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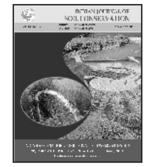

Extraction of geomorphological parameters of Betwa basin using GIS and Watershed Morphology Estimation Tool (WMET)

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ABSTRACT

Geomorphological parameters of any river basin provide information about their hydrological behaviour. Geomorphology of river basins can be used to derive geometrical similarity among basins and relate the flood characteristics to stream network parameters. A study was conducted to extract the geomorphological parameters of the Betwa basin which is located in the central India. The geomorphological parameters were extracted from SRTM 90 m DEM using ArcGIS 9.3 and Watershed Morphology Estimation Tool (WMET) Software. The delineation of the basin boundary and the stream network was done using SWAT tool in ArcGIS 9.3. The stream order of the basin ranged from first to fourth. Drainage density and relief of the basin were 0.046 km^{-1} and 1.016, respectively. The hypsometric curve of the basin indicated that the basin was in equilibrium stage. The value of hypsometric integral of delineated 51 sub-basins also indicated that the basin has reached the equilibrium stage. This information would be helpful in modelling of hydrologic response of the basin.

1. INTRODUCTION

Morphology refers to the measurement of the linear and areal aspects of the drainage basins which is considered as a fundamental geomorphic unit. Quantitative approach to the drainage basins was initiated by Horton (1945). According to Clarke (1996), geomorphometry is the measurement and mathematical analysis of earth's surface and dimensions of the landforms. Geomorphology of watershed is used to analyze geometric similarity among watersheds especially among their stream networks. Morphometric analysis of a river basin provides a quantitative description of the drainage system, which is an important aspect of the characterization of basins (Strahler, 1964). It also provides understanding of hydrological behaviour of any basin. Hydrological phenomena can be correlated with the physiographic characteristics of a drainage basin such as size, shape, slope of the drainage area, drainage density, size and length of the contributories, *etc*. (Rastogi and Sharma, 1976). Geomorphic characteristics of drainage basins play a key role in controlling the basins hydrology (Okoko and Olujimi, 2003). It describes the topographic features of the surfaces and streams, and its relationship with hydrology provides the geomorphological control on basin hydrology (Jain and Sinha, 2003). Researchers have also tried to relate runoff to geomorphology of the basin which will ultimately help in overcoming the difficulties caused due to climate and land use change. The dynamic nature of runoff is controlled by the geomorphologic structure of the catchment area and the induced runoff is very sensitive for the morphometric characteristics of the contributing area (Rudraiah *et al*., 2008). Drainage analysis based on the morphology is also of vital importance for watershed management since it gives an idea about the basin characteristics such as slope, topography, soil condition and stream network. These are also considered as guiding tools for prioritization of watershed to implement the soil and water conservation programs in any basin (Kumar *et al.,* 2011 and Dahiphale *et al.,* 2016). In present time Geographic Information System (GIS) is a powerful tool for estimation of basin parameters. It provides flexible environment for determination, interpretation and analysis of spatial information related to river basins. GIS is an efficient and accurate means for extraction of geomorphological characteristics (National

Institute of Hydrology Report, 2000). With the advent of Digital Elevation Model (DEM), these spatial tools have contributed significantly in terrain analysis capabilities to hydrological studies (Ozdemir and Bird, 2009). The DEM with the help of GIS provide detailed information about morphology and drainage networks of a river basin. Extraction of geo-morphological parameters and drainage networks from DEM is effective and time saving method (Martz and Garbrecht, 2007). The present study focuses on the estimation of different geomorphological parameters and generation of thematic maps of Betwa basin using GIS and WMET.

Description of the Study Area

The Betwa River basin is located in Bundelkhand region in central part of India which originates from Barkhera in Raisen district of Madhya Pradesh. The Betwa River runs over 590 km before it joins the Yamuna near Hamirpur in Uttar Pradesh. Betwa River drains a total area of about 43,900 km^2. It extends between the latitude of 22°59'57" to 26°03'23" N and longitude of 77°05' 51" to 80°13'01" E. The climate of the upper Betwa basin is hot dry sub-humid while in lower part, it is characterised as hot moist semi-arid. The annual precipitation and evaporation are 1138 and 1643 mm, respectively and annual runoff is about 351 mm (Sutcliffe *et al.*, 2009). The long term average of minimum and maximum temperature of the basin ranges from 8 to 43^{o}C, respectively. The Betwa basin is saucer shaped with sand stone hills around its periphery and clays underlain by Deccan trap basalts. Elevation ranges from 63 to 724 m above msl. It flows in a North-Easterly direction through Madhya Pradesh and enters into Uttar Pradesh near village Bangawan of Jhansi district. The location and the district boundary of the Betwa river basin are shown in Fig. 1 and Fig. 2.

2. MATERIALS AND METHODS

In the present study, different thematic maps were prepared from Shuttle Radar Topographic Mission (SRTM) digital elevation model. DEM describes the topography *i.e.* the elevation of a point in an area. A 90 m resolution SRTM data was used in the study. Morphometric analysis based on extracted drainage networks from SRTM DEM gives better results and represents the actual topography more accurately than other DEM's (Sharma *et al.*, 2014). The grids of DEM in which the study area is located were downloaded from the SRTM website and mosaiced. The DEM was used to delineate the basin boundary and to obtain the stream network using SWAT in ArcGIS 9.3. The slope and aspect maps were also prepared from SRTM 90 m digital elevation model in ArcGIS 9.3.

The stream ordering was done by following the method proposed by Strahler (1964). According to Strahler (1964), the 1st order streams are those, which have no tributaries. The 2nd order streams are those, which have tributaries only of 1st order streams, where two 2nd order streams join, a segment of 3rd order is formed. When two 3rd order streams join, a 4th order stream is formed and so on. The different geomorphological parameters of

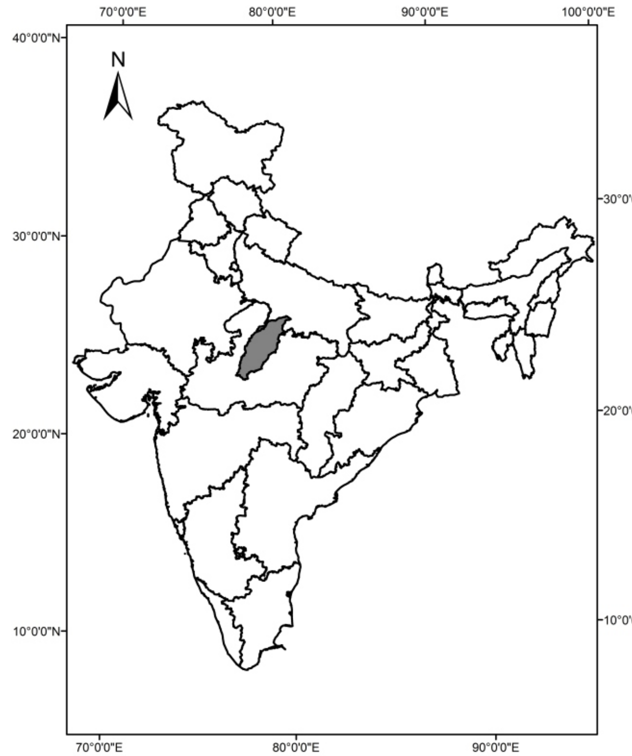

Fig. 1. Location of Betwa river basin

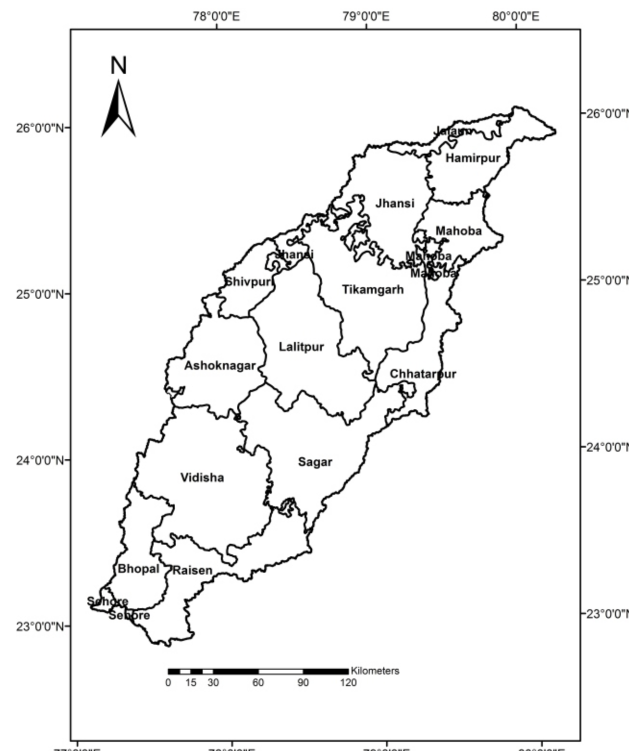

Fig. 2. District boundary of Betwa river basin

Betwa river basin were estimated using WMET (Sarangi *et al*., 2004). A total of 21 geomorphological parameters, drainage and stream order related parameters were estimated in the present study. To draw the hypsometric curve, the information about the contour elevation and area above a particular contour was obtained from the watershed report of SWAT. The contour interval of 100 m was considered and graph was plotted between relative area and relative height to obtain the hypsometric curve of the basin. The curve was used to infer the stage of development of the drainage network. The elevation information of the sub-basins, delineated by the ArcSWAT was used for analysis of hypsometric integral. The estimated geomorphological parameters for the Betwa basin are shown in Table 1.

3. RESULTS AND DISCUSSION

Linear Aspects

The different linear aspects of morphological analysis such as stream order, stream length, mean stream length, stream length ratio and bifurcation ratio are discussed below:

Stream order

Stream ordering is a measure of the position of a stream in the hierarchy of tributaries. The stream ordering was carried out based on the method proposed by Strahler (1964). The total number of stream order delineated in the basin was four. The maximum stream order frequency was observed in case of first order streams and then for second order. This indicates that there is a decrease in stream frequency as the stream order increases. The stream order of the Betwa basin is shown in Fig. 4.

Stream length

The stream length was estimated based on law proposed by Horton (1945). Generally, the total length of stream segment is the maximum in the first order stream and decreases as the stream order increases. The stream lengths of different stream orders in the basin are shown in Table 2.

Mean stream length (L_{sm})

It is a characteristic property related to the drainage network components and its associated basin surfaces

Table: 1
Geo-morphological parameters of Betwa river basin

S.No.	Parameters	
1	Basin Area (km^2)	43946.77
2	Basin Perimeter (km)	2076.44
3	Basin Length (km)	650.00
4	Stream order (Nu)	1 to 4
5	Total Stream Length (km)	2037
6	Drainage Density (D_d)	0.0466
7	Length of Overland flow (L_g)	10.713
8	Fineness ratio (R_{fn})	0.313
9	Constant of channel maintainance (C)	21.426
10	Stream frequency (F_s)	0.0011
11	Drainage texture (T)	0.000054
12	Form factor (R_f)	0.104
13	Circulatory factor (R_c)	0.358
14	Elongation ratio (R_e)	0.364
15	Texture ratio (T)	0.024
16	Compactness constant(C_c)	0.0265
17	Basin relief (H)	661
18	Relief ratio (R_h)	1.0169
19	Relative relief (R_r)	0.318
20	Ruggedness number (R_n)	30.848
21	Shape Factor	9.614

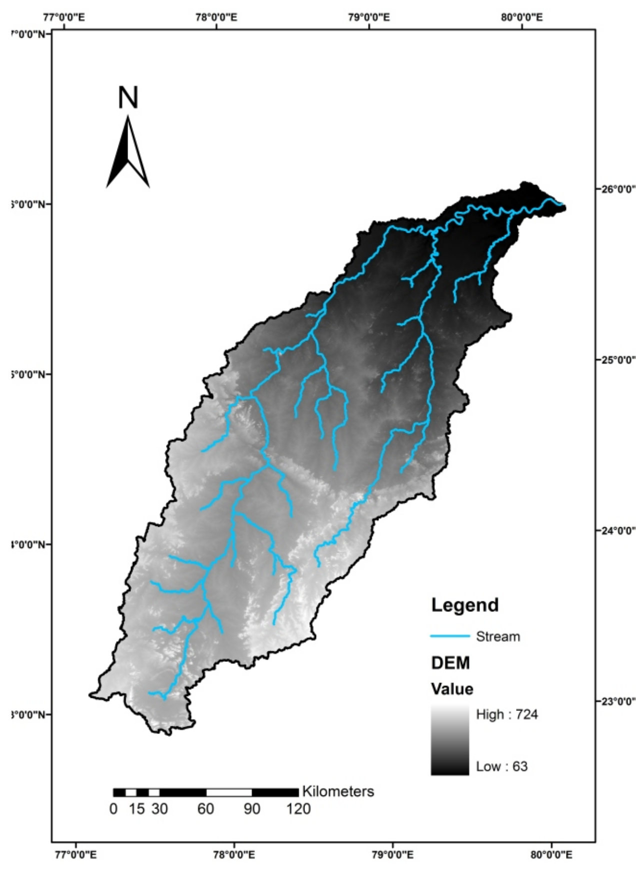

Fig. 3. DEM and stream network of Betwa river basin

Table: 2
Drainage characteristics and stream order related parameters

Stream Order	No. of Streams (Nu)	Length (Lu) km	Mean Stream length (L_{sm}) km	Stream Length Ratio (R_L)	Bifurcation ratio (R_b)
1	25	1115	44.63	3.76	1.923
2	13	4199	323.0	0.08	1.625
3	8	359	44.88	0.39	2.66
4	3	143	47.63		

(Horton 1945). The mean stream length was estimated by dividing total stream length of order 'u' and No. of streams of order 'u'. The L_{sm} value of Betwa basin varied from 44.63 to 323.0 km.

Stream length ratio (L_s)

Horton (1945) proposed the factor stream length ratio, which is the ratio of length of a stream of any given order to the length of a stream of next lower order. Stream length ratio is strongly dependant on the topography and the slope. The L_s between different stream orders is shown in Table 2.

Bifurcation ratio (R_b)

It is the ratio of the number of streams of a particular order to the number of streams of the next higher order (Schumn, 1956). It is a dimensionless property and shows the degree of integration between streams of various orders in a drainage basin. From Table 2, it is observed that the bifurcation ratio is not same from one order to its next order.

Aerial Aspects

Different morphological parameters like drainage density, stream frequency, drainage texture, form factor, circulatory factor, elongation ratio, length of overland flow and constant of channel maintenance are discussed below:

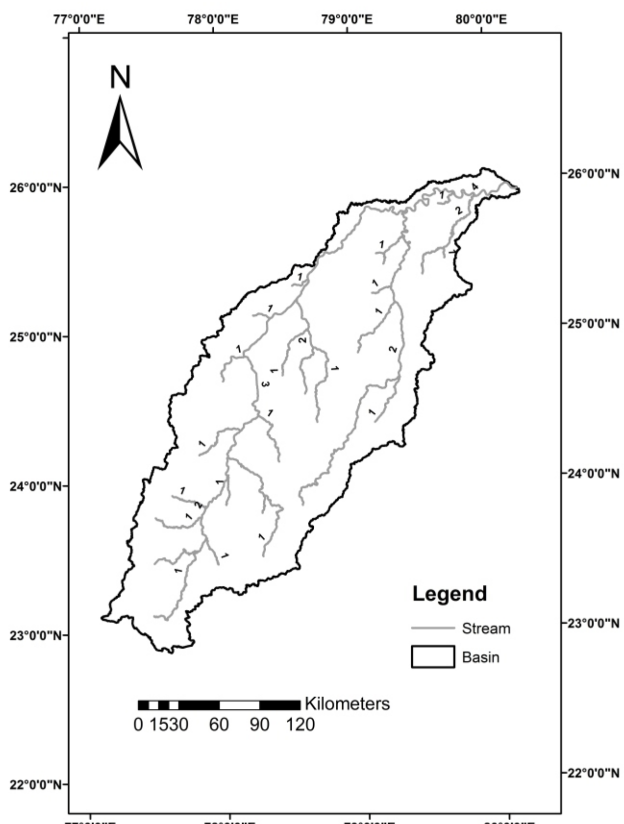

Fig. 4. Stream order of Betwa river basin

Drainage density (D_d)

It is defined as the total length of streams of all orders per drainage area (Horton, 1932). Low drainage density generally results in the areas of permeable subsoil material, dense vegetation and low relief (Nag, 1998). High drainage density is the resultant of impermeable subsurface material, sparse vegetation and mountainous relief. Low drainage density leads to coarse drainage texture while high drainage density leads to fine drainage texture. The value of drainage density of study area was 0.046 km^{-1}.

Stream frequency (S_f)

According to Horton (1932), it is the ratio of the total number of streams in a watershed to the area of the watershed, expressed in sq km. Stream frequencies can be calculated separately for the different order streams also. It is possible to have the basin of same drainage density differing in stream frequency and basins of same stream frequency differing in drainage density. The value of stream frequency of the basin was 0.0011 (Table 1).

Drainage texture

It is the total number of stream segments of all orders divided by perimeter of that area (Horton, 1945). Horton recognized infiltration capacity as the single important factor which influences drainage texture and considered drainage texture which includes drainage density and stream frequency. Drainage texture of Betwa basin was 0.000054, which indicated that the basin has a very coarse drainage texture.

Form factor (R_f)

Horton (1932) defined form factor as the ratio of basin area to square of the basin length. Long-narrow basins have larger lengths and hence smaller form factors. Low form factor value leads to less side flow for shorter duration and high main flow for longer duration and vice versa. The form factor of the basin was 0.104 (Table 1) which indicates that the basin is elongated and flow is for longer duration.

Circulatory factor (R_c)

The circularity ratio is the ratio of the area of the basin to the area of a circle having the same circumference as the perimeter of the basin (Miller, 1953). Low, medium and high circulatory factor is indicative of shape of the basin. The value of circulatory factor of 0.358 indicated elongated shape of the betwa basin. In addition, Miller (1953) described R_c as a significant ratio that indicates the dendritic stage of a watershed. This is mainly due to the diversity of slope and relief pattern of the basin.

Elongation ratio (R_e)

Elongation ratio is defined as the ratio between the diameter of the circle of the same area as the drainage basin and the maximum length of the basin (Schumn, 1956). Strahler (1957) stated that this ratio varies between 0.6 and 1.0 over a wide variety of climatic and geologic types. The value of R_e less than 0.5 indicates more elongated basin. The elongation ratio of the study area was 0.364.

Length of overland flow (L_g)

The length of overland flow approximately equals to half of the reciprocal of drainage density (Horton, 1945). It is the length of water over the ground before it gets concentrated into definite stream channels. From Table 1, the length of overland flow of the Betwa basin was 10.78. The high L_g value indicates that the rainwater had to travel longer distance before getting concentrated into stream channels.

Constant of channel maintenance (c)

Schumn (1956) introduced the factor, constant of channel maintenance, as the inverse of drainage density. It is also the area required to maintain one linear km of stream channel. The value of C for the basin was 21.42. Generally, a higher constant of channel maintenance of a basin indicates higher permeability and *vice-versa*.

Relief Aspect

The different relief aspects of morphological analysis such as basin relief, relief ratio, relative relief and ruggedness number are discussed below:

Basin relief (H)

Basin relief is an important factor in understanding the denudational characteristics of the basin and it is defined as the elevation difference between the lowest and the highest point of a basin. It plays a significant role in landforms development, drainage development, surface and subsurface water flow, permeability, and erosional properties of the terrain. The Basin relief of the study area was 661 m which was the elevation difference between the highest (724 m) and lowest point (63 m) in the DEM of the basin. The highest and lowest elevation in the DEM of Betwa basin is shown in Fig. 3.

Relief ratio (R_h)

It is the ratio of the maximum watershed relief (H) to the maximum length of the watershed (L) along the major slope (towards the outlet), both expressed in the same unit (Schumn, 1956). It is an indicator of the intensity of erosion processes and overall steepness of a drainage basin. High values of relief ratio indicate steep slope and high relief, while the lower values indicate the presence of basement rocks that are in the form of small ridges and mounds with lower degree of slope (GSI, 1981). The value of relief ratio in the study area was 1.016 which indicated the presence of steep slope in the basin.

Relative relief (R_r)

It is the ratio of the maximum watershed relief to the watershed perimeter. The value of relative relief is lower for elongated basins. The value of the relative relief of Betwa basin was 0.318 which indicates that the basin is elongated.

Slope

The slope directly influences the formation of drainage networks. The slope is controlled by the climate-morphogenic processes in areas having rock of varying resistance. Higher degree of slope indicates rapid runoff, higher erosion rates and low recharge potential. The slope map of Betwa basin was prepared from DEM using the slope tool in the ArcGIS 9.3. The degree of slope in the Betwa basin varied from 0° to 103° with more area under 0-3° slope (Fig. 5).

Aspect

Aspect is defined as the direction to which a slope faces. The aspect of a slope has significant influence on its local climate. The aspect map of the basin was created with the help of aspect tool in the ArcGIS9.3. The aspect map of Betwa basin indicated that slopes mainly occur in North, North east and East directions.

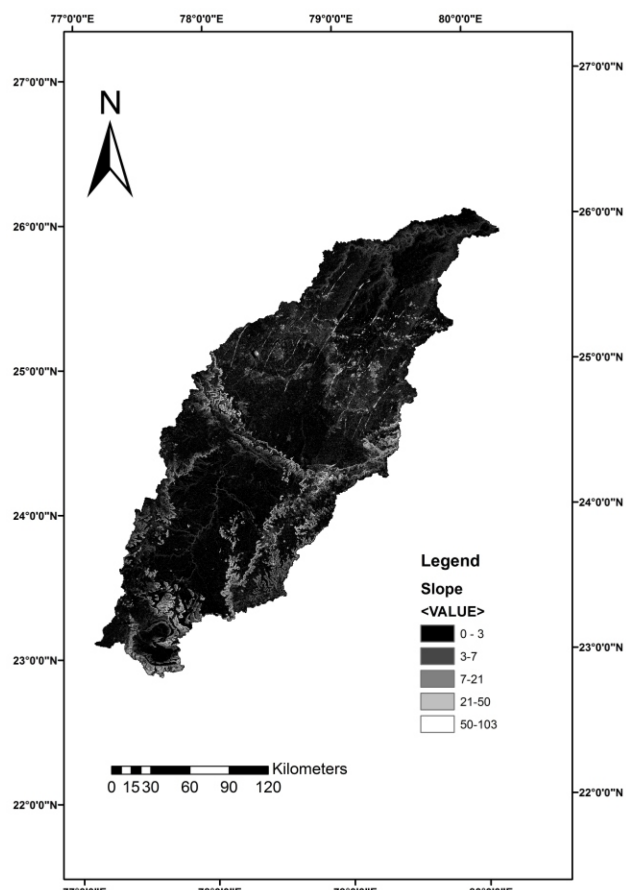

Fig. 5. Slope map of Betwa river basin

Ruggedness number

Schumn (1956) defined ruggedness number as the product of basin relief and drainage density in order to define the slope length and steepness. It is dimensionless and indicates structural complexity of the terrain. The high value of ruggedness number indicates that slopes of the basin are not only steep but long as well. The value of ruggedness number for Betwa basin was 30.48 which indicates presence of steeper and longer slopes.

Hypsometric Analysis

Hypsometric analysis is done to establish relationship between horizontal cross-sectional area of watershed and its elevation in dimensionless form. Hypsometric curve is obtained by plotting relative area along abscissa and relative elevation along ordinate. Hypsometric integral provides information on the geologic stages of development and erosion proneness of the watersheds. According to Strahler (1952), if the value of the hypsometric integral is above 60%, the watershed is in an inequilibrium stage, *i.e.* it is easily susceptible to erosion. If it lies between 35 to 60%, the watershed is in an equilibrium stage, *i.e.*, it is at a mature stage and less susceptible to erosion. If the value is less than 35% then the watershed is in monadnock phase, *i.e.*, it is the most stable or least susceptible to erosion among the known stages. The different Sub-basins in Betwa basin were delineated and their parameters were estimated by the ArcSWAT, in which the elevation data of individual sub-basin was used for hypsometric analysis. To estimate the Hypsometric Integral (HI), elevation-relief ratio formula proposed by Pike and Wilson (1971) was used.

$$HI = \frac{\text{Mean Elev - Min Elev}}{\text{Max Elev - Min Elev}}$$

The hypsometric curve of the basin (Fig. 6) indicated that the basin was in equilibrium stage. The value of HI (Table 3) of delineated 51 sub-basins (Fig. 7) indicated that 4 were in inequilibrium stage, 21 were in equilibrium stage and 26 were in monadnock stage, which proved that most of the part of the basin has reached the equilibrium stage.

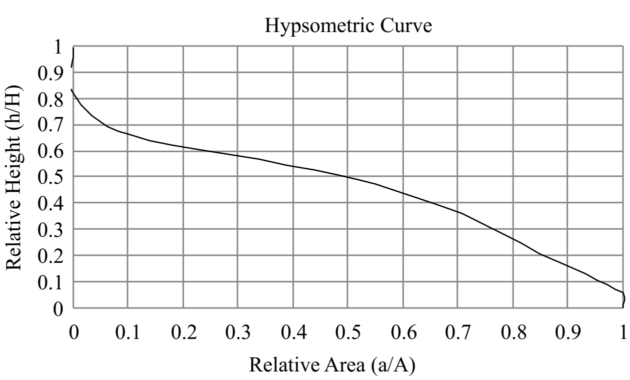

Fig. 6. Hypsometric curve of Betwa river basin

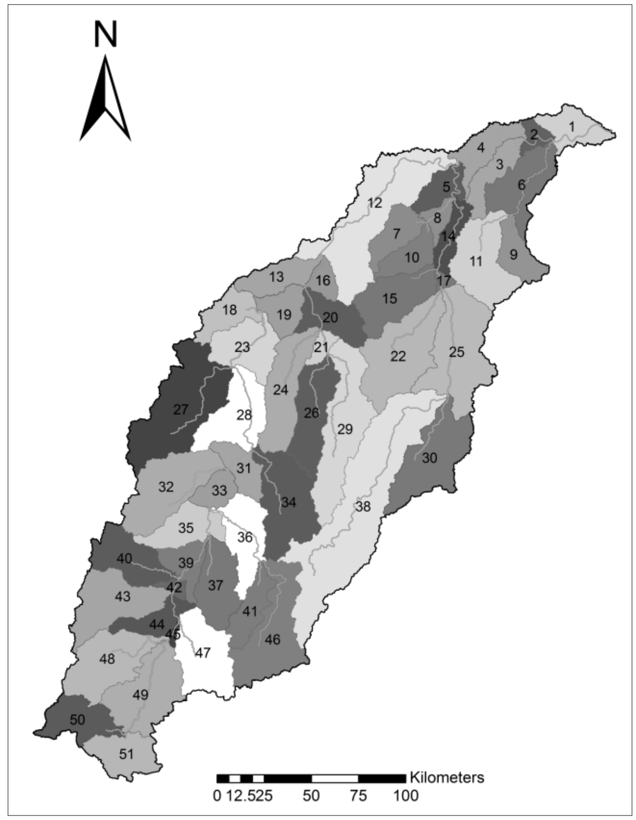

Fig. 7. Sub-basins of Betwa river basin

4. CONCLUSIONS

Application of GIS and WMET along with remote sensing data proved to be efficient tools for extracting morphometric parameters. The estimated morphological characteristics of Betwa basin revealed that this basin is dominated by lower order streams with the total length of stream segments maximum in first order streams. The stream order varied from one to four. The slope map indicated presence of high degree of slope gradient in Betwa river basin. The aspect of the study area revealed that the slopes facing North, North east and East are predominant in the basin. The variation of stream length ratio between different order streams was due to differences in slope and topographic conditions. Bifurcation ratio of the study area indicated that its values were not same for all the stream orders. Low values of drainage density and drainage texture revealed very coarse drainage texture in the Betwa river basin. The form factor, circulatory factor and elongation ratio revealed that basin was elongated with high relief and steep slope. The hypsometric curve indicated that the basin is in the equilibrium stage and value of the hypsometric integral of the sub-basins showed that most of them were in monadnock and equilibrium stage. This also indicates that the basin has reached the equilibrium stage and has undulating land surface. The estimated basin parameters may be useful to simulate hydrological response of the

Table: 3
Sub-basin hypsometric integral (H_{si})

S.No.	Area (km^2)	Min Elev (m)	Max Elev (m)	Mean Elev (m)	Hysometric Integral (H_{si})
1	563.63	63	145	121	0.70
2	190.02	72	144	122	0.69
3	486.69	104	182	147	0.55
4	561.99	86	166	134	0.60
5	410.86	104	263	156	0.33
6	935.28	83	309	143	0.27
7	516.51	150	339	203	0.28
8	213.65	126	277	167	0.27
9	495.28	134	322	195	0.32
10	461.09	158	358	204	0.23
11	1169.97	122	340	198	0.35
12	2285.98	85	363	200	0.41
13	561.03	187	403	291	0.48
14	377.07	119	312	173	0.28
15	951.17	177	393	254	0.36
16	237.41	183	374	265	0.43
17	70.46	171	299	203	0.25
18	541.15	274	521	370	0.39
19	465.19	243	724	299	0.12
20	650.51	243	393	307	0.43
21	165.59	283	411	319	0.28
22	1542.09	186	404	290	0.48
23	845.67	280	697	346	0.16
24	1092.79	285	494	361	0.36
25	1676.04	173	521	270	0.28
26	992.98	297	557	366	0.27
27	1977.54	331	540	457	0.60
28	1037.42	319	533	394	0.35
29	1619.22	298	578	386	0.32
30	1343.47	269	591	403	0.42
31	460.20	343	461	404	0.51
32	1358.80	380	549	456	0.45
33	339.83	362	437	399	0.49
34	1362.38	366	634	439	0.27
35	684.89	372	541	423	0.30
36	869.36	380	564	425	0.24
37	847.48	382	598	430	0.22
38	3576.18	269	711	443	0.39
39	437.55	377	495	414	0.31
40	853.64	393	558	474	0.49
41	522.55	424	624	476	0.26
42	106.64	388	442	415	0.50
43	1155.85	397	575	463	0.37
44	444.85	395	557	432	0.23
45	47.53	402	454	420	0.34
46	1434.70	424	696	526	0.38
47	1105.15	404	669	451	0.18
48	1194.05	406	615	478	0.34
49	1286.93	409	608	461	0.26
50	719.76	433	647	508	0.35
51	700.69	425	651	478	0.23

catchment as they are the major inputs parameters to various hydrological models.

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REFERENCES

Anonymous. 2000. Report on Estimation of geomorphology parameters for small catchments using GIS. National Institute of Hydrology.

Clarke, J.I. 1996. Morphometry from Maps. Essays in geomorphology. Elsevier Publ. Co, New York, pp. 235-274.

Dahiphale, P., Singh, P.K., Bhakar, S.R., Kothari, M. and Yadav, K.K. 2016. Morphometric analysis and prioritization of sub-watersheds in Jaisamand catchment using geographical information system. *Ind. J. Soil Cons.,* 44(1): 79-86.

GSI. 1981. Geological and Mineralogical Map of Karnataka & Goa, Geological Survey of India.

Horton, R.E. 1932. Drainage Basin Characteristics. *Trans. Am. Geophysical Union*, 13(1): 350–361.

Horton, R.E. 1945. Erosional development of streams and their drainage basins; Hydro physical approach to quantitative morphology. *Geol. Soc. Am. Bull*., 56(2): 275-370.

Jain, V. and Sinha, R. 2003. Geomorphological manifestation of the flood hazard. *Geocarto. Int*., 18 (4): 51-60.

Kumar, A., Sharma, H.C. and Kumar, S. 2011. Planning for replenishing depleted groundwater in upper gangetic plains using RS and GIS. *Ind. J. Soil Cons.,* 39(3): 195-201.

Martz, L.W. and Garbrecht, J. 2007. Automated extraction of drainage network and watershed data from digital elevation models. *J. Am. Water Resour. Assoc*., 29: 901-908.

Miller, V.C. 1953. A quantitative geomorphologic study of drainage basin characteristics in the clinch mountain area, Virginia and Tennessee, Columbia University, Department of Geology, Technical Report, No. 3, Contract N6 ONR, 271-300.

Nag, S.K. 1998. Morphometric analysis using remote sensing techniques in the Chaka SubBasin, Purulia District, West Bengal. *J. Indian Soc. Remote Sen*., 26(1): 69-76.

Okoko, E.E. and Olujinmi, J.A.B. 2003. The Role of Geomorphic Features in Urban Flooding: The case of Ala River in Akure, Nigeria. *Int. J. Env. Issues*, 1(1): 192-201.

Ozdemir, H. and Bird, D. 2009. Evaluation of morphometric parameters of drainage networks derived from topographic maps and DEM in point floods. *Env. Geol*., 56: 1405-1415.

Pike, R.J. and Wilson, S.E. 1971. Elevation-relief ratio, hypsometric integral and geomorphic area-altitude analysis. *Geol. Soc. Am. Bull*., 82: 1079-1084.

Rastogi, R.A. and Sharma, T.C. 1976. Quantitative analysis of drainage basin characteristics. *J. Soil Water Cons. India*, 26(1-4): 18-25.

Rudraiah, M., Govindaiah, S. and Srinivas, V.S. 2008. Morphometry using remote sensing and GIS techniques in the sub-basins of Kagna river basin, Gulbarga district, Karnataka, India. *J. Indian Soc. Remote Sen*., 36: 351-360.

Sarangi, A., Madramootoo, C.A. and Singh, D.K. 2004. Development of Arc GIS assisted user interfaces for estimation of watershed morphologic parameters. *J. Soil Water Cons*., 3:139-149.

Schumm, S.A. 1956. Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. *Geol. Soc. Am. Bull*., 67(5): 597-646.

Sharma, C.S., Mishra, A. and Panda, S.N. 2014. Assessing impact of flood on river. 28(9): 2615-2638.

Strahler, A.N. 1952. Hypsometric (area–altitude) analysis of erosional topography. *Geol. Soc. Am. Bull*., 63:1117-1141.

Strahler, A.N. 1957. Quantitative analysis of watershed geomorphology. *Trans. Am. Geophys. Union*, 38(6): 913-920.

Strahler, A.N. 1964. Quantitative geomorphology of drainage basins and channel networks. In: V.T. Chow, edHandbook of Applied Hydrology. McGraw Hill Book Company, New York, Section 4-II.

Sutcliffe, J.V., Agrawal, R.P. and Tucker, J.M. 1981. The water balance of the Betwa basin, India/Le bilanhydrologique du bassin versant de BetwaenInde. *Hydro. Sci. J*., 26(2): 149-158.