis of the Thamirabarani Basin was carried out using DEM-derived elevation and area data. The basin was divided into 32 elevation intervals, and cumulative area and elevation values were computed to generate the hypsometric curve and calculate the hypsometric integral (HI) as shown in Table 1. The computed hypsometric integral value for the basin is 0.47, indicating a mature stage of geomorphic development. This suggests that the basin has undergone significant erosion but has not yet reached complete stabilization. The value reflects a balance between erosional and depositional processes.

Hypsometric Curve and Geomorphic Interpretation

The hypsometric curve derived from the relative area and relative elevation data exhibits an S-shaped profile, characteristic of a mature geomorphic stage.

The (Fig-10) S-shaped curve indicates that the basin has transitioned from a youthful stage towards maturity and is gradually approaching an old stage. This reflects prolonged denudational processes, including channel incision, slope degradation, and sediment redistribution. The moderate slope of the curve suggests that erosion is active but not dominant, indicating a relatively stable geomorphic condition. Such basins typically exhibit balanced hydrological responses with moderate runoff and sediment yield.

Influence of Geological, Climatic, and Anthropogenic Factors

The geomorphic evolution of the Thamirabarani Basin is strongly influenced by geological structure, climatic conditions, and human activities. The contrast between crystalline rocks in the upper basin and sedimentary formations in the lower basin plays a significant role in controlling erosion rates and drainage patterns.

Climatic factors, particularly monsoonal rainfall, contribute to seasonal variations in runoff and erosion intensity. High-intensity rainfall events increase surface runoff and accelerate soil loss, especially in areas with sparse vegetation cover (Ritter et al., 2002).

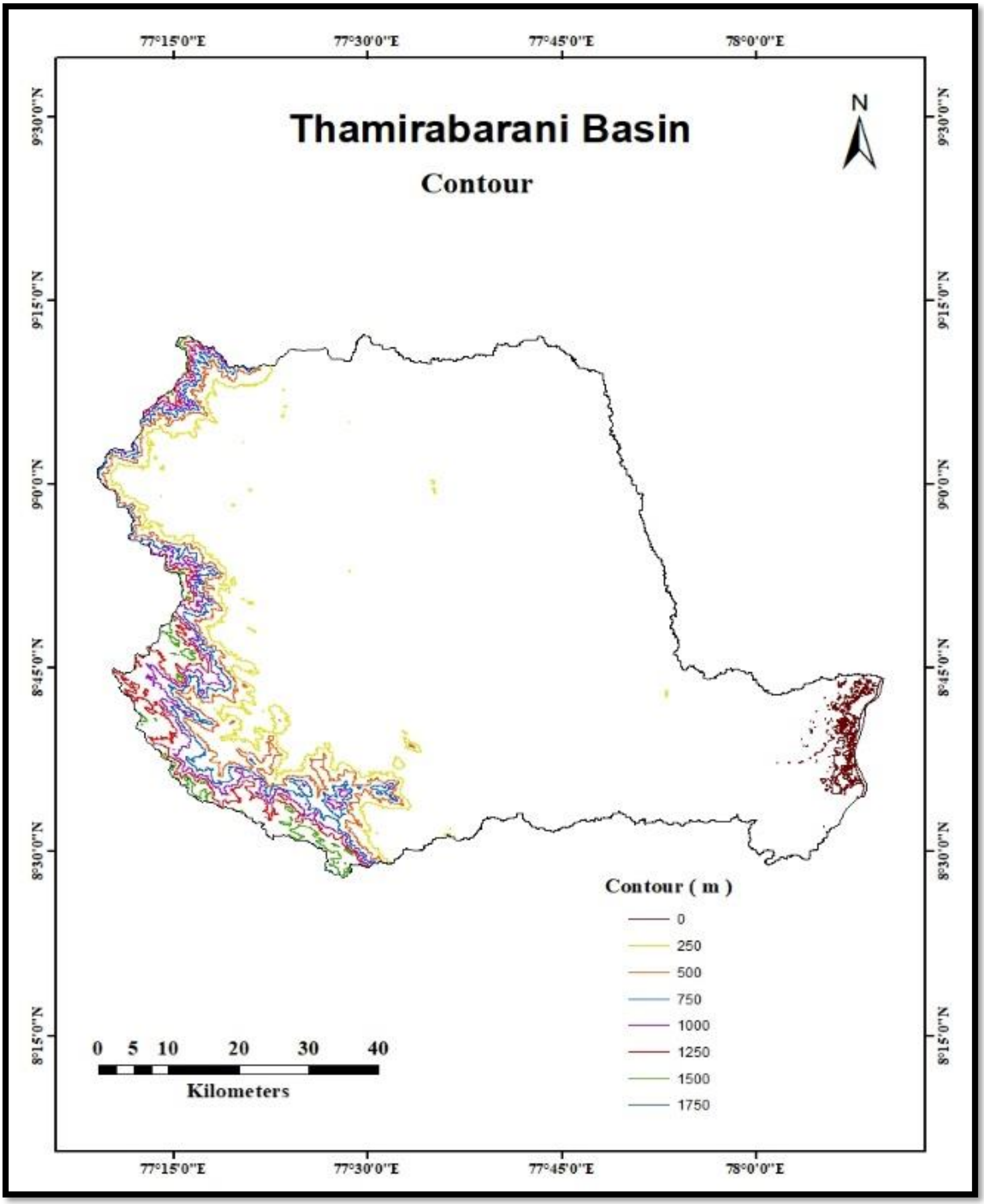

Fig 3: Contour Map of Study Area

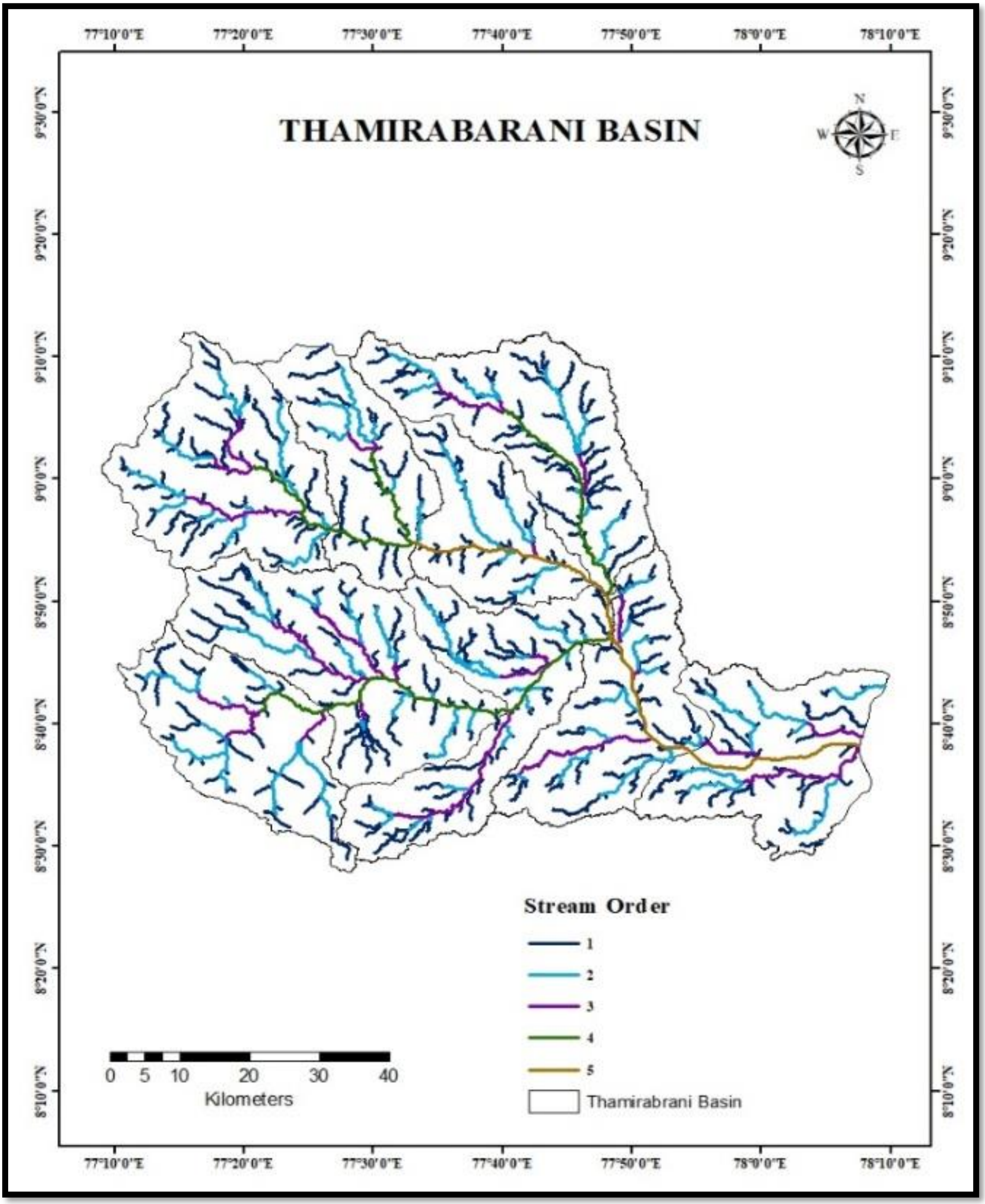

Fig 4: Stream order Map for Thamirabarani Basin

Table 1 – Hypsometric Integral Calculation of Thamirabarani Basin

HYPSOMETRIC INTEGRAL								
S. No	**Area in Sq.km**	**Minimum elevation**	**Maximum Elevation**	**Mean**	**Range (Max - Min)**	**Mean - Min**	**Hypsometric Integral (HI)**	**Geological Stage**
1	1020.98	-14	44	22.38	58	36.38	0.6	**Mature stage**
2	1859.37	45	102	72.87	57	27.87	0.5	
3	1361.49	103	161	128.51	58	25.51	0.4	
4	554.02	162	219	183.97	57	21.97	0.4	
5	124.80	220	277	243.06	57	23.06	0.4	
6	65.57	278	336	306.10	58	28.10	0.5	
7	56.28	337	394	364.98	57	27.98	0.5	
8	50.02	395	452	423.34	57	28.34	0.5	
9	47.55	453	511	481.40	58	28.40	0.5	
10	43.23	512	569	540.36	57	28.36	0.5	
11	43.00	570	627	598.60	57	28.60	0.5	
12	40.99	628	686	656.68	58	28.68	0.5	
13	36.14	687	744	714.75	57	27.75	0.5	
14	32.54	745	802	772.97	57	27.97	0.5	
15	30.56	803	861	832.00	58	29.00	0.5	
16	29.91	862	919	890.06	57	28.06	0.5	
17	28.61	920	977	948.29	57	28.29	0.5	
18	27.07	978	1036	1006.81	58	28.81	0.5	
19	25.33	1037	1094	1065.45	57	28.45	0.5	
20	27.59	1095	1152	1124.15	57	29.15	0.5	
21	33.77	1153	1211	1182.56	58	29.56	0.5	
22	36.69	1212	1269	1240.77	57	28.77	0.5	
23	45.52	1270	1327	1297.72	57	27.72	0.5	
24	36.48	1328	1386	1355.89	58	27.89	0.5	
25	30.15	1387	1444	1414.87	57	27.87	0.5	
26	21.82	1445	1502	1470.24	57	25.24	0.4	
27	12.72	1503	1561	1529.85	58	26.85	0.5	
28	7.83	1562	1619	1587.12	57	25.12	0.4	
29	4.12	1620	1677	1644.74	57	24.74	0.4	
30	1.70	1678	1736	1700.91	58	22.91	0.4	
31	0.44	1737	1794	1756.03	57	19.03	0.3	
32	0.06	1795	1853	1812.97	58	17.97	0.3	
	A = 5736.331195						**HI = 0.47**	

Table 2 – Hypsometric curve Calculation of Thamirabarani Basin

HYPSOMETRIC CURVE										
S. No	**Area in Sq.km**	**Minimum elevation**	**Maximum Elevation**	**Mean**	**Range (Max - Min)**	**Mean - Min**	**Area Accumulation (a)**	**h**	**Relative area (a/A)**	**Relative height (h/H)**
1	1021.00	-14	44	22.38	58	36.38	5736.36	58	1.00	0.03
2	1859.37	45	102	72.87	57	27.87	4715.36	115	0.82	0.06
3	1361.49	103	161	128.51	58	25.51	2855.98	173	0.50	0.09
4	554.02	162	219	183.97	57	21.97	1494.49	230	0.26	0.13
5	124.80	220	277	243.06	57	23.06	940.47	287	0.16	0.16
6	65.57	278	336	306.10	58	28.10	815.67	345	0.14	0.19
7	56.28	337	394	364.98	57	27.98	750.10	402	0.13	0.22
8	50.02	395	452	423.34	57	28.34	693.82	459	0.12	0.25
9	47.55	453	511	481.40	58	28.40	643.80	517	0.11	0.28
10	43.23	512	569	540.36	57	28.36	596.26	574	0.10	0.31
11	43.00	570	627	598.60	57	28.60	553.02	631	0.10	0.34
12	40.99	628	686	656.68	58	28.68	510.02	689	0.09	0.38
13	36.14	687	744	714.75	57	27.75	469.03	746	0.08	0.41
14	32.54	745	802	772.97	57	27.97	432.89	803	0.08	0.44
15	30.56	803	861	832.00	58	29.00	400.35	861	0.07	0.47
16	29.91	862	919	890.06	57	28.06	369.79	918	0.06	0.50
17	28.61	920	977	948.29	57	28.29	339.88	975	0.06	0.53
18	27.07	978	1036	1006.81	58	28.81	311.27	1033	0.05	0.56
19	25.33	1037	1094	1065.45	57	28.45	284.21	1090	0.05	0.59
20	27.59	1095	1152	1124.15	57	29.15	258.88	1147	0.05	0.62
21	33.77	1153	1211	1182.56	58	29.56	231.29	1205	0.04	0.66
22	36.69	1212	1269	1240.77	57	28.77	197.52	1262	0.03	0.69
23	45.52	1270	1327	1297.72	57	27.72	160.83	1319	0.03	0.72
24	36.48	1328	1386	1355.89	58	27.89	115.31	1377	0.02	0.75
25	30.15	1387	1444	1414.87	57	27.87	78.83	1434	0.01	0.78
26	21.82	1445	1502	1470.24	57	25.24	48.69	1491	0.01	0.81
27	12.72	1503	1561	1529.85	58	26.85	26.87	1549	0.00	0.84
28	7.83	1562	1619	1587.12	57	25.12	14.15	1606	0.00	0.87
29	4.12	1620	1677	1644.74	57	24.74	6.31	1663	0.00	0.91
30	1.70	1678	1736	1700.91	58	22.91	2.20	1721	0.00	0.94
31	0.44	1737	1794	1756.03	57	19.03	0.49	1778	0.00	0.97
32	0.06	1795	1853	1812.97	58	17.97	0.06	1836	0.00	1.00
	A = 5736.331195							**H = 1836**		

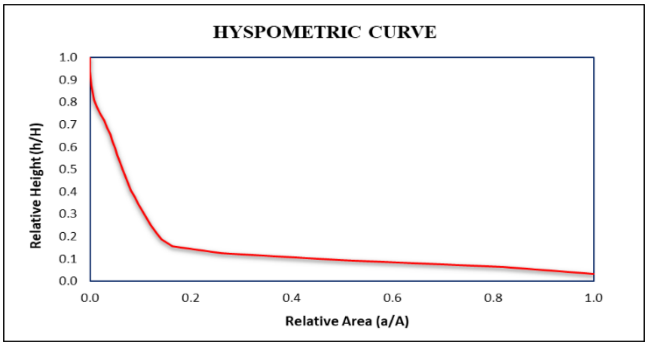

Fig. 5: Thamirabarani basin Hypsometric Curve (S Shape curve)

Anthropogenic activities such as deforestation, agricultural expansion, and urbanization further intensify erosion processes. Removal of vegetation cover reduces soil stability, while increased impervious surfaces enhance runoff, leading to higher sediment transport and landscape modification.

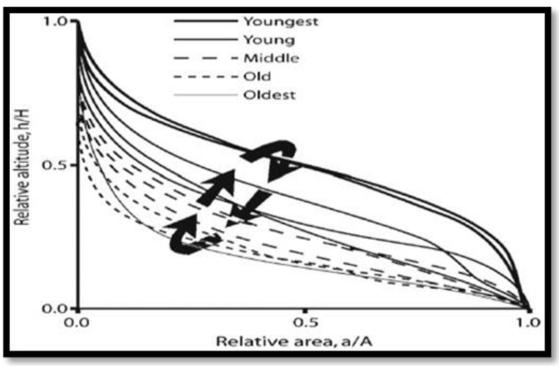

Fig.6: Hypsometric curve and its Stages of Erosion
(Source: Willgoose and Hancock, 1998; J. Harsha1 et al., 2020*)*

Implications for Watershed Management

The results of the hypsometric analysis indicate that the Thamirabarani Basin is in a late mature stage, approaching geomorphic stability. However, localized erosion risks remain significant, particularly in low-elevation and anthropogenically disturbed areas.

These findings highlight the need for targeted soil and water conservation measures, including: vegetative cover restoration, contour bunding and terracing, check dams and water harvesting structures, and sustainable agricultural practices

Such interventions are essential to reduce erosion, enhance groundwater recharge, and ensure long-term sustainability of the watershed.

CONCLUSION

The present study demonstrates the effectiveness of hypsometric analysis as a quantitative tool for evaluating geomorphic evolution and erosion dynamics within river basins. The integration of GIS and remote sensing techniques enabled accurate assessment of elevation–area relationships and facilitated detailed terrain analysis of the Thamirabarani River Basin. The computed hypsometric integral (HI) value of 0.47 indicates that the basin is in a mature stage of geomorphic development, reflecting a balance between erosional and depositional processes. The S-shaped hypsometric curve further confirms this stage, suggesting that the basin has undergone significant denudation while gradually progressing towards geomorphic stability. However, the presence of active erosional processes, particularly in low-elevation and anthropogenically influenced regions, highlights the dynamic nature of the basin.

The study reveals that geomorphic evolution in the basin is controlled by the combined influence of lithology, topography, climatic conditions, and human activities. Processes such as channel incision, downslope movement of soil and bedrock material, and stream bank erosion contribute significantly to landscape modification. Additionally, monsoonal rainfall patterns and increasing anthropogenic pressures, including deforestation and land-use changes, further intensify runoff and erosion.

From a management perspective, the findings emphasize the need for targeted watershed management strategies. Although the basin exhibits relative stability, localized erosion risks necessitate the implementation of both structural and non-structural conservation measures. Structural interventions such as check dams, contour bunding, and farm ponds can effectively reduce runoff and sediment loss, while non-structural approaches including sustainable agricultural practices, afforestation, and land-use planning can enhance long-term environmental sustainability.

REFERENCES

1) Strahler, A. N. (1952). Hypsometric (area–altitude) analysis of erosional topography. Geological Society of America Bulletin, 63(11), 1117–1142.

2) Schumm, S. A. (1956). Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. Geological Society of America Bulletin, 67(5), 597–646.

3) Weissel, J. K., Pratson, L. F., & Malinverno, A. (1994). The length-scaling properties of topography. Journal of Geophysical Research: Solid Earth, 99(B7), 13997–14012.

4) Hurtrez, J. E., Sol, C., & Lucazeau, F. (1999). Effect of drainage area on hypsometry from an analysis of small-scale drainage basins in the Siwalik Hills (Central Nepal). Earth Surface Processes and Landforms, 24(9), 799–808.

5) Girish, G., Ambili, N. P., Jesiya, N. P., & Lemoon, K. (2014). Hydro-hypsometric analysis of tropical river basins using geospatial technology. International Journal of Geomatics and Geosciences, 5(1), 23–34.

6) Abdo, H. G. (2020). Evaluation of morphometric parameters and hypsometric analysis using GIS techniques. *Journal of Remote Sensing and GIS, 9*(2), 1–10.

7) Gopinath, G., Ambili, N. P., Jesiya, N. P., & Lemoon, K. (2015). Hydro-hypsometric analysis of tropical river basins using geospatial technology. *International Journal of Geomatics and Geosciences, 5*(3), 1–12.

8) Ritter, D. F., Kochel, R. C., & Miller, J. R. (2002). *Process geomorphology* (4th ed.). Waveland Press.

9) J. Harsha, A. S. Ravikumar, B. L. Shivakumar (2020). Evaluation of morphometric parameters and hypsometric curve of Arkavathy river basin using RS and GIS techniques. Applied Water Science, 10:86

10) Farr, T. G., Rosen, P. A., Caro, E., Crippen, R., Duren, R., Hensley, S., … Roth, L. (2007). The Shuttle Radar Topography Mission. *Reviews of Geophysics, 45*(2), RG2004.

11) Pike, R. J., & Wilson, S. E. (1971). Elevation-relief ratio, hypsometric integral, and geomorphic area-altitude analysis. *Geological Society of America Bulletin, 82*(4), 1079–1084.

12) Mohammed I. Khattab, Abotalib Z. Abotalib, Abdullah Othman, Maha K. Selim. (2023). "Evaluation of multiple digital elevation models for hypsometric analysis in the watersheds affected by the opening of the Red Sea." The Egyptian Journal of Remote Sensing and Space Sciences, Vol. 26, 2023, pp. 1020-1035.

13) Daniel Asfaw, Getachew Workineh. (2019). "Quantitative analysis of morphometry on Ribb and Gumara watersheds: Implications for soil and water conservation." International Soil and Water Conservation Research, Vol. 7, 2019, pp. 150-157.

14) Padala Raja Shekar, Aneesh Mathew. (2022). "Evaluation of Morphometric and Hypsometric Analysis of the Bagh River Basin using Remote Sensing and Geographic Information System Techniques." Energy Nexus, Vol. 7, Pg. 100104.

15) Arora Aman, Pandey Manish, Singh Abhra, Siddiqui Masood A. (2018). "Study of landscape evolution in North Koel River Basin, Jharkhand, India: tectonic and structural implications based on hypsometric analysis." Forum geografic, Vol. XVII, Issue 2, December 2018, pp. 111-117.