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REVIEW ARTICLE

FORMS, PROCESS AND MEASUREMENT OF BRAIDED RIVERS: A REVIEW

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ABSTRACT

Braiding is one of the three main types of river planform. They are mainly characterized by high energy distribution, steep slopes, fluctuating discharge, abundance of sediments, bank erosion along with bar formation. This review paper is an attempt to present a comprehensive summary on braided river environments, process of braiding, the differences in the making of the type of bars and the measurement of braiding intensity. Bank line erosion along the braided river is associated with the bar or island development. Effect of tributaries to the main channel planform is quite significant as it provides water and sediments both. The measurement of braiding intensity is another important factor which is hard to measure against the dynamism of the flow and renewed shape of the bar more often. The Channel Count Index is found to be more appropriate to measure braiding intensity as it is less sensitive to the flow stage and provides a higher level of accuracy. Interdisciplinary approach for braided river management is required to preserve the ecological diversity and lessen the adverse effect of bank erosion hazard.

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1. INTRODUCTION

A braided river has several sub-channels separated by numerous braids or bars within the main channel flow(Kale, V.S. & Gupta, A., 2001).Miall (1977) distinguished braided rivers are those comprising several waterways are of lower sinuosity and carry a coarser sediment load than the meandering rivers. Coleman (1969) found successive divisions and re-joining of the flow around depositional bars and islands in the braided channel. Braided rivers are highly dynamic and rapid changes can take place in order to make adjustments to the flow regimes. There are many instances where for short reaches braiding can change into meanders or straight patterns or vice-versa, it is mainly due to the local variation in slope, sediment and flow velocity. The braided rivers are observed in all types of climates (Miall, 1977), yet the appearance of braid types is not the same. Overall, the braided river is mainly comprised of wide channels, higher slopes, higher discharge and load, rapid shifting of bed materials, continuous shifting of the river course. The pattern of the channel itself reflects the evident of 'aggradation' rather than the 'overloaded' (Leopold, LB., Wolman, M.G. & Miller, J.P., 1964).The braided channels have generally high width-depth ratio, the Platte river is a classic example of braided rivers in the Alpine climate, used to be termed as 'a mile wide and an inch deep' by the American pioneers (Morisawa, 1985). Some of the other braided rivers found in the humid climates include the Brahmaputra, the Kosi, the Ganga etc. Leopold and Wolman (1957) attempted to define the difference between braided and meandering channel through discharge and slope.

$S = 0.06Q^{-0.4}$ (where, S = slope and Q = discharge)

For a given discharge, a braided channel has a greater slope than meandering channel and at a constant slope, the braided channel has a higher discharge than meandering course. Extensive study has been done over the years through flume experiments (Leopold, L.B. & Wolman, M.G., 1957) (Egozi, R. & Ashmore, P., 2008)or in the fields (Fahnestock, 1963; Brice, 1964; Coleman, 1969; Smith, 1970 etc.) to understand the required conditions for braiding, the process and associated landforms and its measurement. Braiding can occur in both the proglacial conditions associated with diurnal fluctuation in discharge and coarser bed materials or in the monsoonal climates with seasonal discharge fluctuation and finer bed materials. The purpose of the work is to present an unified account on:

- Suitable environment required for the formation of braid.
- The process involved in the formation of braiding.
- Nature and types of braiding.
- Hydraulic characteristics of braided river.
- Different techniques available to measure the braiding intensity.

2.1.Suitable environment for the formation of braid: The combination of eight variables (discharge, the amount of sediment load, the calibre of load, width, depth, velocity, slope and roughness) or might more affect the continuum of natural channels. The reflectance of hydraulic independent factors of discharge, the amount and calibre of load upon the dependent hydraulic factors of width, depth, velocity, slope and roughness represents the quasi-equilibrium condition (Leopold, L.B. & Wolman, M.G., 1957). The pattern of braided channel is a combinational value of those parameters which forms the characteristics of braiding rather than straight and meandering channel.

2.1.1.Steeper Slope: Braiding is generally associated with mountainous regions, especially proglacial or intermontane valleys and semi-arid regions or alluvial fans where the slope is generally steeper, along with they are also found in the lower piedmont zone (Ashmore, 2013). Braiding environment comprises of the abundance of sediment load and high stream power, but the load of sediments is unable to be carried forward.

2.1.2.Highly variable discharge: It is another important element of braided river characteristics, though not necessarily. It was suggested that the two streams with same mean annual discharge will pose different characteristics, if there is a uniform flow throughout the year in one channel and periodic flooding on the other (Fahnestock, 1963). During flood the river Brahmaputra can carry 2.5 million cusecs of water and carries 1 billion tons of sediment yearly. Large discharge and heavy sediment load cause the river to be unstable and further constant lateral migration (Coleman, 1969).

2.1.3.Abundant sediment supply: They are associated with the river discharge, as they increase with the increase in discharge. Braiding is a type of adjustment that may be made possible in a channel, due to too much load to be carried forward by a single channel (Leopold, L.B. & Wolman, M.G., 1957). Braiding environment comprises steeper slope, fluctuating discharge, heavy load of sediments which are the components of independent climatic, hydrologic and geological factors (Ashmore, 2013).

2.1.4.Erodible nature of banks: The process of avulsion is associated with switching of the flow from one channel to another (Charlton, 2008) and rapid changes in the thalweg point occur due to fluctuating discharge and erodible bank which can change the hydraulics of the river in a short span of time.

2.1.5.Wider and shallower channels: Abundant supply of coarser materials and formation of bar or islands within the channel flow cause the river to be unstable. The bed and banks of the White river channel are deficient in silt and clay materials and composed of non-cohesive and erodible materials which provides an abundance of load throughout the year (Fahnestock, 1963). Thus, the river make its path through active erosion of the banks, thereby the channel gets wider and shallower. The width-depth ratio at Brahmaputra river ranges from 100 to 240 (Kale, V.S. & Gupta, A., 2001) while the same ranges between 10 to 71 in 112 channels in White river with a standard deviation of 9.9 (Fahnestock, 1963).

2.2.The process of braid formation: The braiding planform is generally associated with the formation of the bars. There has been considerable analysis, both on the basis of flume experiments and field observations of braiding process. The development of the central bar begins as the coarser fraction of the load, cannot be transported locally(Leopold, L.B. & Wolman, M.G., 1957).While Coleman (1969) found the major cause of developing bars in the middle of the channel is the slack water condition or reverse eddies. As the initial growth of the bar starts, continues to grow downstream and end through the deposition of further bed materials. The bar continues to grow in height as well due to continuous deposition of the sorted materials which forces river to be diverted into several channels. The growth of the bar decreases the cross sectional area of the channel, compensates its by lateral downcutting of the banks and often the bars come up with semi-stable vegetated island(Leopold, L.B. & Wolman, M.G., 1957) (Coleman, 1969).

The bars or islands of the Middle and North Loup rivers are consist of fine and medium grained sand not mandatory of coarser materials as found in the flume experiment or in the White river by Leopold and Wolman (1957). The **North** and Middle Loup rivers, originating in the sandhills are braided rivers, where the bed and bank materials are mainly formed of sand and minimum percentage of gravel or pebbles (<5%). While the South Loup river appeared as sinuous river, where the banks are cohesive consist of silt and clay. Due to the smaller size of the sediment, most of the them are transported through the suspension load (Brice, 1964). The analysis of river bank erosion in the Ganga river, upstream of the Farakkka barrage to Rajmahal from 1955 to 2005 suggeststhat the morphometric measurements, such as Sinuosity Index, Braided Index and percentage of island area to the total area of the river in the reach increased rapidly(Thakur, P.K.,Salui, C.L. & Aggarwal, S.P., 2012). The reason of bank erosion hazard here is the soil stratification in the river bank, the presence of hard rock formation (Rajmahal), heavy load of sediments and construction of Farakka barrage. Since 1977 there have been 1670 ha of agricultural land loss to the river has been observed in Manikchak and Kaliachak-II blocks of Malda district. Yet there are some constrictions or nodal points (Jogighopa near Goalpara, Pandu near Guwahati, Tezpur and Bessemora, Majuli in Brahmaputra river) which control the width of the channel due to hard rock formation (Akhtar, M.P.,Sharma, N. & Ojha, C.S.P., 2011).

2.3.Nature and types of braid and bars: Bars are the accumulation of different sized materials such as, gravels, peebles, sands etc. in the channel-ways. While braid refers to the mosaicking composition of bars separated by multiple channels. The formation of the bars or the islands in the braided river is due to the abundance of sediments and the inability of the river to carry it forward. The South Platte river in Colorado and Nebraska, consisting of numerous longitudinal and transverse bars helped to analyse the distinction of composition and the kind of environment involved in making the different type of bars. The appearance of the bar depends upon the texture of sediment load (Smith, 1970). The median size of the sediments found in the bars of the Brahmaputra riveris in between 0.028mm to 0.34 mm size. The slope upstream of the bars issteeper and lessening downward. In the flood cycle, the area of the bars or islands remains approximately same, only the shape and the position changes (Coleman, 1969). In laboratory experiments made by Leopold and Wolman (1957), braiding process initiated with the formation of the central bar as the coarser fraction of the

Table 1. Classification scheme on Type of bars

Authors	Type of bars	Remarks
Coleman (1969)	Sand waves	Diamond shaped large deposition of sands (8 to 15m in height and 180 to 900m in wavelength) and has steep slope in the upstream end.
Smith (1970)	1.Longitudinal (Diamond shaped) 2.Transverse (Lobate shaped)	Longitudinal bars are made of mainly coarser materials, found in the upstream. Transverse bars are found in the downstream and composed of finer materials and evenly sorted.
Smith (1974)	1.Unit bars 2.Compound bars	Unit bars are mainly formed by deposition and has simple evolution history. Compound bars have complex and episodic history of erosion and deposition.
Miall (1977)	1.Longitudinal 2.Longitudinal with diagonal flow 3.Eroded bar remnant 4.Linguoid 5.Modified Linguoid 6.Point	The bars have been classified from small rivers to average sized rivers. Mainly there are two types; longitudinal and transverse or linguoid, the others are modified forms of the former.
Church & Jones (1982)	1.Longitudinal bars 2.Transverse bars 3.Point bars 4.Diagonal bars	All of these are part of unit bars. Point bars are elongated to the direction of the flow. Diagonal bars run across the channel and attached with the banks.
Robert (2003)	1.Medial bars 2.Lateral bars	Medial bars have symmetrical and lobate shaped. Lateral bars are asymmetrical and connected to one bank.

Table 2. Different techniques and formulas to measure the braiding intensity

Braiding Intensity Indices	Author	Formula	Remarks
1.Bar Indices	Brice (1960,1964)	$B_b = \frac{2\sum L_b}{L_r}$	Highly sensitive to the river stage of discharge.
	Germanoski & Schumm (1993)	$B_b = \frac{2\sum L_b}{L_r} + \frac{\sum N_b}{L_r}$	Modification of Brice's Index, focuses on number of bars also.
	Rust, 1978	$B_\lambda = \frac{\sum N_L}{\lambda}$ $= \frac{\sum N_L}{1.25Ẋ}$	Less sensitive to the river stage as compared to the Brices's index, helpful to measure in the intermediate stage between expansion and contraction phase.
2.Channel Count Index	Howard et. al, 1970	$B_{T1} = \frac{<N_L>}{X}$	Not preferable as certain cross section might not converge the links.
		$B_{T2} = \frac{<N_L>}{p \quad r \quad h}$	Its variability depends on the flow stage and visibility of bars.
		$B_{T3} = \frac{<N_L>}{w \quad cha \quad li}$	Less sensitive to sinuosity and flow stages, thus most preferable at present.
3.Channel length (Sinuosity) Index	Hong & Davis (1979)	$P_T = \frac{\sum L_L}{L_r}$	Useful in the contraction phase of braiding.
	Mosley (1981)	$P_T * = \frac{\sum L_L}{\sum L_M}$	Highly sensitive to the flow stages.
4.Plan Form Index (2004)	Sharma (2004)	$P = \frac{\frac{T}{B} \times 100}{N}$	Not suitable in the expansion phase of braiding.

L_b	Length of bars	<NL>	Mean number of links per reach
L_r	Length of reach	L_L	Length of links
N_b	The total number of bars	L_M	Length of main channel links
N_L	Number of links	T	Flow top width
λ	Channel wavelength	B	Overall width of the channel
Ẋ	The distance between successive confluence and bifurcation	N	Number of braided channels
XS	Cross-section		

load in the flume channel was unable to be carried forward. But braiding in natural channels ismainly formed by two processes depending on the grain size and the amount of load; the aggradation of the longitudinal bars and dissection of the transverse bars (sometime longitudinal bars) (Smith, 1970).

2.3.1.Longitudinal bars

The longitudinal bars mainly composed of coarse and poorly sorted sediments in the upstream. When the coarse fraction of load gets stuck upstream, the finer loads of the river become trapped downstream, the ridge-shaped bar starts to build under the water surface(Smith, 1970). When the water level recedes, the flow of the channel gets dissected. These types of bars are long and narrow, inclined or convex on the top and the size of the sediments decreases downward of the river. The longitudinal bars are also originated due to the breaching of transverse bars by the prevailing current (Brice, 1964).

2.3.2.Transverse bars

The transverse barsfound at the confluence point where the width of the channel expands abruptly (Charlton, 2008). They are flat topped, better sorted deposition of fine materials, occurs due to the downstream migration of fore-sets, perpendicular to the current direction. It continues to be built in planar sheet form deposition and the width of the bar expands downstream. The most submerged bars in Loup river are lobate or wedge shaped, formed at shallower depths characterised by medium or fined grained sand(Brice, 1964). They are found downstream of the longitudinal bars and the ratio of transverse to the longitudinal bars increases downstream.

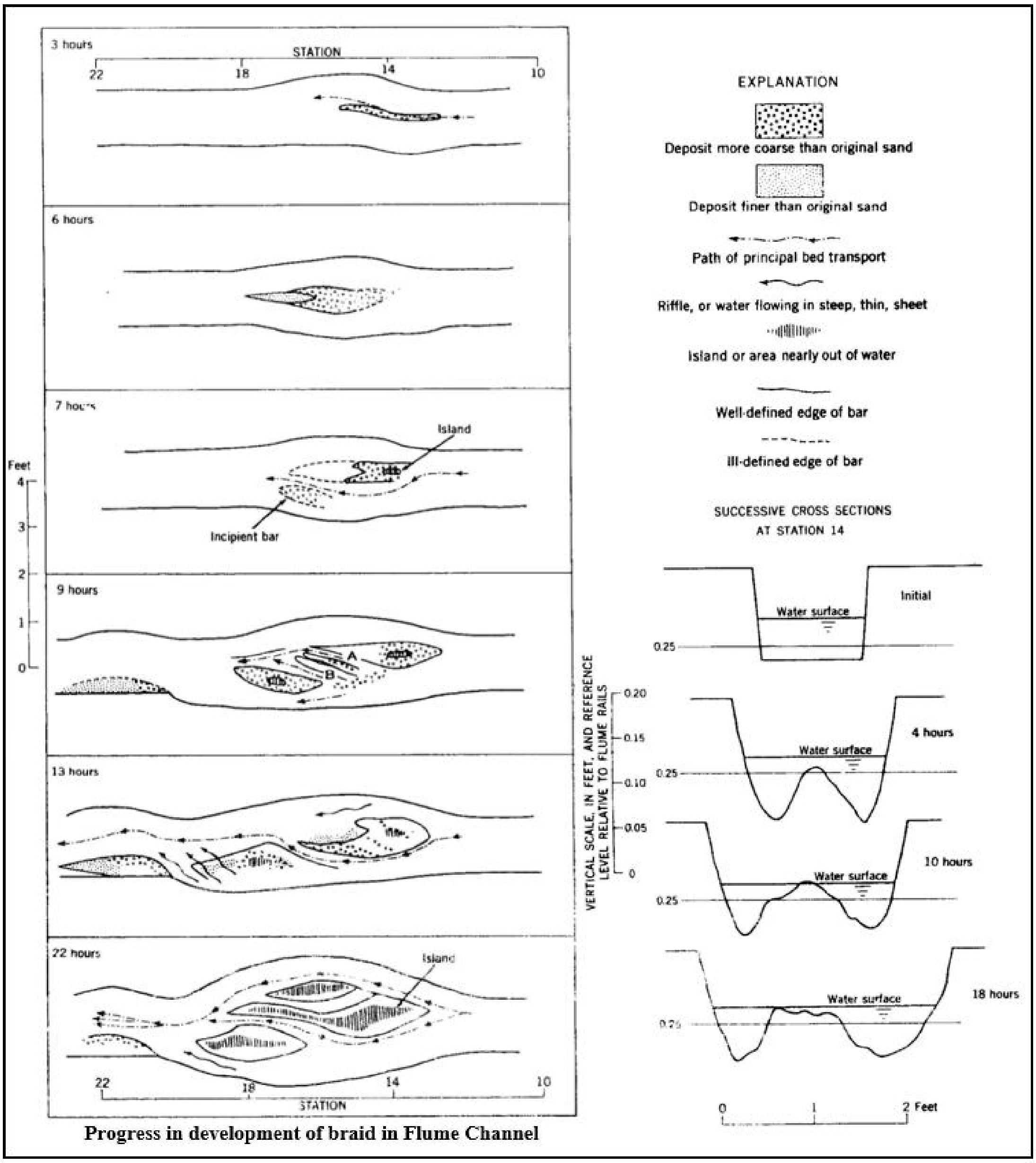


Figure 1. Sketches and cross section in the progress of braid development in flume channel (February 16-22,1954) (Source- Leopold et. al, 1957)

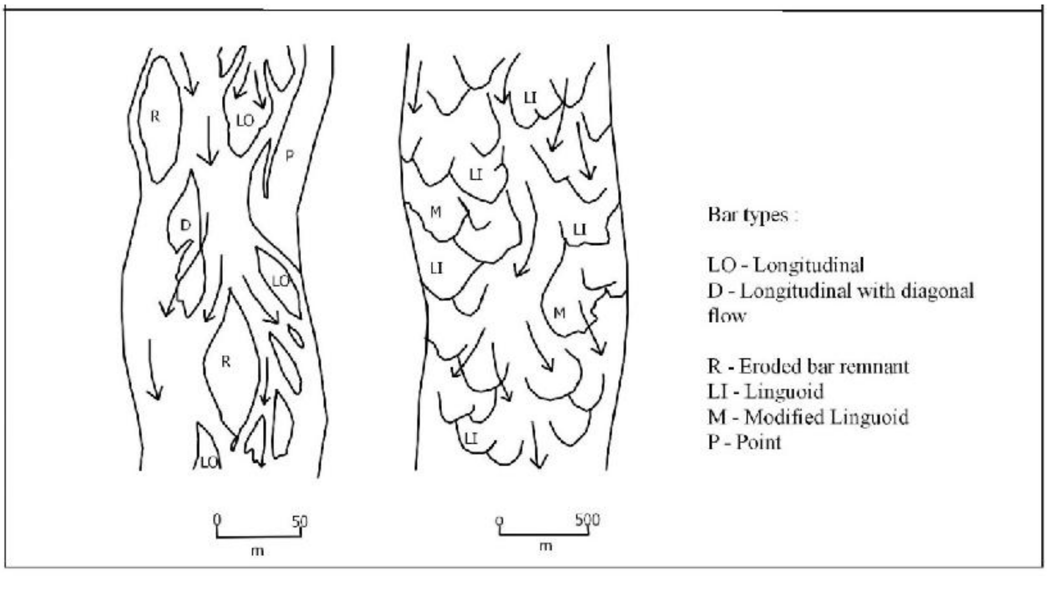


Figure 2. Type of Bars (After Miall, 1977)

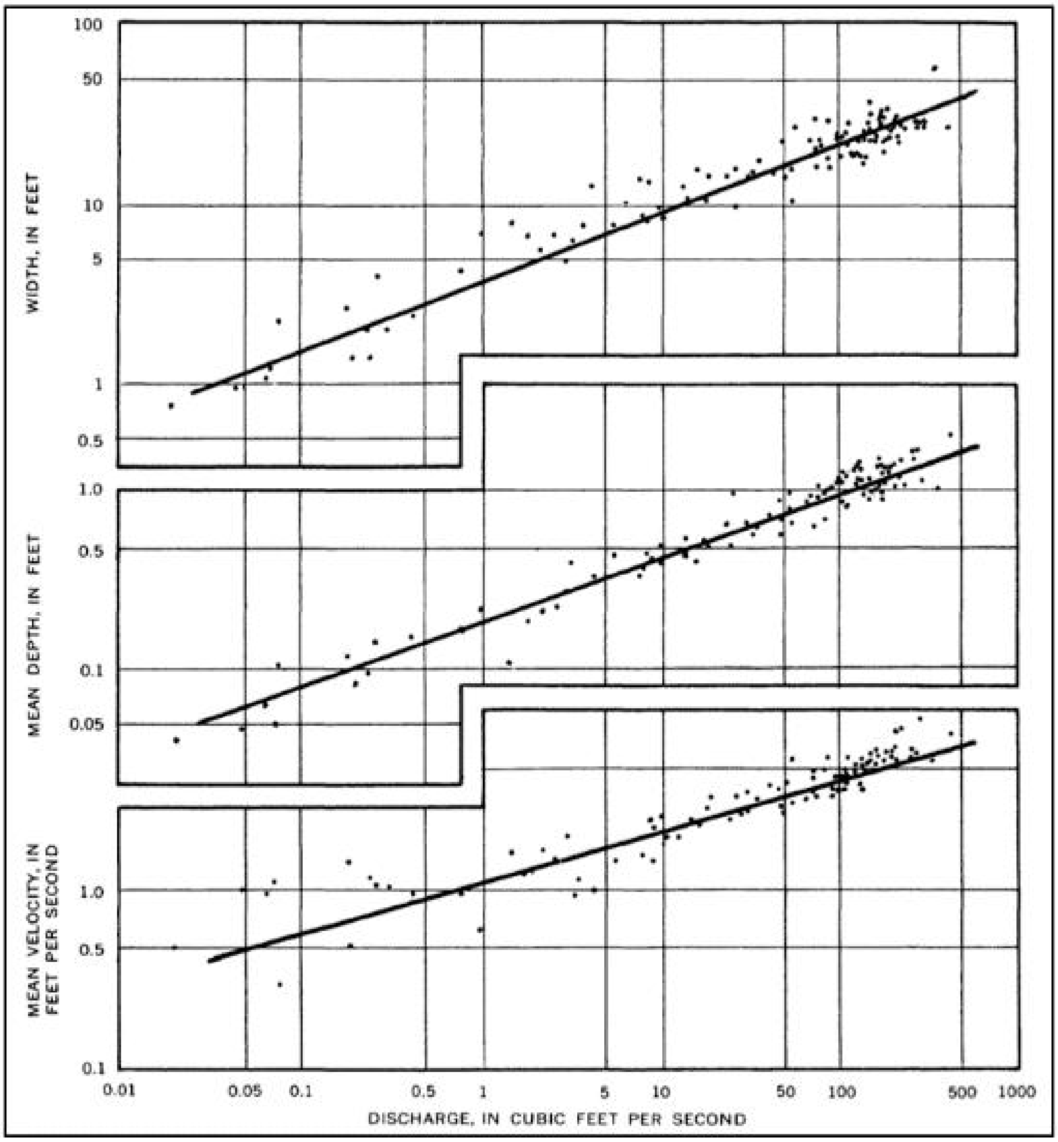
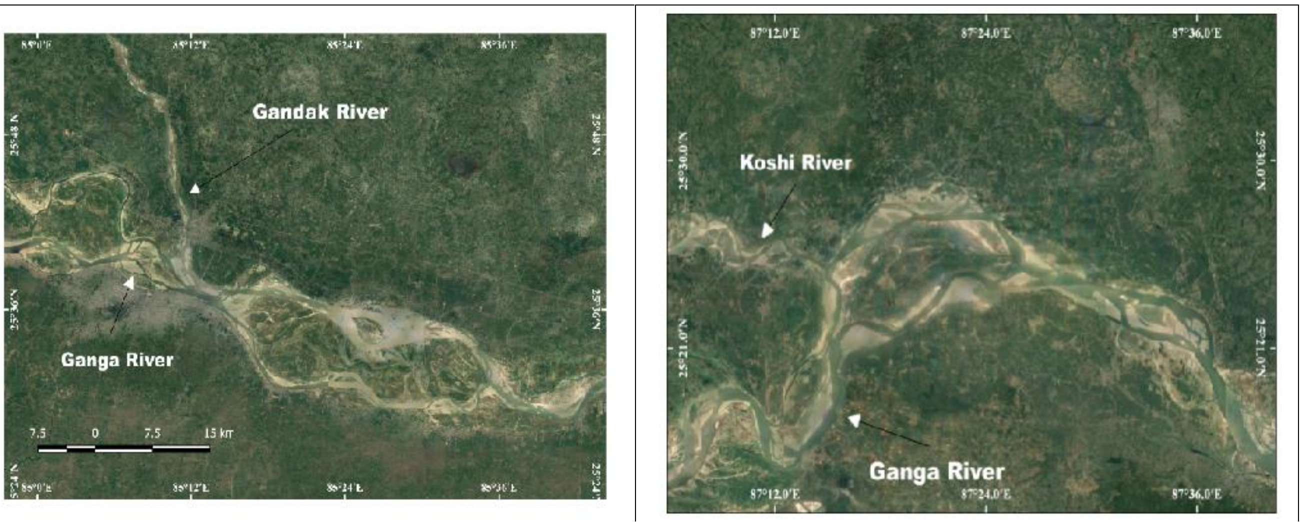


Figure 3. Relation of mean velocity, mean depth, and width to discharge of the White River channels (After Fahnestock, 1963).



(Source: The Google Earth Landsat Satellite Image, 2020)

Figure 4 . (a) Ganga and Gandak river confluence (b) Ganga and Koshi river confluence

The longitudinal bars are comprised by crude horizontal stratification and transverse bars shows better sorted planar cross stratification(Smith, 1970).

2.4. Hydraulics characteristics of braided river: Braided channels have a fairly unstable morphology and complex process, can be found over a range of environments. The hydraulic characteristics can define the range of adjustments can be made by braided channels to the prevailing conditions, the extent of braiding, local variability and dynamics of flow (Ashmore, 2013). Braided channels, adjust readily to changes as there is variation in discharge. Values of exponents of width*(b)*, depth*(f)*and velocity *(m)* for at-a-station geometry in White river channels (0.38, 0.33 & 0.27 respectively) were found to be averaged as found in the South-Western streams (0.26, 0.34 & 0.40 respectively) by Leopold and Maddock (1953). But extremely low values for width *(b)* exponents between 0.04 to 0.08 in Brandywine creek, thought to be the cause of the cohesive nature of bank materials and the high depth*(f)* and velocity*(m)* exponents (0.41 & 0.55) are primarily a factor of scour and deposition determined by previous discharge and higher slopes (Fahnestock, 1963). Though the exponents are quite variable yet sometime the width exponent is as high of 0.5 or more (1.0), as there is no changes with depth and velocity except the widening of the channel (Ashmore, 2013).

If the banks are made of consolidated or cemented materials (constriction or node points), then the channels must scour deep to accommodate the discharge and the transportation of sediment increases. The immediate below of those node points channel gets wider and shallower due to the formation of islands or chars and therefore cross-sectional area increases by lateral down cutting of banks (Coleman’s view of Brahmaputra river, 1969). The construction of barrage in the upstream of Ganga river has increased the bank erosion process and braiding intensity significantly (Singh, P.,Patil, R.G. & Singh, A., 2018)**.**

2.4.1.Hydraulic factors in relation to the tributaries: The contribution of tributaries to the main channel often complex the braiding intensity of the main channel. Downstream of the confluence of Dismal river and Middle Loup river, width and are a increase considerably and with the increasing discharge, but there is no such change has been found in slopes (Brice, 1964). The Ganga river with the confluence points of tributaries (such as Gandak, Koshi), the effective width and area in the main river channel increases to accommodate the combine discharge and sediments of the tributaries. The vegetal growth on bars and islands downstream of the confluence zone helps to stabilize those islands and does increase the braiding intensity.

The sequence and characteristics of braiding observed in flume experiment was same as observed at Horse Creek near Daniel, Wyo., where bar formation deflected the main channel course and widened the channel width. The channel width was primarily seemed to be a function of bank-full discharge. Yet the ratio of the width of the divided to the undivided channel was found between1.6 to 2.0 in the natural rivers and 1.05 to 1.70 in the flume. The ratio of slope between divided to undivided channel was more than 3 times in natural channels and 1.3 to 1.7 times in the flume. The ratio of depth of the same 0.6 to 0.9 in the natural channels and 0.5 to 0.9 in the flume channel (Leopold, L.B. & Wolman, M.G., 1957).

2.5. Techniques and formulas to measure braiding intensity: Braiding intensity is the measurement of complexity and frequency of bars in a braided channel. The study of braided channel measurement is essential to analyse the morphology and dynamics of progress of braiding in channel network. A series of experiments of small scale physical braided channel model were made in a flume using constant-discharge several times, along with the hydrographs and the braid indices were measured by Egozi and Ashmore (2008).The type of measurement on braiding has been divided into three parts; (Table 2); on the basis of bar dimensions and frequency (e.g. Brice, 1960, 1964; Rust, 1978; Germanoski and Schumm, 1993), number of channels in the network (e.g. Howard et al., 1970) and total channel length in a given river length(e.g. Hong and Davies, 1979; Mosley, 1981) (Egozi, R. & Ashmore, P., 2008). Plan Form Index (devised by Sharma, 2004) reflects the exposed bars or islands against the given water level and its lower value is indicative of higher braiding intensity. The PFI value of less than 4 was considered as highly braided, 4 to 19 as moderate and more than 19 to be low (Akhtar, M.P.,Sharma, N. & Ojha, C.S.P., 2011). Reach length at least 10 times of the wetted width (with 20% precision of the mean) would result satisfactorily for Braid Indices. While for Channel Count Indices minimum 10 cross sections needed, each cross section should be at least apart of the average wetted width of the channel (Egozi, R. & Ashmore, P., 2008). Frequency and exposure of bars or islands are sensitive to the flow stages, the values can change dramatically during bank-full stages. The channel count index (BI_{T3}) is most preferable as it is less sensitive to sinuosity and flow stages. They can be measured through oblique photographs and has the smallest co-efficient of variation at different river stages (Egozi, R. & Ashmore, P., 2008). They should be measured at different stages for better assessment of the river dynamics.

3.Research gaps: The braided channel morphology and dynamism has been studied extensively through the analysis of controlling parametric characteristics in different climatic environments. The focus on the some of the facts might result in fruitful future understanding of braided rivers.

The effect of tributaries on the main channel has significant importance in terms and discharge and sediment load. After the immediate confluence point of main channel and tributaries, the main channel tends to be wider and channel bifurcation increases. The analysis of hydraulic and other independent characteristics upstream and downstream from the confluence point would present a better understanding of the braiding characteristics.

The grain-size component of a river differs significantly region to region. If the dominant grain size has any control upon the size of the bars or islands!

The deposition comprising of ex-situ materials of braided river might help to analyse the ecological environment of the source area.

Braided rivers are observed in almost all the climates. Rate of growth of bars over different climatic braided rivers would be valuable for the to analyse the historical background.

The appearance of bars are sensitive to the flow stage of a braided river. The braided intensity increases with the decreasing river stage. Thus, the measurement of braided intensity might provide biased result.

4. Significance of the study: A careful study of the geomorphological setting of an area is of immense interest to carry out management policies. The present study attempts to explain the several aspects associated with the braiding river plan form. Protecting development against flooding and conserving the ecological richness in the braided channels are difficult to manage. Approaches depends on the nature of targets to be achieved. Thus, braided river management requires an interdisciplinary approach of river engineering, environmental studies, geomorphologists, scientists, planning managements, land managements and other communities.

4.1. Flood protection management: Historically, engineering techniques have been applied as a measure to protect inhabitants from the challenge of bank erosion and flooding effect. However, removing excess gravel from Waimakriri river in New Zealand has helped to save the town Christchurch from avulsion (Piegay, 2009). On a long term basis afforestation along the banks is a sustainable way which could lead to a reduction in gravel entering the river. 30% afforestation in upper Waipaoa river in New Zealand by 1995 helped to 5% reduction of gravels entering the area in the lower portion (Piegay, 2009).

4.2. Braided river and ecology: High degree of braiding by flood and complex mosaicking nature of the braid-plain morphology is essential for co-existence of many species along the braided river (Gray, 2017). The Platte river, Nebraska has historically been a major resting and breeding site for many species of migratory birds (lesser sandhill cranes, endangered whooping cranes etc.). But over the past 100 years, dams and diversions have reduced the peak flood and width of the channel (from 450m in 1900 to 100m width in 1970) (Piegay, 2009). Thus, due to the changes in the braided morphology the existence of such biota is in question.

4.3. Agricultural prospect: Agriculture in the braid-plain morphology is associated with the clearings of the vegetation. The classic braided river Brahmaputra in their contraction phases is extensively used for cultivation in the lean months (Coleman, 1969). There should be management policies regarding the activity like cultivation to maintain sustainability.

4.4. Bank erosion and land loss: Gangetic basin faces several bank erosion problems and associated land loss due to frequent change in the channel course. Since 1977 there have been 1670 ha of agricultural land loss to the Ganga river in Manikchak and Kaliachak-II blocks of Malda district (Thakur et. al, 2012). Effective regulation of management strategies can lessen the impact of land loss to the inhabitants.

4.5. Mining: Braided river are source of different types of gravels, sands which are used in constructional work. Sustainable extraction of gravels from braided rivers in Canterbury has helped to guide the river channel and manage other developmental work (Gray, 2017). But, excessive extraction of materials can hamper the sediment transportation process. Thus, sustainability must be maintained.

5. Conclusion

- The width of a braided channel is highly sensitive to the bank full discharge where the cohesivity of bank and bed materials and slope factor has a key role to play. Cohesive bank material with steep slope would increase the depth of the channel due to enhanced scouring rather than widening.
- The process and development of bars vary river to river. The growth of bars at the flume started with the deposition of coarser materials and the same process of development of bars are found at White river. On the other side, the materials of bars and islands in Brahmaputra and in Middle and North Loup are mainly composed of sand.
- Braiding occurs on a channel due to the incompetency in transporting the available materials. The rapidly shifting and bifurcation of channel occurs mainly due to the deposition of those materials on the bed. Erosion and deposition occurs simultaneously in braided course.
- Both the rising and falling stage are hydraulically important. When the flow rises, width increases the frictional resistance due to the shallowness of the channel and thereby lag deposits come into action. During the falling stage, the flow again diverts into channels and modify the configuration of braid and bars.
- The construction of barrages in the path of a natural braided channel can increase the braiding intensity and island area tremendously. It hampers the natural process of transportation and the process of bank erosion is severe in such areas.
- Presently the Channel Count Index is more acceptable with the existing combination of methods. It is less sensitive to the flow stage with low coefficient of variation. The reach should be 10 times of the bank full width and each cross section should be spaced away of bank full width.

The future research over the recommended gaps would provide a broader understanding of braided river morphology and dynamics.

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