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Morphometric Analysis of Three Sub-Catchments of Udaipur District

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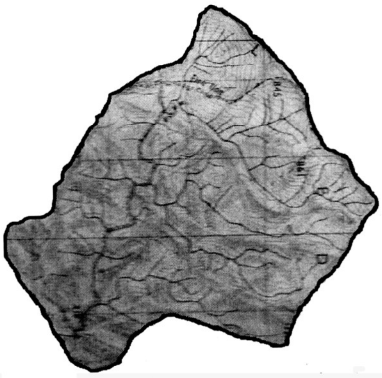
Abstract

The development of morphometric techniques is needed for the quantitative description of the geometry of the drainage basins and its network which helps in characterizing the drainage network, comparing the characteristic of several drainage networks and examining the effect of variables such as lithology, rock structure, rainfall. The sub-catchment of Sukli river is situated between 24°34′to 24°40′N latitude and 73°20′ to 73°60′E longitude, sub-catchment of Sei-river is 24°35′ to 24°40′ N latitude and 73° 35′ to 73°40′ E longitude and sub-catchment of Sabarmati river is 24°37′to 24°40′ N latitude and 73°11′ to 73°14′ E longitude. The elevation of the catchments ranges from 409 m to 861 m. The method of Horton and Strahler was used to rank the stream segments using GT sheet. The relevant numbers of the streams were entered into the attribute table and all other analyses based on the mathematical formulas. The catchment area of three sub-watersheds are 2642.5, 1027.5 and 1440 ha of sub-catchment of Sukli, Sei and Sabarmati rivers, respectively. The results indicated that the form factor 0.87, 0.41 and 0.78, circulatory ratio 0.55, 0.76 and 0.52, elongation ratio 0.82, 0.65 and 0.88, shape factor 1.15, 399 and 1.28, number of segments was 233, 104 and 103 of all order those varied from 1 to 5, 1 to 4 and 1 to 4 of Sukli, Sei and Sabarmati sub-catchments respectively. The stream frequency and drainage density of Sukli, Sei and Sabarmati sub-catchments were 0.088, 0.10 and 0.08 (per ha) and 4.3, 4.5 and 4.15 (km/km^2) respectively. Bifurcation ratios were 3.7, 4.35 and 4.47 and lengths of overland flows were 116.3, 111.3 and 120.5 m of Sukli, Sei and Sabarmati sub-catchments respectively. The results of this analysis would be useful in determining the effect of catchment characteristics such as size, shape, slope of the catchment & distribution of stream net work within the catchment.
Key words : Aerial aspects, Drainage network, Linear aspects, Morphology, Relief aspects.

The method of quantitative analysis of watersheds was developed by Horton (1) and was further modified by Strahler (2). Sufficient work on the quantitative analysis of the geomorphological characteristics of watersheds has been done in India and abroad (3). Relationships between and among different geomorphological and hydrological variables have also been established (4—6). From a considerable number of studies conducted by different scientists and engineers on the development of sediment yield regression models (linear and nonlinear), it was found that a few researchers attempted establishing relationships between dependent variables (sediment yield) and independent variables (an adequate number of geomorphological parameters). Some established sediment yield models, which were functions of runoff and a few selected geomorphological parameters. Such relations suffer from the lacunae that many of the considered causative geomorphological parameters are correlated (7), which is against the principle of regression analysis, which stipulates independentness of the causative variables. Hydrologists have derived a large number of geomorphological parameters to describe various features of a watershed, which are often interrelated. If these are to be treated as causative parameters for expressing sediment yield through a regression approach then to satisfy the requirement of standard regression analysis one ultimately ends up with a few such parameters, which are truly unrelated. Since some of the discarded parameters may have more influence on the dependent variables, the usual statistical procedure is to adopt either maximum R^2 improvement criteria through simultaneous acceptance of one of the discarded parameters in lieu of the corresponding related parameters considered earlier. This will require



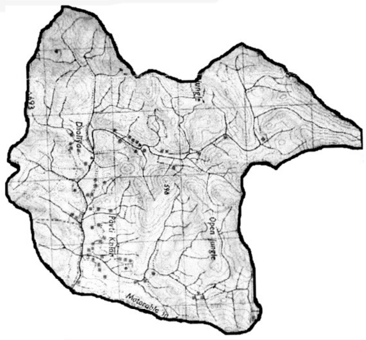


Figure 1. Location map of the Sukli river sub-catchment. **Figure 2.** Location map of the Sei river sub-catchment. **Figure 3.** Location map of the Sabarmati river sub-catchment.

listing all the possible geomorphological parameters and identifying which of them are related and which of them are unrelated. Perhaps a more elegant another procedure would be to adopt the method of Principal Component Analysis in which the set of related parameters are converted to groups of unrelated parameters which are called principal components. With respect to geomorphological parameters therefore, the principal components can be considered as transformed but unrelated geomorphological parameters. The main focus of present study was to develop multiple regression models, for the dependent variable, sediment yield, as functions of principal components. Another feature of the study was to develop the above relations for certain specific ranges of rainfall and runoff (for sediment yield prediction). Thus, in the developed multiple regressions using scores of principal components as independent variables, runoff does not appear as separate independent variables. The empirical quantitative description of river network geometry has provided hydrologists with fundamental physical basis to analyze the mode of responses of the watershed to rainfall input at large scale. The system of landforms evolving from same geologic process and materials possess a high degree of geometrical similarity. Therefore, the characteristics of the watershed having same geometry can be compared.

Methods

The study area comprising three sub-catchments located in two different locations. The first location belongs to the Sirohi district (south-western part of Rajasthan). Sub-catchment of Sabarmati river is comes under this district, and the second location belongs to Udaipur district (south-eastern part of Rajasthan), the remaining two sub-catchments are comes under Udaipur district. The selected sub-catchments under study is situated between 24° 34′ to 24° 40′ N latitude and 73°20′ to 73°60′ E longitude for the sub-catchment of Sukli river, 24°35′ to 24°40′

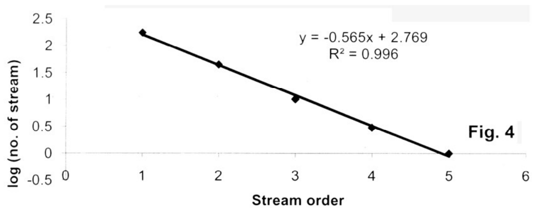


Figure 4. Regression of logarithm of number of streams and stream order.

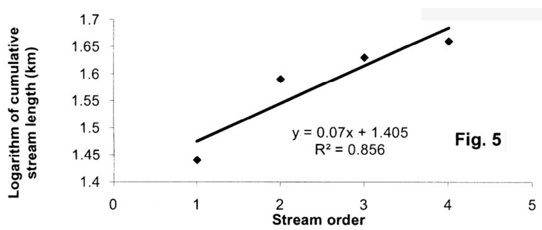


Figure 5. Regression of logarithm of cumulative stream length and stream order.

N latitude and 73°35′ to 73°40′ E longitude for sub-catchment of Sei-river and 24°37′ to 24°40′ N latitude and 73°11′ to 73°14′ E longitude for sub-catchment of Sabarmati river (Figs 1 to 3 respectively). The climatic of the selected sub-catchments are semi arid type. The average annual rainfall ranges from 625 to 650 mm for the study area. About 80% of annual rainfall is received from June to September during the monsoon period.

Geomorphological Characteristics of a Watershed

The hydrological response of watershed is much dependent on the rainfall characteristics and also on drainage pattern of the watershed area. The rainfall characteristics can be measured by any nearby rain gauge station whereas the drainage pattern analysis i.e. morphological characteristics can be evaluated through the drainage map of the area. The drainage map of the selected sub-catchments area was collected from the SWE Department of CTAE, Udaipur.

The quantitative land-form analysis is undertaken for the developed watershed in which flowing water and associated mass gravity movements acting over long periods of time are responsible for development of surface geometry. The watershed is characterized by geomorphological analysis. Geomorphological analysis is the systematic description of watershed's geometry and its stream channel system to measure the linear aspects of drainage network, aerial aspects of drainage basin and relief aspects of channel network and contributing ground slope, too. The first two categories of measurement treat the projected property of watershed on a horizontal plane, termed as 'planimetric', whereas the third category of measurement counts the vertical inequalities of forms of drainage basin. All these aspects are described as under.

Properties Based on Linear Aspect

It is also referred as linear aspect of channel system. Morphological characteristics based on linear aspects considered in the study area were stream order, bifurcation ratio, stream length, stream length ratio and length of overland flow.

Stream Orders. The first step in a drainage basin is designation of stream order, following a system introduced in the United States by Horton (1) and slightly modified by Strahler (8). The stream order represents the degree of stream branching with a watershed. Each length of stream is designated by its order. The smallest fingertip tributaries having no branches are designated as first order streams. When two first order streams are joined in one, then resulting stream segment is termed as second order stream. A third order stream is formed tributary formed by two or more second order streams. Generally an n^{th} order stream is formed by two or more stream of order $(n-1)^{th}$ and streams of lower order. One point should always be kept in view that, when a low order stream segment joins to high order stream segment, then order of stream segment does not change, but high order of stream is remained as it is. The highest order stream is known as trunk or principal stream through which all discharge of the watershed passes through the outlet. The maximum order segment carries the

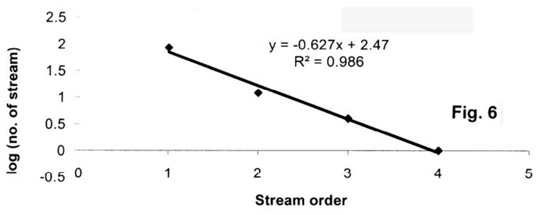


Figure 6. Regression of logarithm of number of streams and stream order.

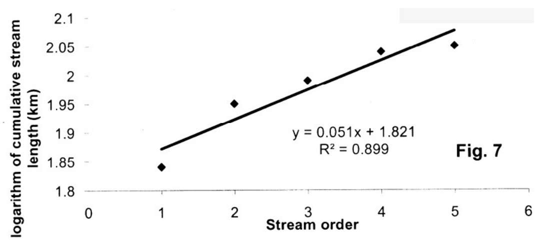


Figure 7. Regression of logarithm of cumulative stream length and stream order.

sediment and flow of water at the outlet of the watershed.

Bifurcation Ratio (R_b). The number of each segment is counted for each order say u and defined as N_u. The bifurcation ratio is defined as the ratio of number of stream of any order to the number of stream of next higher order, expressed as :

$$R_b = \frac{N_u}{N_{u+1}}$$

Where, N_u = number of stream segments of order u ; and N_{u+1} = number of streams of next higher order u + 1.

Stream Lengths (L_u). The extent of stream length in a watershed reveals the characteristics size of different components of drainage system and its contributing surface area. The stream length is determined by two ways : In which one involves the measurement of stream length by using a device called as Chart meter (map measure). The dial of map measures shows the cumulative length of the drainage lines of all orders. For this, the watershed map showing the drainage system is essential. The second method involves computation by using the equation. To find out the mean length of the channel L_u of order u, the total length is divided by the number of segments, N_u of that order, thus

$$\overline{L_u} = \frac{\Sigma_{i=1}^{N} L_u}{N_u}$$

Where, $\overline{L_u}$ = mean length of channel of order u ; L_u =stream length increase with the increase of order number ; and N_u = total number of stream segments of order u.

Stream Length Ratio (R_L). Horton (1) defined the stream length ratio, R_L, as the ratio of mean length, $\overline{L}_u$ of segments of order u to mean length of segments of the immediate lower order, $\overline{L}_{u-1}$. It is expressed as :

$$R_L = \frac{\overline{L}_u}{\overline{L}_{u-1}}$$

Length of Overland Flow (L_g). Horton (1) defined the length of overland flow as the length of flow path, projected on the horizontal plan of non channel flow, from a point on drainage divide to the adjacent stream channel. The length of overland flow is calculated as one-half of the reciprocal of the drainage density i.e.

$$L_g = \frac{1}{2\,D_d}$$

Where, L_g = length of overland flow (m) ; and D_d = drainage density per km.

Properties Based on Aerial Aspects

Many characteristics based on area measurement of the watershed are basin area, basin shape, basin shape factor, and drainage density, constant of channel maintenance and stream frequency.

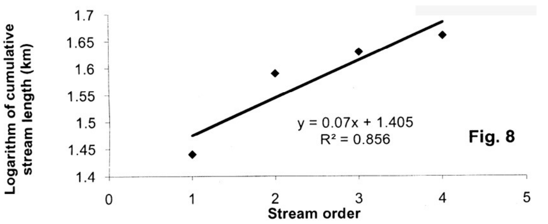


Figure 8. Regression of logarithm of cumulative stream length and stream order.

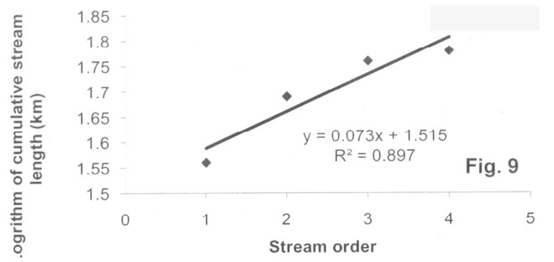


Figure 9. Regression of logarithm of cumulative stream length and stream order.

Area of the Watershed (A). Area of the watershed has been measured with the help of a planimeter. The areas are expressed in ha.

Basin Shape. The basin shape is the shape of projected surface on the horizontal plane of basin map. The basin shape has a significant effect on stream discharge characteristics. The quantitative expression of basin shape can be characterized by : (a) form factor ; (b) circulatory ratio and (c) elongation ratio.

Form factor (R_f). Horton (9) explained the basin shape through a term called as form factor, which is defined as the ratio of basin area (A) to the square of the basin length (L_b), given as :

$$R_f = \frac{A}{L^2_b}$$

Circulatory Ratio (R_c). Circulatory ratio, R_c is defined as the ratio of circumference of a circle of same area as the watershed to the watershed perimeter (10) or ratio of basin area (A) to the area of circle (A_c) having equal perimeter as the perimeter of drainage basin.

$$R_c = \frac{A}{A_c}$$

Elongation Ratio (L_l). Elongation ratio, R_l is defined (11) as the ratio of diameter of a circle (D_c) with the same area as the watershed to the maximum length of the watershed (L_{bm}). This parameter is used to assess whether the shape of the basin approaches of a circle.

$$R_l = \frac{D_c}{L_{bm}}$$

Basin Shape Factor or Compactness Factor (S_b). Basin shape factor has the significant influence on the runoff and sediment transport phenomenon. Horton (9) defined the basin shape factor (S_b) as the ratio between the square of the maximum length of watershed and the area of the watershed (A).

$$S_b = \frac{L^2_{bm}}{A}$$

Drainage Density (D_d). Horton (9) drainage density is defined as the ratio of total length of all streams of all orders (i.e. cumulative length of stream segments of all order) within a watershed to the total area of the watershed (A) i.e.

$$D_d = \frac{\Sigma_{i=1}^{K} \Sigma_{i=1}^{N} L_u}{A_u}$$

Where, D_d = drainage density ; L_u = length of stream segment of order u ; A = total area of watershed ; K = principal order or highest stream order ; and N = total number of streams.

A high value of drainage density indicates a relatively high density of streams and thus a rapid stream response.

Drainage Factor, (D_f). Drainage factor, D_f is the ratio of stream frequency to the square of drainage density. It is dimensionless term and is used in this analysis.

$$D_f = \frac{F}{D^2_d}$$

Constant of Channel Maintenance (C). Schumm (10) constant of channel maintenance defined as the inverse of drainage density, i.e.

$$C = \frac{1}{D_d} = \frac{A}{\Sigma_{i=1}^{K} \Sigma_{i=1}^{N} L_u}$$

It indicates that magnitude of surface area of watershed needed to sustain unit length of stream segment.

Stream Frequency or Stream Density (F). Horton (9) introduced this term to study the basin morphology, which is the number of stream-segments per unit basin area, given as :

$$F = \frac{\Sigma_{i=1}^{k} N_u}{A_k}$$

Where, F=stream frequency ; N_u = number of stream segments of order u ; A_k basin area oif principal order (k) ; K = principal of highest order stream.

Properties Based on the Relief Aspects. Parameters involving elevation difference are important because these parameters define the potential energy or erosion potential of a watershed. These parameters are evaluated with the help of contour maps of the watersheds. The relief characteristics considered for the study are maximum watershed relief, relief ratio, relative relief, ruggedness number and geometric number.

Maximum Watershed Relief (H). Maximum watershed relief H is the elevation difference between watershed outlet and the highest point located on the perimeter of basin. Maximum watershed relief is obtained from the available contour maps of the watersheds. It is expressed in meters.

Relief Ratio R_r. Schumm (11) defined the relief ratio R_r, as the maximum watershed relief divided by the maximum watershed length.

$$R_r = \frac{H}{L_b}$$

Where, R_r = relief ratio ; H=maximum watershed relief (m) ; and L_b = maximum watershed length (m).

Relative Relief (R_R). Melton (12) defined relative relief R_R, as the ratio of the maximum watershed relief to the basin perimeter length. It is computed using following equation.

$$R_R = \frac{H}{L_p} \times 100$$

Where, R_R relative relief (%) ; H = maximum basin relief (m) ; and L_p = basin perimeter length (m).

Ruggedness Number (N_R). The product of relief (H) and drainage density (D_d) is called ruggedness number. i.e. Ruggedness number = $H.D_d$.

Geometric Number. The geometric number is thus a ratio of ruggedness number to the slope of the ground surface. It is given as :

$$\text{Geometric Number} = \frac{H\,D_d}{S_g} = \frac{\text{Ruggedness number}}{\text{Ground slope}}$$

Results and Discussion

Morphometric Analysis

It includes the analysis on systematic description of the watersheds geometry and its stream channel system to measure the linear aspects of drainage network, aerial aspects of drainage basin and relief aspects of channel network. The first two categories of measurement treat the projected property of watershed on a horizontal plane, termed as planimetric, whereas the third category of measurement counts the vertical inequalities of forms of drainage basin. The various morphological features of both the watershed under study, the drainage maps were collected from the department of SWE, CTAE Udaipur and then they were studied in relation to various aspects mentioned in materials and methods.

Linear Aspects

It refers to the analysis of stream order, stream

Table 1. Morphological characteristics of watershed selected for study.

	Characteristics	Estimated values Sub-catch-ment of Sukli river	Sub-catch-ment of Sei river	Sub-catch-ment of Sabar-mati river
	Linear aspects :			
1	Area (ha)	2642.5	1027.5	1440
2	Perimeter (m)	24500	13000	18600
3	Width of basin (m)	5250	3533	3415
4	Number of stream order			
	I	174	82	86
	II	45	17	12
	III	10	04	04
	IV	03	01	01
	V	01		
5	Stream length (m)			
	I	68725	27800	36650
	II	19737.5	10775	12775
	III	8525	3825	7900
	IV	13350	3750	2450
	V	3025		
6	Bifurcation ratio			
	B. R.$_1$	3.87	4.8	3.91
	B. R.$_2$	4.5	4.25	5.5
	B. R.$_3$	3.3	4.0	4.0
	B. R.$_4$	3.0		
	Average	3.7	4.35	4.47
7	Stream length ratio			
	R_{L1}	0.68	1.9	1.24
	R_{L2}	5.22	1.51	3.4
	R_{L3}	1.94	3.92	1.36
	R_{L4}	1.11		
	Average	2.24	2.44	2.0
8	Length of overland flow (m)	116.3	111.3	120.5
	Aerial aspects :			
9	Form factor	0.87	0.41	0.78
10	Circulatory ratio	0.55	0.76	0.52
11	Elongation ratio	0.82	0.65	0.88
12	Compactness or Shape factor	1.15	3.99	1.28
13	Drainage density (km / km^2)	4.3	4.5	4.15
14	Drainage factor	0.48	0.50	0.46
15	Constant of channel maintenance	0.23	0.22	0.24
16	Stream frequency (per ha)	0.088	0.10	0.08
	Relief aspects :			
17	Maximum basin relief (m)	176	443	276
18	Relief ratio	3.9	14	8.6
19	Relative relief	0.72	3.41	1.5
20	Ruggedness number	0.7568	1.994	1.1454
21	Geometric number	19.41	14.24	13.32

length and length of overland flow. All three sub-catchments are shown in table 1. i.e., sub-catchments of Sukli, Sei and Sabarmati rivers ; the highest order of streams was found to be five sub-catchment of Sukli river and four the both sub-catchments of Sei and Sabarmati rivers. In all order numbers, numbers of streams found in sub-catchment of Sukli river were higher than followed by sub-catchment of Sei River and sub-catchment of Sabarmati river. This indicates better drainage network in Sukli river catchment as compared to other two sub-catchments. It is found that the numbers of streams of particular order are more than the next higher order but less than the immediate lower order. It means that the numbers of streams of particular order decreases with the increase in stream order. In sub-catchment of Sukli river length of streams of order 1, 2, 3, 4 and 5 was found to be 68725, 19737.5, 8525, 13350, and 3025 m respectively while both sub-catchments of Sei and Sabarmati rivers have length of streams of order 1, 2, 3 and 4 was found to be 27800, 10775, 3825 and 3750 m and 36650, 12775, 7900 and 2450 m respectively. However, in general, the mean length of the stream of the particular order increase with the increase in the order of stream which means the mean length of a stream of a given order is greater than that of immediate lower order but less than that of the next higher order. This confirms the property of the stream order number and their corresponding length. The average bifurcation ratio was estimated as 3.7, 4.35 and 4.47 in sub-catchments of Sukli, Sei and Sabarmati rivers where as the average stream length ratio estimated to be 2.24, 2.44 and 2.0 in these sub-catchments respectively. The values of bifurcation ratio in study area indicate that the shape of sub-catchments is somewhat belonged to normal basin.

Relation Between Stream Number and Stream Order

According to the Horton's law, the plot of logarithm of stream number (ordinate) as a function of stream order (abscissa) should yield a set of points lying along a straight line. For the present study, this graph was plotted for the sub-catchments of Sukli, Sei and Sabarmati rivers. The graphs are presented in the Fig 4, Fig 5 and Fig 6 respectively. The graph shows a straight line, satisfying the Horton's law (13). The correlation coefficient for the straight line fit for the sub-catchments are 0.996, 0.856 and 0.986 respectively which is quite satisfactory (Figs 4 to 6).

Relation Between Cumulative Stream Length and Stream Order

In the present study, an attempt was made to establish the relation between the stream order and the cumulative stream length. The plot of logarithm of cumulative stream length along ordinate and stream order along abscissa for the sub-catchments of Sukli, Sei and Sabarmati rivers is a straight line fit (Figs 7 to 9). The straight line fit indicates that the ratio between cumulative stream lengths is constant throughout the successive order of a basin and suggests that geometrical similarity is preserved in basins of increasing order (13, 14). The correlation coefficient for the straight line fit for the sub-catchments are 0.899, 0.856, and 0.897, which is quite satisfactory (Figs 7 to 9).

Aerial Aspects

This aspect of morphological study includes the description of arrangements of area elements mainly the basin shape. The evaluation of basin shape has significant importance to predict its effect on stream discharge characteristics. The quantitative expression of drainage basin shape is estimated under different forms. Table 1 shows that values of form factor, circulating ratio and elongation ratio in sub-catchments of Sukli, Sei and Sabarmati rivers are 0.87, 0.41, 0.78, 0.55, 0.76, 0.52 and 0.82, 0.65, 0.88 whereas values of shape factor and drainage factor were estimated as 1.15, 3.99, 1.28 and 0.48, 0.50, 0.46 for sub-catchments of Sukli, Sei and Sabarmati rivers respectively. These values are in confirmation with already reported values (6) that the elongation ratio varies between 0.6 to 0.1. However, these also suggest that sub-catchments are under moderate slopes as values are closer to the lower range values. Further, higher value of elongation ratio in sub-catchment of Sabarmati river and higher value of circulatory ratio in sub-catchment of Sei river indicates that sub-catchments are approaching towards slightly elongated and circulatory shape respectively which is also confirmed through drainage (Figs 2 and 3) maps.

Another important characteristic under this aspect is drainage density. It is an important indication of elements in the stream eroded topography. The study shows that value of drainage density of sub-catchment of Sei river is 4.5 as compared to 4.3 and 4.15 for sub-catchment of Sukli and Sabarmati rivers respectively. Further, related to drainage density another morphological property of drainage basin is constant of channel maintenance which was found to be 0.23, 0.22 and 0.24 sq. km per km in sub-catchment of Sukli, Sei and Sabarmati rivers respectively. The higher value of drainage density in Sei river sub-catchment as compared to other two sub-catchments was due to the fact that former sub-catchment was under less vegetation than the letter and also having high relief. This is also evident from the values of relief ratio i.e. 14, 8.6 and 3.9% in sub-catchment of Sei, Sabarmati and Sukli rivers respectively.

Relief Aspects

Under this section various aspects of relief and associated properties have been discussed. Estimated value of relief in sub-catchments of Sukli, Sei and Sabarmati rivers was 176 m, 443 m and 276 m respectively based on which relief ratio was found to be 0.039, 0.14 and 0.086 respectively (Table 1). The relative relief was estimated to be 0.72, 3.41 and 1.5% all three sub-catchments respectively. Associated to these properties other characteristics are ruggedness and geometric number. It is seen that values of ruggedness number is 0.7568, 1.994 and 1.1454 and geometric number is 19.41, 14.24 and 13.32 respectively in sub-catchments of Sukli, Sei and Sabarmati rivers. The values so estimated indicate that all three sub-catchments of Sukli, Sei and Sabarmati rivers has comparatively longer but gentle slopes. In case of very high values of ruggedness number, it is considered that catchments are having very steep slopes, which is not the case under study.

Results and discussion based on morphometric analysis indicate that sub-catchments are having normal to circular shapes with moderate gentle slope in the area. The values found for various morphological characteristics also reveal that basin is under good vegetation with moderately permeable subsoil materials.

Conclusion

Soil, water and vegetation are the vital natural resources for the survival of man and his animals. For their efficient and sustainable management, one has to look for sustainable unit of management so that these three resources are handled and managed effectively and simultaneously. Watershed which is hydrologic unit of a drainage outlet, forms an integral component of the basic natural resource, the land mass, presents an ideal unit for managing three vital resources. The comprehensive development of a watershed so as to make productive use of all natural resources and also protect them may be termed as watershed management. It was realized that evaluation of such project should include technical and other related aspects. In the study an effort has been made to know the hydrologic response watershed considering morphological characteristics of watersheds.

The evaluation study made under this study of watershed lead to the following conclusions : The value of bifurcation ratio was found to be 3.7, 4.35 and 4.47 of sub-catchments of Sukli, Sei and Sabarmati rivers which reveals that basins are normal basins. The average stream length ratio of Sukli, Sei and Sabarmati rivers sub-catchments was found to be 2.24, 2.44 and 2.0 respectively. The elongation ratio at the study site suggests that watershed is under moderate slope. The drainage density of the sub-catchments are more i.e., 4.3, 4.5 and 4.15 so that the soil loss is more, which confirms the property of morphological characteristics. The drainage factor of Sukli, Sei and Sabarmati rivers was found to be 0.48, 0.50 and 0.46 respectively. The value of ruggedness number and geometric numbers of sub-catchments of Sukli, Sei and Sabarmati rivers was found to be 0.7568, 1.994, 1.1454 and 19.41, 14.24, 13.32 respectively. Based on morphometric analysis indicate that sub-catchments are having normal to circular shapes with moderate gentle slope in the area.

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