

Morphometric analysis of Andhale watershed, Taluka Mulshi, District Pune, India

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Abstract The morphometric analysis coupled with remote sensing and geographical information system techniques evaluates various valuable parameters for the watershed development plan of drought-prone Andhale watershed of Pune district, Maharashtra. The upper part of the watershed shows parallel–sub parallel and rectilinear drainage patterns indicative of structural control, whereas the lower part shows dendritic drainage pattern revealing the homogeneity in texture and lack of structural control. The elongated shape of this basin is indicated by values of form factor, circulatory ratio and elongation ratio. The mean bifurcation ratio is observed to be 4.65 indicating the watershed is less affected by structural disturbances, and drainage pattern is not much influenced by geological structures. The hypsometric integral obtained for Andhale watershed is 0.316 indicating maturity stage of the basin. The longitudinal profile depicts steep gradient at the origin but it gradually flattens out as the river erodes its base level. The high values of drainage density, stream frequency, infiltration number and drainage texture indicate that the study area is underlain by impermeable rocks responsible for high runoff. Thus, the results of this analysis would be useful in determining the effect of catchment characteristics such as size, shape, slope of the catchment on runoff vis-a-vis the scope for water harvesting.

Keywords Morphometry · Hard rock · Watershed development · Pune · India

Introduction

Watershed development and management programmes in hard rock terrain play a key role in establishing the demand and supply side equilibrium. Assessment of drainage and their relative parameters quantitatively give valuable inputs in preparing the plan for the sustainable water resource development and management. Morphometric and hypsometric analysis is widely used to assess the drainage characteristics of the river basins (Rao and Babu 1995; Pakhmode et al. 2003; Sreedevi et al. 2005; John et al. 2006; Manu and Anirudhan 2008; Magesh et al. 2011). Morphometric and hypsometric assessment of a river basin has of late been used for applied purposes. It has also been found to be a useful tool to delineate the glacial till covered overburden material, identify areas prone to flash floods, evaluate the hydrological nature of the rocks exposed within the drainage basin, understand the interrelationship between rock type, structures and drainage network and watershed prioritization, etc., (Esper 2008; Pankaj and Kumar 2009; Bali et al. 2012). The drainage characteristics of a basin reveal the prevailing climatic conditions, rock structure, relief, runoff, permeability of the rocks and tectonic framework of a basin. Rainfall, lithology and slope are the preliminary determinants of surface water functioning at the watershed scale (Mesa 2006, Machiwal and Jha 2014).

Remote sensing and geographical information system (RS-GIS) techniques are in vogue for assessing various morphometric and hypsometric parameters of the drainage basin/watershed, as they provide a user friendly environment and a powerful tool for manipulation and analysis of spatial information (Gangalakunta 2004; Godchild and Haining 2004; Grohmann et al. 2007; Korkalainen et al. 2007; Yu and Wei 2008; Hlaing et al. 2008; Javed et al. 2009; Umrikar et al. 2013).

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Groundwater is the only major water supplying element and thus has a great importance in this large basaltic area of Maharashtra. Every year, the state faces water scarcity due to its naturally prevalent physiographic conditions and erratic rainfall. It is also important to note that the state has more than 80 % dependability on groundwater, especially for drinking water purpose. Therefore, groundwater assumes a greater significance both in terms of quality and quantity and in its development and management. Keeping in view all these facts the author has taken up the computation of morphometric parameters on the basis of watershed to understand the hydrological set up of the Andhale watershed.

Study area

Andhale stream is a tributary of river Mula. The longest stretch of this stream lies in the NW part of the watershed originating at Mandvi and continues its travel through Andhale, Katarkhadak, Khamboli, Gavarwadi, Javal, Kemsewadi, Rihe, Padalgharwadi, and Matarewadi and finally meets river Mula near Ghotawade. The areal extent of Andhale watershed is 54.78 km² and has an elevation ranging from 550 to 1100 m above mean sea level. The study

area is included in the Survey of India toposheet no. 47 F/10. It lies between 18°30'00" and 18°40'00" North latitudes and between 73°30'00" and 73°42'30" East longitudes (Fig. 1). The area is well connected through metal roads and is about 40 km away from Pune city. The study area is under the process of rapid urbanization. The study area is characterized by monsoon climate (Indian Meteorology Department 1982). It receives rainfall from the SW monsoon. The average annual rainfall of the study area is 1688 mm that occurs in the months from June to September. The average temperature in the watershed is relatively lower than the temperature in the central parts of Pune city. For short duration/few days in summer the temperature raises up to 42 °C. April and May are the warmest months with monthly average maximum temperature of 39 °C.

Drainage Network

The study area is drained by river Andhale that is the fifth-order stream. From the drainage map (Fig. 2) it is evident that three distinct types of drainage patterns are present:

- (a) *Parallel to sub-parallel drainage* first- and second-order streams present in the northwest part of the

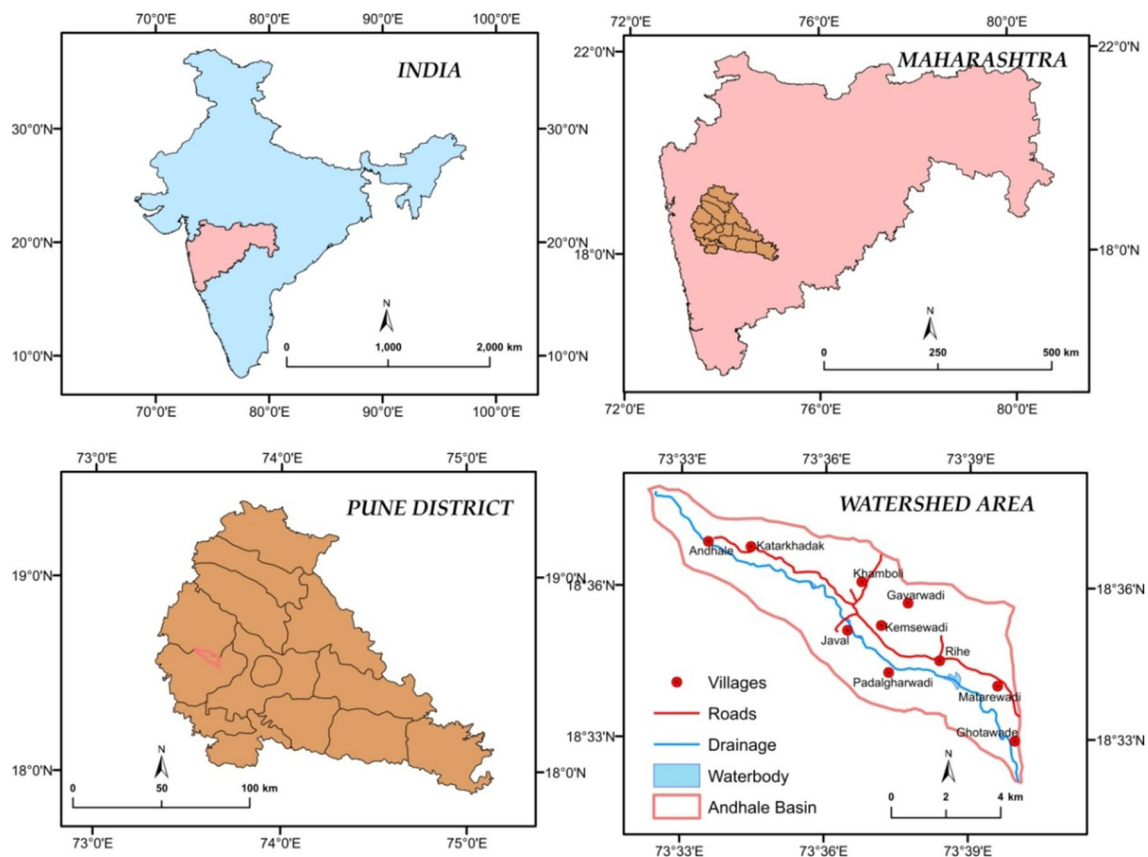


Fig. 1 Location map of the study area

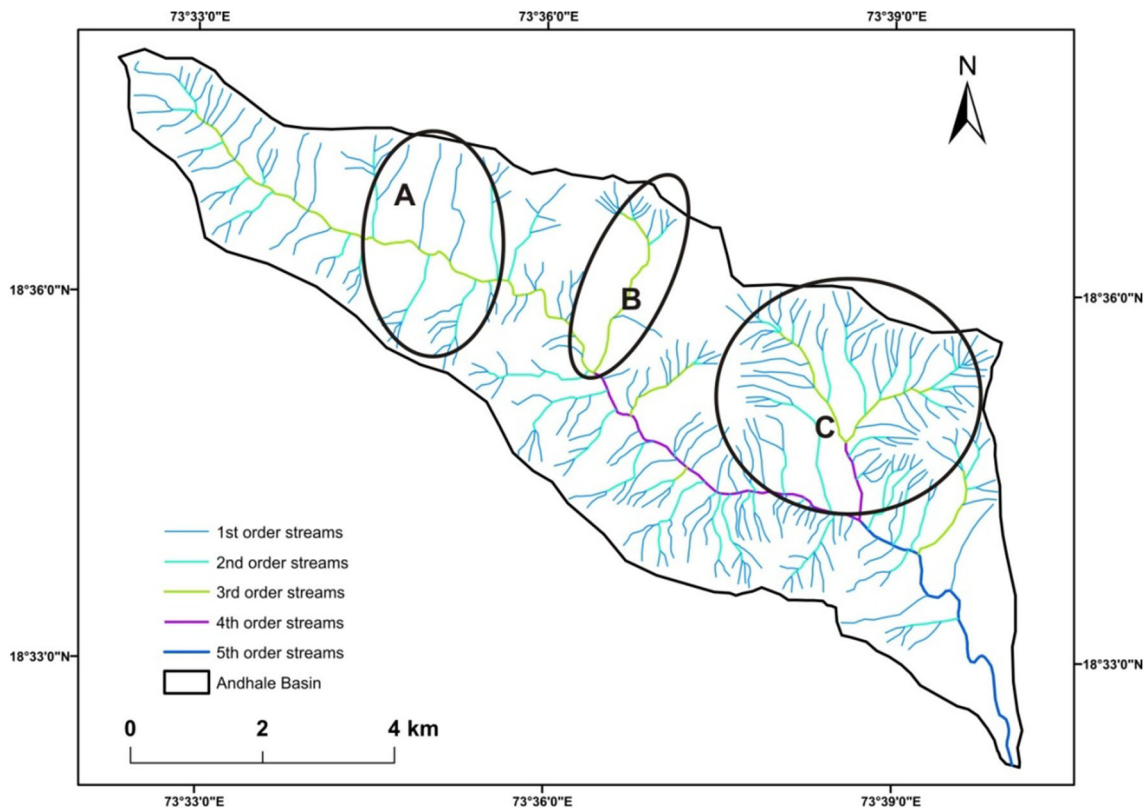


Fig. 2 Drainage map of Andhale watershed

watershed show this pattern. The streams in this area are sparsely distributed compared with lower reaches of the watershed.

- (b) *Rectilinear type* the drainage indicative of the structural control observe towards the north east part of the watershed.
- (c) *Dendritic type* indicates erosional streams. This pattern is found in the higher order streams of the Andhale watershed revealing the homogeneity in texture and lack of structural control.

Geology

The Deccan volcanic province (DVP), representing basaltic flows of Cretaceous to Eocene age, is a unique geological formation in Peninsular India. In Maharashtra, 80 % of the area is occupied by DVP, known for their marked horizontality, characteristic flat-topped hills and step-like terraces. The study area is dominantly constituted of basaltic rocks. The basalts occur in the form of horizontal flows having variation in the thickness and are seen to extend for a considerable distance. A typical spheroidal weathering pattern is very common all over the DVP. On the gentle hill slopes, they are covered by residual and/or colluvial soils.

The alluvium is seen to be developed along the banks of Andhale River. According to Subbarao and Hooper (1988) the present study area falls in the Bushe Formation of the Lonavala sub-group belonging to Deccan Basalt Group. The specific rock types exposed in the area show a variety of basalts viz. Compact Basalt, Vesicular Basalt, Amygdaloidal Basalt or composite of both Vesicular–Amygdaloidal Basalt (Fig. 3).

Methodology

The morphometric analysis of the Andhale watershed has been carried out with the help of Survey of India (SoI) toposheet on the scale of 1:50,000 and ASTER DEM data using Arc GIS software. The slope map was derived from Digital Elevation Model. The drainage was extracted from the ASTER DEM using Arc-Hydro tool. The drainage thematic layer was further superimposed on SoI toposheet for further rectification. The fish net of 1 km × 1 km was overlaid on drainage vector layer to calculate the drainage density. Using identity tool, the stream length was modified at the boundary of the grid to measure the stream length per sq km. Several traverses along stream, road cuttings and ghat sections were chosen for studying the geology of the

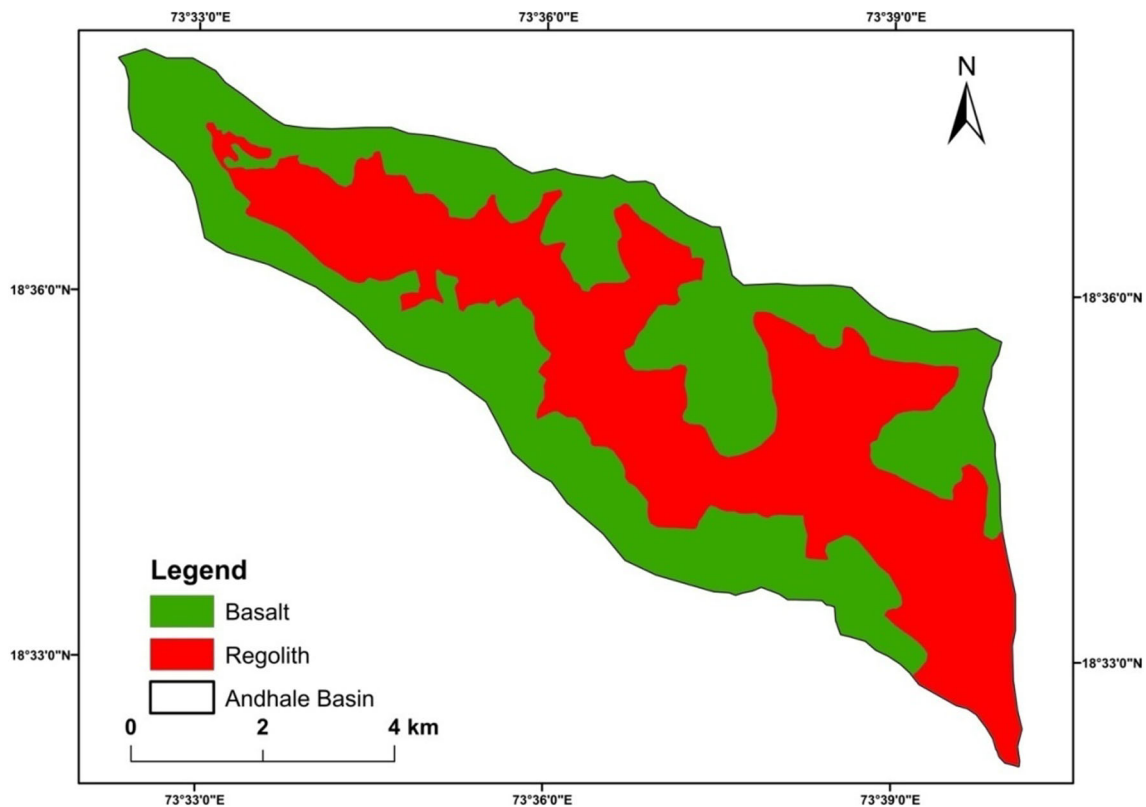


Fig. 3 Geological map of the study area

study area. The transverse and longitudinal profiles of Andhale stream were prepared using Global Mapper (version 14.0). In this study, the entire watershed has been selected for the morphometric analysis under the following heads:

Linear aspects one dimension.

Areal aspects two dimensions.

Relief aspects three dimensions.

Linear parameters

The drainage network transport water and the sediments of a basin through a single outlet, marked as the maximum order of the basin and conventionally the highest order stream available in the basin is considered as the order of that basin. The size of rivers and basins varies greatly with the order of the basin. Ordering of streams is the first stage of basin analysis.

Main stream length

Stream length is the property which reveals the characteristic size of components of drainage network and its contributing basin surfaces. In the present study the stream length obtained for the Andhale River is 19.9 km.

Basin perimeter

Basin perimeter is the outer boundary of the watershed that encloses its area. It is measured along the divide between watersheds and may be used as an indicator of watershed size and shape. The perimeter of Andhale watershed is 40.38 km (Table 1).

Length of the basin

Schumm (1956) defined the basin length as the longest dimension of the basin parallel to the principal drainage line. Basin length of the Andhale watershed is 17.41 km.

Stream order

Stream ordering refers to the determination of the hierarchical position of a stream within drainage basin. The trunk stream is the stream segment of highest order. It is found that Andhale River is the fifth-order stream (Table 1).

Mean stream length

Stream length is the property which reveals the characteristic size of component of the drainage network and its contributing basin surface. In the present study values of

Table 1 Linear parameters computed for Andhale watershed

Stream order (Su)	Number of stream (Nu)	Bifur ratio (Rb)	Total stream length (km) (Lu)	Mean stream length (km)	Cumulative mean stream length (km)	Stream length ratio (RL)	Maximum basin length (km) (Lb)	Basin perimeter (km)
1	260	4.13	132.23	0.51	0.51	1.20	17.11	40.38
2	63	9.0	38.36	0.61	1.12	4.18		
3	7	3.5	17.88	2.55	3.67	2.26		
4	2	2.0	11.53	5.76	9.43	1.82		
5	1		5.63	5.63	5.63			

Table 2 Mean stream length of streams in Andhale watershed

Watershead	1st order	2nd order	3rd order	4th order	5th order
Andhale	0.51	0.61	2.55	5.76	5.22

the mean stream length of fifth-order stream is 5.22 km (Table 2).

Sinuosity index

Sinuosity deals with the pattern of channel of a drainage basin. Sinuosity has been defined as the ratio of channel length to down valley distance. In general, its value varies from 1 to 4 or more. Rivers having a sinuosity of 1.5 are called sinuous, and those above 1.5 are called meandering. According to the present study, Andhale watershed shows the value 1.10.

Bifurcation ratio

It is the ratio of the number of streams of any order to the number of streams in the next lower order (Horton, 1932). It has been observed that the bifurcation ratio for second- and third-order stream is higher than five indicating structural control over them. It is also revealed by the drainage pattern (parallel to sub parallel) in the upper part of the watershed.

Bifurcation ratio (Rb)

$$= \frac{\text{Number of streams of given order (N}\mu\text{)}}{\text{Number of streams of next higher order (N}\mu + 1\text{)}}$$

The mean Rb of Andhale watershed is 4.65 indicating the watershed less affected by structural disturbances, and the drainage pattern is not much influenced by geological structures (Table 3).

Areal parameters

The information of hydrologic importance on fluvial morphometry is derived by the relationship of stream discharge to the area of watershed. The planimetric parameters directly affect the size of the storm hydrograph and magnitudes of peak and mean runoff in the basin area. The maximum flood discharge per unit area is inversely related to the size of the basin.

Drainage/basin area

Drainage area measures the average drainage area of streams in each order; it increases exponentially with increasing order. In the present study, basin area of Andhale is 54.78 km² (Table 4).

Constant of channel maintenance

Schumn (1956) has used the inverse of the drainage density having the dimension of length as a property termed constant of channel maintenance. The drainage basins having higher values of this parameter has low value of drainage density. The value for this parameter is 0.273.

Length of overland flow

It is defined as the length of flow path projected to the horizontal of non-channel flow from a point on the drainage divide to a point on the adjacent stream channel (Gardiner 1975). Horton (1945) expressed it as equal to

Table 3 Bifurcation ratio of Andhale watershed

Stream order	Stream number	Bifurcation ratio
1st order	260	4.13
2nd order	63	9.00
3rd order	7	3.50
4th order	2	2.00
5th order	1	

half of the reciprocal of Drainage density (Dd). The value for Andhale watershed is 0.12 (Table 4).

Elongation ratio

Schumn (1956) defined an elongation ratio (Re) as the ratio of diameter of a circle of the same area as the basin to the maximum basin length. The value of Re varies from 0 (in highly elongated shape) to unity, i.e. 1.0 (in the circular shape). Values close to 1.0 are typical of regions of very low relief, whereas those of 0.6–0.8 are usually associated with high relief and steep ground slope. The value for Andhale watershed is 0.479, indicative of elongated shape.

Drainage texture

Horton (1945) defined drainage texture as the total number of stream segments of all order in a basin per perimeter of the basin. It is important concept in geomorphology which means that the relative spacing of drainage lines. Drainage texture is on the underlying lithology, infiltration capacity and relief aspect of the terrain. Smith (1939) has classified drainage texture into five different textures: very coarse (<2), coarse (2–4), moderate (4–6), fine (6–8) and very fine (>8). The value obtained is 8.3, indicative of very fine texture.

Circularity ratio

The circularity ratio is a similar measure as elongation ratio. The value of circularity ratio varies from 0 (in line) to 1 (in a circle). The values close to one are indicative of the

more circularity obtained by the basin and vice versa. Naturally all basins have a tendency to become elongated to get the mature stage. The value obtained is 0.421.

Infiltration number

The infiltration number is defined as the product of Dd and drainage frequency (Fs). The higher the infiltration number the lower will be the infiltration and consequently the higher will be the run off. This leads to the development of higher drainage density. It gives an idea about the rate of infiltration and reveals impermeable lithology and high relief areas in the watershed. The value obtained here is 22.12.

Lemniscates factor

Chorely (1957) expressed the Lemniscates value to determine the slope of the basin. It is calculated using the formula $k = Lb^{2/4} \times A$, where Lb is the basin length (km) and A is the area of the basin (km²). The lemniscate ratio is 5.53.

Form factor

It is the ratio between the basin area and the square of the basin length. Narrow and deep channels possess low form ratio, whereas shallow, wide channels the high form ratio. The smaller the value of form factor, the more elongated the basin. This ratio obtained for Andhale watershed is 0.19.

Stream frequency

It is the number of streams per unit area and is obtained by dividing total number of streams by total drainage area (Strahler 1968). The stream frequency values for fourth and fifth streams are low as compared to first-order streams (Table 5).

Drainage density

It is the sum of the length of the streams divided by the area of the basin, i.e. the total length of the stream channel per unit area (Gregory and Walling 1968).

Table 4 Areal parameters calculated for Andhale watershed

Basin area (km ²) (A)	Constant of channel maintenance	Length of overland flow	Infiltration number (If)	Drainage texture (Dt)	Form factor (Rf)	Elongation ratio (Re)	Circularity ratio (Rc)	Lemniscates factor	Fitness ratio
54.78	0.273	0.12	22.12	8.3	0.19	0.479	0.421	5.53	0.492

Table 5 Stream length and frequency values obtained for Andhale watershed

Stream order	Stream length (km)	Stream length ratio	Stream number	Stream frequency	Mean stream length (km)
1	132.6	3.45	260	4.75	0.51
2	38.43	2.15	63	1.15	0.61
3	17.85	1.03	7	0.123	2.55
4	17.28	3.31	3	0.054	5.76
5	5.22		1	0.018	5.22

Table 6 Drainage density values obtained for Andhale watershed

Stream order	1	2	3	4	5
Drainage density	2.42	0.70	0.325	0.315	0.095

Strahler (1956, 1964) stated that drainage density depends upon the geologic and climatic factors and increases as the individual drainage unit proportionately decreases. The drainage density affects runoff pattern in that a high drainage density drains runoff water rapidly, decreases the lag-time and increases the peak of hydrograph. Drainage density controls the speed of runoff following a spell of heavy rains. The greater the drainage density, the more the runoff (Kale and Gupta 2001). The drainage density decreases with increasing stream orders (Table 6; Fig. 4) in Andhale watershed.

Compactness coefficient

According to Gravelius (1914) compactness coefficient of a watershed is the ratio of perimeter of watershed to circumference of circular area, which equals the area of the watershed. The compactness coefficient is independent of the size of watershed and dependent only on the slope. The compactness coefficient of Andhale watershed is 1.356.

Drainage intensity

Faniran (1968) defines the drainage intensity as the ratio of the stream frequency to the drainage density. $D_i = F_s/D_d$ stream frequency (F_s)/drainage density (D_d). With the low values of drainage density, stream frequency and drainage intensity, surface runoff is not quickly removed from the watershed, making it highly susceptible to flooding, gully

erosion and landslides. The intensity value for Andhale watershed is 1.663.

Fitness ratio

It is the ratio of main channel length to the perimeter of the watershed which is a measure of topographic fitness. The fitness ratio of Andhale watershed is 0.492.

Relief parameters

Areal features have been considered as the two-dimensional aspect in a plane. The third dimension introduces the concept of relief in morphometry. By measuring the vertical fall from the head of each stream segment to the point where it joins the higher order stream and dividing the total by the number of streams of that order, it is possible to obtain the average vertical fall. The relief aspects cover the parameters viz. basin relief, channel gradient, relief ratio and hypsometric integral (Table 7).

Absolute relief indicates the difference in elevation between a highest location and sea level. The study area has 1256 m of absolute relief.

Dissection index

This parameter implies the degree of dissection or vertical erosion and expounds the stages of terrain or landscape development in any given physiographic region or watershed. In the present watershed the dissection index value obtained is 0.56.

Channel gradient

Channel gradient is the total drop in elevation from the source to the mouth of the trunk channels in each drainage basin. In the present study, Andhale stream has a 25 m/km gradient. The alluvial basins show low channel gradient, whereas the basins draining hard rock terrain show high channel gradient.

Relief ratio

Relief ratio is defined as the ratio between the total relief of a basin, i.e. elevation difference of lowest and highest points of a basin, and the longest dimension of the basin parallel to the principal drainage line (Schumn 1956).

$$\text{Relief ratio} = \frac{\text{Maximum basin relief}}{\text{Maximum basin length}}$$

The high values of R_h indicate steep slope and high relief and vice versa. Relief controls the rate of conversion of potential to kinetic energy of water draining through the

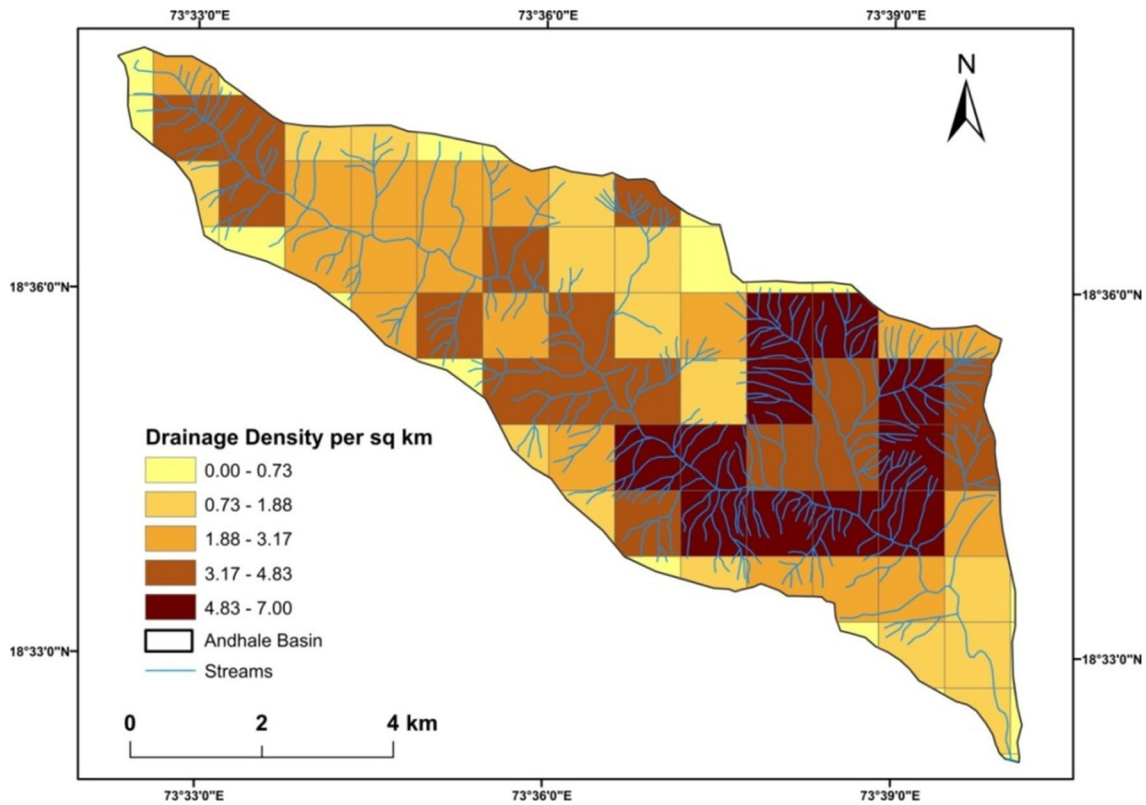


Fig. 4 Map of drainage density per sq km

Table 7 Relief parameters computed for Andhale watershed

Hypsometric integral	Basin relief (H) (m)	Relief ratio (Rr)	Absolute relief (m) (Ra)	Dissection index (Di)	Channel gradient (Cg) (m/km)	Ruggedness number
0.316	690	40.33	1256	0.56	25	2518.5

basin. Run-off is generally faster in steeper basins, producing more peaked basin discharge and greater erosive power. The relief ratio obtained is 40.33.

Disposition of contours within watershed

The distance between consecutive contours gives an idea about the gradient of drainage basin. The disposition of contours thus helps in understanding the nature of land surface. Closely spaced contours have been observed at the boundary of the watershed, and the distance between two consecutive contours increases towards the lower part of the watershed (Fig. 5).

Land slope of the watershed

It controls the rainfall distribution and movement, land utilization and watershed behavior. The degree of slope affects the velocity of overland flow and runoff, infiltration rate and thus soil transportation. The speed and extent of

runoff depend on slope of the land. Where greater slopes are observed there the velocity of water is high. The slope map of Andhale watershed has been prepared with natural slope breaks (Fig. 6). It is observed that the 17.14 km² area lies between 0° and 7.13° slope category (Table 8).

Basin relief

Basin relief is the elevation difference between the highest and lowest points of the valley floor. The basin relief is 690 m above mean sea level.

Ruggedness number

Strahler (1968) describes ruggedness number (HD) as the product of basin relief and drainage density and it usually combines slope steepness with its length. Extremely high values of ruggedness number occur when slopes of the basin are not only steeper but long as well. For the present basin, the ruggedness number obtained is 2518.5.

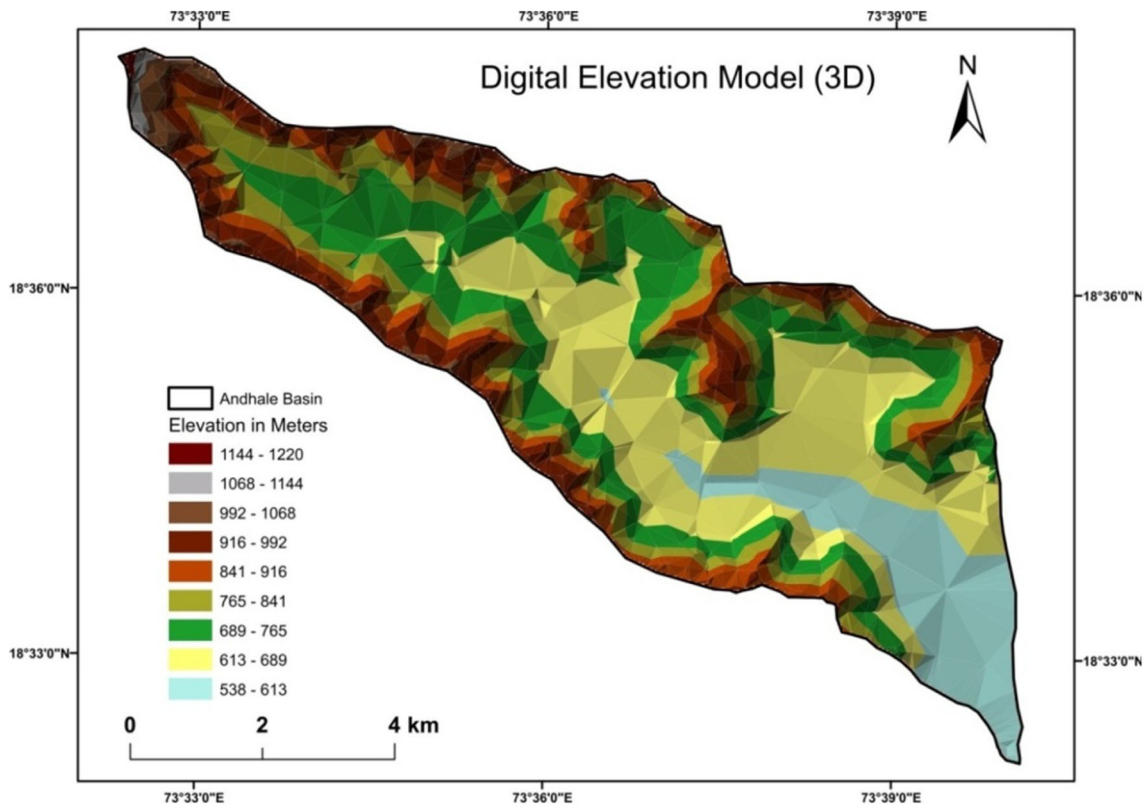


Fig. 5 Digital elevation model of Andhale watershed

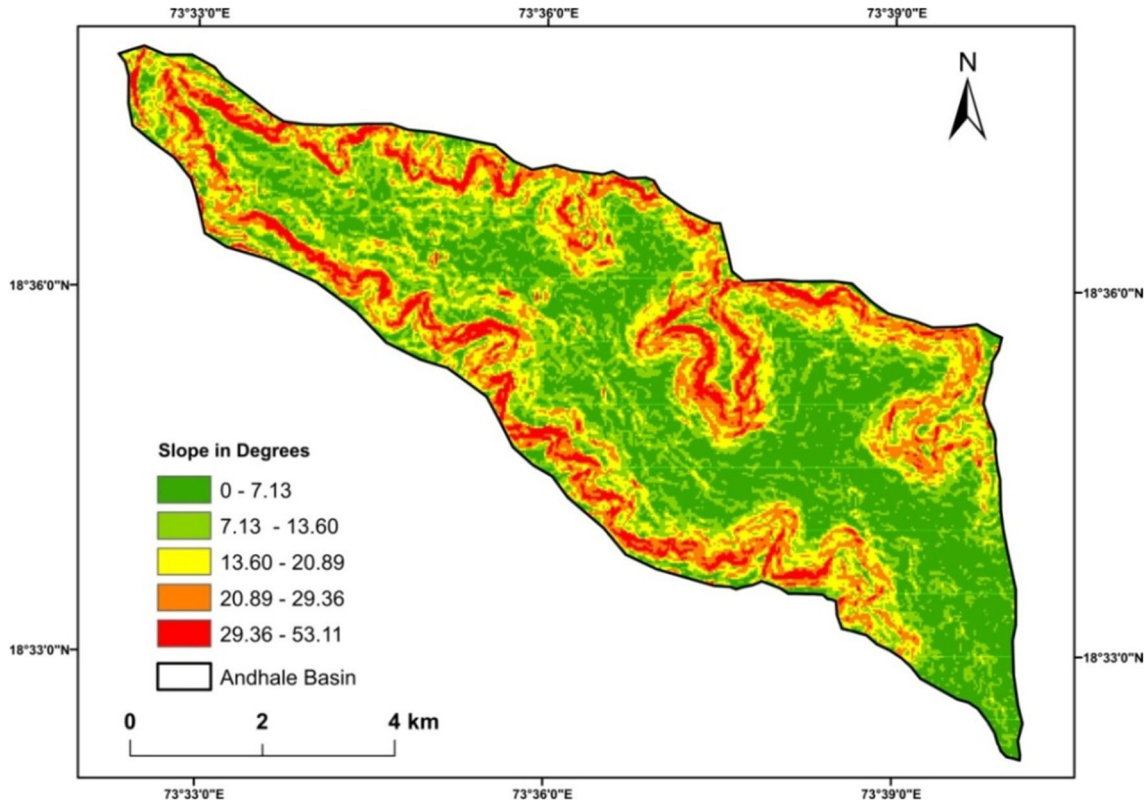


Fig. 6 Slope map of the study area

Table 8 Slope classes with corresponding area in sq km

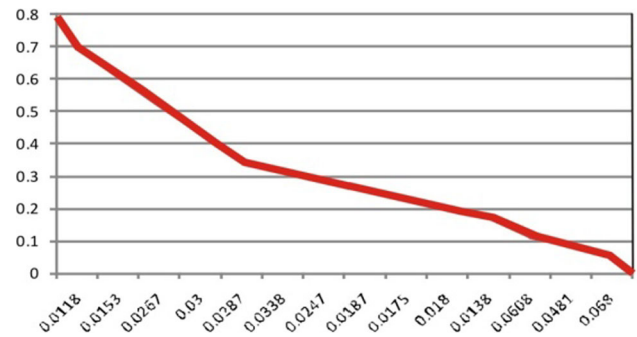
Slope classes	Area (km ²)
0–7.13	17.14
7.13–13.60	14.04
13.60–20.89	10.93
20.89–29.36	8.7
29.36–53.11	3.97

Hypsometric curve

The hypsometric analysis determines the relationship of the horizontal cross-section and the drainage basin area to elongation (Chow 1964). Hypsometric integral is the ratio of the area below the hypsometric curve to the total area. To calculate the hypsometric integral, the data of relative height and relative area (Table 9) were obtained from contour thematic map generated in Arc GIS. The value of relative area (a/A) always varies from 1.0 at the lowest point ($h/H = 0.0$) to 0.0 at the highest point in the basin ($h/H = 1.0$). Strahler (1952, 1964) identified three types of landforms, namely young, mature and monadnock on the basis of hypsometric curve. The hypsometric integral obtained is 0.316, indicating the maturity stage of the basin (Fig. 7).

Longitudinal profile

The longitudinal profile of a stream channel may be shown graphically by a plot of altitude (ordinate) as function of horizontal distance in (abscissa). The construction of longitudinal profile provides an interpretation of the surface

**Fig. 7** Hypsometric curve of the study area

history as they are the erosional curves and the river course flows from the source to mouth at any stage of evolution. Longitudinal profile for entire Andhale stream is constructed and shown in Fig. 8. The profile shows, in the upper stage of a river's course, the river's gradient is steep, but it gradually flattens out as the river erodes towards its base level.

Transverse profiles

River transverse profiles show a cross-section of a river's channel and valley at certain position in the river's course. The cross profile of a river changes as it moves from the upper to lower course as a result of changes in the river's energy and the processes that the river carries out. In the upper course, the valley and channel are narrow and deep as a result of the large amount of vertical erosion and little lateral erosion. The sides of a river's valley in the upper course are very steep earning these valleys the nickname "V-Shaped Valley". In the middle course, the valley

Table 9 Relative area and relative height values computed for Andhale watershed

Contour interval	Area	Relative height	Relative area	a/A	h/H
560–580	1.998	20	0	–	0.0289
580–600	2.646	40	0.647	0.0118	0.0579
600–620	2.842	60	0.843	0.0153	0.0869
620–640	3.465	80	1.466	0.0267	0.1159
640–680	3.643	120	1.644	0.0300	0.1739
680–700	3.572	140	1.573	0.0287	0.2028
700–720	3.852	160	1.854	0.0338	0.2318
720–740	3.356	180	1.357	0.0247	0.2608
740–760	3.024	200	1.025	0.0187	0.2898
760–780	2.959	220	0.960	0.0175	0.3188
780–800	2.986	240	0.987	0.0180	0.3478
800–860	2.755	300	0.756	0.0138	0.4347
860–920	5.332	360	3.333	0.0608	0.5217
920–980	4.635	420	2.637	0.0481	0.6086
>980	5.725	480	3.726	0.0680	0.6956

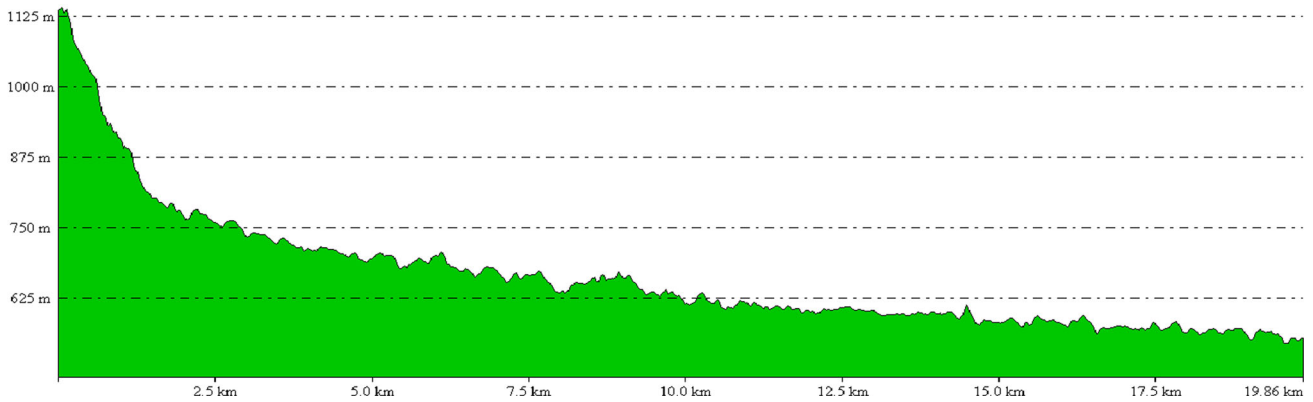


Fig. 8 Longitudinal profile of Andhale River

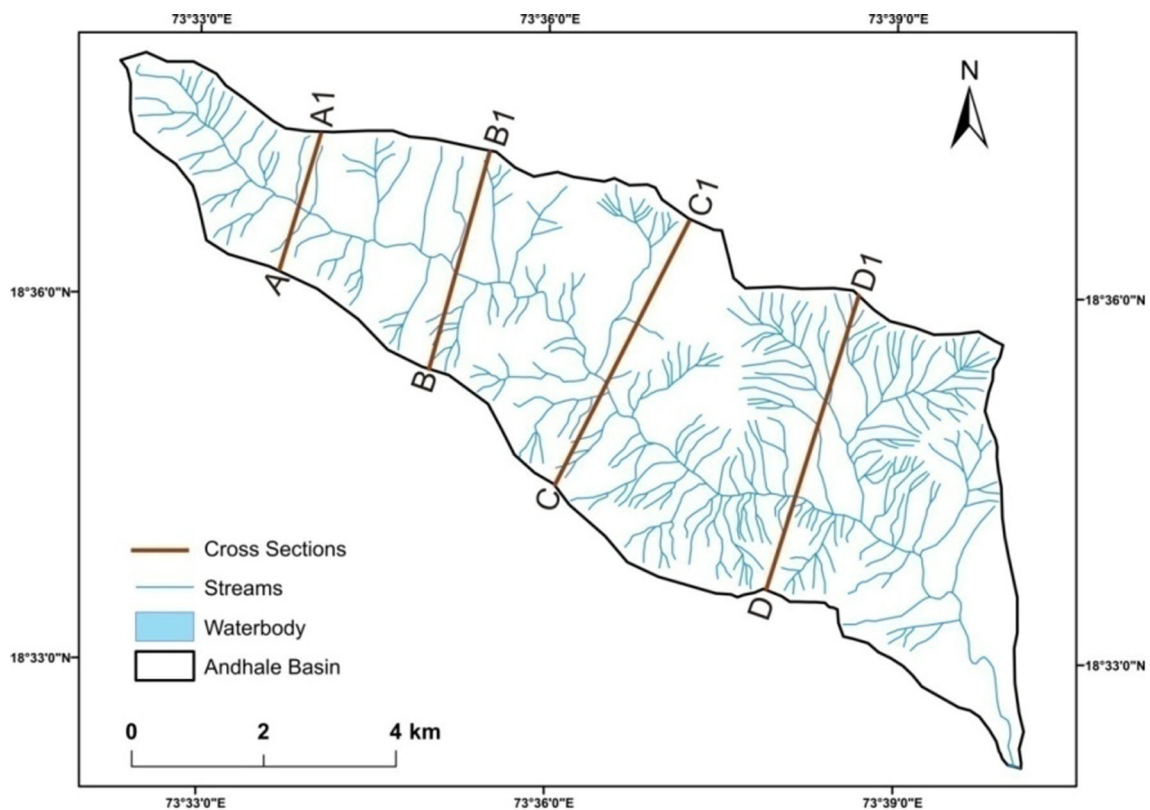


Fig. 9 Location of the transverse profiles of the study area

increases in width due to the increase in lateral erosion, but its depth does not change significantly because vertical erosion has slowed down.

The land to either side of the channel in the valley is the river’s floodplain. In the lower course the valley is very wide and the floodplain has increased greatly in size. Four transverse profiles have been prepared (Figs. 9, 10) to understand the nature of valley and width of the valley from origin to mouth of Andhale River. It has been

observed that in the middle course, the valley increases in width and in the lower course the valley is very wide.

Discussion and conclusion

Morphometric analysis of a drainage basin is a quantitative way of describing the characteristics of the surface form of a drainage pattern and provides important information

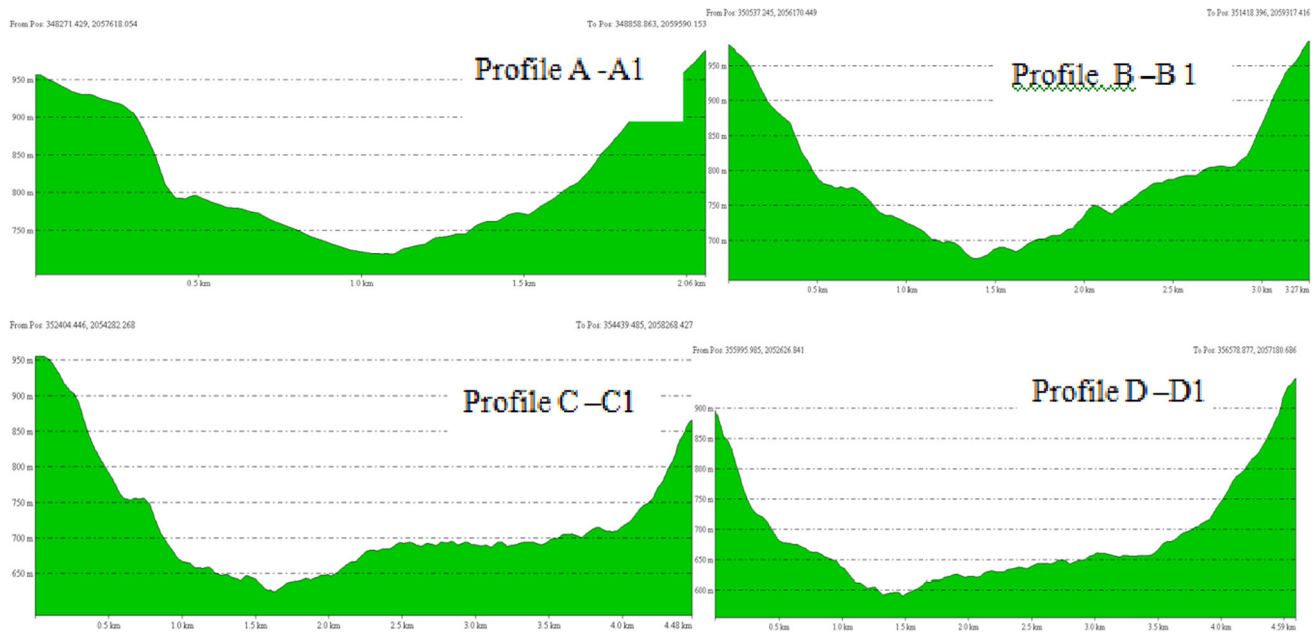


Fig. 10 Transverse section profile across the Andhale watershed

about the region's topography, geological structures, runoff and hydrogeological properties of underlying rock. It also plays an important role in hydrological investigations of a river basin/watershed. In present study, based on the stream order, Andhale River has been designated as a fifth-order basin. The drainage density values reveal that the nature of sub-surface strata is impermeable where the drainage density values are greater than five. Such type of drainage density values constitutes a fine drainage and shows good potential for the construction of surface water harvesting structures. The elongated shape of the basin is indicated by values obtained for form factor, circulatory ratio and elongation ratio. The mean bifurcation ratio is observed to be 4.65, indicating that the watershed is less affected by structural disturbances and that the drainage pattern is not much influenced by geological structures. The hypsometric integral for Andhale watershed is 0.316, indicating maturity stage of the basin. The longitudinal profile depicts steep gradient at the origin, but it gradually flattens out as the river erodes towards its base level. The high values of drainage density, stream frequency, infiltration number and drainage texture indicate that the study area is underlain by impermeable rocks responsible for high runoff. Morphometric analysis of Andhale Watershed of Pune District of Maharashtra reveals much valuable information to set up watershed developmental plan for this area. This region is moderately populated and draught prone. For mitigating the problem a proper ridge to valley watershed developmental plan is essential. In the present scenario where water resources are becoming scarce, this exercise of assigning various attributes to the drainage basin plays a

significant role in watershed development as well as locating sites for water harvesting structures.

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