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DIGITAL ELEVATION MODEL IN HYDROLOGICAL AND GEOMORPHOLOGICAL STUDIES: METHODS AND APPLICATIONS

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Abstract: The present research focuses on using Digital Elevation Models also called DEM and the terrain parameters that are obtained from them for comprehensive landscape analysis, including slope, aspect, curvature, hillshade, flow direction, and flow accumulation. DEM are essential tools for understanding terrain morphology and hydrological processes, enabling the analysis of landforms, water movement, and environmental features. Slope and aspect provide critical insights into land steepness and sunlight exposure, influencing vegetation and land use. Curvature maps highlight the way terrain influences water flow, while hillshade maps enhance the visualization of topographic features by simulating lighting conditions. Flow direction and accumulation models are crucial for studying water pathways and identifying areas of potential flooding or erosion. These terrain attributes, when analyzed together, support several uses in geomorphology, hydrology, urban planning, agriculture, and ecological management, helping to inform Taking considerations regarding environmental sustainability land and management of water resources. This study demonstrates the power of DEM-based analysis in enhancing our understanding of landscape dynamics and addressing environmental challenges through advanced spatial tools and GIS software.

Keywords: Watershed, Morphology, Hydrology, DEM, Geomorphology

I. INTRODAUCTION

The application of DEM in geospatial analysis has become indispensable for understanding and managing the physical landscape. A digital depiction of the Earth's surface topography is called a DEM, which includes elevation values in a grid that describe terrain at specific locations [1]. These models offer important information into the structure, morphology, and hydrological processes of landscapes, offering an invaluable resource for researchers, urban planners, engineers, and environmentalists [2]. The ability to extract detailed topographical information from DEM enables the examination of terrain features like slopes, ridges, valleys, and drainage networks. These terrain attributes form the foundation of various analyses that are crucial for hydrological, geomorphological, and environmental studies [3].

Among the primary advantages of DEM falsehoods in their capacity to serve as an example terrain in three dimensions, enabling the simulation of physical processes such as water movement, erosion, and vegetation growth. For example, slope analysis, which measures the steepness or incline of the land surface, is fundamental for assessing areas susceptible to soil erosion or landslide risks [4]. The aspect of terrain, or the slope direction, influences the amount of solar radiation a region receives, which directly affects its temperature, moisture levels, and, consequently, its vegetation and land use potential. Similarly, the curvature of a surface can provide insights into how water will flow across a landscape, affecting both natural processes and land management strategies [5].

In addition to terrain features, DEM are essential for the analysis of hydrological processes. The DEM-derived flow direction and flow accumulation help identify how water moves across the landscape, forming stream networks and river basins. Flow direction maps reveal the most likely paths that water will take as it moves downhill, while flow accumulation quantifies. The volume of water that flows into a particular point in a watershed [6]. These parameters are crucial in watershed management, flood prediction, and the design of water drainage systems. Understanding flow dynamics can inform decisions about land conservation, agricultural practices, and infrastructure development, all of which depend on accurate knowledge of water distribution [7].

Another powerful feature of DEM-based analysis is the ability to generate hill shade maps, which simulate how terrain would look under various lighting conditions. Hill shade maps enhance the visual interpretation of landscape features, making them invaluable tools for cartography, geology, and environmental monitoring [8]. By adjusting the Azimuth (the horizontal direction of the source of light) and altitude (the vertical angle at which the light comes from), hill shade maps create a shaded relief effect that highlights landforms such as ridges, valleys, and slopes [9]. This visualization aids in understanding the spatial relationships between different landscape features, especially when combined with other thematic maps.

Furthermore, DEM are crucial for spatial analysis in urban planning, agriculture, and environmental management. In urban planning, the analysis of slope, aspect, and flow accumulation can guide the siting of infrastructure, helping to avoid flood-prone areas and ensuring efficient land use. In agriculture, terrain analysis helps determine the best locations for planting based on the slope, aspect, and water availability [10]. In the field of environmental management, DEM aid in assessing habitat suitability, biodiversity conservation, and climate change effects on landscapes.

Over the past few years, the accessibility of DEM data takes greatly risen because of developments in remote sensing technology and the accessibility of satellite-based datasets, such as those provided by NASA's ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) and SRTM (Shuttle Radar Topography Mission). These datasets have democratized access to high-resolution elevation data, making it possible for a wider range of professionals to incorporate DEM into their analyses.

The applications of DEM-based analysis are vast and span across many scientific and practical domains. In hydrology, DEM are essential for modelling surface water flow, studying watershed dynamics, and simulating flood events. In geomorphology, DEMs help researchers study landforms and their evolution, providing insights into the processes that shape landscapes over time [11]. In environmental science, DEM assist in assessing the effects of human activity, such as deforestation, urbanization, and agriculture, on the landscape. Furthermore, in disaster management, DEM are used to assess landslide risks, flood-prone areas, and the vulnerability of regions to environmental hazards, making them an essential tool in disaster preparedness and mitigation [12].

As the study of spatial analysis develops further, the integration of DEM with other geospatial data layers, such as land cover maps, climate models, and soil data, will enhance our ability to understand complex environmental processes [13]. This integrated approach will allow for more effective natural resource management, better urban space design, and superior solutions to environmental concerns. The continued advancement in remote sensing technology and the development of more sophisticated analytical methods will ensure that DEMs remain an essential tool in the ongoing study of landscapes and their dynamics [14].

II. Study Area

The study area is Sillod Taluka, Aurangabad district, Marathwada region, Maharashtra, India. It is located in the northeastern part of Aurangabad (Chh. Sambhajinagr) and borders Aurangabad Taluka. This area is part of the Aurangabad Division in the Marathwada region. Traveling from Aurangabad to Sillod requires a bearing of 33 degrees. This location is roughly 330 meters above mean sea level. Aurangabad is located at 19.88° North and 75.34° East. Show in figure 1.

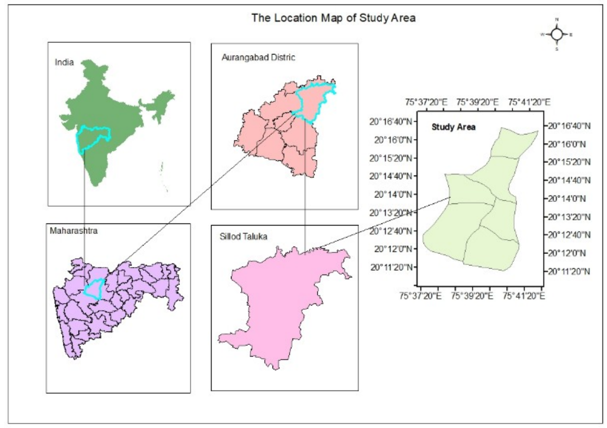

Figure 1. Selected Study Area

III. Dataset Used

DEM data represents the Earth's surface elevations in a grid format and is widely used for topographic analysis, hydrology, urban planning, and environmental modelling. DEM are available from various sources like SRTM (30m and 90m resolution), They provide crucial information for applications such as watershed delineation, slope analysis, flood modelling, and terrain classification.

IV. Methodology

In this study, a DEM was used as the primary input for analysing the terrain characteristics. The DEM was processed to derive slope and aspect, which provide insights into the steepness and orientation of the land surface, respectively. Slope was determined using he rapid rate at which elevation changes, while aspect was determined based on the direction of the steepest slope. The hillshade model was generated to simulate the illumination of the terrain, highlighting topographic features based on light source direction. The curvature was computed to assess the convexity or concavity of the land surface, providing further information on terrain variations. Flow direction and flow accumulation were determined to model water movement across the landscape, with flow direction identifying the steepest downhill path and flow accumulation quantifying the flow intensity at each grid cell. Lastly, stream order was assessed using the Strahler method to classify the hierarchy of streams within the watershed. The figure 2. show the final workflow of our paper.

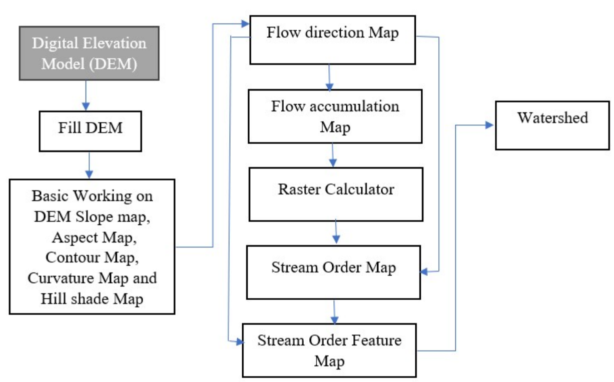

Figure 2. Selected Methodology

V. RESULT AND DISCUSSION

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A. DEM

A DEM is typically produced using remote sensing techniques like LiDAR, photogrammetry, or radar data. In figure 3. shows the elevation information over a continuous surface and are used extensively in geospatial analyses [15]. Key parameters include spatial resolution, which indicates the ground distance between elevation points (e.g., 10 m, 30 m); vertical accuracy, reflecting the error margin in elevation values (e.g., ±2 m); and CRS (Coordinate Reference System), which defines the spatial reference framework (e.g., WGS84). DEM also come in two main types: bare-earth DEM, which exclude vegetation and buildings, and DSM (Digital Surface Models), which capture the top of all surfaces, including vegetation and infrastructure [16]. DEM data formats typically include Geo-TIFF and IMG, and they can be derived from sources like SRTM. DEM are crucial for applications like hydrology modelling, slope analysis, watershed delineation, and 3D terrain visualization [17].

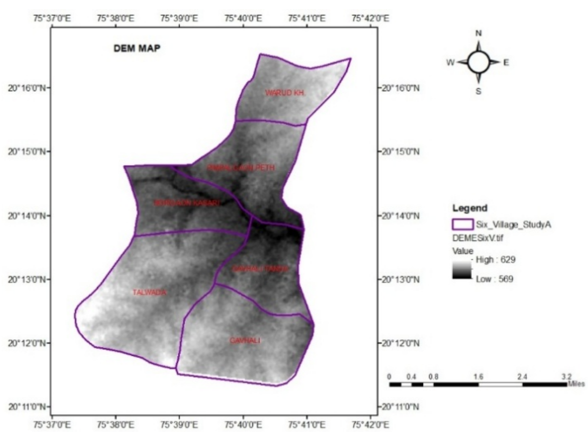

Figure 3. DEM Map

B. Slope

Slope refers to the measure of the steepness or incline of a terrain surface, calculated as the speed at which elevation changes over a given distance. Typically figure 4. stated as elevation in percentage (%). In a DEM, Slope is calculated by examining the variations in elevation between adjacent cells. A higher slope value indicates steeper terrain, while a lower value represents flatter areas [18]. Slope is crucial in fields such as hydrology, agriculture, urban planning, and geomorphology, as it influences water flow, soil erosion, vegetation growth, and construction feasibility. Slope maps help identify areas prone to landslides, assist in watershed management, and guide land use decisions [19].

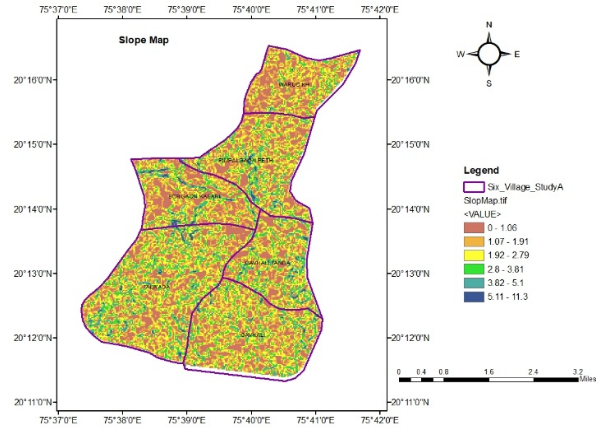

Figure 4. Slope map

Table I. Classifications of the slopes

Sr. No.	*Slope Classes*	*Slope (%)*
1.	*Almost level*	*0-1.06*
2.	*Extremely mild slopes*	*1.07-1.91*
3.	*Moderate slopes*	*1.92-2.79*
4.	*Moderately steep slopes*	*2.8-3.81*
5.	*Steep slopes*	*3.82-5.1*
6.	*High steep slope*	*5.11-11.3*

C. Contour Lines

Continuous lines that join places of equal height above a reference level are known as contour lines on a map, typically mean sea level. These lines help reflect the three-dimensional terrain form on a two-dimensional surface, making it possible to visualize hills, valleys, ridges, and depressions [20]. The steepness of the terrain is shown figure 5. by the distance between contour lines; steep slopes are represented by closely spaced lines, whilst gentle slopes or flat areas are indicated by widely separated lines. Key features of contour lines include the interval of contours, which is the distance measured vertically between adjacent lines (e.g., 10 meters), and index contours, which are thicker lines that appear at regular intervals to provide reference elevations. Contour lines never intersect (except in cases of vertical cliffs or overhangs) and form closed loops around hills or depressions. They are widely used in topographic maps, land use planning, civil engineering, and outdoor navigation to analyse elevation changes and terrain features [21].

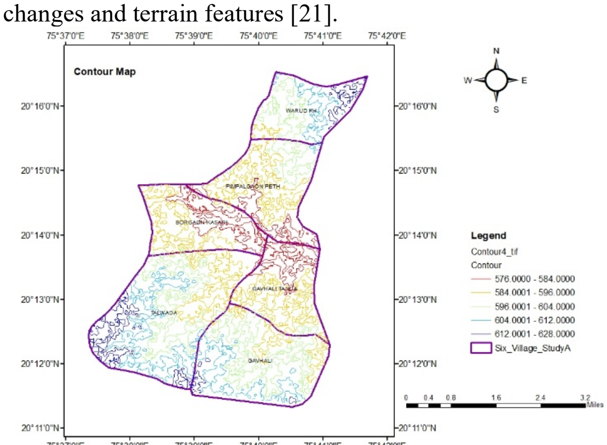

Figure 5. Contour Map

D. *Aspect Map*

Aspect map represents the figure 6. the steepest slope direction for each location on a terrain surface, derived from elevation data like a DEM. In simpler terms, it indicates which direction of the compass the slope is facing. Aspect is typically expressed in degrees with 0° denoting straight north, 90° east, 180° south, and 270° west, the range is 0° to 360° [22]. Typically, flat regions with little slope are given a value of -1, or "no aspect." Aspect maps are critical for understanding solar radiation exposure, wind patterns, soil moisture distribution, and vegetation growth, as different slope orientations receive varying amounts of sunlight and precipitation. For example, slopes facing south receive more sunshine in the Northern Hemisphere, making them warmer and drier compared to north-facing slopes. Aspect analysis is widely used in agriculture, forestry, hydrology, and land management for tasks like determining suitable crop planting zones or wildfire risk assessment [23].

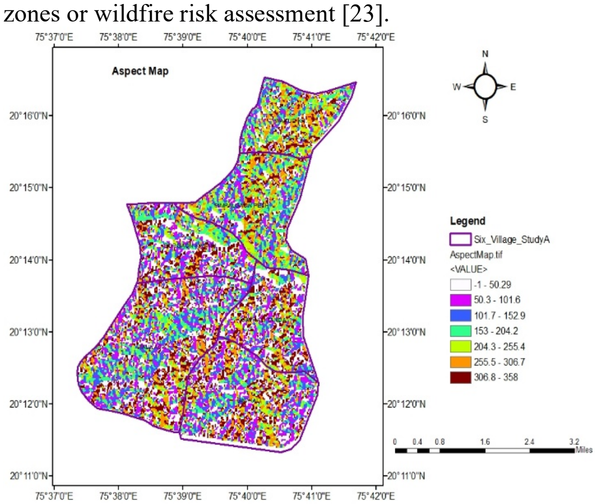

Figure 6. Aspect Map

E. *Hill Shade*

In below figure 7. Hillshade Map is a grayscale representation of terrain that simulates the appearance of sunlight casting shadows on the landscape. Derived from a DEM, it uses light source parameters such as azimuth (the sun's horizontal direction, typically in degrees from north) and altitude (the sun's angle above the horizon) to create a shaded relief effect. This visualization highlights landforms like ridges, valleys, and slopes, showing how they appear under varying lighting conditions [24]. Hillshade values range from 0 to 255, with surfaces facing the light source appearing brighter and areas in shadow appearing darker. Hillshade maps are valuable for topographic visualization, landform interpretation, and enhancing other thematic maps. They provide insight into terrain morphology, making them useful in fields like geology, urban planning, cartography, and environmental studies [25].

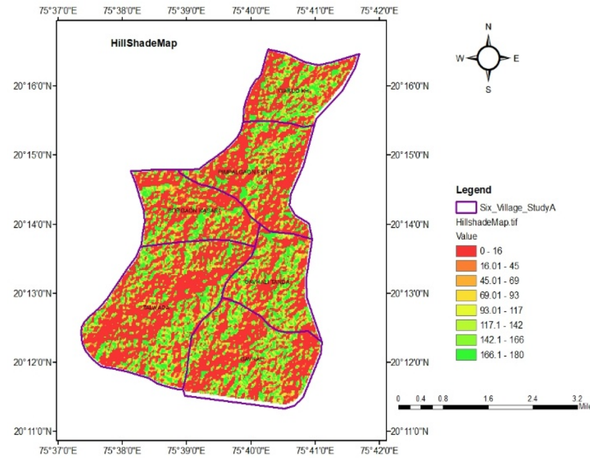

Figure 7. Hill shed Map

F. *Curvature Map*

A figure 8. Curvature Map illustrates the rate at which the slope changes of a terrain surface, derived from a DEM. It helps identify concave and convex landforms, which are essential for understanding terrain processes. Curvature can be classified into profile curvature (affecting water flow along a slope) and plan curvature (influencing water flow convergence or divergence) [26]. Positive curvature values indicate convex surfaces (e.g., ridges), while Negative numbers indicate concave surfaces (e.g., valleys), and Values in flat terrain are close to zero. Curvature maps are useful in applications such as hydrology, soil erosion modelling, and geomorphology [27].

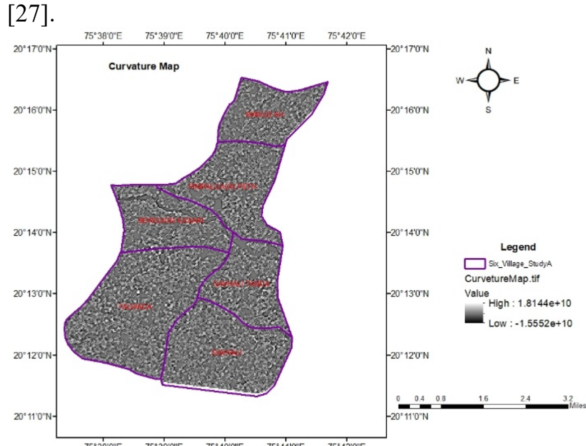

Figure 8. Curvature Map

G. *Flow Direction*

Flow Direction refers to the path that water will follow on a terrain surface, determined by the slope of the terrain. It is a crucial element in hydrological modelling and is typically derived from a DEM [28]. Flow direction map shown figure 9. that assigns a direction to each grid cell, indicating the steepest downhill path for water to flow, usually in one of eight compass directions (e.g., north, northeast, east, etc.). This information is essential for understanding water movement across a landscape, influencing watershed delineation, erosion prediction, and flood modelling. flow direction calculates using algorithms like the D8 algorithm, which ensures that water flows to the lowest adjacent cell [29]. Flow direction maps are widely used in hydrological studies, land management, and environmental planning [30].

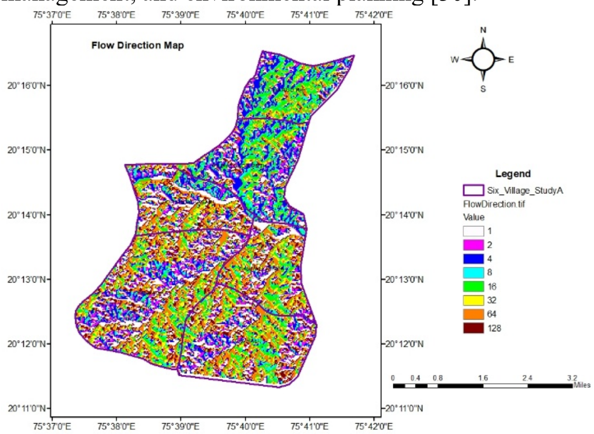

Figure 9. Flow direction Map

H. *Flow Accumulation*

Flow Accumulation quantifies the volume of water flow that gathers at a certain point on a terrain surface calculated by summing the contributing flow from upstream grid cells [31, 46]. It is derived from Flow Direction and is used to identify areas that collect the most runoff or are prone to higher water volumes. In a DEM, flow accumulation maps show below figure 10. help to determine streams, rivers, and watersheds by identifying locations where water converges [32]. High flow accumulation values often indicate the location of streams or rivers, while low values suggest areas with little runoff. Flow accumulation is a critical parameter in hydrological modelling, flood risk assessment, watershed management, and erosion studies [33].

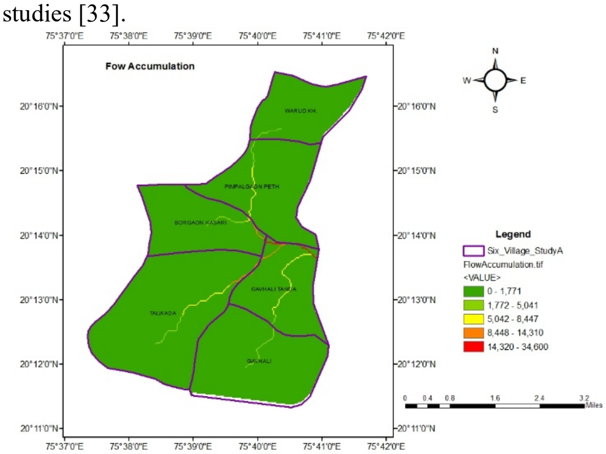

Figure 10. Flow Accumulation Map

I. *Raster Calculator*

The Raster Calculator was used to process elevation data and derive hydrological parameters like the direction and accumulation of the flow, which are essential for stream network analysis [34]. Using the calculated flow direction raster, the Strahler method was applied to classify streams based on their hierarchical order, generating a Stream Order Map [35]. This map was then further analysed to identify the spatial distribution of streams by their order, creating the Stream Order Feature Map show in below figure 11. The feature map visually represents the connectivity and complexity of the stream network, which is crucial for understanding watershed dynamics and streamflow patterns [36]. This methodology integrates raster-based hydrological analysis with stream network classification for enhanced landscape modelling.

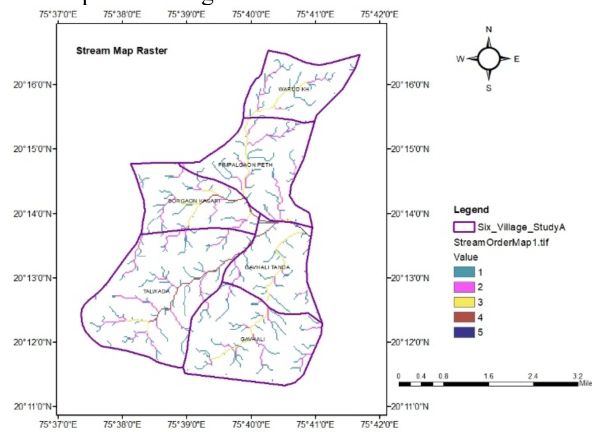

Figure 11. Stream order raster map

J. *Stream Order*

A stream order map was generated using the Strahler method, which classifies streams based on their hierarchy within a watershed [37]. First-order streams were identified as the lowest tributaries with no incoming streams, whereas lower-order streams came together to produce higher-order streams [38]. The map highlights the spatial distribution of streams and their relative positions in the watershed, allowing for an understanding of stream network patterns and water flow dynamics represent in below figure 12. This classification aids in hydrological modelling, watershed management, and understanding the influence of streams on the surrounding landscape.

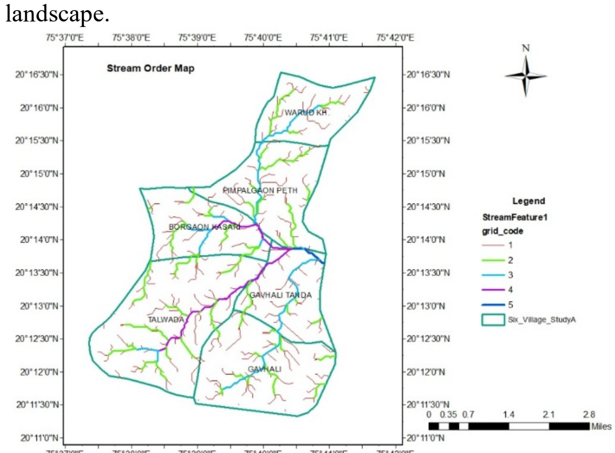

Figure 12. Stream order Map

VI. CONCLUSION

In conclusion, the integrated analysis of terrain and basic morphometric parameters derived from Digital Elevation Models (DEM) provides comprehensive insights into the watershed physical and hydrological characteristics. Terrain attributes such as slope, aspect, hillshade, curvature, flow direction, and flow accumulation play a critical role in understanding surface processes. Slope determines the steepness and influences runoff velocity and erosion potential, while aspect affects microclimatic conditions and vegetation patterns. Hillshade enhances terrain visualization by simulating illumination effects, and curvature identifies concave and convex landforms, essential for assessing terrain stability and water flow behavior. Flow direction and flow accumulation are fundamental for delineating drainage networks and identifying flood-prone or erosion-sensitive zones.

VII. FUTURE WORK

future work will focus on a comprehensive analysis of Shape, areal and relief morphometric aspects to strengthen the understanding of watershed geometry, hydrological behaviour, and erosion potential. The analysis will be extended to include areal parameters such as watershed area, length, and perimeter, form factor, circularity ratio, elongation ratio, compactness coefficient, shape index, and lemniscate ratio, which are crucial for evaluating runoff response, sediment transport, and water retention capacity. In addition, relief morphometric parameters including maximum and minimum elevation, basin relief, relief ratio, relative relief, ruggedness number, gradient ratio, and hypsometric integral and curve will be analysed to assess elevation variability, slope conditions, erosional energy, and sediment yield. The integrated evaluation of linear, areal, and relief morphometric parameters in future studies will provide a more robust framework for watershed characterization, prioritization, and sustainable watershed management planning.

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