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Changes in hydraulic variables with discharge on the Tapi River, India: role of channel geometry

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Abstract

An attempt has been made in this paper to find out at-a-station hydraulic geometry of the Tapi River. Data regarding hydraulic variables associated with Annual Maximum Series (AMS) are available for four sites on the Tapi River. Moreover, data of hydraulic variables are available for a large magnitude 2006 flood for a site. The data have been used to derive at-a-station hydraulic geometry equations. The hydraulic geometry exponents (b, f, and m) have been plotted on Rhodes' ternary diagram. The results illustrate that the rate of change in mean depth (f) and mean velocity (m) with discharges are greater than the rate of change in width (b). The total variance values for two sites are close to the theoretical value (0.33). This suggests that the effects of changes in discharge are absorbed more or less equally by all the three variables. However, the total variance values for the remaining three sites are not close to theoretical value indicating that the effects of changes in discharge are not absorbed equally by all the three variables, but by one or two hydraulic geometry variables. This fact suggests that the alluvial channel of the Tapi River is not a true alluvial channel, which is self-formed through the independent adjustment of the morphological variables. The b-f-m diagram shows that two sites fall in sector 6, two in sector 8 and one in sector 2. The sector 6 represents the channel where Froude number and slope-roughness ratio increases and width-depth ratio and velocity-area ratio decreases with increasing discharge. Sector 8 shows the channel characteristics where width-depth ratio, velocity-area ratio, and slope-roughness ratio decrease and Froude number increases with increasing discharge whereas, the sector 2 reveals decrease in width-depth ratio and increase in competence, Froude number, velocity-area ratio, and slope-roughness ratio with rising discharge. The conclusion is that even high flows that occur at an interval of a decade are accommodated within the channel and therefore overbank flooding is rare. The results of hydraulic geometry analysis, suggest that the behavior of the alluvial Tapi River is not truly alluvial but quasi-bedrock. The channel geometry of the Tapi River plays a significant role in efficient conveyance of monsoon floods through the changes in the hydraulic variables with increasing discharge.

Keywords: *Flood hydrology, flood geomorphology, channel geometry, monsoon floods, Tapi River, ternary diagram*

Introduction

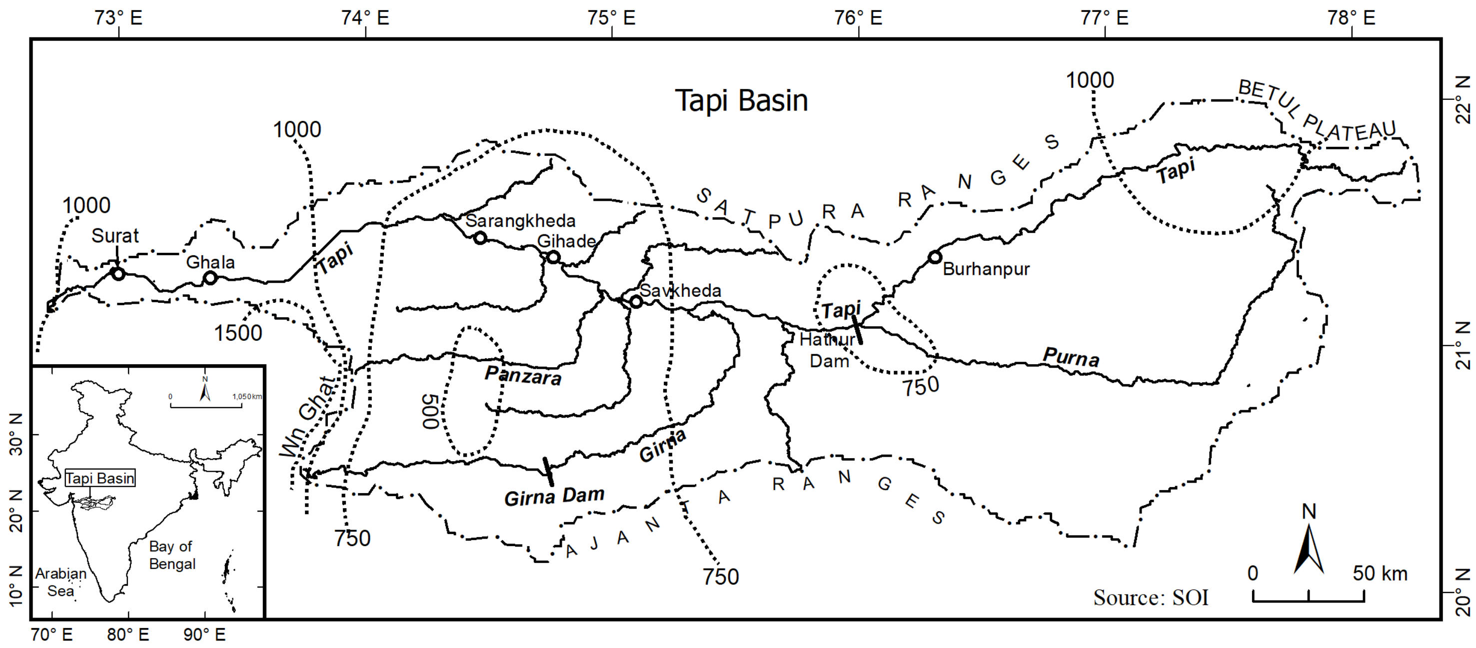
The geomorphic and hydrologic relationships known as hydraulic geometry were first introduced by Leopold and Maddock in 1953, and their application remains critically important for assessing water resources throughout the world (Gleason, 2015).

Hydraulic geometry is of prime significance in design, planning and management of river engineering and training works (Singh, 2004). Hydraulic geometry is an account of how the dynamic properties of a river channel responds to increase in discharge. It may be considered either as at-a-station change or downstream response to increasing discharge. At-a-station hydraulic geometry describes the channel characteristics to the geometric rate of change of hydraulic variables, specifically width (w), mean depth (d) and mean velocity (v) as discharge (Q) increases. These associations are labeled as "hydraulic geometry" (Leopold and Maddock, 1953, Williams, 1978). However, the associations have been based on the numerical similarity of the exponents. The implicit assumptions in such analysis is that channels, as characterized by a particular set of b, f and m values differ only in their rate of response to changing discharge (Rhodes, 1977). Rhodes (1987) in his investigations suggests that the hydraulic geometry equations are simple allometric accounts of a set of extremely complex interrelationships. The geometric relationships cannot entirely explain nor describe river systems. Investigations of the similarities and differences in the hydraulic geometries of rivers have provided understandings into the operation of fluvial systems. The exponents (b, f and m) of hydraulic geometry calculations with their totality by 1.00 for each site are plotted on a Ternary diagram or b-f-m diagram (Rhodes, 1977). The deep alluvial channel of the Tapi River is unique in its class because even high magnitude floods are not sufficient to fill up the entire channel and, therefore, overbank flooding is rare except in lower reaches near Surat. The questions of prime importance of this study are that how the Tapi River channel responds to different discharges. Although, the channel of the Tapi River is alluvial, it behaves like quasi-bedrock during high floods due to its cohesive banks. The objective of this paper is to understand changes in hydraulic variables with discharge on the Tapi River by means of at-a-station hydraulic geometry.

Geomorphological and hydrological characteristics

The Tapi River lies in central India with a total length of 724 km and a catchment area of 65145 km^2 (Fig. 1). It is the second largest west flowing river in India. The river rises near Multai in the Betul District of Madhya Pradesh at an elevation of 730 m ASL. The basin is predominantly underlain by Cretaceous-Eocene Deccan Trap basalts and late Quaternary alluvium. A major part of the middle and lower Tapi and Purna Basins are covered with thick alluvium of late Quaternary period. The basin is highly elongated. The northern tributaries are fewer in number and shorter in length and the majority of the higher order streams namely Panzara, Girna and Purna meet the main river from the south. From the source to Harda (upstream of Burhanpur) the river flows primarily thorough bedrock. The alluvial channel is downstream of Harda up to Surat. In this reach the river has deeply incised into the alluvial deposits. Owing to the deeply incised nature of the channel, in bedrock and alluvium, even high flows are generally insufficient to fill the entire channel (Kale et al, 1994; Kale and Hire, 2004; Kale and Hire, 2007). Large floods, therefore, are confined within the channel banks and spread laterally only through deeply incised gullies.

The Tapi River and its tributaries are rainfed. The basin is located in an environment typical of monsoonal tropics with periodic



Source: SOI

Fig.1: Tapi Basin: Discharge gauging sites on the Tapi River

high-magnitude rainfall. About ninety percent of rain arrives during the monsoon season (June to October) after a long dry season of about seven to eight months. The average annual rainfall of the basin is 814 mm, which is generally received in 44 days (Gunjal and Hire, 2018). July is the rainiest month for the basin and accounts for nearly 30% of the total annual precipitation. Spatially, the annual rainfall displays a marked variation within the basin with annual rainfall between 500 and 1000 mm (Fig. 1). The basin is located within the zone of severe rainstorms (Dhar and Nandargi, 1995). Heavy rains result from invasion of cyclonic storms and depressions originating over Bay of Bengal and adjacent land. The highest 24-hr heavy rainfall within the basin ranges between 86 and 459 mm.

Fluvial regime of the Tapi River and its tributaries reveal the seasonal rhythm of the monsoon rainfall. Annual hydrographs, derived from 8-17 years data of the main stream and the tributaries reflect a simple regime with only one pronounced maximum. As expected, at all the sites the maximum discharge (more than 90%) occurs in the monsoon months (June to October) and the river flow dwindles in the non-monsoon season (November to May). Thus, much of the geomorphic work of erosion and transportation is confined to four-five months of the monsoon season. The flow in the river starts rising rapidly in the month of June with the onset of monsoon over the basin, after a prolonged dry season. This sudden rise in the river discharge has important implications in terms of sediment erosion and transportation.

The river is characterized by one of the most intense flood regimes in the monsoonal tropics (Kale et al., 1994). The available gauged data indicate that the mean discharges range between 1300 and 11000 m^3/s. The highest flood ever recorded on the Tapi River at Surat in 1968 was 42450 m^3/s, which is higher than or comparable with some large rivers of India such as Mahanadi, Krishna

Table 1: Exponent values of at-a-station hydraulic geometry

Site	Width (b)	Depth (f)	Velocity (m)	b/f ratio	m/f ratio	Total Variance
Burhanpur	0.24	0.51	0.26	0.47	0.51	0.39
Savkheda	0.21	0.46	0.33	0.46	0.72	0.36
Gihade	0.03	0.60	0.36	0.05	0.60	0.49
Sarangkheda	0.04	0.59	0.38	0.07	0.64	0.49
Ghala	0.05	0.38	0.57	0.13	1.50	0.47

Table 2: Exponent values of at-a-station hydraulic geometry of the Narmada and the Mahi

River	Site	Width (b)	Depth (f)	Velocity (m)	b/f ratio	m/f ratio	Total Variance
Narmada$^{\$}$	Rajghat	0.04	0.46	0.50	0.08	1.08	0.46
Mahi$^{\#}$	Padardibadi	0.02	0.45	0.53	0.05	1.18	0.48
Mahi$^{\#}$	Khanpur	0.04	0.53	0.43	0.08	0.81	0.47

Source: $^{\$}$ = Kale et al., 1994; $^{\#}$ = Patil et al., 2018

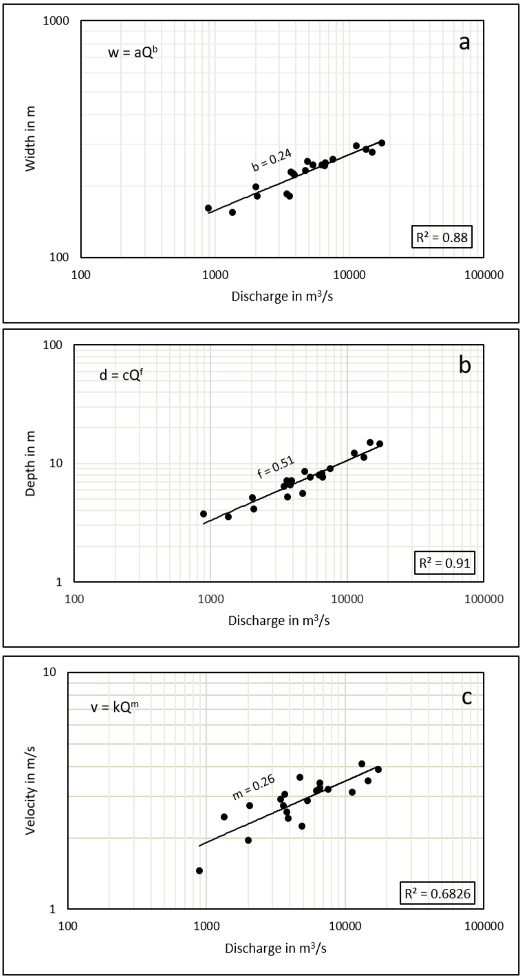


Fig 2: Tapi: At-a-station hydraulic geometry at Burhanpur

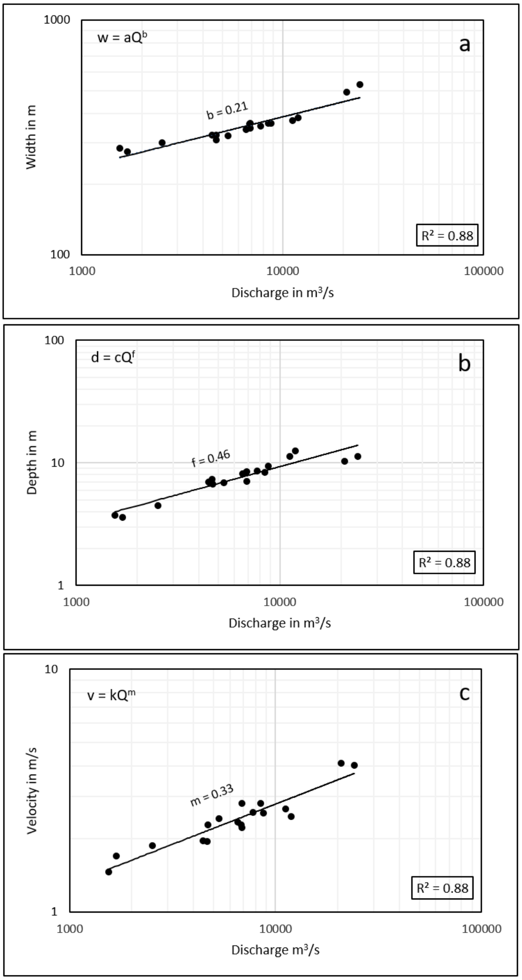


Fig 3: Tapi: At-a-station hydraulic geometry at Savkheda

and Kaveri.

Data and Methodology

In order to derive at-a-station hydraulic geometry equations, the values of width, depth and velocity for mean annual discharge data along the river are required. However, data regarding hydraulic variables associated with annual maximum series (AMS) were available for four sites on the Tapi River namely Burhanpur, Savkheda, Gihade and Sarangkheda (Fig. 1). In addition to this, the data regarding hydraulic variables were available for the 2006 mega-flood at the Ghala site located in the downstream reaches on the Tapi River (Fig. 1). These data have been used to derive at-a-station hydraulic geometry equations to understand the nature of changes in the hydraulic variables with discharge. The equations of hydraulic geometry are as under;

$w = aQb$ …. Eq. 1

$d = cQf$ …. Eq. 2

$v = kQm$ …. Eq. 3

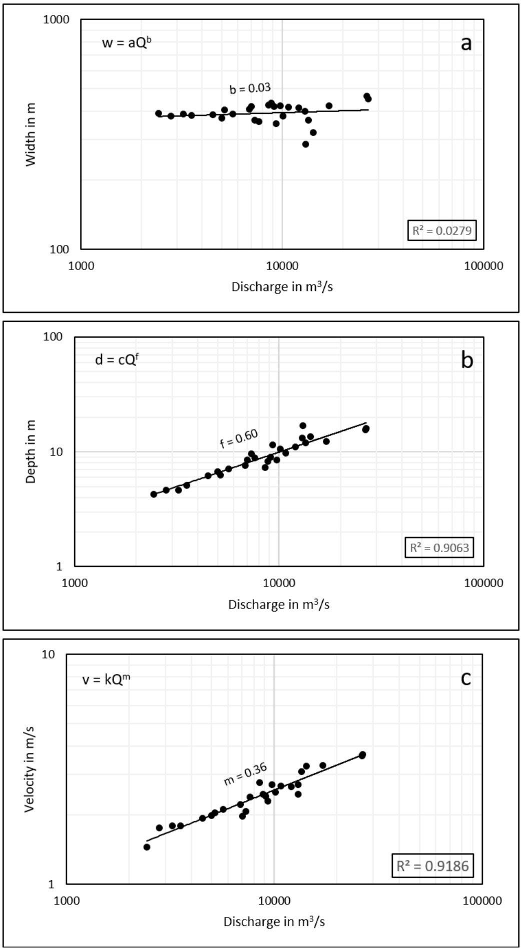


Fig. 4: Tapi: At-a-station hydraulic geometry at Gidhade

Where; w = width; d = mean depth; v = mean velocity; Q = water discharge and a, c, k, b, f and m are numerical constants (Leopold and Maddock, 1953).

Above three equations are mainly used to express and associate stream channels forms. The changes between discharges as the independent variables and the dependent of width, depth, velocity have often been expressed as simple power-functions (Rhodes, 1978; Rhodes, 1987). The b/f ratio, m/f ratio and total variance have been computed for understanding of the rate of change in width, mean depth and mean velocity. All the hydraulic geometry exponents (b, f, and m) of the five sites were plotted on Rhodes' ternary diagram. This kind of analysis provides values statistically more accurate than those obtained by other methods and offers a unique set of equations. The original presentation of the diagram considered only at-a-station hydraulic geometry exponents (Rhodes, 1977). For the graphical data presentation, the divided b-f-m diagram is a tool for the interpretation of the hydraulic geometry (Rhodes, 1987).

Results and Discussion

The results of hydraulic geometry of five sites on the Tapi River are shown in Table 1 and Fig. 2 to 6. The results of the analysis for all the sites clearly show that the rate of change in mean depth (f) and mean velocity (m) with discharges are greater than the rate of change in width (b). The rate of change in width (b) with discharge is much slower for Gidhade, Sarangkheda and Ghala sites on the Tapi River which is attributed to nearly box-shaped nature of channels (Fig. 4a, 5a and 6a). Therefore, the increase in the discharge is primarily compensated by a remarkable increase in depth. This has important implications for competence of the channel since the flood power is directly related to the flow depth (Baker and Costa, 1987; Hire, 2000; Kale and Hire, 2004; Patil et al., 2018). The rate of change in width (b) with discharge is moderate at Burhanpur and Savkheda sites (Fig. 2a and 3a respectively) indicating more or less semicircular channel form.

A comparison of exponent values of at-a-station hydraulic geometry of the Narmada and the Mahi Rivers of western India (Table

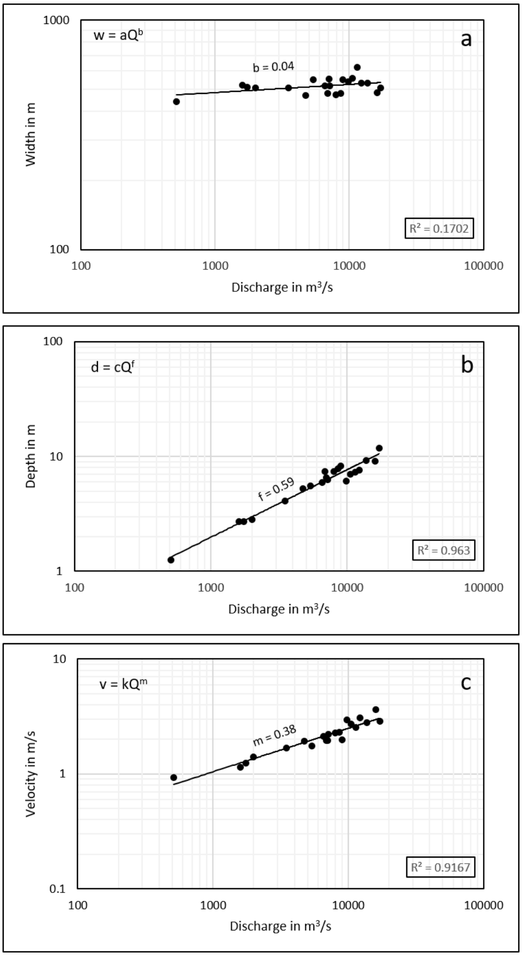


Fig. 5: Tapi: At-a-station hydraulic geometry at Sarangkheda

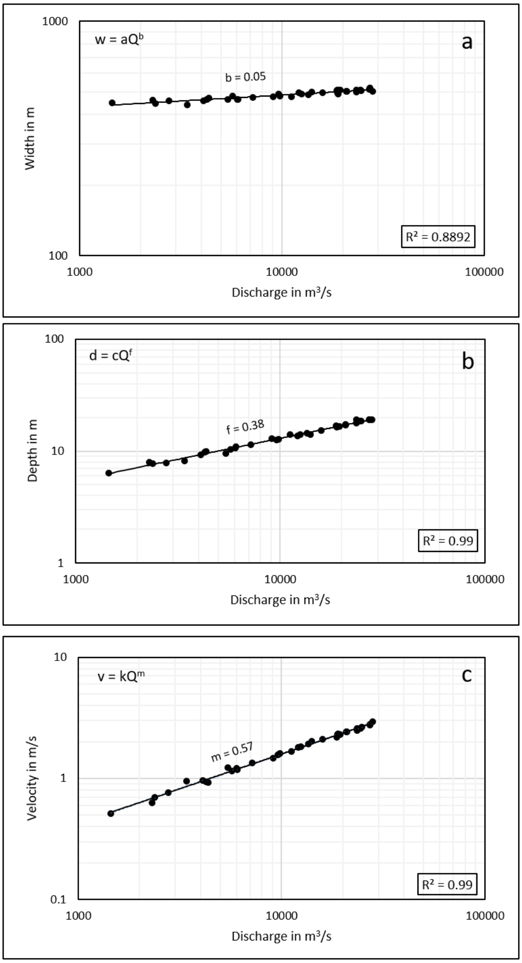


Fig. 6: Tapi: At-a-station hydraulic geometry at Ghala

2) with the Tapi River (Table 1) indicate that both the rivers behave in more or less similar manner with increasing discharge. This similarity is mainly attributed to classical box-shaped nature of the channels of the Tapi, the Narmada and the Mahi Rivers. The beauty of these channels is that even high flows that occur at an interval of a decade are accommodated within the channel and therefore overbank flooding is rare. The results of hydraulic geometry analysis, therefore, suggest that the behaviour of the alluvial Tapi River is not truly alluvial but quasi-bedrock.

The width-depth i.e. b/f ratios of all the sites (Table 1) indicate that the rate of change in width is always lower than the rate of change in mean depth which has important implications for efficiency of the channel since the flood power is directly related to the flow depth and inversely related to width (Baker and Costa, 1987). The velocity-depth

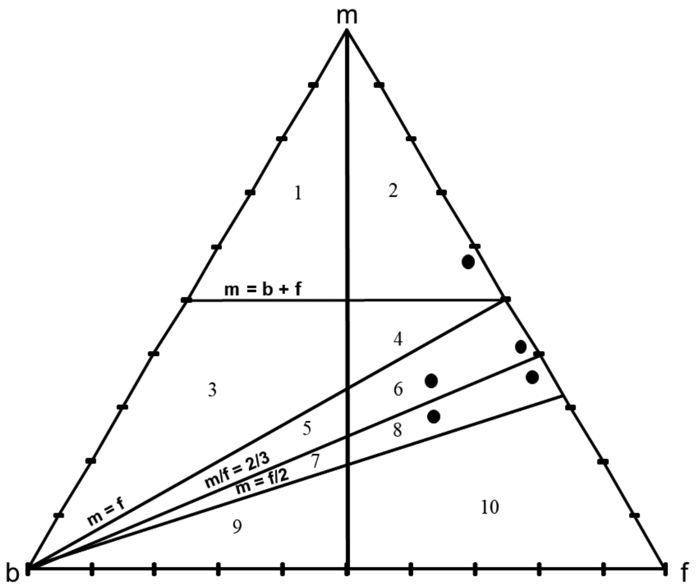


Fig. 7: The width-depth-velocity (b-f-m) or Ternary diagram

i.e. m/f ratio is related to the transportation of sediment load. The higher the ratio, the more rapid the increase of the measured sediment loads with increase of discharge (Leopold et al., 1964). All sites from the Table 1 show relatively higher values of the m/f ratio except for the Burhanpur site. The high ratios indicate that the rate of increase of velocity with discharge is close to the rate of increase of depth with discharge. This fact implies that high flows are associated with an increase in the transportation capacity of the channels. The ratios, therefore, suggest that the capacity of the flows to transport sediments increases rapidly with discharge.

According to Rhodes 1987, hydraulic geometry is linked with Langbein's concept of minimum variance. Hence, the total variance is calculated which is the sum of the square of the hydraulic geometry exponents. On the basis of calculations of the total variance, values for two sites namely Burhanpur and Savkheda sites are 0.39 and 0.36 respectively (Table 1) and are closer to theoretical minimum total variance, which is 0.333 (Rhodes, 1987). On other hand, the total variance values are higher for the sites viz. Gidhade, Sarankheda and Ghala. This proposes that at the latter sites, the effects of changes in discharge are not absorbed equally by all the three variables, but by one or two hydraulic geometry variables (Rhodes, 1987). This behaviour of the hydraulic variables can be attributed to the rectangular appearance of the channel and to the cohesive nature of the bank material of the selected sites. This fact, therefore, suggests that the alluvial river channel of the Tapi River is not a true alluvial channel, which is self-formed through the independent adjustment of the morphological variables (Leopold et al., 1964; Baker and Kale, 1998).

The values of b, f, and m of the five sites were plotted on the ternary diagram (Fig. 7). It indicates that two sites fall in sector 6, two sites in sector 8 and a site in sector 2. The sector 6 represents the channel where Froude number and slope-roughness ratio increases and width-depth ratio and velocity-area ratio decreases with increasing discharge. Sector 8 shows the channel characteristics where width-depth ratio, velocity-area ratio and slope-roughness ratio decrease and Froude number increases with increasing discharge whereas, the sector 2 reveals the decrease in width-depth ratio and increase in competence, Froude number, velocity-area ratio and slope-roughness ratio with rising discharge. The b-f-m diagram offers a means of grouping and comparing hydraulic geometry of the channels of the Tapi River and suggests empirical classification based on hydraulic geometry.

The conclusion is that even high flows that occur at an interval of a decade are accommodated within the channel and therefore overbank flooding is rare. The results of hydraulic geometry analysis suggest that the behaviour of the alluvial Tapi River is not truly alluvial but quasi-bedrock. The channel geometry of the Tapi River plays a significant role in efficient conveyance of monsoon floods through the changes in the hydraulic variables with increasing discharge.

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