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Hydro-hypsometric analysis of tropical river basins, Southwest Coast of India using geospatial technology

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Abstract: The key aspect in planning and management of water resources is to analyze the runoff potential and erosion status of the river basin. For the detailed investigation of hydrological response, freely available Cartosat-1 (IRS-P5) data was used for the preparation of digital elevation model (DEM). The runoff potential and type of erosive process of 22 river basins originating in the global biodiversity hotspot of Western Ghats, was inferred through hypsometric analysis. Several parameters like Hypsometric integral (HI), maximum concavity (Eh), coordinates of slope inflection point (I) given by a* and h* and normalized height of hypsometric curve (h) were extracted from the hypsometric curves and used for understanding the hydrological responses. From the hypsometric curves, the landform evolution processes were inferred. Contribution of diffusive and fluvial processes in slope degradation of the river basins was understood. Basins with lesser area (<100 km^2) were found to have a positive correlation between hypsometric integral and basin area, whereas for large basins no such correlation exists. Based on the study, river basins can be prioritized for the appropriate conservation measures.

Keywords: Hypsometry; Runoff potential; Erosion status; Cartosat-1 data; River Basins

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Introduction

Hydrologic response of a drainage basin is largely dependent on its topographical characteristics. Introduction of hypsometry by Strahler (1952) led to the tool being used popularly in the field of hydrology and tectonics. Topography of a basin is commonly analyzed using Hypsometric curve and Hypsometric Interval (Ramuand Mahalingam 2012), which are important indicators of watershed conditions (Ritter et. al. 2002). Hypsometry is a technical term relating to measurement of height. Hypsometric analysis (area-altitude analysis) provides an understanding of the stage of development of a watershed. Hypsometric curve, which is the graphical representation of the watershed area and elevation, is essentially a normalized cumulative frequency distribution of elevation. (Strahler 1952). Classically, hypsometric analysis has been used to attain valuable information of erosion status and runoff potential of the river. The shape of the curve is also an important indicator in determining the role of topography in streamflow (Marani et al. 2001). The use of hypsometric analysis for the evaluation of the condition of water resources has also been reported (Lin and Oguchi 2004; Singh and Sarangi 2008). The hypsometric integral (HI) is the area beneath the curve which relates the percentage of total relief to cumulative percentage area. This provides a measure of the distribution of landmass volume remaining beneath or above a basal reference plane. Theoretically, hypsometric integral values range from 0-1 (Kusre 2013). Hypsometric integral helps in identifying whether tectonic or erosive forces are predominant in determining the shape of a drainage basin (Khadri and Kokate 2015). It has an association with the erosion process, landform curvature and landscape morphology (Rogelis and Werner 2014). Dimensionless nature of hypsometric integral renders it more effective in comparing different catchments, irrespective of their scale (Dowling et al. 1998).

In the present study hypsometric analysis was performed to study the runoff generation potential and erosion status of 22 river basins in Northern Kerala. All these rivers have their origin in Western Ghats, one of the global biodiversity hotspots with a unique landscape in terms of its geology, biology and ecology (Government of India 2013). Western Ghats, a major contributor topographic precipitation during Southwest Monsoon, plays a major role in shaping the climate of the country (Sajinkumar et al. 2011). Hence, understanding the erosional pattern and runoff generation of this global biodiversity hotspot is significant for its conservation. Advancements in the field of Geographic Information System (GIS) have rendered the hypsometric analysis to be easier and much faster than the conventional methods (Vanderwaal and Ssegane 2013). In the study, GIS was used to obtain hypsometric information coupled with the free available Digital Elevation Model data and Cartosat-1 (IRS-P5), and to calculate associated parameters.

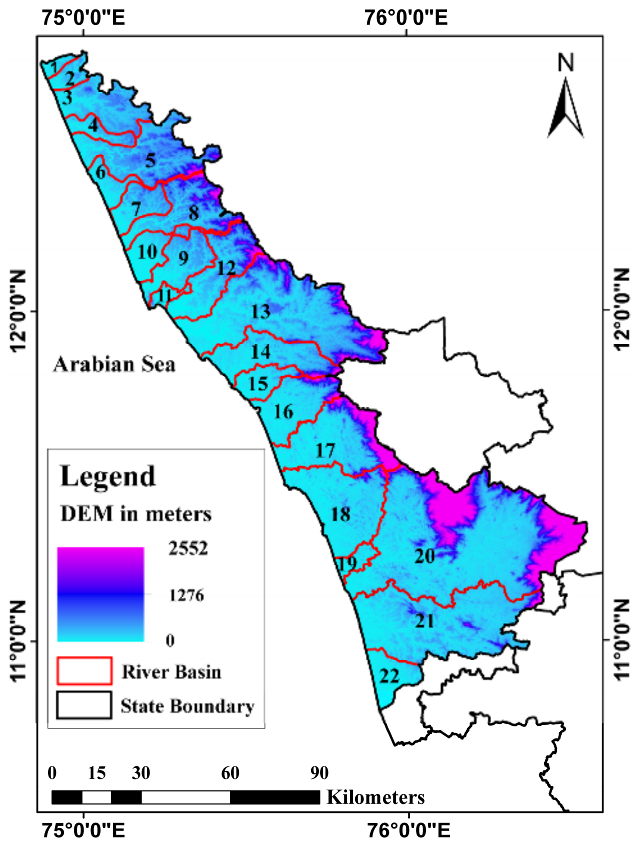

Figure 1 Digital elevation model of 22 river basins (cartosat-1). 1) Manjeswar 2) Uppla 3) Shiriya 4) Mogral 5) Chandragiri 6) Chittari 7) Nileswar 8) Kariangode 9) Peruvamba 10) Kavvayi 11) Ramapuram 12) Kuppam 13) Valapattanam 14) Anjarakandy 15) Thalasseri 16) Mahe 17) Kuttiyadi 18) Korapuzha 19) Kallai 20) Chaliyar 21) Kadalundi 22) Tirur.

1 Study Area

Northern Kerala, also known as Malabar region, lying between Western Ghats and the Arabian Sea, is considered for the present investigation (Figure 1). Twenty two river basins in Northern Kerala are studied, which flows westward towards the Arabian Sea. General features of river basins are given in Table 1. Area of the selected river basins ranges from 52 km^2 to 2535 km^2. The region commonly exhibits wet and maritime tropical climate, which is variable with respect to the rainfall, temperature and humidity. The Northern Kerala river basins receive an average rainfall of 3000 mm and more than 80% of the rainfall is received during the South west monsoon (June- September). North Kerala experiences more rain with every surge of monsoon currents, than South Kerala, during the Southwest monsoon season (Simon and Mohankumar 2004). The rivers are small in the terms of length, breadth and water discharge. The distance between the Western Ghats and the Arabian Sea is relatively short and, therefore, the rivers flow faster owing to the hilly terrain. Rivers are entirely monsoon-fed and many of them shrink into rivulets or dry up completely during summer.

Table 1 General features of River basins in Northern Kerala

<table>
<tr><th>Sl. No.</th><th>River basin Name</th><th>EOR</th><th>LMS</th><th>AAR</th><th>AASF</th><th>PWRDU (2021)</th><th>PWRIU (2021)</th></tr>
<tr><td>1</td><td>Manjeswar</td><td>60</td><td>16</td><td rowspan="2">3478</td><td rowspan="2">309</td><td rowspan="2">13.6</td><td rowspan="2">45</td></tr>
<tr><td>2</td><td>Uppala</td><td>150</td><td>50</td></tr>
<tr><td>3</td><td>Shiriya</td><td>230</td><td>67</td><td>3700</td><td>1415.5</td><td>14.9</td><td>45</td></tr>
<tr><td>4</td><td>Mogral</td><td>250</td><td>34</td><td rowspan="3">4000</td><td>NA*</td><td rowspan="2">32.9</td><td rowspan="2">45</td></tr>
<tr><td>5</td><td>Chandragiri</td><td>1350</td><td>105</td><td>3964</td></tr>
<tr><td>6</td><td>Chittari</td><td>91</td><td>25</td><td>254</td><td>14.5</td><td>45</td></tr>
<tr><td>7</td><td>Nileswar</td><td>140</td><td>46</td><td>3600</td><td>NA*</td><td rowspan="2">36</td><td rowspan="2">45</td></tr>
<tr><td>8</td><td>Kariangode</td><td>1520</td><td>64</td><td>3600</td><td>1356</td></tr>
<tr><td>9</td><td>Kavvayi</td><td>385</td><td>31</td><td>3600</td><td>NA*</td><td rowspan="3">27.1</td><td rowspan="3">45</td></tr>
<tr><td>10</td><td>Peruvamba</td><td>325</td><td>51</td><td>3600</td><td>1143</td></tr>
<tr><td>11</td><td>Ramapuram</td><td>57</td><td>19</td><td>3600</td><td>NA*</td></tr>
<tr><td>12</td><td>Kuppam</td><td>1630</td><td>82</td><td>3800</td><td>1516</td><td>43.9</td><td>45</td></tr>
<tr><td>13</td><td>Valapattanam</td><td>1350</td><td>110</td><td>3600</td><td>4779</td><td>82.4</td><td>90</td></tr>
<tr><td>14</td><td>Anjarakkandy</td><td>600</td><td>48</td><td>3500</td><td>433</td><td>32.5</td><td>45</td></tr>
<tr><td>15</td><td>Mahe</td><td>910</td><td>54</td><td>3900</td><td>247.8</td><td>24.9</td><td>45</td></tr>
<tr><td>16</td><td>Thalasseri</td><td>550</td><td>28</td><td>3500</td><td>155.3</td><td>15.2</td><td>45</td></tr>
<tr><td>17</td><td>Kuttiyadi</td><td>1220</td><td>74</td><td>4500</td><td>1273.5</td><td>58.8</td><td>45</td></tr>
<tr><td>18</td><td>Korapuzha</td><td>610</td><td>40</td><td rowspan="3">3800</td><td>221.8</td><td rowspan="4">631</td><td rowspan="4">450</td></tr>
<tr><td>19</td><td>Kallai</td><td>45</td><td>22</td><td>NA*</td></tr>
<tr><td>20</td><td>Chaliyar</td><td>2066</td><td>169</td><td>5902</td></tr>
<tr><td>21</td><td>kadalundi</td><td>1160</td><td>130</td><td>3400</td><td>1137.3</td></tr>
<tr><td>22</td><td>Tirur</td><td>86</td><td>48</td><td>3400</td><td>165</td><td>28.2</td><td>45</td></tr>
</table>

Notes: EOR = Elevation point of origin of river (m asl); LMS = Length of main stream (km); AAR = Average annual rainfall (mm); AASF = Average annual stream flow (Mm^3); PWRDU = Projected water requirement for domestic use (Mm^3); PWRIU = Projected water requirement for industrial use (Mm^3); NA*= Not Available.

2 Materials and Methods

Topographic maps (1:50,000 scale) of the study area published by Survey of India were georeferenced with Universal Transverse Mercator projection (WGS 1984, zone 43 N) using ERDAS IMAGINE 9.1. The georeferenced toposheets were mosaiced using ERDAS IMAGINE 9.1 by the help of data preparation tool. Each river in Northern Kerala was selected and tributaries of the particular rivers were identified. River basins were identified and outlined in Arc GIS 9.2. Cartosat-1 stereo images have proved to be an excellent source of data for the production of DEM with a ground resolution of 5 m, and DEM thus generated through automatic mode is very effective to carry out hypsometric analysis for the river basin (Gopinath et al. 2014). Digital elevation model (DEM) for the study area has been obtained using Cartosat-1 (IRS-P5) and the derived DEM for each river basin is depicted in Figure 1. Hypsometric curve was derived for each river basins in the study area from the 30m Cartosat -1 (IRS –P5) DEM in Arc GIS environment using Cal Hypso tool. Using hypsometric curves of 22 river basins, various parameters such as maximum concavity (Eh), coordinates of slope inflection point (I) given by a* and h* and normalized height of hypsometric curve (h) were calculated. By the help of hypsometric integral and hypsometric curves, the landforms were classified into youth, mature and old. Downward concave part of right hand side of hypsometric curve is called toe, upward concave part of left hand side of the curve is head and upward concave segment in the centre of the curve between toe and head is called body (Willgoose and Hancock 1998). In this study, hypsometric curve were obtained for all the 22 river basin of northern Kerala in GIS environment. The normalized height of hypsometric curve (h) at 0.2, 0.5, 0.8, 0.9, which provides the elevation relative to maximum height that covers the specific proportion of catchment area, was calculated for all the river basins in Northern Kerala (Table 2). The flow chart (Figure 2) below represents the procedure used in the study.

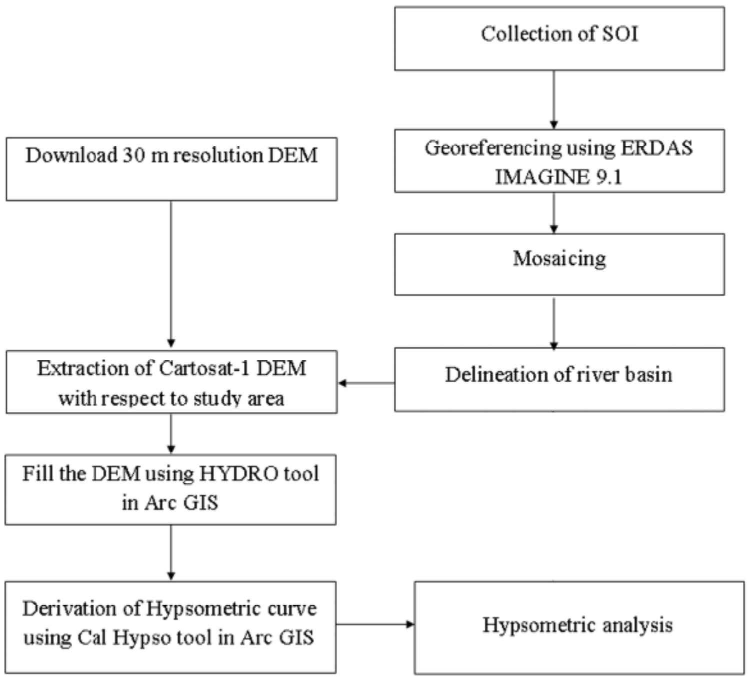

Figure 2 Flow diagram of the study.

3 Results

Erosive processes in the basin are explained on the basis of the shape of the hypsometric curve and hypsometric integral.

3.1 Hypsometric curve shape

Hypsometric parameters and hypsometric curves were prepared for the 22 river basins under study (Table 2, Figure 3). Based on the shapes of the hypsometric curves for 22 basins, they are grouped into three. Those with an upward concave shape come under the first group and represent old stage. This curve represents the flood plain region with low runoff and thus will process more infiltration. The second group is characterized by a concave-convex shape representing fluvial slope wash process. The third group characterized by an upward convex curve representing young stage. This curve represents greater runoff and less infiltration.

Hypsometric curves of Chandragiri, Kuppam, Valapattanam, Anjarakandy, Thalasseri, Mahe, Kuttiyadi, Kadalundi and Korapuzha belong to first group. The steep slope of Kuppam, Valapattanam curves in the toe region indicates that these basins are characterized by greater runoff at the toe. Kuttiyadi, Korapuzha and Mahe basins have curves that have steep slope at the top and the slope decreases at the toe region, indicating greater erosion and runoff at higher altitudes. In the lower regions, infiltration rate is more leading to high soil moisture. Mogral, Kariangode, Peruvamba and Chaliyar basins belong to the second group. The concave-convex shape of the curve suggests upper part of these basins to be having low runoff. This is may be due to the lithological differences in the basin region. Hypsometric curves of Manjeswar, Uppla, Shiriya, Chittai, Nileswar, Kavvayi, Ramapuram, Kallai and Tirur belong to third group, having greater runoff and less infiltration.

3.2 Hypsometric head and toe

The values of hypsometric head and toe have significant importance in hydrological response of the river basin. Higher values of hypsometric head indicate that the contribution of diffusive process is more. As the hypsometric toe value increases, the mass accumulation is greater at the mouth, derived mainly through fluvial process (Markose and Jayappa 2001). Mogral, Chandragiri, Kariangode Kuppam, Valapattanam, Anjarakandy, Thalasseri, Mahe, Kuttiyadi, kadalundi, Chaliyar and Korapuzha river basins have lower values of hypsometric head (<0.56) indicating that the upper reaches of these basins are not much influenced by diffusive process. Uppala, Shiriya, Chittai, Nilesawar, Kavvayi, Peruvamba, Ramapuram and Tirur river basins have moderate influence of diffusive process whereas Manjeswar and Kallai have hypsometric head values greater than 0.75, indicating predominant diffusive process at the upper reaches.

Chandragiri, Kariangode, Kuppam, Valapattanam, Anjarakandy, Thalasseri, Mahe, Kuttiyadi, Kadalundi,Chaliyar and Korapuzhariver basins show low toe values (<0.2) indicating minimum mass accumulation at the basin mouth. Manjeswar, Uppla, Shiriya, Chittai, Nileswar,

Table 2 Hypsometric parameters-hypsometric integral (HI), normalized height of hypsometric curve (h) at 0.2, 0.5, 0.8 and0.9, maximum concavity (Eh) and coordinates of slope inflection point (I) given by a* and h*- of all the 22 river basins in Northern Kerala

Sl. No.	River basin name	Area (Km^2)	HI	Height of hypsometric curve(h)				Eh	Coordinates of (I)	
				At 0.2	At 0.5	At 0.8	At 0.9		a*	h*
1	Manjeswar	90	0.7155	0.80	0.71	0.62	0.60	0.05	0.03	0.93
2	Uppala	76	0.6380	0.72	0.64	0.58	0.51	0.6	0.12	0.78
3	Shiriya	290	0.5641	0.69	0.6	0.51	0.43	0.8	0.18	0.67
4	Mogral	132	0.3613	0.46	0.39	0.30	0.24	2.8	0.06	0.49
5	Chandragiri	570	0.2929	0.38	0.28	0.20	0.18	4.0	0.12	0.41
6	Chittai	145	0.5641	0.60	0.52	0.44	0.42	2.2	0.1	0.05
7	Nileswar	190	0.5081	0.60	0.50	0.49	0.43	2	0.04	0.62
8	Kariangode	429	0.3449	0.46	0.30	0.24	0.22	2.7	0.5	0.15
9	Kavvayi	143	0.5018	0.6	0.43	0.41	0.41	2	0.07	0.66
10	Peruvamba	300	0.4889	0.60	0.50	0.42	0.42	1.7	0.7	0.04
11	Ramapuram	52	0.5839	0.58	0.49	0.44	0.43	2.5	0.6	0.09
12	Kuppam	469	0.2257	0.29	0.20	0.15	0.05	4.5	0.05	0.3
13	Valapattanam	1321	0.2092	0.23	0.18	0.15	0.1	4.5	0.22	0.22
14	Anjarakandy	412	0.2497	0.25	0.20	0.18	0.18	5.1	0.1	0.3
15	Thalasseri	132	0.2639	0.28	0.27	0.24	0.23	0.46	0.30	0.1
16	Mahe	394	0.2548	0.10	0.05	0.02	0.01	6.5	0.2	0.09
17	Kuttiyadi	583	0.1686	0.26	0.03	0.02	0.01	5.2	0.31	0.08
18	Korapuzha	624	0.1101	0.22	0.20	0.15	0.13	5.5	0.06	0.22
19	Kallai	96	0.7365	0.78	0.71	0.68	0.67	0.5	0.05	0.91
20	Chaliyar	2535	0.2129	0.36	0.06	0.02	0.01	0.45	0.49	0.06
21	Kadalundi	1122	0.2011	0.09	0.06	0.05	0.03	5.2	0.19	0.09
22	Tirur	117	0.5717	0.60	0.55	0.53	0.50	1.4	0.06	0.61

Ramapuram, Kallai and Tirur river basins have high toe value (>0.44), indicating greater mass accumulation at the mouth.

3.3 Hypsometric integral and slope inflection point

Hypsometric integral value can be an indirect estimator of the erosion from the watershed system (Singh 2009). Based on the hypsometric integral the river basins are classified into five groups. Mahe, Kuttiyadi, Thalasseri, Anjarakandy, Valapattanam, Kuppam, Korapuzha, Kadalundi, Chaliyar and Chandragiri basins belong to the first group i.e. old stage (0<HI<0.3), representing a more incisive fluvial process. River basin Mogral belong to the second group, in the late mature stage (0<HI<0.4). These two stages are characterized by low runoff rate. Peruvamba river basin belong to the third group, in the mature stage (0.4<HI<0.5). Tirur, Kavvayi, Kariangode, Nileswar, Chittai, Mogral, Shiriya, Ramapuram belongs to fourth group, in late youthful stage (0.5<HI<0.6). Uppala, Manjeswar, Kallai belongs to the fifth stage i.e. young stage (0.6<HI<1). Those basins at the young stage are having greater rate of erosion. HI value is an indicator of the area which has already eroded. Korapuzha river basin, with an HI value 0.11 suggests that 89% of the upland is eroded and remaining 11% is now in the old stage. The river basins at old stage are in equilibrium and thus less prone to further erosion. In Manjeswar river basin, HI value is 0.72, suggesting that 28% of the upland is eroded and remaining 72% is now at the young stage. The position of maximum concavity (Eh) values of 22 water shed are positive, this indicates the more eroded uplands and also points to old and mature stage of development.

Considering the slope inflection points a*, all river basins except Kuttiyadi, Thalasseri, Kariangode, Peruvamba and Ramapuram have low value (<0.23). The value of another slope inflection point (h*), Chittai, Kariangode, Peruvamba, Ramapuram, Valapattanam, Thalasseri, Mahe, Kuttyadi Kadalundi and Korapuzha river basins have lower values (<0.28), Mogral , Chaliyar and Chandragiri river basins , have moderate values (0.41-0.61) and remaining basins have higher

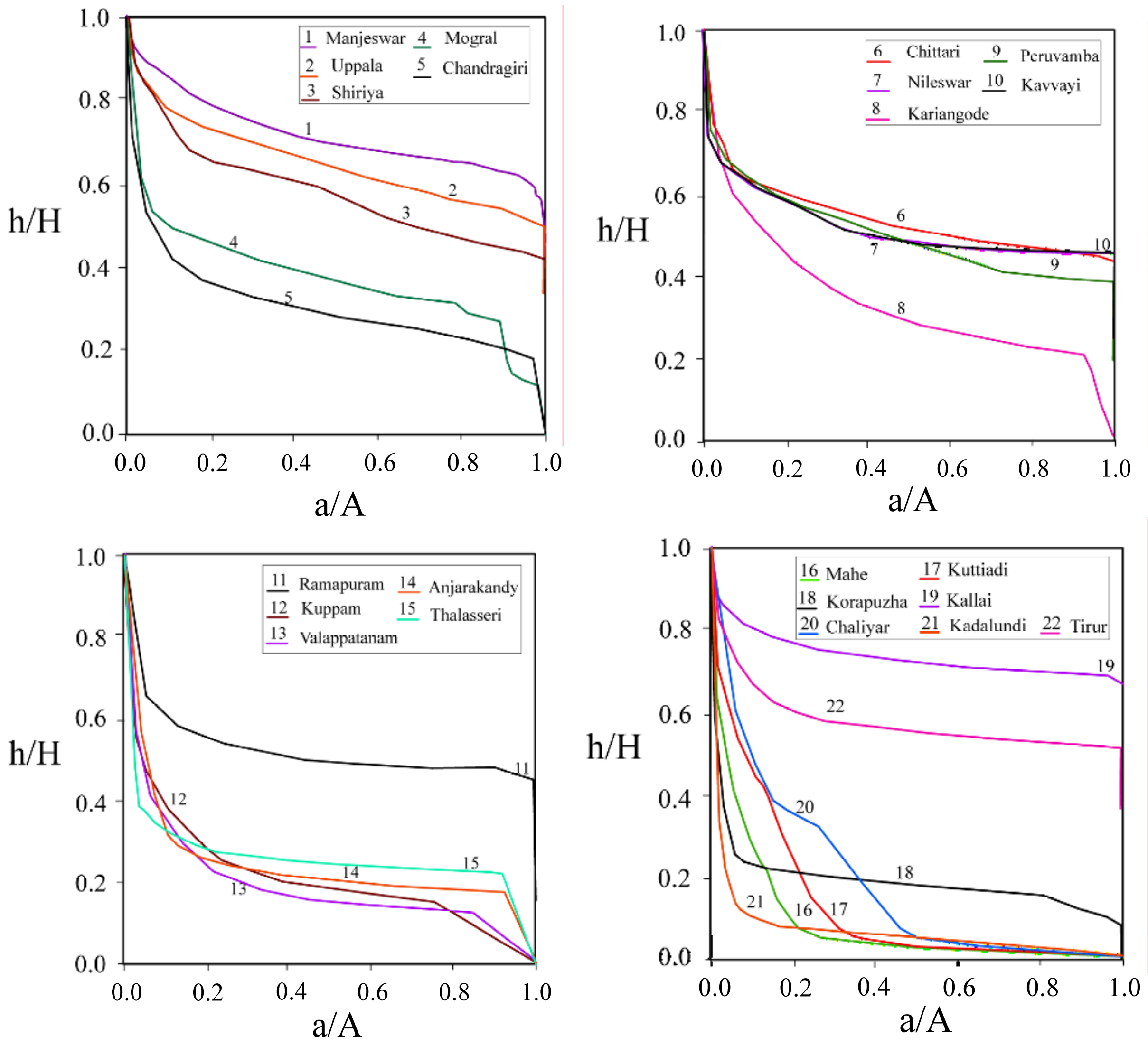

Figure 3 Hypsometric curves of 22 river basin in Northern Kerala.

values (>0.62). Lower the value of a*, greater is the extent of subdued topography approaching Davison style of peneplain and lower the value of h*, higher is the degree of peneplanation (Sinha Roy 2002).

3.4 Hypsometric integral and basin area

For small basins, the hypsometric curve is convex and the value of hypsometric curves approaches to unity indicating the greater rate of runoff and in the case of large basin, the hypsometric curve is concave and the value of the hypsometric curve approaches to zero indicating the low rate of runoff (Willgoose and Hancok 1998). For scale dependency check, statistical analysis has been carried out between area and hypsometric integral.

The river basins under study have area ranging from 52 km² to 2535 km². Regression analysis revealed that basins with area<100 km² have a positive correlation (R^2 = 0.9578) between area and HI. For those basins having area between 100-400 km², HI is negatively correlated with basin area (R^2 = 0.0625). Similar is the case for basins having area>400 km² (R^2 = 0.0825). This shows that HI and area have positive relation in small basins, whereas as the area increases, the relation becomes negative and weak (Figure 4).

4 Discussion

For the concave basins grouped under I based on their hypsometric curve, the total runoff is

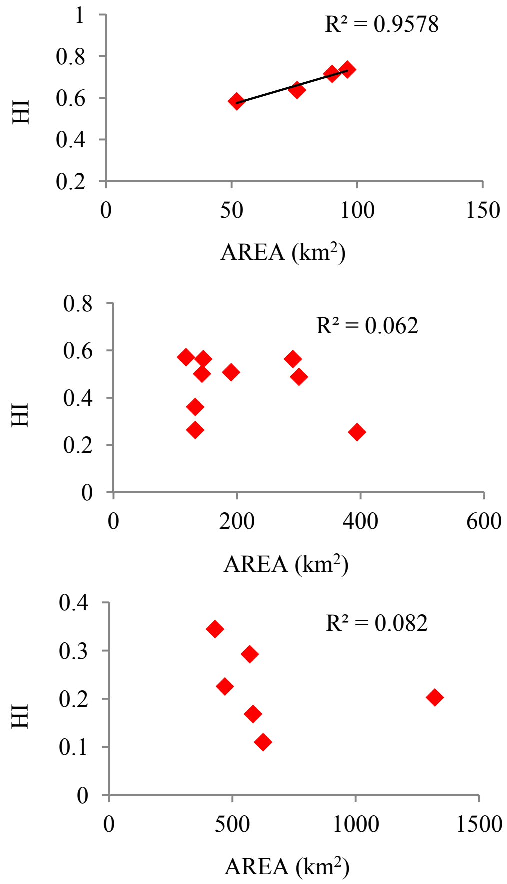

Figure 4 Statistical relations between area and hypsometric integral of river basin of 3 area classes.

mainly contributed by surface runoff, without taking into account the climatic variability (Vivoni et al. 2008). Apart from the upward concavity, the convex nature of the hypsometric curves of Anjarakandy, Thalasseri, Korapuzha, Chandragiri river basins indicates that these basins are predominant by erosion and eroded materials are accumulated in the toe region. The concave convex nature of hypsometric curves classified under group II is an indication that the material production by erosion is more than the transported amounts. Those basins with a convex hypsometric curve have greater contribution of their total runoff from subsurface processes (Vivoni et al. 2008). They are characterized by less developed streams.

Those basins with higher hypsometric integrals classified as to be in youthful stage has higher sediment yields from their watersheds. They are more prone to flash floods with high mean runoff coefficients (Jintao et al. 2015). Water flows at high velocity and soil particles travel shorter distances (Zhang et al. 2015). Uppala, Manjeswar and Kallai river basins, which are at the young stage, are in an inequilibrium state, so they are prone to more erosion. Most of the topography of these basins is high relative to their mean elevation and they witness high down cutting. Since these basins are more prone to erosion, they need to be given priority in soil and water conservation measures, which can arrest the flow of sediments and runoff. Check dam construction in these basins will help trap the sediments and also increase infiltration. The land area in these basins without any vegetative cover would encounter severe erosion. However, the results of this hypsometric analysis need to be compared with the land use of the study basins to recommend on the most suitable soil conservation measures to be adopted. Though hypsometric integral is a clear indicator of basin evolution, the significance of climate controls as well as anthropogenic interactions need not be dismissed.

Basins belonging to the first three groups based on their hypsometric integrals have lesser runoff, characterized by a smooth flood hydrograph. This indicates that these evenly dissected basins have higher storage capacity. Slope processes dominate the denudation and rate of geo-morphological changes in such old basins. They may not need mechanical or vegetative measures for soil conservation, but watershed management has to be focused on water conservation (Singh 2009).

5 Conclusion

Assessment of erosion status of a watershed is an essential prerequisite of integrated watershed management. In order to understand the type of erosive process and runoff potential hypsometric analysis has been carried out for all the 22 river basins of northern Kerala using various parameters such as Hypsometric integral (HI), maximum concavity (Eh), coordinates of slope inflection point (I) given by a* and h* and normalized height of hypsometric curve (h)). This study highlights the importance of GIS for Hypsometric analysis. Hypsometric graphs from the analysis shows erosional status including diffusive and mass accumulation process of the river basins of Northern Kerala. The statistics related to the hypsometric curves also provide useful information regarding erosion processes. The study has shown that the inequillibrium state of Uppala, Manjeswar and Kallai basins in Northern Kerala demand structural measures for soil conservation. Korapuzha, Kuttiyadi, Kadalundi, Valapattanam, Chaliyar, Kuppam, Anjarakandy, Mahe, Thalasseri, Chandragiri and Kariangode river basins have reached a stable state and hence require water conservation measures to tap their high storage potential. The study has also revealed a positive correlation between hypsometric integral and area for smaller basins (area < 100 km^2) and a negative correlation between the two for bigger basins (area > 100 km^2). Hypsometric analysis from this study can be compared with land use map to develop erosion intensity zoning maps of the area, which can aid in water resources management planning. Climatic controls on landscape evolution should also be given due consideration before planning any watershed management activities.

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