

USE OF GEOGRAPHICAL INFORMATION SYSTEM IN HYPSONOMETRIC ANALYSIS OF KANHIYA NALA WATERSHED

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Abstract

Hypsometric analysis of watershed (area-elevation analysis) has generally been used to reveal the stages of geomorphic development (stabilized, mature and young). Hypsometric integral quantifies the geologic stages of development and erosion proneness of the watersheds. Hypsometric integral is estimated by the graphical plot of the measured contour elevation and encompassed area by using empirical formulae. In the present study, hypsometric integral values were estimated for Kanhiya nala watershed which is a tributary of Tons river located in Panna and Satna district of Madhya Pradesh. The watershed was delineated into eight sub-watersheds and hypsometric analysis was carried out for all of them using digital contour maps, which was generated using Arc/Info GIS. Three different approaches were used for estimation of hypsometric integrals and to compare the procedural approach and consequences on erosion status. It was evident from the study that the hypsometric integral calculated by elevation-relief ratio method was more accurate and easy to calculate within GIS environment. The hypsometric integral values for all the sub-watersheds of Kanhiya Nala ranges between 0.39 and 0.67. In the study area, two stages of erosion cycle development, namely equilibrium and youthful stages are identified.

Keywords: GIS, Hypsometry, Watershed, Geological stage

Introduction

Land degradation and topological changes within watersheds are accomplished by weathering processes, stream erosion pattern and sediment transportation by surface runoff. Moreover, the quantification and interpretation of the topological changes becomes very difficult due to complex nature of these hydrological and landform processes acting on watershed systems. In an attempt to simulate the geological stages of development and to study the influence of varying forcing factors (i.e. tectonics, climate, lithology) on watershed topology, the hypsometry of drainage basins (area-elevation analysis) have been evaluated by the researchers. Hypsometric analysis is the relationship of horizontal cross-sectional drainage basin area to elevation. The hypsometric curve has been termed the drainage basin relief graph. Hypsometric curves and hypsometric integrals are important indicators of watershed conditions (Ritter et al., 2002). Differences in the shape of the curve and hypsometric integral values are related to the degree of disequilibria in the balance of erosive and

tectonic forces (Weissel et al., 1994). Hypsometric analysis was first time introduced by Langebein (1947) to express the overall slope and the forms of drainage basin. The hypsometric curve is related to the volume of the soil mass in the basin and the amount of erosion that had occurred in a basin against the remaining mass (Hurtrez et al., 1999). It is a continuous function of non-dimensional distribution of relative basin elevations with the relative area of the drainage basin (Strahler, 1952). This surface elevation has been extensively used for topographic comparisons because of its revelation of three-dimensional information through two-dimensional approach (Harrison et al., 1983; Rosenblatt and Pinet, 1994). Comparisons of the shape of the hypsometric curve for different drainage basins under similar hydrologic conditions provides a relative insight into the past soil movement of basins. Thus, the shape of the hypsometric curves explains the temporal changes in the slope of the original basin. Strahler (1952) interpreted the shape of the hypsometric curves by analyzing numerous basins and classified the basins as young (convex upward curves), mature (S-shaped hypsometric curves which is concave upwards at high elevations and convex downward at low elevations) and peneplain or distorted (concave upward curves). There is frequent variation in the shape of the hypsometric curve during the early geomorphic stages of development followed by minimal variation after the watershed attains a stabilized or mature stage.

Hypsometric analysis is carried out to ascertain the susceptibility of watershed to erosion and prioritize them for treatment. The slope of the hypsometric curve changes with the stage of watershed development, which has a greater bearing on the erosion characteristics of watershed and it, is indicative of cycle of erosion. The hypsometric integral (H_{si}) is also an indication of the 'cycle of erosion' (Strahler, 1952; Garg, 1983). The cycle of erosion is the total time required for reduction of land area to the base level i.e. lowest level (Fig 1). This entire period or the 'cycle of erosion' can be divided into the three stages viz. monadnock (old) (H_{si} 0.3), in which the watershed is fully stabilized; equilibrium or mature stage (H_{si} 0.3 to 0.6); and inequilibrium or young stage (H_{si} > 0.6), in which the watershed is highly susceptible to erosion (Strahler, 1952).

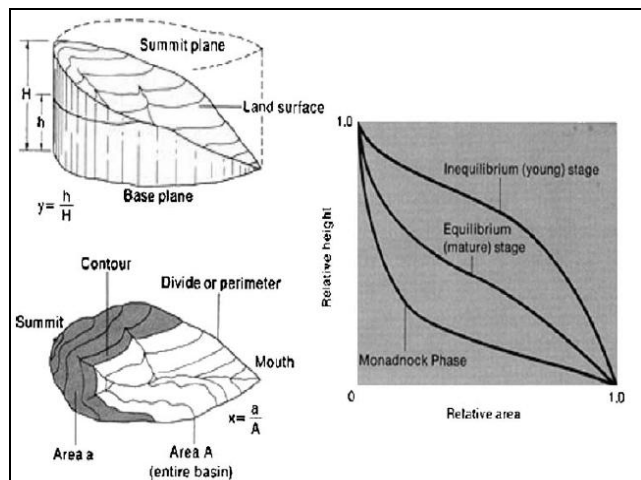


Figure 1. The Concept of Hypsometric Analysis and the Model Hypsometric Curves (Ritter et al. 2002).

Hypsometric curves and hypsometric integral is important watershed health indicator. Hypsometric analysis using GIS has been used by several researchers in India dealing with erosional topography (Pandey et al., 2004; Singh et al., 2008a ;Singh et al., 2008b; Sharma and Seth 2010 and Sharma et al., 2011). The Kanhiya nala watershed under study is vulnerable to erosion looking to its undulating topography. Further, there is lack of hypsometric based studies to watershed health, which is attributable to the tedious nature of data acquisition and analysis is involved in estimation of hypsometric analysis. Employing Geographical Information System (GIS) techniques in hypsometric analysis of digitized contour maps helps in improving the accuracy of results and save time. Considering the above facts, this study was undertaken to compare different hypsometric integral estimation techniques and to determine geological stage of development of sub-watersheds of Kanhiya Nala watershed located in Satna and Panna district of Madhya Pradesh.

Materials and methods

Description of Study Area

The study area Kanhiya Nala watershed which lies within the Tons river catchment $80^{\circ}32'24''$ to $80^{\circ}34'12''$ E longitude and $24^{\circ}06'$ to $24^{\circ}10'48''$ N latitude (Fig 2) with elevation ranges from 480 to 620 m above mean sea level and extends a total area of 25.58 km². The average annual rainfall is 1300 mm. The watershed is situated in Satna and Panna district of Madhya Pradesh.

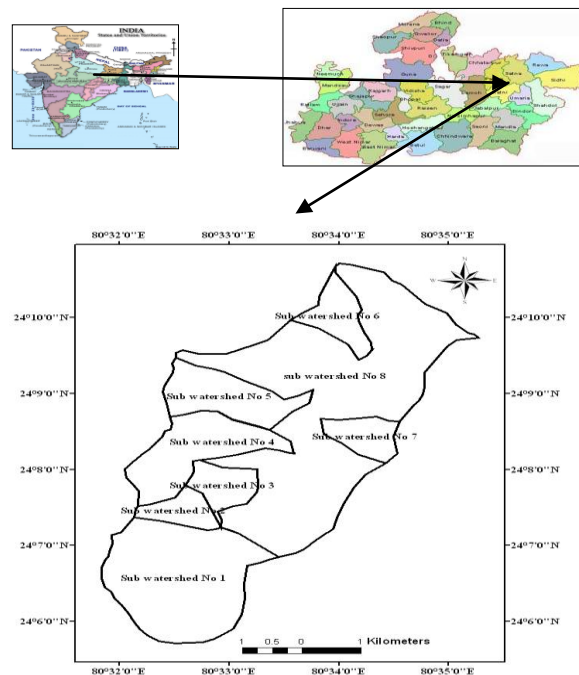


Figure 2. Location map of study area.

Watershed Delineation and Generation of DEM from the Topological Data

The topological information of the study area was georeferenced and digitized from Survey of India (SOI) toposheet 63 D/12 using the capabilities of ArcInfo and ArcGIS tools. The contours were digitized to generate the line feature class in ArcGIS which was further processed using the spatial analyst module to generate the digital elevation model (DEM) representing the watershed terrain topology (Fig 3). Further, the developed DEM was processed to generate or delineate the watershed and sub-watersheds using the hydrology tool of spatial analyst module. The digitized contour and drainage map of the study area are shown in Fig 4 and Fig 5 respectively. The delineated sub-watersheds of the Kanhiya Nala watershed marked from 1 to 8 are also shown in Fig 5. The drainage network ordering was done using the Strahler's stream ordering scheme (Strahler 1964). The attribute tables of the georeferenced feature classes representing the contours and their enclosed area with the sub-watersheds boundaries contained the elevation and length of contours and their respective area and perimeter values. The attribute feature classes containing these values were used to plot the hypsometric curve of the sub-watersheds from which the hypsometric integrals were estimated (Fig 6).

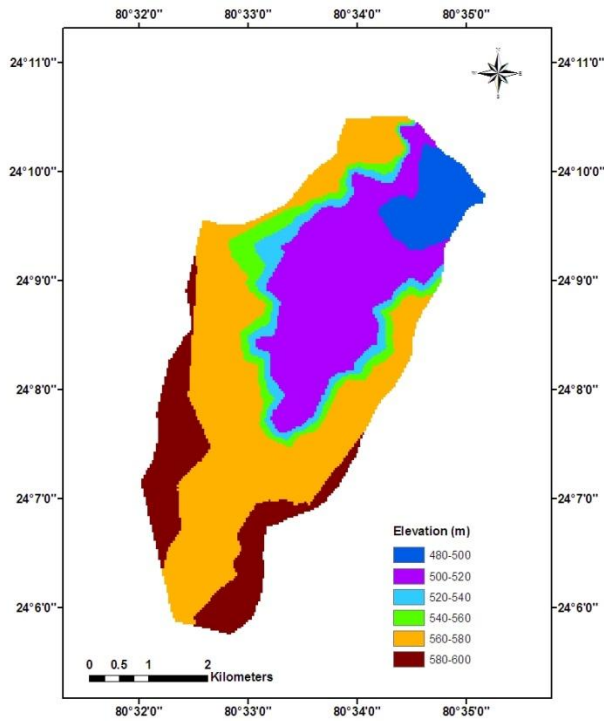


Figure 3. Digital Elevation Model of study area.

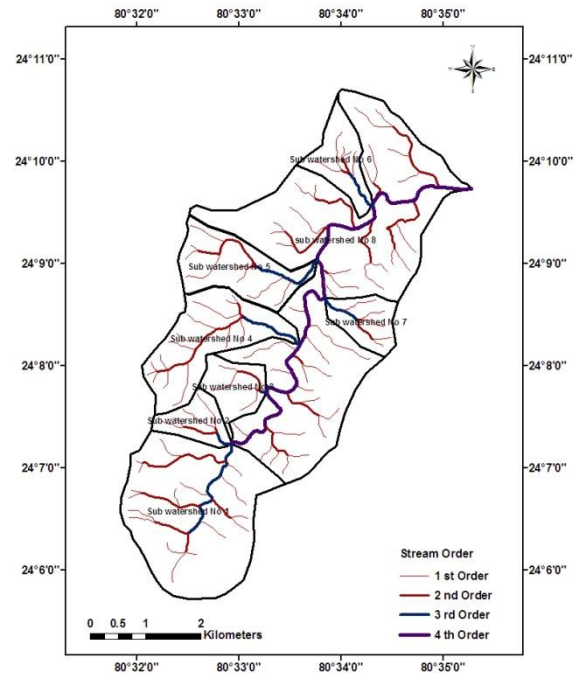


Figure 5. Drainage network of Study area.

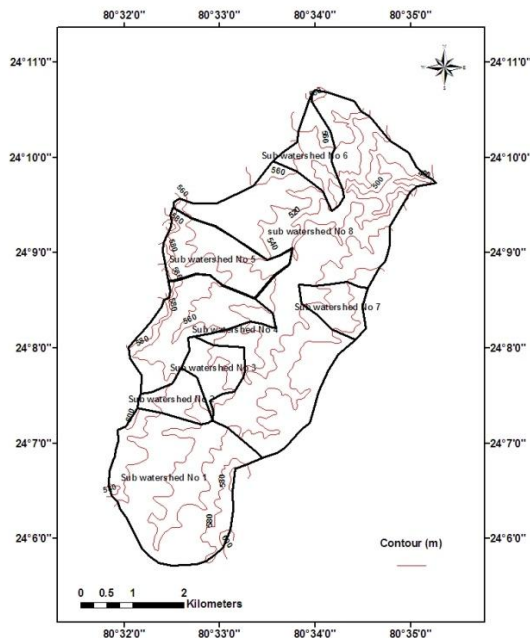


Figure 4. Contour map of study area.

Plotting of Hypsometric Curves (HC) and Estimation of Hypsometric Integrals (H_{si})

Hypsometric analysis aims at developing a relationship between horizontal cross-sectional area of the watershed and its elevation in a dimensionless form. The digital contour map was used to generate the data required for relative area and elevation analysis. Hypsometric curve is obtained by plotting the relative area (a/A) along the abscissa and relative elevation (h/H) along the ordinate. The relative area is obtained as a ratio of the area above a particular contour (a) to the total area of the sub watershed above the outlet (A). Similarly, referring to Fig 1, considering the watershed area to be bounded by vertical sides and a horizontal base plane passing through the outlet, the relative elevation is calculated as the ratio of the height of a given contour (h) from the base plane to the maximum basin elevation (H), (up to the remote point of the sub watershed from the outlet) (Sarangi et al. 2001 and Ritter et al. 2002). The hypsometric integral is obtained from the hypsometric curve and is equivalent to the ratio of the area under the curve to the area of the entire square formed by covering it. It is expressed in percentage units and is obtained from the percentage hypsometric curve by measuring the area under the curve. This provided a measure of the distribution of landmass volume remaining beneath or above a basal reference plane.

In the present study, the hypsometric integral or the area under the curve was estimated using three methods. Besides this estimation, a comparative evaluation was also attempted based on the accuracy of estimation, calculation time and the complexity of methods and tools required to accomplish the task. The methods adopted to calculate the area under the curves are:

1. Integration of Hypsometric Curve (HC)

The plotted hypsometric curves were fitted with a trend line to represent an equation of the curve and the best fitting equation was obtained for highest coefficient of determination (R^2) value. The equation was further integrated within the limits 0 to 1 (due to non-dimensional nature of the graph) for estimating the area under the curve. Thus, the estimated area gives the hypsometric integral value of the hypsometric curve. The developed polynomial equation by fitting the hypsometric curve of the sub-watershed 1 as a sample set is shown in Fig 7. The fitted equation was integrated within the desired limits to estimate the area under the HC. Similar procedure was adopted for other remaining sub-watersheds of Kanhiya nala watershed. However, this method was time consuming and necessitated mathematical integration procedures and subsequent calculation within the desired limits of HC.

2. Use of Planimeter Equipment

Planimeters are widely used by the engineers, geologist, geographers, surveyors and planners to estimate the area. In this study digital Planimeter was used. Initially the pointer of the Planimeter was rotated on the entire graph area and readings were recorded. Further, the Planimeter was rotated on the curved area beneath the hypsometric curve and the readings noted. Finally, the entire graph area readings were divided by the area readings below the hypsometric curve to estimate the hypsometric integral. This method was cumbersome and time consuming in which the estimation error was also due to precision and accuracy of the equipment besides the human error.

3. Use of Elevation-Relief Ratio (E) Relationship

In order to overcome the difficulty faced by above two methods, the elevation-relief ratio method proposed by Pike and Wilson (1971) was used. The relationship is expressed as

$$E \approx H_{si} = \frac{Elev_{mean} - Elev_{min}}{Elev_{max} - Elev_{min}} \quad (1)$$

Where, E is the elevation-relief ratio equivalent to the hypsometric integral H_{si} ; $Elev_{mean}$ is the weighted mean elevation of the watershed estimated from the identifiable contours of the delineated sub-watersheds; $Elev_{min}$ and $Elev_{max}$ are the minimum and maximum elevations within the sub-watersheds.

Results and discussion

The co-ordinates of the hypsometric curves of the eight sub-watersheds of Kanhiya nala watershed as obtained were plotted and presented in Fig 6. It was observed from the hypsometric curves of these sub-watersheds that the drainage system is attaining the monadnock stage from the youth stage, which is true for most of the Tons watershed (Kanhiya nala is one of the tributary of Tons river). The comparison between these curves shown in the Fig 6 indicated a marginal difference in mass removal from the sub-watersheds of study area. It was also observed that there was a combination of convex-concavo and S-shape of the hypsometric curves for the sub-watersheds under study. This could be due to the soil erosion from these sub-watersheds resulting from the incision of channel beds, down slope movement of top-soil and bedrock materials, washout of the soil mass and cutting of streams banks.

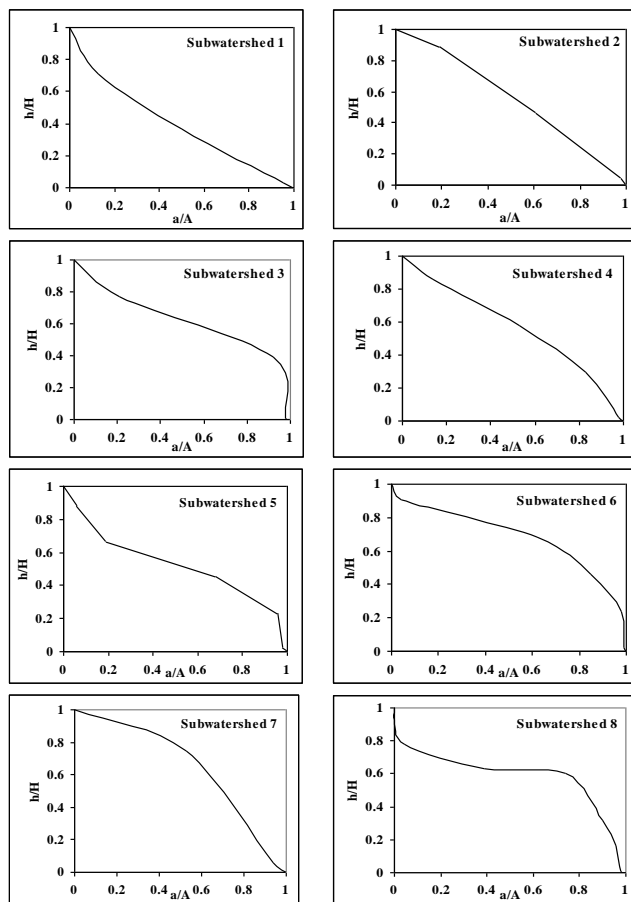


Figure 6. Hypsometric curves of sub-watersheds of study area.

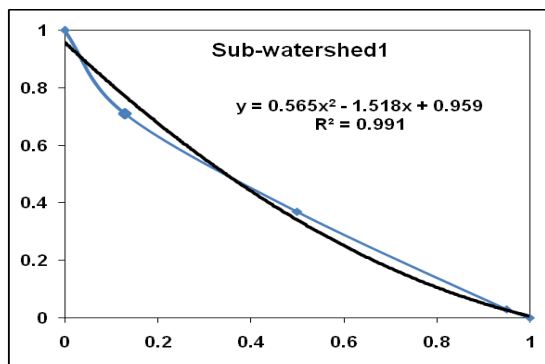


Figure 7. The fitted equation of hypsometric curve as sample set of sub-watershed 1.

Estimation of Hypsometric Integral (H_{si}) values

The hypsometric integral values obtained using the three methods for the eight sub-watersheds of study area are presented in Table 1. It was observed from Table 1 that there was not much difference in the estimated values of the hypsometric integral for all the methods except for minor differences of 0.03 in some cases. However, the elevation-relief ratio method was observed to be less cumbersome and faster than the other two methods. Moreover, the comparison of the estimated H_{si} values from the elevation-relief ratio method and the rest two hypsometric curve based methods revealed that there is no significant difference between the estimated hypsometric integral values. This indicated that, the estimation of hypsometric integral from hypsometric curve using the ratio of areas is not always a better estimator of hypsometric integral. Therefore, the elevation-relief ratio method can be adjudged as the most efficient method for estimation of hypsometric integral.

Table 1 Estimated hypsometric integral values of sub-watersheds

Sub-watersheds	Area (Km ²)	Elevation-relief ratio method	Integration method	Planimeter method	Geologic stage
1	5.4	0.39	0.39	0.39	Late Mature or near Monadnock
2	0.74	0.52	0.52	0.52	Mature
3	0.93	0.59	0.61	0.60	Late Youthful
4	2.61	0.54	0.53	0.55	Late Youthful
5	1.98	0.52	0.50	0.51	Mature
6	1.08	0.68	0.69	0.67	Inequilibrium or Youthful
7	0.89	0.59	0.62	0.61	Late Youthful
8	11.95	0.52	0.52	0.54	Mature

Relevance of Hypsometric Integral (H_{si}) on Watershed Hydrological responses

Surface runoff and sediment losses are the two important hydrological responses from the rainfall events occurring over the watershed systems. The hypsometric integral value can be an indirect estimator of the erosion from the watershed systems. It was observed from the H_{si} values (Table 1) that the sub-watersheds of Kanhiya nala watershed are in young and mature stage and moving towards the peneplanation or the deteriorating stage. This revealed that the soil erosion from these sub-watersheds were derived primarily from the incision of channel beds, down slope movement of top soil and bed rock material, washout of the soil mass and cutting of stream banks. These landforms changes were also reflected in different sub-watersheds of the study watershed. Hypsometric integral values of sub-watersheds of Kanhiya nala watershed were ranged between 0.39 and 0.67. While, comparing standard H_{si} values of sub-watersheds it was observed that the sub-watersheds 1 is in late mature stage or approaching towards monadnock (less susceptible) stage and attributed mainly to human interventions in the form of construction of roads, intensive agricultural practices and deforestation activities. However, the sub-watersheds 2, 5 and 8 are in mature stage. The hydrologic response of the sub-watersheds attaining mature stages will have slow rate of erosion unless there is very high intense storms leading to high runoff peaks (Ritter et al., 2002). Moreover, the sub-watershed 3, 4 and 7 yielded higher hypsometric integral value, explaining its late youthful stage which calls for suitable measures of soil and water conservation. Further, sub-watershed 6 have got very high value of hypsometric integral which takes it to young stage i.e. very susceptible to erosion. Therefore, this sub-watershed is more prone to subsequent erosion activities and needs immediately appropriate soil and water conservation measures.

Conclusion

Hypsometric analysis of watershed expresses the complexity of denudational processes and the rate of morphological changes. Therefore, it is useful to comprehend the erosion status of watersheds and prioritize them for undertaking soil and water conservation measures. But, great care must be exercised in interpreting and comparing hypsometric curves due to its complex nature of computation. Out of the three methods used to compute the hypsometric integral, the elevation-relief-ratio method was the best because of its easiest estimation procedure in minimal time without any equipment. Moreover, the results obtained from the equation were in line with other methods. The results of hypsometric integrals revealed that the sub-watershed 6 is more prone to erosion in comparison to other sub-watersheds of Kanhiya nala watershed which would necessitate construction of soil and water conservation structures at appropriate locations of the sub-watersheds to arrest sediment outflow and conserve water. Fur-

ther, the sub-watersheds, which are having hypsometric integral values more than 0.5 (i.e. approaching youthful stage) need construction of both vegetative and mechanical soil and water conservation structures to arrest sediment load and conserve water for integrated watershed management. However, the hypsometric integral values less than 0.5 (i.e. approaching monadnock stage) needs minimum mechanical and vegetative measures to arrest sediment loss but may require more water harvesting type structures to conserve water at appropriate locations in the watershed for conjunctive use of water.

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