Channel morphology and hydraulic geometry of River Kolong, Nagaon district, Assam, India: a study from the standpoint of river restoration

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River Kolong of Nagaon district, Assam, India has been facing serious degradation since 1964 as a result of building of an embankment across the river at its take-off point from River Brahmaputra. The river Kolong, once a thriving anabranch (distributary) of the Brahmaputra marked by its active navigability, rich biodiversity and high productivity, is presently in a moribund state. Under these circumstances, the issue of eco-hydrological restoration of the river gained added urgency among the people living in its valley. The 'natural-channel design approach' for river restoration based on the estimates of natural channel geometry and discharge is presently being applied in rivers across the globe. Adopting a similar approach in this study, based on field measurements, we determine the baseline channel dimensions (bankfull width, mean bankfull depth, bankfull cross-section, flood-prone width and entrenchment ratio) across the river at four different sites, so that these parameters can be utilized in natural channel design process for restoration purpose. The study reveals that, the river is significantly entrenched with entrenchment ratio varying from 1.19 to 1.79. Moreover, bankfull discharge has also been determined and values are found to be varying from 13.85 to 918.36 cumec in the downstream direction, with an average return period of 1.7 years. The average values of 'at-a-station' hydraulic geometry exponents *b*, *f* and *m* are 0.22, 0.38 and 0.4 respectively, while the average values of downstream direction exponents *b*, *f* and *m* are found to be 0.32, 0.23 and 0.44 respectively. These values compare well with those arrived at by pioneering workers in this field and are considered useful in river restoration programmes.

Keywords: Channel dimensions, embankment, flood hazard, hydraulic geometry, river restoration.

RIVERS are dynamic systems of a landscape, fostering a wide range of biotic diversity based on habitat availability. The fluvial process operating in a river in terms of its flow and sediment regime plays a decisive role in describing the health of the river. However, stream alterations in the form of widespread pollution and physical restrictions (embankments, dykes, etc.) have now become a global problem, affecting many of these fluvial systems which need urgent attention. These stream alterations have led to excessive habitat loss in addition to consequent socio-economic and environmental losses[1]. In order to reverse these negative impacts of stream alteration, projects to restore stream channels to their original, more precisely to their natural conditions, have been undertaken in different parts of the world.

River Kolong, Assam, India is bearing the brunt of persistent deterioration mainly caused due to an illogical human intervention in 1964 as an ad hoc flood control measure. As an aftermath of the great Assam earthquake of 1950 measuring 8.7 on the Richter scale, the magnitude and frequency of flood events in the low-lying riparian tracts, including the Kolong basin, have assumed serious proportions primarily as a result of aggradation of the river beds due to increased sedimentation[2]. In order to tackle the increasing threat from flood hazard, especially to save the district headquarter town of Nagaon, in 1964, the Kolong River was blocked by erecting an earthen embankment across its take-off point from the River Brahmaputra at Hatimura[3]. This historic alteration of the river course has left the channel incised and mostly disconnected from its former floodplain, thus shattering the fragile agro-economic base of the Kolong basin.

The consequences of this intervention are rather upsetting, converting the once free-flowing river, into a string of alternating dry stretches and stagnant pools, during the decades that have followed, worsening the health of the river and the ecosystem it fosters. The present-day Kolong River is marked by much reduced flow, increased pollution load and greatly disturbed ecological and economic services, with a highly impaired aquatic habitat. This reduction of flow has also affected the balance between water and sediment, and has led to aggradation of the channel bed. There is, therefore, an urgent need for formulating a scientific and viable river restoration strategy, in order to restore its health, which in turn will provide long-term sustainable economic, ecological and socio-cultural security to the region and its people[4].

River restoration planning generally focuses on restoring channel morphology which in turn will shape other factors such as hydrological and ecological restoration.

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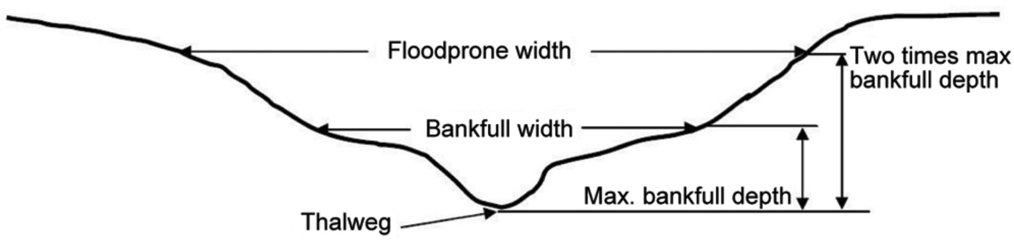

Figure 1. Typical stream channel cross-section for measurement of channel geometry.

Drainage basin hydrology and channel discharge are the two factors that primarily determine the size of the channel, whereas the calibre and amount of sediment load determine channel pattern and cross-sectional morphology[5]. Shields *et al.*[6] described the application of hydraulic engineering tools for the assessment of watershed geomorphology, channel-forming discharge analysis, and hydraulic analysis of flow and sediment transport. Schiff *et al.*[7] pointed out the fact that for integrating any successful river restoration technique, both the physical and biological components of an aquatic system need to be considered simultaneously. Hence, as an essential prerequisite for the restoration of the Kolong, the present study has been carried out.

During the last decade, methods have been developed that require channel morphology to assess relative stream stability and devise stable channel configurations[8]. A key to proper use of these methods is the determination of bankfull discharge – an index of streamflow that is considered to be closely related to channel shape, size and slope. Bankfull discharge is the maximum flow magnitude that is contained within a channel, without overtopping its bank[9]. Bankfull discharge is significant in creating the shape and size of alluvial channels and on an average, this flow has a recurrence interval of about 1.5 years[10]. Dunne and Leopold[11] suggested that bankfull discharge plays a pivotal role in shaping the general morphological characteristics of a channel, and thus is often referred to as channel-forming or effective discharge. Other attributes determining bankfull geometry are bankfull width, mean bankfull depth and bankfull cross-sections (Figure 1). Bankfull width is described as the width of the full lateral extent of the bankfull channel measured perpendicular to the direction of flow, while mean bankfull depth is the average depth of a stream cross-section under bankfull condition. Another important physical–morphological parameter is active floodplain/floodprone width, which is defined as the stream width at which the discharge level is twice the maximum bankfull depth.

Finally, in order to formulate a proper river restoration design, it is obligatory to analyse the association between channel variables and discharge at given cross-sections, as well as between channel variables and discharge of a constant frequency in the downstream direction[12]. Thus the ‘hydraulic geometry’ provides a basic framework for operational river restoration. Hydraulic geometry relations for various rivers of the Indian sub-continent, viz. Narmada, Tapi, Godavari, Burhi Dihing, etc. have been determined by various workers[13,14]. However, there have been no such studies earlier on River Kolong.

Study area

The present study was carried out on River Kolong (Figure 2). This river with a total length of about 219 km is an anabranch of the Brahmaputra, which branches out from it near Jakhalabandha, about 77 km upstream of Nagaon town, and meets it again at Kajalimukh, near Guwahati in a joint channel with River Kopili. The Brahmaputra follows an almost west-southwesterly course along the northern part of the basin. River migration and meandering courses have formed numerous lakes, beels (local name for wetlands), swamps, palaeochannels and abandoned channels, especially in the vicinity of major rivers like Kolong and Kopili.

Methodology

The present study was chiefly based on primary data collected in the field by the researchers. The first step for determination of bankfull channel geometry was the selection of appropriate sites known as reference sites for field experiments. Once the reference sites were finalized, bankfull width, mean bankfull depth, floodprone width and entrenchment ratio were measured. Channel morphology data were collected for three seasons, viz. pre-monsoon (January–March), monsoon (April–September) and post-monsoon (October–December) between January 2012 and February 2016.

Selection of reference sites

Generally, sites along a river channel which have permanent gauging stations in some unaltered portions of a stream are considered as reference sites. Although the flow of the entire Kolong River is anthropogenically disturbed, four sites are identified as reference sites based on

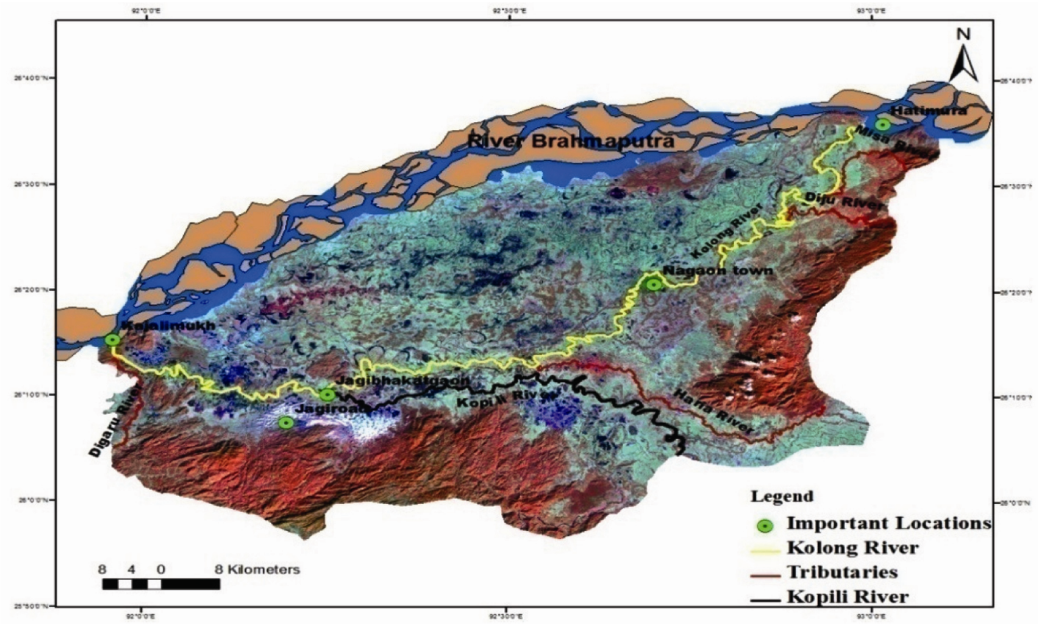

Figure 2. Catchment area of River Kolong.

their stable nature under the current hydrophysiographic and run-off conditions. These four reference sites are:

Site 1 (S1) = Kolong River near RCC bridge, Missamukh.
Site 2 (S2) = Kolong River near RCC bridge, Nagaon.
Site 3 (S3) = Kolong River near RCC bridge, Jagibhakatgaon.
Site 4 (S4) = Kolong River near RCC bridge, Kajalimukh.

Measurement of channel morphological characteristics

Bankfull stage was readily identified at all the reference sites by bankfull indicators, such as change of a vertical bank to a horizontal floodplain, and change in size distribution of materials along a bank. Occasionally vegetation was also used as a bankfull indicator.

In the present study, all the channel geometry measurements (bankfull width, bankfull depth, bankfull cross-section) were made with regard to the bankfull stage, and finally a comparative analysis was carried out between actually observed values and bankfull values (Figure 3). Measurements were done using measuring tape and graduated staff.

Secondary parameters, viz. bankfull cross-sectional area, width/depth ratio and entrenchment ratio were then calculated for each of the reference sites using the formulae

Bankfull cross-sectional area

= Bankfull width × mean bankfull depth.

Entrenchment ratio = Flood prone width/bankfull width.

Estimates of bankfull discharge were made using the following empirical relationship[15]

$$OD/BD = OQ/BQ,$$

where OD is the observed depth, BD the bankfull depth, OQ the observed discharge and BQ is the bankfull discharge. In the field, three of these parameters (i.e. observed depth, bankfull depth and observed discharge) were measured and thus the fourth parameter could be computed. Observed discharge was calculated for different seasons (pre-monsoon, monsoon and post-monsoon) using the continuity equation[16], and compared with the bankfull discharge (Figure 4).

Return period indicates the average number of years within which a given discharge will be equalled or exceeded. Return period corresponding to bankfull discharge was estimated from the flow frequency curves (Figure 5).

Results and discussion

Table 1 lists the bankfull dimensions as estimated from field survey.

The analysis of channel morphological attributes showed that bankfull width for Kolong River ranged between 31.75 and 200.34 m. The channel was wider towards downstream with a maximum value of 200.34 m at site S4. Bankfull depth exhibited an overall positive correlation to bankfull width and its values varied between 1.9 and 7.9 m (Table 1). Floodplain is generally asymmetrical in nature, throughout the river stretch, with a general trend of widening towards downstream. Distinct

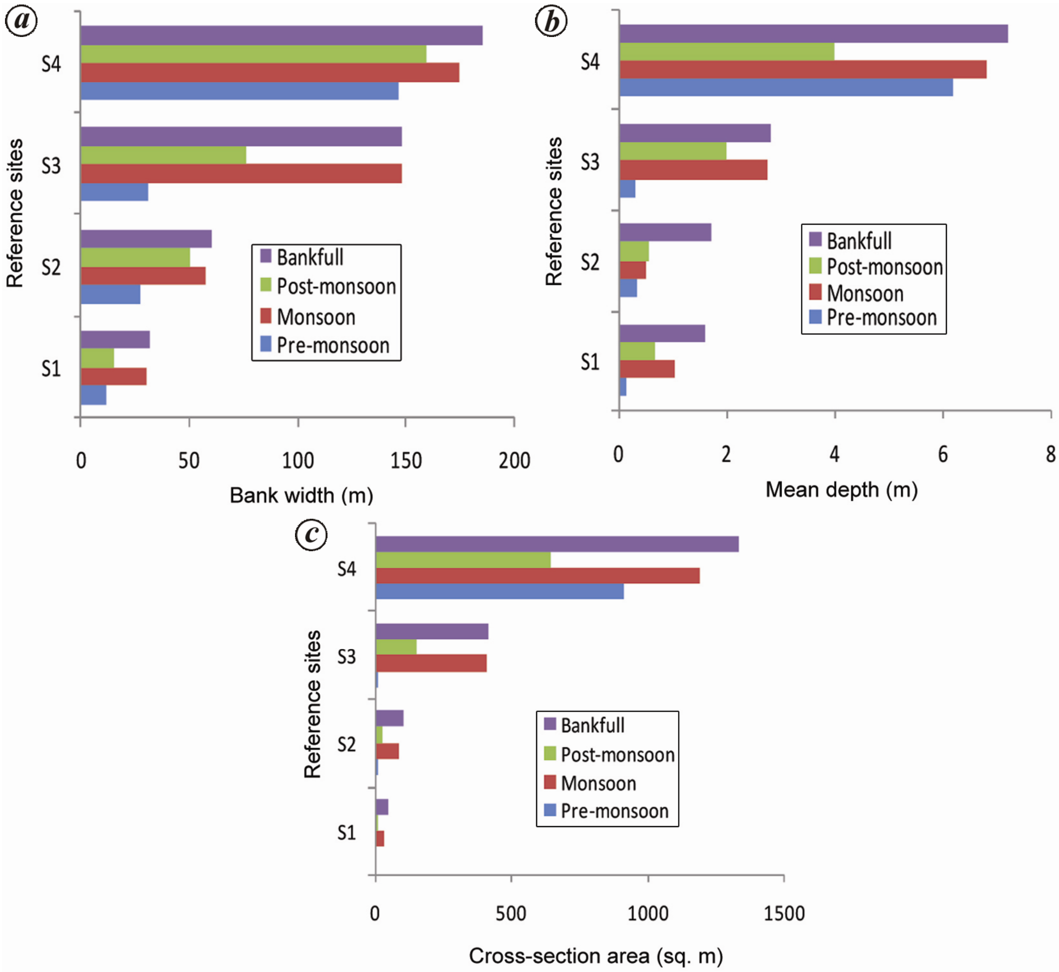

Figure 3. Difference between observed and bankfull channel morphological parameters. ***a***, Bank width; ***b***, Mean depth; ***c***, Cross-section area.

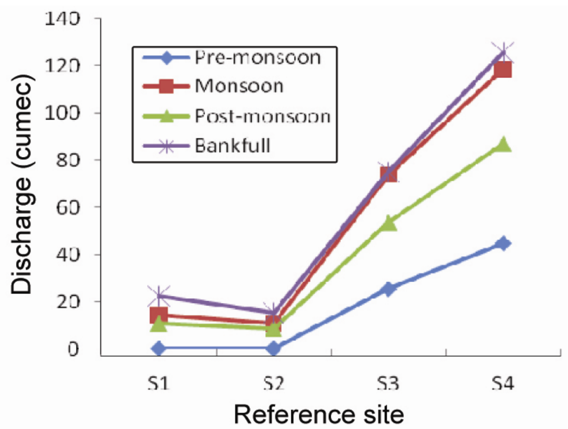

Figure 4. Seasonal variation of discharge at reference sites.

active floodplain was absent near Nagaon town, i.e. site S3, during the study period. Terrace development was also not a common scenario in the study area.

The entrenchment ratio defines the vertical containment of a river relative to its adjacent floodplain. According to Rosgen[8], entrenchment ratio in the range 1–1.4 represents entrenched streams; 1.41–2.2 represents moderately entrenched streams, and ratio greater than 2.2 indicates rivers only slightly entrenched in a well-developed floodplain. The Kolong River channel was found to be entrenched at all the reference sites, except at site S1 where the river channel was moderately entrenched, with an entrenchment ratio of 1.79. In case of an entrenched river channel, flood water is less likely to spill over stream banks, than in less entrenched channel.

Comparison of seasonally observed physical parameters of the channel against bankfull parameters showed that none of the parameters had crossed their limits during the study period; only during monsoon season did the parameters get close to their threshold limits, i.e. bankfull condition at all the four reference sites (Figure 3).

Bankfull discharge as mentioned earlier is an important parameter defining channel morphology and its determination is essential for proper channel design during stream restoration. Site S4 accounted for the highest bankfull discharge, i.e. 918.36 cumec, while the lowest

Table 1. Channel morphological attributes of reference sites

Reference site	Bankfull dimensions					
	Bankfull width (m)	Mean bankfull depth (m)	Bankfull cross-section area (sq. m)	Floodprone width (m)	Width/depth ratio	Entrenchment ratio
S1	31.75	1.9	60.325	56.75	16.71	1.79
S2	60.4	2.7	163.08	77.9	22.37	1.29
S3	148.5	5.5	816.75	203.5	27	1.37
S4	200.34	7.9	1582.7	221.99	25.36	1.11

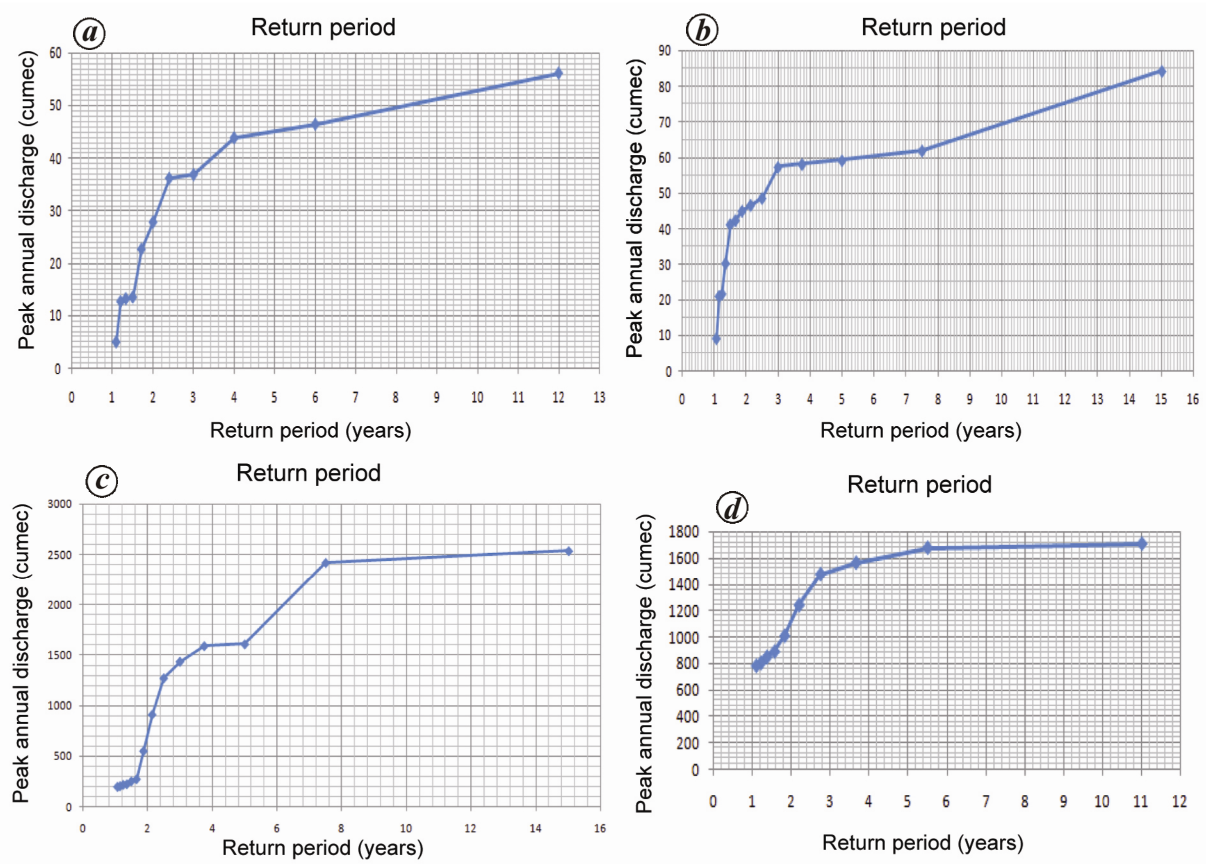

Figure 5. Flow frequency curves. ***a***, Site S1; ***b***, Site S2; ***c***, Site S3; ***d***, Site S4.

value was for site S1, i.e. 13.85 cumec (Table 2). The high difference in bankfull discharge between headwater and mouth is due to the confluence of River Kopili at site S3.

Figure 4 presents the variation of seasonal observed discharge with regard to bankfull discharge. Only during monsoon season, observed discharge was close to bankfull discharge; during lean seasons, discharge was observed to be much below bankfull discharge at all the reference sites (Figure 4).

The return period of bankfull discharge for River Kolong as estimated from the flow frequency curves (Figure 5) was found to range from a minimum of 1.6 years (at site S1) to a maximum of 1.8 years (at site S2), with an average of 1.7 years. The average return period was within the range of two years as reported in Leopold[9].

Hydraulic geometry of River Kolong

Hydraulic geometry is of great practical significance in the engineering and design of river restoration. The concept of 'hydraulic geometry' emphasizes the relationship between channel geometry and discharge, both at-a-station and along downstream direction of a given river. Channel geometry includes three variables, viz. width, mean depth and velocity. The hydraulic geometry relations inquire the rate of increase of these channel geometry

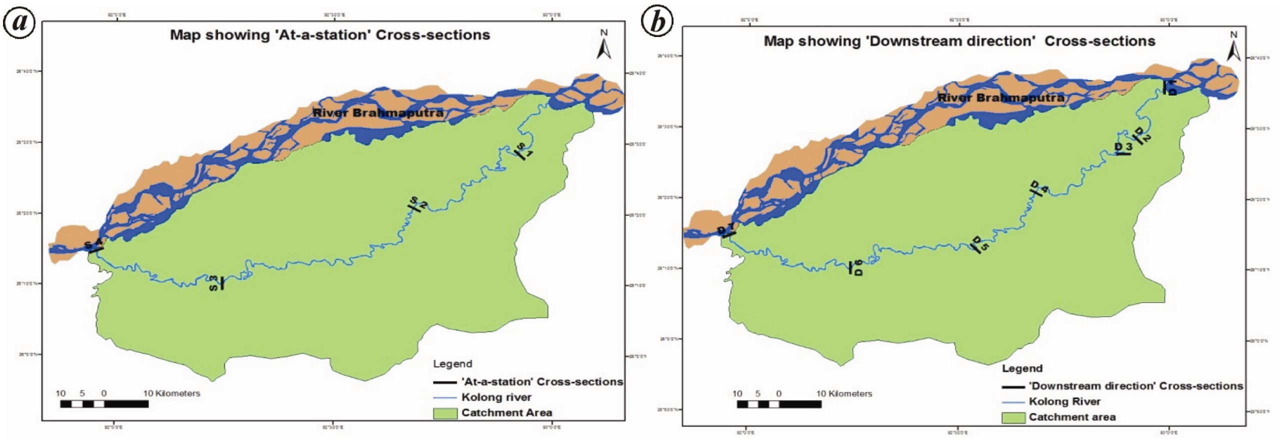

Figure 6. Maps showing cross-sections for hydraulic geometry study. ***a***, At-a-station; ***b***, downstream direction.

parameters with increasing discharge. The study of hydraulic geometry of River Kolong helps describe the pattern in which the river channel adjusts in cross-section and in longitudinal profile from its headwater to its mouth with changing discharge. Leopold and Maddock Jr[17] were the pioneers on the concept of hydraulic geometry. They expressed the hydraulic geometry relations for a stream in the form of power functions of discharge as

$$W = aQ^{b},$$

$$D = cQ^{f},$$

$$V = kQ^{m},$$

where W is the channel width (m); D the mean channel depth (m); V the flow velocity (m/s); Q the discharge corresponding to the channel dimensions (cumec); a, c and k are coefficients; and b, f and m are the exponents expressing the rate of change of W, D and V with Q respectively.

Under normal conditions the hydraulic variables – width, depth and velocity satisfy the continuity equation

$$Q = W \times D \times V.$$

Therefore, the exponents of hydraulic geometry relations should satisfy

$$b + f + m = 1.$$

The present hydraulic geometry study has been divided into two parts. The first part incorporates the verification of behaviour of width, depth and velocity at the four reference cross-sections along the river channel as the flow varies, known as 'at-a-station hydraulic geometry' (Figure 6*a*). While in the second part, progressive variation of the same variables in the downstream direction with increasing discharge of constant frequency is described for seven stations in the downstream [Hatimura (D1), Missamukh (D2), Dizumukh (D3), Nagaon (D4), Hariamukh (D5), Jagibhakatgaon (D6) and Kajalimukh (D7)], known as 'downstream direction hydraulic geometry' (Figure 6*b*). At each cross-section the observed width, depth and velocity are plotted against discharge on log–log plot and thus each variable is displayed as a power function of discharge, with certain coefficients and exponents.

At-a-station hydraulic geometry: Figures 7 and 8 and Table 3 show the rates of change of width, depth and velocity with discharge at the reference sites, where b, f and m are the rate of change of width, depth and velocity respectively. Figures 7 and 8 indicate that all the three variables increase with increasing discharge at all the four stations. The graphs relating width to discharge indicate that in all the stations, except S1, the rate of change of width with respect to discharge is trivial. The mean value of b is estimated as 0.22, which is close to the mean b value given by Leopold and Maddock Jr[17]. The smaller b values suggest the rectangularity of the river channel[18]. Both the depth and velocity, however, experience rapid changes with increasing discharge at each cross-section, indicated by the higher values of f and m. The points on the curves for depth and velocity clearly indicate that both are closely related.

On an average, at-a-station exponents reveal that as the discharge increases the width increases to about 0.22 power, depth to 0.38 power and velocity to 0.4 power of discharge. This indicates that stream flow gets faster and its depth deeper as discharge increases and there is reasonably diminutive change in width. The experimental result of '$b + f + m$' is approximately 1 in all the four stations (Table 3), thus supporting the continuity equation.

Downstream hydraulic geometry: This is determined for River Kolong in which stream flow characters are plotted for different cross-sections along the length of the river.

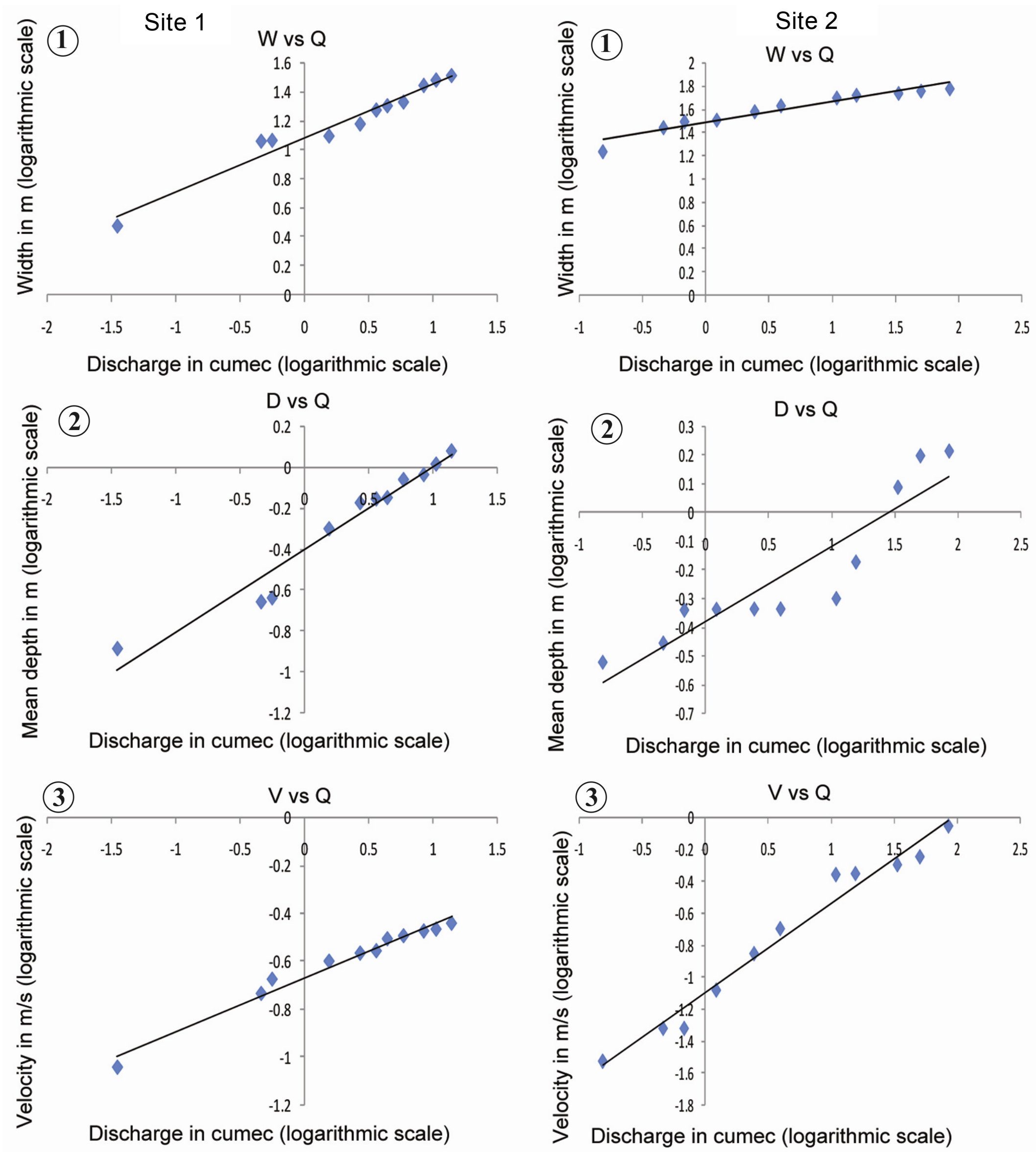

Figure 7. Relation of hydraulic variable (1) width (W), (2) depth (D) and (3) velocity (V) to discharge (Q) of River Kolong at site S1 and site S2.

Table 2. Calculation of bankfull discharge

	Observed		Bankfull	
Site	Depth (m)	Discharge (cumec)	Depth (m)	Discharge (cumec)
S1	0.65	4.74	1.9	13.85
S2	1.12	18.55	2.7	44.72
S3	2.49	127.9	5.5	282.51
S4	6.38	741.67	7.9	918.36

Generally, comparison of various cross-sections downstream along the length of a river is valid only when they experience constant frequency of discharge. On the basis of this average annual discharges of the cross-sections in the downstream direction are considered for 'downstream hydraulic geometry' calculations[17]. In Figure 9, width, depth and velocity corresponding to average annual discharges are plotted against average annual discharge for the downstream reference sites. Each reference cross-section is depicted as a point in each diagram, with the abscissa representing the average annual discharge.

Figure 9 indicates that width, depth and velocity of River Kolong increase as a log-linear function of discharge in the downstream direction. Proceeding downstream, the hydraulic geometry relations provide b, f and m values of 0.32, 0.23 and 0.44 respectively. Based on the above downstream hydraulic geometry relations, we can infer that velocity increases most rapidly with discharge in the downstream direction, followed by width and depth.

Leopold and Maddock Jr[17] argued that downstream hydraulic geometry relations for many of the world's

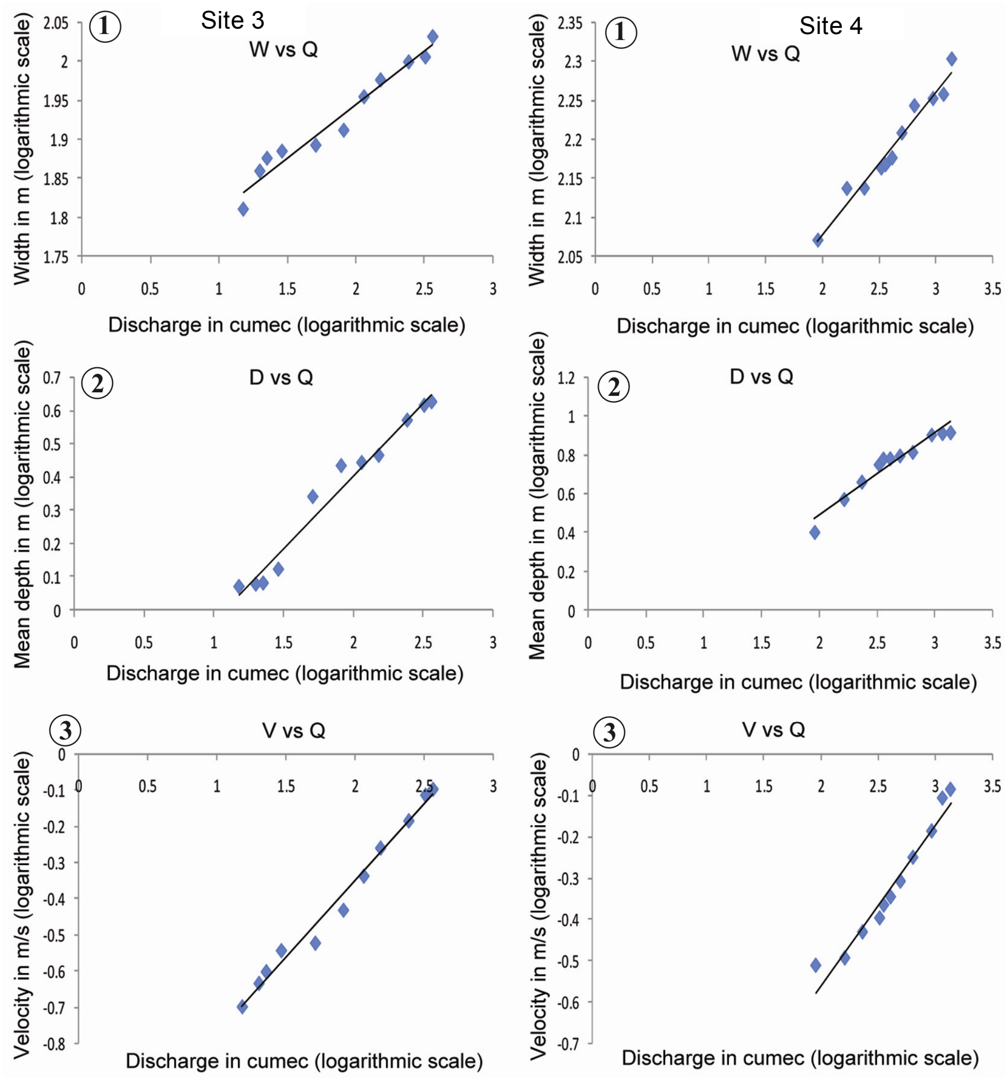

Figure 8. Relation of hydraulic variable (1) width (*W*), (2) depth (*D*) and (3) velocity (*V*) to discharge (*Q*) of River Kolong at site S3 and site S4.

Table 3. Summary of rate of change of width, depth and velocity in relation to discharge

Reference sites	b	f	m	$b + f + m$
S1	0.37	0.404	0.224	0.99
S2	0.18	0.26	0.557	0.99
S3	0.137	0.437	0.425	0.99
S4	0.183	0.422	0.39	0.99
Mean	0.22	0.38	0.4	1

b, f and m are the exponents expressing the rate of change of width, depth and velocity with discharge respectively.

watersheds follow a common trend (i.e. $b = 0.5$, $f = 0.4$ and $m = 0.1$), with a stream getting wider downstream in relation to its depth, while velocity exhibits minimal rate of change. However, downstream hydraulic relations for River Kolong differ from this common pattern, experiencing highest rate of increase of velocity with discharge in the downstream direction. This aberrant behaviour due to the fact that its velocity is almost insignificant near the headwater due to anthropogenic interferences in the form of embankment at that section, thus curbing the entry of water at source and leaving the river only with the monsoon run-off. On the contrary, in the downstream direction velocity increases significantly towards the mouth contributed mainly by discharge of the inflowing tributaries. Thus, based on the above discussion, we can conclude that regional factors unique to this river subsequent to human intervention in 1964 influence the general hydraulic pattern of River Kolong regime.

Conclusion

Proper knowledge and understanding of channel morphological parameters are valuable for the planning and design of river restoration projects as they provide valuable inputs for various integral designing methods, such as engineering modelling and empirical hydraulic geometry relationships. The present study shows that the exponents for 'at-a-station' hydraulic geometry relationships are within the range of values reported in previous standard works, although the downstream relationships indicated that River Kolong tends to experience greater change in velocity and lesser with regard to depth, than the internationally known average pattern. This is because of the large variation in velocity between its headwater and mouth, which can be primarily attributed to the altered river regime. Thus, the proposed river restoration scheme will involve partial reconstruction of the existing channel, which has otherwise been severely degraded. The channel reconstruction requires criteria for estimating channel size and configuration, and thus the derived hydraulic geometry relations can be effectively used after due appraisal for planning and preliminary design, towards restoration and rehabilitation of the river. Consequently, by considering bankfull discharge as the design discharge for River Kolong, the hydraulic geometry formulae can be used for designing the physical dimensions at bankfull or channel-forming discharge, which in turn will help in flow simulation during restoration process. Further analyses of the application of these relationships in flow routing are required in future.

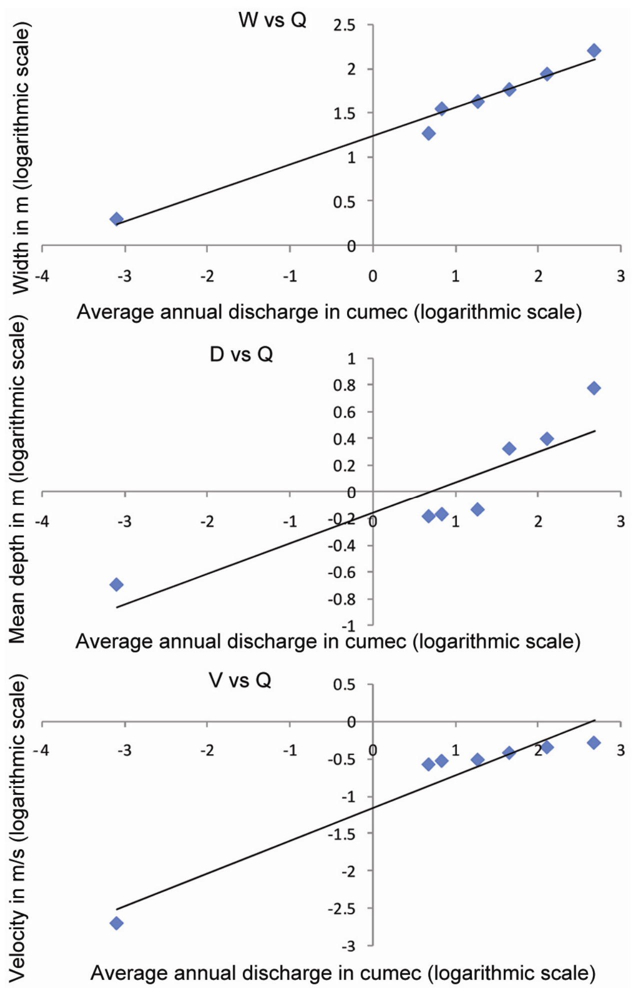

Figure 9. Relationship of width (*W*), depth (*D*) and velocity (*V*) to discharge (*Q*) in the downstream direction.

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