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Hypsometric Analysis for Determining Erosion Proneness of Dehar Watershed, Himachal Himalaya, North India

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Abstract

Assessment of erosion proneness is quite essential in tectonically active, highly fragile and environmentally sensitive hilly regions. The assessment not only helps in knowing erosion proneness but also supports in adopting best practices for integrated watershed management. The hypsometric analysis performed was to know the geological stages of development of erosional landscapes that reveal the health of a watershed. The present study was carried out to assess erosion susceptible areas of the Dehar River Watershed, which forms a tributary of the Beas river catchment of Himachal Pradesh. Eight sub-watersheds were delineated from the Dehar Watershed for performing hypsometric analysis using contours generated from the DEM in a GIS environment. The hypsometric integral values were quantified by the elevation-relief method for all the sub-watersheds and are ranging between 0.43 (DW1) and 5.0 (DW4, DW5). Further, it is found that almost all the sub-watersheds are comparatively matured and erosional processes are in the course of stabilization. The present study reveals that some sub-watersheds primarily DW4 and DW5 of the Dehar Watershed are highly susceptible to erosion. Therefore, suitable remedial measures such as structural and non-structural methods may be adopted to mitigate soil erosion and also in enhancing sustainable conservation and management practices.

Keywords: Hypsometric Analysis, Erosion Proneness, Dehar Watershed, Himachal Himalaya, GIS.

Introduction

Hypsometric analysis helps to comprehend various driving factors that influence the topographical features of a drainage basin. It evaluates data especially related to water structures at different elevation levels within an area (Strahler, 1952). It is not only used for assessing smaller water bodies but also larger bodies covering the whole Earth and even other terrestrial bodies (Rosenblatt and Pinet, 1994). Langebein (1947) was the first to introduce hypsometric analysis to ascertain the overall slope and relative forms of a watershed. Hypsometry describes the distribution of the relative percentage of area covered at various elevations within the area of interest. Likewise, the hypsometric curve represents the spread over the surface of a particular area to its elevation (Strahler, 1952). It is an important tool to estimate the evolution of geomorphic landforms and to infer the various driving factors that are acting on landscape structures of a drainage basin (Horton, 1945; Strahler, 1952; Schumm, 1956; Markose and Jayappa, 2011).

Hypsometry can be demonstrated by a 'hypsometric curve' (HC) or as an integral parameter known as 'hypsometric integral' (Hsi). The HC is related to the overall volume of soil mass concentration in a drainage basin and the total sum of erosion taken place in a drainage basin in comparison to the left-over mass (Hurtrez *et al*., 1999). The shape of the HC forms an important constituent that is used in quantifying evolutionary stages of a drainage basin. It is a plot of a continuous function of dimensionless distribution of relative elevation to the relative area of a drainage basin (Strahler, 1952; Chow, 1964). The elevational distribution of an area has been widely used for topographical assessment since it is more advantageous in portraying three-dimensional data by a two-dimensional representation (Harrison *et al*., 1983). The shape of the HC for various watersheds with comparably similar hydrological settings will possibly ascertain the past mass movement in the watersheds. Thus, the shape of the HC also describes the past variations in the slope of the focused watershed.

Ritter *et al*. (2002) described that the HC and Hsi are the two main constituents to deal with the status of erosion and health of a drainage basin. Thus, the intensity of exposure is indicated by the Hsi value and shape of the HC (Weissel *et al*., 1994). Strahler (1952) viewed that the HC indicates the phases of the erosional cycle of landforms by studying various drainage basins; they were grouped into different classes based on the shape of the HC as i) peneplain or distorted for a drainage basin where the curve is concave upwards, ii) S-shaped curve for the mature basin, where the curve is convex downwards showing low altitude and concave upwards indicating high altitude and iii) convex curve upward for a basin in youth stage. It is noticed that there is constant change in the shape of the curves in the initial phases of the geomorphic cycle and is stabilized after attaining the mature stage. The HC influences erosional characteristics of a drainage basin and it also indicates the cycle of erosion. A suitable model for interpreting the HC is given here (Ritter *et al*., 2002; Fig. 1).

In the same way as the HC, the Hsi specifies 'cycle of erosion' and advancement in the geological stages of watershed development (Strahler, 1952). And, useful for subsequent prioritization for achieving sustainable soil and water conservation practices (Singh *et al*., 2008, Manjare *et al*., 2020). The Hsi values provide a comprehensive knowledge about the erosional status and the threshold limits as suggested by Strahler (1952) are: i) in-equilibrium (young) stage, if the Hsi ≥ 0.6, ii) equilibrium (mature) stage, if the Hsi is between 0.3 and 0.6 and iii) monadnock (old) stage, if the Hsi ≤ 0.3. The Hsi shows an inverse correlation with different morphometric parameters such as drainage density, channel gradient, slope and total relief (Strahler, 1952). Thus, Hsi is useful in elucidating the soil degradation that occurred in a watershed during the geological past due to various hydrological and erosional factors (Bishop *et al*., 2002).

Till recently, hypsometry analysis has been used for various studies in different parts of the world for erosion estimation and prioritization of watersheds (Mishra, 1988; Ohmori, 1993; Moglen and Bras, 1995; Willgoose and Hancock, 1998; Bishop *et al*., 2002; Pradhan and Senapati, 2002; Huang and Niemann, 2006; Sivakumar *et al*., 2011; Shukla *et al*., 2014; Gajbhiye *et al*., 2014; Babu *et al*., 2016; Fenta *et al*., 2017; Lamsoge *et al*., 2018; Singh and Singh, 2018; Harsha *et al*., 2020; Kumari *et al*., 2021).

The hilly watersheds of the Himalayan region are prone to erosion due to the insistent rainfall during monsoon, pre-monsoon and post-monsoon seasons. In this context, the HC and the Hsi are the two important parameters useful in estimating the health of watersheds in ecologically sensitive and fragile ecosystems like those of the Himalaya. During the literature survey, it is found that few studies have been carried out in the Himalayan region using hypsometry to evaluate the watershed health (Goel and Singh, 2000; Awasthi *et al*., 2002; Singh and Sarangi, 2008; Singh, 2009; Walia *et al*., 2018; Sharma and Mahajan, 2020). However, it is highly cumbersome to estimate and acquire data in the rugged terrains of the Himalayan region. Thus, the advent of new technologies like remote sensing and Geographical Information System (GIS) had eased the estimation process

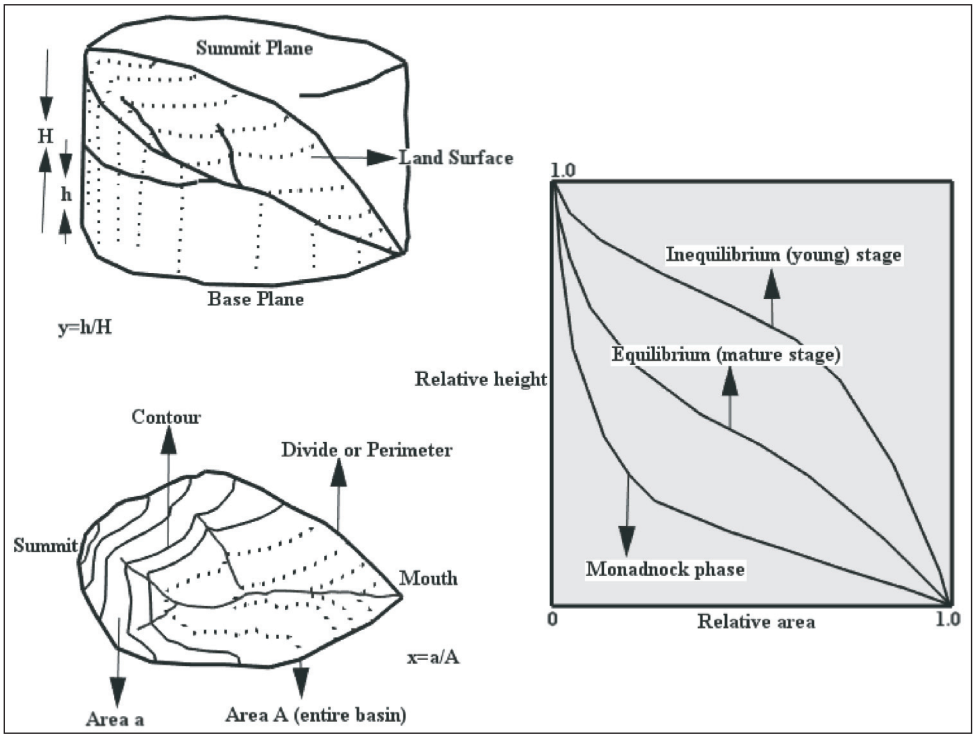

Fig.1. A conceptual model representing hypsometric analysis and curves (*modified after* Ritter *et al.,* 2002).

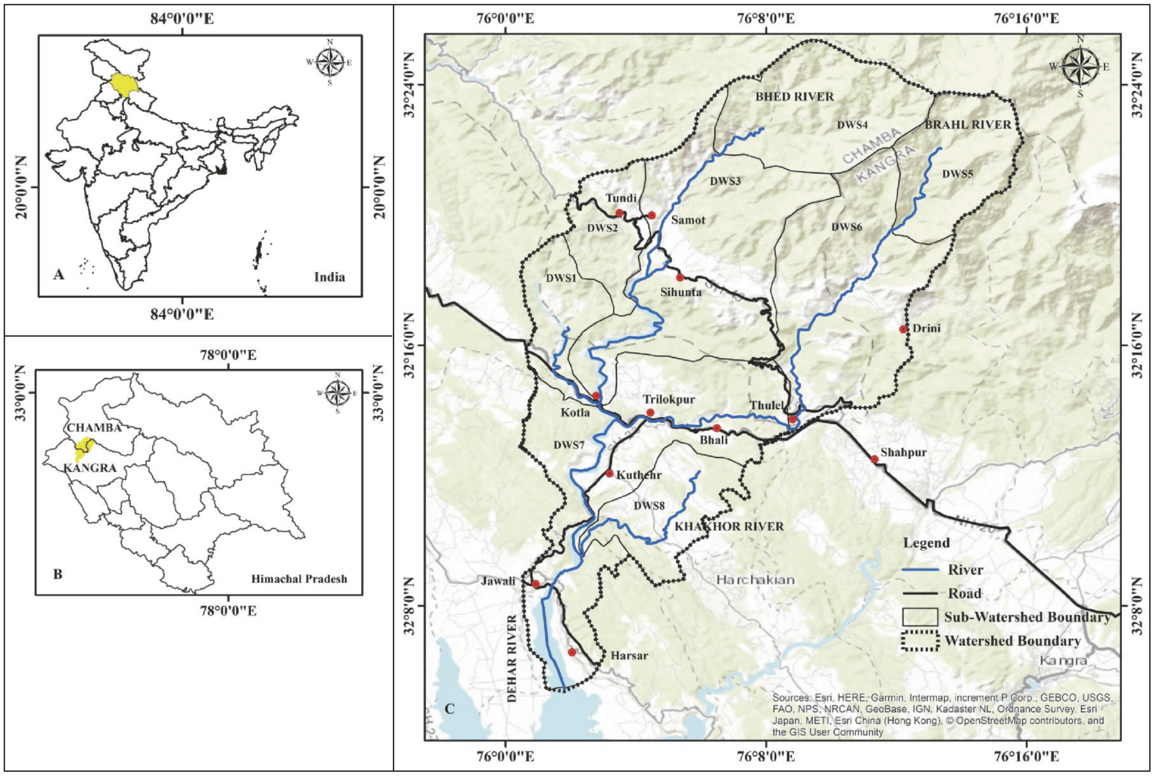

Fig.2. Location map of the study area.

with more precision (Manjare and Pophare, 2020). Based on the literature review and to fill the research gap, an attempt had been made with an objective to carry out hypsometric analysis in a Himalayan watershed that forms a major tributary of highly ecologically sensitive Pong reservoir (Ramsar site). The study was undertaken to know the erosional behavior and health of the Dehar Watershed and its eight sub-watersheds that influence the sediment yield of the Pong reservoir.

Study Area

The Dehar River originates in the Himachal Himalaya thatlies between the Indus and Sutlej rivers by crossing the boundaries of Kangra and Chamba districts of the Himachal Pradesh state, Northern India. It is situated between latitudes 32º5'21" N to 32º23'47" N and longitudes 76º0'25" E to 76º12'29" E (Fig. 2). The Dehar Watershed covers an area of about 450km^2 with an altitude range between 395 and 4080m above mean sea level and falls under the Survey of India (SOI) top sheets maps no. 52D/3, 52D/4 and 52D/7 with a 1:50000 scale. Physiographically, the Dehar Watershed is manifested with parallel hills and disconnected longitudinal valleys. The Dehar River constitutes an important tributary of the Beas River, and after crossing several habitations like Trilokpur, Kotla and Jawali joins the Maha Rana Pratap Sagar (also known as the Pong Reservoir) in the Kangra District of the Himachal Pradesh (Fig. 2). The maximum temperature of the area is 38°C and the minimum temperature is around 0°C. Climate is diverse with low temperate in the higher elevations and sub-tropical in the lower elevations. The sandy skeletal, coarse-loamy, fine loamy and mesic loamy soils are dominant soils of the study area (Sidhu *et al*., 1997). Geologically, it consists of the Siwalik Group rocks in the Outer Himalaya and rocks of the Lesser Himalayan zone (Srikantia and Bhargava, 1998; Prashanth *et al*., 2021). Tectonically, the area is a highly active zone, which is ascertained by the presence of various thrusts such as Main Boundary Thrust, Chail Thrust, and Drini Thrust and several northeast-southwest trending faults/lineaments (Srikantia and Bhargava, 1998).

Materials and Methods

The 30m resolution Shuttle Radar Topography Mission Digital Elevation Model (*SRTM DEM*) was downloaded from the USGS Earth explorer portal (https://earthexplorer.usgs.gov/). And, the DEM was employed for delineating the natural drainage layer and the boundaries of the Dehar Watershed and its eight sub-watersheds along with their drainage lines using hydrology tools (Fig. 3). Based on the delineated sub-watershed boundaries, the DEM for the Dehar Watershed and its sub-watersheds was generated by using the extract mask tool in the ARC GIS environment (Fig. 4). The slope maps were prepared for the Dehar Watershed and its sub-watersheds by using slope tool of the spatial analyst module in the ARC GIS platform (Fig. 5).

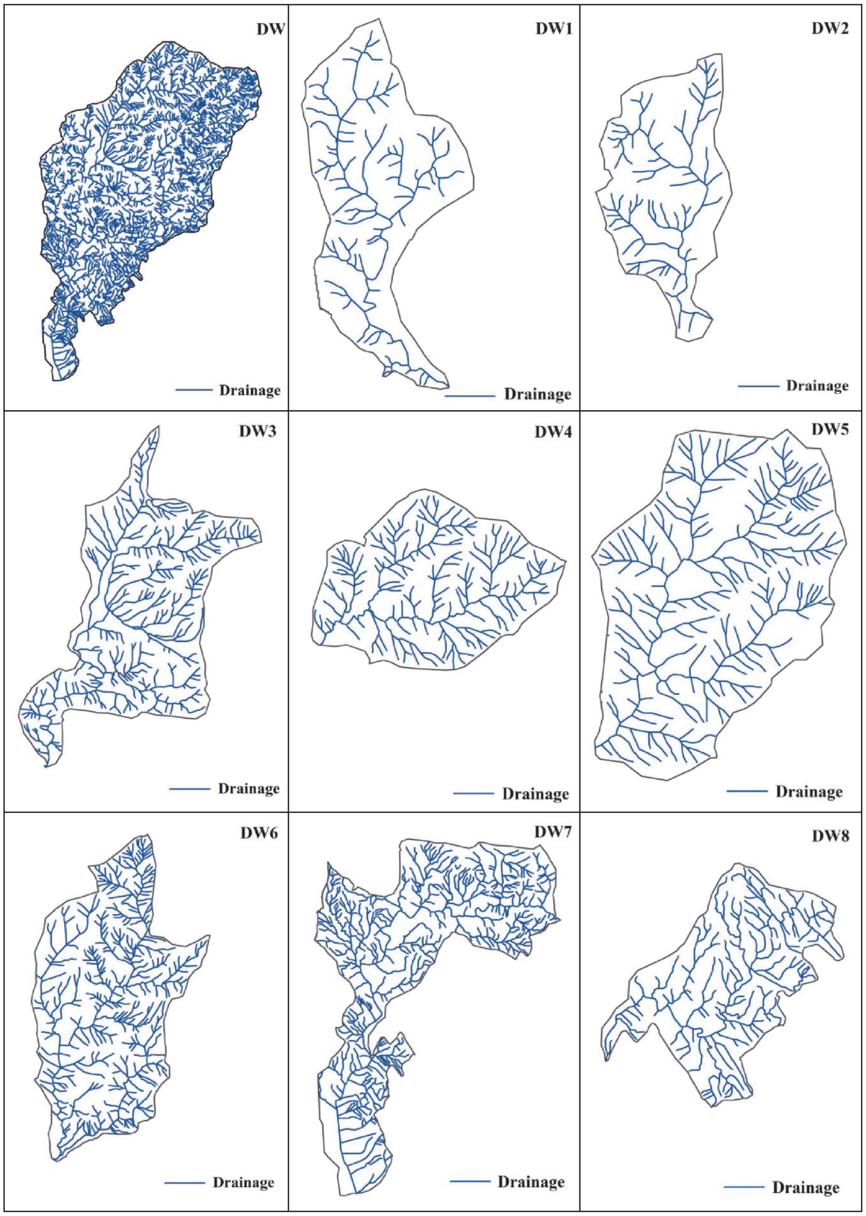

Fig.3. Drainage network of the Dehar Watershed and its eight sub watersheds.

Hypsometric Curve (HC) Estimation

Hypsometric analysis for the Dehar Watershed named as DW and all the eight sub-watersheds, as DW1, DW2, DW3……. and DW8 was carried out to know different stages of the erosional cycle that the sub-watersheds were succumbed to. The HC for the Dehar Watershed and all the sub-watersheds were generated by plotting the relative area (the area overhead of a particular contour (a) to the total watershed area (A)) on the abscissa and the relative height (elevation of a certain contour (h) from the basal plane to the maximum elevation of the watershed (H)) on the ordinate. The resulting HC helps to provide details of the volume of landmass present underneath or overhead of the reference basal plane (*e.g.*, Markose and Jayappa, 2011).

Hypsometric Integral (Hsi) Estimation

The Hsi is generally calculated from the HC, where it is demonstrated precisely (Pike and Wilson, 1971). The elevation-relief ratio (E) proposed by them is demarcated as follows:

$$E \approx \text{Hsi} = \text{Elev}(\mathit{mean}) - \text{Elev}(\mathit{min})/\text{Elev}(\mathit{max}) - \text{Elev}(\text{min}) \qquad (1)$$

Where, E – equivalent to Hsi

Elev(*mean*) – weighted mean elevation of the delineated watershed assessed from the noticeable contours derived from the DEM; and

Elev (*min*) and Elev(*max*) – are the minimum and maximum elevations in the watershed.

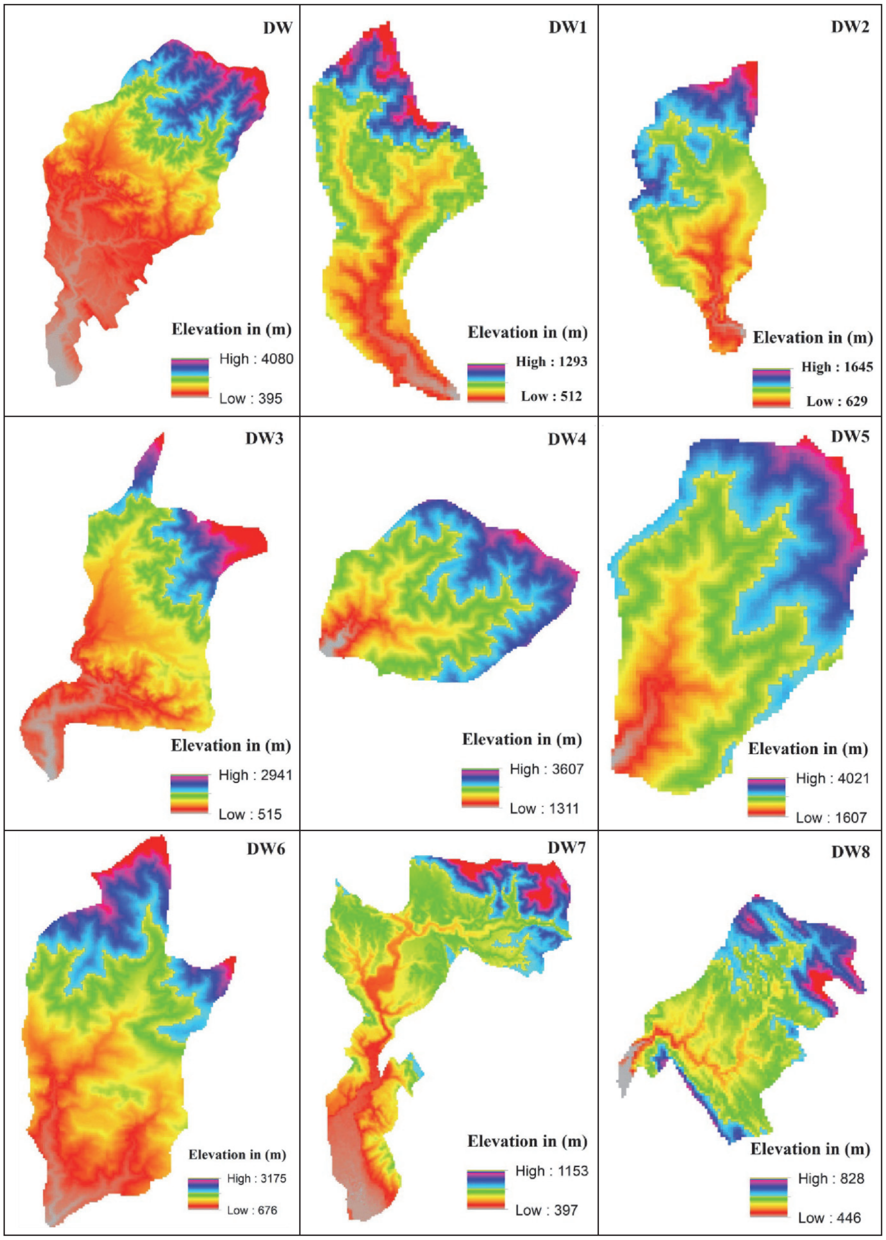

Fig.4. DEM of the Dehar Watershed and its eight sub-watersheds.

The values derived from the HC and Hsi are helpful in determining advances in the stages of geological development. The criteria for determining stages of watershed development proposed by Strahler (1952) were used in obtaining geological stages of watershed development depending upon the Hsi values. If the Hsi value is ≤ 0.35, it indicates that the monadnock stage of landform of a watershed where the HC is distorted and the area is represented by projected monadnock hills; if the Hsi value is between 0.35 to 0.6, it shows an equilibrium and mature dissection stage of landform within the watershed indicating a steady state of development and finally, if the Hsi value is ≥ 0.6, it indicates the watershed is in youth stage or in-equilibrium which is under development (Kusre, 2013).

Results and Discussion

Results achieved from the present study are discussed in terms of the following sub-sections: hypsometric curve, hypsometric integral, and prioritization, conservation and management of watershed.

Hypsometric Curve

For the Dehar Watershed and its eight sub-watersheds hypsometric curves had been prepared based on the hypsometric parameters (Table 1; Fig.6). Later, the shoulders of plotted curves were interpreted; as they form an important source in the study of erosional advances in a drainage basin

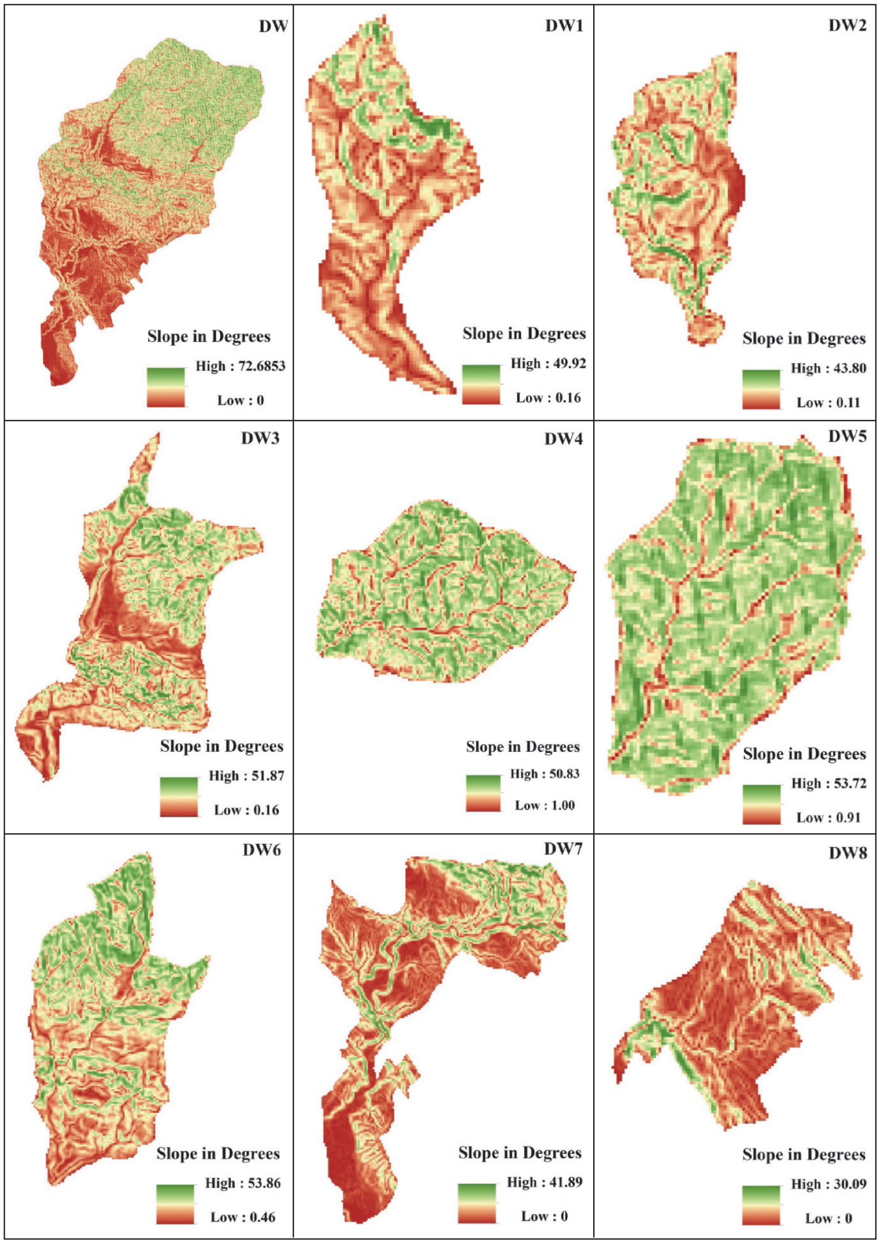

Fig.5. Slope map of the Dehar Watershed and its eight sub-watersheds.

(Strahler, 1957). The interpreted shoulders of most of the sub-watersheds indicate that they are concave in shape and reached a mature stage from the youth stage. Thus, the outcome of the study is in agreement with the other western Himalayan watersheds where most of the watersheds showed change over from younger stage to mature stage (Singh *et al*., 2008). It is noticed from the interpretation of the curves that there is a little variation in the erosional advancement among the different sub-watersheds of the Dehar Watershed.

Hypsometric Integral

Runoff and mass movement are the two significant hydrological processes responsible for the precipitation

Table 1: Hypsometric integral values of the Dehar Watershed and its eight sub-watersheds

Watershed/ Sub-watershed	Area (Km^2)	Max Elevation (m)	Min Elevation (m)	Mean Elevation (m)	Hypsometric integral (Hsi)	Geological stage
DW	450	4080	395	2208	0.49	Mature
DW1	23.32	1293	512	847	0.43	Mature
DW2	23	1645	629	1098	0.46	Mature
DW3	96.31	2941	515	1588	0.44	Mature
DW4	53.71	3607	1311	2467	0.50	Mature
DW5	37.66	4021	1607	2815	0.50	Mature
DW6	81.75	3175	676	1773	0.44	Mature
DW7	101.67	1153	397	736	0.45	Mature
DW8	31.41	828	446	625	0.47	Mature

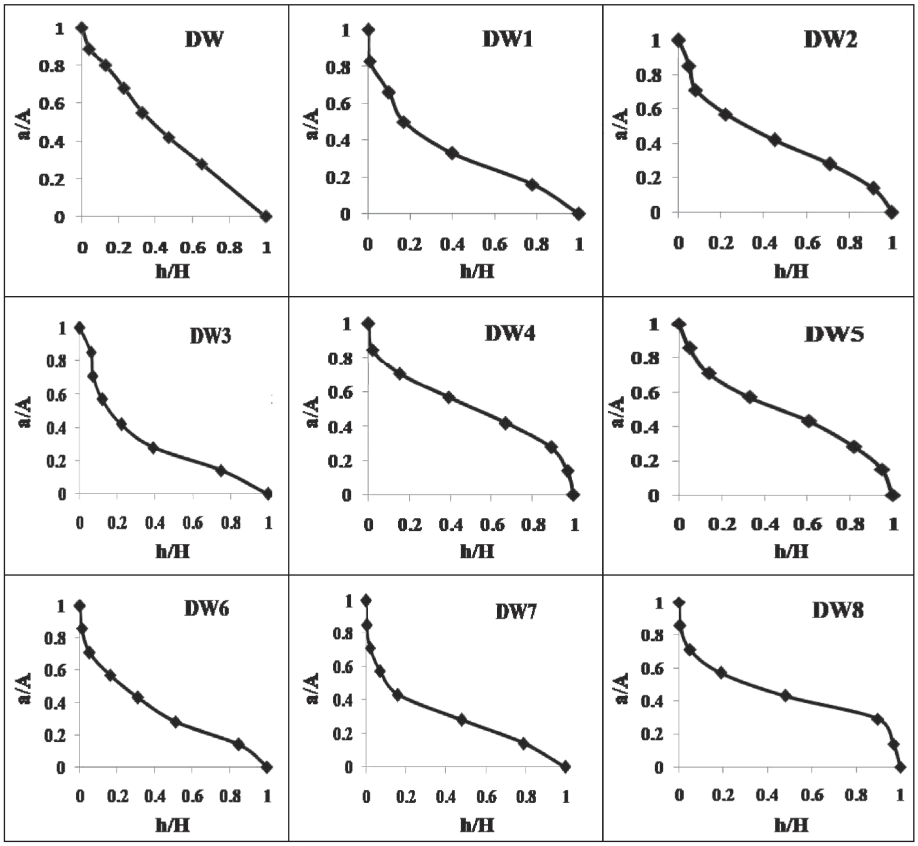

Fig.6. Hypsometric curves of the Dehar Watershed and its eight sub-watersheds.

advances in a watershed system. The Hsi value plays a significant role in measuring erosional processes though it is indirectly used in soil loss estimation in a watershed system. In small watersheds, the HCs are convex and the values of Hsi are in unity signifying active hill slope processes in comparison to the large watersheds. In large watersheds, the HCs are concave, integral approaches zero and with the dominance of fluvial processes (Willgoose and Hancock, 1998). The Hsi value of the Dehar Watershed is 0.49 indicating the equilibrium stage. Similarly, the Hsi values for all sub-watersheds range between 0.43 (DW1) and 0.50 (DW4, DW5), specifying that 43% and 51% of the original rock mass is present in the sub-watershed (DW1) and sub-watersheds (DW4 and DW5), respectively. As shown in Table-1, the Hsi values of the Dehar Watershed and almost all the sub-watersheds are in mature stage and are in a process of transforming stage of peneplanation or the geological stage of deterioration. Strahler (1957) observed that hypsometry describes the age of a watershed. Moglen and Bras (1995) stated that hypsometric distribution is influenced by the subsurface rock formation.

Hence, it is inferred from the soil degradation activity that most of the sub-watersheds were formed from cutting of channel beds, downward passage of quantifiable topsoil and bed rock mass from higher elevations, and soil mass removal and erosion of stream banks. Ritter *et al*. (2002) studied that the sub-watersheds that are in the process of reaching mature stage will exhibit slow pace of erosional activity except in some circumstances where there is high storm intensity and peak runoff.

Prioritization, Conservation and Management of Watershed

It is inferred from the hypsometry analysis that the study area is prone to high runoff. Therefore, it is quite essential to take the necessary steps to regulate the surface runoff. The Hsi values show that all the eight sub-watersheds are affected by the maximum total surface runoff. Accordingly, the Hsi values can be considered for prioritization of sub-watersheds. While identifying sub-watersheds, proper steps can be adopted to moderate and check the surface runoff and resulting erosion. It is quite important that both structural and non-structural measures are to be established to restrain the process of sediment loss and conserve water by adopting integrated watershed management practices. The structural control measures include construction of check dams, farm ponds, contour bunds and other related structures to restrain from flooding and encourage water conservation practices. In addition, sustainable agricultural practices are to be implemented by practising strip farming, crop rotation, agroforestry, *etc*. The non-structural measures include early warning system especially in flood forecasting and awareness programmes to discourage traditional farming practices.

Conclusions

The hypsometric analysis is useful to determine the complex nature of denudational activity and also to assess the change in morphological characteristics occurring in a watershed. It comprises the HC and Hsi, which act as indicators to evaluate the runoff and associated erosion in a watershed and particularly, in the hilly area where most of the terrain is inaccessible. In addition, the analysis is a convenient method in scheduling and planning engineering structures where the information available is scanty. Hence, it is advantageous to know the erosional status and prioritize the sub-watersheds to adopt conservation strategies. Its application in the present study revealed that all the sub-watersheds of the Dehar watershed are comparatively matured and erosional processes are in the process of stabilization. The outcome of the Hsi values had shown that certain sub-watersheds notably DW4 and DW5, are highly vulnerable to erosion in contrast to other associated sub-watersheds of the Dehar Watershed. Therefore, these sub-watersheds require utmost care and appropriate remedial measures such as structural and non-structural methods may be initiated on a priority basis to minimize soil erosion and encouraging water conservation for integrated watershed management.

Authors' Contributions

Manthena Prashanth: Conceptualization, Methodology, Investigation, Visualization, Supervision and Formal Analysis, Writing-Original Draft, Reviewing and Editing. **Arun Kumar:** Conceptualization, Methodology, Investigation, Data Collection and Data Generation, Writing, Reviewing and Editing. **Sunil Dhar:** Conceptualization, Methodology, Investigation, Writing, Reviewing and Editing. **Omkar Verma:** Writing, Reviewing and Editing. **Kakoli Gogoi:** Writing, Reviewing and Editing.

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