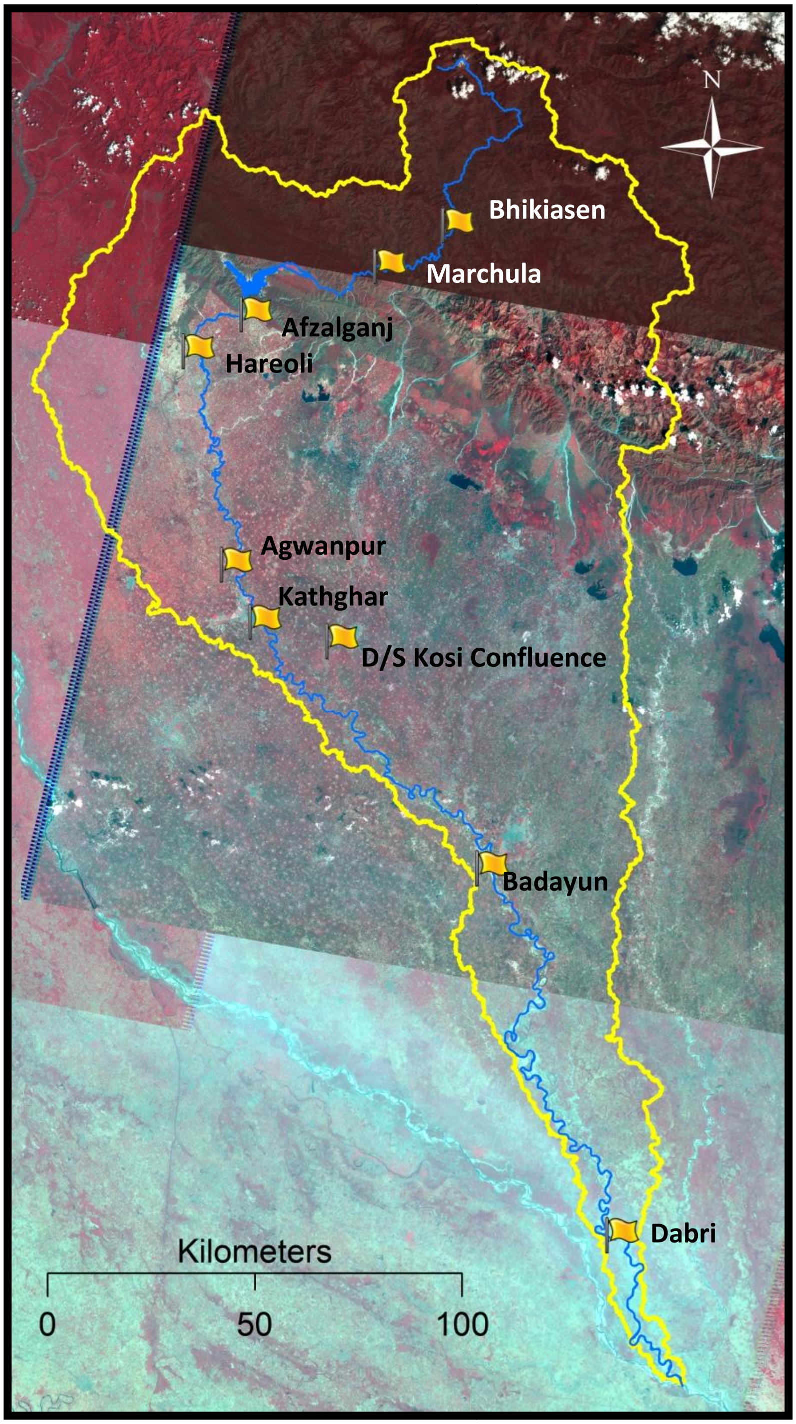
Starter Document

Fluvial geomorphology of the Ramganga River basin for environmental flow assessment



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March 2015

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1.0 PREAMBLE

The Ramganga is one of the main tributaries of the Ganga River which contributes large quantity of water and sediments. The primary objective of this project is to assess environmental flow at several locations along the river. This report pertains to the fluvial geomorphology component of this project. Our team has been involved in geomorphic mapping and cross sectional surveys along the river. The cross sectional survey was carried out by the BHU team but we participated in the survey and have processed the results for interpretation and have also recorded geomorphic attributes during the field work. Using the plan form maps and cross sectional surveys, several geomorphic parameters have been computed which have been used for environmental flow and river health assessment.

1.1 IMPORTANCE OF GEOMORPHIC PARAMETERS

Fluvial geomorphology is the study of the form and function of rivers and the mutual interaction between rivers and the landscape around them. River morphology is dynamic and constantly changing in both space and time, as a function of topography and hydrology, and this in turn influences the habitat in river channel as well as floodplains. Therefore, the documentation of geomorphologic diversity is crucial for understanding the various riverine processes and for overall river health assessment. Our study is focused on both channel belt (i.e. main channel and bars) and the floodplain. Channel width, floodplain width, sinuosity, braid channel ratio, bar area, bar perimeter are some of essential parameters to characterize the physical condition of a stream.

Planform sinuosity is the ratio of channel length to the direct down valley (axial) length which is the measure of meandering of a river (Friend and Sinha, 1993). A moderate to high degree of sinuosity provides diverse habitat and fauna and the river is better able to absorb surges when the river flow fluctuates as a result of storms (Refs). An ideal river should not shift or change much in long term whereas short-term changes are acceptable. Channel shifting is a measure of large-scale changes in the thalweg of the river channel. In urban and agricultural areas, rivers are straightened, deepened, or diverted into concrete channels, often for flood control, irrigation, or other property protection purposes. Such rivers have far fewer natural habitats for fish, aquatic invertebrates, and plants than do naturally meandering rivers. Similarly there should be negligible change in sinuosity and braid channel ratio in the long run.

A stable channel is in a state of equilibrium or in a balanced position and responds physically to the stream flow and sediment it receives from upstream channel. An ideal condition of the river for habitat suitability is when the water overtops or when < 10% of the channel bed is exposed. Bank stability is important for the alluvial rivers as the eroded banks characterize sediment movement and deposition and hence scarcity of vegetation cover and organic input to the rivers. Steep banks are more likely to collapse and suffer from erosion compared to gently sloping banks, and are therefore considered to be unstable. Sediment deposition and storage in river channels is a part of the equilibrium condition of many river types. The sorting and distribution of sediment into the bars of the equilibrium channel, concentrates flow, enhances sediment transport, and results in a diversity of morphological types. When a river is out of balance, sediment accumulation may raise the elevation of the river bed and result in the formation of point bars, mid channel bar or islands that accentuate vertical and lateral channel adjustments. These types of morphological units often favour the establishment of aquatic vegetation, which provides surface area for aquatic invertebrates, cover for fish and spawning site for turtles. Bank stability governs the channel cross section. The channel cross section defines the flow condition and in turn affect the processes within the channel. In the bedrock channel, channel cross-section defines the way in which available energy is expended in the reaches. However, in the alluvial river reaches, there exists a mutual feedback relationship between channel morphology and energy expenditure.

Along with planform parameters cross sectional parameters are also very important. Maximum depth, width/depth ratio, cross sectional area, and stream velocity are important parameters to understand the morpho-hydrological characteristics of the river. Fish and other aquatic organisms move long distance for feeding and breeding. The riffle pool sequence, typically in high gradient rivers, is a measure of frequency of riffles and pools with respect to the river width. Since pools are the deeper zones and the rifles are the shallower parts of the river, this parameter is also a measure of depth zones. Fish, amphibians and aquatic invertebrates use different depths at different stages of their life.

So, the availability of different depth zones is a desirable condition for habitat suitability. Again, the width to depth (w/d) ratio typically reflects channel stability and percentage of silt-clay in the channel perimeter and banks. A low w/d ratio is preferable in rivers from an ecological point of view.

Similarly, the characteristics of river bed substrate e.g. sediment size and sorting determine the suitability or unsuitability of specific biota at particular locations of the river (Dauwalter et al., 2007; Gorman and Karr, 1978; Wilhelm et al., 2005; Moir and Pasternack, 2008). The sorting of bed materials which is also known as embeddedness is a result of large-scale sediment movement and deposition, and is a parameter evaluated in the riffles and runs of high-gradient rivers. This is a measure of the degree to which rocks (gravel, cobble and boulders) and snags are covered or sunken into the silt, sand or mud of the river bottom. The spaces between the rocks are filled with fine sediments, leaving little room for fish, amphibians, and bugs to use the structures for cover, resting, spawning, and feeding. For habitat suitability, the 'excellent' condition is the moderately sorted embeddedness when gravel, cobble and boulder particles are 0-25% surrounded by fine sediment. Also, layering of cobble provides diversity of niche space for their spawning and feeding.

Further, floodplains are considered as important ecotones, which regulate the interchange of food and nutrients between the river and the floodplain and enhance the productivity of the river system (Fisher et al., 2007; Richards et al., 2002; Thoms, 2003; Ward et al., 2002).

2.0 GEOMORPHIC ATTRIBUTES OF THE SITES

2.1 Methodology and Data for geomorphic mapping

The LISS IV data with 5m resolution of pre-monsoon period 2013 were used to map the different geomorphic features using the false color composite (321 band combination on RGB planes). Each of the E-flow locations is characterized by certain geomorphic attributes and we have generated a common template to describe the geomorphic features at each site. These attributes are as follows. (See Table 1).

Table 1. Geomorphic Attribute table for sites covered

Landscape setting	Landscape setting is defined as the general geomorphic setting based on topographic characteristics and characteristic pattern of landforms through which the river flows (e.g. Himalayan bedrock, Interfluves)
Geomorphic features	All morphologic features of the main channel and its active floodplain such as channel bars, point bars, side bars, abandoned channels, lakes and backswamp areas.

Active floodplain and valley margin	Boundaries of active floodplain based on geomorphic features, soil moisture and vegetation patterns and of valley margin based on topographic breaks using digital elevation models.
Riparian vegetation	Presence of riparian vegetation on both sides of the river.
Riffle pool sequence	Presence of riffle or pool and riffle-pool sequence.
Bed material	The grain size of the bed material as observed and measured in field.
Bank material	The grain size of the bank material as observed and measured in field.
LU/LC	The land utilization in active floodplain as well as in the different bars as observed in field.

2.2 Field investigations and major geomorphic attributes of sites

Field investigations involved documentation of various geomorphic attributes and cross section survey and this was done in two phases. The first phase involved the surveys for two sites upstream of the Kalagarh dam, where the river Ramganga is flowing in the hilly region and the second phase covered five sites downstream of the Kalagarh dam in the plains. At each site, three cross sections were measured and geomorphic attributes were recorded in terms of planform morphology, bed material, and riparian vegetation condition (See Table 2).

Table 2. Geomorphic Attribute table for sites

Site no. and Name	Landscape setting	Geomorphic attributes
Bhikiasain CS1 (Jainal)	Himalayan Bed rock	Single channel sinuous river, channel belt is characterized by vegetated lateral bars with boulders, pebbles and cobbles, riffle pool sequence is observed. Small pockets of floodplains, patches of riparian vegetation. Bank material consists of boulder and coarse sand. Settlements and trees above HFL on both sides. Remarks- Golden Mahaseer is identified here.
Bhikiasain CS2 (CWC Site)	Himalayan Bed rock	Single channel sinuous river, channel belt is characterized by vegetated lateral bars, confluence bars with boulders, pebbles and cobbles, riffle pool sequence is observed, small pockets of floodplains, patches of riparian vegetation. Bank material consists of boulder and coarse sand and silt. Remarks- Golden Mahaseer is identified here.
Bhikiasain CS3 (d/s of CWC Site)	Himalayan Bed rock	Multi-channel sinuous river, channel belt is characterized by vegetated lateral bars, mid channel bars with boulders, pebbles and cobbles, riffle pool sequence is observed, small pockets of floodplains, patches of riparian vegetation. Bank material consists of boulder and coarse sand and silt. Remarks- Golden Mahaseer is identified here.

Marchula CS1 (u/s of CWC site)	Himalayan Bed rock	Single channel sinuous river, channel belt is characterized by boulders, pebbles and cobbles, riffle pool sequence is observed, small pockets of floodplains, no riparian vegetation, Bank material consists of boulder and coarse sand and silt. Remarks- Mahaseer is identified here.
Marchula CS2 (CWC Site)	Himalayan Bed rock	Single channeled sinuous river, channel belt is characterized by boulders, pebbles and cobbles, riffle pool sequence is observed, small pockets of floodplains, no riparian vegetation, Bank material consists of boulder and coarse sand and silt. Remarks- Mahaseer is identified here.
Marchula CS3 (d/s of CWC Site)	Himalayan Bed rock	Channel belt is characterized by boulders, pebbles and cobbles, riffle pool sequence is observed, side bars, small pockets of floodplains, patches of riparian vegetation. Bank material consists of boulder and coarse sand and silt. Remarks- Mahaseer is identified here.
Hareoli CS1	Valley interfluve	A multichannel river, channel belt is characterized by vegetated side bars and mid channel bars. Embankment on the left side and wide floodplain on the right side, patches of riparian vegetation, bank material consists of fine sand, silt and clay. Vegetation and seasonal cropland on both sides of the river. Remarks- Sand mining area
Hareoli CS2	Valley interfluve	A multichannel river, channel belt is characterized by vegetated side bars and mid channel bars. Wide floodplain on both side, patches of riparian vegetation, Bank material consists of fine sand, silt and clay. Vegetation and seasonal cropland on both sides of the river. Remarks- Sand mining area
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Agwanpur CS1	Valley interfluves	A multichannel river, channel belt is characterized by vegetated side bars and mid channel bars. Cliff on left side and floodplain on right side, patches of riparian vegetation, Bank material consists of silt and clay. Vegetation and seasonal cropland on both sides of the river as well as in the mid channel bars.
Agwanpur CS2	Valley interfluves	A multichannel river, channel belt is characterized by vegetated side bars and mid channel bars. Wide floodplain on both sides, patches of riparian vegetation, Bank material consists of silt and clay. Vegetation and seasonal cropland on both sides of the river as well as in the mid channel bars.

Agwanpur CS3	Valley interfluves	A multichannel river, channel belt is characterized by vegetated side bars and mid channel bars. Wide floodplain on both sides, patches of riparian vegetation, Bank material consists of silt and clay. Vegetation and seasonal cropland on both sides of the river as well as in the mid channel bars.
Kathghar CS1 (Near temple)	Valley interfluves	A multichannel river, channel belt is characterized by side bars and mid channel bars. Cliff on left side with floodplain and embankment on the right side, patches of riparian vegetation, Bank material consists of silt and clay. Vegetation and seasonal cropland on left side settlements on right side above HFL.
Kathghar CS2 (d/s Railway bridge)	Valley interfluves	A multichannel river, channel belt is characterized by side bars and mid channel bars. Cliff on left side with floodplain and embankment on the right side, patches of riparian vegetation, Bank material consists of silt and clay. Vegetation and seasonal cropland on left side settlements on right side above HFL.
Kathghar CS3 (Near Road Bridge)	Valley interfluves	A multichannel river, channel belt is characterized by side bars and mid channel bars. Cliff on left side with floodplain and embankment on the right side, patches of riparian vegetation, Bank material consists of silt and clay. Vegetation and seasonal cropland on left side settlements on right side above HFL.
Chaubari CS1	Valley interfluves	A multichannel river, channel belt is characterized by vegetated side bars and mid channel bars. Cliff on left side and floodplain on right side, patches of riparian vegetation, Bank material consists of silt and clay. Vegetation and seasonal cropland on both sides of the river as well as in the mid channel bars
Chaubari CS2	Valley interfluves	A multichannel river, channel belt is characterized by vegetated side bars and mid channel bars. Wide floodplain on both sides, patches of riparian vegetation, Bank material consists of silt and clay. Vegetation and seasonal cropland on both sides of the river as well as in the mid channel bars.
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Dabri CS1 (u/s Bridge)	Valley interfluves	A multichannel river, channel belt is characterized by side bars, point bars and mid channel bars. Embankment on left side and wide floodplain on right side, patches of riparian vegetation, Bank material consists of fine sand, silt and clay. Vegetation and seasonal cropland on both sides. Remarks- Shells and Turtles are identified.

Dabri CS2 (d/s Bridge)	Valley interfluves	A multichannel river, channel belt is characterized by side bars, point bars and mid channel bars. Little cliff on left side and wide floodplain on right side, patches of riparian vegetation, Bank material consists of fine sand, silt and clay. Vegetation and seasonal cropland on both sides. Remarks- Shells and Turtles are identified.
Dabri CS3	Valley interfluves	A multichannel river, channel belt is characterized by side bars and mid channel bars. Cliff on right side and wide floodplain on left side, patches of riparian vegetation, Bank material consists of fine sand, silt and clay. Vegetation and seasonal cropland on left side settlements on right side above HFL. Remarks- Shells and Turtles are identified.

2.3 Riparian Vegetation

In a balanced ecosystem riparian vegetation plays a major role along with geomorphic features. During the field survey riparian vegetation is identified in some of the sites. These are given in table no 3.

Table 3: Riparian vegetation

Identified species	Location
 ***Canaabis sativa*, Family: Cannabaceae**	The sites Jainal and Bhikiasain (cwc site) were dominated by *Canaabis sativa* as major riparian vegetation on both sides of the river. *Cannabis sativa* is an annual herbaceous plant in the *Cannabis* genus, a species of the Cannabaceae family. People have cultivated cannabis sativa throughout recorded history as a source of industrial fibre, seed oil, food, recreation, religious and spiritual moods, and medicine. Each part of the plant is harvested differently, depending on the purpose of its use.

 ***Polygonum hydropiperoids*, Family: Polygonaceae**	Another common type of riparian vegetation in the hilly terrain around the sites Jainal and Bhikiasain (included the *Polygonum hydropiperoids* which is a species of flowering plant in the knotweed family known by the common name swamp smartweed. It grows in moist and wet habitats, and is sometimes semi-aquatic. In general, this plant is a rhizomatous perennial herb growing upright or erect and approaching a maximum height of one meter. Roots may emerge from nodes on the lower stem.
 ***Saccharum arundinaceum*, Family: Poaceae**	In the plains (downstream of Kalagarh dam), the most common riparian vegetation is *Saccharum arundinaceum* on both sides of the river at all sites, Hareoli (both sides, in all 3 sections), Agwanpur (both sides, in all 3 sections), Kathgarh(both sides in the last section (road bridge), Chaubari (occurred in patches), and Dabri (both sides, in all 3 sections). This plant, commonly known as Hardy Sugar Cane, is a grass native to South Asia.

2.4 Landuse and Landcover (LULC)

During the field survey in each E-Flow sites settlements are marked on both of the banks. in maximum location settlements are above the HFL. These are listed below. (See Table 4).

Table 4: Landuse and landcover

Sites		LULC in AFP	LU/LC above HFL
	CS1.Jainal	No floodplain	Settlements on both sides. Step cultivation on the left side.
	CS2.Bhikiasain (CWC Site)	Patches of croplands on left side	Settlements on both sides.
	CS2.Bhikiasain (DS of CWC Site)	Patches of vegetation on right side	Settlements on right side.

Ramganga Hill	CS1.Marchula (US of bridge)	No floodplain	Settlements on left side.
	CS2.Marchula (Near bridge)	No floodplain	Settlements on left side.
	CS3.Marchula (DS of bridge)	No floodplain	Settlements on left side.
Ramganga Plain	CS1. Hareoli (DS)	Vegetation	Vegetation and croplands on both sides
	CS2. Hareoli (DS)	Vegetation and seasonal cropland	Vegetation and croplands on both sides
	CS3. Hareoli (DS)	Vegetation and seasonal cropland	Vegetation and croplands on both sides
	CS1.Agwanpur(US)	Vegetation and seasonal cropland	Vegetation and croplands on both sides
	CS2.Agwanpur	Vegetation and seasonal cropland	Vegetation and croplands on both sides
	CS3.Agwanpur(US)	Vegetation and seasonal cropland	Vegetation and croplands on both sides
	CS1.Kathghar(US) (Near temple)	Vegetation on left side	Temple and settlements on right side. Vegetation on left side.

3.0 Systematic description of sites

3.1 Bhikiasain (Hilly area)

The Landscape setting of all the three points of Bhikiasain is Himalayan Bedrock and the entire stretch of the river falls in High mountainous area. River valley is narrow and is confined on both sides by valley walls.

River channel is generally single thread with low sinuosity and channel belt is characterized by vegetated sidebars with boulders, pebbles and cobbles. Riffle-pool sequence is observed at several places in this stretch. (See Figure 1).

No floodplains are present except for small pockets of floodplains in a few reaches. Patches of riparian vegetation are observed on both sides. Bank material consists of boulder and coarse sand.

Settlements are observed in some places above the HFL on both sides. Some areas are covered by trees on both sides above the HFL.

3.2 Marchula (Hilly area)

The Landscape setting of the Marchula site is Himalayan Bedrock; the distinctive characteristics are very narrow valley and highly sinuous channel. Channel belt is characterized by large point bars and vegetated sidebars with boulders, pebbles and cobbles. The downstream reaches show mid channel bars in spite of high sinuosity. Riffle-pool sequence is observed at some locations in this stretch. (See Figure 2).

This site is otherwise quite similar to Bhikiasen. No major floodplain development is observed except for small pockets but with no significant floodplain feature. Riparian vegetation is patchy on both sides. Bank material consists of boulder and coarse sand.

3.3 Afzalgarh (Plain area)

This is the transition zone between the hilly area and the plain area and the Landscape setting is classified as valley interfluves. Channel belt is characterized by large side bars and vegetated sidebars with boulders, pebbles and cobbles near the barrage. The downstream reaches show mid channel bars with silty and clayey bed materials. Sinuosity is very less in the entire stretch with an average sinuosity of 1.07. Riffle-pool sequence is absent in this stretch. (See Figure 3).

No active floodplains on the upper reaches, but continuous floodplain starts on both sides from the middle reaches. Riparian vegetation is patchy on both sides. Bank material consists of boulder and coarse sand on the upstream and silt with clay are encountered on the downstream. Settlements are above HFL on bothsides.

3.4 Hareoli (Plain area)

The Landscape setting of the Hareoli site is Valley interfluves; the distinctive characteristics are very wide floodplain and high bar density. Channel belt is characterized by sidebars, mid channel bars and point bars. Fine sand and clay are observed in the channel belt. The downstream reaches show high sinuosity. (See Figure 4).

Significant floodplain features like ox bow lakes and meander cutoffs are mapped. Riparian vegetation is available on both sides. Bank material consists of fine sand and clay.

3.5 Agwanpur (Plain area)

Landscape setting at Agwanpur is defined as valley-Interfluves. This stretch falls in the alluvial part and the channel is characterised by multi-thread system but still have high sinuosity in certain stretched. Large mid-channel bars and extensive sidebars composed of sand characterize the stretch which is generally vegetated. Banks are muddy.

In contrast to the mountainous reaches, wide floodplains are observed in this area on both sides with significant floodplain features (ox bow lake, meander cutoff etc.). Large patches of riparian vegetation are observed on both sides. (See Figure 5).

Seasonal croplands are observed on both sides of the river as well as in the mid channel bars. However, settlements are located far away from the river.

3.6 Kathghar

Landscape setting of Kathghar is Interfluves but this stretch is characteristically straight and the channel is hugging the left bank (embankment) all along. There is a very wide floodplain and a large meander cut-off is conspicuous. Elongated bars, both mid-channel bars as well as side bars, are dominant in the entire stretch.

Both bed and Bank material consists of fine-grained sediments; the channel beds are composed of fine to very fine sand and banks have silt and clay. (See Figure 6).

3.7 Chaubari

Landscape setting in this zone is valley-Interfluves. There is a very wide floodplain on both sides. Elongated side bars, mid channel bars and point bars, are dominant in the entire stretch. In the active floodplain, a number of dry channels and flood channels are identified. (See Figure 7).

Bed materials as well as bank materials are composed of fine sand and clay. Riparian vegetation occurred in patches on both sides.

3.8 Dabri

Landscape setting at Dabri is defined as valley-Interfluves. This stretch falls in the alluvial part and the channel is characterised by multi-thread system but still have high sinuosity in some reaches. Large mid-channel bars and extensive side bars composed of sand characterize the stretch which is generally vegetated. Banks are muddy. (See Figure 8).

In contrast to the mountainous reaches, wide floodplains are observed in this area on both sides with significant floodplain features (ox bow lake, meander cutoff etc.). Riparian vegetation is identified on both sides.

4.0 E-Flow sites in Ramganga in a River Styles Framework

Apart from mapping the specific windows around the E-flow sites, we have also attempted to look at these sites in a broader context of river style framework (Brierley and Kirstie, 2005). For this, a large area had to be mapped and this section describes this approach in detail. River Styles framework explains the mutual linkages between the river forms and the geomorphic processes within a specific zone in the river. It consists of attributes at different scales that provide a platform to distinguish different types of rivers. River Styles classification is accomplished in different steps. For the identification of distinct River Styles three parameters namely, valley setting, geomorphic units and bed material texture are necessary. Each parameter plays a major role in defining one style. For an example, channel plan form of an alluvial river shows distinct behaviour between different valley settings whereas the bed material texture is important in defining the processes operative in a particular river reach. Sedimentological composition and the mutual association of channel planform and channel geometry with the geomorphic units provide the distinct attributes for the different River Styles. Sinuosity and braid channel ratio are important from channel morphometry point of view. River Styles is a useful concept to characterize the geomorphic diversity of a river system as well as to recognize the comparable stretches along the river so that suitable management strategies can be designed.

The Ramganga river flows in hilly area as well as in plain area. In the hilly area 3 River styles are identified. Similarly, in the plain area Ramganga is classified into 3 Different river styles. The transition area between the hill and plain near the Ramganga reservoir is not assigned to any River styles and kept as a special case.

4.1 River Style 1: Himalayan Bedrock, partly confined floodplain and channel braided (Upstream of Khira Village to Jim Corbet park)

Two E-Flow sites in the mountainous stretch, namely **Bhikiasain** and **Marchula,** fall in this River Style which occurs in a stretch of ~99 km. River valley is very narrow throughout the stretch. No Active floodplain is present on both sides of channel. An partly confined channel is flowing with an increasing sinuosity towards downstream. A few bars are encountered. Riffle and pools are present along the river in the whole river style. River channel width decreases and more mid channel bars are exposed during low flow stage. River attains the bankfull stage regularly during the monsoon. Overbank stage is rarely attained as there is no significant floodplain. (See Figure 9).

4.2 River Style 2: Valley-interfluves, unconfined floodplain and channel, braided (Bodhapur to Mughalpur)

This river style occurs in an alluvial valley setting. Here the landscape setting is Valley interfluves. The Afzalgarh E-Flow site falls in this stretch. Relatively wide river valley showing asymmetricity in the lower reaches due to fluctuation of left margin. Active floodplain is present on both sides of channel except on upper reaches where channel approaches the left and margin of the floodplain alternately and therefore discontinuous floodplain occurs. An unconfined river channel belt shows highly tortuous meandering in most of the reaches and attains max sinuosity in the central portion. It shows braiding only in the upper reach and comprise prominently of point bars, side bars with few mid channel bars. Point bars are dominant throughout the reach due to tortuous meandering. Floodplain shows meander cutoffs, few meander scrolls, flood channels and ox-bow lakes. Occasionally dry channels and small wetlands are also present. Small to medium size tributaries of not much importance follow the margins of floodplain. (See Figure 10).

4.3 River Style 3: Valley-interfluves, partly confined floodplain and channel, braided (Mughalpur to Bareilly)

This river style is set in a valley-interfluves landscape setting. Agwanpur and Kathghar E-Flow sites fall in this stretch. For a major part of this stretch, the channel flows along the right bank. The active floodplain is mostly on the left side of the river and controlled by the position of the channel with respect to the valley margin. In low flow stage river channel width decreases and more mid channel bars are exposed. Large mid channel bars are used for seasonal cultivation. river attains the bankfull stage regularly during the monsoon; mid channel bars and alluvial islands are partly submerged and the average width of the channel increases in the bank full stage. The flood channels fills with water supplying water/sediment to the floodplain and in many cases joins back the main channel. In the overbank Stage River floods both the banks regularly. Places where the river flows near the valley margin, a narrow floodplain has developed due to restricted overtopping of the river on that side. (See Figure 11).

4.4 River Style 4: **Valley interfluves, Unconfined floodplain, partly confined, Sinuous** (Bareilly to Kannauj)

This river style of ~295km long is set within the valley-interfluve landscape setting. **Chaubari** and **Dabri** E-Flow sites fall in this style. The valley width is relatively uniform while the floodplain is very irregular in this stretch. The channel flows through the center of the valley and active floodplain has developed on both banks of the river. The channel is characterized by moderate to high sinuosity and very low braid channel ratio. The channel belt comprises of side and point bars while mid channel bar is rare. Floodplain features like meander scrolls and cutoffs are very prominent. Ox bow lakes are big and numerous in this stretch. In this stretch maximum floodplain width is ~10.5 km and minimum ~1.4km with an average of ~ 5.7km. The floodplain is highly irregular and extends on both banks of the river. Here this style shows FP: VM width = 1:2.2. Floodplain margin does not coincide with the valley margin. There are big Ox bow lakes, meander scrolls, cutoffs in the floodplain suggesting active lateral migration of the river. In the alluvial channel belt 37.2% of the channel belt has water and the rest covered by bars. No major tributaries are present in this stretch. At Kannauj it flows into Ganga. Side and point and mid channel bars are dominant in the channel belt. In the Low flow stage river channel width decreases and more mid channel bars are exposed. River attains the bankfull stage regularly during the monsoon bankfull stage. River floods both banks regularly overbank stage. (See Figure 12).

5.0 Environmental flows Assessment

Environmental flow assessment is a process of consideration of how much of the original flow of a stream should flow in the channel belt in order to maintain specified requirements or Environmental Flows are a regime of flow in a river or stream that describes the temporal and spatial variation in quantity and quality of water required for freshwater as well as estuarine systems to perform their natural ecological functions (including sediment transport) and support the spiritual, cultural and livelihood activities that depend on these ecosystems.

5.1 Importance of E-Flows

(a) Low flows: Low flows are important to maintain water table in the floodplain and enable fish and other stream biota to move to spawning areas. It also maintains pools and minor flow in the riffles, to provide survival conditions and longitudinal connectivity for aquatic biota. It provides drinking water to other terrestrial animals and maintains the required water temperature.

(b) High flows: High flows are important to restore normal water quality conditions by flushing away waste products and pollutants. It provides physical attributes of river channel, including pools and riffles. It maintains lateral connectivity with submergence of sidebars. It submerges riparian vegetation. It maintains sediment transport and stream power.

(c) High Floods: High floods control distributions and abundance of plants on floodplains and deposit nutrients on floodplain. They enable the aquatic biota to spawn on floodplain and maintain ecological diversity in floodplain and channel belt. From a geomorphic perspective, they restore lateral connectivity with submergence of floodplain forming new habitats (i.e. secondary channels, ox bow lake etc.). High floods also recharge floodplain water table and provide new feeding opportunities for fish and other stream biota.

5.2 Method and approach

E-Flows at the sites selected depend on the hydraulic and hydrological requirement of river ecology and geomorphology, the cultural, spiritual and livelihood requirements being within these limits in these rivers. In deciding E-Flow, depth of water required and velocity of water are the two factors used in working out flows. In normal conditions, velocities cannot be modified, and therefore, water depths in river to fulfill ecological and geomorphologic requirements are the deciding factors of E-Flows at any site. Flows corresponding to these depths, which can be considered as E-Flow, are then determined using established stage-discharge curve for particular site.

From a geomorphic perspective, we use the following criterion to determine the e-flows at a given site:

(a) Low flows in a regular year should be maintained in such as way that the longitudinal connectivity is maintained in the river and the river remains in flowing condition. The approach then is to determine the water depth at which longitudinal connectivity will be lost and the convert this value to flow through hydraulic model for the section. Geomorphic features which help in determining this criteria include the bar density and height, and the general slope of the channel (determines the flow velocity).

(b) High flows in a regular year is determined using several geomorphic criteria:

   (i) Lateral connectivity should be established at least once in a year; with submergence of the lateral bars and active floodplain.

(ii) Sediment dynamics is an important function of the river. River should have enough stream power to transport the requisite sediment grains (normally the dominant grain size in the reach) to maintain the desired morphology or to attain a desired morphology

(c) Ocassional high floods perform a very important fuction from a geomorphic perspective. At the same time, they may tend to desctroy the geomorphic and ecological integrity, if not managed properly at critical sites. We propose that apart from the flows in a regular year, high floods should also be managed at critical sites such that:

  a. Riparian zones and vegetation should be inundated. Flow variability is necessary for the functioning of the river ecosystem.
  b. While the bars should be inundated, the floods should not erode them completely so as to modify the channel morphology significantly.

Further discussion on these criteria will be done at the E-fow setting workshop.

6.0 River Health Index (RHI) Assessment

Apart from e-flow assessment, an important aspect of this project is to develop criteria for a holistic assessment of river health. River Health is defined as the state of the river system as it is today and it links to 'health' in ecological terms. Generally, a healthy river is the river that can satisfy the sustaining need of humans while maintaining the ecosystem requirements of a river. Assessing whether river structure is appropriate for its environmental/landscape setting for performing various functions such as sediment transport, nutrient cycling and energy exchange, support for riparian vegetation and ecosystem (in-channel and floodplain), maintaining longitudinal and lateral connectivity, and maintaining geodiversity and biodiversity. Therefore, any criteria to define river health must be (a) process-based, (b) framed in terms of the type of river (geomorphic diversity), and (c) framed in terms of river change (morphodynamics).

This report is limited to the geomorphic criteria for river health assessment and these criteria will need to be integrated with other criteria particularly those based on ecological and hydrological considerations. Table 5 shows the important geomorphic parameters for river health assessment developed by us as a result of our long-term research. We intend to apply these parameter for river health assessment of the Ramganga river in conjunction with other criteria developed by other groups.

Table 6 show the plots of the river health parameters computed for the Ramganga river. At this stage, we only offer a basic interpretation of this data. Work is ongoing to develop the relative importance of each of these factors using the Analytical Hierarchy Process (AHP) and the same will be discussed in the e-flow setting workshop in April.

Table 5: River Health Index (RHI) Parameters

Parameter	*Measure*	*Details*	*Remarks*
Occupancy	$R1 = \frac{AFLw + AFRw}{Vw}$	Find centre line of the channel belt (i.e., union of in-channel features, including water). Draw perpendicular lines at equally spaced (e.g., 5km apart) points along centre line. Measure width of active floodplain (channel belt margin to active floodplain margin) along the perpendiculars. Measure the left (AFLw) and the right (AFRw) floodplains separately.	Measures landscape scale equilibrium of the river system. A value close to 1 would indicate that the channel belt and its floodplains fully occupying the lateral accommodation space. A small value (say, > 0.5) would indicate an under-fit system.
Floodplain Development	$R2 = \frac{Cbw}{Sw}$	Use the same perpendicular lines. Measure width of the channel belt (Cbw) and the width from the left active floodplain margin to right active floodplain margin (Sw).	Low values might indicate flood prone / avulsive system. Moderate values (say, around 0.5) should indicate a stable system with good lateral connectivity. High values should indicate incised/embanked or partly abandoned system.
Bar density	$R3 = \frac{\sum Ba}{\sum Ca}$	Use "reach polygons" to clip in-channel features. Compute total area of all in-channel bar features (Ba) and total area of all in-channel, channel features (Ca). Repeat for all reaches.	High values indicate high sediment-water discharge ratio. Very high values will indicate degeneration of river. Moderate values good for biota as it would indicate the presence of ample substrate for biological activities.
Flow line sinuosity	$R4a = \frac{Arc\ Length_{primary}}{Straight\ Length_{prima}}$	Sinuosity of primary channel centre line. The values for multi-channel and single-channel reaches are to be treated separately.	Complexity of water flow. A high value would indicate better support for biological activity. A very high value in multi-channel reach might reflect imbalance in sediment-water ratio.
Channel belt sinuosity	$R4a = \frac{Arc\ Length_{channel\ b}}{Straight\ Length_{chann}}$	Sinuosity of channel belt centre line. The values for multi-channel and single-channel reaches are to be treated separately.	In single-channel reach higher values might indicate rising base level. In multi-channel reach a high value would indicate structural controls.
Valley sinuosity	$R4v = \frac{Arc\ Length_{valley}}{Straight\ Length_{valley}}$	Sinuosity of valley centre line.	Higher sinuosity would indicate structural control.
Bar Complexity	$R6a = \overline{\left[\frac{Bar\ Perimeter}{Bar\ Area}\right]}$	Average of the perimeter area ratio of all kind of bars	Measures complexity of the bar margins. Higher values are good for biota
Width to Depth (w/d) Ratio	Bankfull width/ Maximum Depth	Ratio of Bankfull width and Maximum depth of the same cross section	Indicates channel shape, reflects channel stability and percentage of muddy sediments in channel perimeter and banks; positively related to discharge and sediment loads; Low to moderate w/d ratios favor turbulence and oxygenation; increased w/d ratio results in less canopy cover

5.1 Interpretation of RHI Parameters

In the mountainous reaches, the occupancy is very low ranging from 0.19 to 0.24. Around Bhikiasain and Marchula, the width of the active floodplain is very low which reduces the occupancy.At Afzalgarh, occupancy is low as it falls in the transition zone of hill and plain. In the upper reaches no floodplain is available which decreases the value. Again in Chaubari (in some lower reaches), valley width is very high causing low occupancy.

In terms of floodplain development, Marchula shows very low value due to narrow active channel in the mountainous reaches. In some of the upper reaches around Afzalgarh, channel width is very wide compared to the active floodplain as the area falls in the transition zone. As a consequence the floodplain development value high there.

At all sites sinuosity is low ranging from 1.05 to 1.29 except for Marchula where a slightly higher sinuosity of 1.55 is recorded. At Afzalgarh, Chaubari and Kathghar, braid-channel ration is high (give values…) due to high channel multiplicity in some reaches. At other places, braid channel ratio is moderate.

Around Chaubari, large sidebars are exposed on both sides of the river which leads to a high bar density. Similarly, in some reaches of Agwanpur bar density is high due to more side and point bars, but in Hareoli the main channel is very narrow which enhances the bar density. Further, in the upper reaches of Bhikiasain and Marchula, elongated side and mid channel bars are identified. As a consequence, bar complexity is high in these zones, which translates to habitat suitability for stream biota. At Agwanpur and Chaubari few bars with larger area reduces the bar complexity value.

Further, at Hareoli, Kathghar and Chaubari the bankfull width is very high which increases the width/depth Ratio. Both the hilly zone Bhikiasain and Marchula show high stream power due to the high channel slope. In Afzalgarh stream power is more compared to the all zones as discharge is more in some reaches (down stream of the barrage).

Table 6: River health parameters for the Ramganga

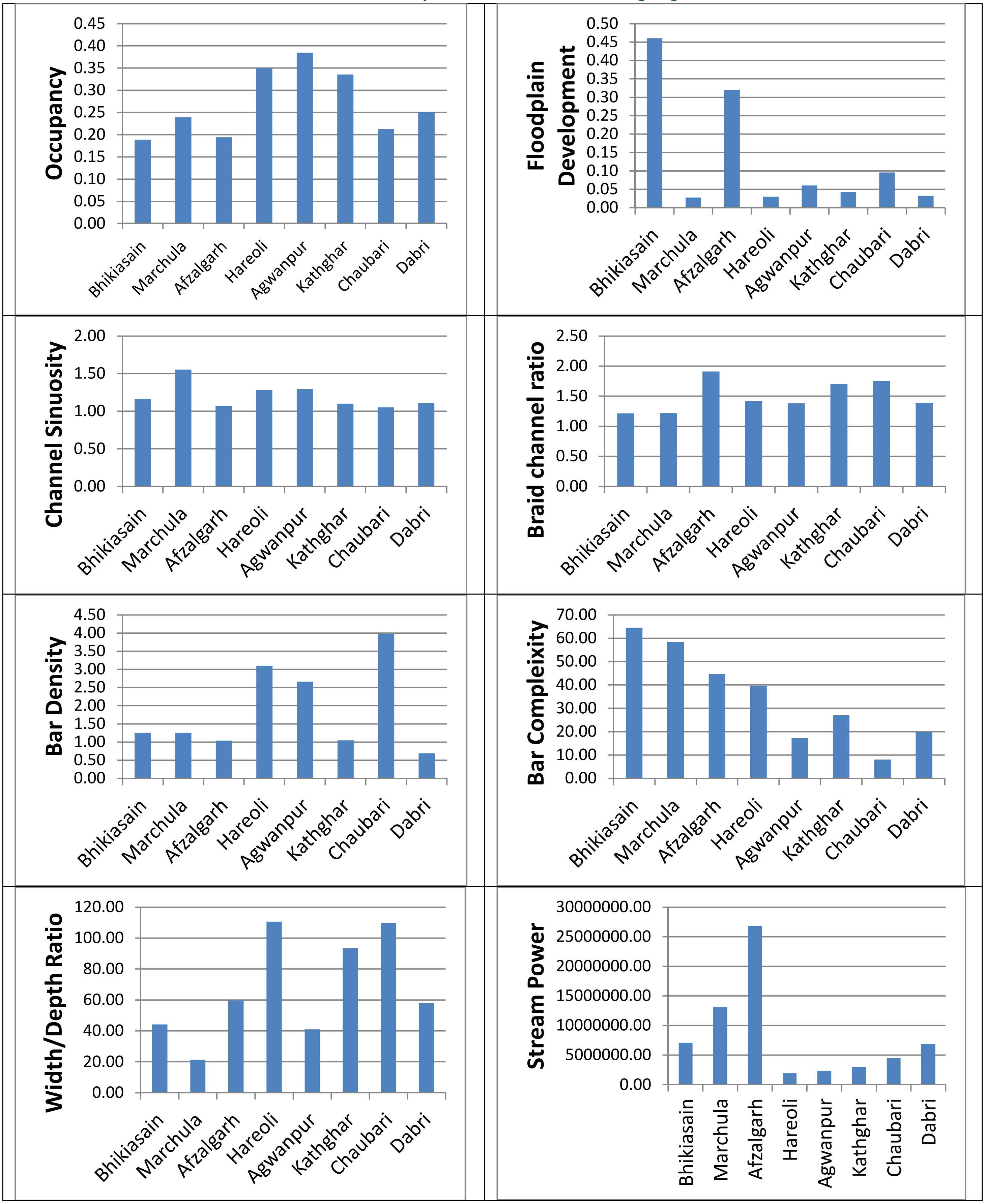

Table 7: Appendix I- Reach wise RHI Parameters

Zone	Reach No.	Occupancy	Floodplain Development	Channel Sinuosity
Bhikiasain	1	0.15	0.26	1.32
	2	0.09	0.47	1.29
	3	0.27	0.32	1.08
	4	0.12	0.55	1.03
	5	0.11	0.44	1.20
	6	0.27	0.36	1.04
	7	0.26	0.37	1.08
	8	0.29	0.54	1.06
	9	0.05	0.79	1.37
	10	0.27	0.51	1.14
Marchula	1	0.20	0.05	1.62
	2	0.20	0.07	1.97
	3	0.47	0.03	1.42
	4	0.16	0.01	1.23
	5	0.22	0.02	1.29
	6	0.22	0.01	2.08
	7	0.16	0.01	1.27
	8	0.24	0.05	2.24
	9	0.31	0.03	1.15
	10	0.22	0.01	1.26
Afzalgarh	1	0.10	0.58	1.05
	2	0.19	0.46	1.08
	3	0.08	0.56	1.04
	4	0.47	0.24	1.20
	5	0.43	0.13	0.90
	6	0.20	0.37	1.06
	7	0.09	0.44	1.06
	8	0.12	0.16	1.15
	9	0.10	0.20	1.14
	10	0.15	0.06	1.04
Hareoli	1	0.39	0.05	1.06
	2	0.38	0.02	1.05
	3	0.23	0.06	1.14
	4	0.37	0.02	1.08
	5	0.33	0.02	1.02
	6	0.37	0.02	1.04
	7	0.33	0.04	1.73
	8	0.34	0.02	1.64
	9	0.37	0.02	1.34
	10	0.40	0.03	1.70

Zone	Reach No.	Occupancy	Floodplain Development	Channel Sinuosity
Agwanpur	1	0.32	0.09	1.23
	2	0.36	0.03	1.18
	3	0.33	0.02	1.30
	4	0.35	0.05	1.81
	5	0.35	0.06	1.08
	6	0.23	0.08	1.04
	7	0.38	0.07	1.08
	8	0.33	0.13	1.76
	9	0.73	0.05	1.22
	10	0.45	0.04	1.20
Kathghar	1	0.41	0.04	1.15
	2	0.41	0.04	1.07
	3	0.37	0.05	1.03
	4	0.29	0.05	1.05
	5	0.32	0.03	1.02
	6	0.31	0.06	1.04
	7	0.30	0.05	1.04
	8	0.28	0.07	1.12
	9	0.33	0.04	1.39
	10	0.34	0.01	1.08
Chaubari	1	0.44	0.10	1.06
	2	0.23	0.06	1.07
	3	0.18	0.05	1.03
	4	0.34	0.06	1.19
	5	0.25	0.08	1.06
	6	0.21	0.08	1.02
	7	0.06	0.13	1.01
	8	0.11	0.19	1.01
	9	0.16	0.15	1.05
	10	0.13	0.07	1.04
Dabri	1	0.37	0.036	1.09
	2	0.27	0.019	1.01
	3	0.33	0.021	1.04
	4	0.29	0.032	1.11
	5	0.25	0.029	1.37
	6	0.19	0.028	1.19
	7	0.23	0.042	1.09
	8	0.13	0.035	1.02
	9	0.19	0.039	1.06
	10	0.25	0.043	1.10

Zone	Reach No.	Braid Channel Ratio	Bar Density	Bar Compleixity	Stream Power
Bhikiasain	1	1.00	0.62	92.33	4587454.1
	2	1.25	0.46	95.67	4924319.746
	3	1.00	0.63	99.33	3348207.114
	4	1.08	0.71	82.75	8534791.558
	5	1.18	0.89	62.00	6241407.05
	6	1.20	1.69	47.22	5606118.239
	7	1.26	0.61	81.00	13990962.39
	8	1.77	2.23	28.25	11322737.72
	9	1.00	2.49	27.58	5782295.171
	10	1.41	2.20	28.94	6473093.83
Marchula	1	1.14	0.65	101.71	16043912.27
	2	1.09	0.66	76.80	10544948.89
	3	1.23	0.70	81.00	17303722.73
	4	1.26	0.79	65.88	11159565.31
	5	1.18	0.77	44.63	9561691.24
	6	1.04	3.58	17.97	13612671.09
	7	1.00	1.34	48.82	12190683.41
	8	1.07	0.90	65.14	10917142.71
	9	1.27	1.02	54.67	14491839.5
	10	1.87	2.14	27.32	15048479.22
Afzalgarh	1	1.00	0.00	0.00	33180.67108
	2	1.00	0.08	180.80	33745.76801
	3	1.15	1.00	11.25	33833.22884
	4	1.16	2.27	0.00	189550489.2
	5	1.00	1.57	22.96	44707160.79
	6	2.57	0.00	0.00	6818010.195
	7	1.45	1.09	19.80	7382125.1
	8	4.28	2.01	39.68	7990880.028
	9	3.60	1.95	42.65	5304017.053
	10	1.87	0.41	129.00	6435380.227
Hareoli	1	1.58	1.88	32.60	960630.7706
	2	1.00	1.57	30.55	1883280.006
	3	2.22	1.25	60.00	1500925.69
	4	2.09	0.50	113.50	1380526.422
	5	1.33	7.14	6.32	4149039.243
	6	1.00	3.29	21.48	1463301.171
	7	1.38	2.00	29.92	2871076.317
	8	1.29	2.20	47.73	929118.5559
	9	1.17	1.20	48.33	1350479.845
	10	1.11	10.00	5.67	3067132.743

Zone	Reach No.	Braid Channel Ratio	Bar Density	Bar Compleixity	Stream Power
Agwanpur	1	1.00	4.62	14.26	1986532.984
	2	1.18	2.67	16.44	2092696.407
	3	1.19	1.86	17.54	231070.6466
	4	1.30	3.10	11.65	8098724.549
	5	1.79	2.62	18.32	1295407.768
	6	1.34	1.98	19.15	5800335.017
	7	1.26	4.11	9.78	3145487.586
	8	1.43	2.91	10.41	61679.72218
	9	1.93	1.34	33.29	61693.25329
	10	1.41	1.43	20.81	589631.5371
Kathghar	1	1.48	1.44	24.24	3039801.227
	2	2.30	1.77	19.72	5432063.041
	3	2.38	0.99	32.63	71093.28874
	4	1.96	0.82	41.54	1892179.505
	5	1.93	0.59	60.50	4789356.037
	6	1.41	1.09	23.73	4776851.559
	7	1.47	1.42	20.47	821623.9077
	8	2.08	1.25	26.44	6900440.474
	9	1.00	1.08	20.25	1658725.365
	10	1.00	0.00	0.00	733703.1017
Chaubari	1	2.12	1.33	12.03	2630442.982
	2	2.75	1.79	11.46	251213.9977
	3	1.89	1.88	9.31	17180599.95
	4	1.74	2.82	9.08	3317902.39
	5	1.00	3.81	5.59	3818696.184
	6	1.00	3.85	10.16	5753232.873
	7	1.52	6.74	4.10	1455633.037
	8	1.00	8.34	3.30	474814.393
	9	2.34	4.00	9.51	3356399.495
	10	2.19	5.22	6.01	6931991.113
Dabri	1	1.00	1.08	13.09	3152102.382
	2	1.00	0.31	28.00	8778507.225
	3	1.00	0.58	22.47	5318643.892
	4	1.26	0.77	19.00	6281562.614
	5	2.46	0.65	33.94	12575542.15
	6	1.64	0.99	13.62	17268613.17
	7	1.69	1.01	20.07	3686212.017
	8	1.46	0.42	17.50	3780007.732
	9	1.38	0.40	20.64	3907331.078
	10	1.00	0.70	10.78	3874298.054

Figure 1 - Bhikiasain Geomorphic map

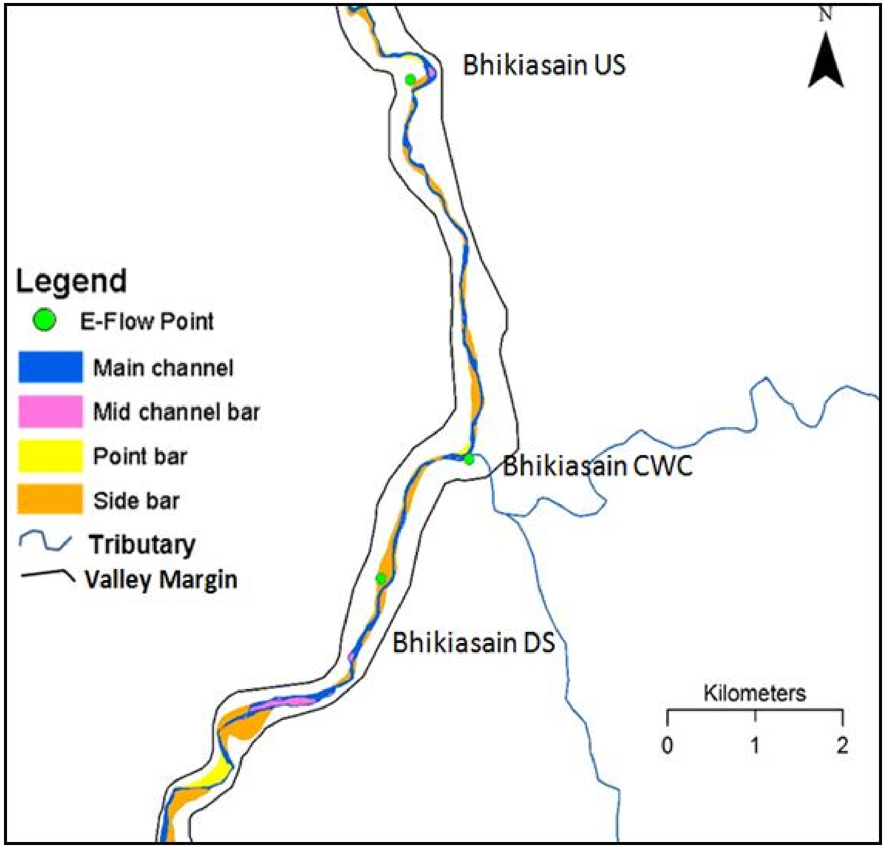

Figure 2 - Marchula Geomorphic map

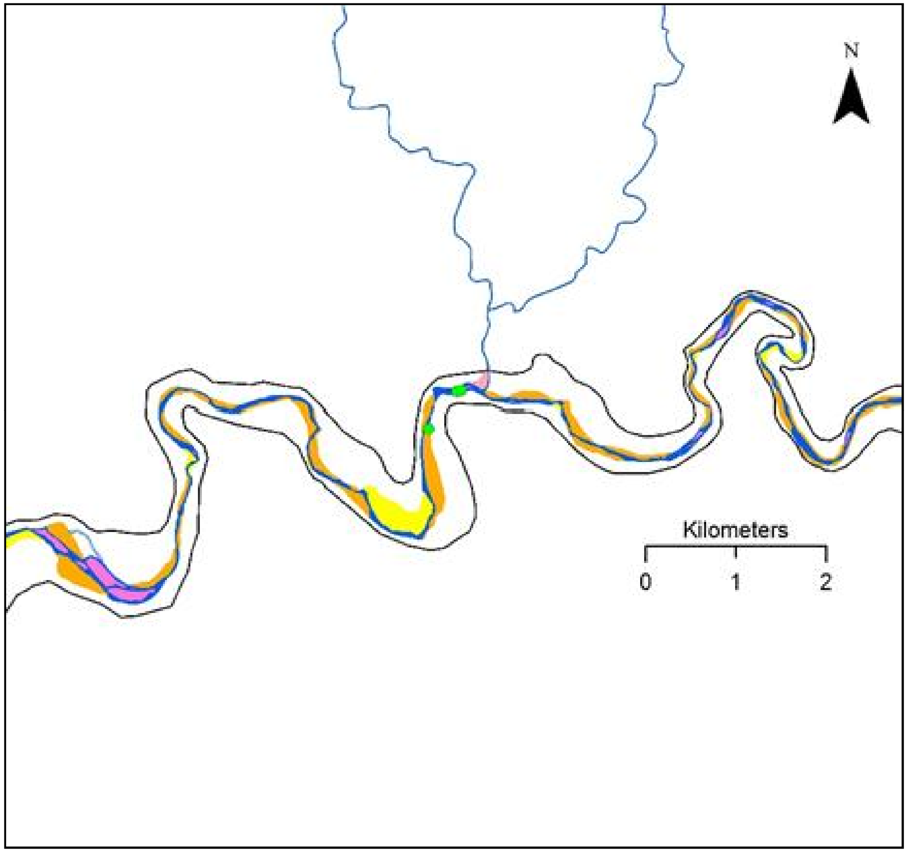

Figure 3 - Afzalgarh Geomorphic map

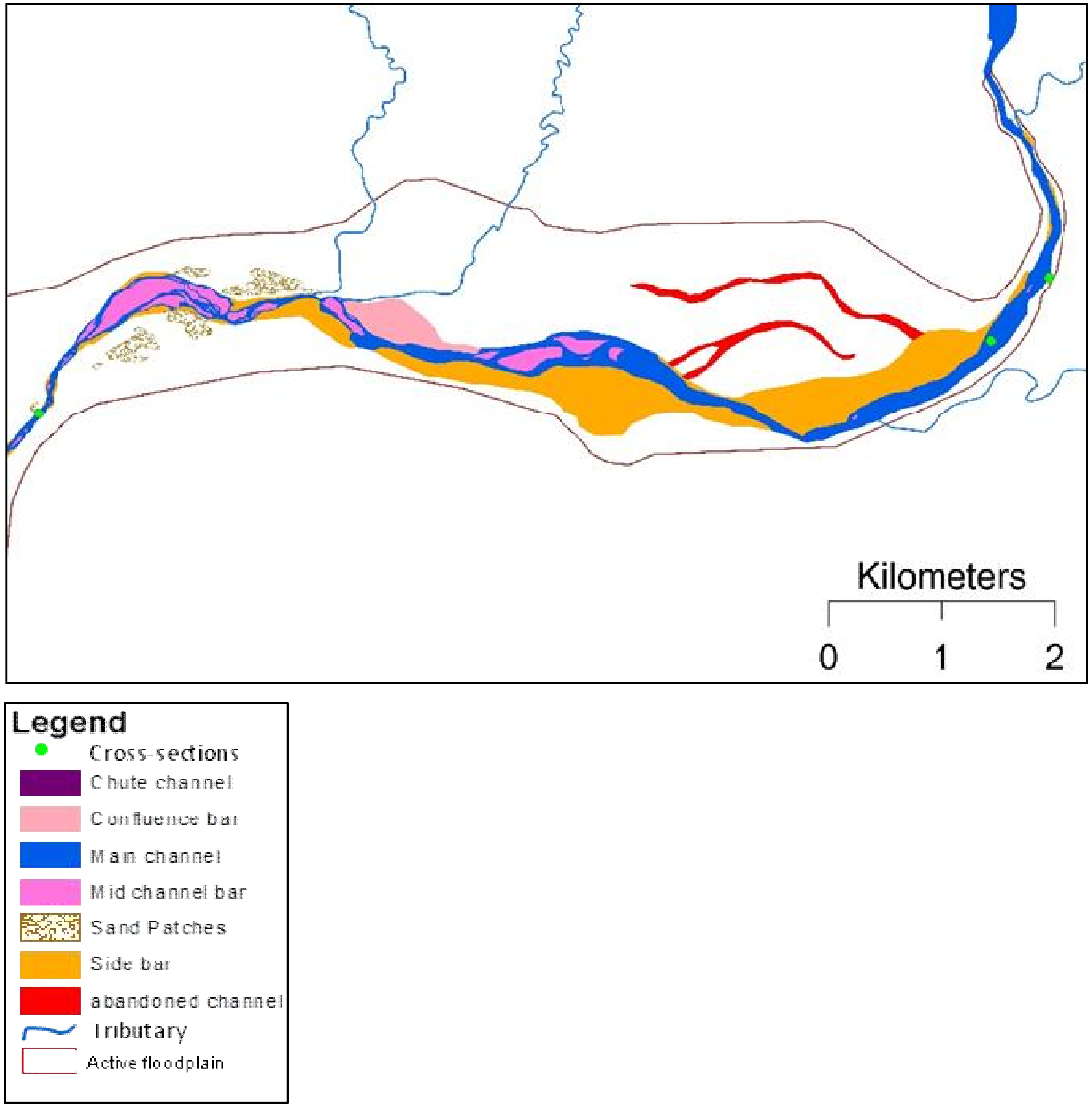

Figure 4 - Hareoli Geomorphic map

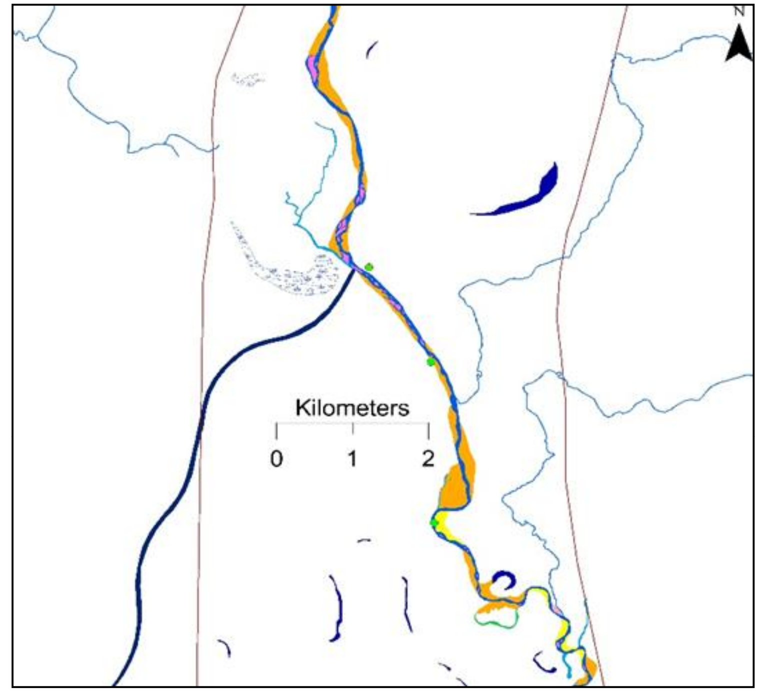

Figure 5 - Agwanpur Geomorphic map

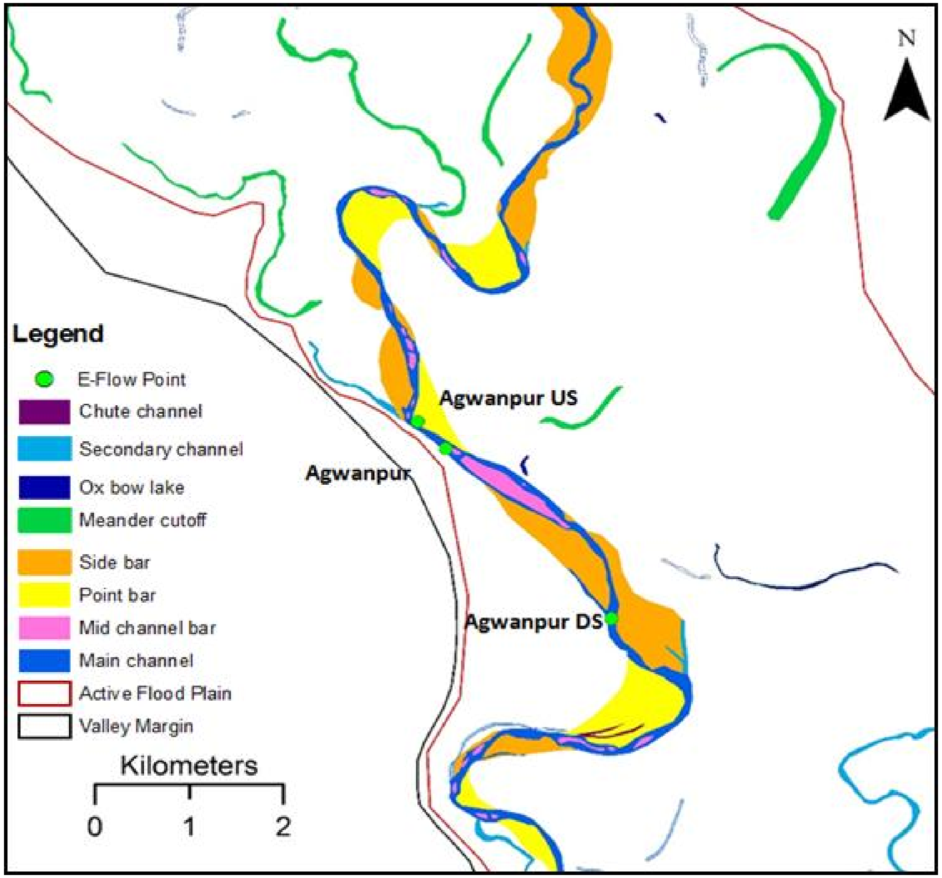

Figure 6 - Kathghar Geomorphic map

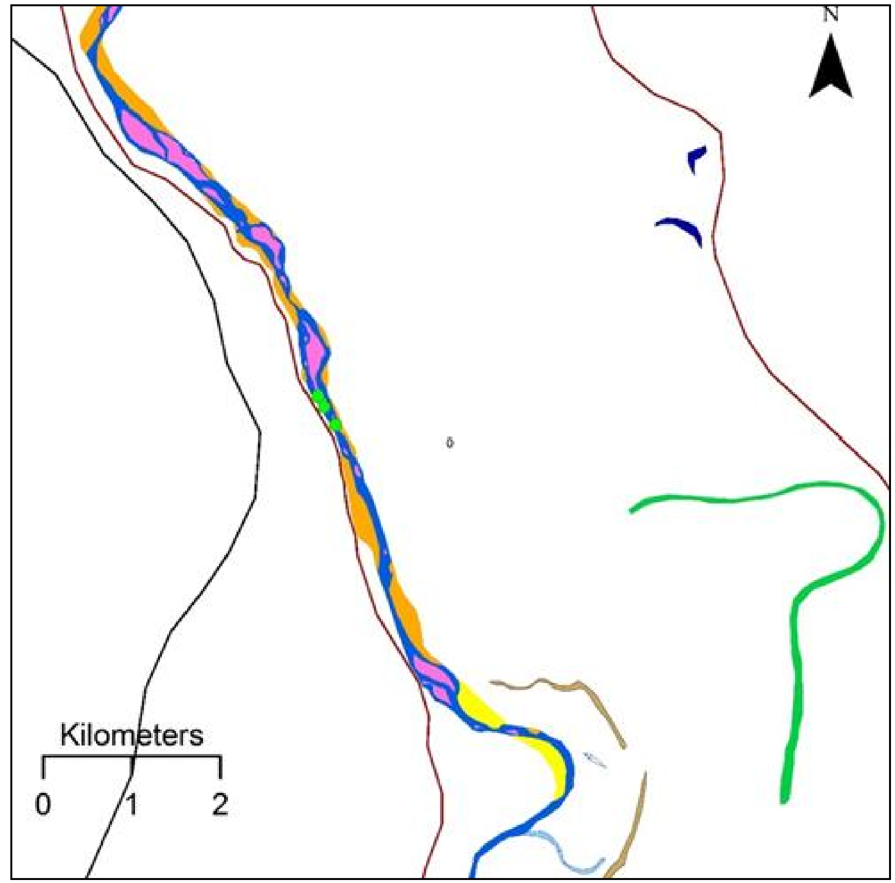

Figure 7 - Chaubari Geomorphic map

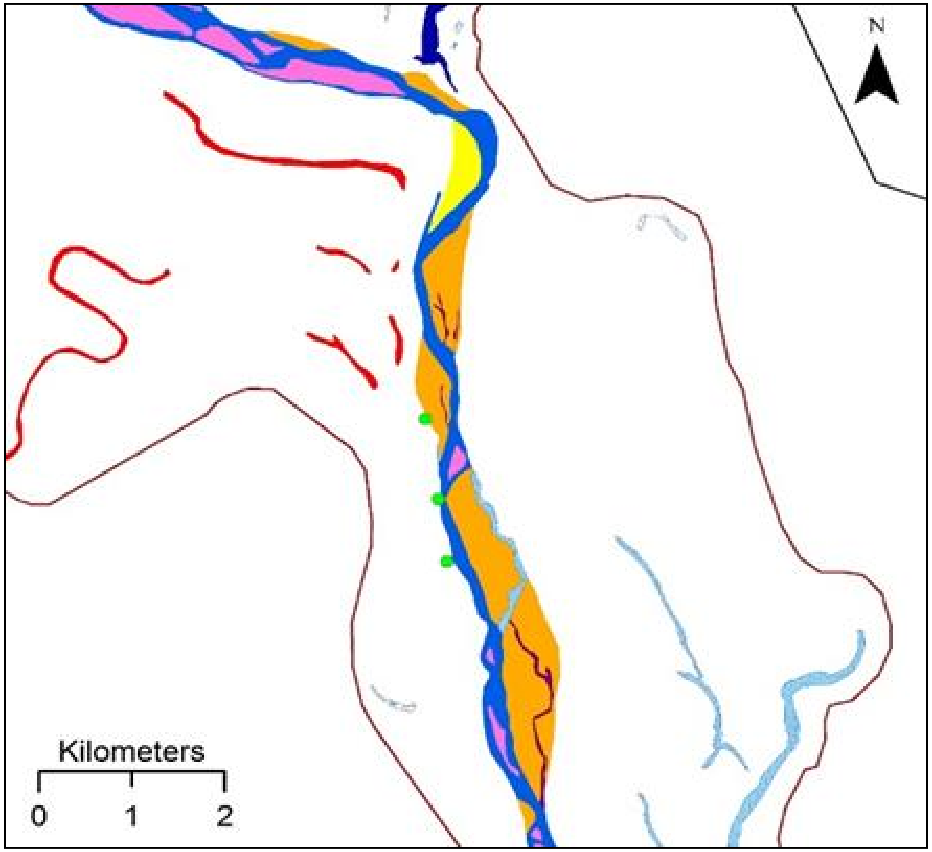

Figure 8 - Dabri Geomorphic map

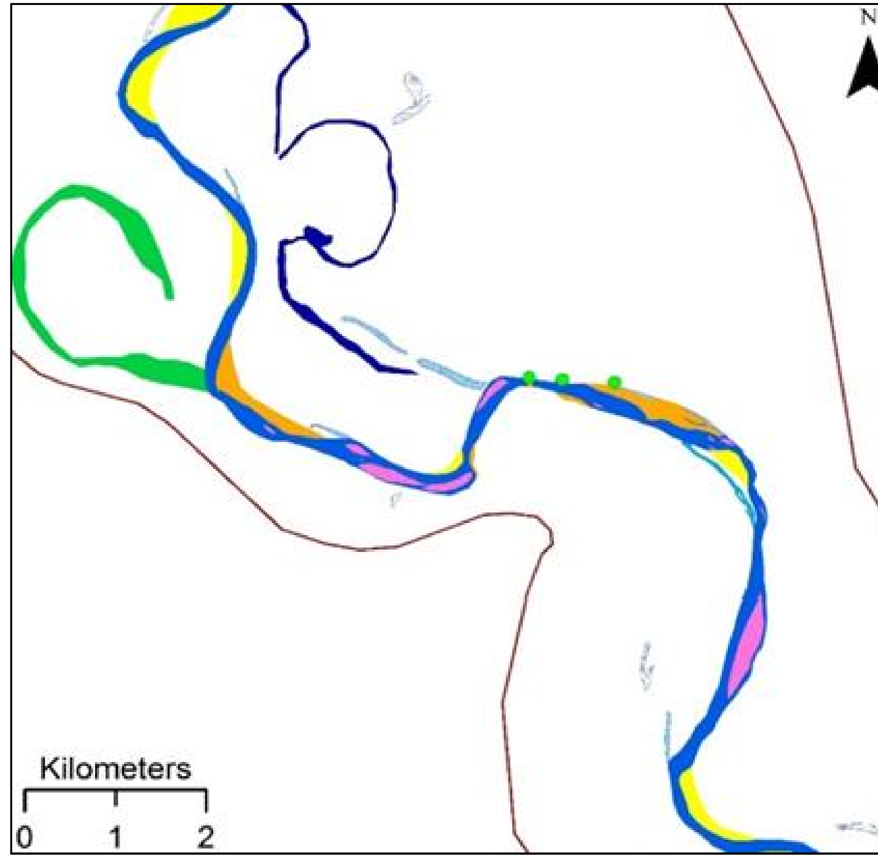

Figure 9 - River Style 1 (Upstream of Kheera Village to Jim Corbet park)

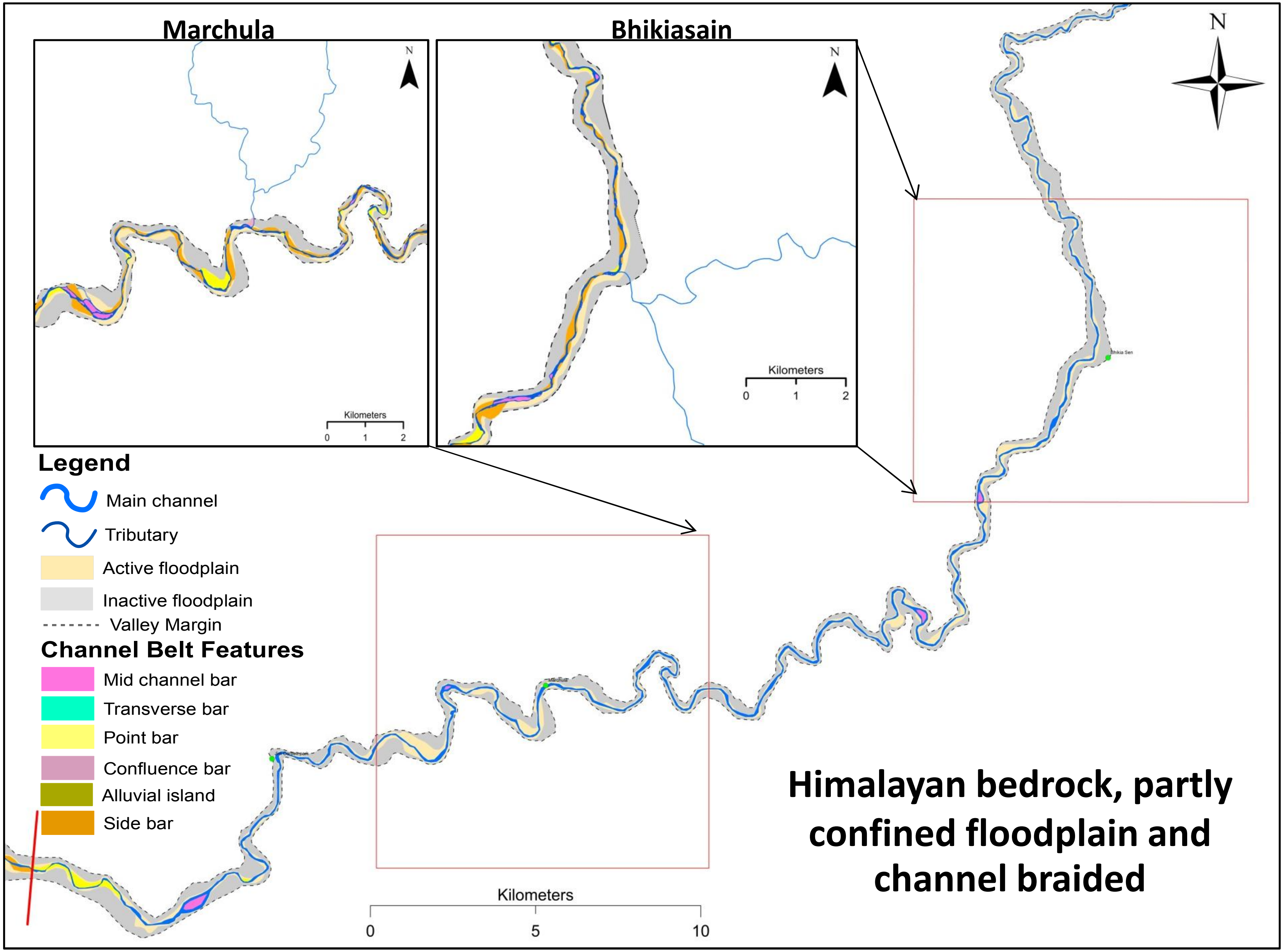

Figure 10 - River Style 2 (Bodhapur to Mughalpur)

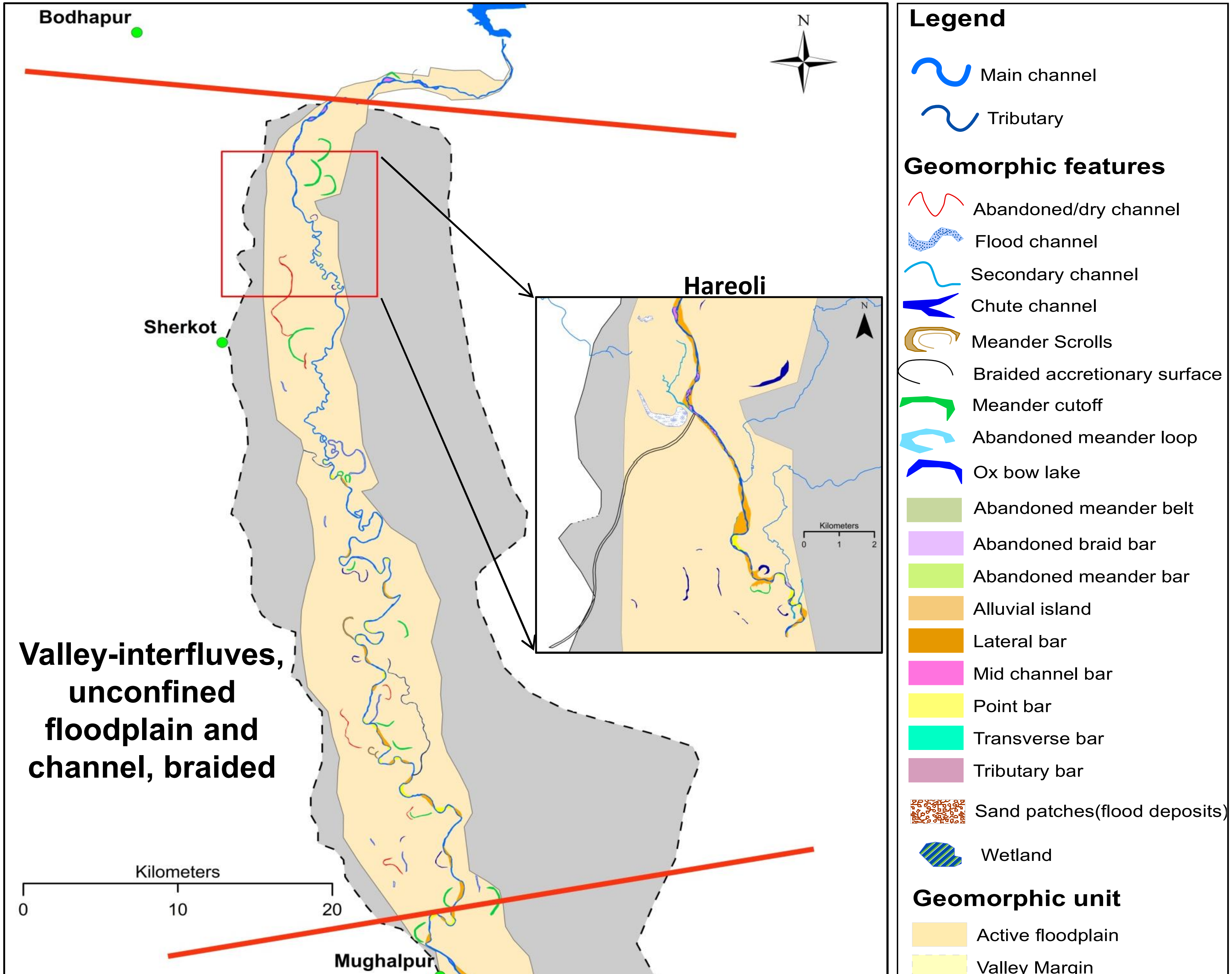

Figure 11 - River Style 3 (Mughalpur to Bareilly

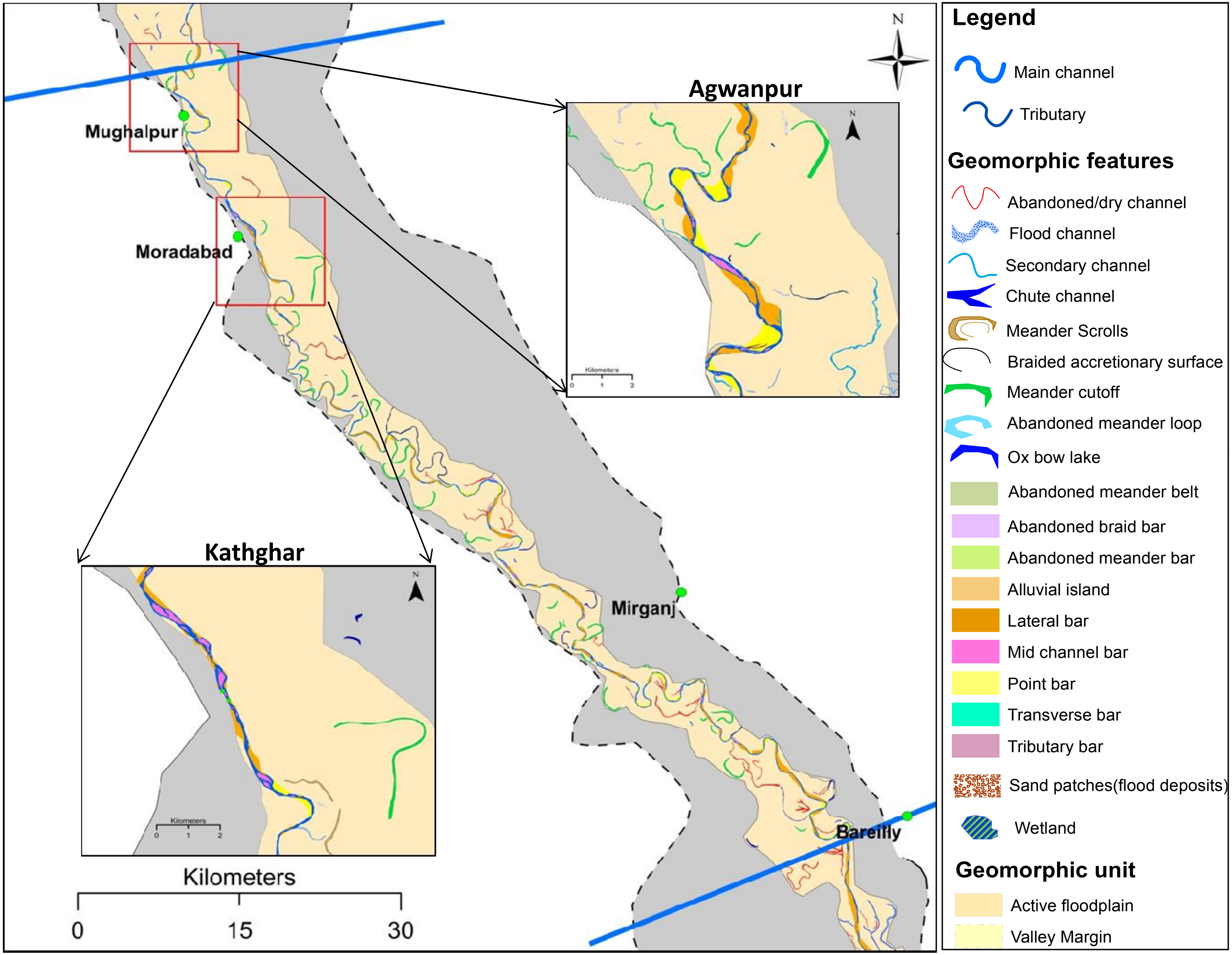

Figure 12 - River Style 4 (Bareilly to Kannauj)