Morphometry and Network of Hydrological Stations: Betwa River Catchment

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ABSTRACT: *Average yield estimates of runoff can differ significantly in terms of their areal extent and thus may affect developmental designs of irrigation projects. It is the extension of point-based hydrological data record to areal estimates that decides the practical utility of potential yield. Morphometry provides one of the most important basis for analysing the spatial pattern of river flow over terrain. Hence, a detailed geo-hydrological investigation of the Betwa catchment falling in lower basin of Yamuna river has been presented in this paper that may provide useful clues about the existing and optimum standards of hydrological stations. With the help of digital elevation model prepared in GIS software, a flow directional map has been prepared. Observed runoff is also compared for some of the stations. Prioritization of watersheds for location of gauge and discharge sites based on limited runoff data and landuse characteristics obtained from satellite images has also been attempted.*

Key Words*:* Morphometry, Areal Estimates, Digital Elevation Model (DEM), Synthetic Flow Map, Location of Discharge Stations

INTRODUCTION

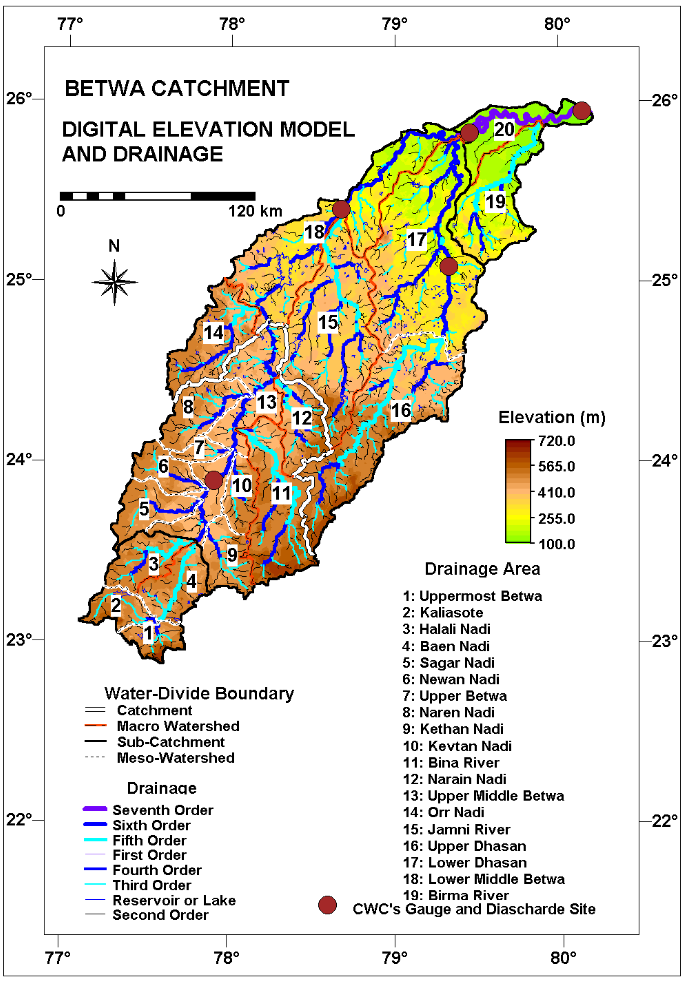
As many of the stream gauges, used to measure discharge rate, are also used to monitor salt loads coming into the river, therefore, other uses of data were suggested jointly at these points. An assessment of hydrological data network is, thus, rightly integrated with water resources study carried out in Brunei, Darussulem. Rainfall, streamflow and evaporation record were assessed separately with regard to their spatial distribution and length of record. The study revealed that the greater preponderance of gauges in the coastal plains with very few stations in the remoter parts of the interior poses difficulty in accurate inventory and planning of water resources. In addition, the access to limited data dispersed in various departments was also highlighted in this comprehensive study, where water supply and demand were anticipated along with the problem of droughts, floods and water quality (Chuan, 1992).

MATERIALS AND METHODS

The catchment area of Betwa river, a geologically and historically strategic region in central India, is selected for the case study. It is bounded by northern alluvial plains and southern Vindhyan plateau and extends from 22°20' N. to 26°0' N. latitudes and 77°10' E. to 80°20' E. longitudes covering (including parts) four districts of southern Uttar Pradesh and ten districts of Madhya Pradesh. The catchment area suffers from uneven agricultural and irrigational developments. Presumably, it has been affected by the spatial network of hydrological data also. Hydrological monitoring of Betwa river catchment falling in lower Yamuna basin has special significance in the wake of recently announced Betwa-Ken link. Problems like soil erosion in the ravenous belt and large-scale silting of its largest reservoir, *i.e.* Matalila, can be better monitored if a scientific assessment of data record is made. Moreover, the potentiality of water resources in the basin exists in seasonal streams and small water bodies because the water of the perennial river Yamuna cannot be diverted to south due to general relief of the region (Saxena, 1968). Therefore, the study of hydrological data network and pattern of drainage network becomes important in this region dominated by seasonal tributaries.

The analysis is based on data collected from secondary sources. Long-term annual rainfall and runoff data for hydrological stations is obtained from Indian Meteorological Department (IMD) and Central Water Commission (CWC) respectively. Besides annual data, monthly data from these and other state-level organisations is also collected for monsoon season. Base maps are drawn using 11 toposheets of Survey of India at 1:250,000 scale and 4 plates of drainage and water resources series of National Atlas Thematic Mapping Organisation (NATMO) at 1:1,000,000 scale. Further, primary data regarding the nature and functioning of data stations, maintenance, communication and publication of data, and the economic or other managerial problems, is also gathered at some of the selected sites (Ahlawat, 2006).

In the absence of runoff data at every watershed level, flow characteristics and the need for gauging stations has been estimated indirectly from morphometric analysis. The measurement and mathematical analysis of selected parameters (of both linear and aerial aspects) based on Strahler's hierarchic ranking of streams has been carried out in GIS software- ILWIS 3.6. Digital elevation model, drainage and watershed boundaries have been overlaid and various hydrological parameters were extracted from these (Fig. 1).



Source: Computed in ILWIS Based on SOI Toposheets (1:250000)

Fig. 1

RESULTS AND DISCUSSIONS

Optimality of Hydrological Data Network

There exist five CWC gauge and discharge (GD) sites in the catchment area of Betwa river besides gauge sites maintained by respective state governments. Out of these, only three stations have long-term data record. The average density of hydrological stations, thus, works out to be 8626 Km^2. According to modern WMO standards, minimum density of 3000-5000 Km^2 per stream gauge is required in the flat plains and undulating or hilly regions like Betwa catchment. To attain the desired level of optimality according to WMO standards, there should be, at least, 14 stream-gauging stations. But, before making uniform recommendation for the establishment of new hydrological stations, other aspects like variability of terrain, runoff and all other parameters have to be considered.

Gauge-Discharge Sites and Basin Morphometry

The morphometric analysis (Table 1a, b & c) based on digital measurement of linear, aerial and relief aspects of sub-catchments/watersheds and their relative contributions in all tributaries of Betwa river provides useful hints for relative requirement of gauge and discharge stations.

Linear Aspects

Stream Order (u): Estimated runoff contribution from different order streams varies according to watershed characteristics. Hierarchic ranking of streams based on Strahler's method resulted into Betwa river as 7th order stream after its joining with *Dhasan* - the largest tributary with 6th order. Flow in Betwa river becomes significant at Bhojpur where it joins with its uppermost tributary from Vindhyachal range and its own easterly flow along with rivers from Bhopal plateau. Thereafter near Vidisha, after joining with *Halali nadi* – a 5th order stream, it broadens and comes out from plateau. It is here that the first important CWC's GD site is located at Basoda. In its undulating terrain, *Bina and Narain* are two important 5th order tributaries from Bhander range (girdling the region as semi-circular central plateau) where at least one regular GD site needs to be maintained. At Rajghat - now a dam site, the entire flow from upper Betwa is regularly monitored and it is used for all regional hydrological designs besides sharing water information between two states. In middle reaches, *Orr nadi* on left bank and *Jamni nadi* on right bank have significant runoff potential. *Jamni*'s drainge area is second largest after *Dhasan* and it is dammed at various places in Bundelkhand. *Dhasan*, after leaving Sagar plateau where two 5th order streams join, becomes lifeline of Bundelkhand. It has only one CWC site at Garrauli where silt load is also measured from its gravel bed. On main Betwa, too, a series of reservoirs were constructed by Britshers like Matatila, Paricha and Dukwa-Sukwa in order to provide relief to farmers during famines in this ravinous belt. Thus, user-based hydrological records exist at these sites. It was only after 80's that some rationality was considered while locating new GD sites like at Mohana, which is downstream of

*Dhasan'*s confluence with Betwa. *Birma* is another larger 5th order stream in lower reaches after *Dhasan* but no central station exists on it. Finally, Sahijina on Betwa river, near Hamirpur before its confluence with Yamuna, is an oldest CWC site. In all, there is a strong linear decrease in number of streams as the stream order increases. There are more than 4000 ephemeral first order streams and even out of 45 fourth order streams, four are ephemeral till their mouth. Hence, seasonal monitoring stations are justified.

<u>Stream Length (Lu)</u>: Generally, the total length of stream segments is highest in first order streams and it decreases as the stream order increases. However, in case of *Halali*, *Bina*, *Birma* and *Dhasan* sub-catchments the stream segments in 5th order have larger length than in preceding lower order. This change may indicate flowing of streams from high plateau surface, lithological variations and moderate slopes to larger section of streams in undulating lowland areas. Therefore, GD sites are required both in upstream and downstream reaches of these sub-catchments.

Table 1: Results of Morphometric Analysis of Watersheds in Betwa Catchment

Table 1a): Linear Aspects – Stream Order and Stream Length

Watershed	*Area*	*P*	*u*						*Lu*					
	(km^2)	*(km)*	*I*	*II*	*III*	*IV*	*V*	*VI*	*I*	*II*	*III*	*IV*	*V*	*VI*
Uppermost Betwa	621.41	130.22	57	13	4	1	--	--	215.22	95.88	34.01	13.37	--	--
Kaliasote	735.14	142.99	73	11	2	1	--	--	250.05	77.15	58.75	11.32	--	--
Halali	1160.30	173.66	95	22	7	2	1	--	357.25	110.15	59.33	20.09	47.83	--
Newan	1098.88	171.50	114	27	5	1	--	--	421.19	153.61	79.59	27.08	--	--
Baen	1148.76	180.22	56	13	4	1	--	--	313.75	81.53	32.67	49.68	--	--
Sagar	840.91	142.13	49	10	2	1	--	--	239.44	95.81	23.80	39.55	--	--
Upper Betwa	1976.72	374.55	126	27	5	0	1	1	548.73	202.59	38.78	0.00	70.16	49.73
U. M. Betwa	2570.05	429.48	326	62	16	1	0	1	916.51	253.43	86.22	18.82	--	135.10
Bina	2820.55	338.78	302	64	12	4	1	--	962.74	311.44	136.37	86.99	99.49	--
Narain	1338.98	185.72	184	40	11	3	1	--	556.17	162.80	78.63	48.68	37.91	--
Kevtan	799.70	133.45	82	19	4	1	--	--	293.67	102.01	44.06	39.20	--	--
Naren	348.38	92.68	29	5	2	1	--	--	106.90	46.19	19.25	10.69	--	--
Kethan	1347.82	176.24	126	24	6	1	--	--	517.65	155.90	93.37	54.05	--	--
L. M. Betwa	4028.68	572.65	479	*98*	18	3	0	1	1422.23	378.90	213.98	33.24	13.97	187.38
Orr	1985.96	268.18	228	52	12	2	1	--	672.22	210.65	127.00	69.31	26.07	--
Jamni	4777.76	379.70	608	124	27	6	1	--	1734.25	484.62	179.17	179.69	138.10	--
U. Dhasan	469.80	453.14	850	155	35	5	2	--	2107.21	643.14	299.30	131.97	161.10	--
L. Dhasan	4908.49	433.04	789	140	29	7	2	1	2212.43	651.35	357.98	80.28	74.63	152.89
Lowermost Betwa	6266.85	261.28	39	8	1	0	0	0	133.03	56.87	17.51	0.00	0.00	0.00
Birma	1424.97	267.48	278	65	13	4	1	--	763.43	252.19	84.84	60.31	127.24	0.00
Betwa	43132.3	1317.20	4890	979	215	45	11	4						

Source: Computed in ILWIS from Drainage maps of 11 Toposheets (Scale 1:250000)

Table 1(b): Mean Stream Length, Bifurcation Ratio and Stream Length Ratio

Watershed	*Lsm*						*RL*					*Rb*					*Rbm*
	I	*II*	*III*	*IV*	*V*	*VI*	*II/ 1*	*III/ II*	*IV/ III*	*V/ IV*	*VI/ V*	*I/ II*	*II/ III*	*III/ IV*	*IV/ V*	*V/ VI*	
Uppermost Betwa	3.78	7.38	8.50	13.37	--	--	0.45	0.35	0.39	0.00	--	4.38	3.25	4.00	--	--	3.88
Kaliasote	3.43	7.01	29.38	11.32	--	--	0.31	0.76	0.19	0.00	--	6.64	5.50	2.00	--	--	4.71
Halali	3.76	5.01	8.48	10.05	47.83	--	0.31	0.54	0.34	2.38	0.00	4.32	3.14	3.50	2.00	--	3.24
Newan	3.69	5.69	15.92	27.08	--	--	0.36	0.52	0.34	0.00	--	4.22	5.40	5.00	--	--	4.87
Baen	5.60	6.27	8.17	49.68	--	--	0.26	0.40	1.52	0.00	--	4.31	3.25	4.00	--	--	3.85
Sagar	4.89	9.58	11.90	39.55	--	--	0.40	0.25	1.66	0.00	--	4.90	5.00	2.00	--	--	3.97
Upper Betwa	4.36	7.50	7.76		70.16	49.73	0.37	0.19	0.00	--	0.71	4.67	5.40		0.00	1.00	2.77
U. M.Betwa	2.81	4.09	5.39	18.82	--	135.10	0.28	0.34	0.22	0.00	--	5.26	3.88	16.00	--	0.00	4.19
Bina	3.19	4.87	11.36	21.75	99.49	--	0.32	0.44	0.64	1.14	0.00	4.72	5.33	3.00	4.00	--	4.26
Narain	3.02	4.07	7.15	16.23	37.91	--	0.29	0.48	0.62	0.78	0.00	4.60	3.64	3.67	3.00	--	3.73
Kevtan	3.58	5.37	11.02	39.20	--	--	0.35	0.43	0.89	0.00	--	4.32	4.75	4.00	--	--	4.36
Naren	3.69	9.24	9.63	10.69	--	--	0.43	0.42	0.56	0.00	--	5.80	2.50	2.00	--	--	3.43
Kethan	4.11	6.50	15.56	54.05	--	--	0.30	0.60	0.58	0.00	--	5.25	4.00	6.00	--	--	5.08
L.M.Betwa	2.97	3.87	11.89	11.08		187.38	0.27	0.56	0.16	0.42	13.41	4.89	5.44	6.00	--	0.00	4.08
Orr	2.95	4.05	10.58	34.65	26.07	--	0.31	0.60	0.55	0.38	0.00	4.38	4.33	6.00	2.00	--	4.18
Jamni	2.85	3.91	6.64	29.95	138.10	--	0.28	0.37	1.00	0.77	0.00	4.90	4.59	4.50	6.00	--	5.00
U.Dhasan	2.48	4.15	8.55	26.39	80.55	--	0.31	0.47	0.44	1.22	0.00	5.48	4.43	7.00	2.50	--	4.85
L.Dhasan	2.80	4.65	12.34	11.47	37.32	152.89	0.29	0.55	0.22	0.93	2.05	5.64	4.83	4.14	3.50	2.00	4.02
Lowermost Betwa	3.41	0.87	1.35			--	0.43	0.31	0.00			4.88	8.00	--	--	--	4.29
Birma	2.75	3.88	6.53	15.08	127.24	--	0.33	0.34	0.71	2.11	0.00	4.28	5.00	3.25	4.00	--	4.13
Betwa	3.02	4.62	9.60	21.65	72.41	131.27	0.31	0.46	0.47	0.82	0.66	4.99	4.55	4.78	4.09		4.19

Source: Computed in ILWIS based on 11 SOI Toposheets at 1:250000 scale.

Mean Stream Length (Lsm) - A characteristic property related to the drainage network and its associated surfaces, varies from 2.48 km (1^{st} order) to 152.89 km (6^{th} order) (Table 1b). Magnitude of lower order mean stream length is higher in watersheds of upper Betwa sub-catchment. It is greater than that of the lower order and less than that of its next higher order till 3^{rd} order in all sub-catchments/watersheds. But, in case of higher orders, mean stream length is lesser in case of *Kaliasote* and lower *Dhasan* watersheds - both dominated by more ephemeral streams. In case of *Orr nadi* watershed as well, fifth order mean stream length is lesser than that of 4^{th} order. In addition, the mean length of highest order, *i.e.* 7^{th} order is lesser than that of 6^{th} order. Hence, location of Mohana GD site near the junction of 6^{th} order is justified. However, it would have been better if the site is located upstream of the junction.

Stream Length Ratio (RL): Horton's law of stream length states that mean stream length segment of each of successive orders of a basin tends to approximate a direct geometric series with stream length increasing towards higher order of streams. The RL between streams of different order reveals that there exists a variation in each watershed. Uppermost Betwa, *Baen*, *Bina*, *Narain*, *Kevtan* and *Jamni* watersheds – all originating from higher reaches in plateau region, show an increasing trend in the length ratio from lower order to higher order indicating their mature geomorphic stage. In remaining watersheds, there is a change from one order to another indicating their late youth stage of geomorphic development mainly in ravineous terrain creating badlands. It is due to these variations in number and length of streams in different orders, more GD sites are required on the tributaries, which do not follow general rule.

Bifurcation Ratio (Rb): Rb is not same for each order and it shows variation among different watersheds. These irregularities are dependent upon the geological and lithological development of the drainage basin. The higher values of Rb observed in *Kaliasote, Naren, Kethan* and *Dhasan* watersheds at their lowest orders are indicative of strong structural control on the drainage pattern while the lower values in the these regions are indicative of drainage that are not affected by structural disturbances at higher orders. Reverse erratic trend is observed in the watersheds falling mainly in the middle Betwa sub-catchment. As mean bifurcation ratio varies from 3.24 to 5.08, therefore, all watersheds fall under normal category. Nevertheless, watersheds having more variation in Rb from one order to another- like *Kaliasote, Orr, Jamni,* upper *Dhasan, Kethan, Sagar, Halali, Bina* and *Birma* require monitoring sites at their tributaries as well due to more susceptibility of change in drainage pattern.

Areal aspects

The relief measurements - basin length (Lb), total relief (maximum and minimum), relief ratio (Rh) and areal aspects – drainage density (D), stream frequency (Fs), Drainage texture ratio (Rt), form factor (Rf), circularity ratio (Rc), elongation ratio (Re), length of overland flow (Table 1c) provide significant clues for location of GD sites.

Table 1(c): Relief and Areal Aspects

Watershed	*Mi*	*Mx*	*H*	*Lb*	*Rh*	*Rf*	*Re*	*Rc*	*Rt*	*D*	*Fs*	*Lg*
Uppermost Betwa	400	520.8	0.12	24.38	0.0050	1.05	16.23	0.46	0.58	0.58	0.12	*3.47*
Kaliasote	400	630	0.23	44.47	0.0052	0.37	10.52	0.45	0.61	0.54	0.12	*3.70*
Halali	400	600	0.20	62.34	0.0032	0.30	11.85	0.48	0.73	0.51	0.11	*3.90*
Newan	400	634	0.23	50.71	0.0046	0.43	13.80	0.47	0.86	0.62	0.13	*3.23*
Baen	399	576	0.18	58.23	0.0030	0.34	12.56	0.44	0.41	0.42	0.06	*4.81*
Sagar	400	552	0.15	51.42	0.0030	0.32	10.41	0.52	0.44	0.47	0.07	*4.22*
Upper Betwa	399.5	612	0.21	92.94	0.0023	0.23	13.54	0.18	0.43	0.46	0.08	*4.34*
U. M. Betwa	350	501	0.15	12.29	0.0123	17.02	133.13	0.18	0.95	0.55	0.16	*3.65*
Bina	400	714	0.31	104.7	0.0030	0.26	17.15	0.31	1.13	0.57	0.14	*3.53*
Narain	383.8	578.6	0.19	63.23	0.0031	0.33	13.48	0.49	1.29	0.66	0.18	*3.03*
Kevtan	400	599	0.20	51.53	0.0039	0.30	9.88	0.56	0.79	0.60	0.13	*3.34*
Naren	400	548	0.15	38.81	0.0038	0.23	5.71	0.51	0.40	0.53	0.11	*3.81*
Kethan	400	538	0.14	65.28	0.0021	0.32	13.14	0.55	0.89	0.61	0.12	*3.28*
L. M. Betwa	138.9	500	0.36	168.13	0.0021	0.14	15.25	0.15	1.05	0.56	0.15	*3.58*
Orr	350	544	0.19	82.08	0.0024	0.29	15.40	0.35	1.10	0.56	0.15	*3.59*
Jamni	254.8	577.7	0.32	147.14	0.0022	0.22	20.67	0.42	2.02	0.57	0.16	*3.52*
Upper Dhasan	250	658	0.41	156.68	0.0026	0.20	19.94	0.30	2.31	0.68	0.21	*2.94*
Lower Dhasan	149	507	0.36	138.66	0.0026	0.33	28.77	0.42	2.24	0.56	0.15	*3.55*
Lowermost Betwa	100	208.3	0.11	86.35	0.0013	0.19	10.51	0.26	0.19	0.24	0.03	*8.23*
Birma	114.6	366	0.25	95.33	0.0026	0.28	16.98	0.45	1.35	0.51	0.14	*3.95*
Betwa	445.16	100.0	0.63	24.38	0.0014	0.22	61.68	0.31	4.67	0.55	0.14	*3.63*

Source: Computed from 11 SOI topographic sheets at 1:250,000

Relief aspects: The aggregate minimum and maximum heights for different watersheds derived from digital elevation model reveal that there exists larger variation in relative relief in middle Betwa sub-catchment. The lowest point on valley floor of Betwa river is about 100 m from mean sea level in its lower reaches and the maximum point is at a height of *714* m in *Bina* watershed. The values of Rh range from 0.0030 (*Baen* and *Sagar*) to 0.0052 (*Halali*). It generally increases with decreasing drainage area and size of watershed in the region. Although high values of Rh indicate steep slope and high relief but due to large size of watersheds in middle Betwa relief ratio becomes less. The low values of Rh indicate the presence of basement rocks that are exposed in the form of small ridges and mounds with lower degree of slope in middle and lower reaches.

Drainage density (D): Drainage density, a measure of closeness of spacing of channels, varies from 0.42 to 0.68 km/km^2. This low value of drainage density indicates that the Betwa catchment has highly permeable subsoil, vegetation cover, and low relief. The range of spatial variation in drainage density is low. Relatively higher values are found in the central plateau region. The need for monitoring stations is therefore more in this region as compared to high precipitation watersheds in upper reaches that are not able to contribute significant runoff due to permeable sub-stratum.

Steam frequency (Fs): Stream frequency in the catchment is also low varying from 0.06 to $0.21/km^2$. It exhibits close correspondence with drainage density (r=0.85) indicating the increase in stream population with respect to increase in drainage density. However, spatial variation in stream frequency value is more than that of drainage density value. *Sagar* and *Baen* watersheds lying on left bank of upper Betwa river have low drainage density and frequency but their runoff potential is high. Hence one GD site is required here also.

Drainage texture ratio (Rt): Texture, one of the important geomorphic parameter, includes both drainage density and texture. It depicts the drainage density of coarse texture in case of *Dhasan* and *Jamni* (Rt>2 in these two large tributaries) to very coarse drainage texture in rest of the watersheds. Relatively more drainage lines in these watersheds suggest impermeable areas. Hence, not only flows on main tributary but also sub-tributaries need to be seasonally monitored here. The fact can be realised by the presence of existing storage reservoirs on tributaries of Jamni river like *Sahzad* and *Sajnam*, which testify their runoff potential.

Form Factor (Rf): The highest value of Rf (1.05) in uppermost Betwa (*Godar nadi*- the first tributary to main Betwa) watershed indicates that it is circular in shape, where all tributaries originate from Vindhyachal range. Due to smaller basin length, the runoff potential of these first tributaries is limited, making their seasonal flow important for water use and conservation in this area. Hence, location of seasonal monitoring stations can be considered. All other watersheds in the Betwa river catchment are elongated in shape resulting into lower value of Rf.

Circularity Ratio (Rc): Its value, a more appropriate relative measure of circularity, ranges from 0.18 to 0.56. Figures higher than 0.50 in case of *Kevtan*, *Naren* and *Kethan* watersheds all lying in upper middle Betwa sub-catchment and *Sagar* in upper Betwa sub-catchment indicate that they are more or less circular, characterized by high to moderate relief and structurally control over drainage system. However, no conclusion can be drawn regarding their runoff potential except the clue regarding less randomness in temporal variations of runoff.

Elongation Ratio (Re): A circular watershed is considered to be more efficient in discharge of runoff than an elongated one. Highest elongation ration of more than 100 was observed in case of upper middle Betwa.

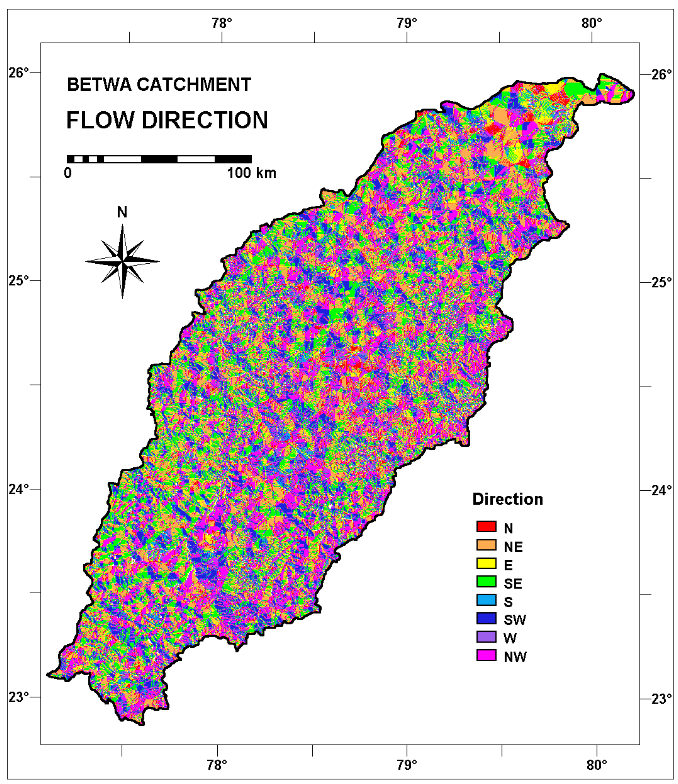


Fig. 2 (Source: Computed in ILWIS from Fig. 1)

Length of Overland Flow (Lg): Length of water over the ground before it gets concentrated into definite channel is an important hydrological parameter at micro-level particularly in the region infested with many small ephemeral streams. It varies from 2.94 (upper *Dhasan*) to 4.81(*Baen*). Watersheds having higher drainage density show smaller Lg values because it is inversely related to drainage density. Thus, areas with lesser Lg values have to be given priority over other watersheds for location of upstream GD sites.

Further, digital elevation model (DEM) optimized flow direction and flow accumulation maps based on ordered drainage network help in prioritisation and hierarchy of sites (Fig 2).

CONCLUSIONS

Morphometry can help in designing and adequacy of network hydrological data stations. In Betwa river catchment fed by numerous ephemeral tributary streams potential of runoff varies considerably in different reaches. Hence, more seasonal GD sites and maintenance is required especially in upper reaches. Although both State and central government sites are in the process of digital records under Hydrology project and at dam sites the regular monitoring has started. But, synchronization with scientific accuracy and ease in data collection is still a task at micro level.

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