Ganga River Basin Management Plan-2015

Volume 5: Thematic Studies – Geomorphic Analysis and Wetlands

VOLUME 5 OF 12

Centre for Ganga River Basin Management and Studies
Indian Institute of Technology Kanpur

NATIONAL MISSION FOR CLEAN GANGA (NMCG)

NMCG is the implementation wing of National Ganga Council which was setup in October 2016 under the River Ganga Authority order 2016. Initially NMCG was registered as a society on 12th August 2011 under the Societies Registration Act 1860. It acted as implementation arm of National Ganga River Basin Authority (NGRBA) which was constituted under the provisions of the Environment (Protection) Act (EPA) 1986. NGRBA has since been dissolved with effect from the 7th October 2016, consequent to constitution of National Council for Rejuvenation, Protection and Management of River Ganga (referred to as National Ganga Council).

www.nmcg.in

CENTRE FOR GANGA RIVER BASIN MANAGEMENT AND STUDIES (cGanga)

cGanga is a think tank formed under the aegis of NMCG, and one of its stated objectives is to make India a world leader in river and water science. The Centre is headquartered at IIT Kanpur and has representation from most leading science and technological institutes of the country. cGanga's mandate is to serve as think-tank in implementation and dynamic evolution of Ganga River Basin Management Plan (GRBMP) prepared by the Consortium of 7 IITs. In addition to this it is also responsible for introducing new technologies, innovations and solutions into India.

www.cganga.org

ACKNOWLEDGEMENT

This document is a collective effort of a number of experts, institutions and organisations, in particular those who were instrumental in preparing the Ganga River Basin Management Plan which was submitted to the Government of India in 2015. Contributions to the photographs and images for this vision document by individuals are gratefully acknowledged.

SUGGESTED CITATION

GRBMP by cGanga and NMCG

CONTACTS

Centre for Ganga River Basin Management and Studies (cGanga)
Indian Institute of Technology Kanpur, Kanpur 208 016, Uttar Pradesh, India

or

National Mission for Clean Ganga (NMCG)
Major Dhyan Chand National Stadium, New Delhi 110 002, India

GANGA RIVER BASIN MANAGEMENT PLAN - 2015

Volume 5: Thematic Studies – Geomorphic Analysis and Wetlands

12 VOLUMES

01 Extended Summary & Overview

02 GRBMP Missions

03 Ganga River Basin and its Management- Salient Aspects

04 Thematic Studies – Aviral Ganga

05 Thematic Studies – Geomorphic Analysis and Wetlands

06 Thematic Studies – Biological Profile of Ganga River System

07 Thematic Studies – Demographic, Socio- Economic, Urbanization & Industrialization

08 Thematic Studies – Agricultural Practices and Trends

09 Thematic Studies – Domestic Pollution Load from Basin States

10 Thematic Studies – Domestic and Industrial Pollution in Ganga Sub Basins

11 Thematic Studies – Managing Pollution Load

12 Thematic Studies- Policies, Laws and Governance

Ganga river in Himalayas mountains

River Style® Framework for the Ganga River

GRBMP : Ganga River Basin Management Plan

by

Indian Institutes of Technology

IIT Bombay | IIT Delhi | IIT Guwahati | IIT Kanpur | IIT Kharagpur | IIT Madras | IIT Roorkee

Preface

In exercise of the powers conferred by sub-sections (1) and (3) of Section 3 of the Environment (Protection) Act, 1986 (29 of 1986), the Central Government has constituted National Ganga River Basin Authority (NGRBA) as a planning, financing, monitoring and coordinating authority for strengthening the collective efforts of the Central and State Government for effective abatement of pollution and conservation of the river Ganga. One of the important functions of the NGRBA is to prepare and implement a Ganga River Basin Management Plan (GRBMP).

A Consortium of 7 Indian Institute of Technology (IIT) has been given the responsibility of preparing Ganga River Basin Management Plan (GRBMP) by the Ministry of Environment and Forests (MoEF), GOI, New Delhi. Memorandum of Agreement (MoA) has been signed between 7 IITs (Bombay, Delhi, Guwahati, Kanpur, Kharagpur, Madras and Roorkee) and MoEF for this purpose on July 6, 2010.

This report is one of the many reports prepared by IITs to describe the strategy, information, methodology, analysis and suggestions and recommendations in developing Ganga River Basin Management Plan (GRB EMP). The overall Frame Work for documentation of GRBMP and Indexing of Reports is presented on the inside cover page.

There are two aspects to the development of GRBMP. Dedicated people spent hours discussing concerns, issues and potential solutions to problems. This dedication leads to the preparation of reports that hope to articulate the outcome of the dialog in a way that is useful. Many people contributed to the preparation of this report directly or indirectly. This report is therefore truly a collective effort that reflects the cooperation of many, particularly those who are members of the IIT Team. Lists of persons who are members of the concerned thematic groups and those who have taken lead in preparing this report are given on the reverse side.

Dr Vinod Tare
Professor and Coordinator
Development of GRBMP
IIT Kanpur

The Team

1.	Bimlesh Kumar, IIT Guwahati	bimk@iitg.ernet.in
2.	J K Pati, Allahabad University	jkpati@gmail.com
3.	Kirteshwar Prasad, Patna University	kriteshwar.geopat@gmail.com
4.	Parthasarthi Ghosh, ISI Kolkata	pghosh@isical.ac.in
5.	Rajiv Sinha, IIT Kanpur	rsinha@iitk.ac.in
6.	Ramesh Shukla, Patna University	rshuklapat@gmail.com
7.	Kalyan Rudra, WBPCB	rudra.kalyan@gmail.com
8.	S K Tandon, University of Delhi	sktand@rediffmail.com
9.	Saumitra Mukherjee, JNU Delhi	saumitra@mail.jnu.ac.in
10.	Shashank Shekhar, University of Delhi	shashankshekhar01@gmail.com
11.	Soumendra Nath Sarkar, ISI Kolkata	soumendra@isical.ac.in
12.	Tapan Chakarborty, ISI Kolkata	tapan@isical.ac.in
13.	Vikrant Jain, University of Delhi	vjain@geology.du.ac.in

Lead Author

1. Rajiv Sinha, IIT Kanpur

Contents

List of Figures

List of Tables

List of Appendices

1. Preamble

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. According to the practical set of objective criteria used in river reach analysis by Kellerhals et al. (1976), and the nested hierarchical framework proposed by Frissell et al. (1986), the River Styles framework provides a physical basis to describe and explain within a catchment distribution of river forms and processes, and predict future river behavior. Within a catchment, River Style framework gives a holistic framework for data collection and organization and provides a framework to interpret its behavior and the adjustment potential over time.

Scale is very important to define the hierarchical River Style framework. The nested hierarchical River Styles framework consists of five scales: catchment, landscape, reach, geomorphic and hydraulic. Catchment scale explains the geological setting and climatic condition over the entire catchment. Similarly, the landscape setting defines the large-scale landforms that directly impact the processes operative in different reaches. River reaches are stretches over which the basic riverine processes are more or less uniform. River Styles are identified and interpreted at the reach scale using valley setting and assemblage of geomorphic units. Geomorphic units and their sedimentology is defined for both the channel and the floodplain of the river. Within the geomorphic units, homogeneous sets of flow type and substrate define the hydraulic units that are used to interpret aquatic habitat patches along the river.

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.

Field investigation assists the River Style framework by providing some necessary data. Bed material texture can be interpreted from the field data. In general terms, bed material size and texture reflects regional geology, flow energy and sediment flux from upstream. Confined valley settings are dominated by bed rock with coarse textured geomorphic units. In Partly confined valley settings bed rock may or may not be present and bed materials are of variable sizes. Fine-grained suspended deposits are encountered in the floodplain pockets. Unconfined valley settings comprise all kinds of textures with locally significant bedrock. Bed material textures and its relation to the bank composition translate to the river character and behaviour.

River Styles concept has primarily been developed for a smaller river system and in this work we attempt to apply this for a large river system such as the Ganga for the first time. Our efforts so far have shown that for a large tropical river such as the Ganga, the River Styles framework can be very useful to define geomorphic diversity from the source (Gangotri) to sink (Ganga sagar). The Ganga River basin has significant diversity in terms of landscape setting, valley setting, valley morphology, geomorphic features; morphometric parameters that will be reflected in the River Style based classification. Additionally, River Style is a hierarchical approach, which includes geomorphic characteristics at different scales. The large scale attributes for the Ganga River include landscape setting, valley setting, valley morphology, valley confinement and the small scale (reach scale) attributes consist of bar area, bar percentage, sinuosity, braid channel ratio etc.

The Ganga river is not just a large river in terms of area, length, discharge and sediment load, it also traverses through very diverse settings through its journey from the source to the sink. The Bhagirathi is the source stream of the Ganga which originates from the Gangotri Glacier at Gomukh. At Devprayag, where the Alaknanda joins the Bhagirathi, the river acquires the name Ganga. The course of the Ganga river up to Haridwar falls into the mountainous reach and it then debouches into the plains. The Ganga river is joined by numerous tributaries in the plains before flowing into the Bay of Bengal. The River Ramganga joins the Ganga near Kannauj, and the Yamuna confluences the Ganga at Allahabad, making a major contribution to the river flow. Beyond Allahabad, the Ganga is joined by several tributaries, most of which are from the north and a few from the south. At Farakka, the barrage diverts some of the water into a feeder canal. Downstream of this barrage, River Ganga splits into two, the Bhagirathi (Hooghly) on the right and Padma on the left. The Bhagirathi (Hooghly) meets the Bay of Bengal about 150 km downstream of Kolkata. The Padma enters Bangladesh and meets the Brahmaputra and Meghna before finally joining the Bay of Bengal. The complexity and diversity of the Ganga river are important to understand the ecological diversity in the system and the River Style Framework provides a good opportunity to document such variability in the system from the source to the sink.

In the Ganga River, landscape setting is determined on the basis of position and the physiographic characters of the basin. Similarly, valley setting is characterized with respect to the type of the valley such as bedrock, alluvial or mixed. The next step is to determine channel confinement from the mutual relation between the channel and the adjacent floodplain. This is followed by the identification of geomorphic units. In the Ganga River, the various geomorphic units like mid channel bar, side bar, point bar, alluvial island, confluence bar in the channel belt area and meander cut off, meander scrolls, meander loop, abandoned meander bar, ox bow lake, abandoned braid bars, flood channels, chute channel, abandoned channel, flood channel have been interpreted in the active flood plain region. These geomorphic units vary in spatial and temporal scale in different River Styles framework. Some features may be used as geomorphic indicators to define certain geomorphic status of the river.

From the application point of view, River Styles framework will provide a present base line to evaluate the physical status of a river with respect to the geomorphic character, its present day condition in terms of geomorphology, flow characteristics and biota and allow us to develop a framework for comparison with the past condition and future trends of the river. On the basis of characterization of the river following the River Style framework approach we propose to approach the work of river restoration and management.

2. Data used

2.1 *Geomorphic maps*

The key geomorphic units that have been mapped for the river Ganga are valley margin, active floodplain and channel belt each characterized by several geomorphic features. Landsat imagery, SRTM generated DEM along with Google Earth images were used to prepare these maps. Details of the procedure used for geomorphic mapping have already been discussed in the previous report. These geomorphic maps for the entire stretch of the Ganga River have been used as one of the inputs to define the different River Styles for the Ganga. The geomorphic maps were also used to calculate different parameters such as sinuosity, braid channel ratio, the bar area, etc and has been used for characterizing the River Styles.

2.2 *Field Observation*

While characterizing a river reach, several parameters are needed such as bed material character, types of riparian vegetation; these were recorded during field visits to key points along the river. Field trip was organized in June-July 2011 and November 2011 to study these parameters. Cross section survey was carried by professional surveyors along with participants from FGM and WRM group members, along pre-defined section lines and cross sectional parameters like depth, bankfull width, wetted perimeter, etc were computed.

2.3 *DEM (ASTER/SRTM)*

ASTER DEM data of the year 2009 has been used to generate the slope data in the hilly terrain. ASTER has a spatial resolution of 30 m in comparison to SRTM's 90 meter and is thus better suited for computing slope in the high altitude areas. It has been used to compute slope between Gomukh (source of Ganga) to Haridwar. But ASTER data has much more noise and is totally unsuitable in the plains area. So, for computing slope in the low altitude area (downstream of Haridwar) SRTM has been used.

3. Methodology

In order to characterize the stretches of Ganga River and divide it into geomorphologically significant and distinctive portions, the guidelines outlined in the River Style® framework (Brierly & Fryirs, 2005) have been used. However, as Ganga is a much larger and complex system as compared to smaller drainages of Australia studied by Brierly and others, we have designed a set of parameters and criteria that can be applied in the present scenario to document geomorphic diversity and function of the Ganga River. This has formed the basis for differentiating the Ganga River into distinct River Styles.

The River Style® framework has a nested hierarchical top-down approach and is arranged in three key scales. The following section describes the key parameters at each scale that are assessed to define a River Style.

1. **Landscape/Valley setting:** Landscape setting is readily identifiable from topographic features with a characteristic pattern of landforms through which the river flows. In the Ganga River five landscape units have been identified based on landscape position and physiographic character. Usually, ***the valley setting constitutes the next hierarchy but in the case of the Ganga River, this is inclusive in the landscape setting***. They are: -
    - *Himalayan Bedrock*: when the river is flowing through the Himalayan mountain range.
    - *Piedmont*: a terrain close to the mountain front as the river leaves the mountainous terrain and enters the plain.
    - *Alluvial Valley*: an alluvial plain where the river flows through its own alluvium.
    - *Craton Margin*: a low-lying plain where the river is flowing through an area that is flanked or underlain partly by the Indian cratonic basement rock and partly by its own alluvium.
    - *Valley-Interfluve*: when the river flows through an alluvial terrain that has been deposited in the interfluve region of the two major river valleys.
    - Fan-Interfan: when the river emerges from mountain front and flows out onto a more gently sloping plain resulting into a distinct landform called fans. The area between two fans is called interfan.
    - Badland: this is typical for the Yamuna and Chambal rivers that flow through the Vindhyans creating ravines. Badlands are highly dissected regions.

2. **Channel confinement:** This describes the relationship between the channel and its adjacent floodplain and can be divided into:
    - *Confined*: When more than 90% of channel abuts the valley margin and there is no active floodplain on both the banks of the channel.

- *Partly confined*: When 10% to 90% of channel is hugging the valley margin; active floodplain is present only in parts of the study reach and is absent or very poorly developed on the other parts.
- *Unconfined*: Where less than 10% channel abuts the valley margin or the channel mostly flows centrally; active floodplain extends on both the banks of the channel.

3. **Floodplain boundation:** The nature of floodplain boundation defines the relationship between the active floodplain and the valley margin. They can be divided into:
   - *Confined*: Active floodplain boundary coincides with the valley margin on both the sides of the channel.
   - *Partly confined*: Active floodplain boundary coincides with the valley margin in certain reaches of significant length but remains unconfined in the remaining reaches.
   - *Unconfined*: Active floodplain boundary and the valley margin are usually separated by an older floodplain.

In addition to these three parameters that formed the first level of differentiation, channel type (braided, sinuous or anabranching) was also added to the River Style description, although it did not always formed the basis for distinction.

After the River Style® boundary was marked on the geomorphic map, each stretch of a particular style was further divided into reaches for which various channel morphometric and meander parameters were calculated. Cross sectional parameters were calculated at specific field locations. Table 1 lists the different parameters that were calculated and Figures 1 and 2 illustrate the planform and meander parameters respectively.

Table 1: Planform and cross-sectional parameters

Parameters	Term	Definition	Expression	Figure
Planform	**Sinuosity (P)**	Ratio of valley gradient to channel gradient over a stream reach.	**Lcmax/Lr** where, Lcmax is the length of the midline of the channel (for single-channel rivers), or the widest channel (for multi-channel rivers) and Lr is the overall length of the reach	1 a
	Braid-channel ratio (B)	It distinguishes between rivers with single and multiple thalwegs. Higher value indicates that the stream has a network of small channels separated by small sediment deposition called bars.	**Lctot/Lcmax** where Lctot is the total of the mid-channel lengths of all the channels in a reach	1 b

Table continued to next page ... ...

... ... Table continued from previous page

Parameters	Term	Definition	Expression	Figure
	Average Channel width	Average width of the trunk (primary) channel.		
	Channel area	Area occupied by water in the stream.		
	Bar area	Area occupied by different depositional units like mid channel bar, side bar, point bar, alluvial island and confluence bar.		
Meander	**Radius of curvature (Rc)**	Radius of a best-fit circle passing through points on a meander curve.		2 a
	Axial wavelength (L)	Distance between two consecutive inflection points.		2 a
	Amplitude (Am)	Width of the meander bends measured perpendicular to the straight line axis.		2 a
Cross-sectional	**Bankfull width (w)**	Maximum width that the stream can attain before flooding.		2 b
	Maximum depth (dmax)	Depth at which the deepest point (thalweg) of the stream is found.		2 b
	Left sub area (Al)	The sub area or zone formed by a vertical line drawn from the surface of the water to the thalweg on the left side of water flow.		2 b
	Right sub area (Ar)	The sub area or zone formed by a vertical line drawn from the surface of the water to the thalweg on the right side of water flow.		2 b
	Channel capacity (A)	Cross sectional area of the channel at bankfull discharge.	**Al + Ar**	
	Channel asymmetry (A*)	Quantifies the asymmetry of the channel cross section. If negative then the left sub area is bigger than the right sub area. If positive then vice versa.	**(Ar - Al) /A**	
	Wetted perimeter (P)	Surface of the channel bottom and sides which is wet i.e. which is in direct contact with water during bankfull discharge.		2 b
	Hydraulic radius	Measure of channel efficiency. The greater the efficiency of the channel, the less likely it is to flood. The highest values occur when channels are deep, narrow and semi circular in shape.	**A/P**	

Based on the geomorphic maps prepared for different stretches of Ganga, ARCGIS 10.0 has been used for calculating different parameters. Representative geomorphic maps and field photographs are given in Appendix I. Appendix II shows the reaches in the Ganga River along with the position of the meanders for which parameters have been calculated. Appendix III lists the channel morphometric data with diagramatic representation and Appendix IV shows the meander parameter data and the bar plot of the parameters reach wise.

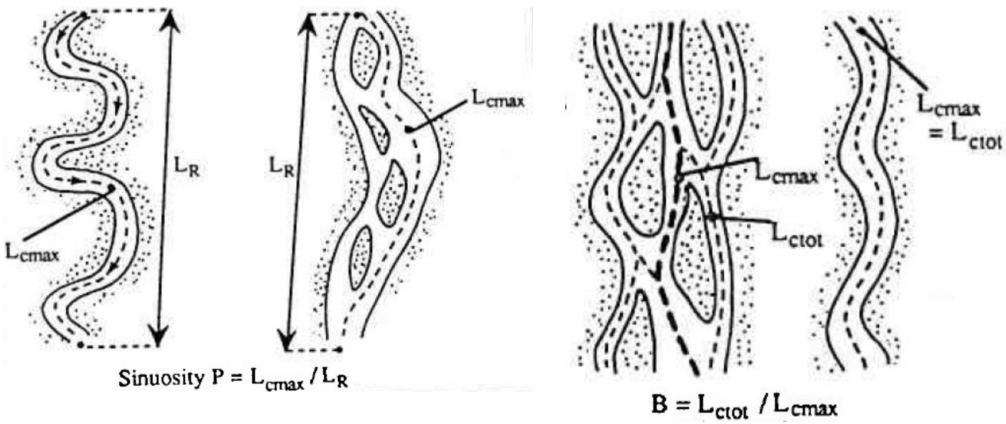


Figure 1 a, b: Sinuosity and Braid Channel Ratio of A Meandering and Braided River After Friend and Sinha, (1993).

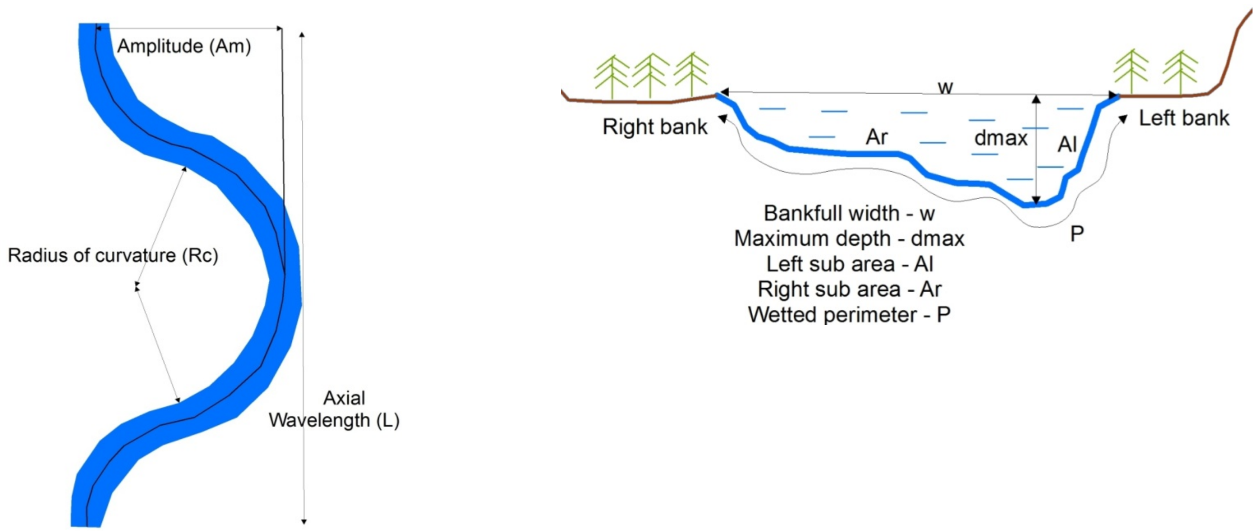


Figure 2 a, b: Meandering and Cross Sectional Parameters of a Channel

We have followed slightly different approaches to develop the River Style Framework of the Ganga river in the Himalayan catchment and in the plains. Two parameters that form the major point of distinction are:

- **Slope**: It is an important parameter that has been used in characterizing the river in the Himalayan catchment where it varies remarkably. It is of little importance in the plains area as the slope remains more or less uniform with very little variation. Slope has been calculated using the hydrology tools of ARCGIS.

- **Active Floodplain**: It is a prominent feature in the plains area but it is either absent or patchy in the mountainous terrain.

The template for documenting the characteristics of the different River Styles of Ganga River is based on the documentation by Brierley and Fryirs (2005) with some modifications. Table 2 shows the template designed for documenting the River Style description for the Ganga River.

Table 2: Template for River Style description of the Ganga River

<table>
<tr><td colspan="2">Defining attributes: A brief synopsis about the particular River Style®.

Stretch: Location names giving the extent of the particular style.</td></tr>
<tr><td colspan="2">Details of Analysis</td></tr>
<tr><td colspan="2">Data used: The data that was used for interpretation Date:
Analyst: Name of the person creating the template.</td></tr>
<tr><td colspan="2">River Character: The different factors that characterize a particular stretch of river .</td></tr>
<tr><td>Landscape setting</td><td>Broad terrain characteristics as defined above (p.4 of the report)</td></tr>
<tr><td>Valley Morphology</td><td>Here the river valley width and its general configuration are documented. Based on the average valley width, the valley is characterised as : <1 km – very narrow, 1 to 3 km – Narrow, 3 to15 – moderate, 15 to 35 km – wide, > 35 km – very wide</td></tr>
<tr><td>Channel confinement</td><td>Channel confinement by the flanking floodplains and may be confined, partly confined or unconfined.</td></tr>
<tr><td>Active Floodplain characteristics</td><td>The morphology of the active floodplain along with its width and its relation (boundation) with valley margin.</td></tr>
<tr><td>Channel Characteristics</td><td>The different parameters that are calculated are given here corresponding to the particular style.</td></tr>
<tr><td rowspan="2">Diagnostic Geomorphic Features (geometry, sedimentology)</td><td>Channel belt- alluvial/Himalayan Bedrock
Document all the geomorphic features of the main channel and its active floodplain.</td></tr>
<tr><td>Flood plain</td></tr>
<tr><td rowspan="2">Land Use/Land Cover association</td><td>Flood plain
The land utilization in active floodplain as well as in the different bars as observed in field/Google Earth/LULC map of NRSC.</td></tr>
<tr><td>Channel belt</td></tr>
<tr><td>Channel and Floodplain material</td><td>The grain size of the bed material as well as the active floodplain as observed and measured in field.</td></tr>
</table>

River Behavior and Process Zone
Document the river dynamics, bank erosion/stability, sediment supply and tectonic processes that have influenced the River Style® along with the river characteristics during low flow, bankfull flow and overbank flow.
Ecological Significance
The ecological diversity that is present in the particular River Style.

4. River Style® Framework For The Ganga River

Using the first order parameters and the channel characteristics, the Ganga has been divided into 10 distinct river styles. Distinguishing attributes of River Style® are summarized in Table 3. Figure 3 shows the distribution of the River Styles for the Ganga River from source to Farakka. A brief description of each River Style® is presented below. The templates describing characteristics of each style are given in section 5.

1) ***Himalayan, Steep Valley*** River Style® has been defined for the stretch of the Ganga from Gomukh to Rishikesh where the valley margin is adjacent to the active channel, and consequently, no floodplain has formed. The Ganga River in this stretch is mostly a single channel. Channel bed and valley walls consist of Himalayan bedrock, providing the key control on the path of the river. The river gradient varies from moderate to steep (2 degree). Riffles and pools are the dominant geomorphic features. Bed material consists of boulders, cobbles, pebbles and coarse sand.

2) ***Himalayan, Partly Confined Floodplain and Channel, Braided*** River Style® occurs at the transition of alluvial and Himalayan bedrock confined channel reach. This style between Rishikesh and Haridwar differs from Style 1 mainly in terms of development of narrow floodplain pockets. The floodplain as well as the channel is partially confined by the valley. The river is highly braided, multichannel and of low sinuosity. It is characterized by a gentle gradient (0.518 degree). Bed material is dominated by gravel/ coarse sand.

3) ***Piedmont, Partly Confined Floodplain and Channel, Braided*** River Style® is observed when the Ganga River leaves the confines of Himalayan mountainous region downstream of Haridwar and enters the alluvial plain. The river is highly braided in this style between Haridwar and Bijnor and both valley and active floodplain widths show a remarkable increase. Both the floodplain and the channel are partly confined.

4) ***Valley-Interfluve, Partly Confined Floodplain and Channel, Braided*** River Style® from Bijnor to Narora is characterized by an interfluve setting where the channel is restricted

on one side (in this case on the right bank) by a cliff or the valley margin itself and the active floodplain has developed only on the opposite (left) bank of the river in this style. In some reaches, the channel is unconfined as the floodplain has developed on both banks but the floodplain is partly confined on the left bank by the valley margin. Side bars and mid channel bars are the dominant in-channel geomorphic feature here whereas abandoned braid bars are common in the active floodplain. Asymmetry is very much pronounced here. Channel bed is composed of fine sand and the banks are muddy.

5) ***Valley-Interfluve, Unconfined Floodplain and Channel, Braided*** River Style® between Narora and Fatehgarh has similar features as the previous style except that both the active floodplain and channel are unconfined and the valley margin is quite wide on both sides. The stretch of the Ganga between Sirathu and Allahabad also shows the same style except that the channel is a little more sinuous. Abandoned braid bar is the dominant geomorphic feature. Bed material in this River Style varies from very fine sand to coarse sand and the bank comprises an alternate succession of mud and fine sand. The sandy bars appear more common in the channel belt downstream of the Narora barrage.

6) ***Valley-Interfluve, Unconfined Floodplain, Partly Confined Braided*** River Style® between Fatehpur and Sirathu is characterized by incised channel and very narrow, discontinuous active floodplain on either side. Channel is partly confined by the cliffs (mostly on the right bank) but the active floodplain, where present, is bordered by a narrow but continuous valley margin (inactive floodplain). Channel is braided and mid channel bars and alluvial islands are noted. Bed material comprises of fine to medium grained sand and the floodplain is muddy.

7) ***Alluvial Valley, Unconfined Floodplain and Channel, Sinuous*** River Style® has been defined between Allahabad and Gopiganj and this stretch marks a sharp transition from valley interfluve setting to alluvial setting. The stretch between Chunar and Chapra also shows the same River Style. The river is highly sinuous and large point bars are present bordered by adequately wide active floodplain. Valley margin is narrow and mimics the channel sinuosity. Numerous scrolls, abandoned meander loops and ox-bow lakes are common. Fine-grained sand is the bed material in this style.

8) ***Craton Margin, Partly Confined Floodplain and Channel, Sinuous*** River Style® is marked between Gopiganj and Chunar when the river is bordered by the craton margin along its right bank. Further downstream, the stretch between Pansalla and Kursela also shows the same style. Active floodplain has developed only along the left bank. Point bars are common and so is abandoned meander belt. Though the river is mostly sinuous (1.27-2.03), some reaches in this river style show multi-thread braided morphology

where abandoned braid bars are found. Medium to fine grained sand is the bed composition with clayey, silty to fine grained sand as the floodplain material.

9) ***Valley-Interfluve, Partly Confined Floodplain and Channel, Anabranching*** River Style® defined between Chapra and Pansalla again marks a sharp change from craton margin setting to valley-interfluve setting. A large part of the valley is occupied by the channel belt and floodplain. The most diagnostic geomorphic features in this river are large, stable alluvial islands dividing the channel into anabranches that rejoin downstream. Some stretches in this style show significant sinuosity.

10) ***Craton Margin, Confined Floodplain, Partly Confined Braided*** River Style® between Kursela to Farakka is similar to River Style 8 above except that the floodplain is confined by valley side and the channel is partly confined. Alluvial islands and large braid bars are the dominant geomorphic features. Channel sediments comprise of very fine-grained sand and floodplains have silt and clay.

The following sections of the report present the systematic description of each of the river styles in the form of detailed templates.

Table 3: Distinguishing attributes of River Styles in the Ganga River

River Style® No.	River Style® Name	Stretch (Length in Km.)	Landscape Setting	Channel Confinement	Flood Plain Boundation	FP:VW	Nature of Symmetry	Channel type	Mean Slope	Sinuosity	Braid Channel Ratio	Bar %	Special feature/Defining attribute
1	Himalayan, Steep Valley	Gomukh to Rishikesh (~236)	Himalayan Bedrock	Confined	No floodplain	-	Symmetric	Sinuous	2°	1.03 - 2.39	1.0 - 1.25	13-64	Incised channels in Himalayan bedrock. No floodplain with none to very few bars.
2	Himalayan, Partly Confined Floodplain and Channel, Braided	Rishikesh to Haridwar (~27)	Himalayan Bedrock	Partly confined	Partly confned	1:5	Asymmetric	Braided	0.518°	1.18 - 1.40	1.21 - 2.78	63	Discontinuous floodplain in Himalayan bedrock confined channel with dominant mid channel bars and alluvial islands.
3	Piedmont, Partly Confined Floodplain and Channel, Braided	Haridwar to Bijnor (~79)	Piedmont	Partly confined	Partly confined	1:1.8	Asymmetric	Braided	0.124°	1.15 - 1.25	1.8 - 3.7	68	Abrupt increase in valley and floodplain width. Channel width also increases significantly with very high braiding index.
4	Valley-Interfluve, Partly Confined Floodplain and Channel, Braided	Bijnor to Bugrasi (~110.7)	Valley-Interfluve	Unconfined	Partly Confned	1:1.5	Symmetric	Braided	0.034°	1.2 - 1.43	1.4 - 2.4	60	Active Floodplain is dominantly on the left bank of the river with abundant floodplain features. Valley is prominent on the left side of the river and the river flows very close to the right valley margin.
		Bugrasi to Narora (~59)	Valley-Interfluve	Partly confined	Partly confned	1:5	Asymmetric	Braided		1.12 - 1.27	1.72 - 2.1	72	
		Fatehgarh to Fatehpur (~224)	Valley-Interfluve	Partly confined	Partly confined	1:1.6	Asymmetric	Braided	0.027°	1.07 - 1.25	1.2 -2.3	71	

Table continued to next page ... ...

... ... Table continued from previous page

River Style® No.	River Style® Name	Stretch (Length in Km.)	Landscape Setting	Channel Confinement	Flood Plain Boundation	FP:VW	Nature of Symmetry	Channel type	Slope	Sinuosity	Braid Channel Ratio	Bar %	Special feature/Defining attribute
5	Valley-Interfluve, Unconfined Floodplain and Channel,Braided	D/S Narora to Fatehgarh (~201)	Valley-Interfluve	Unconfined	Unconfined	1:3.8	Symmetric	Braided	0.24˚	1.13 - 1.42	1.27 - 2.25	85.5	Abandoned braid bar common. The valley margin is highly irregular.
		Sirathu to Allahabad (~82)	Valley-Interfluve	Unconfined	Unconfined	1:1.9	Symmetric	Braided	0.055˚	1.1 - 1.5	1.96 - 2.18	66	
6	Valley-Interfluve, Unconfined Floodplain, Partly Confined Braided	Fatehpur to Sirathu(~102)	Valley-Interfluve	Partly confined	Unconfined	1:2.4	Symmetric	Braided	0.035˚	1.22 - 1.63	1.54 - 2.27	68.9	Narrowest portion of active floodplain and valley margin in plain area with discontinuous floodplain. Only style with an unconfined floodplain but with a partly confined channel.
7	Alluvial, Unconfined Floodplain and Channel, Sinuous	Allahabad to Gopiganj(~115)	Alluvial	Unconfined	Unconfined	1:1.3	Asymmetric	Sinuous	0.018˚	1.4 - 2.4	1.15 - 1.95	70.5	Valley margin shows alternate widening and narrowing. Meander scrolls are abundant. Big patches of abandoned meander belt with meander scrolls are the prominent feature without the influence of Indian craton. Big patches of abandoned meander belt with meander scrolls are the prominent feature without the influence of Indian craton.
		Chunar to Chapra (311)	Alluvial	Unconfined	Unconfined	1:1.3	Asymmetric	Sinuous	0.010˚	1.11 - 2.6	1.0 - 2.59	38 - 60	

Table continued to next page ... ...

.... Table continued from previous page

River Style® No.	River Style® Name	Stretch (Length in Km.)	Landscape Setting	Channel Confinement	Flood Plain Boundation	FP:VW	Nature of Symmetry	Channel type	Slope	Sinuosity	Braid Channel Ratio	Bar %	Special feature/Defining attribute
8	Craton Margin, Partly Confined Floodplain and Channel	Gopiganj to Chunar(~74)	Craton Margin	Partly confined	Partly confined	1:1.8	Asymmetric	Sinuous	0.019˚	1.27 - 2.03	1.22 - 1.44	58.4	Big patches of abandoned meander belt with meander scrolls are the prominent feature with a cratonic setting.
		Pansalla to Kursela(~141)	Craton Margin	Partly confined	Partly confined	1:1.7	Asymmetric	Braided	0.024˚	1.36-1.4	1.7-1.76	62	
9	Valley-Interfluve, Partly Confined Floodplain and Channel, Anabranching	Chapra to Pansalla (~183)	Valley-Interfluve	Partly confined	Partly confined	1:1.3	Asymmetric	Anabranching	0.028˚	1.13 - 1.25	1.03-2.09	67 - 80	Alluvial islands are prominent and formed by the anabranches of the main channel.
10	Craton margin, Confined Floodplain, Partly Confined Braided	Kursela to Farakka (~145)	Craton Margin	Partly confined	Confined	1:1.7	Symmetric	Braided	0.011˚	1.61	3.57	64	Wide floodplain and valley margin totally coinciding, Big patches of alluvial island.

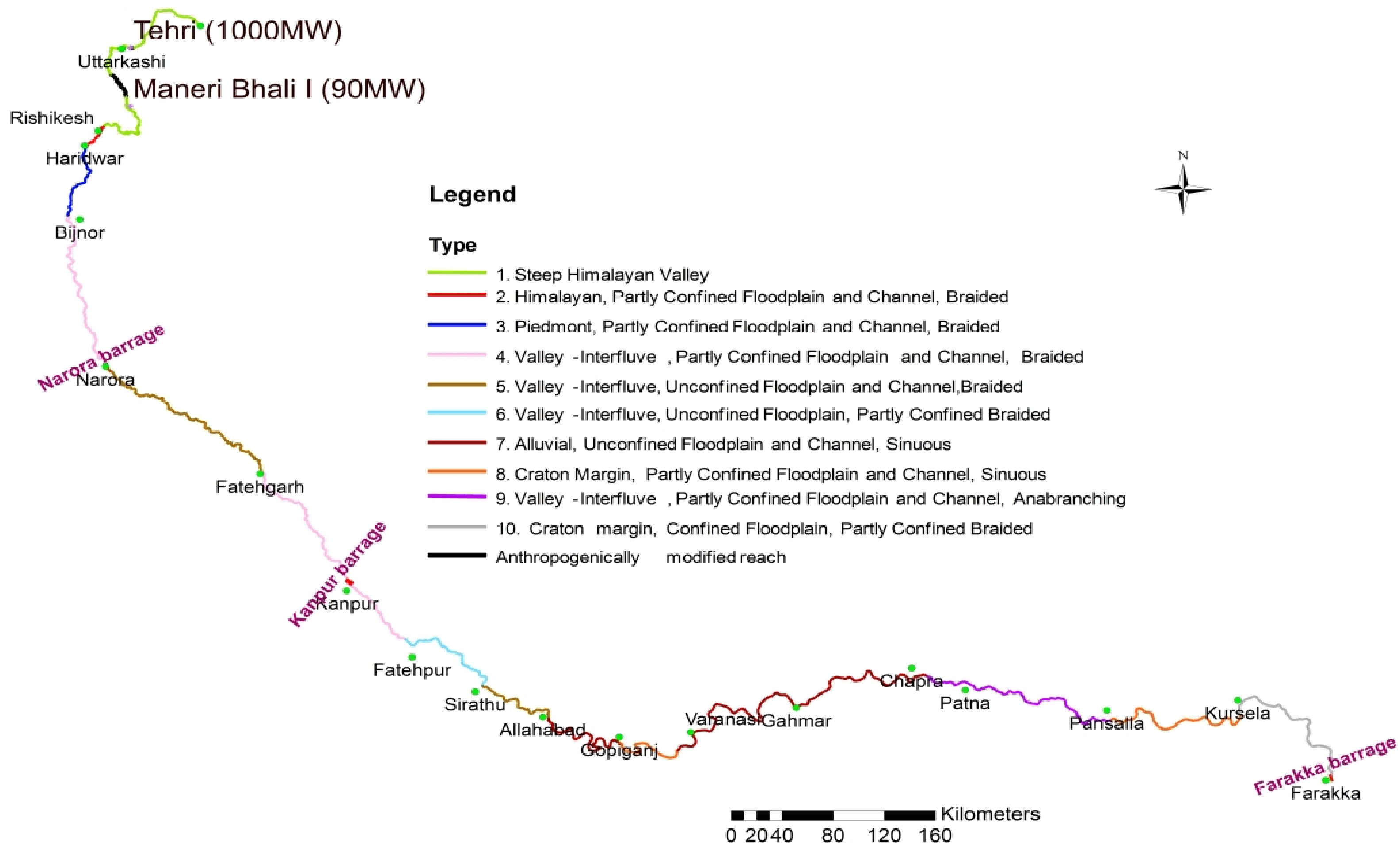


Figure 3: Distribution of River Styles in Ganga River from Gomukh to Farakka

5. Templates of the Different River Style® of Ganga River

5.1 River Style 1: Himalayan Steep Valley

Defining attributes: This river style covers a stretch of ~236 km in Himalayan bed rock valley setting. Channel belt geomorphic features are negligible or absent in this river style except in a small stretch between Dharali to Sunagarh. Valley is relatively narrow in upper reaches from Gomukh to Tehri while it becomes wider near Dharali and downstream from Tehri to Rishikesh. Channel follows the central position mostly except near Uttarkashi and Kaudiyala where it moves in oscillating manner. In this part, channel is characterized by high sinuosity ranging up to 2.42 otherwise channel shows low sinuosity. The braid channel ratio ranges from 1.0 to 1.4.

Stretch: Gomukh to Rishikesh - 236 Km

Details of Analysis	
Data used: Geomorphic feature mapped from Google earth, LISS IV MX and Landsat TM (5th May 2010)*; Valley margin delineated from SRTM 90m DEM (2000).* ***Analysts***: Ritesh Sipolya, Vikas Kamal *and Dr.Rajesh Kumar* ***Date***: 8th May, 2012	
River Character	
Landscape setting	Himalayan bed rock: • Greater Himalayan Mountains of central crystalline with undifferentiated metamorphic rocks. • Lesser Himalayas of undifferentiated metamorphic/igneous rocks, containing quartzite with associated argillaceous bands and calcareous hard sedimentary and slate phyllite, low grade schists.
Valley Morphology	• Moderate valley width, average width 3.12 km (max.7.74 km and min1.23 km). • Valley showing a maximum width at downstream of Devprayag and minimum at downstream of Maneri. • Valley is deep with moderate width. It is generally narrow in upper reaches from Gomukh to Tehri while the valley becomes wide downstream from Tehri to Rishikesh.
Channel confinement	• Confined channel in the entire river style.

Channel Characteristics	• Sinuosity (P): 1.03-2.42
	• Total channel area = 12.86 sq.km.
	• Average channel width = 113.42 m
	• Braid channel ratio (B): 1.0-1.25
	• Total bar area = 3.14 sq.km.
	• Side bars: ~2.49 sq.km, Length:58m –1.12km; Width: 6.2 m – 256 m
	• Alluvial islands: none
	• Mid channel bars: ~0.325 sq.km; Length: 22.7m - 412m Width: 8.1 m –103m
	• Point bars: ~0.283 sq.km; Length: 118m - 204m; Width: 45 m - from 106km
	• Confluence bars: 0.11 sqkm
	• Meandering parameters:
	  ○ 81 meanders
	  ○ Radius of curvature (rc) : 0.06 km to1.24km
	  ○ Wavelength (L):0.4 to 17.63km
	  ○ Amplitude (Am):0.14 km to 2.54km.
	• It is mostly single channel with few near-emergent bars comprising 10-12% of the channel reach excepting in few reaches where bar percentage exceed 50%

Diagnostic geomorphic features (geometry, sedimentology)	*Channel belt – Himalayan Bedrock* • Incised symmetrical channel without floodplain. • Depositional features are in few stretches only. • Moderate to steep slope ranges from 0.625° to 2.48°. a. Gomukh to Dharali ~ 2.48˚ b. Dharali to Sunagarh ~0.625˚ c. Sunagarh to Maneri ~ 2.22˚. d. Maneri to Tehri dam~ 2.10˚. e. Tehri to Rishikesh~1.83˚ • Riffle and pools are present along entire stretch except at dam sites.
Land Use/Land cover association	*Channel belt* Mostly barren land with some patches of grass.
Channel and floodplain material	Boulders, cobbles, pebbles and coarse sand in channel belt.
River Behaviour and Process Zone River channel width decreases and as a consequence, side and mid channel bars are exposed during low flow stage. The bankfull stage is attained during south west summer monsoon; mid channel bars are submerged while side bars are partly inundated. Diurnal variations in discharge due to snow melt are observed in upper reaches. Overbank stage is never attained as there is no flood plain. Geomorphologically, this style is characterized by degradational regime.	
Ecological Significance From an ecological point of view, following species dominate in their respective groups: 1. Phytoplankton- diatoms and green algae 2. Zoobenthos –Stone fly (Plecoptera), May fly, Diptera (Two wing fly), Dragon fly and Damsel fly. 3. Fishes- Trout fish, Mahseer fish	

5.2 River Style 2: Himalayan, Partly Confined Floodplain and Channel, Braided

Defining attributes: This river style is ~ 26.85 km long. This river style has the maximum valley width of 9.2 km and minimum of 2.9 km and is set within an alluvial-Himalayan bedrock transition valley setting. Large alluvial island and mid channel bar are prominent channel belt geomorphic features. The channel is characterized by partly confined and braided channel with low sinuosity ranging from 1.18 to 1.40. The braid channel ratio ranges from 1.21 to 2.78, highest value recorded in the reach between Raiwala and Rishikesh. Narrow active flood plain pockets are observed in this river style. Ganga River is flowing along GTF (Ganga Tear Fault) in the eastern margin of Doon valley.

Stretch: Rishikesh (Ramjhula) to Haridwar (27 Km)

Details of Analysis	
Data used: Geomorphic and active floodplain mapped from Landsat *4-5TM imagery 5thMay 2010; Valley margin delineated using SRTM-90m (2000)* *Analysts*: Ritesh Sipolya,Vikas Kamal and Dr.Rajesh Kumar *Date*: 15th November, 2011	
River Character	
Landscape setting	• Transition zone of alluvial and Himalayan bed rock with following: – Alluvium, unconsolidated sand, silts with/without clay (cumulative high permeability, low bearing capacity and poor foundation characteristics). – Piedmont deposits with non-calcareous hard sedimentaries (low permeability, medium to high bearing capacity and good foundation characteristics) – Sub Himalayan moderately hard sedimentaries of sandstone, shale, boulder conglomerate (Low to moderate permeability, fair bearing capacity and poor foundation characteristics).

Valley Morphology	• Moderate valley width, average width 6.5 km • Valley showing a maximum width between Rishikesh and Raiwala (9.2 km) and minimum near Haridwar (2.9 km). • Nearly linear valley bulges in elliptical shape at right margin between Raiwala and Rishikesh
Channel confinement	• Partly confined except in the upper reach.
Active floodplain characteristics	• Maximum floodplain width is ~ 0.66 km and minimum ~ 0.32km with an average width of 0.52km. • Approximately, 1/5th of Active floodplain margin oscillates within valley margin. The active floodplain is partly confined similar to the channel confinement. • Continuous active floodplain is present along either side of bank. • Ratio of Active flood plain to Valley width is 1:5

Channel Characteristics	• Sinuosity (P): 1.18-1.40
	• Total channel area = 7.47 sq.km.
	• Average channel width =826.7m
	• Braid channel ratio (B): 1.21-2.78.
	• Total bar area = 13.152sq.km.
	• Side bars: ~1.83 sq.km, Length:265.37m – 2.09km; Width: 82.52m – 486.13m
	• Alluvial islands: ~7.9 sq.km ; Length: 1.23 km – 4.96km; Width: 590.69m – 1.79km
	• Mid channel bars: ~3.412 sq.km; Length: 161.58m – 2.14km; Width: 46.6m –766.3m
	• 7 tributaries
	• Meandering parameters:
	  o 4 meanders
	  o Radius of curvature (rc) : 0.32 km to 0.66km
	  o Wavelength (L):2.62 km to 4.21km
	  o Amplitude (Am):0.93km to 1.37km.

Diagnostic geomorphic features (geometry, sedimentology)	*Channel belt – alluvial, bedrock transition.* • Transition zone of alluvial and Himalayan bed rock • Valley is narrow at rishikesh and Haridwar • Alluvial Island is prominent. • Rishikesh to Haridwar ~0.518˚
	Floodplain • Flood plain pockets are visible.
Land Use/Land cover association	*Floodplain* Flood plain is covered by agricultural land, vegetation and settlements.
	Channel belt • Alluvial islands are covered with dense natural vegetation. • Mid channel bars are slightly vegetated. • Side bars are mostly barren.
Channel and floodplain material	Sand, Pebble, Cobble and conglomerates.

River Behaviour and Process Zone

River channel width decreases considerably and therefore, vegetated alluvial islands, side bars and chute channels are exposed in low flow stage. River attains the bankfull stage regularly during monsoon season; alluvial islands are marooned whereas side and mid channel bars are inundated. River water inundates either side of bank in over bank stage. A good lateral connectivity with active flood plain is observed specifically in lower reaches.

Geomorphologically, this style is characterized by an aggradational regime.

Ecological Significance

From an ecological point of view, following species dominate in their respective groups:

1. Phytoplankton- diatoms and green algae.
2. Zoobenthos –Dragon fly and Damsel fly.
3. Fishes- Mahaseer fish

5.3 River Style 3: Piedmont, Partly Confined Floodplain and Channel, Braided

Defining attributes: This River Style occur in a stretch of ~79 km in an alluvial valley setting. As soon as river Ganga leaves the mountainous region and comes in the plain area in Haridwar, valley width and floodplain width abruptly increases and a wide valley and active floodplain formed. Low to moderate sinuosity channel follow the left and right margin of the valley alternatively. Channel is highly braided and wide in the upper reach and it is partly confined by valley margin. Channel belt is comprised of number of big mid channel bars, alluvial islands and small side bars dissected by chute channels and some dry channels. Occasionally abandoned braid bars and sand patches are also present. Floodplains are characterized by flood channels, dry channels, and few meander scrolls and meander cutoffs. Long anabranch channels follow the main trunk; some tributaries originating from Himalaya also join the river Ganga.

Stretch: Haridwar to Bijnor (79 Km)

Details of Analysis	
Data used : Landsat 4-5TM Apr and Oct 2010; Valley margin maps from SRTM 2000 Analysts: Ritesh Sipolya, Vikas Kamal and Dr.Rajesh Kumar Date: 28 April, 2012	
River Character	
Landscape setting	• Piedmont setting, unconsolidated sand, silts with/without clay (cumulative high permeability, low bearing capacity and poor foundation characteristics).
Valley Morphology	• Wide valley with an average width of 17.7 km. • Valley width is narrow (2.7 km) in Haridwar, and abruptly bulges into the centre and attains max width of 28.3 km in Laksar, again width reduces downstream.
Channel confinement	• Partly confined by valley margin and approaches the left margin of the floodplain in the entire river style from Haridwar to Bijnor.
Channel Characteristics	• Max and min channel width is 2.4 km and 0.4 km respectively covering an area of ~18.9 sq.km. • Sinuosity (P) value ranges between 1.15-1.25 • Braid Channel ratio (B) ranges between 1.8 - 3.7. Channel is highly braided (B=3.7) in the upstream. • Total channel belt area is ~100.96 sq.km in which bars cover ~72.6 sq.km of area • Side bars up to 1.5 km in length and 0.6 km width covers 5.84% of total channel belt area. • Small to large mid channel bars having 4.2 km in length and 2 km in width are the most prominent unit and cover max area of 21.88% of total channel belt. • Big alluvial islands the second prominent unit are 10 km in length and 2.7 km in width cover 44.17% of channel belt. They are dissected by chute channels and dry channels. • Long anabranch channel follow the right margin and left margin alternatively. • Meandering parameters (2 meanders): o Radius of curvature (rc) : 1.2 km to 1.6 km o Wavelength (L) : 7.2 km – 8.6 km o Amplitude (Am) : 1.8 km – 2.9 km
Active floodplain characteristics	• Active floodplain is present only on right bank of river; on the left bank very small patches are present at few places. • Average floodplain width is ~9.9 km; max width14.9 km and min width 1.2 km. • Approximately 2/3rd of Active floodplain margin coincides with the valley margin on the left bank. • Active floodplain width:Valley margin width = 1:1.8
Diagnostic geomorphic features	*Channel belt – alluvial* • High Braid Channel ratio (B=3.7), braiding gradually decreases towards downstream. • Big alluvial island and mid channel bars are dominated and covered 66.06% of total channel belt area.

(geometry, sedimentology)	• Partly confined channel in the entire river style. 27.04% of the channel belt has water and rest is covered with bars.
	Floodplain • Active floodplain present only along the right bank of the river and it is confined by valley margin on left bank
Land Use/Land cover association	*Floodplain* • A large part of flood plain is used for agricultural purpose.
	Channel belt • Alluvial islands are covered with vegetation and cultivated land. • Mid channel bars have mixed landuse i.e. agricultural land and barren land. • Side bars are used for agricultural purpose.
Channel & floodplain material	Pebbles and sand are found in channel while silt and clay are prominent in floodplain.
River Behaviour and Process Zone In low flow stage, channel width reduces to considerable size and most of the mid channel bars and alluvial islands are exposed which are used for seasonal cultivation. At bankfull stage, most of the mid channel bars and side bars are submerged fully and alluvial islands fully or partly on regular basis during monsoon. Anabranch channels filled with water supplying water and sediment during this stage. Low-lying floodplain is also affected in bank full stage. At most places, right bank is high and steep and generally not submerged but left bank is inundated during bankfull stage. Geomorphologically, this style is characterized by aggradational reach. The translation of meanders occurs along valley slope and therefore an eastward shift is observed.	
Ecological Significance From an ecological point of view , following species dominate in their respective groups: 1. Phytoplankton- diatoms and green algae. 2. Zooplanktons- Rotifers and Cladocera. 3. Phytobenthos-Pediastrum and Scenedesmus 4. Zoobenthos-Trichoptera (Caddish fly) and Beetle (Coleoptera). 5. Fishes- Major Carps and Minor Carps. 6. Higher vertebrates- Turtles and Ghariyals.	

5.4 River Style 4: Valley-Interfluve, Partly Confined Floodplain and Channel, Braided

Defining attributes: This river style is set within a valley-interfluve setting. The river valley width is variable which is more prominent in the lower reaches than in the upper reaches. The channel mostly follows the right valley margin having an active floodplain dominant only on left bank of river. In reaches where it flows centrally, active floodplain is present on both banks. The right margin of the floodplain, almost totally, coincide with valley margin except downstream of Kanpur. The channel shows low sinuosity and high braid channel ratio. Channel belt is comprised of number of bars; mid channel bars, side bars and prominent, alluvial islands are dominant only in the lower stretch. Big patches of abandoned braid bars are present in both stretches. Small to big tributaries including Ramganga join the main trunk in FGFP stretch and confluence bars formed.

Stretch: 1. Upper Reach: Bijnor to Narora - 170 Km
2. Lower reach: Fatehgarh to Fatehpur - 224 km

Details of Analysis	
Data used: Geomorphic and active floodplain mapped from Landsat *4-5TM and Awifs imagery April 2010; Valley margin maps from SRTM 2000* *Analysts*: Ritesh Sipolya,Vikas Kamal, Dr.Rajesh Kumar and Shamiuddin Ahmad *Date*:13Dec, 2011	
River Character	
Landscape setting	• Valley-Interfluve setting
Valley	• Wide valley having an average width ranges between 15.2 km

Morphology	• Valley width is variable and controlled by cliff line at places. Max width is in upstream of Narora (28.39 Km) and near Kanpur (27.44 Km) whereas near Fatehpur valley shows min width of 7 km. The width is quite unofrm in the upper stretch. • The valley is oriented in N-S direction in the upper reach while in the lower reach it is oriented along NW-SE direction.
Channel confinement	• Channel is mostly partly confined, either by valley margin or by cliff. • Channel is symmetric in the upper reaches(till Bugrasi) after which it flows along the southern boundary of the valley resulting in an asymmetric channel.
Active floodplain characteristics	• Active floodplain of variable width is dominantly present on left bank of river except in few reaches where it is present on both banks. • Active floodplain is partly confined by valley/cliff on the right bank of the river. • Average width of active floodplain is 7.57 Km with the minimum value of ~ 2.5 Km (downstream of Kanpur) and maximum value of 17 Km (at Kanpur). • Between Narora to Kanpur floodplain is quite wide. • Nearly 40% of floodplain margin coincide with valley margin (southern side), resulting in a partly confined floodplain. • Active floodplain: Valley margin width = 1:2 (average)
Channel Characteristics	• Channel is quite wide in the upper reaches while the lower reaches are narrow. The average width of the channel is ~ 356 m. • The channel is not sinuous with the sinuosity(P) value ranging from 1.07 to 1.5 • Braiding is quite prominent and the braid channel ratio ranges from 1.21 to 2.31 • In the upper reaches till the Narora barrage mid channel bar is the dominant unit (covers maximum area of 23% of the channel belt) along with side bar (20%). • In the lower reaches, alluvial islands (18%) cover an equally large area as mid channel bars (16%). As in the upper reaches side bars(29%) are very common. • Abandoned braid bars are also quite dominant in both upper and lower reaches. • Numerous chute channels are present that dissect the bar surfaces. • Secondary channels are more prominent in the lower reaches than in the upper reaches. • Point bars are quite few and occupies about 2% in the upper reaches and 4% in the lower reaches. • Kannauj is a major confluence point where the Ramganga, Garra and Kali joins Ganga. In the lower reaches small rivers like Pandu, Khar nadi, Isan nadi flows into Ganga near Kanpur. • Meandering is not prominent and the different values recorded for the different meandering parameters are: – Radius of curvature: 0.7 to 2.9 Km – Axial wavelength: 2.6 to 11.9 Km – Amplitude: 1.1 to 4.5 Km
Diagnostic geomorphic features (geometry, sedimentology)	*Channel belt – alluvial* • Channel is multiple with very low sinuosity and high braid channel ratio. • The main channel occupies 38% of the area while the rest is covered by bars. • The area covered by the main channel is higher in the upper reaches (64 sq. km.) than in the lower reaches(47 sq. km.). This is due to the presence of the Narora barrage downstream of the upper reach.
	Floodplain • Small to big abandoned channels, flood channels are quite common on the floodplain. • Patches of sand deposition are present in the lower reaches. • Meander cutoffs, meander scrolls and Ox bow lake are common on the left bank of the river suggesting that the river has a southward shift in the lower reaches. There is an abandoned meander loop near Kanpur.

Land Use Land cover association	*Floodplain* • The whole of floodplain in this style is covered by agricultural/fallow land. Rabi wheat, Kharif rice, Zaid pulses, rice are the major crops. • In Safipur, marsh is present that supports crane.	
	Channel belt Most of bars are used for seasonal cultivation like cucurbita. In the upper reaches, most mid channel bars are vegetated. In the lower reaches, cultivation of watermelon on bars are more common.	
Channel and floodplain material	• The channel bed material in the lower reaches are composed of fine sand and both banks are muddy. There is very little riparian vegetation with thorny plants. At some exposed sections near Kanpur, silt and clay sediments alternate (levee sequence).	
River Behaviour and Process Zone During lean period or the low flow stage the bars are exposed as the river width decreases. Due to this these bars are used for seasonal cultivation in the lower reaches. While in the upper reaches vegetation is present on the bars. At bankfull stage the bars get submerged partly or fully. In the overbank stage the left bank is inundated in the lower reaches while both banks are flooded in the upper reaches. this is beacuse at most places the right bank is high and steep. Geomorphologically, the upper stretch is characterized by an aggradational regime and the lower stretch by degradational regime as evidenced from high cliff line all along the right bank. The upper stretch is marked by a major confluence zone between the Ganga and Ramganga. The confluence zone has been dynamic at historical-scale as reported in the literature and a shift upto 10-12 km has been documented.The presence of meander scrolls, cutoffs and ox bow lake in the floodplain in the lower stretch suggest a significant river dynamics and a dominant southward movement of the river.		
Ecological Importance From an ecological point of view, Phytoplanktons dominate (diatoms/green algae); Zooplanktons are characterized by Protozoans, Rotifers and Cladocera; Among the fishes, Indian major Carps are 40-50% and Cat fishes are 10-15% as estimated from their catch; Forage and other fishes are also found; Among the higher vertebrates are characterized by soft/hard shelled turtles are present, Ghariyals are very rare/scarce and dolphins are spotted.		

5.5 River Style 5: Valley-Interfluve, Unconfined Floodplain, Unconfined Braided

Defining attributes: This river style is set in a valley-interfluve, alluvial valley setting. The Ramganga flows from North and joins Ganga at Kannauj (downstream of Fatehgarh) while Yamuna flows from south west and joins Ganga at Allahabad. The channel occurs centrally within the valley with floodplain on both banks of the river. Although there is a continuous floodplain on both banks of the river, the floodplain widths are quite variable and controlled by the position of the channel with respect to the valley margin. The channel in general has lower sinuosity and higher braid channel ratio.

Stretch: 1. Upper reach: Narora to Fatehgarh - 201 Km
2. Lower reach: Sirathu to Allahabad - 82 Km

Details of Analysis	
Data used: Geomorphic and active floodplain mapped from Landsat *4-5TM and Awifs imagery April 2010; Valley margin maps from SRTM 2000* *Analysts*: Haridas Mohanta and LipiBasu *Date*:5thDec, 2011	
River Character	
Landscape setting	• Valley-Interfluve setting
Valley Morphology	• Valley width varies from 2.26 km to 35.67 km • Valley width is variable controlled by the interfluve and cliffs at few places • The valley boundary is irregular with alternate widening and narrowing at places.
Channel confinement	• Unconfined channel • Symmetric channel, river flows centrally to valley.

Active floodplain characteristics	• Active floodplain on both banks of varying width. • Width of active floodplain varies from 2.26 km to 13.45 km. • Active floodplain: Valley margin width varies from 1:1.9 to 1:3.78
Channel Characteristics	• The average width of channel in the upper stretch is ~130 m compared to ~ 265 m in the lower stretch due to the presence of Narora barrage. There is no effect of any man made structure in the lower stretch. • Sinuosity ranges from 1.1 to 1.5 • Braid channel ratio ranges from 1.27 to 2.25(dominantly braided) • In the upper stretch, alluvial islands (45%) cover a large area and side bars (25%) and mid channel bars (13%) are distributed almost in all reaches. • In the lower stretch, side bars (26%) cover a large area and alluvial islands (20%) are very common. • Alluvial islands are present in the upper reaches and mid channel bars characterize the lower reaches . • Side bars are common in both the stretches. • There are no confluence bars in either of the stretches. • Point bars are relatively rare. • The meanders in upper stretch are relatively tighter (smaller wavelengths) compared to the ones in lower stretch which have a greater wavelength. • Meanders are very prominent in both the stretches. – Radius of curvature: 0.73 to 2.49 Km – Axial wavelength: 3.65 to 12.32 Km – Amplitude: 1.6 to 5.8 Km
Diagnostic geomorphic features (geometry, sedimentology)	*Channel belt – alluvial* • The presence of alluvial islands and mid channel bars results in high braiding value of the river in both the stretches. • The main channel occupies 19% of the area while the rest is covered by bars.
	Floodplain • Abandoned braid bars, sandy patches and meander scrolls are the most dominant geomorphic feature in this style suggesting a dynamic river. • Abandoned channels, flood channels are quite common on the floodplain. • The lower reaches have meander cutoffs, abandoned meander belt which are relatively less in the upper reaches.
Land Use Land cover association	*Floodplain* • The whole of floodplain in this style is covered by agricultural/fallow land. Rabi wheat, Kharif rice, Zaid pulses, rice are the major crops. • Mid channel bars are used for seasonal cultivation. • Small plants of babool, sheesham, chilbil, parthenium and small shrubs with grasses constitute the riparian vegetation in this style. • Above HFL vegetation is mixed trees, Juliflora (small babool like plants), babools, and shrubs.
	Channel belt Lateral and point bars and few mid channel bars are used for agriculture. At some places these bars have vegetation along with alluvial islands.
Channel and floodplain material	• The bed has loose materials and the grain size increases from very fine sand to coarse sand. Floodplain is mostly muddy. • Alternate succession of mud and sand is observed on the bank. • Bank is steep in the lower reaches compared to upper ones.

River Behaviour and Process Zone

River channel width decreases at the low flow stage and more mid channel bars are exposed. Large mid channel bars are used for seasonal cultivation. The flood channels dry up and in some cases is used for cultivation. Every monsoon river attains bankfull stage. Mid channel bars, alluvial islands, side bars are partly submerged and the average width of the channel increases. The flood channels fills with water. During the

bankfull 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. In some cases abandoned braid bar and abandoned channel gets filled with water. Geomorphologically, the upper stretch is characterized by an aggradational regime. The lower reach has a sinuous channel belt which suggests a dominance of lateral erosion processes and influences the floodplain width significantly. The downstream end is a major confluence zone between Ganga and Yamuna.
Ecological Importance From an ecological point of view, Phytoplanktons dominate (diatoms/green algae); Zooplanktons are characterized by Protozoans, Rotifers and Crustaceans. Among the fishes, Indian major Carps are 40-50% and Cat fishes are 10-15% as estimated from their catch; Forage and other fishes are also found; Among the higher vertebrates are characterized by soft/hard shelled turtles are present. Ghariyals are very rare/scarce and dolphins are spotted.

5.6 River Style 6: Valley-Interfluve, Unconfined Floodplain, Partly Confined Braided

Defining attributes: - This river style occurs in a stretch of ~102 km in an alluvial valley setting. River valley is relatively narrow, nearly linear and of uniform width except near Dalmau area where it attains a larger width. Floodplain width also follows a similar trend. Low to moderate sinuosity river channel follows the left and right margins of the floodplain alternately, and as a consequence, discontinuous floodplain occurs on either side of the river. Channel is highly braided in most reaches and channel belt is comprised of a number of bars. Mid channel bars, side bars, abandoned braid bars and alluvial islands are most frequent and dissected by small to large chute channel. Point bars are very few in this stretch. Floodplains are characterized by flood channels, abandoned channels and occasional meander cutoffs.

Stretch: Fatehpur to Sirathu (~ 102 Km)

Details of Analysis	
Data used: Landsat 4-5 TM 2009-10 ***Analysts***: Lipi Basu, Shamiuddin Ahmad and Haridas Mohanta *Date:*17Aug2011	
River Character	
Landscape setting	• Valley-interfluve setting between Ganga in the north and Yamuna in the south.
Valley Morphology	• Moderate valley with an average width of 5.02 km. Valley width is fairly uniform except near Dalmau where it attains a width of 9.0 km. The minimum width recorded is 2.4km. • Nearly linear valley oriented in NW-SE direction except near Dalmau where it is W-E trending.
Channel confinement	• River channel at places is partly confined by cliff/valley margin. It swings from northern to southern boundary of the valley alternately.
Active floodplain characteristics	• Narrow active floodplain (discontinuous) prominent only on one side of the river (either on the left or right bank of the river) due to the swinging nature of the river. • Average flood plain width is 2.13 km (excluded channel width). Max. floodplain width is 4.3 km and min. width recorded is 0.8 km. • The floodplain is unconfined as the valley margin is at a distance from the active floodplain boundary, separated from it by inactive floodplain. • Flood plain width:valley margin width=1:2.4
Channel Characteristics	• A continuous channel having an average width of 201.5 m (min and max channel width is 66 m and 451 m respectively) covering an area of 21.25 sq.km. • Sinuosity (P) value ranging between 1.22 – 1.63 • Braided channel system with Braid channel ratio (B) ranges from 1.54 – 2.27, maximum braiding in reach near Dalmau area. • Total Channel belt area is 76.8 sq.km in which bars covers 52.95 sq.km. area. • Side bars up to 6.5 km in length and 1.0 km in width are the most prominent unit and

<table>
<tr><td></td><td>cover max area of 33.9% of total channel belt.
• Small to large mid channel bars (prominent in reach 1) having 2.5 km length and 0.96 km width cover 12.1% of total channel belt area.
• Sharp-edged point bars up to 3.6 km length and 1.1 km width are very rare and cover 3.5% of the channel belt area.
• Comparatively large oval-shaped patches of alluvial island with max length of 5.5 km and 1.9 km width are the second most prominent unit and cover an area of 19.4% of total channel belt.
• Large patches (up to 6.0 km length and 1.03 km width) of abandoned braid bars are most prominent along the main channel.
• Chute channels (mostly <1 km in length and average width of 30m) dissect the bars and island.
• Occasionally flood channels follow the outer margin of bars, but sometimes dissect the alluvial island.
• Secondary channels are prominent in upstream reaches and follow the outer margin of bars and alluvial island.
• Meander cutoff are scarce; large patch of abandoned meander belt near Dalmau.
• Short, discontinuous, anabranching abandoned channels mostly dissect the abandoned braid bar, elongated to river somewhere are seen.
• Meandering parameters (4 meanders):
o Radius of curvature (rc) : 0.74 km - 2.15km
o Wavelength (L) : 8.3km – 16.5km
o Amplitude (Am) : 2.7km – 5.4km
• River Cross Sectional Parameters (average):
o Channel Asymmetry {A*=(Ar-Al)/A}= 0.04 (highly asymmetric channel)
o Bankfull Width (w) = 819.4 m
o Max Depth (dmax) = 6.5 m
o w/ dmax =126.2
o Wetted Perimeter(bankfull) (P) = 933.4 m (standard deviation is 258.6)
o Hydraulic radius (bankfull) (A/P) = 3.3</td></tr>
<tr><td rowspan="2">Diagnostic geomorphic features (geometry, sedimentology)</td><td>Channel belt – alluvial
• The main channel occupies 38% of the area while the rest is covered by bars.
• Low to moderately sinuous channel flowing along the margins of flood plain; highly braided in upper reaches and braiding gradually decreases downstream and attains the maximum sinuosity in lower reaches.</td></tr>
<tr><td>Floodplain
Narrow and fairly uniform width extending only on one side of the river resulting in discontinuous floodplain. Near Dalmau there is abandoned meander belt suggesting that the river shifted from North to South in that area. Abandoned channels are abundant in the narrow floodplain.</td></tr>
<tr><td rowspan="2">Land Use Land cover association</td><td>Floodplain
• Most of the floodplain are muddy and used as single cropland. Flat muddy flood plain are used for wheat, mustard, bajra (chari) etc. whereas on sloping and silty flood plain vegetables like pointed gourd (parwal), bitter gourd (karela) are very common.
• At many places floodplains are covered with open scrub land and plants like parthenium (Gandhak in local language).
• Loose sand deposits are also present at a few places.</td></tr>
<tr><td>Channel belt
Mid channel bars and side bars are commonly cultivated with zaid crops like watermelon, cucumber, pumpkins etc. On alluvial islands wheat, mustard and coarse grain crops are cultivated.</td></tr>
<tr><td>Channel and floodplain material</td><td>• River bed is composed mostly of fine to medium grain loose sand.
• Floodplain is mostly covered by muddy sediments underlain by silty/sandy sediments.</td></tr>
</table>

River Behaviour and Process Zone
In low flow stage, channel width reduces to considerable size and most of the mid channel bars are exposed which are used for zaid cultivation. On alluvial islands, wheat and mustard crop cultivation is common with seasonal zaid crop. At bankfull stage, most of the mid channel bars and side bars are submerged fully and alluvial islands fully or partly on regular basis during monsoon. Low-lying floodplain is also affected in bank full stage. During overbank stage the river floods in restricted pockets. Geomorphologically, the degradational regime continues as in the upstream reaches as evidenced from high cliff line along the right bank. Pockets of aggradational reaches are characterized by alluvial islands.
Ecological Significance Phytoplanktons (diatoms/green algae/blue algae) common but in reduced numbers compared to upstream reaches; Zooplanktons are characterized by Protozoans, Rotifers and Crustaceans and their numbers are higher compared to upstream reaches; Among the fishes, Indian major Carps reduced to 30% and Cat fishes increase marginally to 15-20% as estimated from their catch; Forage and other fishes are also increased; Among the higher vertebrates soft/hard shelled turtles are reported upto Allahabad; Ghariyals are very rare/scarce and reported upto Allahabad; dolphins are frequent.

5.7 River Style 7: Alluvial, Unconfined Floodplain and Channel, Sinuous

Defining attributes: This river style extending nearly WNW-ESE Is characterized by moderately sinuous channel the channel flow predominately along the central valley except for few reaches where it swings from one bank to other bank; however there are wide flood plains in either side of river. The channel belt comprises various geomorphic unit and they are fairly stable on the temporal scale. The alluvial island vegetated. In some reaches upto Ghagra confluence bar the river is sinuous with meanders in a valley characterized by three large asymmetrical abandon meander belts with flood plain feature like Oxbow lake meander scars meander cutoff and scrolls. These meander belts are located at alternate banks of river channel highlighting prominent migrating of river channel.

Stretch: Upper Reach: Allahabad to Gopiganj (115Km)
Middle reach: Chunar to Chapra (321.17 Km)

Details of Analysis	
Data used: Geomorphic and active floodplain mapped from Landsat 4-5TM,February 2010 and Valley margin maps from SRTM 2000 ***Analysts**:* Sanjeet Sharma and Desh Deepak Pandey *Date:*17Aug2011	
River Character	
Landscape setting	• Alluvial valley setting with valley margin extending on either side of the river
Valley Morphology	• Valley width is highly variable in this river style • Maximum valley width is 35.80 km near Ballia and minimum is 3.57 in Handia
Channel confinement	• Channel is Unconfined but at a few reaches it is partly confined by a cliff
Active floodplain characteristics	• Flood plain width is very variable the max active flood width is 28.87 km and min width is 2 km. • Flood plain is distributed symmetrically at both side of channel. • FP:VM width = 1:
Channel Characteristics	• Sinuosity (P): value ranging between 1.11 to 2.6 • Braid channel ratio (B) ranges between 1 to 2.59 • Total bar area is 477.83Km^2 while the total channel area is 295.65 Km^2 • The individual bar area is given as below: o Alluvial islands: 103.07 Km^2 o Mid channel bars: 31.00 Km^2 o Point bars: 102.28 Km^2 o Side Bar: 110 Km^2 Four tributaries joins the Ganga in this stretch of which two are very significant Tons and

	Ghaghra
Diagnostic geomorphic features (geometry, sedimentology)	*Channel belt – alluvial* Moderately sinuous carrying dominantly fine silt to sand sized sediment and in channel there are large number of mid channel bars which are used as cultivation land.
	Floodplain Flood plain is characterized by the presence of Abandoned meander belts, Meander scrolls and Abandoned braid bars. It is present in both side of channel but at few reaches it's become narrow.
Land Use/Land Cover association	***Floodplain*** Here the large part of flood plain is used cultivation land , Most of the flood plain is muddy and used as cultivation as a different types of vegetable.
	Channel belt Most of the exposed bars are used as cultivation.
Channel and Floodplain material	• Channel carry fine to slit sized sediment • Floodplain material is dominantly clayey and muddy.

River Behaviour and Process Zone

In low flow stage the river channel width decreases and alluvial island bar are exposed and the bars are used for cultivation and agriculture. During bankfull stage there is increased water level and the bars get submerged. In overbank stage, the river floods water submerges left and right bank alternatively. During most of the flood, lateral bars are nearly submerged. Similarly, many of the mid channel bars are also submerged; In the long term the sinuous reaches and bars shifts, giving rise to meander scrolls and abandoned braid bars.

Geomorphologicaly, the degradational regime continues in the upstream reach as evidenced from the high cliff line along the both banks. Pockets of aggradational reaches are characterized by alluvial islands and bars, in upstream stretch at Allahabad Yamuna joins in the Ganga and it increase the sediment load with water. So in this stretch channel always contain significant amount of water. In this style river is so much dynamic, flow is high and depth is deep which is good for cultivation and fish population**.** Dolphin are recorded during field survey.

Ecological Significance

At Varanasi, the water quality is very poor. This is probably because of the reduction of the water volume and the subsequence increase in concentration of chemicals. Trichopterans dominate the benthic population here. Major carps and catfish are dominant.

5.8 River Style 8: Craton Margin, Partly Confined Floodplain and Channel, Sinuous

Defining attributes: This river style, comprising of two discontinuous stretches, extending nearly East-West, is characterized by moderately sinuous channel. While abandoned meander bars are observed in the floodplain, the in-channel features include both mid-channel and lateral bars. Thus, in spite of its sinuous nature, the river here is characterized by moderate Braid Channel Ratio. Channel flows symmetrically within the valley in the lower stretch excepting near Munger and Bhagalpur where basement rocks laps on its southern margin. In the upper reach, the channel flows close to the southern boundary of the valley. Active flood plain is better developed towards the northern side of the river.

Stretch: Upper Reach: Gopiganj to Chunar - 74Km
Lower reach: Pansalla to Kursela - 142 Km

Details of Analysis
Data used: Geomorphic and active floodplain mapped from Landsat 4-5TM,February 2010 and Valley margin maps from SRTM 2000 ***Analysts***: Sanjeet Sharma, Sayan Sinha, Haridas Mohanta and Lipi Basu *Date:*17Aug2011

River Character	
Landscape setting	• Craton Margin in an alluvial bedrock transition setting
Valley Morphology	• Maximum valley width is 36 Km. and minimum is 4.09 Km. with an average width of 16.74 Km (wide valley) • The maximum width is observed near Kursela while the minimum width is downstream of Gopiganj. • In the upper stretch the valley alternately widens and narrows, while in the lower stretch the valley narrows down significantly near Munger before widening out again.
Channel confinement	• The channel is partly confined by valley margin, mostly. At a few locations in the lower stretch, the channel is unconfined with floodplain on both banks. • Vindhyan rocks are exposed in southern side of river bank at few places like Chunar. • FP:VM width = 1:1.4
Active floodplain characteristics	• Maximum floodplain width is 20.85 km and minimum is 2.15 km with an average FP width of 11.24 km. • The southern margin is mostly marked by basement rocks. • Active floodplain is partly confined coinciding at few places with the valley margin. • Floodplain is dominantly present on the northern side of the river.
Channel Characteristics	• Sinuosity (P): value ranging between 1.27 to 2.03 • Braid channel ratio (B) ranges between 1.22 to 1.76 with the maximum braiding near Munger. • Total bar area is 230.29 Km^2 while the total channel area is 198 Km^2 • The individual bar area is given as below: o Alluvial islands: 69.56 Km^2 o Mid channel bars: 16.91 Km^2 o Point bars: 32.46 Km^2 o Abandoned Braided Bar: 230.75 Km^2 o Abandoned Meander Bar: 158.27 Km^2 o Side Bar: 110 Km^2 o Transverse Bar: 1.63 Km^2 o Confluence Bar: Nil • Two major tributaries join the Ganga in the lower stretch.
Diagnostic geomorphic features (geometry, sedimentology)	*Channel belt – alluvial* • The main channel occupies 41% of the area while the rest is covered by bars. • Slightly sinuous carrying dominantly fine sand sized sediment. In spite of sinuous nature and fine-grained channel sediments size, the reach is characterized by moderately high braid channel ratio. The channel has many side bars. Transverse bars are also present in the lower reaches.
	Floodplain The floodplain is characterized by the presence of abandoned meander belt. Abandoned braid bars dominate in the lower stretch.
Land Use/Land Cover association	*Floodplain* • Large part of flood plain is used as cultivated land. Most of the flood plain is muddy and used as single cropland. Flat muddy flood plain are used for wheat, mustard, Bajra etc. whereas on sloping and silty flood plain vegetables like pointed gourd, bitter gourd is common. • Many places the unused flood plain is covered by Parthanium and straw. • Few permanent structures have been constructed on the floodplain and there are only a few settlements close to the river bank in the lower stretch..
	Channel belt Most of the exposed bars are vegetated and at places cultivated or used for grazing. Pisiculture is well developed. Most of the bars, particularly the bank attached lateral ones, are extensively mined for brick kiln and construction. In the upper reaches the bars

	are used for seasonal cultivation.
Channel and Floodplain material	• Channels carry medium to fine grained sand. • Floodplain material is dominantly clay or silt to very fine sand.
River Behaviour and Process Zone In low flow stage the river channel width decreases and alluvial island bar are exposed and the bars are used for cultivation and agriculture. During bankfull stage there is increased water level and the bars get submerged. In overbank stage, like in 2011 monsoon, the river has flooded most of the floodplain and inundated the villages situated on the active flood plain requiring the administration to start relief measures. During most of the flood, lateral bars are nearly submerged. Similarly, many of the mid channel bars are also submerged; In the long term the sinuous reaches and bars shifts, giving rise to meander scrolls and abandoned braid bars. Geomorphologicaly, the degradational regime continues in the upstream reach as evidenced from the high cliff line(~20m) along both the banks. Pockets of aggradational reaches are characterized by alluvial islands and bars . The river style is characterized by exposure of bed rock in the channel in the right bank, which make channel partly confined. In the lower stretch, the bars are extremely dynamic over a period of few to several years	
Ecological Significance The benthos is very low at Bhagalpur and the insect population is dominated by hemipterans. Fish yield (major carps, ilish) have reduced over a period of time. Phytoplankton and zooplankton are common.	

5.9 River style 9 -Valley Interfluve, Partly Confined Floodplain and Channel, Anabranching

Defining attributes: The river style stretches for 183 Km, is trending West-East and is set within an alluvial setting. It attains a maximum valley width of 20.0 kms across Patna and minimum of 8.10 km downstream Gandak confluence. Active floodplain almost totally coincides with valley margin except for the most downstream reaches. Active flood plain is mainly limited to left bank while the right bank is devoid of flood plain because of a southern embankment near Patna up to the confluence of river Punpun from south. The channel has a low sinuosity of 1.21.It is characterized by presence of mid channel bars (31) and large alluvial islands (max. length – 34km, width – 12.5km). Alluvial islands seem to have gained prominence in width and area downstream of the confluence of Ghagra and Gandak rivers from the north and Son river from the south.

Stretch: Chapra to Pansalla (183 Km)

Details of Analysis	
Data used: Geomorphic and active floodplain mapped from Landsat 4-5TM and Awifs imagery April 2010; Valley margin maps from SRTM 2000**.** Analysts: K.N Mishra and Anubhav Rathee Date:18.9.2011	
River Character	
Landscape setting	• Alluvial setting and is trending W-E
Valley Morphology	• Wide valley with an average width of 15.88 km.; valley width : max. 25.56 km, min 8.19 km. • Valley showing maximum width at Pansalla and minimum near Patna downstream of the Gandak confluence. • Valley narrows down across Patna and upstream Mokama and widens downstream in the central stretch and near Mokama.
Channel confinement	• Partly confined by the embankment on the right bank of the river.

Active Floodplain characteristics	• Average floodplain width is 13.04 km. (max. width 21.03 Km; min. width 7.45 Km). • Active flood plain is mainly limited to left bank while the right bank is devoid of flood plain because of a southern embankment in the stretch near Patna up to the confluence of river Punpun from south. • Floodplain width: valley margin width = 1: 1.2

Channel Characteristics	• Min. Channel width: 540m
	• Max. Channel width: 1550m
	• Channel Area : 170.68 sqkm
	• Sinuosity (P): 1.08 -1.31
	• Braid channel ratio (B) : 2.09 - 2.48.
	• Total bar area: 720.54 sq.Km.
	• Side bar: 79.46 sq.Km. ; Length: 2.20 km-12.80 km; width: 0.66km-3.29 km.
	• Alluvial Island : 552.09sq.Km. ; Length: 5.02 km-35.40 km; width: 2.47km-11.72 km.
	• Mid channel bar : 60.63 sq.Km. ; Length: 0.36 km-4.92 km; width: 0.20 km-2.53 km.
	• Point bars: 22.87sq.Km. ; Length: 2.50 km-5.17 km; width: 0.55 km-01.60 km.
	• Confluence bars: 5.49 sq.Km.; Length: 2.69 km-4.12 km; width: 1.30 km-1.32 km.
	• Flood channels: varying length from 1.93 km to 14.07 km.
	• Chute channels: Of varying lengths (6.37 km to 14.11 km), dissecting bars/ island.
	• Meandering parameters:
	  o 4 meanders
	  o Radius of curvature (rc): 1.92 km-3.32 km.
	  o Wavelength (L): 5.25 km-12.19 km.
	  o Amplitude (Am): 2.52 km-4.88 km.
	• Anabranches resulting in large alluvial islands characterizes this river style. A number of flood and chute channels dissects the island.
	• The lower reaches are dominated by mid channel bars and side bars and there are smaller patches of alluvial islands and other floodplain features like meandering scrolls.
	• Oxbow lakes, more conspicuous downstream, indicate distinct shifting / migration of the channel.
	• Gandak River joins Ganga from the north, with a distinct patch of confluence bar in the floodplain.
	• Sone and Punpun river joins the Ganga from South.

Diagnostic geomorphic features (geometry, sedimentology)	*Channel belt- alluvial* • ~ 20 % of the channel belt has water and the rest is covered by bars. • Partly confined by artificial embankment on the right bank of the river. • Alluvial island cover more than 75% of the channel belt. • Mid channel bars, side bars increases downstream. • Braiding is maximum in the middle.
	Flood plain • Active floodplain almost totally coincides with valley margin except for the most downstream reaches. • Mainly limited to left bank while the right bank is devoid of flood plain because of a southern embankment near Patna up to the confluence of river Punpun from south.
Land Use Land cover association	*Flood plain* • Large part of flood plain is used as cultivated land.
	Channel belt • Alluvial islands are used for agriculture throughout the year; side bars are also used for agriculture during low flows.
Channel and floodplain material	• River Bed Material consist of loose sediments. • Floodplain material is silty sand.

River Behaviour and Process Zone River channel narrows down in width, mid channel bars and alluvial islands are well exposed and used for seasonal agricultural activities during low flow stage. The river attains bankfull stage during monsoon, the sidebars and point bars are submerged and alluvial island are partly submerged. The river flood water submerges left bank overtopping it regularly in overbank stage. Geomorphologically this style is characterized by an aggradational regime and a major confluence zone between the Ganga and Gandak and also between Ganga and Son. The confluence zone has been dynamic at historical scale.
Ecological Significance Water degradation is less due to less variation of water volume. Ganga is fed here by the tributaries Ghagra, Sone, Punpun and Gandak. The ecosystem of this region comprises of phytoplanktons, zooplanktons, other invertebrates and macro fauna including fishes. Benthos is more at Patna with less insects and high molluscs. Due to the presence of barrage, fish yield have decreased. Major carps, large catfish and Ilisha have reduced significantly over the years.

5.10 River Style 10: Craton Margin, Confined Floodplain, Partly Confined Braided

Defining attributes: This part of the river is ~ 145 km long and is typified by high braiding index low sinuosity and presence of many large islands and mid-channel bars. The setting is semi-confined with the presence of the cratonic basement rock on one side. Floodplain has developed asymmetrically. Downstream of Kursela it is on the right bank of the river while 52 Km downstream of Kursela the floodplain is well developed only on the left bank. Floodplain typically consists of abandoned braid bars and two major tributaries (Kosi and Mahananda) joins Ganga in this stretch.

Stretch: Kursela to Farakka (145 Km)

Details of Analysis	
Data used: Geomorphic and active floodplain mapped from Landsat 4-5TM,February 2010 and Valley margin maps from SRTM 2000 ***Analysts**:* Lipibasu and Sayan Sinha *Date:*17Aug2011	
River Character	
Landscape setting	• Craton Margin on the southern side of the river
Valley Morphology	• Maximum valley width is 26.6 Km near Farakka and minimum is 7.72 km. with an average width of 15.83 Km(wide valley)
Channel confinement	• Partly confined by the valley margin. In very short stretches river is confined by cratonic basement on its southern side.
Active Floodplain characteristics	• Maximum floodplain width is 18.23 Km and minimum-6.01 Km. with an average width of 12.31 Km. • Floodplain is confined by cratonic basement on its right bank while left bank is confined by alluvium. • FP:VM width = 1:1.2
Channel Characteristics	• Sinuosity (P) in this style is 1.61 • Braid channel ratio (B) is high with a value of 3.57 • Two tributaries joins Ganga in this stretch • The total bar area is 406.58 sq km and channel area is 224.08 sq km. The area of the individual units are: o Alluvial islands: 331.56 sq km o Mid channel bars: 32.13 sq km o Point bars: 4.77 sq km o Abandoned Braided Bar: 157.64 sq km o Abandoned Meander Bar: Nil o Side Bar: 33.81 sq km o Transverse Bar: 4.31 sq km o Confluence Bar: 5.02 sq km

Diagnostic Geomorphic Features (geometry, sedimentology)	*Channel belt- alluvial* • High braiding index • The main channel occupies 35% of the area while the rest is covered by bars. • Large sandy islands with braided accretion surfaces • Medium to fine sand size dominant component of the bars/islands
	Flood plain • Floodplain marked by abundant meander scrolls.
Land Use/Land Cover association	*Flood plain* Many large villages occur on the active floodplain with permanent structures.
	Channel belt Most of the large islands have been extensively cultivated. In some islands small villages have been built that are subject to flood hazard. Many of the uncultivated bars show dense growth of grassy vegetation.
Channel and Floodplain material	Channel and channel bars are mostly made up of fine grained sand; floodplains comprise clay, silt and very fine sand.

River Behaviour and Process Zone

In-channel bars are very dynamic in this part of the river and changes remarkably within a period of 1 to 6 years, resulting in loss of cultivated land and appearance of new emergent bars. During flood most of the bars and large part of the islands remains submerged.

This part of the river channel appears to be aggrading rapidly by depositing sandy sediments as bars and island. Two tributaries that join Ganga in this stretch probably carry a lot of sand resulting in the braided pattern and aggradational regime of the river.

Ecological Significance

Phytoplanktons are more dominant than zooplankton at Farakka. The major fish was ilish here but after the construction of the Farakka barrage the ilish has been replaced by other species (common carp and telapia) and the ecosystem changed. Tenualosa ilisha and Pangasius pangasius are badly affected in this region. Birds have been reported in the area adjoining the Farakka barrage as below:

- Near threatened bird: Black-bellied Tern, Darter, Ferruginous Pochard
- Vulnerable bird: Baer’s Pochard, Indian Skimmer, Lesser Adjutant
- Critically endangered bird: Long-billed Vulture, Oriental White-backed Vulture

6. Conclusions and Recommendations

This report has presented the different River Styles® of the Ganga River some of the major findings are as follows:

1. The Ganga River displays significant morphological diversity from the source (Gangotri) to Farakka which has been documented as 10 different River Styles. Primarily, such morphological diversity should translate into different physical habitat. This data should therefore be integrated with the ecological diversity recorded in the Ganga river for understanding the present distribution of biota and for planning the restoration/rehabilitation activities.
2. The Himalayan (mountainous) part of the River (Gomukh to Haridwar) is distinctly different from the reaches in the plains. Two River styles identified in the mountainous reaches primarily differ in terms of presence or absence of floodplains and channel morphology. While the upper part is sinuous with no floodplains, the lower part shows discontinuous floodplain and braided morphology. This differentiation reflects strong control of bedrock valley walls in the upper reaches; the valley walls guide the river course and provide no space for sediment storage due to high slopes. In the lower reaches, slope decreases a bit and a part of the sediment flux is stored in the floodplains and within the channels as bars.
3. The first major change in River Style is observed at Haridwar where the river debouches into the plains and an abrupt change in slope results in a sharp increase in valley as well as floodplain width. The Ganga River seems to be quite unstable in this reach and has been swinging across the valley as evidenced by several paleochannels.
4. The stretch of the Ganga River from Bijnor to Allahabad is characterized by valley-interfluve setting and we have recognized three distinct River Styles in this stretch which are differentiated in terms of valley-floodplain relationships and reach-scale channel morphology. A major and common feature in this stretch is that the river is incised dominantly along the right bank and floodplain is preferentially developed along the left bank. This reflects the differential stability of the banks and also implies that flooding characteristics would also be different along the two banks. Such differences would mean that lateral connectivity of the river would be quite different on the left and right banks which should in turn be manifested in terms of floodplain ecology.
5. The stretches from Allahabad to Gopiganj and then from Chunar to Chapra fall into alluvial setting and include the confluence of the Yamuna and the Ganga at Allahabad channel morphology shows a sharp change in these stretches. The River Style for both these stretches is characterized by abundant meander scars and sinuous channel suggesting a dynamic regime where meander migration is a common mechanism of river dynamics. Downstream of Chapra and upto Pansalla, the valley-interfluve setting takes over again and the most diagnostic feature in this style is the presence of large alluvial islands and anabranching channel. Overbank flooding along both banks of the river is common and an aggradational regime dominates in this style. Such morphological variability in River Styles should characterize distinct physical habitats. It is also clear that river management strategy in these stretches will need a strong focus on flooding and sediment control.

6. The lower reaches of the Ganga river have a distinct river style as the southern bank of the river coincides with the craton margin. The diagnostic features of this river style include wide valley and floodplain, large patches of abandoned meander belt, and alluvial islands. Large scale dynamics of the channel has been recorded in these stretches and a prominent aggradational regime is inferred.

Similar work on River Style Framework has been carried out on the major tributaries of the Ganga which will be presented in the next report. River Style Framework developed for the Ganga River has provided a valuable document to highlight the geomorphic diversity along the Ganga. This has also provided a database for reach-scale morphological characteristics which can be easily related to the habitat conditions of the indicator species of the reaches or an individual river style. Apart from providing a descriptive documentation of geomorphic diversity, this data will be of immense value in geomorphic assessment of the river condition in different reaches and also for the assessment of E-flow at different points along the river.

References

Brierley, Gary and Fryirs, Kirstie, 2005, Geomorphology and River management, Applications of the River Styles® framework

Reid, Helen E., Gregory, Claire E., Trahan, Nadine C. and Brierley, Gary J., Implementation of the River Styles® Framework in the twin streams catchment West Auckland, New Zealand.

Gibling, M.R, Tandon, S.K., Sinha, R. and Jain, M., Journal of Sedimentary research, vol 75, May 2005, Discontinuity-bounded alluvial sequences of the southern gangetic plains, India, Aggradation and degradation in response to monsoonal strength.

Brierley, Gary and Fryirs, Kristie, 2002, The River Styles® Framework: The short course conceptual book.

Friend, P. F. and Sinha, R. (1993). Braiding and Meandering Parameters, in J. L. Best and C. S. Bristow (ed.) 'Braided Rivers', Geological Society of London Special Publication, 75, p.105-111.

Kellerhals, R.; Church, M.; Bray, D. I. (1976). Classification and analysis of river processes.Journal of the Hydraulic Division, Proceedings of the American society of Civil Engineers 102(HY7), 813-829.

Frissell,C.A., Liss, W.J., Warren, C.E. and Hurley, M.D.(1986). A hierarchical framework for stream habitat classification:Viewing streams in a watershed context, Environmental Management 10, 199-214.

Active Floodplain Mapping:

Defining the "River Space"

GRBMP : Ganga River Basin Management Plan

by

Indian Institutes of Technology

IIT Bombay	IIT Delhi	IIT Guwahati	IIT Kanpur	IIT Kharagpur	IIT Madras	IIT Roorkee

Preface

In exercise of the powers conferred by sub-sections (1) and (3) of Section 3 of the Environment (Protection) Act, 1986 (29 of 1986), the Central Government has constituted National Ganga River Basin Authority (NGRBA) as a planning, financing, monitoring and coordinating authority for strengthening the collective efforts of the Central and State Government for effective abatement of pollution and conservation of the river Ganga. One of the important functions of the NGRBA is to prepare and implement a Ganga River Basin: Environment Management Plan (GRB EMP).

A Consortium of 7 Indian Institute of Technology (IIT) has been given the responsibility of preparing Ganga River Basin: Environment Management Plan (GRB EMP) by the Ministry of Environment and Forests (MoEF), GOI, New Delhi. Memorandum of Agreement (MoA) has been signed between 7 IITs (Bombay, Delhi, Guwahati, Kanpur, Kharagpur, Madras and Roorkee) and MoEF for this purpose on July 6, 2010.

This report is one of the many reports prepared by IITs to describe the strategy, information, methodology, analysis and suggestions and recommendations in developing Ganga River Basin: Environment Management Plan (GRB EMP). The overall Frame Work for documentation of GRB EMP and Indexing of Reports is presented on the inside cover page.

There are two aspects to the development of GRB EMP. Dedicated people spent hours discussing concerns, issues and potential solutions to problems. This dedication leads to the preparation of reports that hope to articulate the outcome of the dialog in a way that is useful. Many people contributed to the preparation of this report directly or indirectly. This report is therefore truly a collective effort that reflects the cooperation of many, particularly those who are members of the IIT Team. Lists of persons who are members of the concerned thematic groups and those who have taken lead in preparing this report are given on the reverse side.

Dr Vinod Tare
Professor and Coordinator
Development of GRB EMP
IIT Kanpur

The Team

1. Bimlesh Kumar, IIT Guwahati bimk@iitg.ernet.in
2. J K Pati, Allahabad University jkpati@gmail.com
3. Kirteshwar Prasad, Patna University kriteshwar.geopat@gmail.com
4. Parthasarthi Ghosh, ISI Kolkata pghosh@isical.ac.in
5. Rajiv Sinha, IIT Kanpur rsinha@iitk.ac.in
6. Ramesh Shukla, Patna University rshuklapat@gmail.com
7. Kalyan Rudra, WBPCB rudra.kalyan@gmail.com
8. S K Tandon, University of Delhi sktand@rediffmail.com
9. Saumitra Mukherjee, JNU Delhi saumitra@mail.jnu.ac.in
10. Shashank Shekhar, University of Delhi shashankshekhar01@gmail.com
11. Soumendra Nath Sarkar, ISI Kolkata soumendra@isical.ac.in
12. Tapan Chakarborty, ISI Kolkata tapan@isical.ac.in
13. Vikrant Jain, University of Delhi vjain@geology.du.ac.in

Attributions

1. Haridas Mohanta, PhD Scholar, IIT Kanpur
2. Lipi Basu, Sr Project Associate, IIT Kanpur

Contents

1. Introduction

A river must have 'adequate space' to perform its myriad function. The river 'valley' and 'active floodplain' define that space for the river albeit with different functionality. It is important that the functionality of the river valley and floodplains are recognized and documented properly for a sustainable river management. For example, a river with a complete floodplain is not just considered as the one in equilibrium but also in good health. Floodplains support a wide variety of rich life forms ranging from riparian vegetation to different species of organism which have a direct influence on soil fertility. Thus, these areas are good for agriculture due to its high nutrient content, and that is why, they are frequently occupied by local population at the cost of other ecosystems. Another important aspect of preserving river's active floodplain is that it reduces the risk to life and property due to annual flooding. It is therefore critical that the active floodplain of the river is mapped accurately as this will have an important bearing on the restoration of the naturalness of the river.

An obvious question is, what is active floodplain of the river, and how to define this? A river floods when it crosses the bank-full stage. Active floodplain is defined as an area on either side of a stream/river which is regularly flooded on a periodic basis. A typical hydrological criterion to designate an active floodplain in a given reach is the 2.33 year return period of the flood. A river valley is a wider and more extensive area which is primarily defined on the basis of a topographic low across the river. The course of the river may not be necessarily symmetric to its valley.

This report presents a first order assessment of the active floodplain of the main Ganga channel based on satellite data which needs to be validated through field checks. Identification of the valley margin of the river and the present and suggested usage of the valley as well as floodplains will be done subsequently.

2. Data used and Methodology

The following data and criteria are used for mapping the active floodplain:

i) ***Landsat 4-5 TM with 30 m resolution and 7 bands.***
It was observed that the 742 band combination for Landsat provides a distinct tone for high moisture content area. Figure 1a shows Landsat (2003) imagery of Kanpur area on which the active floodplain has been mapped. Figure 1b shows the Landsat (2010) data for the same area when a large flooding occurred in this region and this validates the geomorphic delineation of the active floodplain.

ii) ***IRS P6 AWIFS data with 56 m resolution and 4 bands.***
For the AWIFS data, the band combination of 432 was found suitable for interpretation. Further, the AWIFS data was processed to generate a Tasseled cap and NDWI imagery. In NDWI the formula that was used was (NIR – Green)/(NIR + Green) while for tasseled cap the default coefficients were used as in ERDAS. Both

these images have a distinct tone for high moisture area. Figures 2a and 2b show the various ways as to how the AWIFS data was used for interpretation. Figures 3a is the grey scale image of AWIFS data which prominently show the water related features. Figure 3b shows the actual floodplain extent on the AWIFS data after collating all the information from the different imageries. Further, the plotting was corroborated by the flood inundation maps of the Dartmouth Observatory (http://www.dartmouth.edu/~floods/hydrography). Figure 3c shows a clipped window from this map for the Kanpur area.

Figure 1: (a) LANDSAT 2003 data showing the meander scroll and the stretch of Ganga upstream of Kanpur. The active floodplain of the river is shown with a dashed line. Note that the right bank of the river does not have any active floodplain whereas the left bank has a wide floodplain. (b) LANDSAT data of the Kanpur area during the flood of 2010.

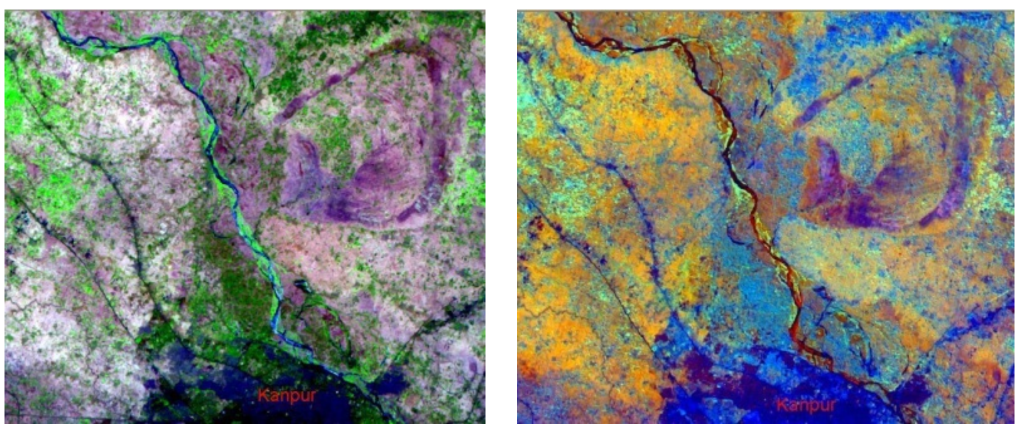


Figure 2: (a) AWIFS data for floodplain mapping; an FCC using 432 bands on RGB provided the best results, (b) Tasseled cap of the same area.

iii) Google Earth

The Google Earth images are very useful in identifying and delineating features because of its high resolution. Figure 3d shows a snapshot of the Kanpur area for the year 2010.

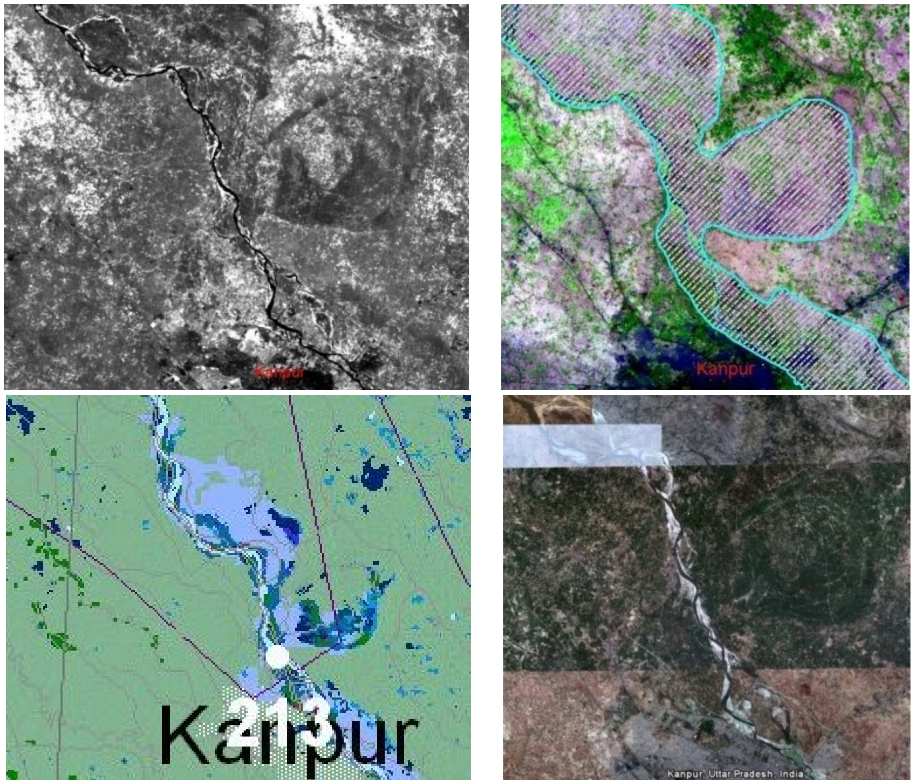


Figure 3: (a) NDWI (Normalized difference water index) map, (b) Actual floodplain mapping after integrating all the data, (c) MODIS data from the Dartmouth Flood observatory site for the Kanpur area, (d) Google Earth imagery of Kanpur

For mapping of geomorphic unit for a small window LISS IV data was used wherever available along with the LANDSAT data.

3. Result and Discussions

3.1 Basin scale mapping

Figure 4 shows the active floodplain for the river Ganga from Haridwar to Farakka. The active floodplain from Haridwar to Farakka does not show any uniformity. At some sites, the floodplain is broad and at some other site it is narrow. In some cases, there is total absence of floodplain on one bank.

Based on distribution of active floodplain, the Ganga River can be divided into four distinct reaches between Haridwar and Farakka (the reaches upstream of Haridwar have not been mapped yet):

(a) Haridwar to Narora: As soon as Ganga leaves the mountainous part and enters the plains downstream of Haridwar, the floodplain is quite wide (~28km). Around Bijnore (latitude $29^{o}22'$ N and longitude $78^{o}8'$ E) the floodplain width narrows down to ~ 10km. Further downstream, it becomes even narrower and at Narora barrage (Latitude $28^{o}13'$ N and longitude $78^{o}23'$ E) it is only about 5 km wide.

(b) Narora to Kanpur: Downstream of Narora barrage the floodplain starts widening and at the confluence with Ramganga it attains a maximum width of ~28km. Further down the floodplain starts narrowing again and at upstream of Kanpur maximum width is ~15 km and downstream of Kanpur it is ~9 km.

(c) Kanpur to Buxar: The floodplain starts narrowing down downstream of Kanpur to a minimum of about 1 km. As the river approaches Allahabad, the flood plain starts widening again and at Allahabad (Latitude 25^{o}28' N and longitude 81^{o}52' E) it is about 7.5 km. This width is more or less maintained with little variation till Buxar (latitude 25^{o}33' N and longitude 83^{o}59' E) after which the floodplain becomes very wide.

(d) Buxar to Farakka: Downstream of Buxar the floodplain reaches the maximum width in the whole of the basin and just downstream of Munger (latitude 25^{o}23' N and longitude 86^{o}28' E) the width is about 42km and at Farakka (latitude 24^{o}48' N and longitude 87^{o}55' E) about 26km.

3.2 Detailed mapping for Kachla Bridge and Kanpur

Geomorphic units are the building blocks of river systems. They have a distinct morphology, bounding surface and sedimentalogical associations. These units tend to occur at distinct locations where particular sets of flow energy conditions create and modify their forms. Detailed mapping of major geomorphic units has also been initiated and some initial results for the stretch of Ganga in and around Kachla bridge (latitude 27^{o}56' N and longitude 78^{o}52' E) and Kanpur (latitude 26^{o}25' N and longitude 80^{o}20' E) are presented.

Two geomorphic units are mapped, instream and floodplain. The different elements that were distinguished are shown in the Figure 5 for Kachla bridge and Figure 6 for Kanpur.

(a) In-stream geomorphic unit: The most common instream geomorphic units are accumulation of deposits referred to as bars. They are produced as rivers rework their bed material. Flow strength, material type and availability along with vegetation determine the type of depositional feature that will be formed. The different elements that were identified include (a) Mid channel bars, (b) Point bars, and (c) Lateral bars.

(b) Floodplain geomorphic unit: These units reflect river history and channel stability indicating the relationship among a range of floodplain formation and reworking processes. Two major elements that were identified include (a) Meander scroll, and (b) Flood channel.

4. Ongoing Work

Similar mapping work for the remaining part of the main Ganga River and other major tributaries is in progress. These maps will provide the basic framework for the River style Framework which may be used for the assessment of geomorphic condition of the river.

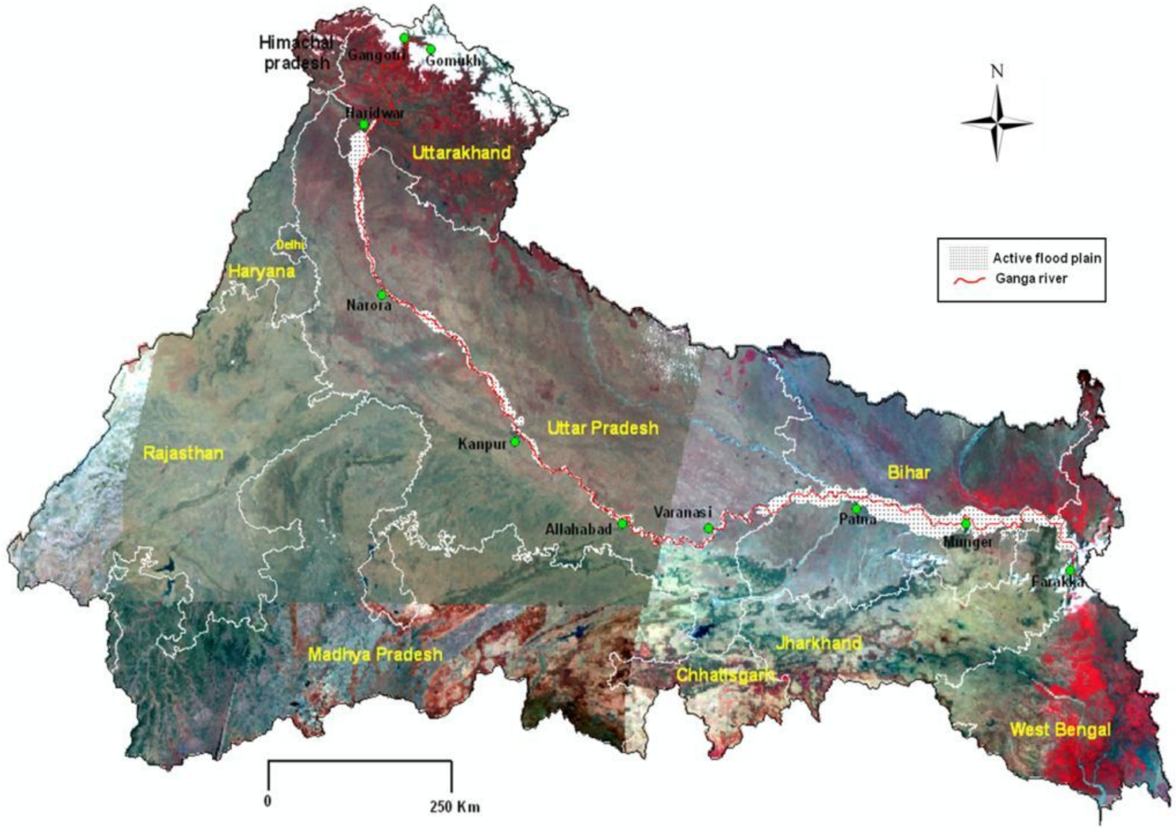


Figure 4: **Ganga Basin boundary map showing the major states, the river Ganga and the active floodplain associated with it on AWIFS**

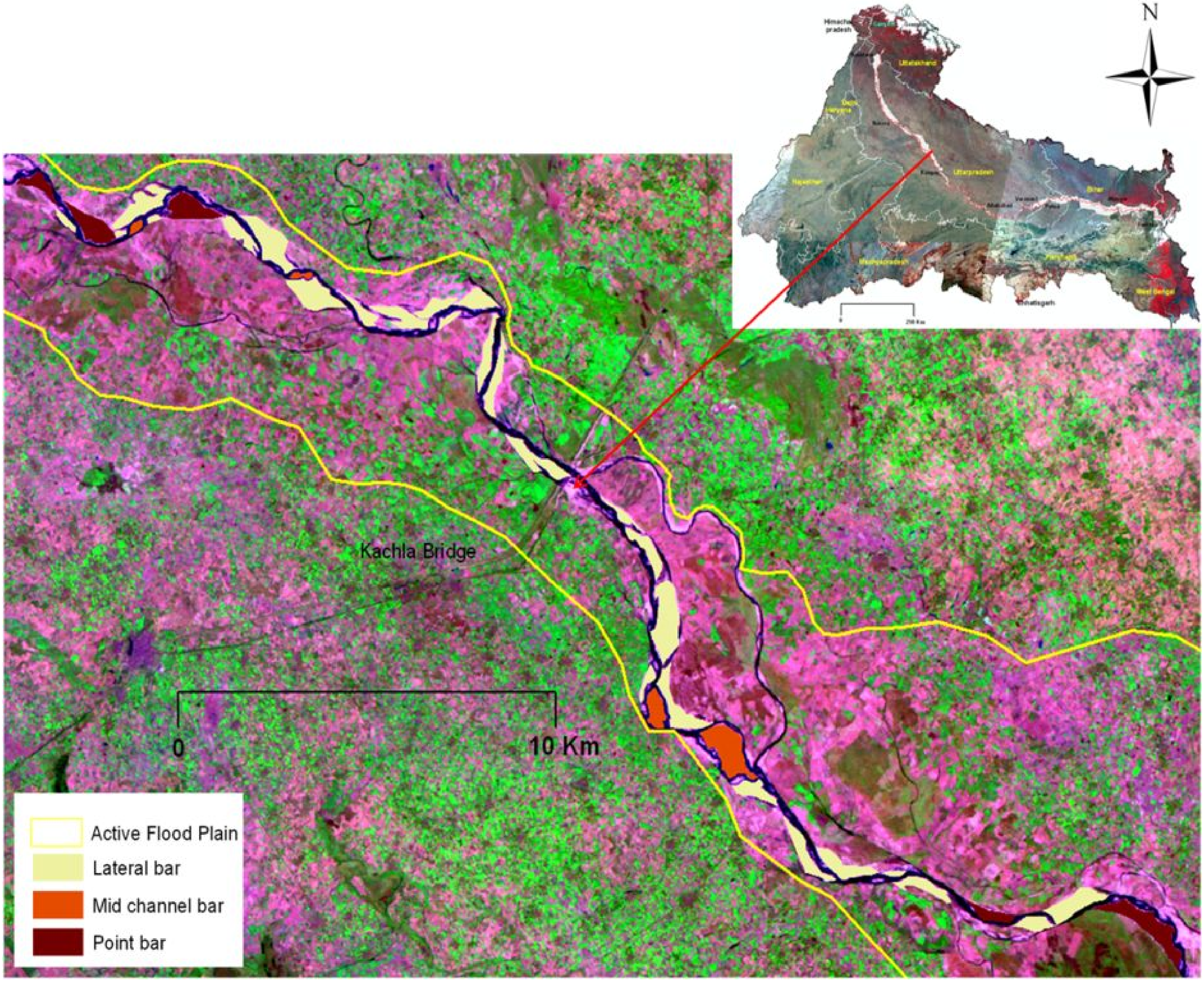


Figure 5: Enlarged view of the stretch of Ganga around Kachla Bridge plotted on Landsat 2010 data

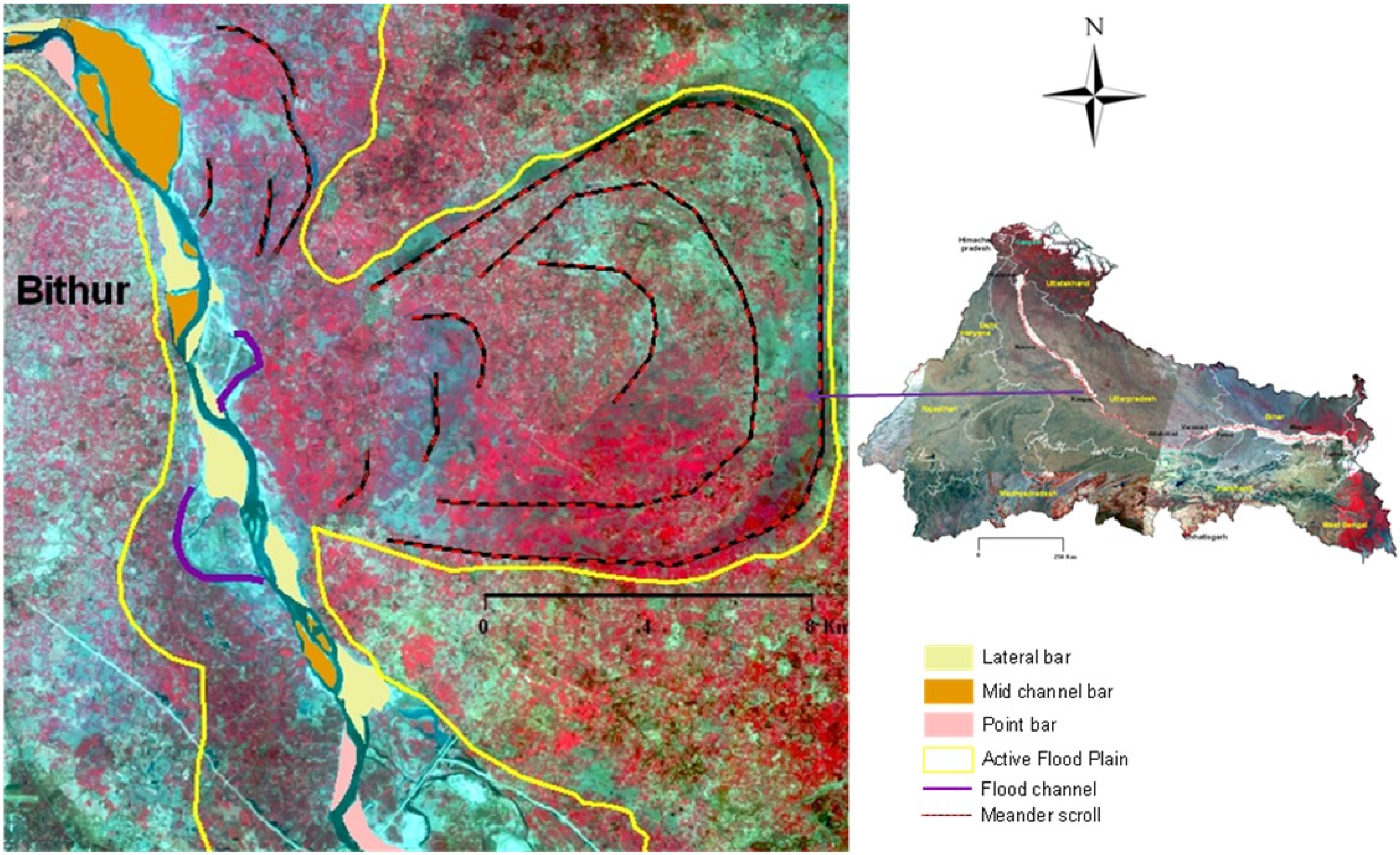


Figure 6: **Enlarged view of the stretch of Ganga around Kanpur with the major geomorphic elements plotted on LISS IV 2007 data.**

Delineation of Valley Margin and Geomorphic Mapping

along the Ganga River Basin and the Yamuna Sub-basin

GRBMP : Ganga River Basin Management Plan

by

Indian Institutes of Technology

IIT Bombay | IIT Delhi | IIT Guwahati | IIT Kanpur | IIT Kharagpur | IIT Madras | IIT Roorkee

Preface

In exercise of the powers conferred by sub-sections (1) and (3) of Section 3 of the Environment (Protection) Act, 1986 (29 of 1986), the Central Government has constituted National Ganga River Basin Authority (NGRBA) as a planning, financing, monitoring and coordinating authority for strengthening the collective efforts of the Central and State Government for effective abatement of pollution and conservation of the river Ganga. One of the important functions of the NGRBA is to prepare and implement a Ganga River Basin Management Plan (GRBMP).

A Consortium of 7 Indian Institute of Technology (IIT) has been given the responsibility of preparing Ganga River Basin Management Plan (GRBMP) by the Ministry of Environment and Forests (MoEF), GOI, New Delhi. Memorandum of Agreement (MoA) has been signed between 7 IITs (Bombay, Delhi, Guwahati, Kanpur, Kharagpur, Madras and Roorkee) and MoEF for this purpose on July 6, 2010.

This report is one of the many reports prepared by IITs to describe the strategy, information, methodology, analysis and suggestions and recommendations in developing Ganga River Basin Management Plan (GRBMP). The overall Framework for documentation of GRBMP and Indexing of Reports is presented on the inside cover page.

There are two aspects to the development of GRBMP. Dedicated people spent hours discussing concerns, issues and potential solutions to problems. This dedication leads to the preparation of reports that hope to articulate the outcome of the dialogue in a way that is useful. Many people contributed to the preparation of this report directly or indirectly. This report is therefore truly a collective effort that reflects the cooperation of many, particularly those who are members of the IIT Team. A list of persons who have contributed directly and names of those who have taken lead in preparing this report is given on the reverse side.

Dr Vinod Tare
Professor and Coordinator
Development of GRBMP
IIT Kanpur

The Team

1. Bimlesh Kumar, IIT Guwahati bimk@iitg.ernet.in
2. J K Pati, Allahabad University jkpati@gmail.com
3. Kirteshwar Prasad, Patna University kriteshwar.geopat@gmail.com
4. Parthasarthi Ghosh, ISI Kolkata pghosh@isical.ac.in
5. Rajiv Sinha, IIT Kanpur rsinha@iitk.ac.in
6. Ramesh Shukla, Patna University rshuklapat@gmail.com
7. Kalyan Rudra, WBPCB rudra.kalyan@gmail.com
8. S K Tandon, University of Delhi sktand@rediffmail.com
9. Saumitra Mukherjee, JNU Delhi saumitra@mail.jnu.ac.in
10. Shashank Shekhar, University of Delhi shashankshekhar01@gmail.com
11. Soumendra Nath Sarkar, ISI Kolkata soumendra@isical.ac.in
12. Tapan Chakarborty, ISI Kolkata tapan@isical.ac.in
13. Vikrant Jain, University of Delhi vjain@geology.du.ac.in

Attributions

1. Haridas Mohanta, PhD Scholar, IIT Kanpur
2. Lipi Basu, Sr Project Associate, IIT Kanpur

Contents

1. Preamble

In the first report (005_GBP_IIT_FGM_DAT_01_Ver 1_Dec 2010) of the Fluvial Geomorphology Thematic Group, the 'active floodplain' was mapped from satellite imagery to define the 'river space'. This report presents the mapping of the valley margin and geomorphic features in the channel belt as well as active floodplain. As has already been emphasized, it is important to recognize and document the various hydrological and ecological functions of the river valley and floodplains for developing a sustainable river management plan.

A river valley is a wider and more extensive area, compared to active floodplain, and is primarily defined on the basis of a topographic 'break' across the river. The course of the river may not be necessarily symmetric to its valley. The valley margin primarily defines:

a) the 'water divide' which is the line dividing neighbouring drainage basins (catchment) on a land surface. It can be visualized as a line on the ground on either side of which water droplet will start a journey to different rivers and even to different sides of the region. It is analogous to the 'hydrological boundary' between two watersheds.

b) the limit of 'lateral connectivity' between the river channel and floodplain or in other words, the hydrological and functional connection between the river and the riparian zone.

c) the 'recharge area' of the river in question i.e. the area in which the surface water infiltrates and is added to the groundwater because of the topographic low. It is important to note here that the areas for any 'artificial recharge' (reservoirs/ditches) must be located within the river valley margin.

In addition, the geomorphic features within the active floodplain delineated earlier have been mapped with an idea to document river character and behavior for understanding the distinctive physical processes operating in different reaches.

2. Data used and Methodology

2.1 Mapping of Valley Margin using SRTM data

The Shuttle Radar Topography Mission (SRTM) launched in February 2000 obtained digital elevation data at 90 m resolution for most parts of the world. Elevation changes can be identified by classifying the SRTM into multiple classes, and then assigning a color code. Figure 1(a) shows such a color-coded map for the Kanpur area of SRTM data, classified into 4 classes. The valley margin was marked based on the profiles from generated SRTM data (Figures 2a-f). Figure 1 (b) shows the profile lines and the black dots represent the topographic break indicating the valley margin and the mapped valley margin is shown in Figure 1 (c).

2.2 Mapping of geomorphic features

The Landsat TM data of pre-monsoon period 2010 was used to map the different geomorphic features using the false color composite (432 band combination on RGB planes). Figure 2(g) shows the Landsat data for the Kanpur city area. Table 1 lists the different geomorphic features that were mapped with their definitions. Google Earth images were also used for identification of features. Figure 2(h) shows a snapshot of the same area as given in the Landsat imagery.

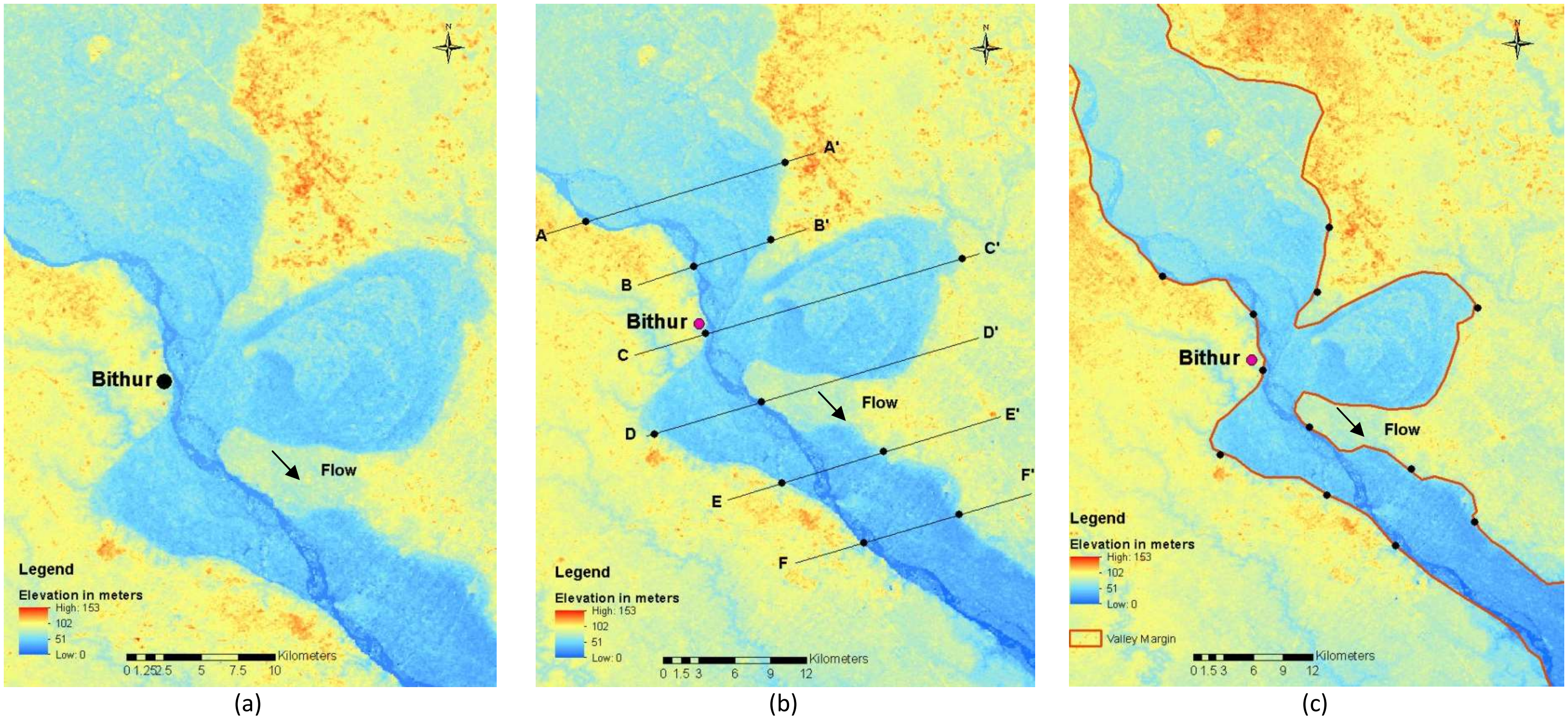
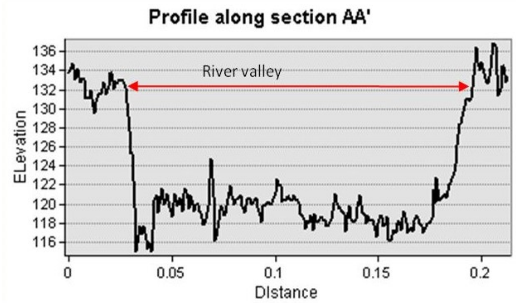
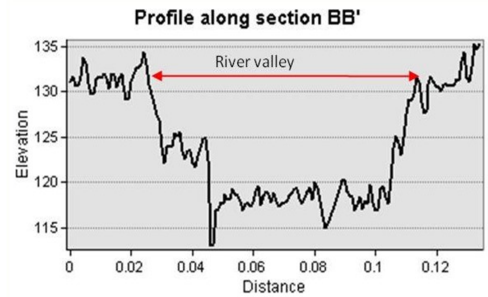


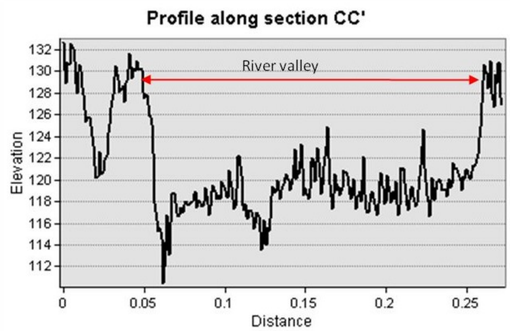
Figure 1: (a) Color coded SRTM data, (b) sections across which profiling have been done, (c) final valley margin of the area



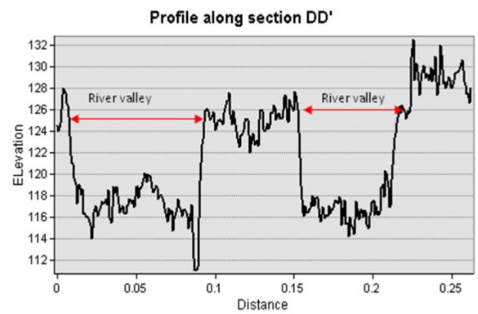
(a)



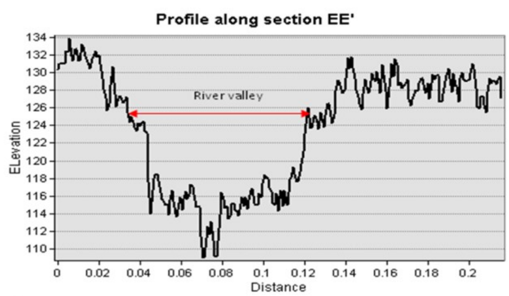
(b)



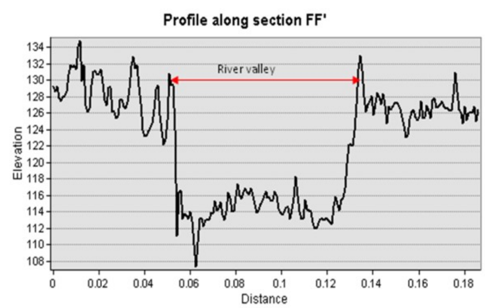
(c)



(d)



(e)



(f)

Distance in decimal degrees vs Elevation in meters

Figure 2 (a-f): Showing the profiles along the selected sections

(g) (h)

Figure 2 (g-h): (g) a snapshot of Landsat imagery, (h) snap shot of the same area in Google Earth

Table 1: List of Channel belt and Floodplain geomorphic units

Major Geomorphic Unit, Channel belt

Feature	Definition and characteristics
Mid channel bar or longitudinal bar	Mid channel tear drop shaped unit bar, elongated in flow direction in gravel and mixed bed channels. Bar deposits typically decrease in size downstream away from a coarser bar head. This can be vegetated.
Transverse bar or linguoid bar	Mid channel unit bar oriented perpendicular to flow generally in sand bed channels. Reflects downstream movement of sand as ribs. If crescent form then it is linguoid bar.
Point bar	Bank attached arcuate shaped unit bar developed along convex banks of meander bends. Bar forms follow the alignment of the bend with differing radii of curvature. The bar surface is typically inclined towards the channel. Grain size typically fines down bar (around the bend) and laterally (away from the channel). Typically these unit bar forms are largely unvegetated.
Tributary bar	Formed at, and immediately downstream of, the mouth of tributaries. Generally poorly sorted gravels and sands with complex and variable internal sedimentary structures.
Alluvial island	Vegetated mid channel compound bars that generally comprise an array of smaller scale geomorphic units. Elongate ridge forms are commonly aligned with flow direction along these major in channel sediment storage units. Scaled to one or more channel widths in length. Especially found when river is anastomosing. Also, size is much larger than mid channel bar.
Lateral bar	Bank attached unit bar developed along low sinuosity reaches of gravel and mixed bed channels. Bar surface is generally inclined towards the channel.
Chute channel	Elongate channel that dissects a bar surface. A common feature on compound point bars, islands and mid channel bars.
Secondary channel	Pattern of coexistant multiple-anastomosing channels (repeated bifurcating and rejoining) with low width/depth ratio. Open channels that remain connected to the trunk stream or the main channel.
Abandoned Braid bars	At places the paleobars that are now part of the flood plain, clearly display accretion surfaces of braid bars. The accretion surfaces within them cannot be related to growth and abandonment of point bars rather they show clear pattern of a braided mid-channel or lateral bars.

Table 1 continued to next page … … … …

… … … … ***Table 1 continued from previous page***

Feature	Definition and characteristics
Alluvial terrace	Typically a relatively flat (planar), valley marginal feature that is perched above the contemporary channel and/or floodplain. Generally separated from the floodplain by e steep slope (a terrace riser). Can be aired or unpaired. Often present as a flight of terraces.
Ox bow lake	Channel depressions of arcuate or sinuous planform (generally one meander loop). Horse show or semi circular in planview, reflecting the morphology of the former channel bends with water.
Levee	Raised elongate asymmetrical ridge that borders the channel, with steeper proximal margins. Best developed along concave banks and in some confined settings. Scaled in proportion to the adjacent channel, levee crests may stand several meters above the floodplain surface. Composed almost entirely of suspended load sediments, i.e. dominantly silt, often sandy.
Flood channel	Gently curved, subsidiary channel to a primary channel. Generally of low sinuosity. Entrance height near bankfull floodstage. May exist as a depressed tract of the floodplain that occasionally conveys floodwaters.
Water body/Wetland	Stagnant water bodies in the flood plain which are of permanent nature. Is distinguishable from Ox bow lake as it does not have the typical shape of ox bow.
Accretion surfaces	These are curved lines occurring within a bar or in the floodplain within the abandoned bar deposits (similar to meander scrolls). They represent different paleo-position of an accreting bar (both meander and braided bars). Whereas some of them can be related to the accretion surfaces of meander bars (meander scrolls), many of them cannot be related to accretion surfaces of point bars. Some of them are related to mid-channel braid bar or lateral bar accretion surfaces.
Meander cut off	Channel depressions of arcuate or sinuous planform (generally one meander loop). Horse show or semi circular in planview, reflecting the morphology of the former channel bends without water.
Meander scroll	Ridge like morphology associated with successive migrating channel. Difference with meander cut-off is they are multiple and in a succession.
Abandoned meander belt	Especially in the stretch of Ganga downstream of Allahabad; coalesce of abandoned successive meandering channel resulting in a unique geomorphic unit.
Abandoned Meander Bars	These occur in the flood plain with point bar accretion surfaces and with/without ox bow lakes.
Abandoned channel	They are dry channels which were active in the past but at present have become dry.
Abandoned meander loop	These features are similar to ox bow lake but at a much larger scale.
Sand patch (flood deposits)	Occurring typically along the stream these are areas of dry sand which have been deposited during flooding. They do not have any distinct shape and can be distinguished from channel bars.

3. Results and Discussions

3.1 Delineation of basin scale Valley margin along the Ganga River

Figure 3 shows the 'valley margin' for the river Ganga from Haridwar to Farakka. The 'valley width' is not uniform along the entire stretch. Based on this, distinct reaches were identified as shown in Table 2.

Table 2: Valley Margin of the Ganga River

Stretch	Maximum and minimum width, km	Major characteristics
Haridwar to Narora	28/9.7	North-south trending valley suddenly widens immediately downstream of Haridwar to a maximum of 28 km on the western side; river is flowing at the eastern edge of the valley; valley width narrows down considerably around Bijnor (9.7 km) and the river swings to the western edge upstream of Bijnor forming a wide valley; river valley widens again downstream of Bijnor and maintains a similar width up to Garmukteshwar; downstream of Garhmukteshwar, the river is characteristically flowing along the western edge all the way to Narora and a wide NNW-SSE trending valley is mapped dominantly on the eastern side
Narora to Fatehgarh	27.8/12.7	Fairly symmetric, NW-SE trending valley with wide valley margins on both sides of the river; Just upstream of Fatehgarh, the river swings to the western edge of the valley and a wide valley is mapped on the eastern side.
Fatehgarh to Kanpur	27.4/3.8	Highly asymmetric valley trending NW-SE, much wider along the eastern valley margin; incised valley margin along the western bank; a large meander around Kanpur causes a significant widening of the valley; valley margin coincides with the active floodplain boundary in a large part of this reach.
Kanpur to Allahabad	11.3/~1	Wide valley along the eastern bank continues to ~ 42.8km downstream of Kanpur and then suddenly narrows down to ~ 1km around Dalmau and Unchahar region with only a few patches of wide valley on the eastern side close to Allahabad; valley margin merges with active floodplain in most parts.

Table 2 continued to next page … … … …

… … … … Table 2 continued from previous page

Stretch	Maximum and minimum width, km	Major characteristics
Allahabad to Varanasi	14.2/1.8	Valley width quite variable and extends to both banks of the river, sinuous course of the river frequently swings from the right edge to the left edge of the valley.
Varanasi to Munger	36.1/7	Valley widens significantly downstream of Varanasi and is evenly distributed on left and right bank of the river; valley width reduces significantly downstream of Patna and also becomes asymmetric, mostly spread along the left bank.
Munger to Farakka	39.2/7.3	Large parts of the valley are spread towards the left bank and the river is flowing at the southern edge of the valley up to 95 km downstream of Munger after which it swings to the northern and southern edges alternately.

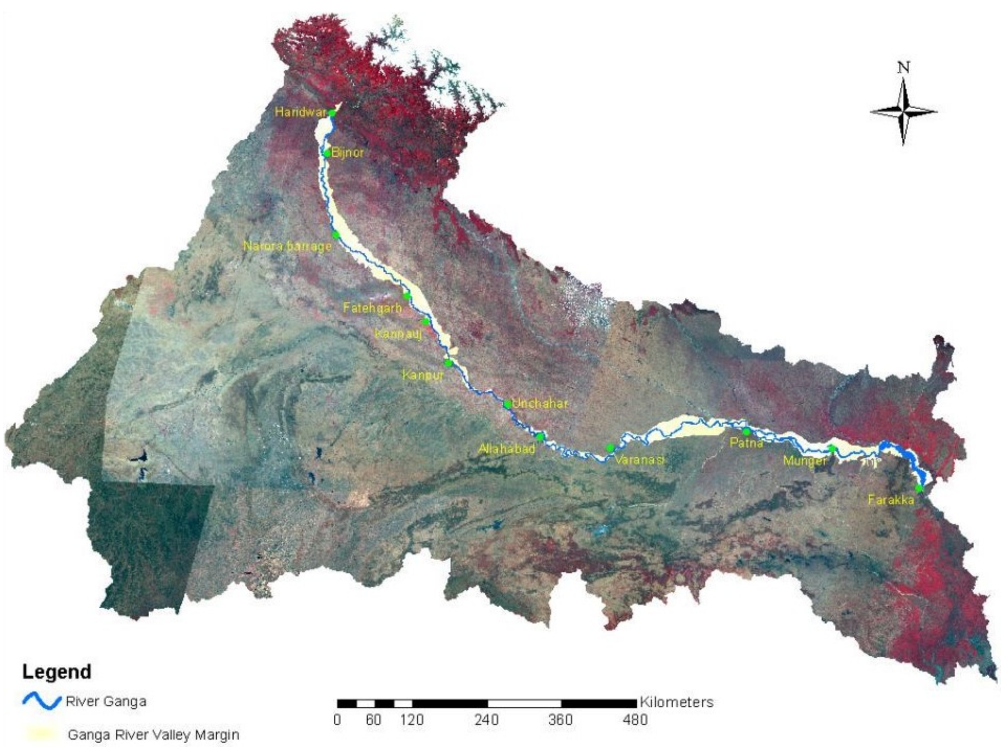


Figure 3: Ganga river valley margin from Haridwar to Farakka plotted in AWiFS image

3.2 Geomorphic Mapping

This section presents the important geomorphic features in the channel belt and active floodplain along the Ganga River. At this stage, diagnostic features are discussed in windows for the sake of clarity but eventually the data will be integrated into distinct zones based on ecological characteristics and biodiversity. We will then characterize River Styles in each zone.

3.2.1 Gangotri to Haridwar

The major part of the Gangotri to Haridwar extent is occupied by structural ridges, valleys and at some places features of fluvial origin. This extent mainly shows the highly and moderately dissected hills of Himalayan range. This stretch of the Ganga River between Gangotri to Haridwar has significantly narrow valley on both sides of the river and the river itself is quite narrow with a much thin water line which is clearly shown in the satellite image. Very narrow flood plain has been observed. The geomorphic fluvial origin features include lateral bar, mid channel bar, alluvial island, chute channel and point bar. Valley margin has also been marked along the Ganga River. Figure 4 shows the geomorphic mapping of the stretch.

3.2.2 Haridwar to Narora

A major part of the Haridwar to Narora stretch is occupied by fluvial geomorphic features. In this stretch, wide flood plains have been marked. The flood plain is composed of sand, gravel, silt and clay. This stretch of the Ganga River has a considerably wide valley on either side of the river. The river channel in this stretch is highly braided. As a result, mid channel braid bars form a significant geomorphic feature followed by lateral bars, and point bars. For the mapping clarity, the geomorphic map in this stretch has been shown into two parts. Figure 5a shows from Haridwar to Mawana in which the river is flowing towards the eastern edge of the valley in the upper parts and then swings to the western and eastern parts alternately. An extremely wide valley immediately downstream of Haridwar is due to a sudden decrease in slope as the river debouches into the plains and forming a large depositional area (piedmont fan). A large number of paleochannels on the western side of the main channel suggest an eastward migration of the river in recent times. In the reach upstream of Bijnor has a large alluvial island which splits the channel into two parts. Downstream of Bijnor, the river has a wide floodplain on both sides. However, this situation changes dramatically downstream of Garhmukteshwar. The river now flows close to the western edge of the valley and has developed a wide valley on the eastern side (Figure 5b). The active floodplain is much narrower compared to the valley all the way to Narora where a barrage is located. The river channel as well as active floodplain have simple forms composed of a few mid-channel bars and fewer meander cut-offs.

3.2.3 Narora to Fatehgarh

This stretch of the river has significantly wide valley on both sides of the river but the river itself is quite narrow with a much thin water line (Figure. 6a) which is clearly a manifestation of the Narora barrage. The river is highly braided but with significant sinuosity in several reaches. As a result, abandoned braid bars form a significant geomorphic feature followed by lateral bars. A number of abandoned channels are mapped which bound the abandoned braid bars and therefore representing the secondary channels of the Ganga. Some of them probably get activated during the high flows. Frequent sand patches on the southern side represent flood deposits.

3.2.4 Fatehgarh to Kanpur

In this stretch, two important tributaries, the Ramganga and the Garra join from the northern side and the river Kali from the southern side around Kannauj. The Ganga river flows along the southern margin of the valley (Figure 6b) and is incised in most reaches with a cliff line varying in height from 10-15 meters. As a result, a wide floodplain runs along the northern bank and very narrow floodplain along the southern bank. The channel is multi-thread with frequent and large mid-channel bars and infrequent lateral bars. Abundant meander cutoffs, scrolls and abandoned meander loop in the active floodplain on the northern side suggests that the river has been gradually shifting towards the south. The presence of an abandoned meander loop upstream of Kanpur is conspicuous because of which the valley width suddenly widens.

3.2.5 Kanpur to Allahabad

Downstream of Kanpur, the river continues to flow along the western edge of the valley for ~ 30 km and 12.8 km further downstream the valley narrows down considerably (Figure. 6c). The river starts swinging to the northern and southern edge within the limited space and narrow floodplains have developed on both sides alternately. From a point ~ 71 km downstream of Kanpur the river flows in an east-west trend for ~ 21.2 km and then resumes NW-SE trend at Dalmau. The river valley also narrows down downstream of Dalmau and attains a minimum width of ~1 km at Unchahar. A wide abandoned meander belt is mapped at Dalmau but apart from this, there is very little evidence of channel migration suggesting this to be a relatively stable stretch. The valley starts widening again downstream of Unchahar (Figure 6d) and attains a width of ~ 7 km at Allahabad. Pockets of wide floodplain have developed in the stretches upstream of Allahabad which are as wide as the valley margin in this region. Frequency of abandoned channels and meander cut-offs also increases and a large abandoned meander belt is noted at Allahabad.

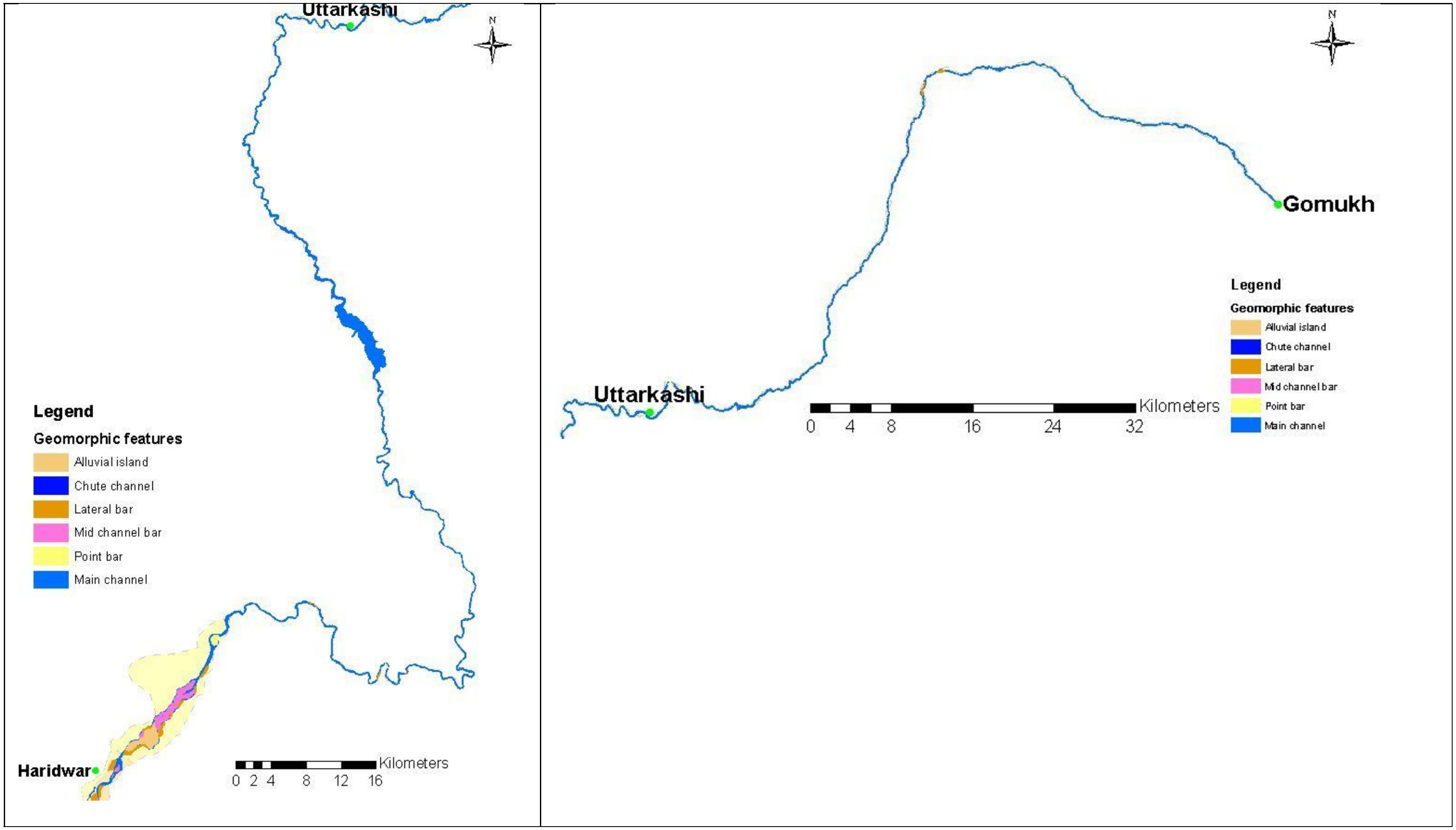


Figure 4: **Geomorphic mapping of Ganga between Haridwar to Gomukh**

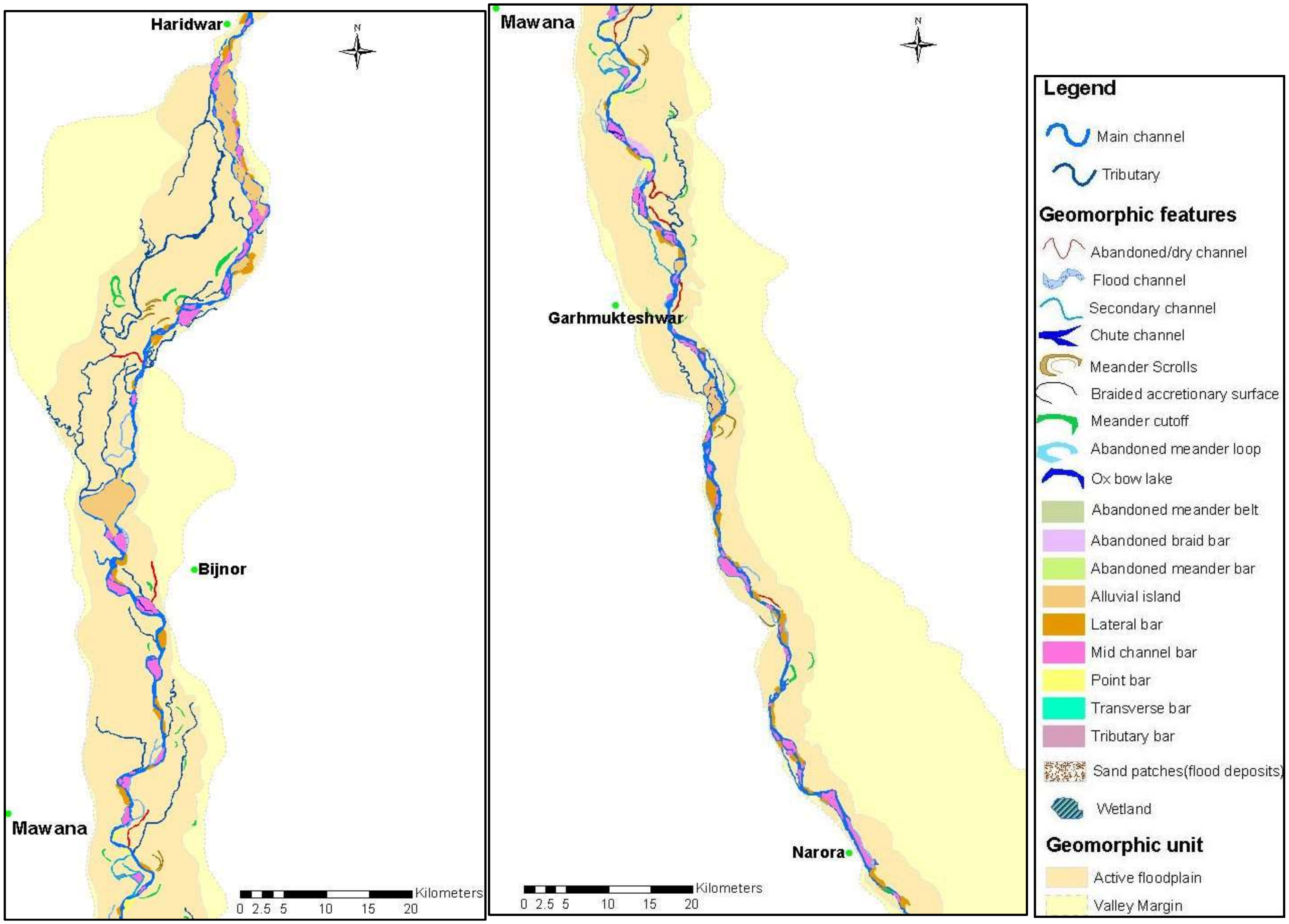


Figure 5 (a-b): Geomorphic map of the Haridwar to Narora stretch

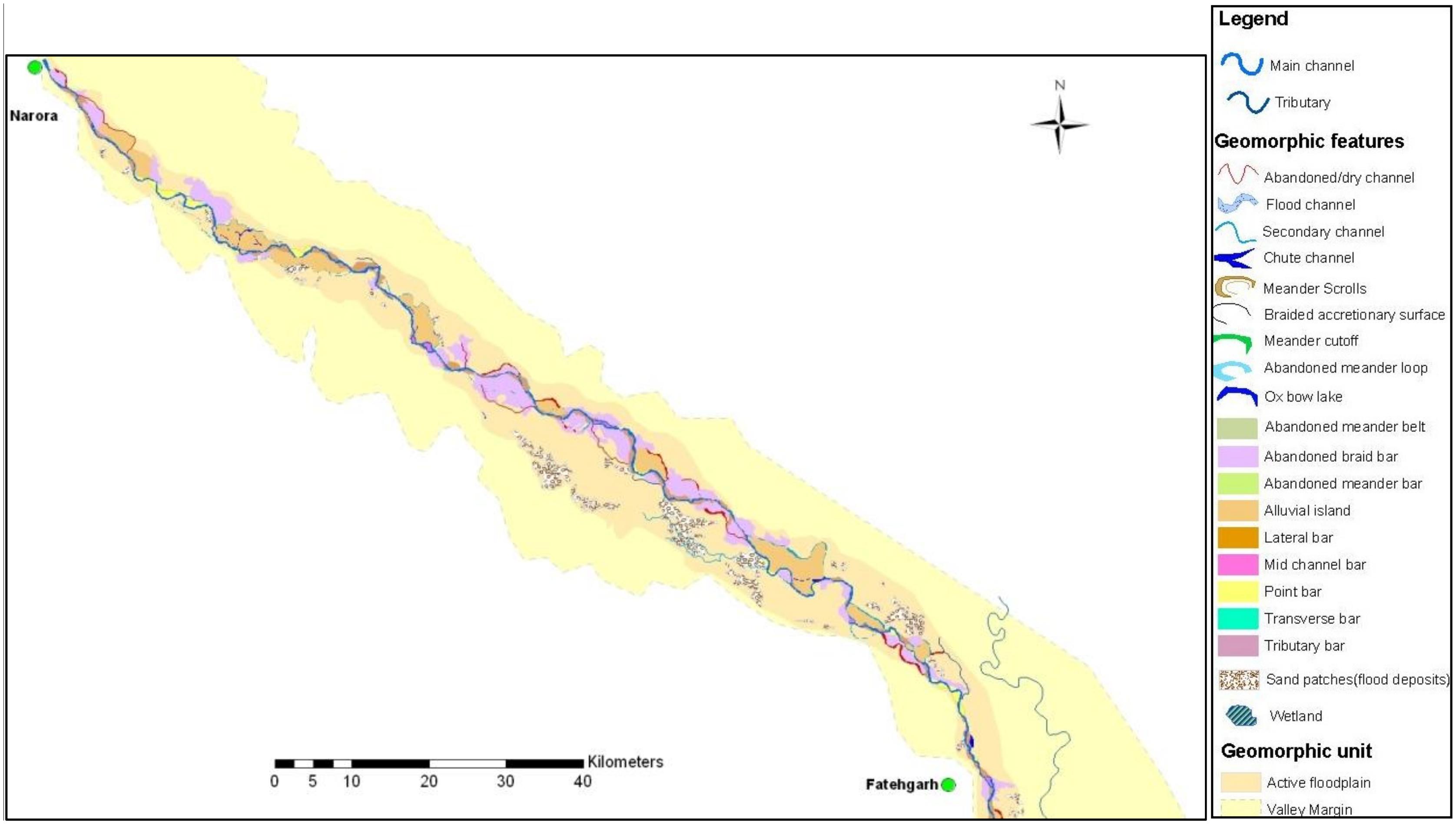


Figure 6a: Geomorphic map of the Narora to Fatehgarh stretch

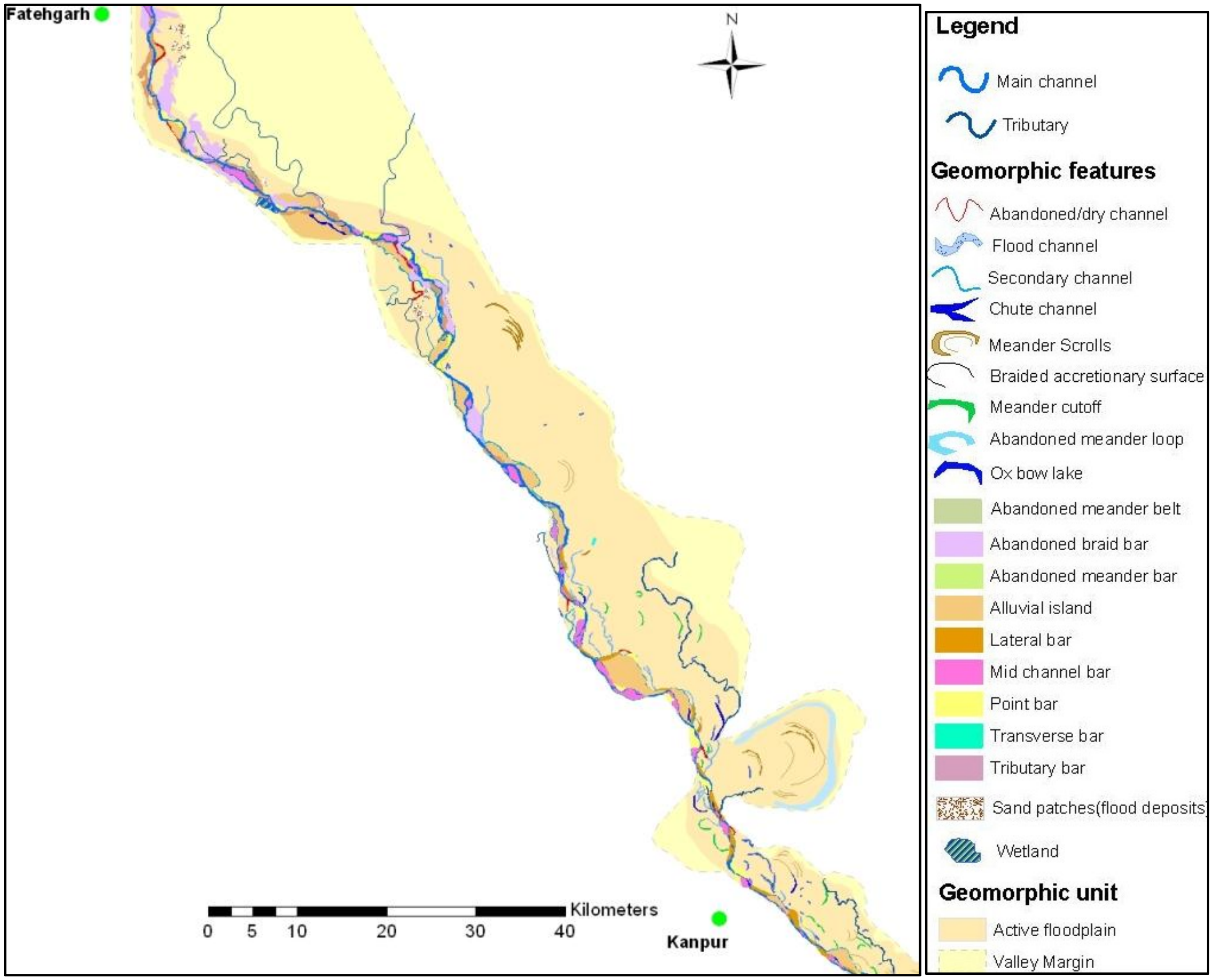


Figure 6b: Geomorphic map of the Fatehgarh to Kanpur stretch

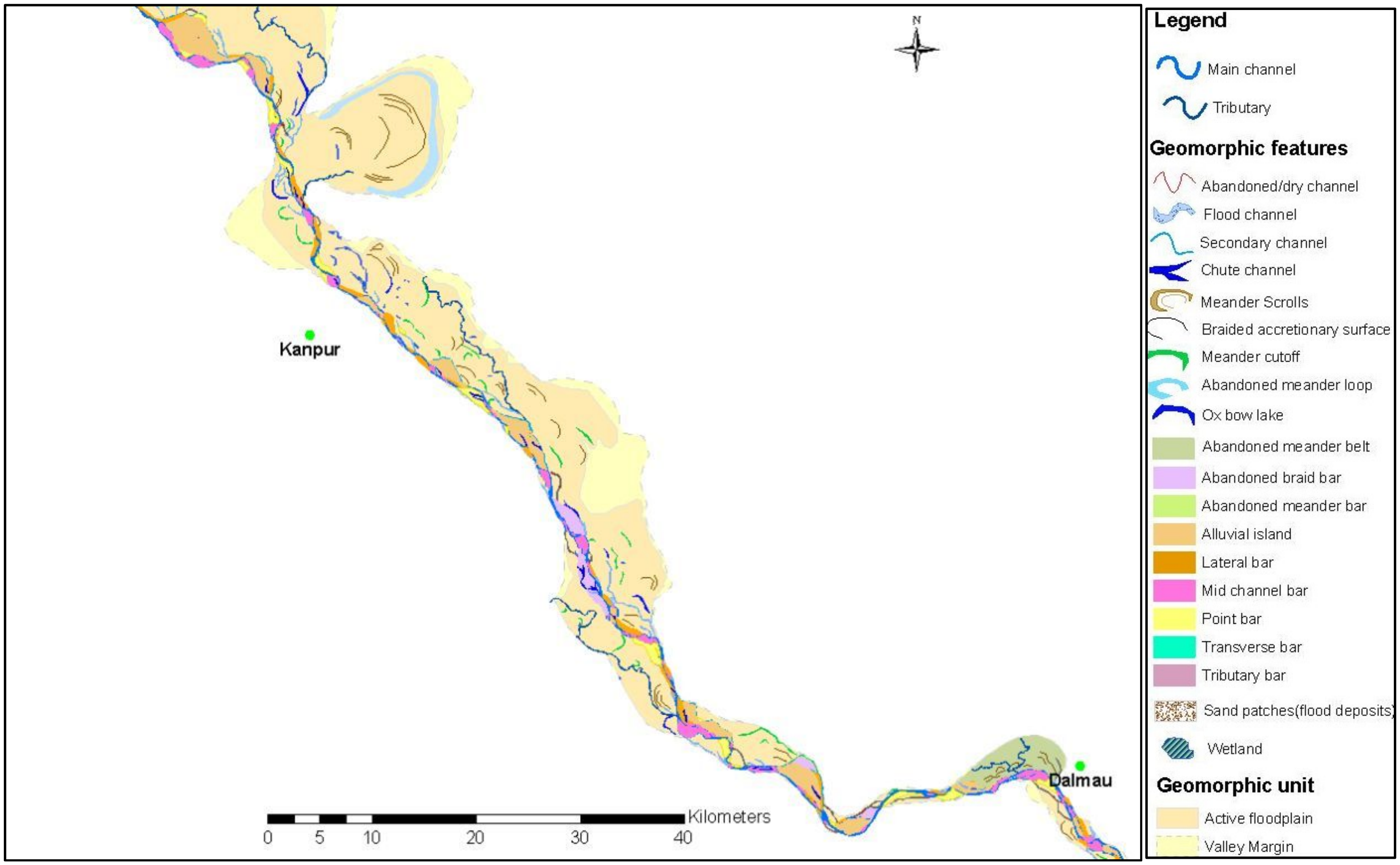


Figure 6c: Geomorphic map of the Kanpur to Dalmau stretch

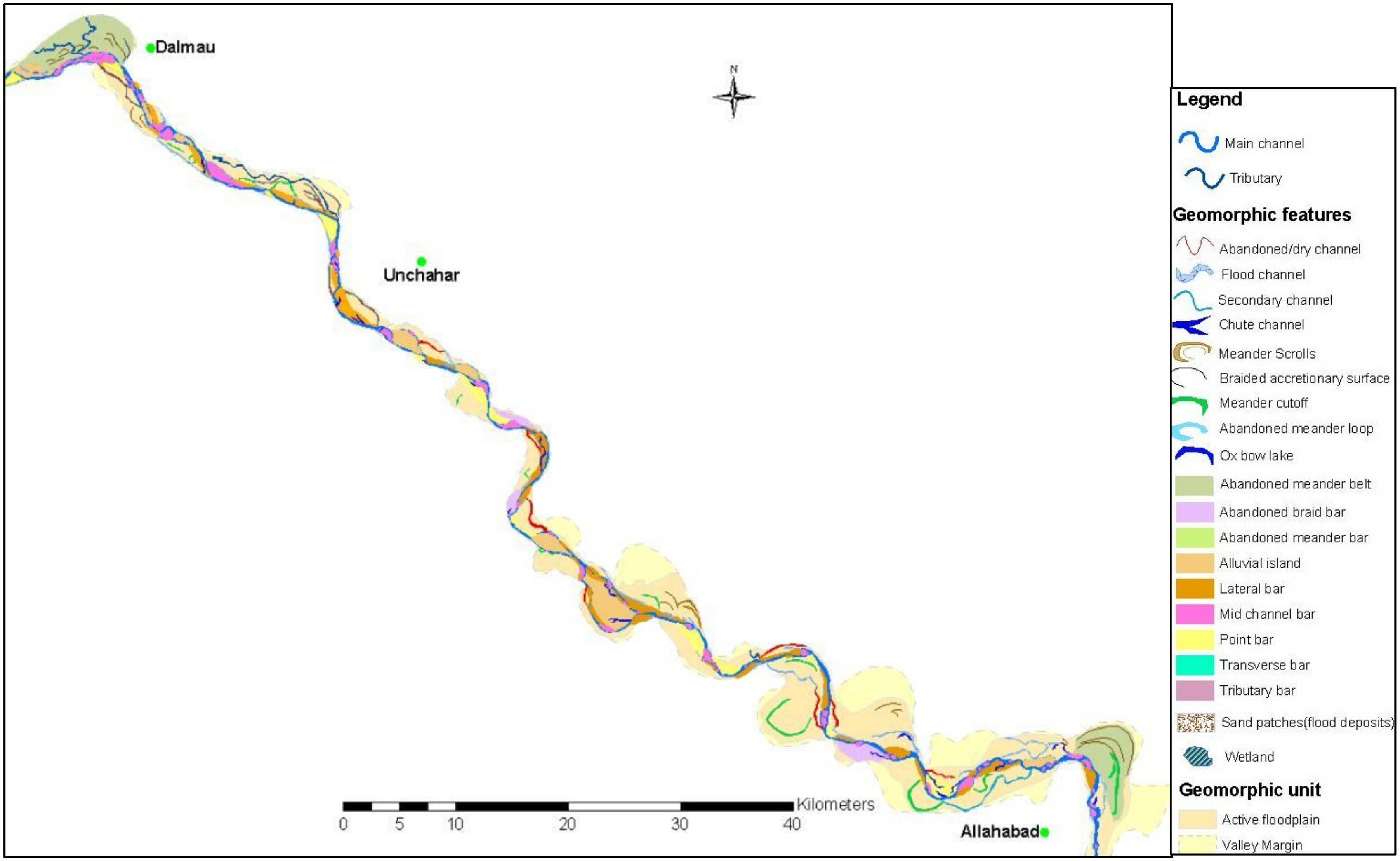


Figure 6d: Geomorphic map of the Dalmau to Allahabad stretch

3.2.6 Allahabad to Varanasi

The river stretch between Allahabad and Varanasi (Figure 7) over a length of 245 km is a unique segment of the Ganga River as it nearly approaches (~7 km; near Meja) the peninsular shield and exhibits a strong basement/tectonic control with a maximum sinistral shift of about 16 km towards SSE (Allahabad). In addition, these two cities are the most popular religious centers along the river course. The mapping of the river course based on remote sensing data with limited field checks has shown the various geomorphic units with their respective numbers and areal coverage which includes mid-channel bars (134.59 sq km), point bars (110.76 sq km), alluvial islands (56.17 sq km), lateral bars (245.34 sq km), meander scrolls (3.18 sq km), flood channels (9.42 sq km), and vegetation patches (69.17 sq km). The width of the flood plain varies between 1.4 (SE of Handia) and 8.4 km (near Mirjapur). The maximum (14.2 km) and minimum (1.8 km) valley margin width have noted ~ 63 km downstream of Allahabad and Varanasi, respectively. The distinctive feature of this stretch of the Ganga River is its partly confined valley fills (cratonic) nature between Chunar and Mirjapur and the remaining part is grouped under unconfined alluvial valley.

3.2.7 Varanasi to Munger

For the sake of clarity, the geomorphic map in this stretch has been presented into two parts, one from Varanasi to Madhubani (Figure. 8a) and then from Madhubani to Munger (Figure. 8b). The minimum width of floodplain in this stretch is 1.8 km downstream Varanasi, while the maximum width went up to 28 km near Ara. The minimum Valley margin width is 7 km d/s Varanasi, while the maximum Valley margin width increases to 36.1 km at the location 23 km d/s Buxar. Alluvial Islands are a significant geomorphic characteristic in this reach of Ganga river (Figure 8a, b). While the first island 30 km downstream of Buxar is only 3.0 km in width, 2 major islands of over 12 km. maximum width are present u/s and d/s Patna and there are 2 more islands further downstream -- between Barh-Mokama (5.5 km max. width) and upstream of Munger (2.0 km wide). Alluvial islands seem to gain prominence in width / area downstream of the confluence of Ghaghra and Gandak rivers from the North and Son river from the South, probably due to the contribution of a huge sediment load from the Himalayan terrain. Two major areas of meandering belts, one each on the northern and southern banks of Ganga river, d/s of Varanasi between Zamania and Buxar, have been identified. Another special stretch between Buxar and Ara (downstream) and confined only to the southern bank of river Ganga, is a zone of meander scrolls, meander scars and ox-bow lakes.

3.2.8 Munger to Farakka

Total along channel length of the studied area is about 330 km and the valley setting is semi-confined (Figure 9). The southern margin is controlled by basement rocks of the craton whereas the northern valley margin is unconfined and merges with/bound by the alluvium of Kosi and Mahananda river. Maximum floodplain width in the study stretch is about 23.3 km and minimum width 7.2 km. The sinuosity of the stretch has increased a little bit as compared to the immediately upstream stretch, but the river is braided all through the sector with many mid-channel bar or large islands, lateral bar, etc. The increase in sinuosity is plausibly related to irregular configuration of the basement block on the southern margin of the valley (e.g. Munger-Bhagalpur-Sahibganj stretch).

The major geomorphic characteristic of the river in this stretch is the braided-sinuous pattern, with numerous fine-grained sandy bars in channel (Fig. 9). These channels are extremely mobile and the active channel is seen to migrate more than a km within a year. Active floodplain is marked by abandoned meander and braided bars. Abandoned channel and bar accretion surfaces at places marked fine clayey fine-grained sediment. Levees, newly grown bars and many abandoned slough channels (flood channels) over braid bars are marked by dry sandy patches. Most of these abandoned bars (now part of the floodplain) and in channel large islands are now agricultural fields.

4. Endnote

The mapping of valley margin and geomorphic features in the active floodplain along the Ganga river shows significant diversity in terms of valley width and geomorphic features in different reaches of the river. These differences have important implications for water resource management and ecological restoration. The stretches with wide valleys and active floodplains could provide sites for creating artificial recharge sites keeping in view the present-day landuse. The channel-belt and floodplain features should provide important insights to the possible habitats for aquatic and land biota. These maps should be integrated with the present distribution of biodiversity along the river and the causal factors for their abundance/absence can be ascertained. In terms of hydrology, the geomorphic features such as the variety of bars are suggestive of river processes which would ultimately relate to the hydrological regime and would provide an important input for E-Flows assessment.

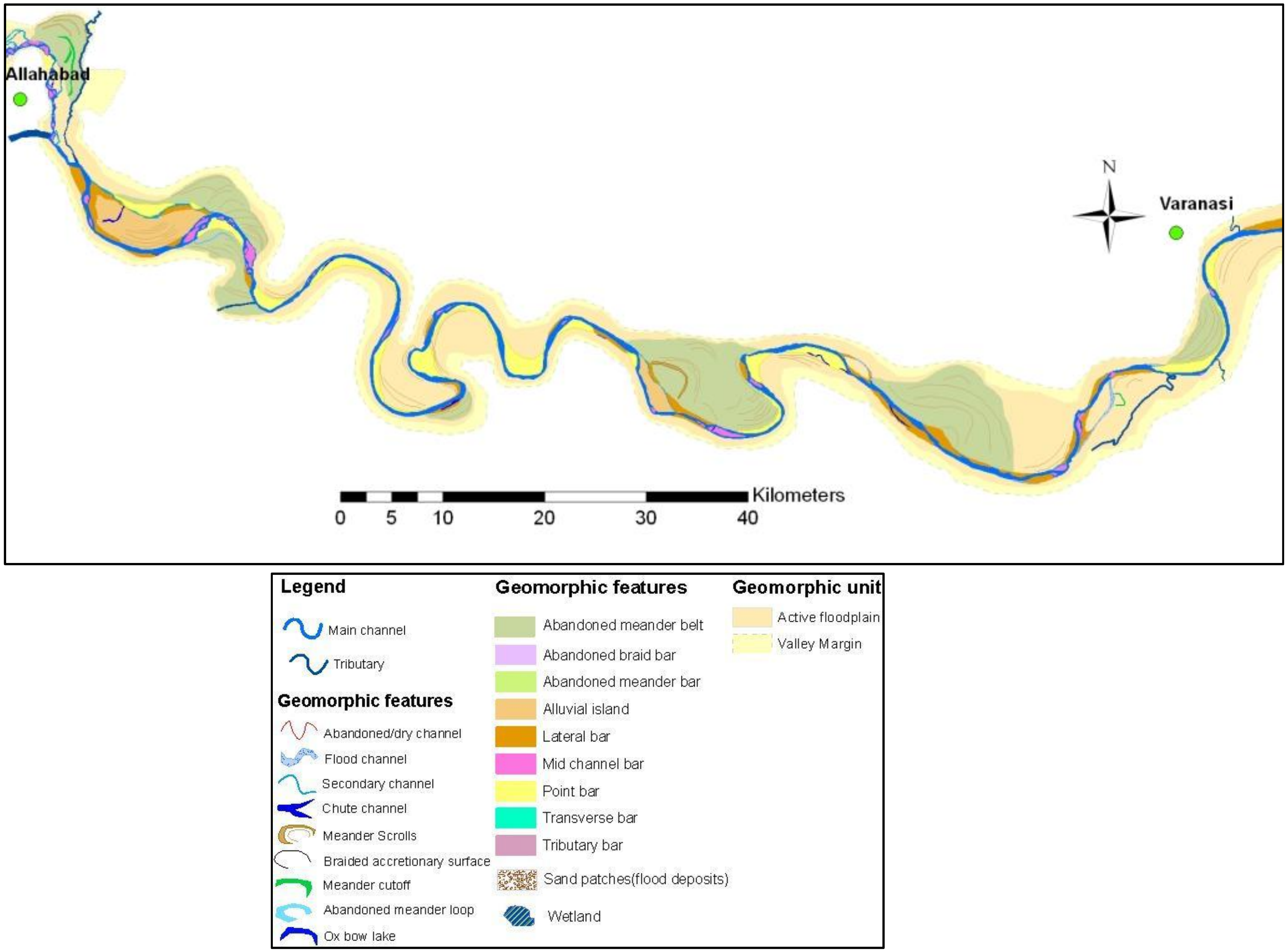


Figure 7: Geomorphic map of the Allahabad to Varanasi stretch

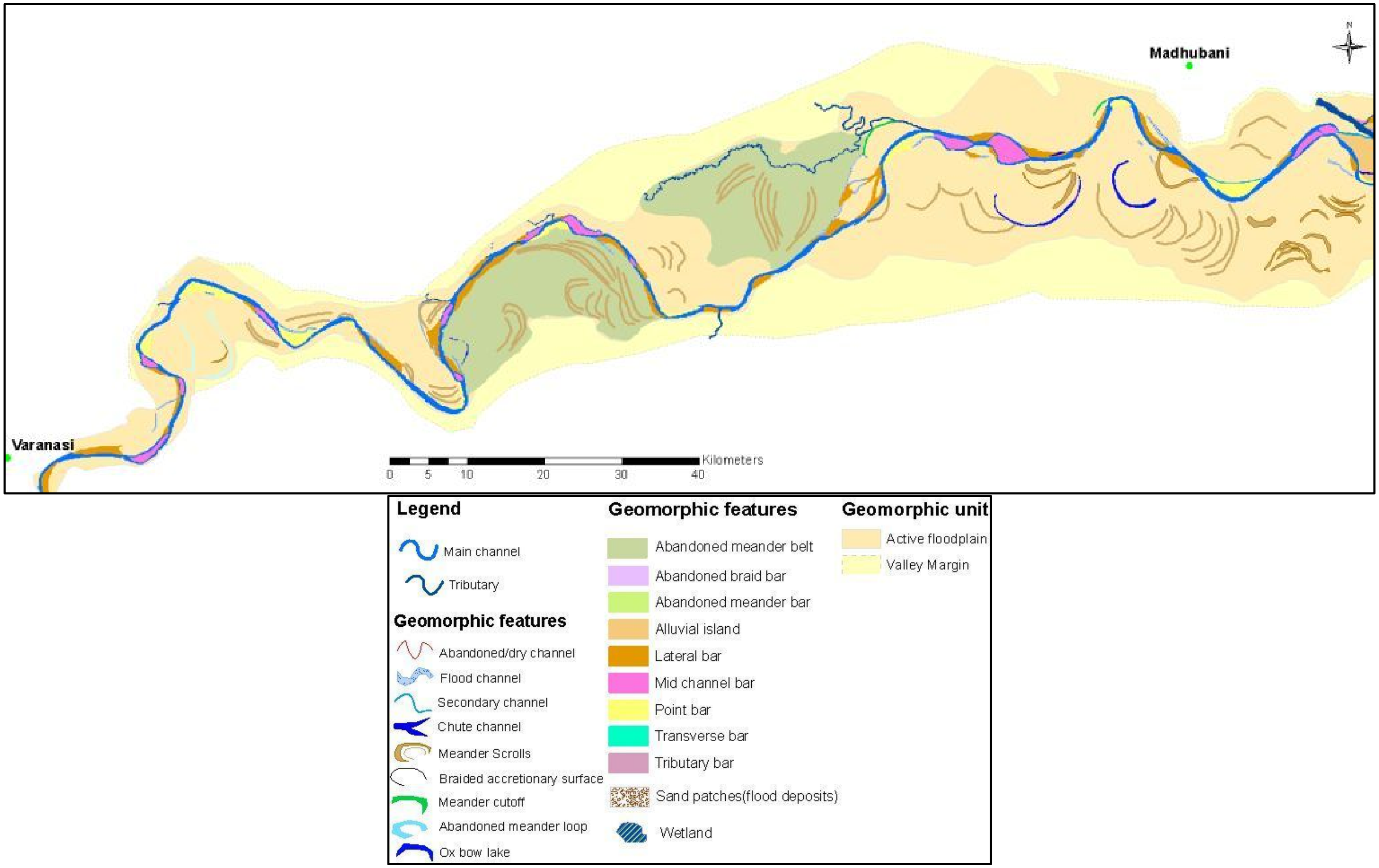


Figure 8 (a): Geomorphic map of the Varanasi to Madhubani stretch

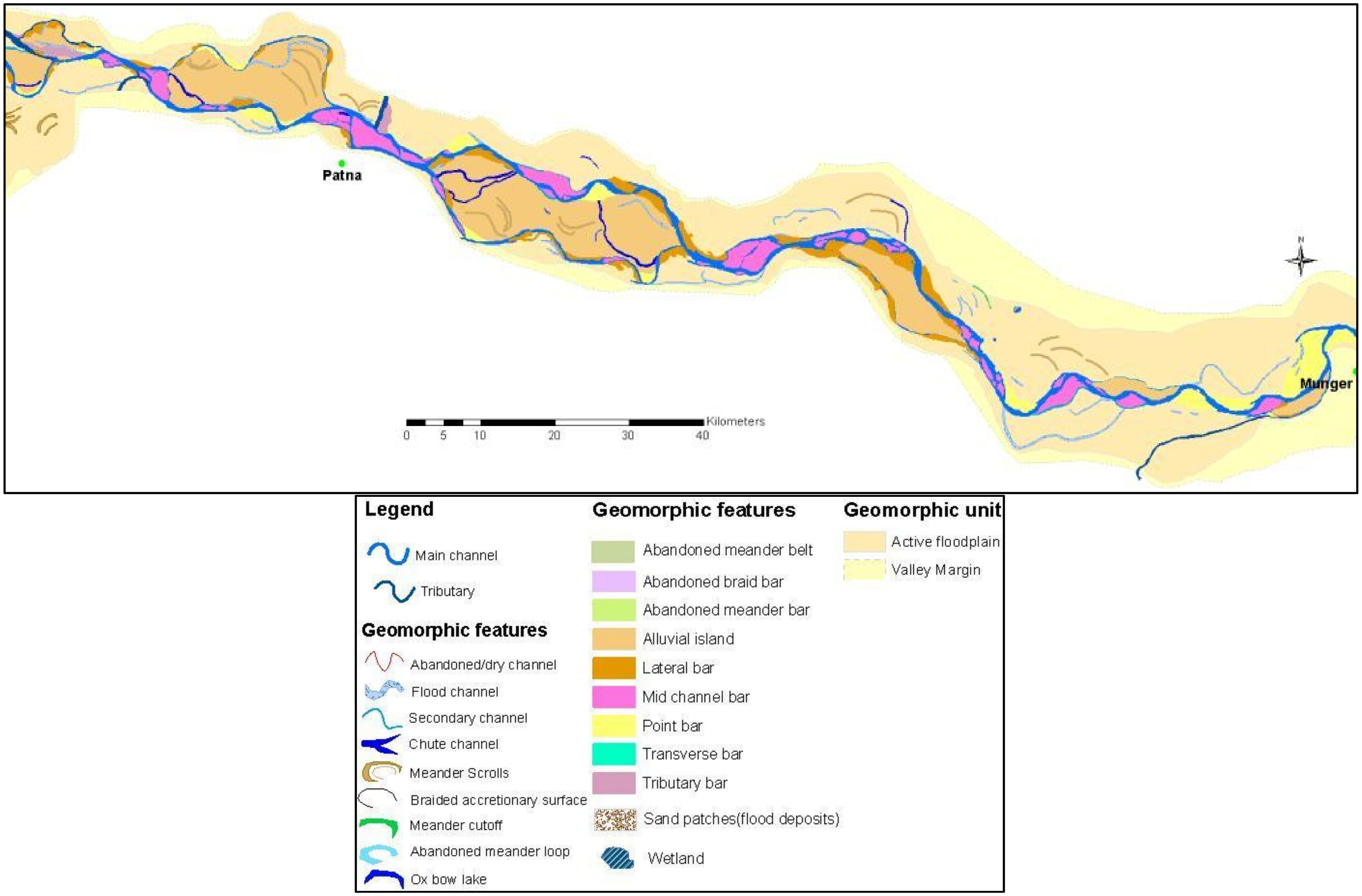


Figure 8 (b): Geomorphic map of the Madhubani to Munger stretch

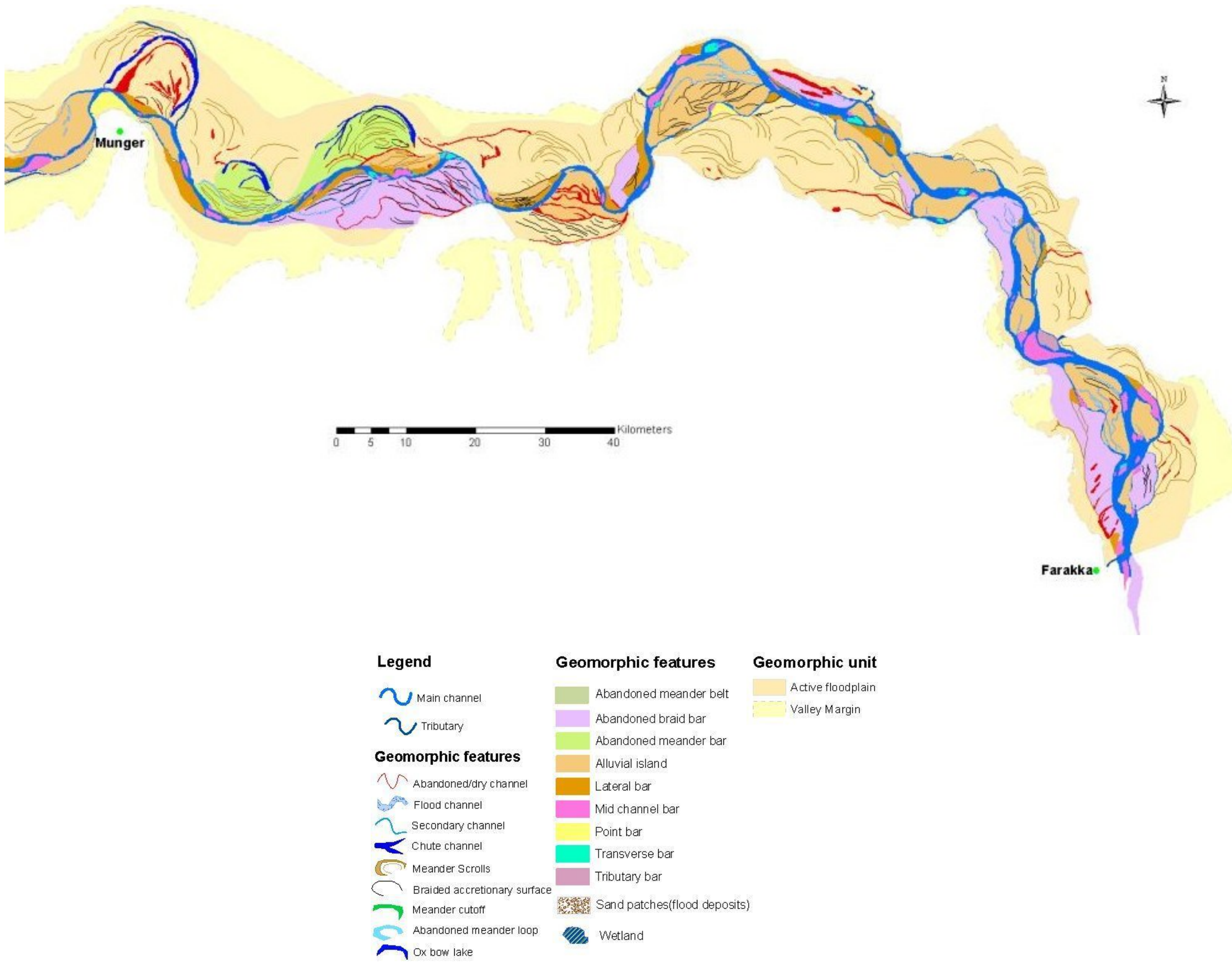


Figure 9: Geomorphic map of the Munger to Farakka stretch

Stream Power Distribution Pattern of the Ganga River and its Tributaries

GRBMP : Ganga River Basin Management Plan

by

Indian Institutes of Technology

IIT Bombay | IIT Delhi | IIT Guwahati | IIT Kanpur | IIT Kharagpur | IIT Madras | IIT Roorkee

Preface

In exercise of the powers conferred by sub-sections (1) and (3) of Section 3 of the Environment (Protection) Act, 1986 (29 of 1986), the Central Government has constituted National Ganga River Basin Authority (NGRBA) as a planning, financing, monitoring and coordinating authority for strengthening the collective efforts of the Central and State Government for effective abatement of pollution and conservation of the river Ganga. One of the important functions of the NGRBA is to prepare and implement a Ganga River Basin Management Plan (GRBMP).

A Consortium of 7 Indian Institute of Technology (IIT) has been given the responsibility of preparing Ganga River Basin Management Plan (GRBMP) by the Ministry of Environment and Forests (MoEF), GOI, New Delhi. Memorandum of Agreement (MoA) has been signed between 7 IITs (Bombay, Delhi, Guwahati, Kanpur, Kharagpur, Madras and Roorkee) and MoEF for this purpose on July 6, 2010.

This report is one of the many reports prepared by IITs to describe the strategy, information, methodology, analysis and suggestions and recommendations in developing Ganga River Basin Management Plan (GRB EMP). The overall Frame Work for documentation of GRBMP and Indexing of Reports is presented on the inside cover page.

There are two aspects to the development of GRBMP. Dedicated people spent hours discussing concerns, issues and potential solutions to problems. This dedication leads to the preparation of reports that hope to articulate the outcome of the dialog in a way that is useful. Many people contributed to the preparation of this report directly or indirectly. This report is therefore truly a collective effort that reflects the cooperation of many, particularly those who are members of the IIT Team. Lists of persons who are members of the concerned thematic groups and those who have taken lead in preparing this report are given on the reverse side.

Dr Vinod Tare
Professor and Coordinator
Development of GRBMP
IIT Kanpur

The Team

1. Bimlesh Kumar, IIT Guwahati bimk@iitg.ernet.in
2. J K Pati, Allahabad University jkpati@gmail.com
3. Kirteshwar Prasad, Patna University kriteshwar.geopat@gmail.com
4. Parthasarthi Ghosh, ISI Kolkata pghosh@isical.ac.in
5. Rajiv Sinha, IIT Kanpur rsinha@iitk.ac.in
6. Ramesh Shukla, Patna University rshuklapat@gmail.com
7. Kalyan Rudra, WBPCB rudra.kalyan@gmail.com
8. S K Tandon, University of Delhi sktand@rediffmail.com
9. Saumitra Mukherjee, JNU Delhi saumitra@mail.jnu.ac.in
10. Shashank Shekhar, University of Delhi shashankshekhar01@gmail.com
11. Soumendra Nath Sarkar, ISI Kolkata soumendra@isical.ac.in
12. Tapan Chakarborty, ISI Kolkata tapan@isical.ac.in
13. Vikrant Jain, University of Delhi vjain@geology.du.ac.in

Lead Author

1. Rajiv Sinha, IIT Kanpur

Contents

List of Figures

List of Tables

1. Introduction

Meaningful river management strategies must build on explanation of what a river looks like, how it behaves, and how it is likely to adjust in response to changing linkages of physical processes within a catchment. These aspects can be effectively explained through process based understanding using the distribution of stream power along river courses.
Channel morphology at any point is controlled by the dominance of aggradation or degradation processes, which in turn is governed by: (1) energy of flow and (2) sediment load (Bull, 1979; Graf, 1987, Church, 1992; Lawler, 1992; Montgomery et al., 1996; Leece, 1997; Knighton, 1999; Blum and Tornqvist, 2000; Jain et al., 2006, 2008).

The rate of flow energy expenditure in a river can be expressed as stream power (Ω), as defined by the rate of liberation of kinetic energy from potential energy (Bagnold, 1966). Stream power (Ω) is expressed as (Bagnold, 1966) –

$$\Omega = \gamma . Q . s \qquad \text{... (1)}$$

Whereγ -unit weight of water, Q- discharge, s- energy slope which is equivalent to the water slope.

Variation in stream power defines changes in the amount of energy available to do work on the bed of the stream. Thus, the energy distribution in a river system is a major control on channel morphological variations. Hence, stream power distribution pattern for the Ganga river and its major tributaries are derived.

2. Data used

Discharge and slope are two important components of stream power. Stream power distribution profile was derived using the profiles of discharge and slope. Discharge analysis was carried out using peak discharge data recorded at various gauging sites, which was obtained from Centre Water Commission (CWC). Channel slope was estimated from longitudinal profile, which was derived from Digital Elevation Model (DEM).

The Shuttle Radar Topography Mission(SRTM) DEM data of 90m horizontal (3 arc second) resolution was used for the analysis**.** The SRTM digital elevation data, produced by NASA provides a major advance in the accessibility of elevation data for large portions of the tropics and other areas of the developing world.It provides earth's surface elevation with respect to WGS84 datum. The data was downloaded from the cigar website (http://seamless.usgs.gov/ or http://srtm.csi.cgiar.org/).

The DEM data was analyzed using ArcGIS software, whereas hydrological analysis was carried out in Excel. Fig. 1 shows raw DEM of the Ganga river basin.

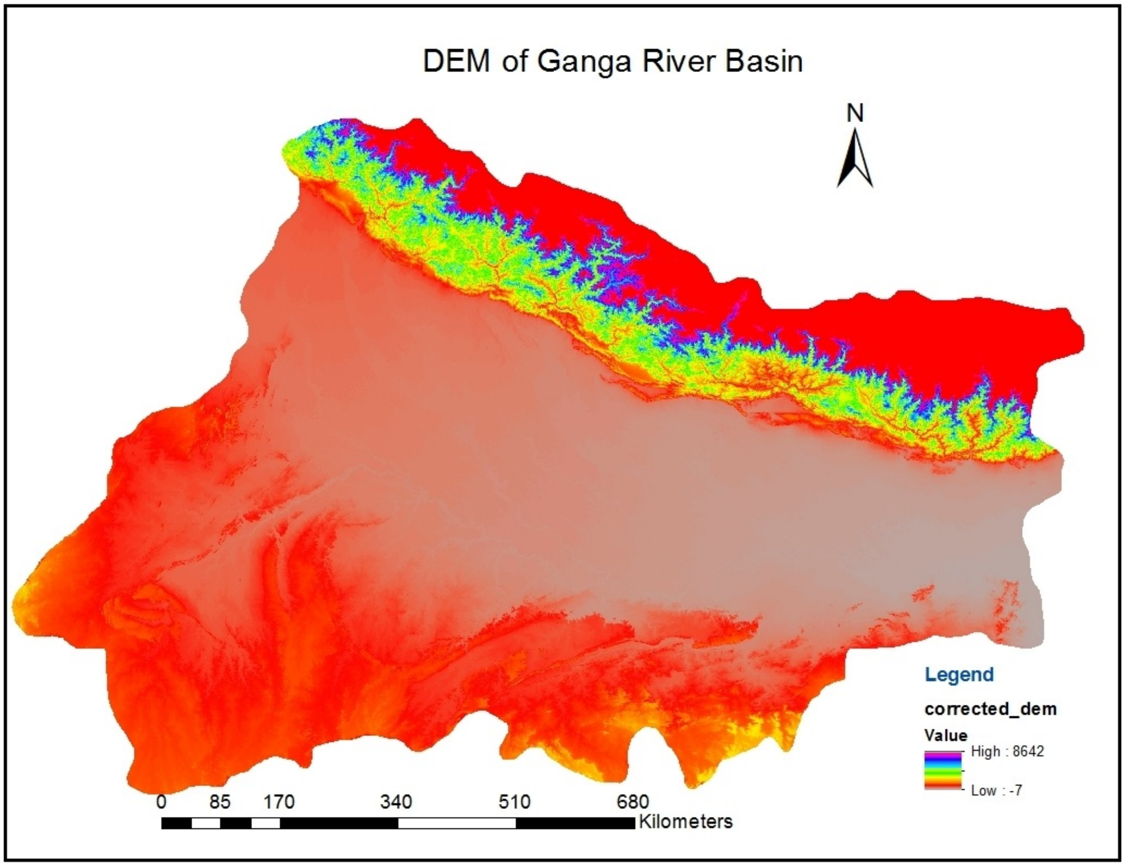


Figure 1: Raw DEM (SRTM) of Ganga River Basin with Spatial Resolution of 90m

3. Methodology

Calculation of stream power involved two main steps, which includes DEM analysis and hydrological analysis. The DEM data was processed to generate the drainage network of the Ganga river and to derive long profile. The resultant long profile was processed though the curve smoothing method and superimposed over the discharge profile to generate stream power distribution pattern (Jain et al., 2006).

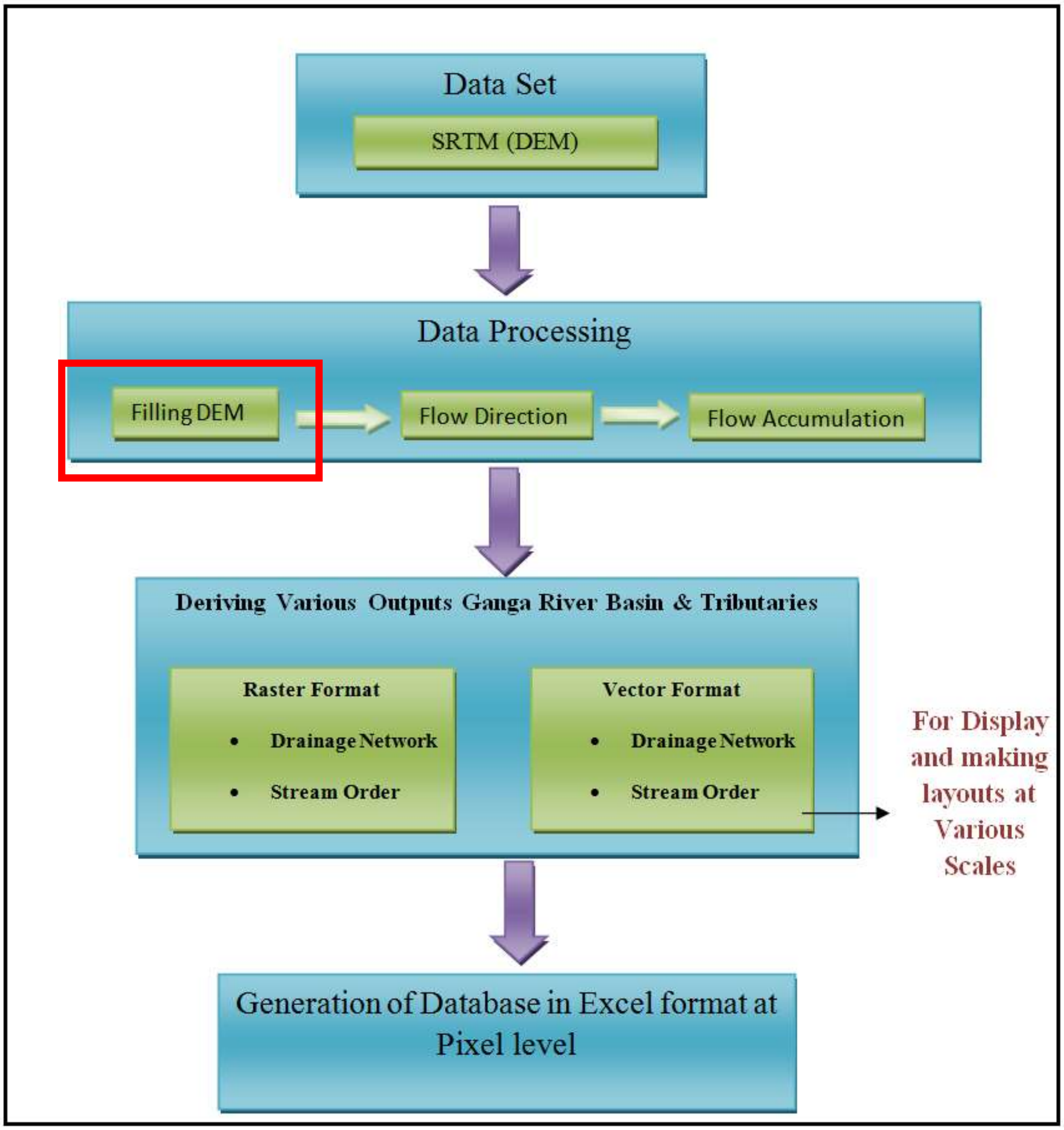


Figure 2: Flow Diagram Showing the various Steps of Methodology

3.1 Derivation of Drainage Network from DEM Data

A summary of methodology for DEM analysis is provided in fig. 2. Initially, the data was hydrologically corrected through sink filling. A **filled DEM** or elevation raster is void of depressions. A depression is a cell in an elevation raster that are surrounded in all sides by pixels having higher elevation values, and thus represents an area of internal drainage. If the cell has at least one cell adjacent to it, at a higher elevation, and no cells adjacent to it at a lower elevation then it is said to be in flow sink. Most sinks in Digital Elevation Models (DEMs) result from low accuracy, low resolution and interpolation errors in DEM creation, which can cause the DEM to contain some cells characterized by higher elevation of the neighboring pixels. Hence sinks have to be removed. It is important to have a depression less DEM for all subsequent hydrological analyses. Areas of internal drainage can cause problems later in the watershed delineation process.(Tarboton et al., 1991).Fig. 3shows filled DEM of Ganga river basin.

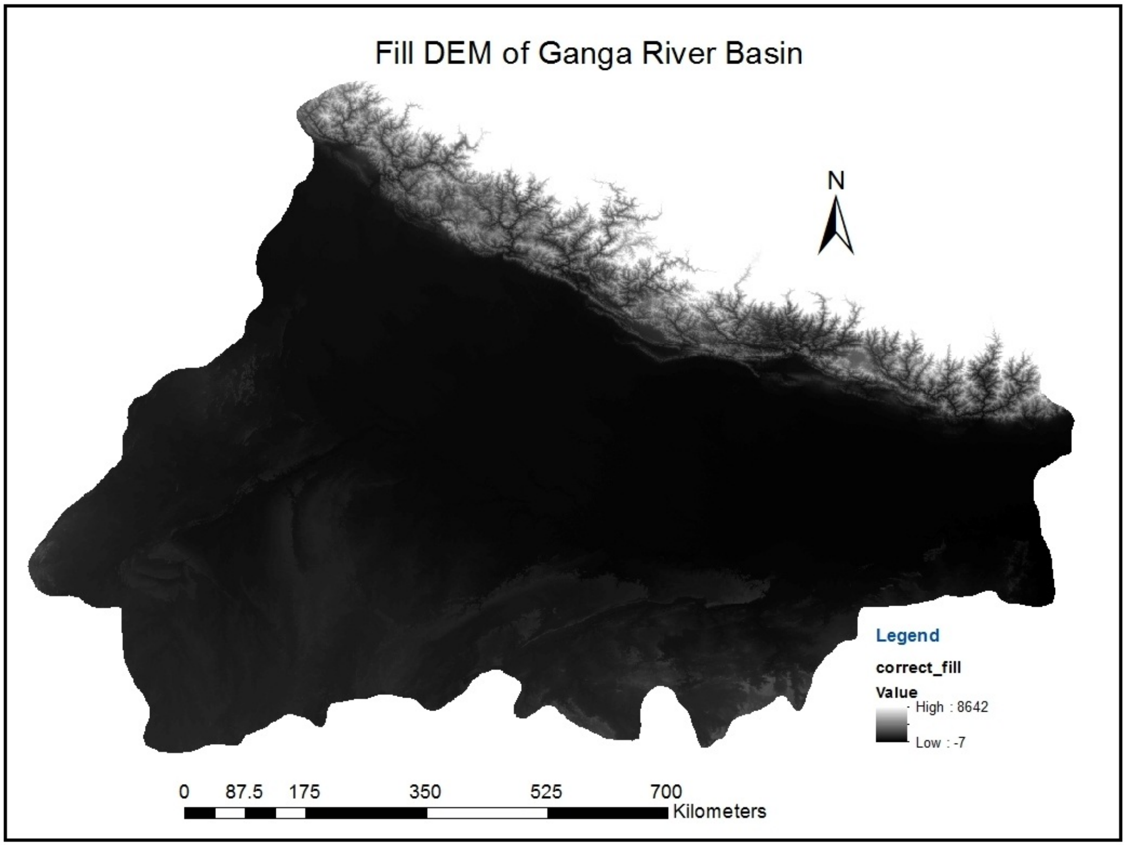


Figure 3: Filled Dem Generated from Raw Dem

Sink filled DEM was used to generate a **flow direction** raster map, which shows the direction of water flow out of each cell of a filled elevation raster. The basic principle for assigning flow directions is given as: from a cell, water flows to the neighboring cell that has the highest positive distance-weighted drop. A widely used method for deriving flow direction is the D8 method. The D8 method assigns a cell's flow direction to the one of its eight surrounding cells that has the steepest distance-weighted gradient. The method does not allow flow to be distributed to multiple cells. The D8 method produces good result in zones of convergent flows and along well defined valleys (Freeman 1991). For each cell C[i, j] in the DEM, the following steps are performed:

A. Calculation of distance weighted drop to neighboring cells: The distance-weighted drop to a neighboring cell is defined as((d). The distance (d) will depend on the position of cells in the DEM. For cells which are horizontally or vertically adjacent to C, d =1, while for cells which are diagonally adjacent to C, d = √ 2.

B.Flow Direction (FD) was estimated through slope comparison between neighbouring pixels.The Flow Direction (FD) value of cellis define as –

(Flow DirectionFD)[i, j]= [Value of the cell C(i, j) – Value of the neighboring cell]/[Distance to the neighboring cell]

On the basis of values from all neighbouring pixels, the cell was given the direction code of the neighboring cell with the largest positive weighted drop.

A special case is when the largest positive weighted drop occurs in more than one direction. In this case, the cell FD [i, j] is given the sum of the direction codes of all the directions in which the largest positive weighted drop occurs. The resulting code is called a combined direction code.

A. If the cell is a no data cell, the Flow direction value will be set as $-(1*10^{-4})$ (nodata=it is not filled due to insufficient neighbor information)

After the above steps, some cells in FD have a combined direction code. These are the cells for which the largest positive weighted drop occurs in more than one direction. These cells are assigned a single direction code using a lookup table(Greenlee et al., 1987).

The distance is calculated between cell centers. Therefore, if the cell size is 1, the distance between two orthogonal cells is 1, and the distance between two diagonal cells is 1.414 (the square root of 2). If the maximum descent to several cells is the same, the neighborhood is enlarged until the steepest descent is found.

When a direction of steepest descent is found, the output cell is coded with the value representing that direction.

If all neighbors are higher than the processing cell, it will be considered noise, be filled to the lowest value of its neighbors, and have a flow direction toward this cell. However, if a one-cell sink is next to the physical edge of the raster or has at least one NoData cell as a neighbor, it is not filled due to insufficient neighbor information. To be considered a true one-cell sink, all neighbor information must be present.

If two cells flow to each other, they are sinks and have an undefined flow direction. This method of deriving flow direction from a digital elevation model (DEM) is presented in Jenson and Domingue (1988).

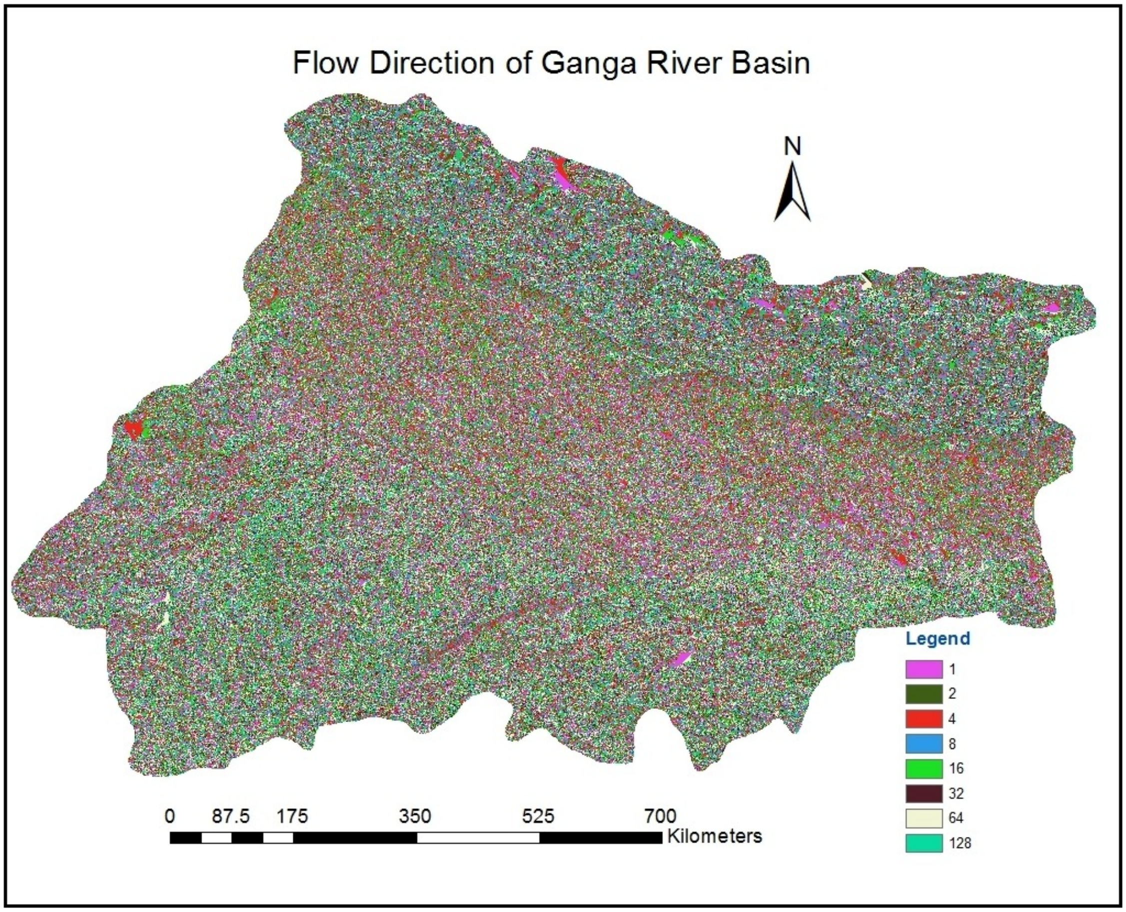


Figure 4: Flow Direction map of the Ganga river basin

Flow direction map was used to derive a flow accumulation map. A **flow accumulation** raster tabulates the number of cells that will flow to any particular given cell. The flow accumulation value of a cell is the sum of the flow accumulation values of the neighboring cells which flow into it. A flow accumulation raster records how many upstream cells will contribute to the drainage. The flow accumulation layer has a value for each cell; that value represents the number of cells upstream from that cell that can contribute to it. Cells with higher values will tend to be located in drainage channels rather than on hillsides or ridges.Flow accumulations are important because they allow us to locate cells with high cumulative flow(Jenson and Domingue, 1988).The flow accumulation map of the Ganga river basin is shown in Fig. 5.

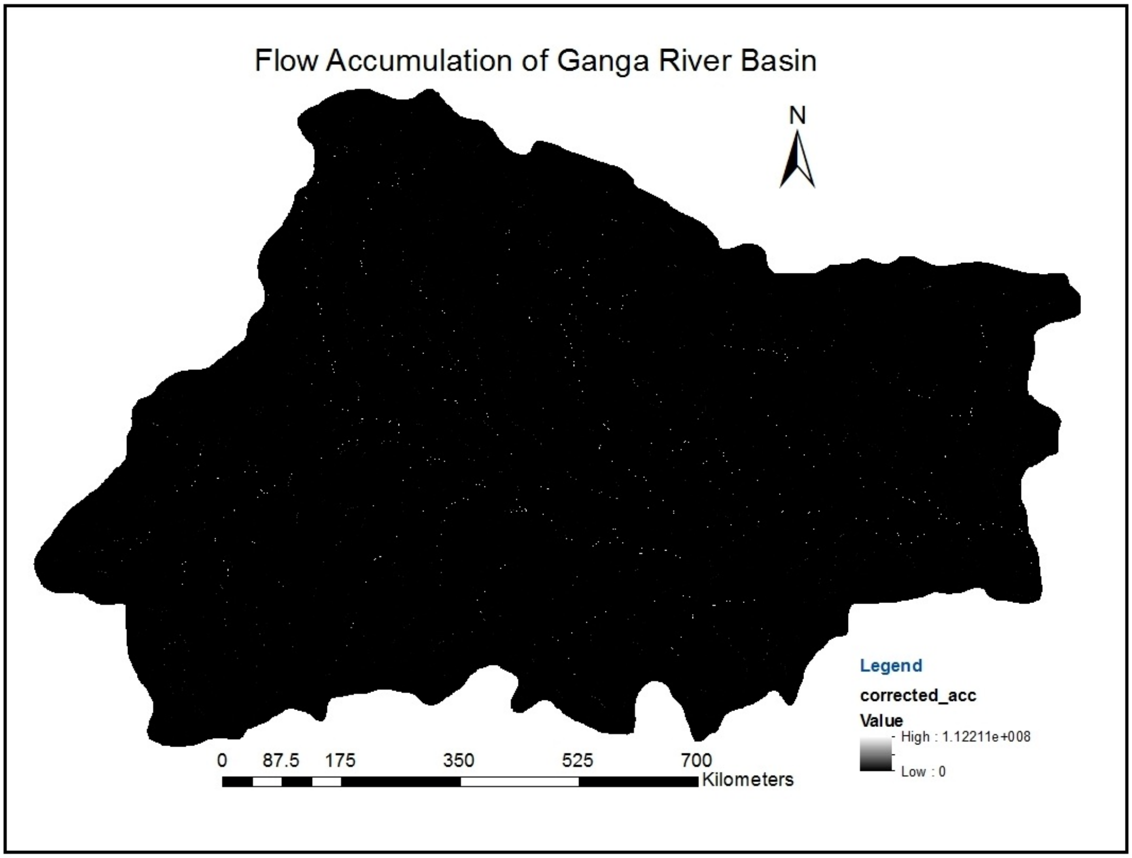


Figure 5: Flow Accumulation Map of the Ganga River Basin

Flow accumulation map was utilised for generation of stream network of the Ganga river basin. Further, stream ordering system after Strahler (1957) was applied for the whole drainage map. Stream ordering is a method of assigning a numeric order to links in a stream network. It helps in identifying and classifying types of streams based on their numbers of tributaries. Some hydro-geomorphic characteristics of streams can be inferred by simply knowing their order.

For example, first-order streams are dominated by overland flow of water; they have no upstream concentrated flow. Because of this, they are most susceptible to non-point source pollution problems and can derive more benefit from wide riparian buffers than other areas of the watershed. The higher order streams are larger channels and are affected by the processes occurring in the 1st order streams.

The drainage map of the Ganga river basin was classified on the basis of stream ordering method after Strahler (1957). According to the Strahler method, the stream order increases when streams of the same order intersect. Therefore, the intersection of two first-order links will create a second-order link, the intersection of two second-order links will create a third-order link, and so on. The intersection of two links of different orders, however, will not result in an increase in order. For example, the intersection of a first-order and second-order link will not create a third-order link but will retain the order of the highest ordered link.

The Strahler method is the most common stream ordering method. However, because this method only increases in order at intersections of the same order, it does not account for all links and can be sensitive to the addition or removal of links. (Tarboton et al., 1991).Fig. 6shows stream order of the Ganga river.

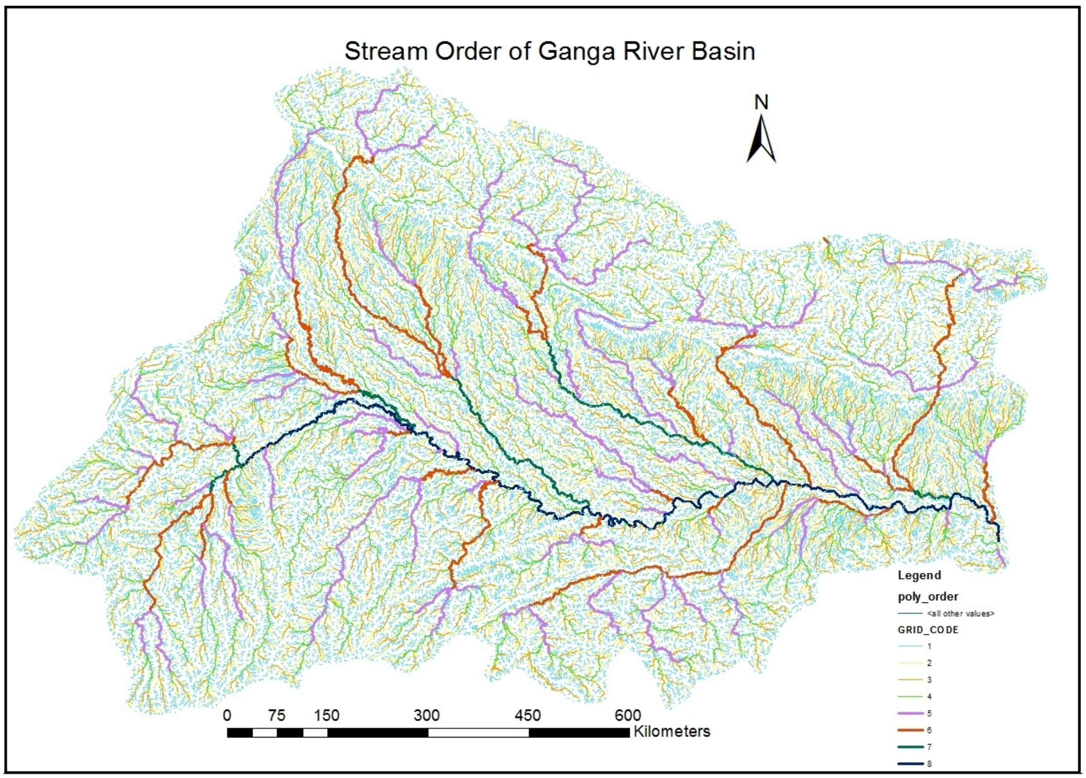


Figure 6: Stream Ordering Structure of the Ganga River Basin

3.2 Generation of Long Profile for all Streams

The long profile was derived through defining the drainage line from source using 'cost path' analysis, which determines the least-cost path from a destination point to a source. The least-cost path travels from the destination to the source. This path is one cell wide, travels from the destination to the source. When applying the tool to a river network example, the resulting path is the easiest route for river from destination to source. Figure 7 Shows path of the main Ganga River channel, for which the long profile data was extracted. The long profile data was extracted along the defined path of the Ganga River channel through export of the x, y and z coordinates of each pixel of the drainage line.

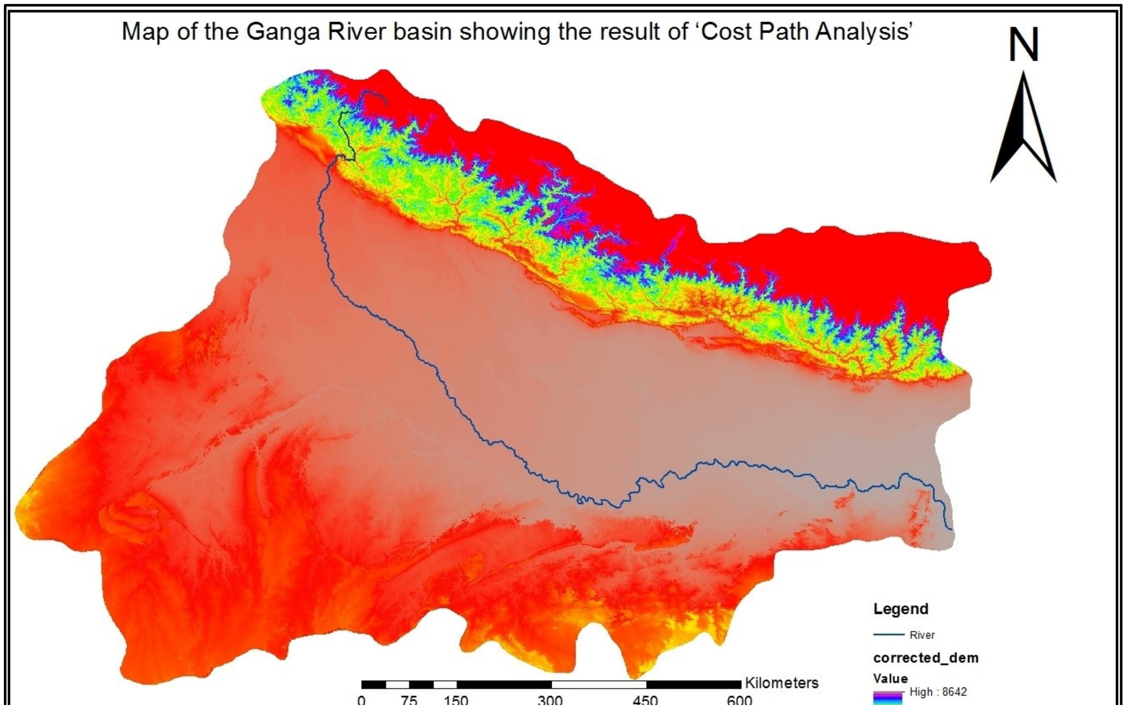


Figure 7: Map of the Ganga River Basin Showing the Result of 'Cost Path Analysis'

Above all, there are few issues prevailing with DEM such as artifacts and depressions apart that DEM consumes lots of processing time and resources while dealing with such artifacts and depression. As presence of artifacts creates secondary sinks which generates complications and may shift the hydrological features from the actual ground. These DTM derived artifacts and depression errors, influence river network. Thus this paper describes the technique attempting to address / resolve such problems with special focus on high resolution DTM.

Generally artifacts are common in urban centres, which obstruct the water flow in digital data. To overcome this, graphic polyline is drawn over identified artifacts taking care to place the vertices of the polyline on pixels of lower elevation values. Verification is done through Google Earth and other high resolution remote sensing images. The long profile was extracted along the channel line after its verification with the digitized channel map using Landsat data.

The extracted long profile was used for slope estimation. Long profile data includes height and distances for each pixel along the all major river channels. The long profile data was also processes to remove the kinks. At the first step, the anomalous peaks in the long profile were identified and replaced by the average of 30 preceding points to obtain smooth long profile. This step has suppressed the kink and long profile has been smoothen. In the case of large kinks the smoothening process has been repeated on the long profile data. The channel slope was estimated through this smooth long profile. The Slope was estimated for each pixel by fitting a 2 km Best Fit Line at adjacent upstream pixels.

3.3 Hydrological Analysis:

Hydrological characteristics of the Ganga river system was analysed through return period analysis using the peak discharge data at different gauging stations.The hydrological data was obtained from Centre Water Commission (CWC), government of India. The flood frequency analysis was carried out using Log Pearson (III) distribution method. This statistical method of frequency analysis is the most extensively used procedure and have been reported as the base method by USA federal interagency group (Benson, 1968) for estimating flood frequency. Log Pearson distribution was hence used to estimate Return Period flood for all the hydrological stations. The stream power distribution pattern was derived for a return period flood event which was closer to its bankfull capacity. Application of return period flood event in the stream power model will not be affected by the spatial variability in bankfull discharge. As the rivers of Western Ganga Plain (WGP) are incised in comparison to the aggrading rivers of East Ganga Plains (EGP), the 10 years return period discharge was used in the stream power analysis of the WGP rivers while 2 years return period discharge was used for the EGP river (after Sinha and Jain, 1998). The hydrological analysis was focussed on the main Ganga River andits higher order tributaries.

Catchment area-discharge relationship was derived separately for the Western Ganga Plains (WGP) and Eastern Ganga Plains (EGP) using the above mentioned discharge flood characteristics, because they are very distinct in term of hydro-geomorphic characteristics (Sinha et al., 2005). The following equations were got for WGP and EGP rivers respectively after fitting a power law relationship between discharge and basin area used –

$$Q = 361A^{0.72} \quad \text{(WGP)}, \quad R2 = 0.58$$

$$Q = 2.78\ A^{0.71} \quad \text{(EGP)}, \quad R2 = 0.65$$

Due to significant anthropogenic disturbance to these river system, the discharge area relationship is not showing good correlation. However, in the condition of available data, the following equations were used to replace the discharge by catchment area in the calculation of stream power. In general, the stream power variability is mostly affected by slope variability (Knighton, 1998; Jain et al., 2006). The data was combined with long profile based slope estimation to get downstream stream power distribution patternfollowing the methodology after Jain et al. (2006). This data will provide a coarse resolution distribution of stream powerfor the large Ganga River basin.

4. Results

4.1 Drainage network of the Ganga River Basin

The derived drainage network from DEM data was compared and validated with the geomorphic maps digitised from the Landsat data. Figures 8(a) to Fig. 8(d) provide such comparison for the Ganga River and its major tributaries. The figures shows that DEM derived drainage line passes through the digitised channel belt area, and it confirms that the DEM derived channel network data is reliable and can be used for extraction of long profile from DEM dataset.

In the alluvial terrain, the main channel position never remains same in each year, because it will keep on shifting its position within the channel belt. However, channel belt of the large rivers remains stable at 10^1-10^2 years-time scale. As the DEM derived data closely superimpose over the channel belt area, it will provide average channel position of a stable channel belt. The elevation data of long profile will represent the elevation of thalweg points on the basis of DEM data, i.e. average thalweg position in the channel belt. Verification of the drainage network was followed by derivation of morphometric analysis, which were also used in the basin area-discharge relationship. Morphometric characteristics derived from this drainage network analysis are presented in the Table 1.

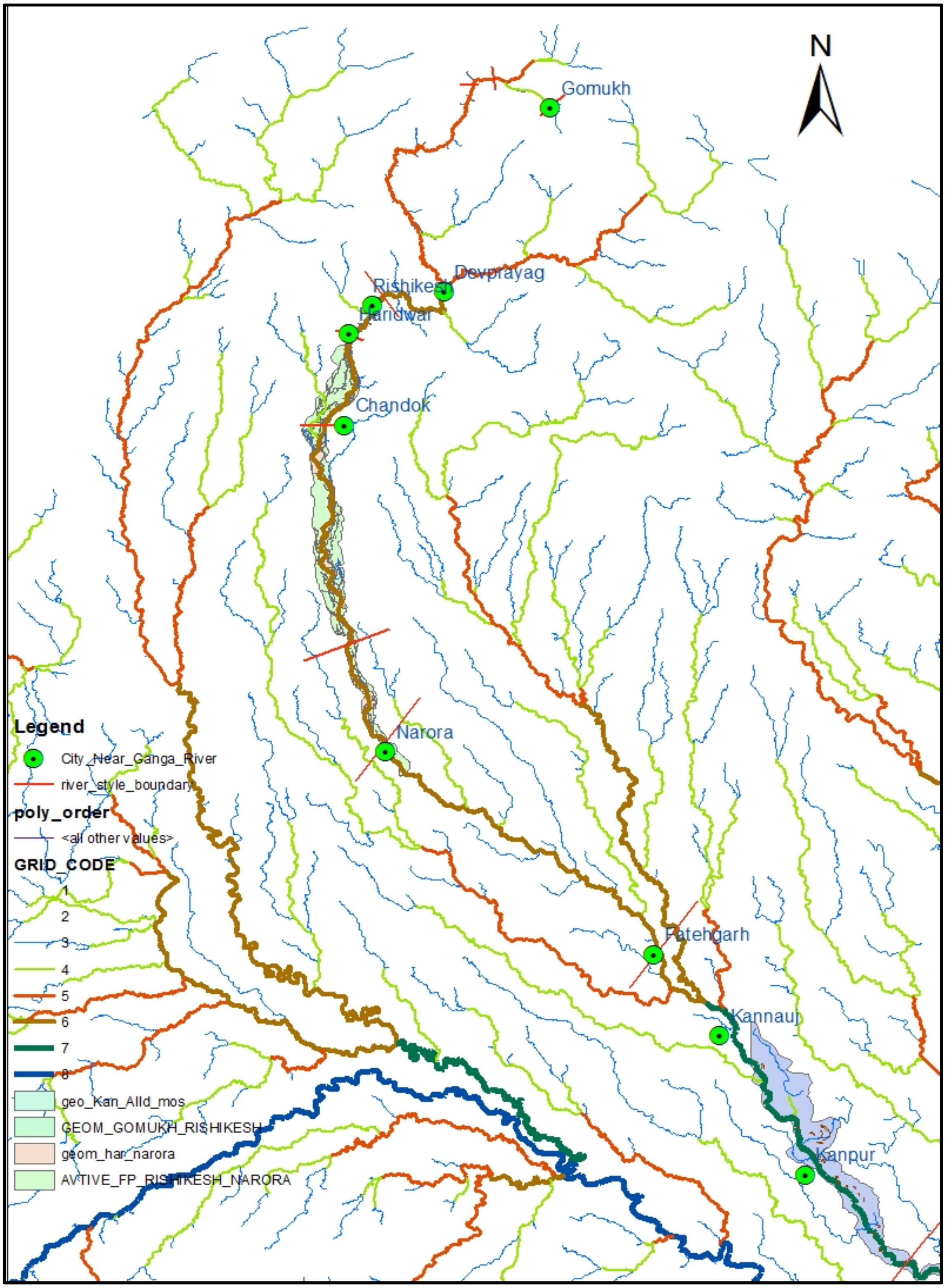


Figure 8(a): Comparison of the Drainage Map of the Ganga River with the Digitized Geomorphic Map from Landsat Data Between Reach of Gomukh to Kanpur. Polygons Defines the Digitized Geomorphic Map of the Channel Area.

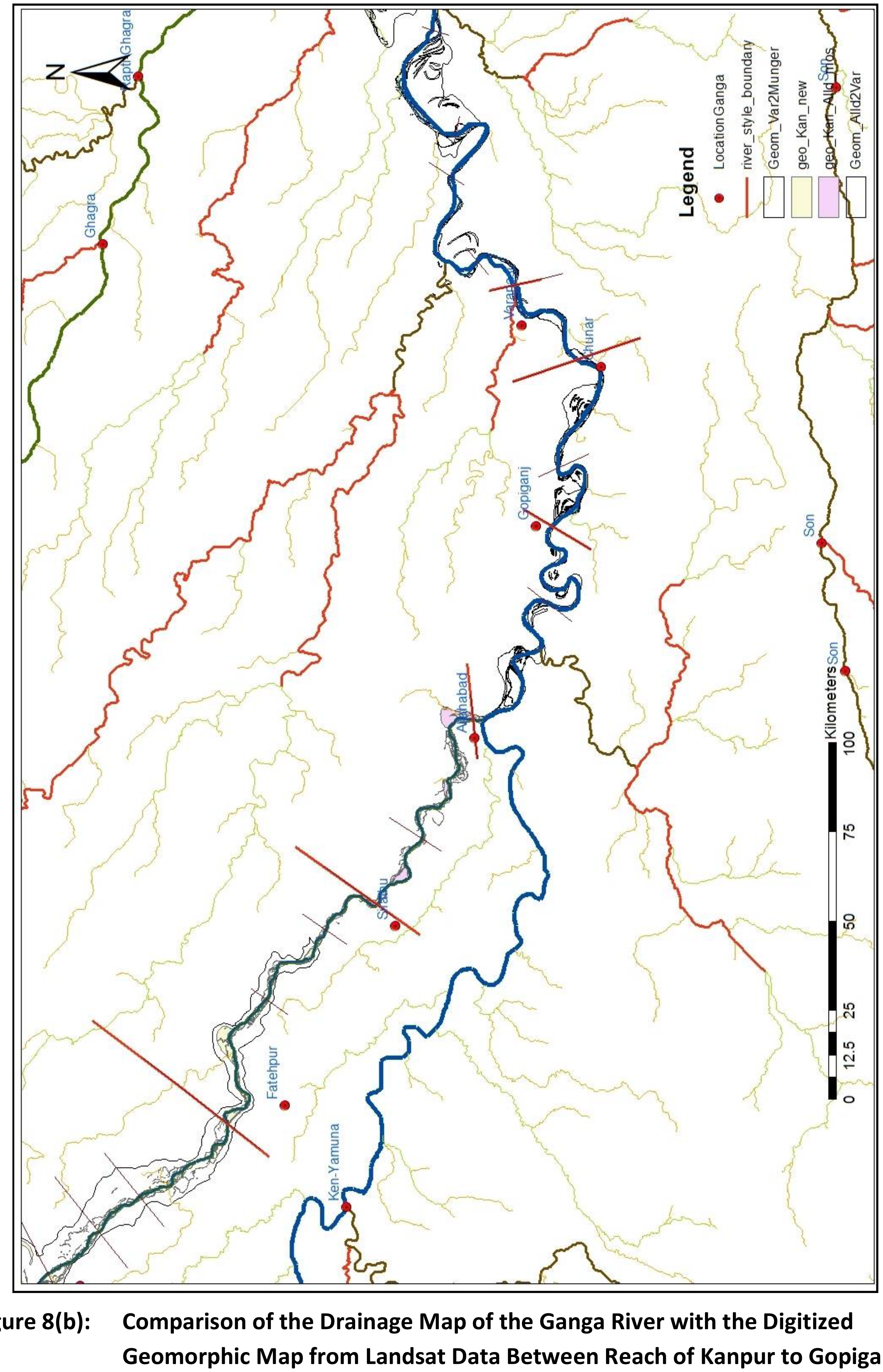


Figure 8(b): Comparison of the Drainage Map of the Ganga River with the Digitized Geomorphic Map from Landsat Data Between Reach of Kanpur to Gopiganj

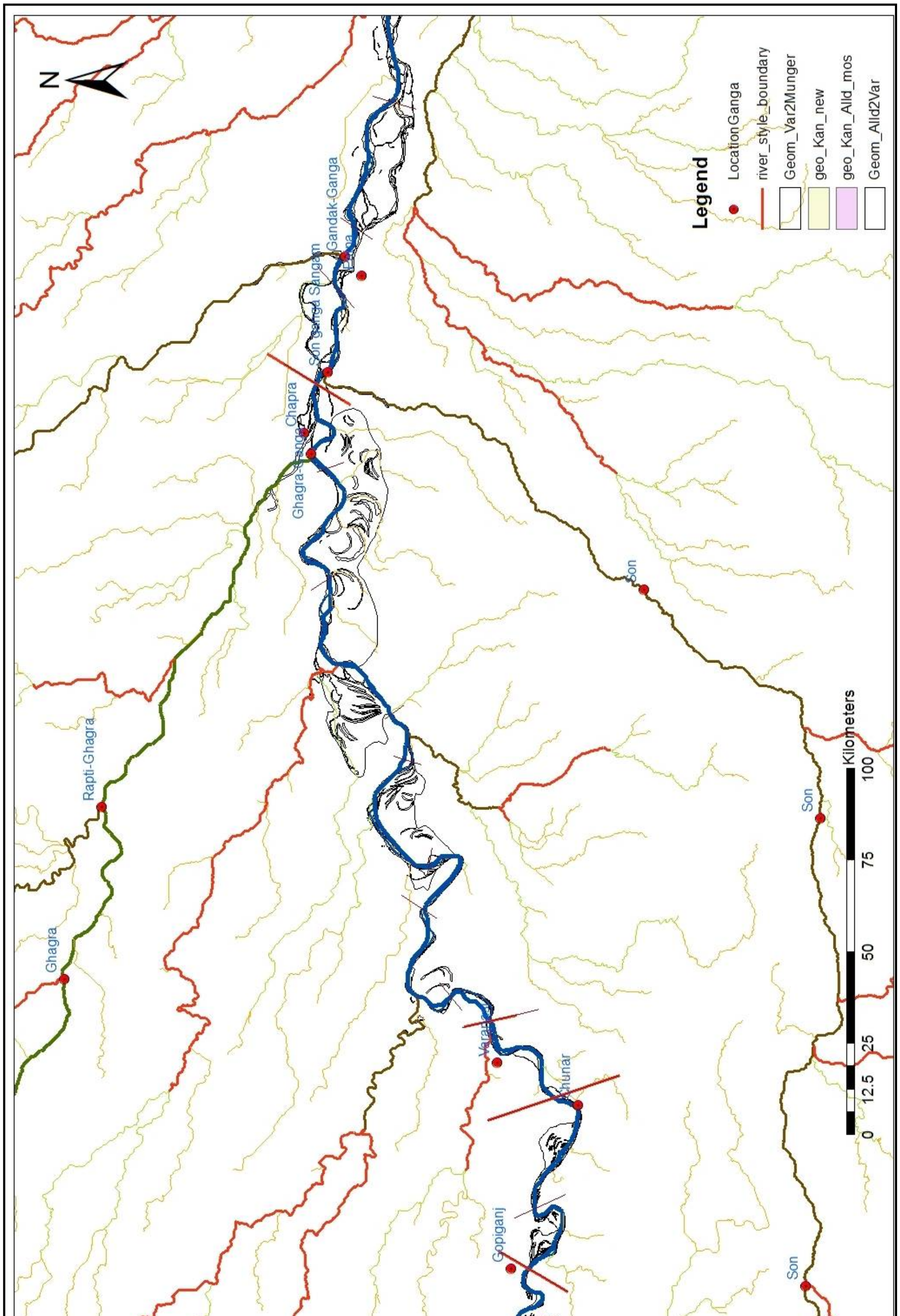


Figure 8(c): Comparison of the Drainage Map of the Ganga River with the Digitized Geomorphic Map from Landsat Data Between Reach of Gopiganj to Patna

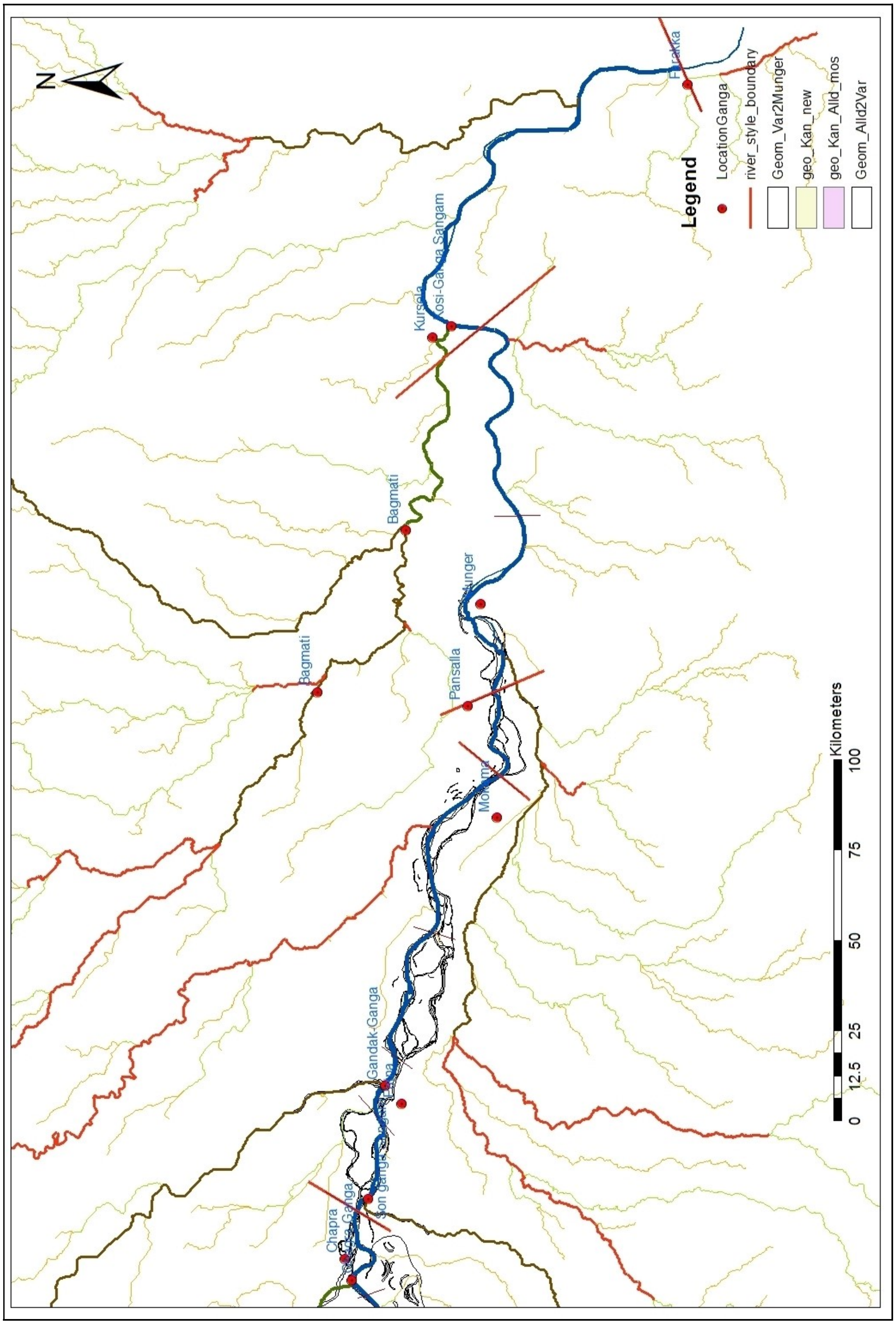


Figure 8(d): Comparison of the Drainage Map of the Ganga River with the Digitized Geomorphic Map from Landsat Data Between Reach of Patna to Farakka

Table 1: Drainage Network and Basin Area of Tributaries of the Ganga River Basin

Confluence Point	Tributaries	Channel Length (Km)	Basin Area (Km Sq.)	Stream Order
1	Alaknanda	190	10381	5
	Bhagirathi	208	7389	5
2	Yamuna	1054.3	203492	7
	Chambal	1009	141386	8
3	Ganga	1151	93322	7
	Yamuna	1506	331061	8
4	Ganga	1606	507553	8
	Ghaghara	1173	131893	7
5	Ganga	1673	709199	8
	Gandak	769	42464	6
6	Ganga	1953	801528	8
	Kosi	763	88680	7
7	Ganga	783	51566	6
	Ramganga	598	22470	6

4.2 Distribution pattern of stream power and its components

Distribution pattern of stream power for each river is shown with distribution of its individual parameters namely discharge and channel slope. The downstream variability in different parameters of stream power has been shown by two figures for each river. The first figure provides the pattern of long profile derived from DEM, corrected long profile after smoothening process and distribution of 2 km average slope derived from the smooth long profile. The second figure presents the distribution pattern of stream power with long profile shape and pattern of downstream increase in the catchment area. The catchment area plot represents discharge variability, which is derived using the discharge-area relationship. The steps like features in the catchment area plot are reflection of tributary contribution at the given points. Downstream variability in the stream power distribution pattern has been discussed below. The major peaks in the stream power have been sequentially numbered from higher magnitude to lower magnitude peaks.

The Ganga Riverhas a very well developed concave shape long profile, though local scale slope variability is prominent (Fig. 9). Stream power distribution pattern is highly variable with larger peaks in the upstream area (Fig. 10). First four peaks lies in the Higher Himalaya while fifth peak lies close to mountain front. Stream power variability is higher in the alluvial plains area, which will be significant in explaining reach scale variability in channel processes along the alluvial reach.

Yamuna river is also characterised by concave shape long profile, though its alluvial reach is characterised by steeper slope in comparison to the Ganga river (Fig. 11). Upstream mountainous reaches have less stream power variability in comparison to the Ganga river. Downstream reaches of the river, which are also characterised by badland topography has significantly high variability of stream power (Fig. 12).

DEM derived long profile of the Ghaghara river is characterised by various kinks, which have been removed through smoothening process (Fig. 13). Upstream mountainous reach is characterised by large variability in channel slope. It has lead to multi-peak stream power distribution pattern (Fig. 14). Most of these peaks lie in the Himalayan area, which could be responsible for higher sediment supply in downstream region. The Ghaghara river system is characterised by various small stream, as highlighted by small and various steps incatchment area plot. However, the stream power variability in downstream reaches is less compared to other major rivers.

Long profile of the Gandakriver is characterised by various kinks, which highlights strong geological control on long profile shape (Fig. 15). The first 100 km upstream area is a steeply sloping bed, which is followed by almost vertical fall of around 1500 m. This sudden change in bed slope is responsible for very steep slope and hence a major stream power peak in the Higher Himalayan region (Fig. 16). Another stream power peak in downstream region occurs around 350 km distance in the alluvial region, which is related with tributary contribution. Downstream reaches of the river are characterised by less variability in stream power.

Similar to the Gandak river, the long profile of the Kosi has anomalous shape and has shown the influence of geological controls (Fig. 17). The midstream reach, which falls in the mountainous Himalayan area, is characterised by significant decline in bed elevation from 4000 m to around 500 m. It has resulted very steep slope of around 100 m/km. Therefore, all the major stream power peaks of the Kosi river lies in this region (Fig. 18). Stream power values reduce significantly in downstream alluvial region. It is responsible for significant aggradation in the downstream regions.

Stream power distribution pattern of some foothill-fed river systems (after Sinha and Friend, 1994) has also been derived. It mainly includes Ramganga, Baghmati and Kamla-Balan rivers. Long profile of the Ramganga river is very distinct, which can be easily divided into two parts namely steep profile in the mountainous reaches and flat profile in the alluvial reaches (Fig.19). Mountainous reaches are characterised by large variability in channel slope (Fig. 19). However, this slope variability has not resulted into stream power peaks because of less discharge value in upstream reaches (Fig. 20). A single peak of stream power (1) is because of a dam and is not a natural expression of flow energy. Increase in discharge in downstream reaches and minor variability in reach scale channel slope has resulted variability in stream power at downstream reaches. It may causes major geomorphic variability along the alluvial reaches.

Bagmati River is characterised by a well-developed concave shaped long profile (Fig. 21). The steep profile at upstream reaches is characterised by well-developed peak of local channel slope. These peaks of channel slope are strongly controlling the distribution pattern of stream power, as the same reaches are characterised by major stream power peaks (Fig. 22). Stream power variability is also present at downstream reaches, which is the result of increase in discharge and slope variability at downstream reaches. Variable stream power distribution pattern along the alluvial reaches will be responsible for major geomorphic diversity and dynamic behaviour of river along these reaches.

Kamla-Balan river is characterised by well-developed concave shape long profile, but significant variability in local channel slope (Fig. 23). The channel slope variability has also been reflected in the stream power distribution pattern (Fig. 24). The most of the stream power peaks of the Kamla-Balan river lies in the midstream and downstream region. These peaks will be responsible for dynamic nature of river in midstream and downstream regions.

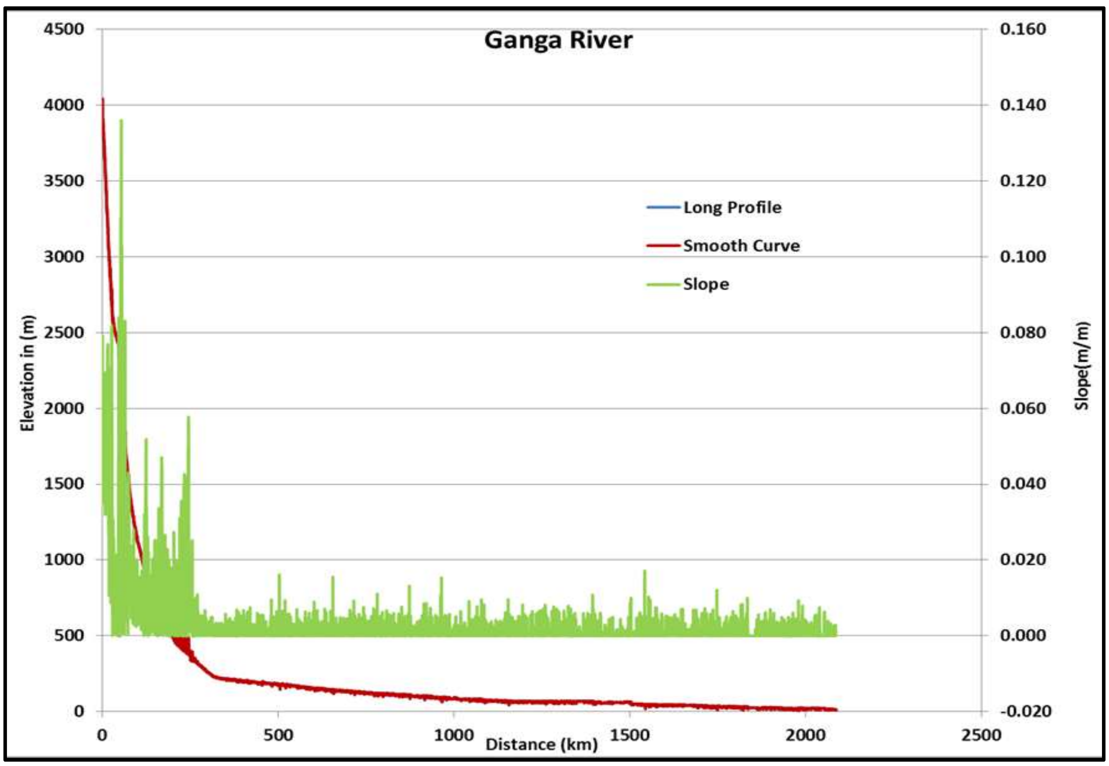


Figure 9: **Shape of Long Profile of the Ganga River and its Effect on Slope Distribution along the River.**

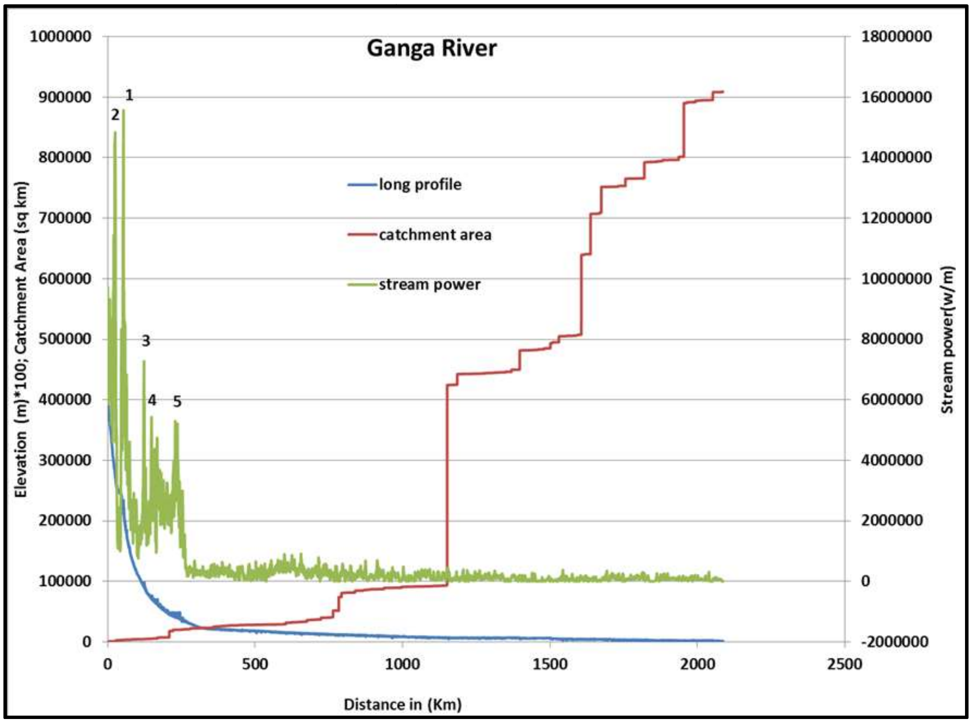


Figure: 10: **Stream power distribution pattern in the Ganga river.**

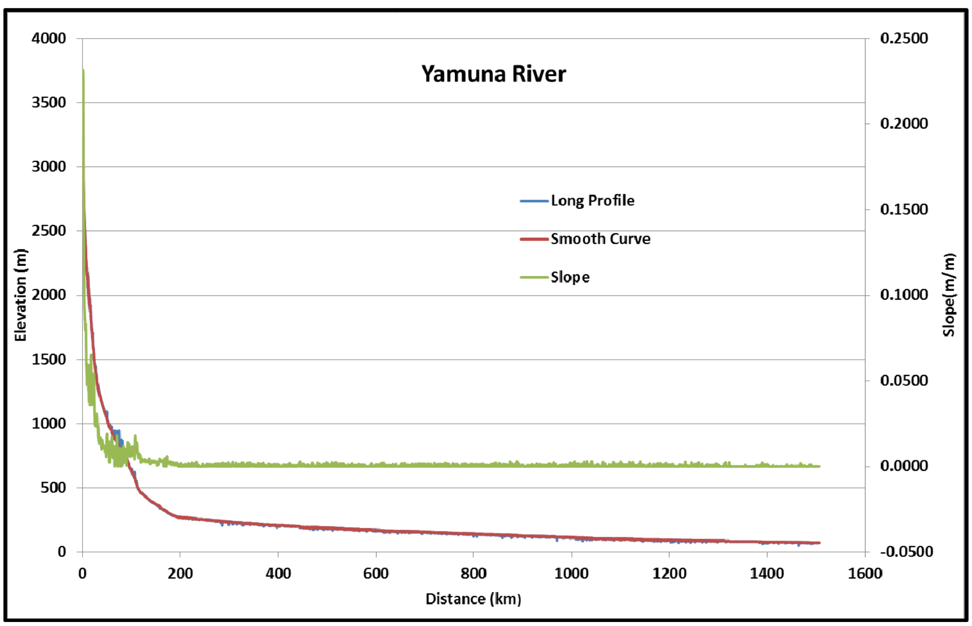


Figure: 11: **Shape of Long Profile of the Yamuna River and its Effect on Slope Distribution along the River.**

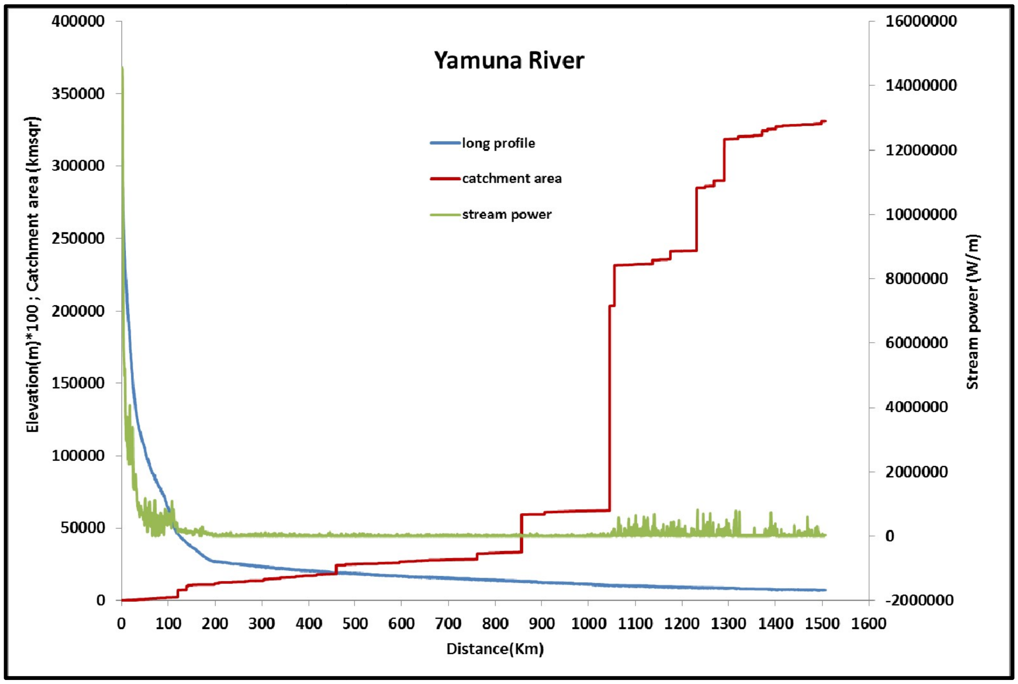


Figure 12: **Stream Power Distribution Pattern in the Yamuna River. The Figure Also Shows the Distribution Pattern of the Long Profile and Contributing Catchment Area**

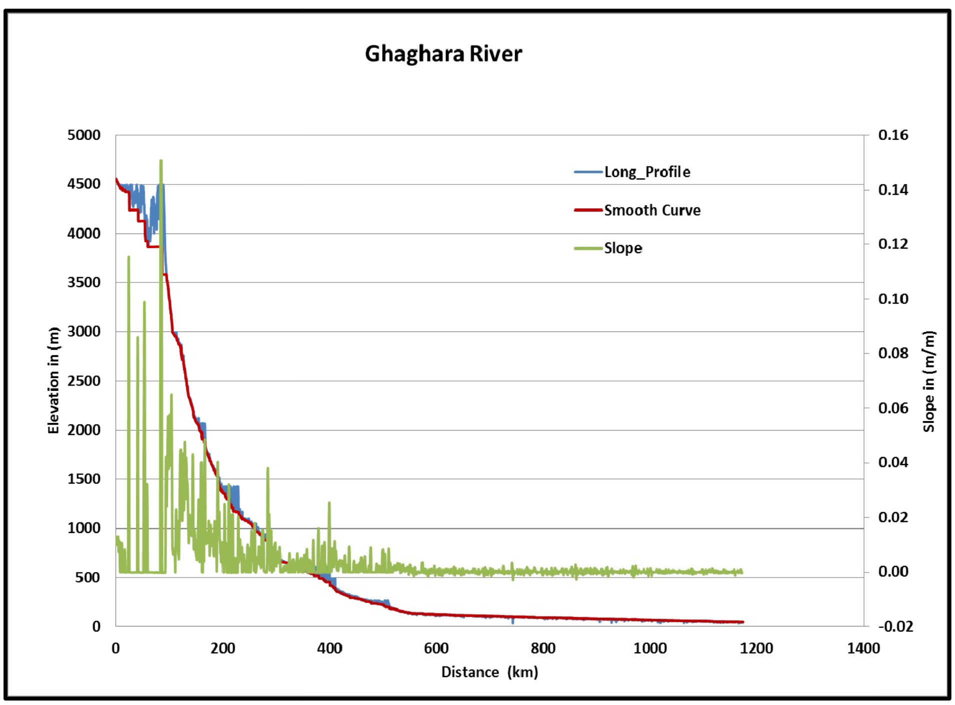


Figure 13: **Shape of Long Profile of the Ghaghara River and its Effect on Slope Distribution along the River.**

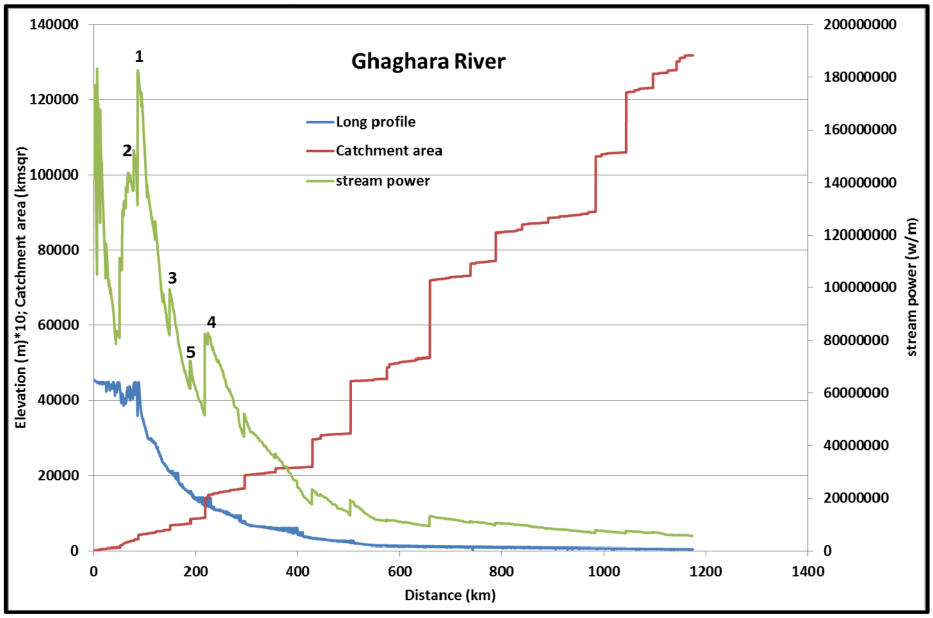


Figure 14: **Stream Power Distribution Pattern in the Ghaghara River. The Figure also Shows the Distribution Pattern of the Long Profile and Contributing Catchment Area.**

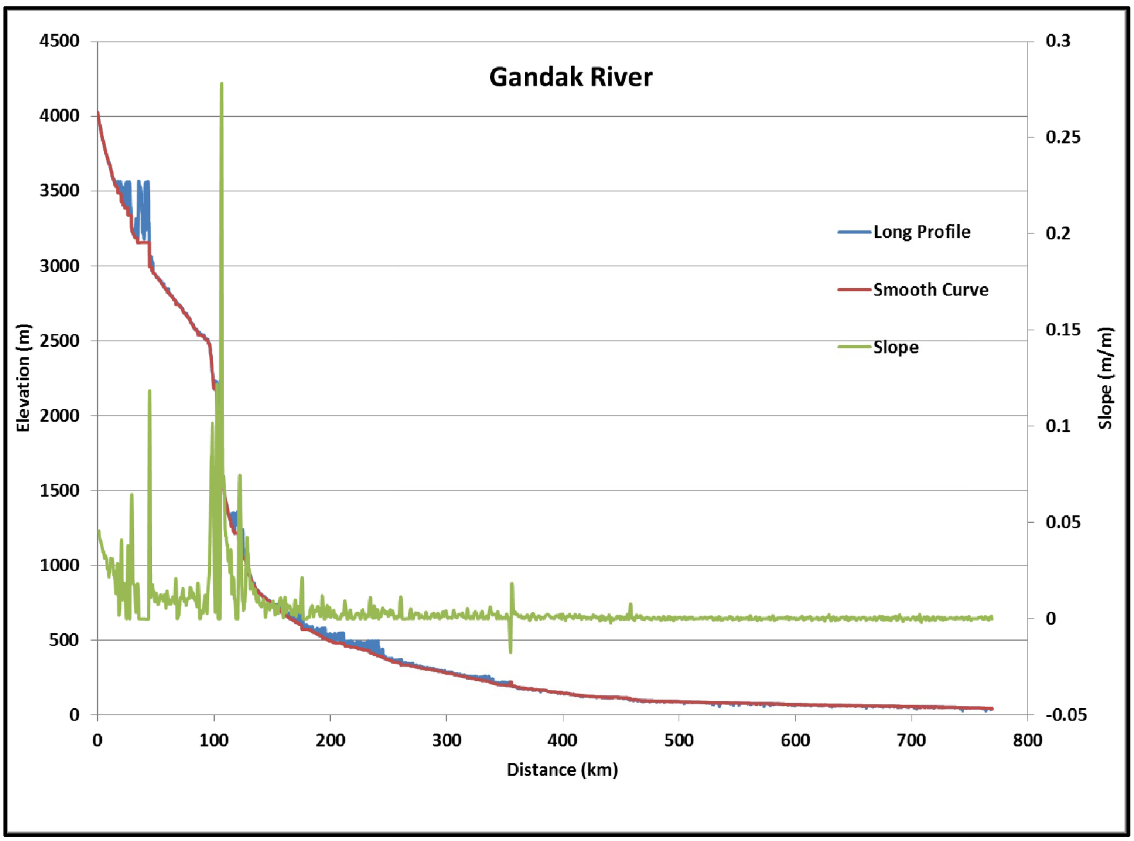


Figure 15: **Shape of Long Profile of the Gandak River and its Effect on Slope Distribution Long the River.**

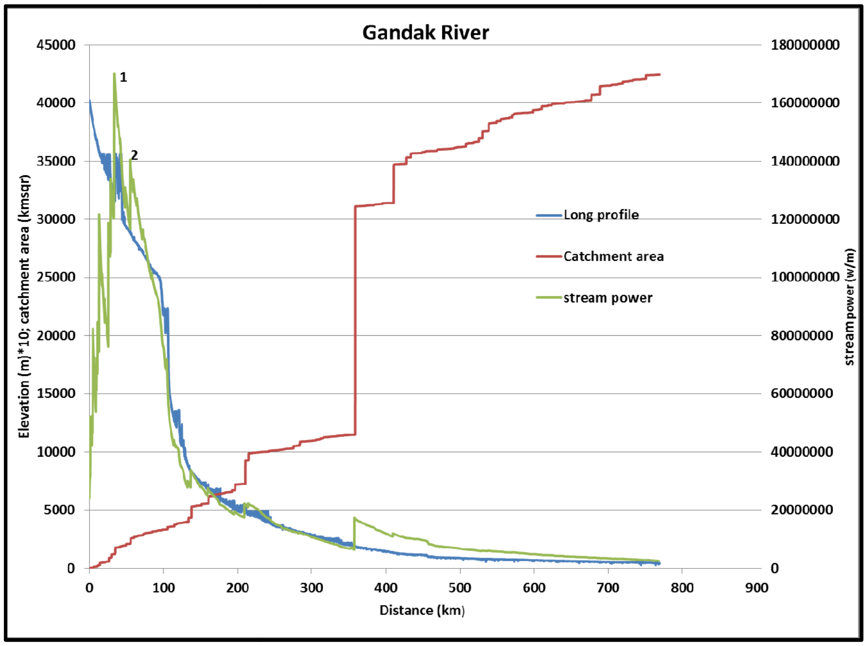


Figure 16: **Stream Power Distribution Pattern in the Gandak River. The Figure also Shows the Distribution Pattern of the Long Profile and Contributing Catchment Area.**

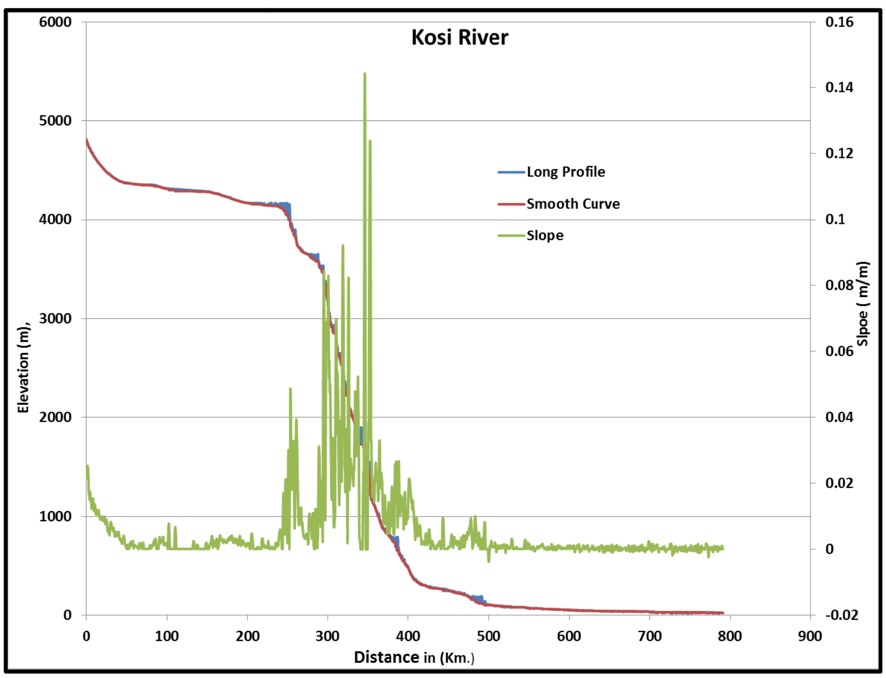


Figure 17: **Shape of Long Profile of the Kosi River and its Effect on Slope Distribution along the River.**

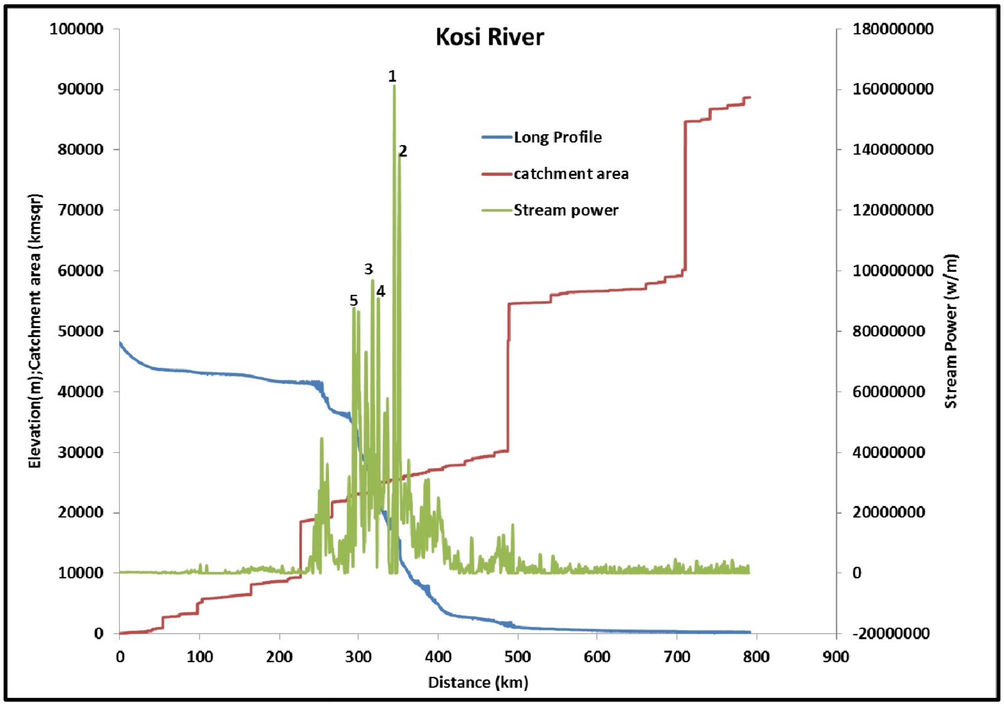


Figure 18: **Stream Power Distribution Pattern in the Kosi River. The Figure also Shows the Distribution Pattern of the Long Profile and Contributing Catchment Area.**

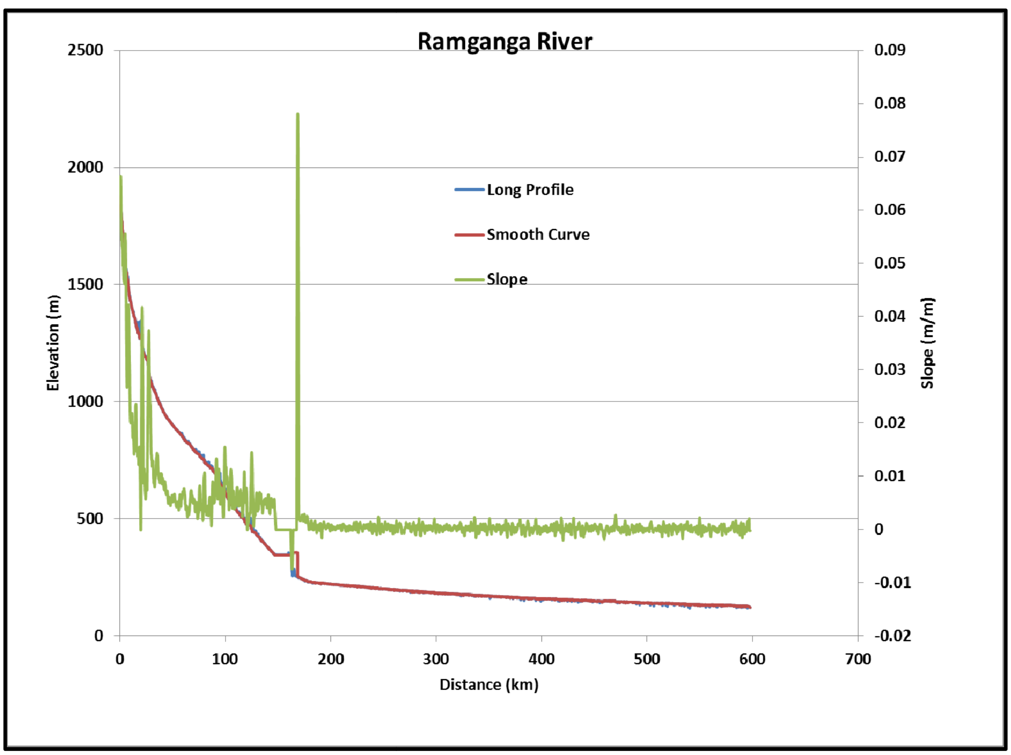


Figure 19: **Shape of Long Profile of the Ramganga River and its Effect on Slope Distribution Along the River.**

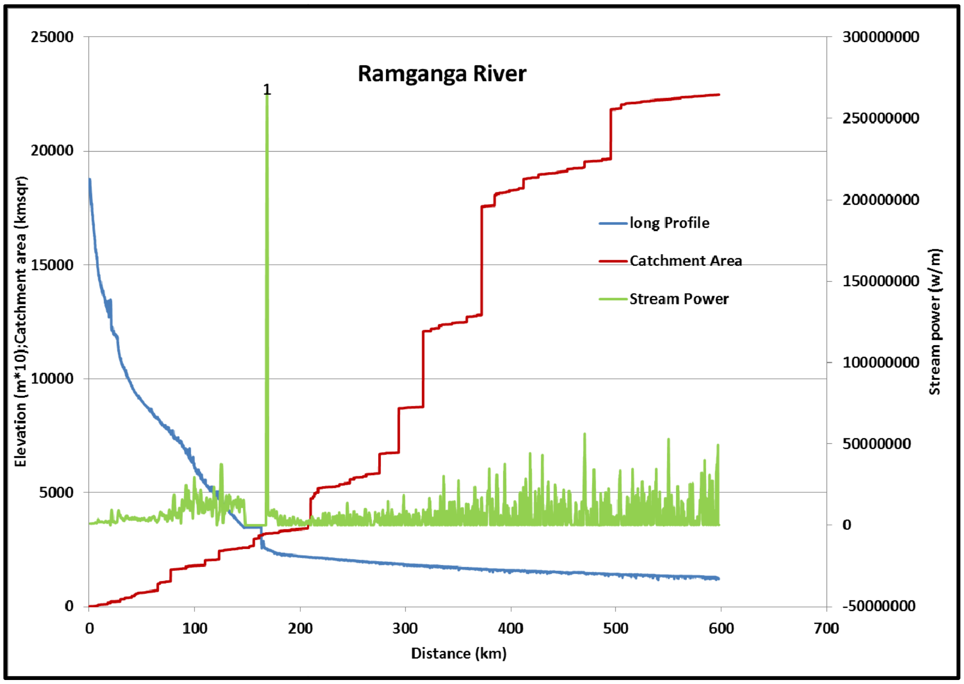


Figure 20: Stream Power Distribution Pattern in Ramganga River. The Figure also Shows the Distribution Pattern of the Long Profile and Contributing Catchment Area.

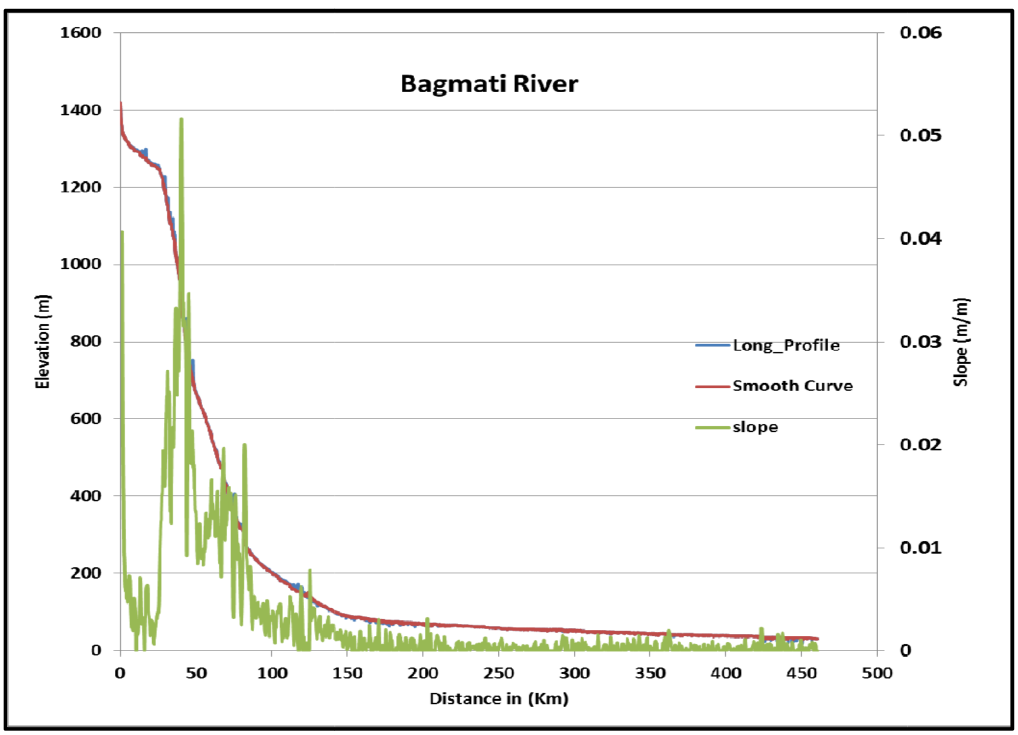


Figure 21: Shape Of Long Profile Of The Bagmati River and its Effect on Slope Distribution along the River.

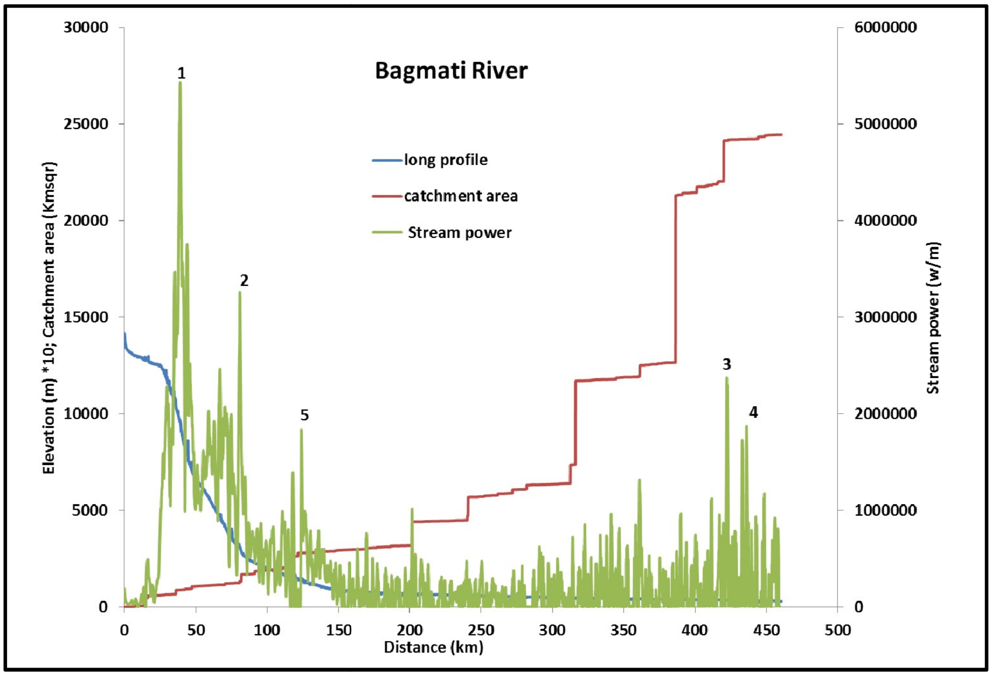


Figure 22: **Stream Power Distribution Pattern in Bagmati River. The Figure also Shows the Distribution Pattern of the Long Profile and Contributing Catchment Area.**

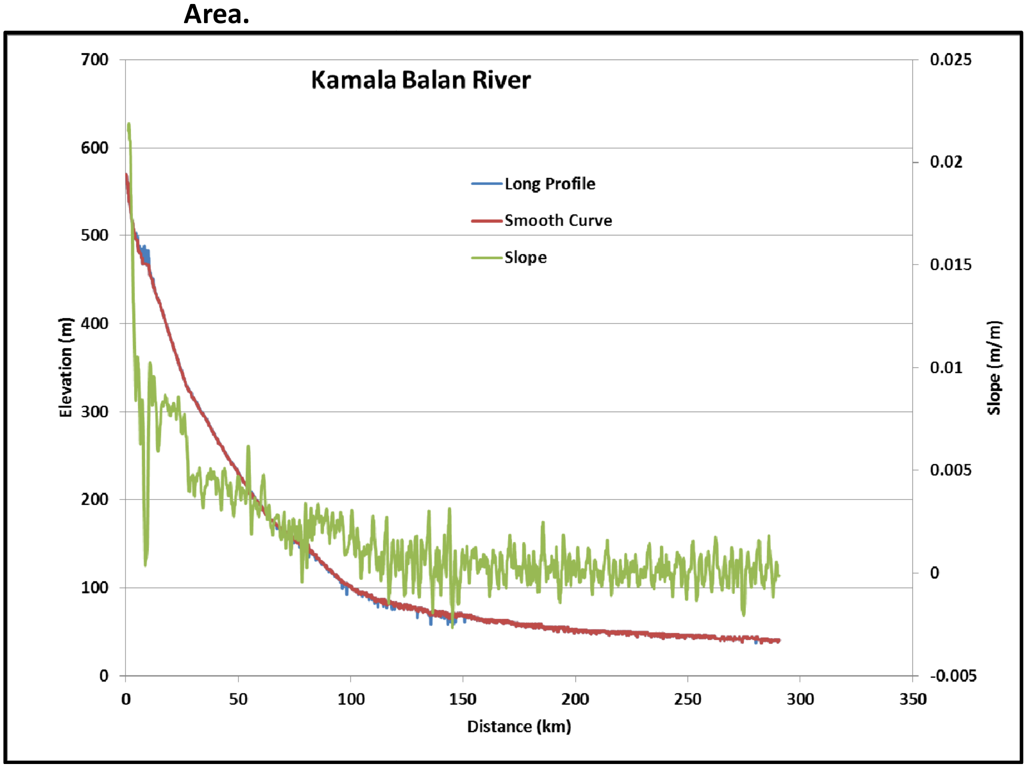


Figure 23: **Shape of Long Profile of Kamla-Balan River and its Effect on Slope Distribution along the River.**

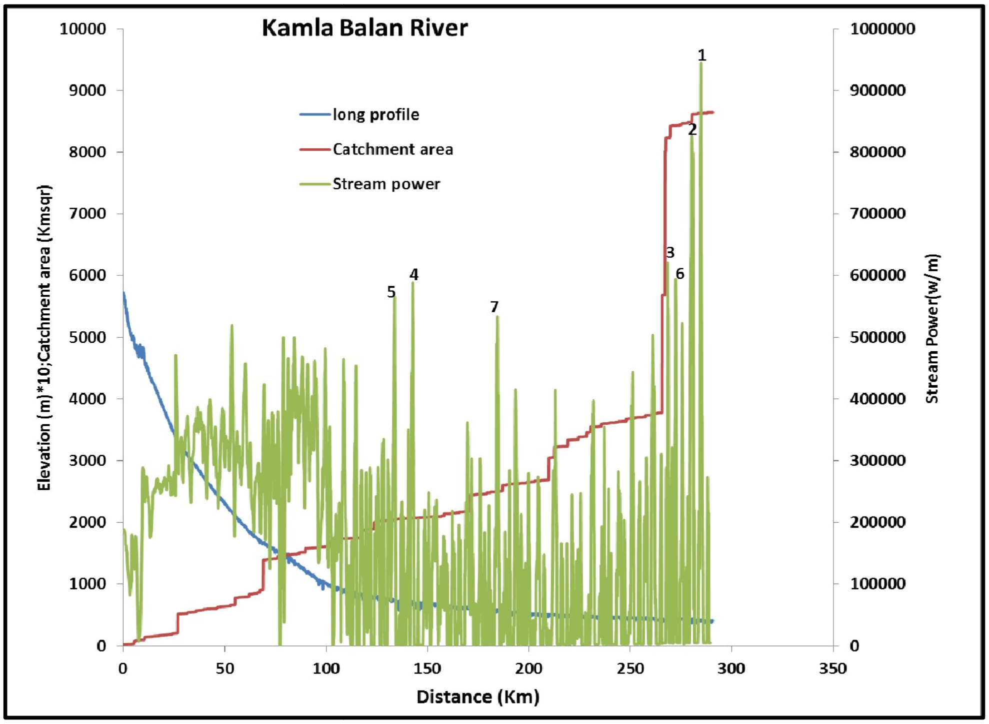


Figure 24: **Stream Power Distribution Pattern in Kamla-Balan River. The Figure also Shows the Distribution Pattern of the Long Profile and Contributing Catchment Area.**

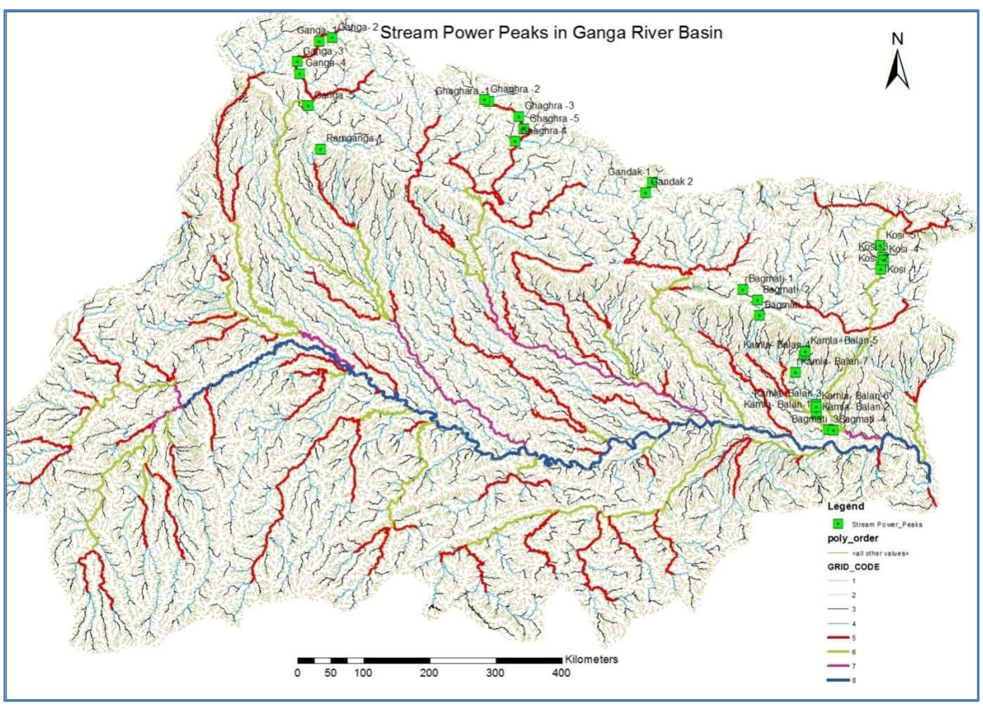


Figure 25: **Location of Stream Power Peaks in the Planform Map. The Most of the Stream Power Peaks Lies it the Higher Himalayan Areas, which is also the Major Sources of Sediment Supply in Downstream Reaches.**

5. Conclusions

The stream power distribution pattern of all the rivers are characterised by various peaks. These peaks are the zone of the erosion processes and extensive sediment transport. In most of the cases these peaks lies in the Higher Himalayan area, which explains the high sediment supply from this region. There is significant decrease in stream power of all rivers from mountainous region to alluvial plain area. Sudden decrease of stream power is responsible for extensive deposition in the alluvial plains area. However, alluvial reaches of all the rivers are characterised by reach scale variability in stream power, which will explain the reach scale geomorphic variability in the Ganga river system.

Stream power distribution pattern in all the streams is mostly governed by local slope variability. Hydrological variation which is represented by tributary confluence doesn't have a major control on the stream power distribution pattern. However, downstream hydrological variability in the current model is based on the discharge-area relationship and mostly highlights the tributary confluence on hydrological fluxes. Improvement of data regarding downstream discharge variability through flow routing for the Ganga river and its tributaries will further improve stream power data of the Ganga river basin.

References

Bagnold, R. A. (1966) An approach to the sediment transport problem from general physics, *USGS Prof. Pap*. 422I. Pp. 37.

Blum, M. and Tornqvist, T. E. (2000) Fluvial response to climate and sea-level change: a review and look forward. *Sedimentology*, 47 (Suppl. 1), 2-48

Benson, M.A.(1968) Uniform flood-frequency estimating methods for Federal Agencies. *Water Resour. Res.* 4(5), 891-908.

Bull, W.B. (1979) Thresholds of critical power in streams. *Geological Society of America Bulletin*, 90, 453-464.

Church, M. (1992) Channel morphology and typology. In Calow, P. and Petts, G.E. (eds.) *The Rivers Handbook.* Blackwell Scientific Publications, Oxford, 1, 26-143.

Freeman 1991

Greenlee, D. D. (1987) Raster and Vector Processing for Scanned Linework. *Photogrammetric Engineering and Remote Sensing* 53 (10), 1383–1387.

Graf, W.L. (1987) Late Holocene sediment storage in canyons of the Colorado Plateau. *Geological Society of America Bulletin*. 99, 261-271.

Jain, S. K.Agarwal, P.K., Singh, V.P. (2007).Hydrology and water resources of India- Volume 57 of Water science and technology.

Jain, V., Preston, N., Fryirs, K., Brierly, G.(2006) Comparative assessment of three approaches for deriving stream power plots along long profiles in the upper Hunter River catchment, New South Wales, Australia. *Geomorphology* 74(1), 297–317.

Jain, V., Fryirs, K., Brierley, G. (2008) Where do floodplains begin? The role of total stream power and longitudinal profile form on floodplain initiation processes. *Geological Society of America Bulletin*, 120(1-2), 127-141.

Jenson, S. K.and Domingue, J.O.(1988) Extracting Topographic Structure from Digital Elevation Data for Geographic Information System Analysis. Photogrammetric *Engineering and Remote Sensing* 54 (11), 1593–1600.

Knighton, D.A. (1999) Downstream variation in stream power. *Geomorphology*. 29:293-306.

Lawler, D.M. (1992) Process dominance in bank erosion systems. In Carling, P.A. & Petts, G.E (eds.) *Lowland Floodplain Rivers: Geomorphological Perspectives*. John Wiley & Sons, Chichester.

Leece, S.A. (1997) Nonlinear downstream changes in stream power on Wisconsin's Blue River. *Annals of the Association of American Geographers*. 87, 471-486.

Montgomery D.R., Abbe, T.B., Buffington, J.M., Peterson, N.P., Schmidt, K.M. & Stock, J.D. (1996) Distribution of bedrock and alluvial channels in forested mountain drainage basins. *Nature*. 381, 587-589.

Sinha, R. and Jain, V.,(1998) Flood hazards of north Bihar rivers, Indo- Gangetic Plains. In *Flood Studies in India* (ed. Kale, V. S.), *Geological Society of India Memoir*, 41, 27–52.

Sinha, R. and Friend, P. F. (1994) River systems and their sediment flux, Indo-Gangetic plains, northern Bihar, India. *Sedimentology*, 41, 825–845.

Sinha, R., Jain, V., Babu, G.P., Ghosh, S. (2005) Geomorphic characterisation and diversity of the fluvial systems of the Gangetic Plains. *Geomorphology*, 70 (3-4), 207-225.

Status Paper of river Ganga – Alternate Energy Center IIT RoorkeeAugust 2009.

Strahler, A. N.(1957) Quantitative analysis of watershed geomorphology. *Transactions of the American Geophysical Union* 38 (6), 913-920.

Tarboton, D. G., R.L. Bras, and I. Rodriguez–Iturbe (1991) On the Extraction of Channel Networks from Digital Elevation Data. *Hydrological Processes,* 5, 81–100.

Wetlands

in Ganga River Basin

GRBMP : Ganga River Basin Management Plan

by

Indian Institutes of Technology

IIT Bombay	**IIT Delhi**	**IIT Guwahati**	**IIT Kanpur**	**IIT Kharagpur**	**IIT Madras**	**IIT Roorkee**

Preface

In exercise of the powers conferred by sub-sections (1) and (3) of Section 3 of the Environment (Protection) Act, 1986 (29 of 1986), the Central Government has constituted National Ganga River Basin Authority (NGRBA) as a planning, financing, monitoring and coordinating authority for strengthening the collective efforts of the Central and State Government for effective abatement of pollution and conservation of the river Ganga. One of the important functions of the NGRBA is to prepare and implement a Ganga River Basin Management Plan (GRBMP).

A Consortium of 7 Indian Institute of Technology (IIT) has been given the responsibility of preparing Ganga River Basin Management Plan (GRBMP) by the Ministry of Environment and Forests (MoEF), GOI, New Delhi. Memorandum of Agreement (MoA) has been signed between 7 IITs (Bombay, Delhi, Guwahati, Kanpur, Kharagpur, Madras and Roorkee) and MoEF for this purpose on July 6, 2010.

This report is one of the many reports prepared by IITs to describe the strategy, information, methodology, analysis and suggestions and recommendations in developing Ganga River Basin Management Plan (GRBMP). The overall Frame Work for documentation of GRB EMP and Indexing of Reports is presented on the inside cover page.

There are two aspects to the development of GRB EMP. Dedicated people spent hours discussing concerns, issues and potential solutions to problems. This dedication leads to the preparation of reports that hope to articulate the outcome of the dialog in a way that is useful. Many people contributed to the preparation of this report directly or indirectly. This report is therefore truly a collective effort that reflects the cooperation of many, particularly those who are members of the IIT Team. Lists of persons who have contributed directly and those who have taken lead in preparing this report is given on the reverse side.

Dr Vinod Tare
Professor and Coordinator
Development of GRB EMP
IIT Kanpur

The Team

1. A K Thakur, IIT Kanpur akthakur@iitk.ac.in
2. M D Behera, IIT Kharagpur mdbehera@coral.iitkgp.ernet.in
3. Naveen Navania, IIT Roorkee navnifbs@iitr.ernet.in
4. Partha Roy, IIT Roorkee paroyfbs@iitr.ernet.in
5. Pruthi Vikas, IIT Roorkee vikasfbs@iitr.ernet.in
6. R P Mathur, IIT Kanpur rpm_2k1@yahoo.com
7. R P Singh, IIT Roorkee rpsbsfbs@iitr.ernet.in
8. Ramasre Prasad, IIT Roorkee rapdyfbs@iitr.ernet.in
9. Ranjana Pathania, IIT Roorkee rpathfbs@iitr.ernet.in
10. Sandeep Behera, WWF-India, New Delhi sbehera@wwfindia.net
11. Utpal Bora, IIT Guwahati ubora@iitg.ernet.in
12. Vinod Tare, IIT Kanpur vinod@iitk.ac.in

Lead Persons

1. Utpal Bora, IITGuwahati
2. Ranjan Tamuli, IIITGuwahati
3. Mrinal Kanti Dutta, IIITGuwahati
4. Shamim Rahman, IITGuwahati
5. Ajoy Kumar Das, IITGuwahati
6. Ranjan Baruah, IITGuwahati

Contents

1. Introduction

Wetlands are defined as 'lands transitional between terrestrial and aquatic eco-systems where the water table is usually at or near the surface or the land is covered by shallow water (Mitsch and Gosselink 1986). Ramsar Convention on Wetlands defines wetlands as: "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters"

1.1. Importance of wetlands

Wetlands are the repository of vital ecosystem information services. They perform many functions and provide many ecosystem services, such as maintenance of food web, providing habitat to aquatic flora and fauna, as well as numerous species of birds, including migratory species, filtering of sediments and nutrients from surface water maintaining of nutrients recycling, purification of water, controlling of flood, recharging of ground water, providing drinking water, fish, fodder, fuel and providing source of livelihood and recreation to local people.

The Millennium Assessment (MA) uses the following typology to categorise ecosystem services-

- **Provisioning services**: The resources or products provided by ecosystems, such as food, raw materials (wood), genetic resources, medicinal resources and ornamental resources (skin, shells, flowers).
- **Regulating services**: Ecosystems maintain the essential ecological processes and life support systems, like gas and climate regulation, water supply and regulation, waste treatment, pollination, etc.
- **Cultural and Amenity services**: Ecosystems are a source of inspiration to human culture and education throughout recreation, cultural, artistic, spiritual and historic information, Science and education.
- **Supporting services**: Ecosystems provide habitat for flora and fauna in order to maintain biological and genetic diversity.

1.2. Importance of wetlands in river basin management

Wetlands provide good support to invertebrates (e.g. insects) and lower vertebrates (e.g. herpetofauna). They are the indicators of healthy ecosystem. The wholesomeness of higher strata depends on them. Thus the whole food web is well maintained. Wetlands are the resting and breeding place for many species. Many fishes migrate and breed in wetlands. Wetlands reseed the river. 'Wetlands-river' maintains a 'leaf-trunk' relationship of a tree.

Wetland filters sediments and nutrients from surface water, maintains nutrients recycling, and purifies water and it acts as natural kidney. During flood the river interacts with the wetlands and the neighbouring system.

1.3. A global look for wetland management

The Ramsar Convention, an Inter-Governmental treaty to maintain the ecological character of wetlands of international importance bears the philosophy of 'wise use concept' which is defined as "the maintenance of their ecological character, achieved through the implementation of ecosystem approach, within the context of sustainable development".

1.4. Data on wetlands of India

Prasad *et al* (2002) mentioned that wetlands in India occupy 58.2 million hectares, including areas under wet paddy cultivation. They quoted Deepa and Ramachandra (1999) as freshwater wetlands alone support 20 per cent of the known range of biodiversity in India.

During 1992-93, Space Application Centre (ISRO) mapped wetlands of India for the Ministry of Environment and Forest, Govt. of India using remote sensing data. In 2004, Salim Ali Centre for Ornithology and Natural History prepared atlas on wetland habitat and species conservation. National Wetland Inventory and Assessment project was initiated in 2007 by SAC, approved and funded by MoEF.

2. Wetlands of the Ganga basin

The main stem of the river Ganga flows through the states of Uttarakhand, Uttar Pradesh, Bihar and West Bengal in India. Only the Sahebganj district of Jharkhand can be taken when main stem of Ganga River is considered. Ministry of Environment and Forest, Govt. of India sponsoring National Wetland Inventory and Assessment (NWIA) project reported 103882 ha area under wetlands in Uttarakhand, 1242530 ha in Uttar Pradesh, 403209 ha in Bihar and 1107907 ha in West Bengal.

2.1. Wetlands in Uttarakhand

Uttarakhand is the source region of two important rivers of India, *viz* Ganga and Yamuna. This is mainly a hilly state with high altitude wetlands. Wetlands of this state are both spring fed as well as river fed. As per the National Wetland Atlas, the three districts Uttarakashi, Tehri Garhwal and Haridwar include a total of 461 wetlands with a cumulative area of 25185 ha. The wetlands include high altitude wetlands (3 nos.) river and streams and wetlands (< 2.25 ha) area. The river and stream contribute 85.69% area (ha). The district wise distribution is represented in Figure 1 (a, b, c). Many wetlands in this state are considered as sacred. Important wetlands of this state are Arolital, Badhanital, Bhikaltal, Devtal, Hemkund, Roopkund, Sahstrabahu Lake, Ramganga reservoir, Nainital lake, Kedar tal, Nanak sagar, Tehri reservoir, Dhauliganga, and Tumaria reservoir. Biodiversity valuation of many wetlands is yet to be established. The details related to area assessment are given in Table 1 (a, b, c). Geographical location of some important wetlands is also shown in Google earth Figure 2.

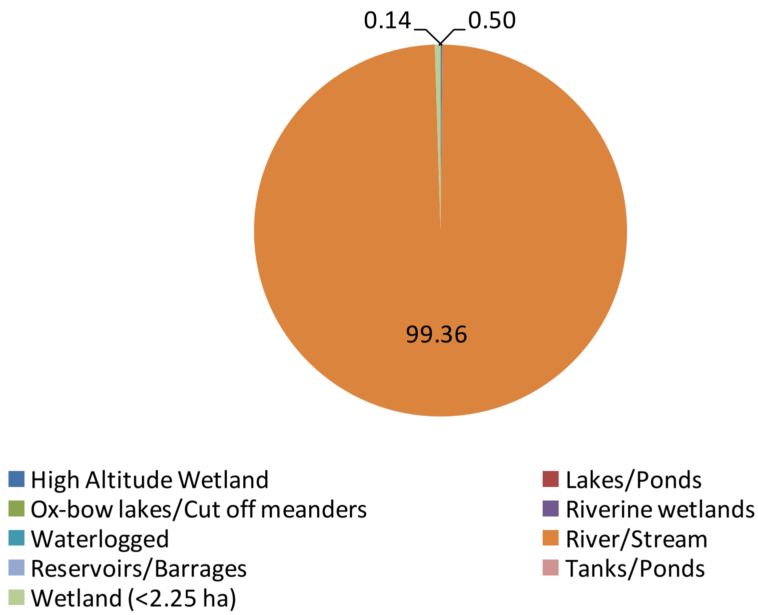


Figure 1a: Wetlands in district Uttarkashi (Uttarakhand)

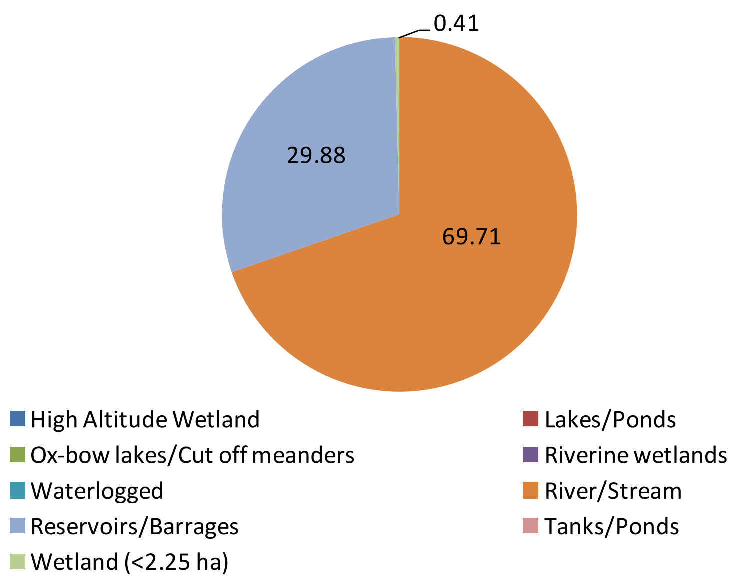
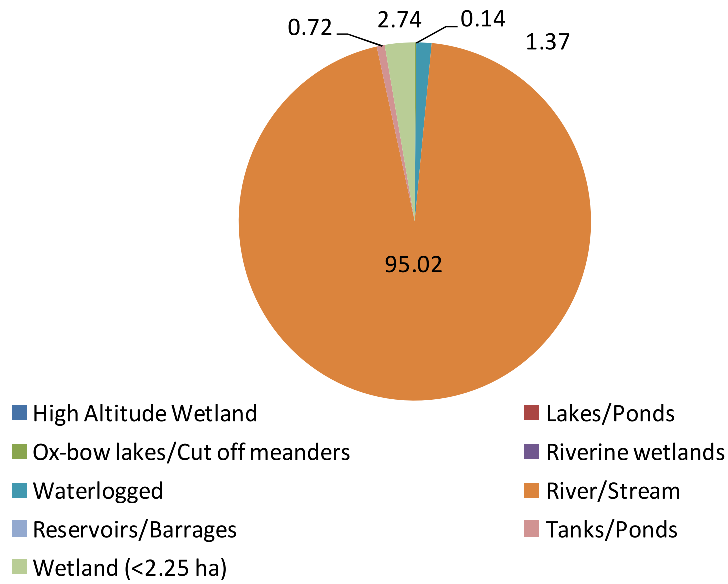


Figure 1b: Wetlands in district Tehri Garhwal (Uttarakhand)



T

Figure 1c: Wetlands in district Haridwar (Uttarakhand)

Table 1 a: Area estimates of wetlands in district Uttarkashi

SNo	Wetland category	No. of wetlands	Total area wetland (ha)	% of wetland area
1	High altitude wetland	3	12	0.14
2	River/stream	12	8477	99.36
3	Wetland (<2.25 ha)	43	43	0.50
4	Total	58	8532	100.00

Table 1 b: Area estimates of wetlands in district Tehri Garhwal

S No	Wetland category	No. of wetlands	Total area wetland (ha)	% of wetland area
1	River/stream	11	2909	69.71
2	Reservoir/Barrages	1	1247	29.88
3	Wetland (<2.25 ha)	17	17	0.41
4	Total	29	4173	100.00

Table 1 c: Area estimates of wetlands in district Haridwar

Sl. No.	Wetland category	No. of wetlands	Total area wetland (ha)	% of wetland area
1	Ox-bow lakes/cut off meanders	4	18	0.14
2	River/stream	9	11859	95.02
3	Tanks/Ponds	18	90	0.72
4	Waterlogged	1	171	1.37
5	Wetland (<2.25 ha)	342	342	2.47

6	Total	374	12480	100.00

District wise area information of wetlands in the Ganga River Basin (Source: National Wetland Inventory and Assessment. National Wetland Atlas. MoEF, Govt. of India. Space Applications Centre, Indian Space Research Organization

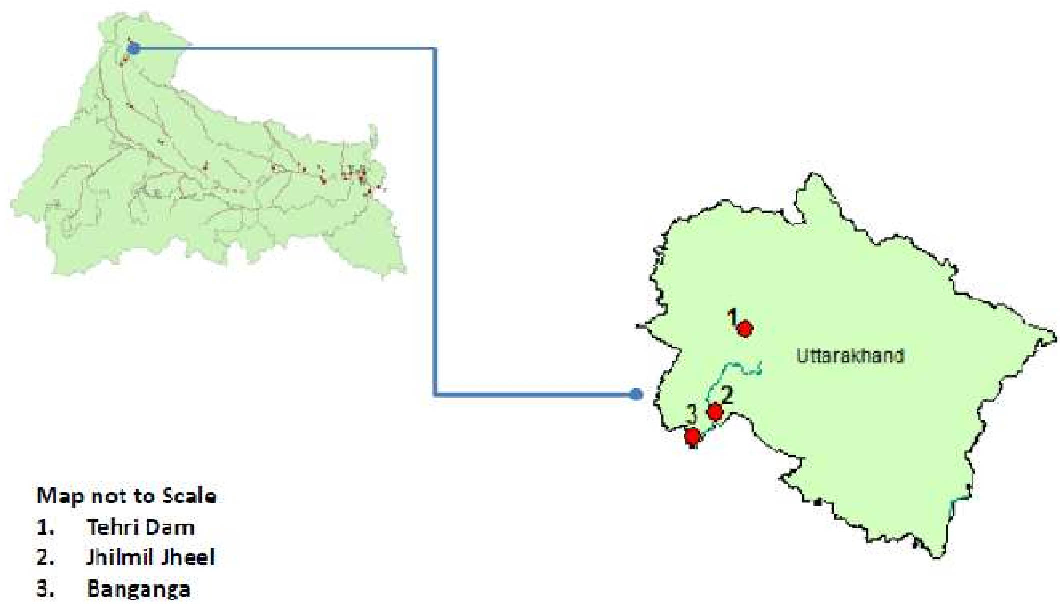


Fig. 2 The wetlands of Uttarakhand

2.2 Wetlands in Uttar Pradesh

Uttar Pradesh is the most populated state of India. Rivers and tributaries flowing through the state are Ganga, Yamuna, Ghaghra, Rapti, Gandak, Ramganga, Gomti, Hindan, Chambal, Saryu, Sai, Kosi, Betwa, Belan, Dhasan, Tons, Son etc. Huge numbers of lakes, ponds, canals are present in the state. Majority of these wetlands are related to the rivers directly or indirectly. 17 districts of Uttar Pradesh fall in the Ganga River Basin directly. Those are Bijnor, Saharanpur, Jyotiba Phule Nagar, Bulandshahar, Raebareli, Farrukhabad, Kannauj, Kanpur Dehat, Kanpur Nagar, Fatehpur, Allahabad, Azamgarh, Ballia, Varanasi, Sant Ravidas Nagar, Mirzapur and Ghazipur.

The entiredistricts collectively have 25113 wetlands with cumulative area of 314775 ha. The river/ stream accounts for 181935 ha approximately 57.7% of the wetlands in Uttar Pradesh followed by 13.6% water logged areas and wetlands (< 2.25 ha). The Figure 3 (a-q) represent distribution of wetlands as lakes/ ponds, ox-bow lakes/ cut off meanders, river and stream, reservoir/ barrages, tanks/ ponds and wetlands (< 2.25 ha). The area estimate of the districts is given in Table 2 (a-q). A location map of Google earth for some important locations is shown in Figure 4.

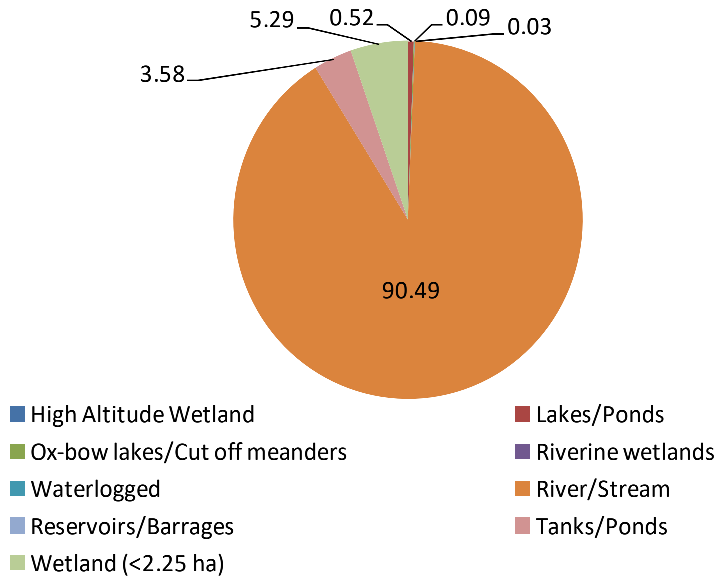


Fig. 3a Wetlands in district Bijnor (Uttar Pradesh)

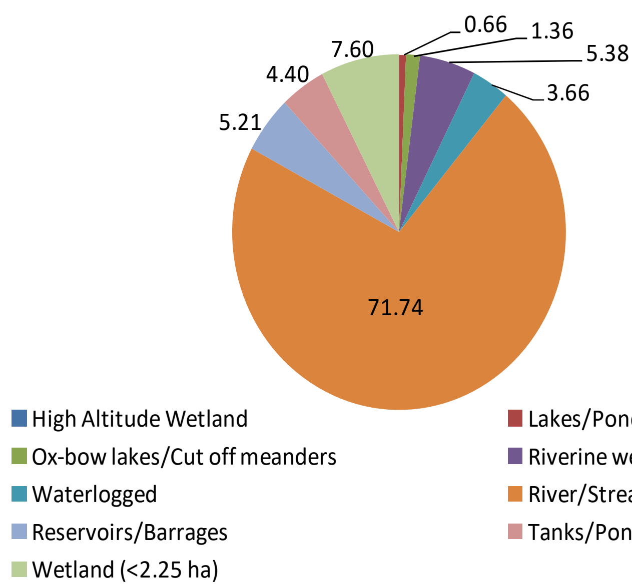


Fig. 3b Wetlands in district Saharanpur (Uttar Pradesh)

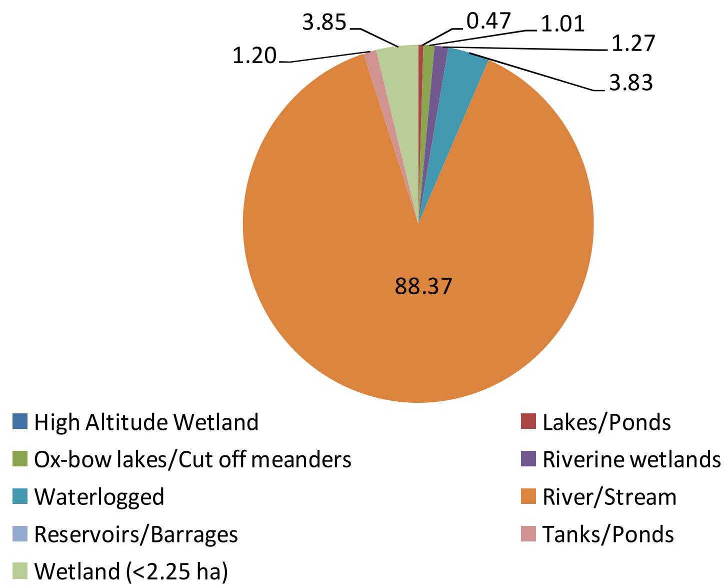


Fig. 3c Wetlands in district Jyotiba Phule Nagar (Uttar Pradesh)

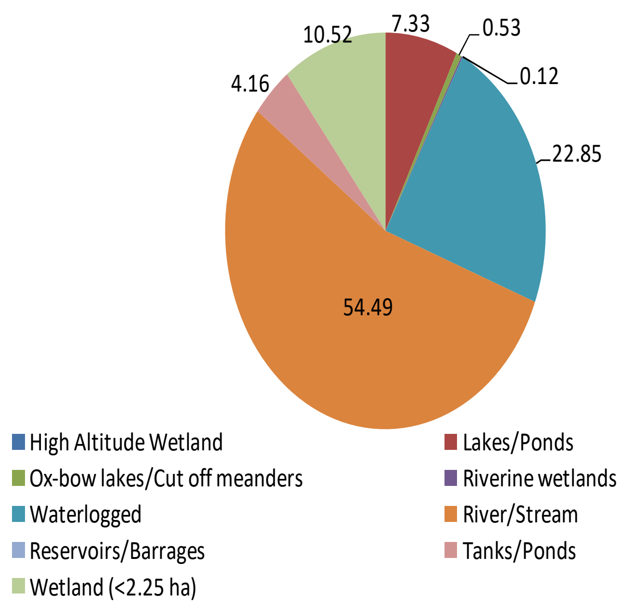


Fig. 3d Wetlands in district Bulandsahar (Uttar Pradesh)

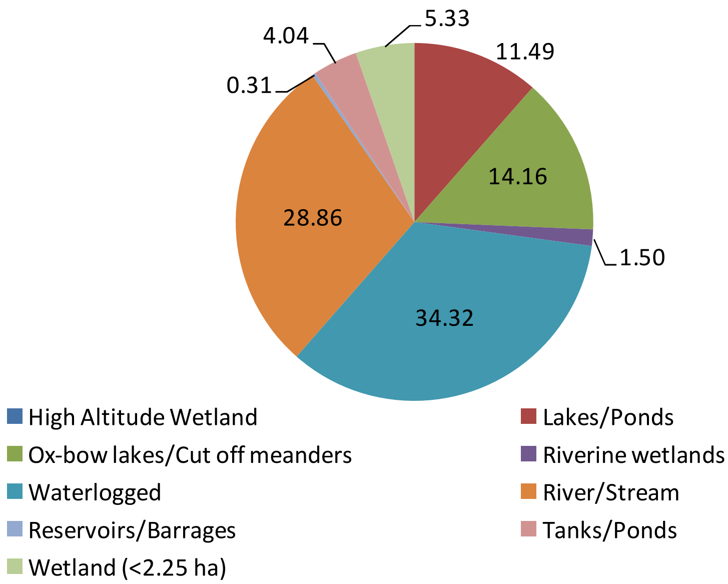


Fig. 3e Wetlands in district Raebareli (Uttar Pradesh)

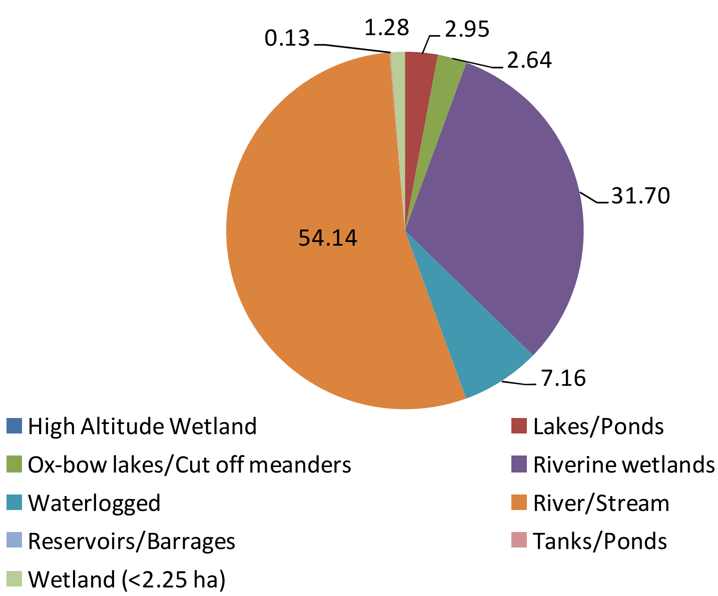


Fig. 3f Wetlands in district Farrukhabad (Uttar Pradesh)

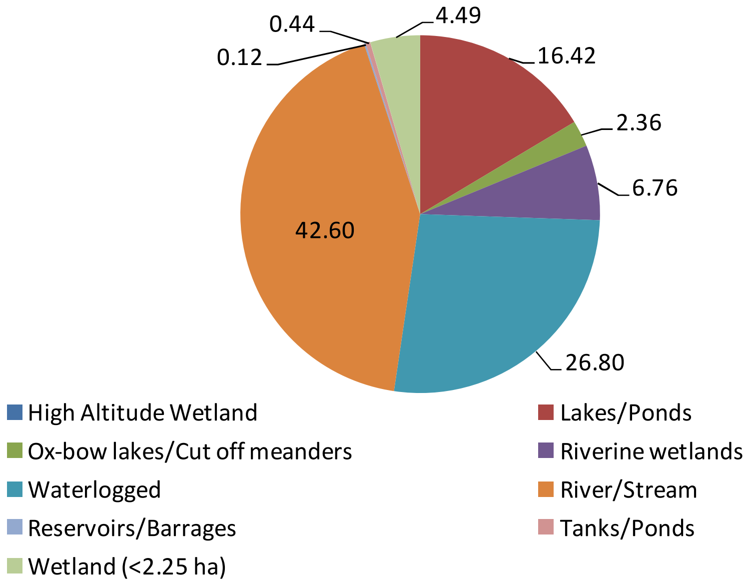


Fig. 3g Wetlands in district Kannauj (Uttar Pradesh)

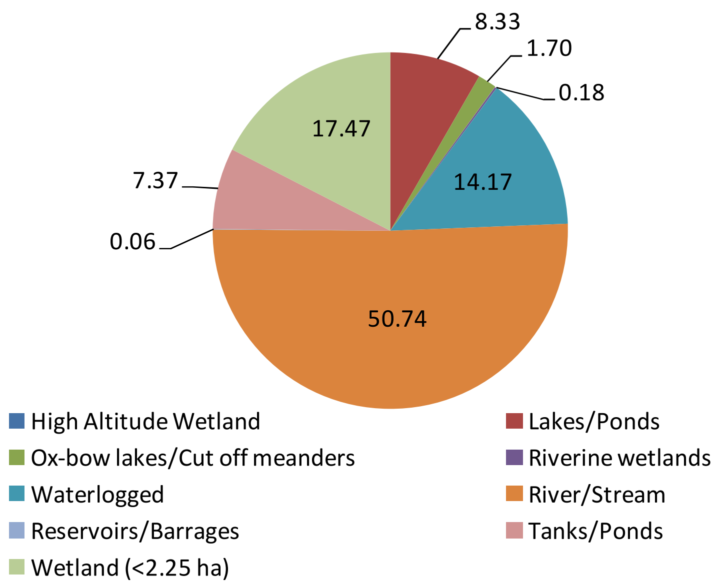


Fig. 3h Wetlands in district Kanpur Dehat (Uttar Pradesh)

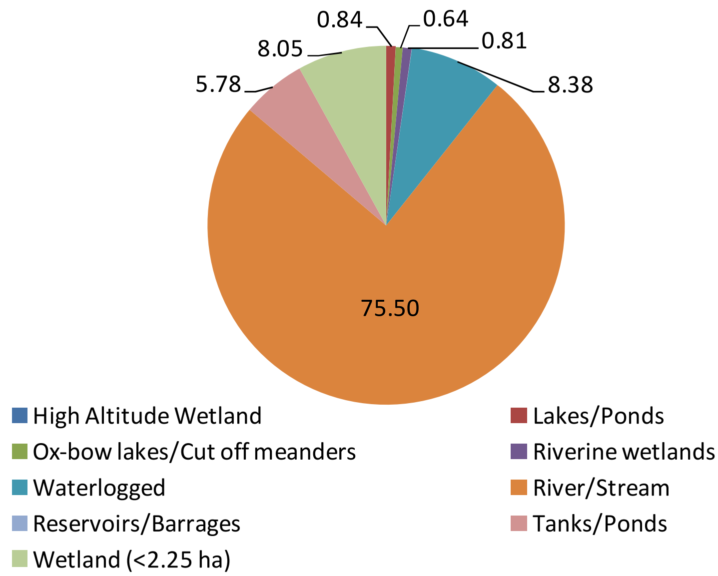


Fig. 3i Wetlands in district Kanpur Nagar (Uttar Pradesh)

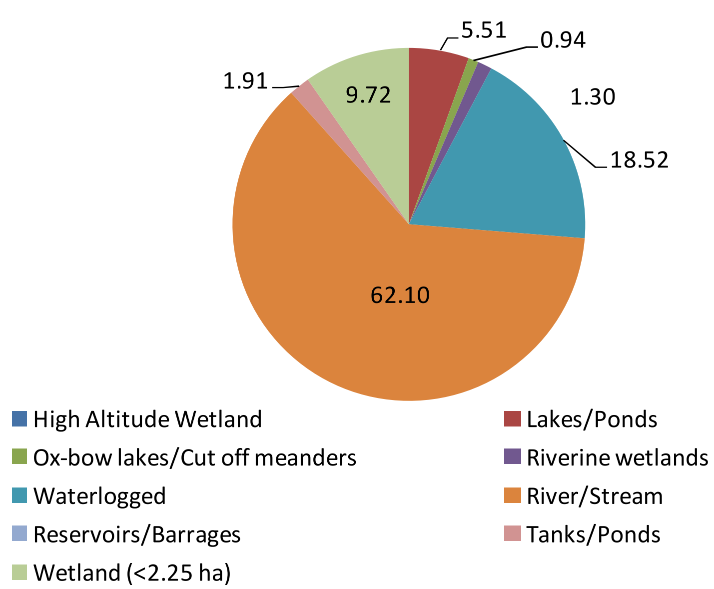


Fig. 3j Wetlands in district Fatehpur (Uttar Pradesh)

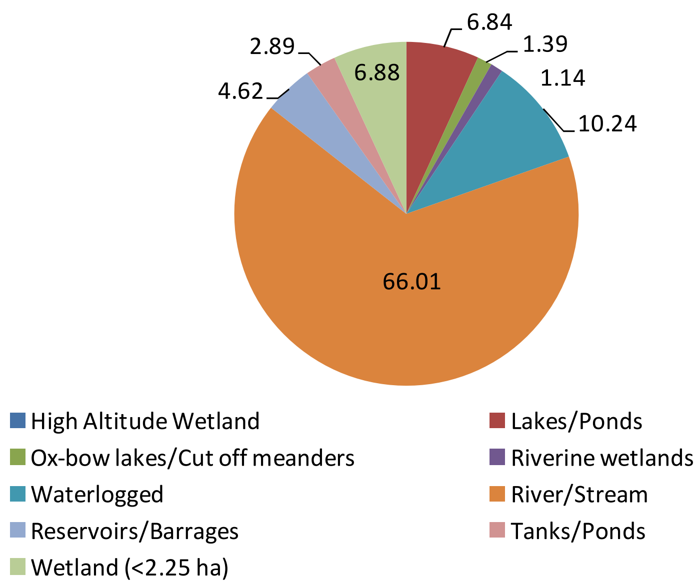


Fig. 3k Wetlands in district Allahabad (Uttar Pradesh)

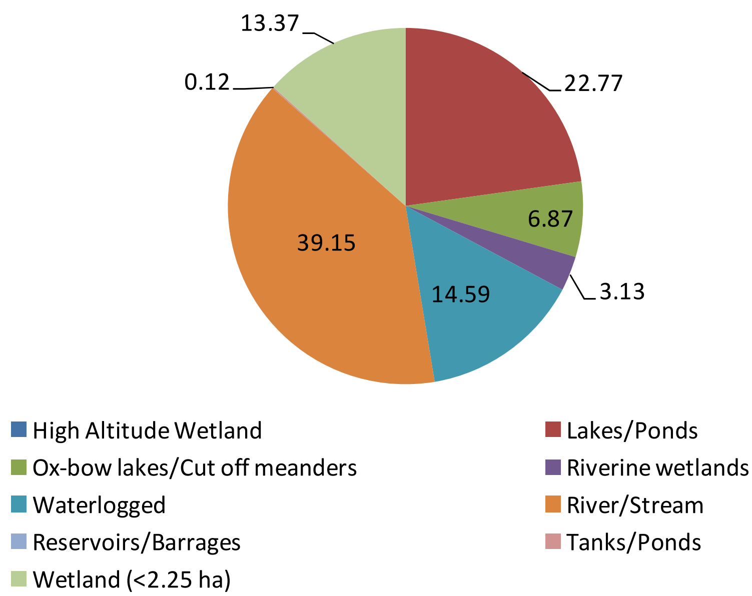


Fig. 3l Wetlands in district Azamgarh (Uttar Pradesh)

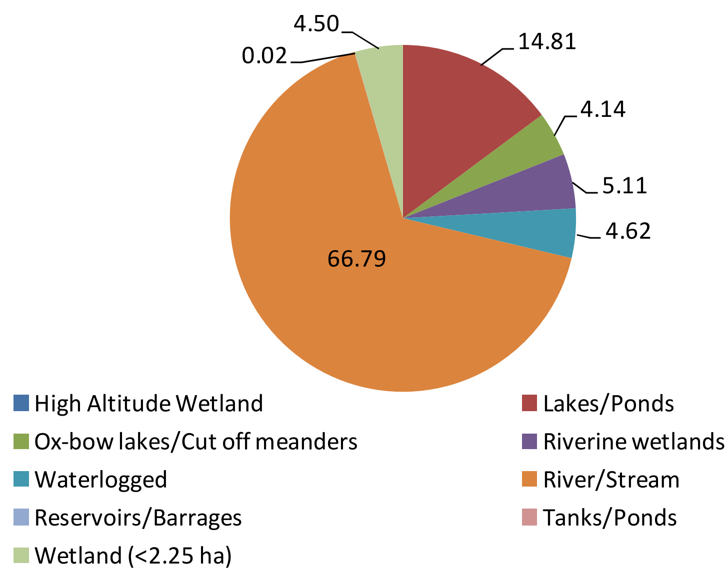


Fig. 3m Wetlands in district Ballia (Uttar Pradesh)

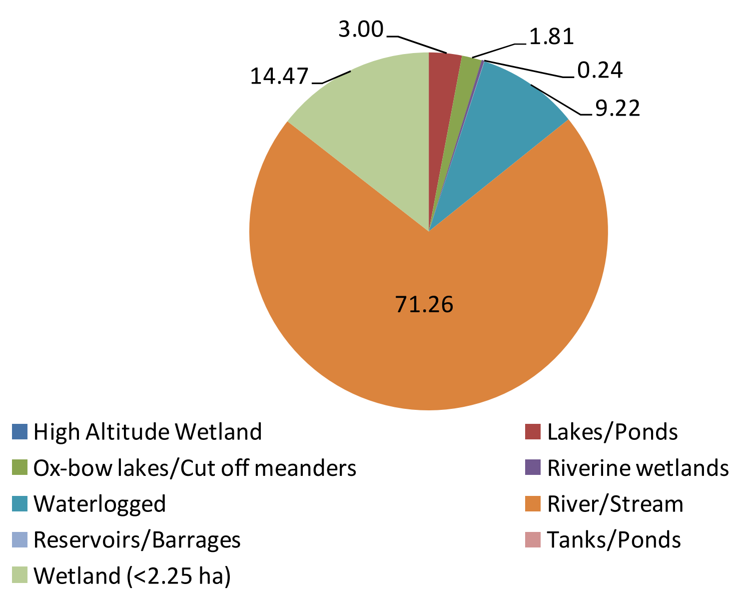


Fig. 3n Wetlands in district Varanasi (Uttar Pradesh)

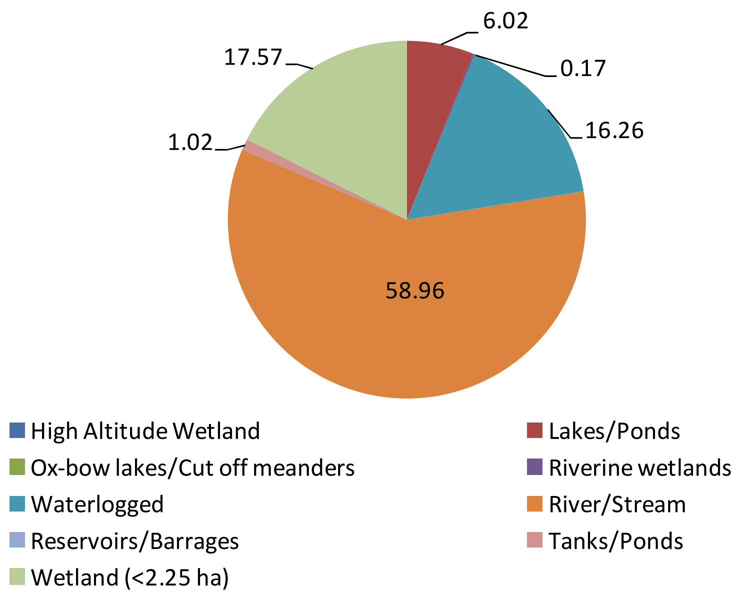


Fig. 3o Wetlands in district Sant Ravidas Nagar (Uttar Pradesh)

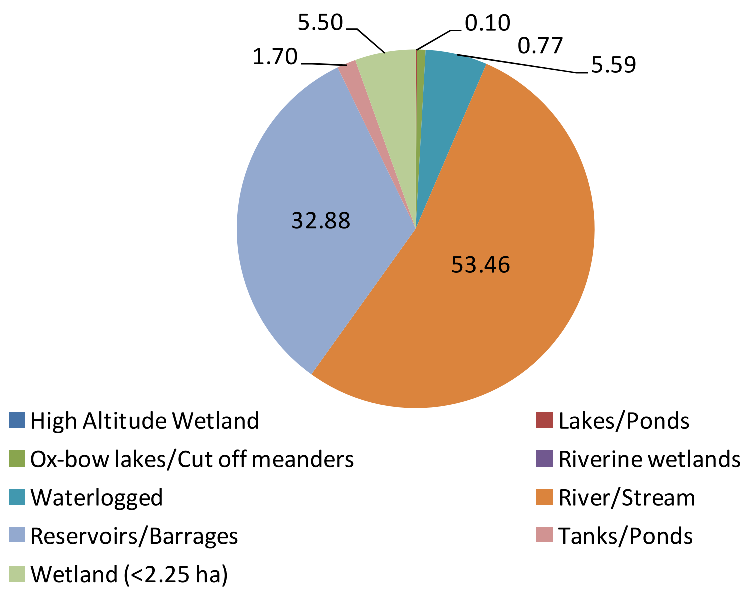


Fig. 3p Wetlands in district Mirzapur (Uttar Pradesh)

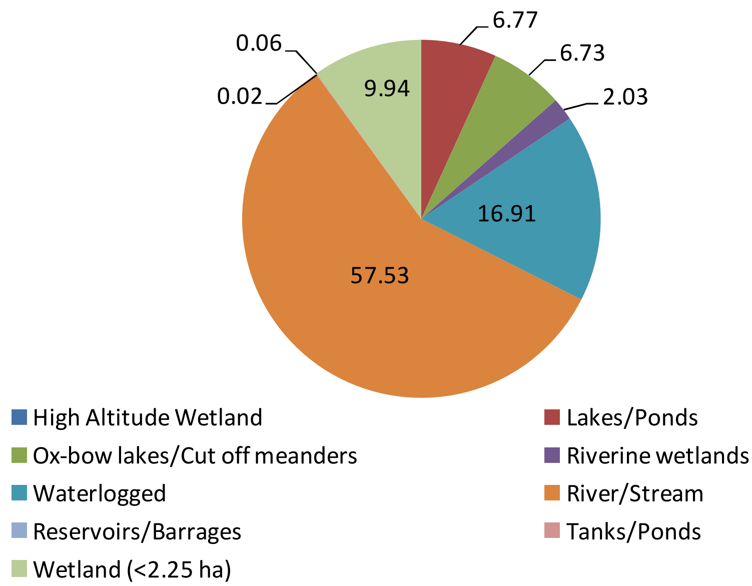


Fig. 3q Wetlands in district Ghazipur (Uttar Pradesh)

Table 2 a: Area estimates of wetlands of Saharanpur

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	4	60	0.52
2	Ox-bow lakes/cut off meanders	2	10	0.09
4	Waterlogged	1	4	0.03
5	River/stream	64	10440	90.49
6	Tanks/Ponds	108	413	3.58
7	Wetland (<2.25 ha)	610	610	5.29
8	Total	789	11537	100.00

Table 2 b: Area estimates of wetlands in district Bijnor

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	21	118	0.66
2	Ox-bow lakes/cut off meanders	16	243	1.36
3	Riverine wetlands	16	962	5.38
4	Waterlogged	40	654	3.66
5	River/stream	64	12826	71.74
6	Reservoirs/Barrages	6	931	5.21
7	Tanks/Ponds	186	786	4.40
8	Wetland (<2.25 ha)	1359	1359	7.60
9	Total	1708	17879	100.00

Table 2 c: Area estimates of wetlands of Jyotiba Phule Nagar

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	8	52	0.47

2	Ox-bow lakes/cut off meanders	12	111	1.01
3	Riverine wetlands	5	140	1.27
4	Waterlogged	29	422	3.83
5	River/stream	33	9744	88.37
6	Tanks/Ponds	30	132	1.20
7	Wetland (<2.25 ha)	425	425	3.85
8	Total	542	11026	100.00

Table 2 d: Area estimates of wetlands in district Bulandshahar

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	37	674	7.33
2	Ox-bow lakes/cut off meanders	3	49	0.53
3	Riverine wetlands	2	11	0.12
4	Waterlogged	134	2101	22.58
5	River/stream	10	5009	54.49
6	Tanks/Ponds	90	382	4.16
7	Wetland (<2.25 ha)	967	967	10.52
8	Total	1243	9193	100.00

Table 2 e: Area estimates of wetlands in district Raebareli

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	90	4428	11.49
2	Ox-bow lakes/cut off meanders	136	5457	14.17
3	Riverine wetlands	7	577	1.50
4	Waterlogged	602	13227	34.33
5	River/stream	35	11123	28.87
6	Reservoirs/Barrages	1	119	0.31
7	Tanks/Ponds	133	1556	4.40
8	Wetland (<2.25 ha)	2053	2053	5.28
9	Total	3057	38540	100.00

Table 2 f: Area estimates of wetlands in district Farrukhabad

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	23	658	2.95
2	Ox-bow lakes/cut off meanders	107	589	2.64
3	Riverine wetlands	170	7073	31.70
4	Waterlogged	98	1598	7.16

5	River/stream	81	12078	54.14
6	Tanks/Ponds	6	28	0.13
7	Wetland (<2.25 ha)	285	285	1.28
8	Total	770	22309	100.00

Table 2 g: Area estimates of wetlands in district Kannauj

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	32	1345	16.42
2	Ox-bow lakes/cut off meanders	10	193	2.36
3	Riverine wetlands	9	554	6.76
4	Waterlogged	97	2195	26.80
5	River/stream	65	3489	42.60
6	Reservoirs/Barrages	1	10	0.12
7	Tanks/Ponds	10	36	4.44
8	Wetland (<2.25 ha)	368	368	4.49
9	Total	592	8190	100.00

Table 2 h: Area estimates of wetlands in district Kanpur Dehat

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	36	883	7.61
2	Ox-bow lakes/cut off meanders	7	180	1.55
3	Riverine wetlands	9	19	0.16
4	Waterlogged	189	1502	21.57
5	River/stream	58	5380	46.37
6	Reservoirs/Barrages	2	6	0.05
7	Tanks/Ponds	160	781	6.73
8	Wetland (<2.25 ha)	1852	1852	15.96
9	Total	2313	11603	100.00

Table 2 i: Area estimates of wetlands in district Kanpur Nagar

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	17	124	0.84
2	Ox-bow lakes/cut off meanders	5	94	0.64
3	Riverine wetlands	11	120	0.81
4	Waterlogged	89	1238	8.38
5	River/stream	87	11152	75.50
6	Tanks/Ponds	129	853	5.78
7	Wetland (<2.25 ha)	1189	1189	8.05
8	Total	1527	14770	100.00

Table 2 j: Area estimates of wetlands in district Fatehpur

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	59	1125	5.51
2	Ox-bow lakes/cut off meanders	5	192	0.94
3	Riverine wetlands	2	266	1.30
4	Waterlogged	274	3785	18.52
5	River/stream	39	12691	62.10
6	Tanks/Ponds	76	390	1.91
7	Wetland (<2.25 ha)	1986	1986	9.72
8	Total	2441	20435	100.00

Table 2 k: Area estimates of wetlands in district Allahabad

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	22	1879	6.84
2	Ox-bow lakes/cut off meanders	21	382	1.39
3	Riverine wetlands	6	313	1.14
4	Waterlogged	186	2814	10.24
5	River/stream	39	18143	66.01
6	Reservoirs/Barrages	19	1270	4.62
7	Tanks/Ponds	192	794	2.89
8	Wetland (<2.25 ha)	1892	1892	6.88
9	Total	2377	27487	100.00

Table 2 l: Area estimates of wetlands in district Azamgarh

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	145	5800	22.77
2	Ox-bow lakes/cut off meanders	34	1750	6.87
3	Riverine wetlands	29	797	3.13
4	Waterlogged	72	3716	14.59
5	River/stream	69	9972	39.15
6	Tanks/Ponds	5	31	0.12
7	Wetland (<2.25 ha)	3406	3406	13.37
8	Total	3760	25472	100.00

Table 2 m: Area estimates of wetlands in district Ballia

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	111	4747	14.81
2	Ox-bow lakes/cut off meanders	27	1328	4.14
3	Riverine wetlands	31	1636	5.11
4	Waterlogged	43	1481	4.63
5	River/stream	34	21405	66.79
6	Tanks/Ponds	3	8	0.02
7	Wetland (<2.25 ha)	1442	1442	4.50
8	Total	1691	32047	100.00

Table 2 n: Area estimates of wetlands in district Varanasi

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	8	224	3.00
2	Ox-bow lakes/cut off meanders	1	135	1.81
3	Riverine wetlands	3	18	0.24
4	Waterlogged	20	689	9.22
5	River/stream	17	5323	71.26
6	Wetland (<2.25 ha)	1081	1081	14.47
7	Total	1130	7470	100.00

Table 2 o: Area estimates of wetlands in district Sant Ravidas Nagar

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	8	347	16.02
2	Ox-bow lakes/cut off meanders	1	-	-
3	Riverine wetlands	1	10	0.17
4	Waterlogged	30	938	16.26
5	River/stream	75	3400	58.96
6	Tanks/Ponds	2	59	1.02
7	Wetland (<2.25 ha)	1013	1013	17.57
8	Total	1130	5767	100.00

Table 2 p: Area estimates of wetlands in district Mirzapur

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	4	31	0.10
2	Ox-bow lakes/cut off meanders	5	234	0.77
3	Waterlogged	153	1692	5.59
4	River/stream	58	16193	53.46
5	Reservoirs/Barrages	254	9960	32.88

6	Tanks/Ponds	118	515	1.70
7	Wetland (<2.25 ha)	1666	1666	5.50
8	Total	2258	27487	100.00

Table 2 q: Area estimates of wetlands in district Ghazipur

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	75	1597	6.77
2	Ox-bow lakes/cut off meanders	27	1588	6.73
3	Riverine wetlands	13	478	2.03
4	Waterlogged	120	3987	16.90
5	River/stream	62	13567	57.53
6	Reservoirs/Barrages	1	5	0.02
7	Tanks/Ponds	3	15	0.06
8	Wetland (<2.25 ha)	2344	2344	9.94
9	Total	2645	23581	100.00

***District wise area information of wetlands in the Ganga River Basin (Source: National Wetland Inventory and Assessment. National Wetland Atlas. MoEF, Govt. of India. Space Applications Centre, Indian Space Research Organization**

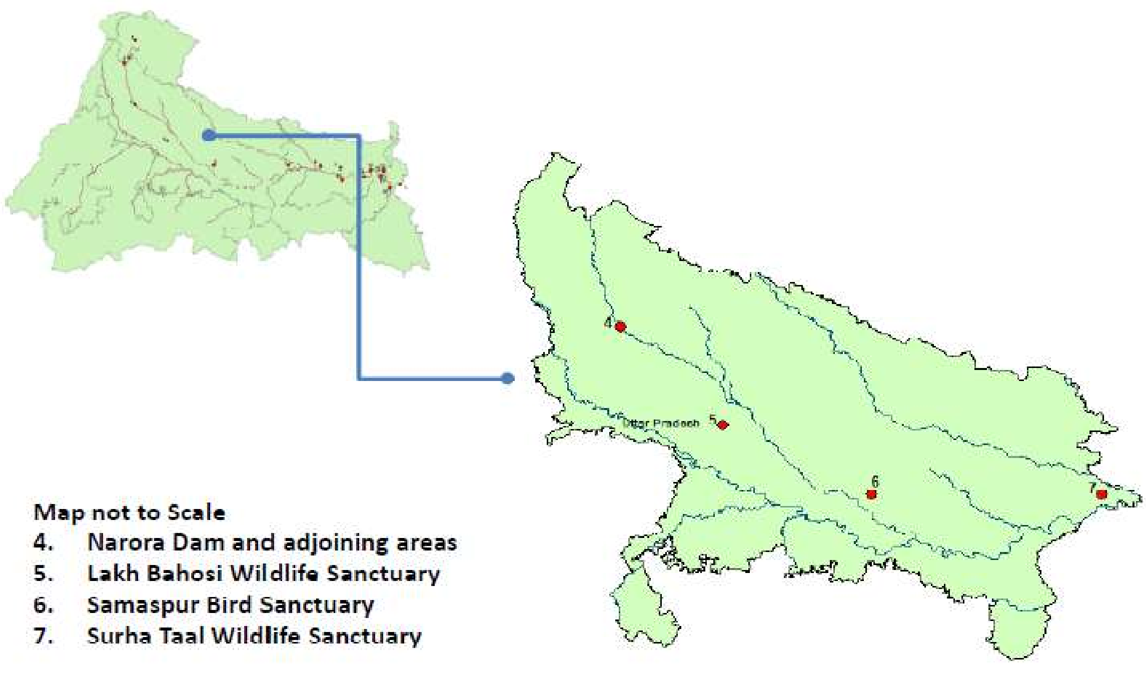


Fig. 4 The wetlands of Uttar Pradesh

2.3 Wetlands in Bihar

The state of Bihar is divided into two unequal parts by the river Ganga which flows through the middle from west to east. Wetlands in Bihar are locally known as chaurs, mauns and pats. In Bihar, the main stem of Ganga passes through 12 districts viz. Begusarai, Bhagalpur, Buxar, Katihar, Khagaria, Lakhisarai, Munger, Patna, Purnia, Saran, Sheikhpura, and Vaishali.

The total wetlands in all the district are 5183 which includes Lakes/ Ponds, Ox-bow lakes/cut off meanders, Riverine wetlands, Waterlogged areas, River/stream, Tanks/Ponds and Wetland (<2.25 ha). The total area of all types in all districts cumulative is around 168758 ha. The largest component is in river and streams (138218 ha) approximately 81.9% followed by small wetlands <2.25 ha, lakes and ponds. A graphical representation is shown in Figure 5 (a-l). The area estimates district wise is depicted in Table 3 (a-l). Geographical locations are shown in Google earth Figure 6.

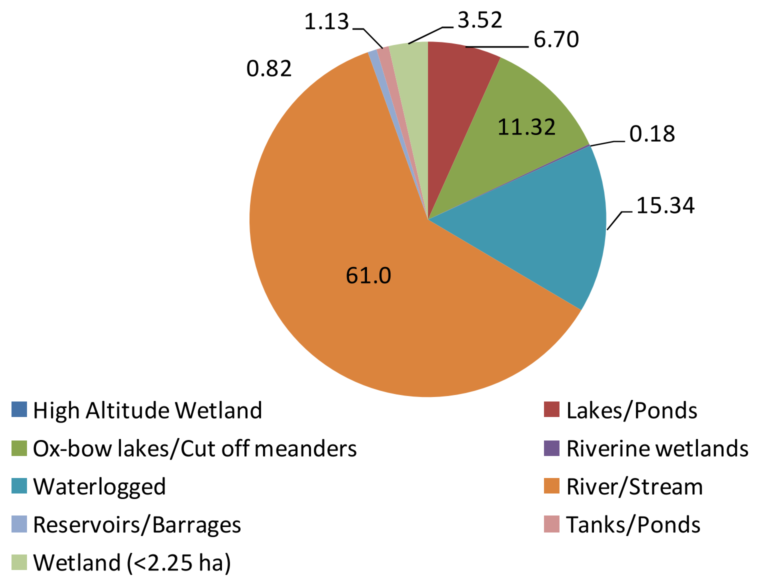


Fig. 5a Wetlands in district Purnia (Bihar)

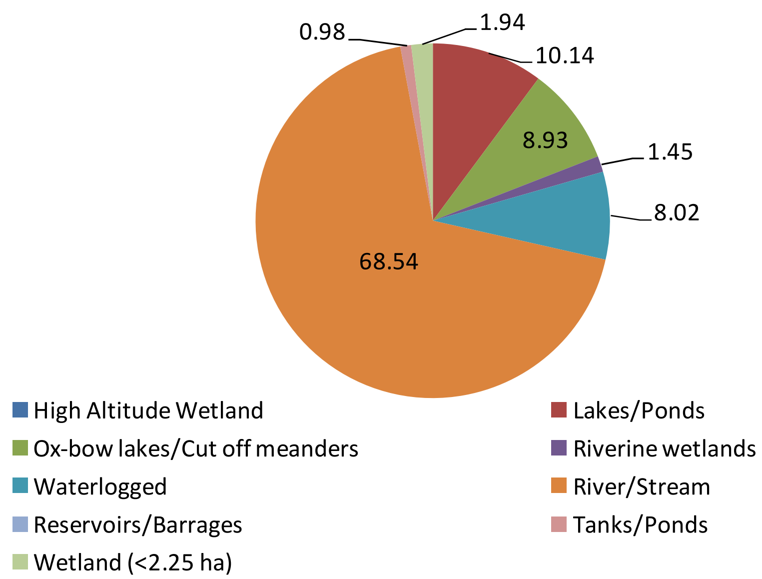


Fig. 5b Wetlands in district Katihar (Bihar)

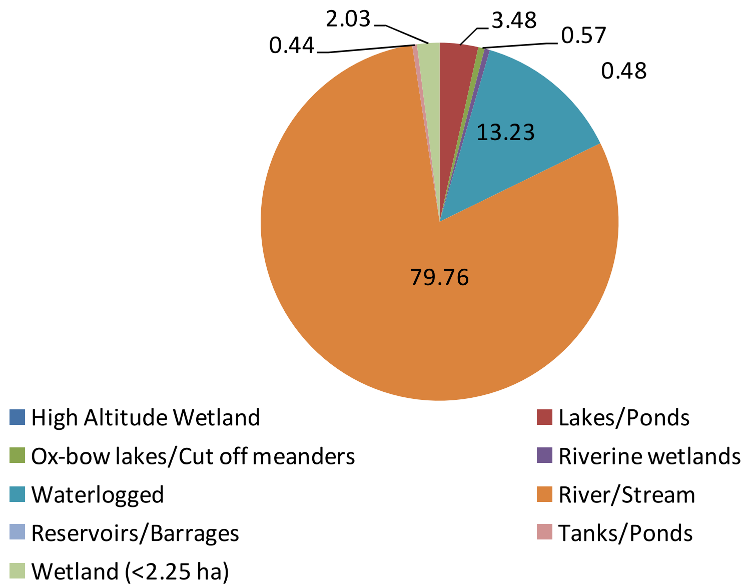


Fig. 5c Wetlands in district Saran (Bihar)

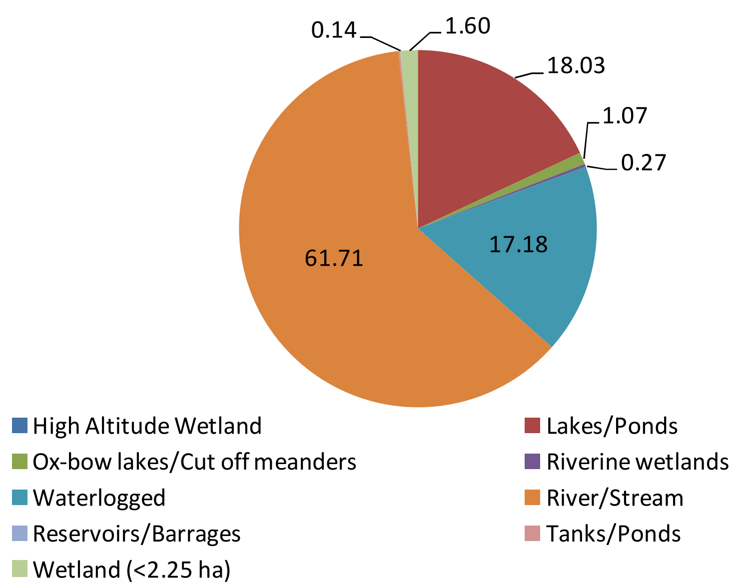


Fig. 5d Wetlands in district Vaishali (Bihar)

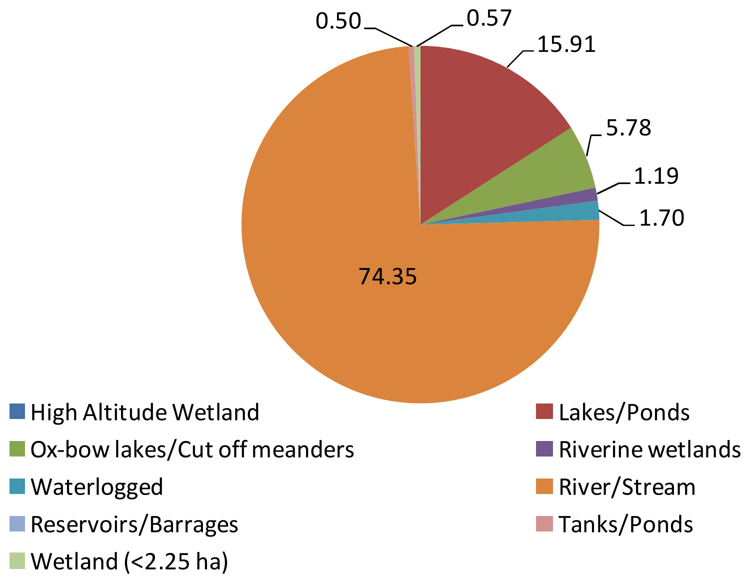


Fig. 5e Wetlands in district Begusarai (Bihar)

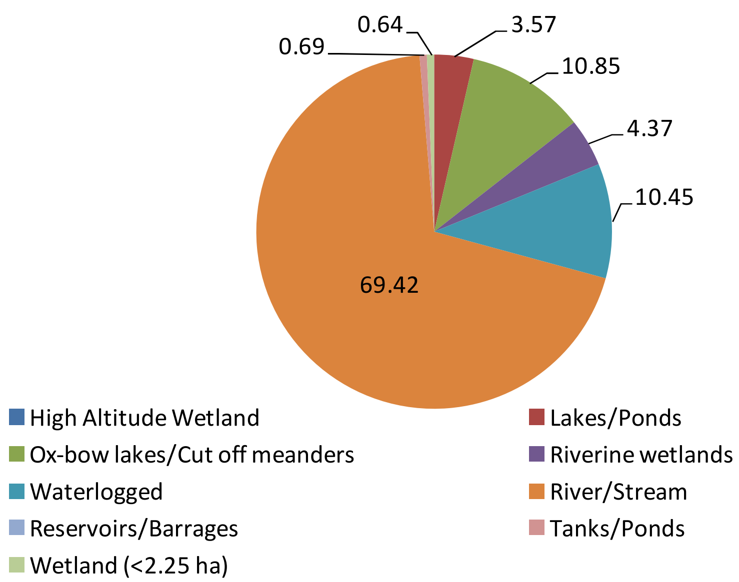


Fig. 5f Wetlands in district Khagoria (Bihar)

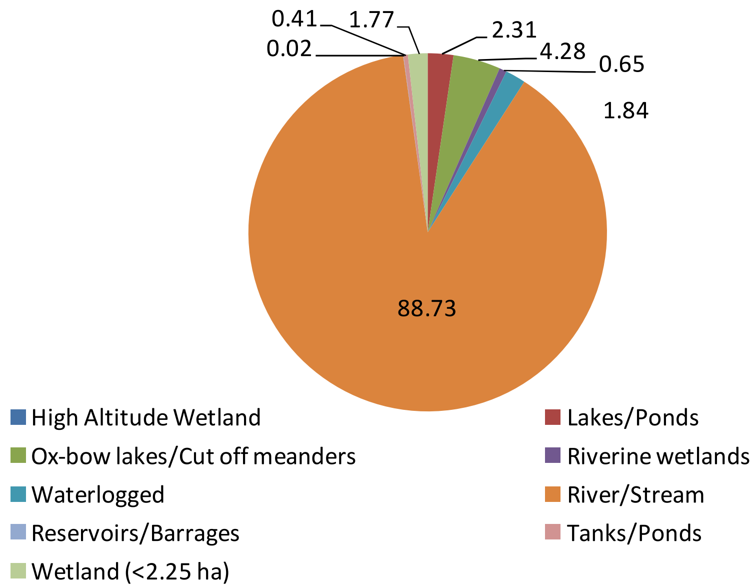


Fig. 5g Wetlands in district Bhagalpur (Bihar)

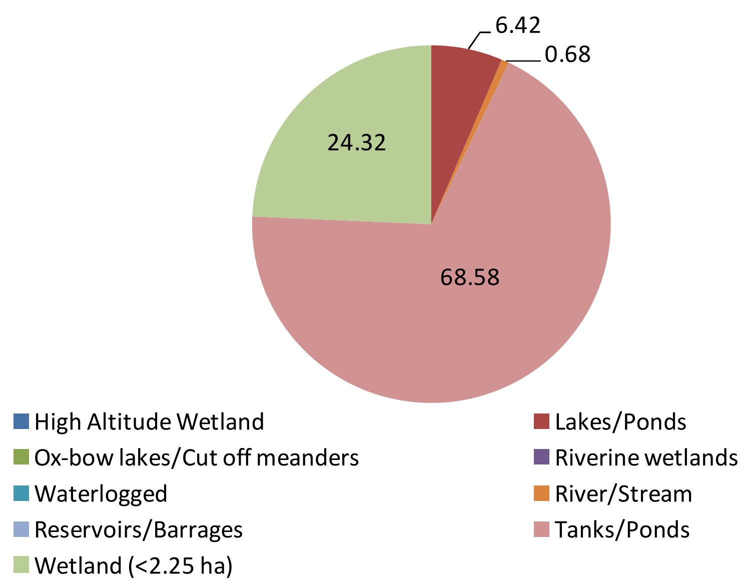


Fig. 5h Wetlands in district Sheikhpura (Bihar)

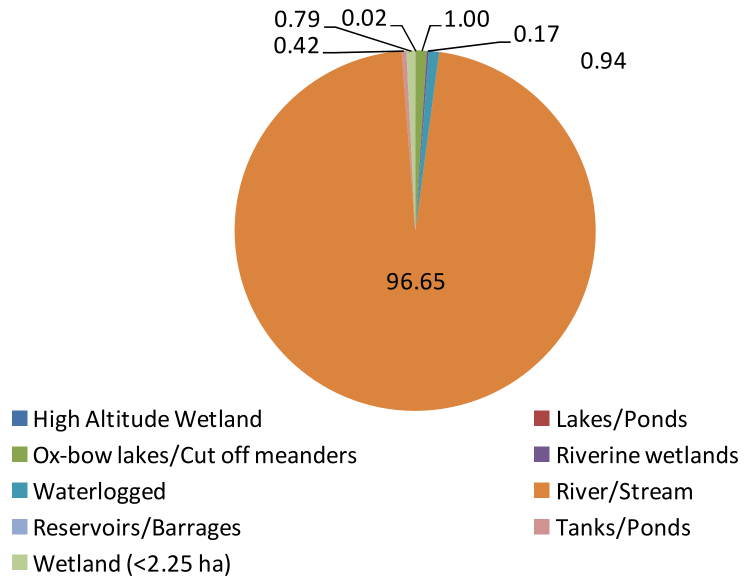


Fig. 5i Wetlands in district Patna (Bihar)

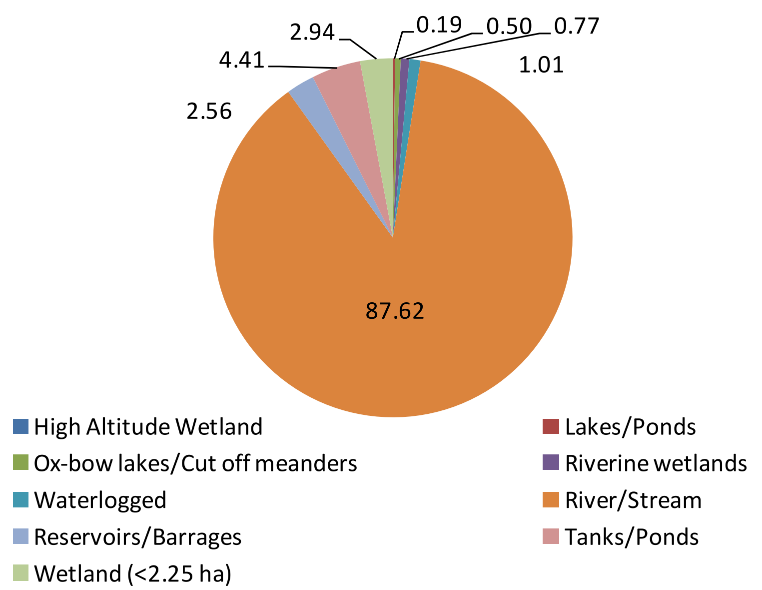


Fig. 5j Wetlands in district Lakhisarai (Bihar)

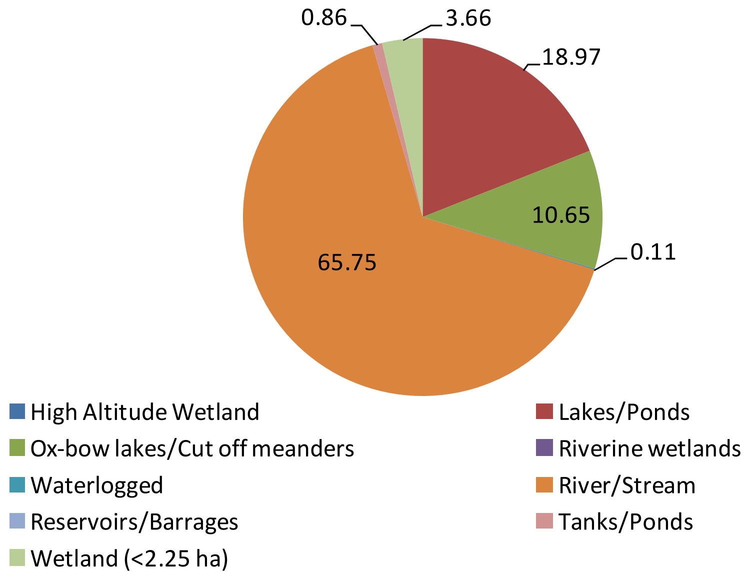


Fig. 5k Wetlands in district Buxar (Bihar)

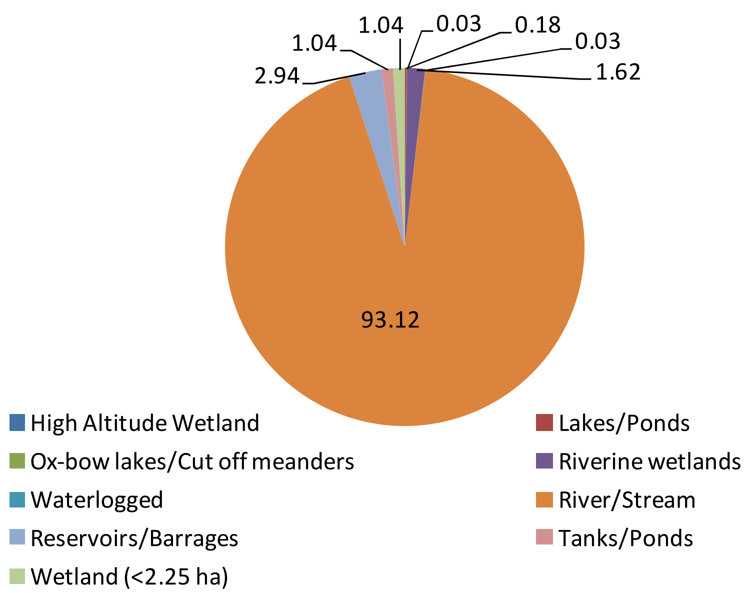


Fig. 5l Wetlands in district Munger (Bihar)

Table 3 a: Area estimates of wetlands in district Purnia

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	47	831	6.70
2	Ox-bow lakes/cut off meanders	176	1404	11.32
3	Riverine wetlands	6	22	0.18
4	Waterlogged	141	1902	15.34
5	River/stream	26	7564	61.00
6	Reservoirs/Barrages	2	102	0.82
7	Tanks/Ponds	42	140	1.13
8	Wetland (<2.25 ha)	436	436	3.52
9	Total	876	12401	100.00

Table 3 b: Area estimates of wetlands in district Katihar

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	128	3146	10.14
2	Ox-bow lakes/cut off meanders	237	2768	8.39
3	Riverine wetlands	35	451	1.45
4	Waterlogged	186	2486	8.02
5	River/stream	34	21255	68.54
6	Tanks/Ponds	80	303	0.98
7	Wetland (<2.25 ha)	602	602	1.94
8	Total	1302	31011	100.00

Table 3 c: Area estimates of wetlands in district Saran

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	26	737	3.48
2	Ox-bow lakes/cut off meanders	10	121	0.57
3	Riverine wetlands	10	102	0.48
4	Waterlogged	30	2801	13.23
5	River/stream	27	16886	79.76
6	Tanks/Ponds	10	93	0.44
7	Wetland (<2.25 ha)	430	430	2.03
8	Total	543	21170	100.00

Table 3 d: Area estimates of wetlands in Vaishali

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	31	3095	18.05
2	Ox-bow lakes/cut off meanders	6	184	1.05
3	Riverine wetlands	5	46	0.27

4	Waterlogged	62	2950	17.08
5	River/stream	16	10594	61.78
6	Tanks/Ponds	7	24	0.14
7	Wetland (<2.25 ha)	275	275	1.60
8	Total	402	17168	100.00

Table 3 e: Area estimates of wetlands in Begusarai

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	23	3240	15.91
2	Ox-bow lakes/cut off meanders	54	1177	5.78
3	Riverine wetlands	16	242	1.19
4	Waterlogged	15	347	1.70
5	River/stream	21	15142	74.35
6	Tanks/Ponds	22	101	0.50
7	Wetland (<2.25 ha)	116	116	0.57
8	Total	267	20365	100.00

Table 3 f: Area estimates of wetlands in Khagoria

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	24	416	3.57
2	Ox-bow lakes/cut off meanders	55	1264	10.85
3	Riverine wetlands	42	509	4.37
4	Waterlogged	31	1217	10.45
5	River/stream	44	8084	69.42
6	Tanks/Ponds	17	80	0.69
7	Wetland (<2.25 ha)	75	75	0.64
8	Total	288	11645	100.00

Table 3 g: Area estimates of wetlands in Bhagalpur

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	16	558	2.31
2	Ox-bow lakes/cut off meanders	63	1034	4.28
3	Riverine wetlands	23	157	0.65
4	Waterlogged	21	445	1.84
5	River/stream	28	21446	88.73
6	Reservoirs/Barrages	1	5	0.02
7	Tanks/Ponds	26	99	0.41
8	Wetland (<2.25 ha)	427	427	1.77
9	Total	605	24171	100.00

Table 3 h: Area estimates of wetlands in Sheikhpura

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	2	19	6.42
2	River/stream	2	2	0.68
3	Tanks/Ponds	50	203	68.58
4	Wetland (<2.25 ha)	72	72	24.32
5	Total	126	296	100.00

Table 3 i: Area estimates of wetlands in Patna

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	1	5	0.02
2	Ox-bow lakes/cut off meanders	11	207	1.00
3	Riverine wetlands	2	35	0.17
4	Waterlogged	14	194	0.94
5	River/stream	22	19986	96.65
6	Tanks/Ponds	13	87	0.42
7	Wetland (<2.25 ha)	164	164	0.79
8	Total	227	20678	100.00

Table 3 j: Area estimates of wetlands in Lakhisarai

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	1	8	0.19
2	Ox-bow lakes/cut off meanders	3	21	0.50
3	Riverine wetlands	4	32	0.77
4	Waterlogged	2	42	1.01
5	River/stream	11	3660	87.62
6	Reservoirs/Barrages	1	107	2.56
6	Tanks/Ponds	49	184	4.41
7	Wetland (<2.25 ha)	123	123	2.94
8	Total	194	4177	100.00

able 3 k: Area estimates of wetlands in Buxar

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	2	705	18.97
2	Ox-bow lakes/cut off meanders	5	396	10.65
3	Waterlogged	1	4	0.11
4	River/stream	6	2444	65.75
5	Tanks/Ponds	8	32	0.86
6	Wetland (<2.25 ha)	136	136	3.66
7	Total	158	3717	100.00

Table 3 l: Area estimates of wetlands in Munger

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	3	22	0.18
2	Ox-bow lakes/cut off meanders	1	3	0.03
3	Riverine wetlands	19	194	1.62
4	Waterlogged	1	4	0.03
5	River/stream	13	11155	93.12
6	Reservoirs/Barrages	3	352	2.94
7	Tanks/Ponds	31	125	1.04
8	Wetland (<2.25 ha)	124	124	1.04
9	Total	195	11979	100.00

District wise area information of wetlands in the Ganga River Basin (Source: National Wetland Inventory and Assessment. National Wetland Atlas. MoEF, Govt. of India. Space Applications Centre, Indian Space Research Organization

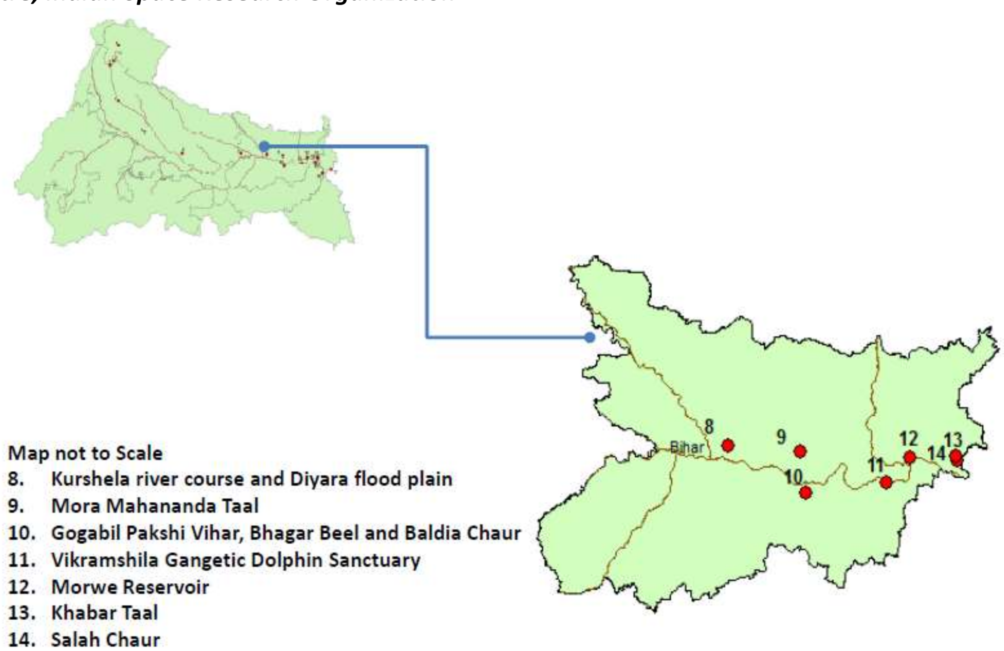


Fig. 6 The wetlands of Bihar

2.4 Wetlands in Sahibganj

Only the Sahibganj district of Jharkhand falls directly into the Ganga river basin. The district has 555 wetlands having the area of 16118 ha. Like Uttar Pradesh and Bihar rivers and streams constitute nearly 65% of the wetland area followed by lakes and ponds17.75% and wetlands <2.25 ha and riverine wetlands. The numerical relation of wetlands is graphically represented in Figure 7. The area estimates are shown in Table 4. Geographical locations are shown in Google earth Figure 7.

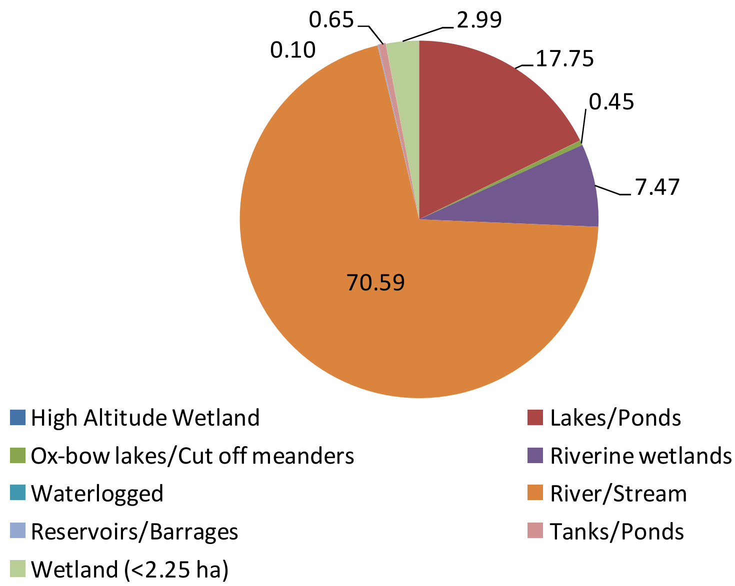


Fig. 7 Wetlands in district Sahibganj (Jharkhand)

Table 4: Area estimates of wetlands in Sahibganj

Sl. No.	Wetland category	No. of wetlands	Total area wetland (ha)	% of wetland area
1	Lakes/Ponds	10	2861	17.75
2	Ox-bow lakes/cut off meanders	15	73	0.45
3	Riverine wetlands	14	1204	7.74
4	River/stream	13	11378	70.59
5	Reservoirs/Barrages	3	16	0.10
6	Tanks/Ponds	18	104	0.65
7	Wetland (<2.25 ha)	482	482	2.99
8	Total	555	16118	100.00

District wise area information of wetlands in the Ganga River Basin (Source: National Wetland Inventory and Assessment. National Wetland Atlas. MoEF, Govt. of India. Space Applications Centre, Indian Space Research Organization

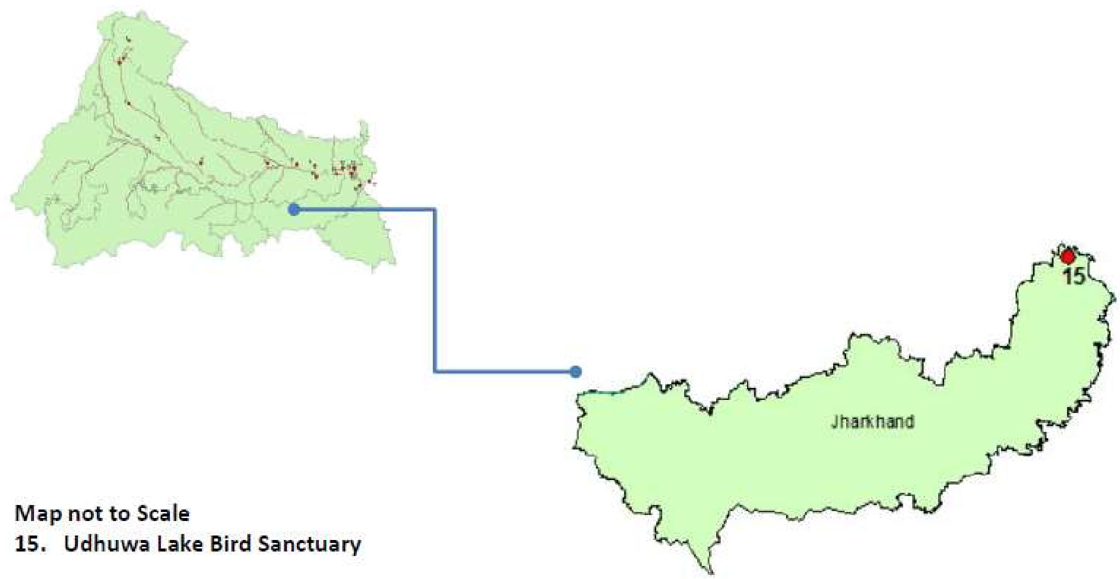


Fig. 8 The wetlands of Jharkhand represented in the Google earth map

2.5 Wetlands in West Bengal

The Ganga is the perennial river in the state of West Bengal. One branch of Ganga enters Bangladesh in the name of Padma and the other flows through the state in the names of Bhagirathi and Hooghly. In West Bengal, 7 district fall directly into the Ganga river basin. Wetlands up to Malda district (Farakka Barrage) are considered in this report. Malda district has 123 wetland aggregate area of 4608 ha. The river/ streams contribute the largest wetlands of 51.27% followed by lakes/ ponds 18.31% and wetlands <2.25 ha 17.63%. The wetlands types are given in Figure 9 and geographical locations are shown in Google earth Figure 10. The area estimates are shown in Table 5.

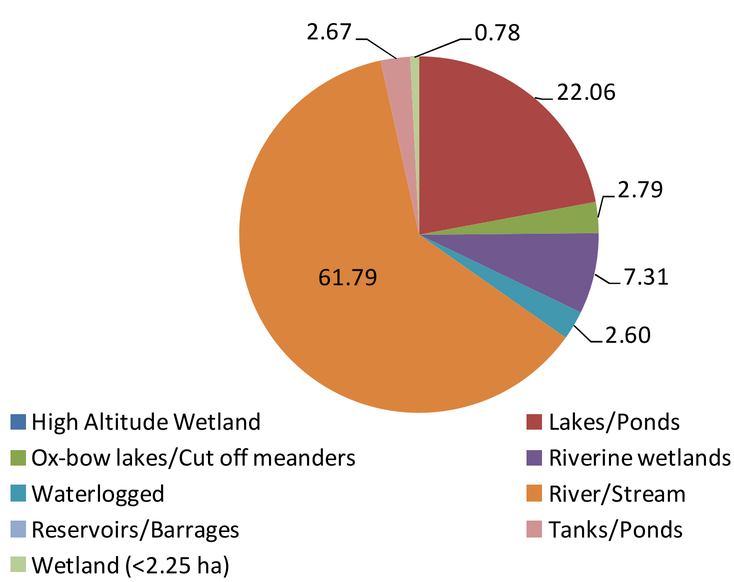


Fig. 9 Wetlands in district Malda (West Bengal)

Table 5: Area estimates of wetlands in Malda

Sl. No.	Wetland category	No. of wetlands	Total area wetland(ha)	% of wetland area
1	Lakes/Ponds	123	4608	18.31
2	Ox-bow lakes/cut off meanders	31	582	2.31
3	Riverine wetlands	148	1527	6.07
4	Waterlogged	63	544	2.16
5	River/stream	32	12906	51.29
6	Tanks/Ponds	105	558	2.22
7	Wetland (<2.25 ha)	4437	162	17.63
8	Total	4939	20887	100.00

District wise area information of wetlands in the Ganga River Basin (Source: National Wetland Inventory and Assessment. National Wetland Atlas. MoEF, Govt. of India. Space Applications Centre, Indian Space Research Organization

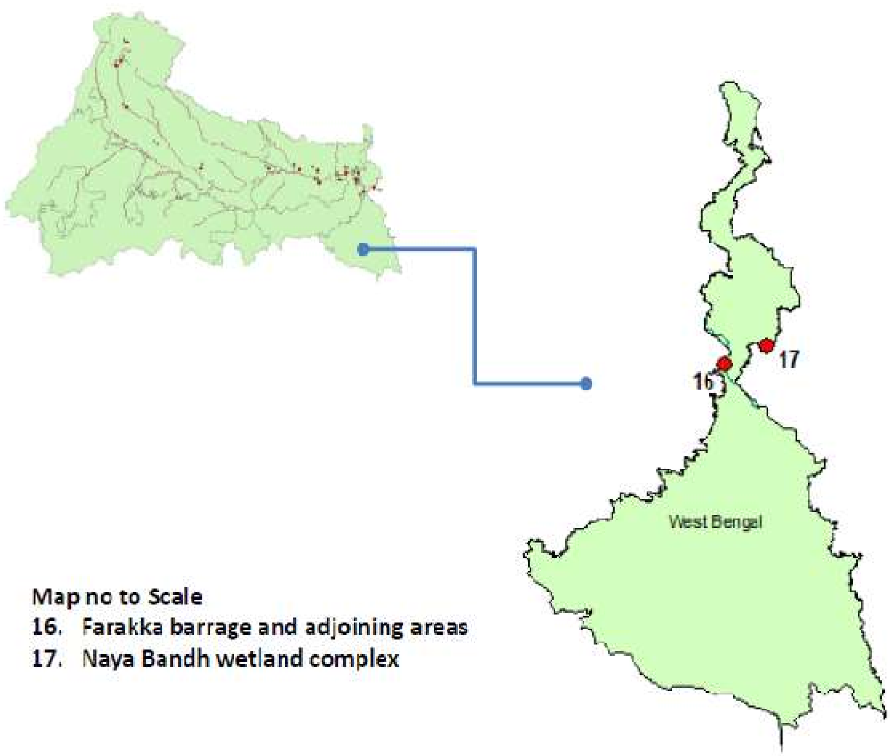


Fig. 10 The wetlands of Malda (West Bengal)

3. Biodiversity of some wetlands in the Ganga river basin

1. Banganga wetland: Banganga wetland is situated in the state of Uttrakhand. It is a riverine wetland and originates near Bishenpur and flows through the Haridwar district of Uttrakhand. In this region many small islands are formed. These are the home to threatened species like Swamp deer (*Cervus duvauceli*). These provide habitat for Hog deer (*Axisprocinus*) and Otter (*Lutra lutra*). 70 species of birds and 40 species of fishes are reported from this region. Globally threatened avian species include *Sarus crane*, Darter and Black tailed godwit (*Limosa limosa*). Small population of marsh crocodile *Crocodylus palustris* are reported here. Indian flapshell turtle, Spotted pond turtle and Red crowned roofed turtle (*Batagur kachuga*) are reported here. *Phragmites karka*, *Ipomoea* sp., *Polygonum barbatum*, and *Polygonum glabrum* are mostly seen plant species in the islands. Reported free floating plants are *Azolla*, *Eichhornia*, and *Lemna*, semi submerged are *Ludwigia*, *Potamogeton*, *Nymphaea*, *Nymphoides, Marsilea* and *Trapa*, submerged *are Ceratophyllum, Hydrilla, Najas, Potamogeton* spp. and *Vallisneria*. Weed infestation occurs by *Eichhorniacrassipes, Enydra fluctuans*, and *Ipomoea* etc. Adhikari *et al.* (2008) reported 178 plant species from a part of the wetland (Table 6).

2. Jhilmil Jheel: This wetland is situated on the bank of river Ganga in the Haridwar district of Uttarakhand. Tall grassland and moist deciduous forest are seen in this region. 160 bird species are reported from this region. Critically endangered *Gyps bengalensis* are reported here. Other threatened avian species including Egyptian vulture, Lesser adjutant stork, Black bellied tern, Black necked stork are also reported. Other common and rare fauna include Spotted deer, Sambar, Barking deer, Swamp deer, Elephant, Nilgai, Leopard, Tiger, Golden jackal, Jungle cat, Civet, Common langur, *Rhesus macaque*, Python, Common krait, Monitor lizard etc.

3. Tehri dam: Tehri dam is situated on the Bhagirathi river with an area of 1245ha. In the riparian zone trees like Chir, Oaks, Conifers, Sal, Deodar, Haldu, Yew, Cypress, Rhododendron etc. are found. This region is well known for the medicinal plants like Brahmi and Ashwagandha. Fruits like Cornel, Figs, Kaiphal, Mulberry, Kingora, Raspberry, Blackberry, Currants, Medlars, Gooseberries, Hazelnuts, Apples, Pears, Apricots, Plums, Peaches, Oranges, Limes, Bananas, Pomegranates and Walnuts are found in the forest area. The riparian forest is full with animals like Monkey, Langur, Wild-Cat, Goat, Pig, Fox, Wild-Dog, Black Bear and Flying Squirrel. Musk deer found in the forest is a threatened species. Pheasants, Kalij, Koklas, Cheers, Monal, Wild Fowls, Harial, Parrots, Chatak, Papiha, Haldu, Neelkanth, Pigeons, Partridges, Kala Titar, Chakor and Neora are some reported avian fauna.

4. Lakh Bahosi Wildlife Sanctuary: It is situated in the Farrukhabad district of Uttar Pradesh. Two ox bow lakes, Lakh and Bahosi are situated here. Other small wetlands are also found in the vicinity. Globally threatened avian species, *Aquila clanga* (Greater spotted eagle), *Grus antigone* (*Sarus crane*) are reported from here. Black necked stork and Bar headed goose are also reported. Bluebull, Jungla Cat, Golden Jackal amd Blacknaped Hare are other the key species found here.

5. Samaspur Bird Sanctuary: It is situated in the Raebareily district of Uttar Pradesh. Earlier it was named as Salon wetland. Six small lakes are connected here. More than 110 bird species are reported from here. Among these, 14 species are reported as ducks, 13 species as waders, 4 species as stork and 10 species as raptors. Black necked stork and Pallas's fish eagle breed in this region. More than 10 fish species of economic importance are reported from this region.

6. Surha Taal Wildlife Sanctuary: It is situated in the Ballia district of Uttar Pradesh. This area is important because of the huge flock of birds during winter. Anatidae is numerous, followed by Phalacrocoracidae, Jacanidae and Ardeidae are reported avian families. *Sarus crane* breeds here.

7. Naroradam and adjoin areas: It is situated in the state of Uttar Pradesh. When the water level goes low, many small sand bars are formed near the barrage and the adjoining lakustrine region. These islands provide resting and breeding place for ducks, geese, cranes, terns, lapwings and Indian skimmer. 133 bird species are reported from this region. Sarus, Diving Ducks, Common Pochard, Red Crested Pochard, Tufted Pochard, White Eyed Pochard, Pallas's Fish Eagle and Black Necked Stork are reported avian fauna in this place. Other key species include Gangetic Dolphin, Mugger, Gharial, Fishing Cat and Hog Deer. 11 species of freshwater turtle are reported from this region.

8. Gogabil Pakshi Vihar, Bhagar Beel and Baldia Chaur: This wetland is situated in the Kathihar district of Bihar. 71 bird species are reported from this ox-bow lake. Out of these 1 is Vulnerable, 3 Near Threatened and 4 biome restricted.

9. Kursela river course and Diyara flood plain: It is situated in the Kathihar district of Bihar. Threatened avian species like *Gyps bengalensis* (Oriental white backed vulture*), Leptoptilos javanicus* (Lesser adjutant stork), *Haliaeetus leucoryphus* (Pallas's fish eagle), *Leptoptilos dubius* (Greater adjutant stork) are reported avian fauna from this region. Endangered Gangetic Dolphin inhabits here.

10. Mokama Tal: It is situated in the Patna, Samastipur and Begusarai district of Bihar. About 149 bird species are reported from this region. *Pseudibis papillosa* (Black ibis), *Plegadis falcinellus* (Glossy ibis), *Platalea leucorodia* (Eurasian spoonbill), *Anser anser* (Greylag goose), *Anser indicus* (Bar headed goose), *Dendrocygna javanica* (Lesser whistling duck) and*Dendrocygna bicolour* (Large whistling duck) are reported avian species.

11. Vikramshila Gangetic Dolphin Sanctuary: This wetland is present in the Bhagalpur district of Bihar and famous for the endangered Gangetic Dolphin. *Leptoptilos dubius* (Greater adjutant stork), *Leptoptilos javanica* (Lesser adjutant stork), *Mycteria leucocephala* (Painted Stork), *Ciconia nigra*, *Ephippiorhynchus asiaticus*, *Anstomus oscitans* (Asian openbill), *Grus grus* (Common crane) and*Platalea leucordia* (Eurasian spoonbill) etc. are reported avian fauna.

12. Salah Chor: This wetland is situated in the Vaishali district of Bihar with an area of 638 ha. Major flora is not present. Stork and Cormorant are common avian fauna.

13. Morwe reservoir: This reservoir is situated in the Lakhisarai district of Bihar with an area of 107 ha. Stork and Cormorant are commonavian fauna. Rohu, Magur, Singhi are cultured fishes.

14. Khabar Tal: This natural lake is situated in the Begusarai district of Bihar with an area of 2680 ha. 55 species of macrophytes are found. They are submerged, floating or emergent type. As this lake support huge number of resident and migratory birds, it is declared as a bird sanctuary. Dabchick, herons, egrets, openbill stork, black ibis, whistling ducks, cotton teal, purple moorhen, little grebe, grey pelican, raylag goose, golden plover and common snipe are found here. Indian major and minor carps (*Labeo rohita, Catla catla, Cirrhinus mrigala, Cirrhinus reba*), snake headed fishes (*Channa punctatus, Channa striatus*) and air breathing fishes (*Heteropneustes fossilis, Notopterus notopterus, Anabas testudineous*) are found here. *Pila globosa* is common in this area. This wetland is under threat due to poaching of birds, infestation of aquatic vegetations, agricultural encroachment and eutrophication by the use of fertilizers and pesticides.

15. Mora Mahananda Tal: This is natural riverine wetland. It is situated in the Katihar district of Bihar with an area of 68 ha. Macrophytes are found around the wetland. Filamentous algae are found in the wetland. It is the home to many resident birds. Migratory birds are also reported. Tortoises are observed frequently from this wetland. Indian carps and freshwater prawns are cultured in this wetland. Due to the poor communication facility of this area, the wetland is not under severe threat. However aquaculture and other agricultural activities have increased the eutrophication problem with a consequence of weed infestation.

16. Udhuwa Lake Bird Sanctuary: It is situated in the Sahebganj district of Jharkhand. Two water bodies, Pataura and Berhale are found here. The sanctuary is connected with the Ganga river at Farakka. 97 bird species are reported from this region. Near threatened *Ephippiorhynchus asiaticus* (Black necked stork) is reported from this place.

17. Naya Bandh wetland complex: This is situated in the Malda district of West Bengal. About 150 bird species are reported from this region, of these 6 are globally threatened, 5 near threatened, 11 biome species.

18. Farakka barrage and adjoining areas: It is situated in the Malda district of state of West Bengal. The small riverine islets formed during winter provide diurnal activity place for birds. About 70 bird species are reported from this region. *Dendrocygna bicolour* (Large whistling duck), *Aythya fuligula* (Tufted duck) etc. are some important avian species found here. This area provide habitat for endangered Gangetic Dolphin, Gharial, Marsh Crocodile and Otters. More than 50 economically important fishes are found in this region.

Table 6: Plant species in the Banganga wetland (Source: Adhikari, B.S., Babu, M.M. Floral diversity of Baanganga Wetland, Uttarakhand, India. Check List 4(3): 279–290, 2008)

Sl. No.	Scientific name	Family
1.	*Hygrophila polysperma*	Acanthaceae
2.	*Rungia parviflora*	Acanthaceae
3.	*Rungia pectinata*	Acanthaceae
4.	*Sagitaria sagitifolia*	Alismataceae
5.	*Achyranthes aspera*	Amaranthaceae
6.	*Alternanthera paronychioides*	Amaranthaceae
7.	*Alternanthera philoxeroides*	Amaranthaceae
8.	*Alternanthera sessilis*	Amaranthaceae
9.	*Amaranthus spinosus*	Amaranthaceae
10.	*Centella asiatica*	Apiaceae
11.	*Hydrocotyle sibthorpioides*	Apiaceae
12.	*Psamogeton canescens*	Apiaceae
13.	*Seseli diffusum*	Apiaceae
14.	*Oxystelma secamone*	Asclepiadaceae
15.	*Ageratum conyzoides*	Asteraceae
16.	*Ageratum houstonianum*	Asteraceae
17.	*Bidens bitternata*	Asteraceae
18.	*Blumea laciniata*	Asteraceae
19.	*Blumea membranacea*	Asteraceae
20.	*Blumea mollis*	Asteraceae
21.	*Centipeda minima*	Asteraceae
22.	*Cirsium arvense*	Asteraceae
23.	*Eclipta prostrata*	Asteraceae
24.	*Elephantopus scaber*	Asteraceae
25.	*Enydra fluctuans*	Asteraceae
26.	*Erigeron bonariensis*	Asteraceae
27.	*Gnaphalium pensylvanicum*	Asteraceae
28.	*Gnaphalium polycaulon*	Asteraceae
29.	*Grangea maderaspatana*	Asteraceae
30.	*Ixeris polycephala*	Asteraceae
31.	*Launaea procumbens*	Asteraceae
32.	*Parthenium hysterophorus*	Asteraceae
33.	*Pulicaria crispa*	Asteraceae
34.	*Sonchus asper*	Asteraceae
35.	*Sonchus oleracea*	Asteraceae
36.	*Tridax procumbens*	Asteraceae

37.	*Vernonia cinerea*	Asteraceae
38.	*Xanthium strumarium*	Asteraceae
39.	*Azolla pinnata*	Azollaceae
40.	*Cordia dichotoma*	Boraginaceae
41.	*Cynoglossum zeylanicum*	Boraginaceae
42.	*Brassica junceae*	Brassicaceae
43.	*Coronopus didymus*	Brassicaceae
44.	*Rorippa nasturtium-aquaticum*	Brassicaceae
45.	*Cassia tora*	Caesalpiniaceae
46.	*Parkinsonia aculeate*	Caesalpiniaceae
47.	*Tamarindus indica*	Caesalpiniaceae
48.	*Campanula wallichii*	Campanulaceae
49.	*Cannabis sativa*	Cannabinaceae
50.	*Stellaria media*	Caryophyllaceae
51.	*Ceratophyllum demersum*	Ceratophyllaceae
52.	*Chenopodium album*	Chenopodiaceae
53.	*Chenopodium ambrosioides*	Chenopodiaceae
54.	*Suaeda fruticosa*	Chenopodiaceae
55.	*Terminalia arjuna*	Combretaceaes
56.	*Commelina benghalensis*	Commelinaceae
57.	*Commelina hasskarlii*	Commelinaceae
58.	*Ipomoea carnea*	Convolvulaceae
59.	*Ipomoea aquatica*	Convolvulaceae
60.	*Momordica dioica*	Cucurbitaceae
61.	*Carex* sp.	Cyperaceae
62.	*Cyperus bulbosus*	Cyperaceae
63.	*Cyperus compressus*	Cyperaceae
64.	*Cyperus cyperoides*	Cyperaceae
65.	*Cyperus kyllingia*	Cyperaceae
66.	*Cyperus pygmaeus*	Cyperaceae
67.	*Cyperus rotundus*	Cyperaceae
68.	*Cyperus triceps*	Cyperaceae
69.	*Elaeocharis palustris*	Cyperaceae
70.	*Fibristylis falcata*	Cyperaceae
71.	*Scirpus* sp.	Cyperaceae
72.	*Scirpus tuberosus*	Cyperaceae
73.	*Dryopteris* sp.	Dryopteridaceae
74.	*Equisetum ramosissimum*	Equisetaceae
75.	*Euphorbia hirta*	Euphorbiaceae
76.	*Euphorbia prostrata*	Euphorbiaceae

77.	*Kirganelia reticulata*	Euphorbiaceae
78.	*Trewia nudiflora*	Euphorbiaceae
79.	*Acacia catechu*	Fabaceae
80.	*Acacia farnesiana*	Fabaceae
81.	*Acacia nilotica*	Fabaceae
82.	*Dalbergia sissoo*	Fabaceae
83.	*Desmodium triflorum*	Fabaceae
84.	*Lathyrus aphaca*	Fabaceae
85.	*Medicago lupulina*	Fabaceae
86.	*Melilotus alba*	Fabaceae
87.	*Melilotus indica*	Fabaceae
88.	*Pongamia pinnata*	Fabaceae
89.	*Trifolium tomentosum*	Fabaceae
90.	*Trigonella foenum-graecum*	Fabaceae
91.	*Trigonella hamosa*	Fabaceae
92.	*Vicia hirsute*	Fabaceae
93.	*Vicia sativa*	Fabaceae
94.	*Vicia tetrasperma*	Fabaceae
95.	*Exacum pedunculatum*	Gentianaceae
96.	*Hydrilla verticillata*	Hydrocharitaceae
97.	*Vallisneria natans*	Hydrocharitaceae
98.	*Leucas cephalotes*	Lamiaceae
99.	*Nepeta hindostana*	Lamiaceae
100.	*Perilla frutescens*	Lamiaceae
101.	*Salvia plebeia*	Lamiaceae
102.	*Lemna perpusilla*	Lemnaceae
103.	*Spirodela polyrhiza*	Lemnaceae
104.	*Linum usitatissimum*	Linaceae
105.	*Ammannia baccifera*	Lythraceae
106.	*Rotala densiflora*	Lythraceae
107.	*Malvastrum coromandelianum*	Malvaceae
108.	*Sida rhombifolia*	Malvaceae
109.	*Urena lobata*	Malvaceae
110.	*Marslea quadriolia*	Marseliaceae
111.	*Martynia annua*	Martyniaceae
112.	*Albizia procera*	Mimosaceae
113.	*Pithecellobium dulce*	Mimosaceae
114.	*Ficus palmata*	Moraceae
115.	*Ficus racemosa*	Moraceae
116.	*Syzygium cumini*	Myrtaceae

117.	*Najas graminea*	Najadaceae
118.	*Najas minor*	Najadaceae
119.	*Boerhavia diffusa*	Nyctaginaceae
120.	*Nymphaea nouchali*	Nymphaeceae
121.	*Nymphoides cristata*	Nymphaeceae
122.	*Nymphoides indica*	Nymphaeceae
123.	*Ludwigia adscendens*	Onagraceae
124.	*Zeuxine strateumatica*	Orchidaceae
125.	*Oxalis corniculata*	Oxalidaceae
126.	*Argemone mexicana*	Papaveraceae
127.	*Avena sativa*	Poaceae
128.	*Brachiaria distachya*	Poaceae
129.	*Brachiaria ramosa*	Poaceae
130.	*Cynodon dactylon*	Poaceae
131.	*Eleusine indica*	Poaceae
132.	*Imperata cylindrical*	Poaceae
133.	*Oplismenus burmanii*	Poaceae
134.	*Phalaris minor*	Poaceae
135.	*Phragmites karka*	Poaceae
136.	*Polypogon fugax*	Poaceae
137.	*Saccharum bengalensis*	Poaceae
138.	*Saccharum spontaneum*	Poaceae
139.	*Setaria verticillata*	Poaceae
140.	*Triticum vulgare*	Poaceae
141.	*Polygonum barbatum*	Polygonaceae
142.	*Polygonum glabrum*	Polygonaceae
143.	*Polygonum hydropiper*	Polygonaceae
144.	*Polygonum lapathifolium*	Polygonaceae
145.	*Polygonum plebeium*	Polygonaceae
146.	*Rumex dentatus*	Polygonaceae
147.	*Rumex nepalensis*	Polygonaceae
148.	*Eichhornia crassipes*	Pontederiaceae
149.	*Monochoria vaginalis*	Pontederiaceae
150.	*Potamogeton crispus*	Potamogetonaceae
151.	*Potamogeton nodosus*	Potamogetonaceae
152.	*Potamogeton pectinatus*	Potamogetonaceae
153.	*Anagallis arvensis*	Primulaceae
154.	*Primula umbellata*	Primulaceae
155.	*Ranunculus muricatus*	Ranunculaceae
156.	*Ranunculus sceleratus*	Ranunculaceae

157.	*Zizyphus mauritiana*	Rhamnaceae
158.	*Potentilla supina*	Rosaceae
159.	*Hedyotis corymbosa*	Rubiaceae
160.	*Wendlandia exserta*	Rubiaceae
161.	*Bacopa monnieri*	Scrophulariaceae
162.	*Bacopa procumbens*	Scrophulariaceae
163.	*Lindernia ciliata*	Scrophulariaceae
164.	*Mazus pumilus*	Scrophulariaceae
165.	*Verbascum chinense*	Scrophulariaceae
166.	*Veronica anagallis-aquatica*	Scrophulariaceae
167.	*Nicotiana plumbaginifolia*	Solanaceae
168.	*Physalis minima*	Solanaceae
169.	*Solanum nigrum*	Solanaceae
170.	*Solanum torvum*	Solanaceae
171.	*Solanum viarum*	Solanaceae
172.	*Tamarix dioica*	Tamaricaceae
173.	*Trapa natans var bispinosa*	Trapaceae
174.	*Typha elephantina*	Typhaceae
175.	*Pouzolzia pentandra*	Urticaceae
176.	*Pouzolzia zeylanica*	Urticaceae
177.	*Utricularia* sp.	Utriculariaceae
178.	*Phyla nodiflora*	Verbenaceae

4. Threats to wetlands

The biodiversity of freshwater ecosystem is declining faster than other biomes. The rate of loss of freshwater biodiversity during 1970-2000 was almost double that of marine and terrestrial biomes. Wetlands perform many functions, provide ecological services and support thousands of lives. However, overexploitation of resources and other anthropogenic and natural processes put stress and continuous threats on the wetlands. With the increase of human population and land demand, wetland areas are encroached for agriculture. As a consequence erosion and nutrient runoff to the wetland increases leading to eutrophication. Accidental or illegal introduction of alien species push threat to indigenous biodiversity of wetlands altering the food chain and the nutrient cycle in lentic water ecosystem. Ahmed et al (2002) estimated an average of 100 waterbirds traded illegally per week at one area of Uttar Pradesh. Major illegally traded waterbird species are *Pelecanus onocrotalus, Mycteria leucocephala, Ephippiorhynchus asiaticus, Ciconia ciconia, Platalea leucorodia, Phoenicopterus ruber, Grus antigone, Anthropoides virgo, Anser indicus, Anser anser, Anus acuta, Ans clypeata, Anas crecca, Tadorna ferriginea, Anas Penelope, Nettapus coromandelianus, Rostratula benghalensis, Hydrophasianus chirurgus, Metopidius* *indicus, Dendrocygna javanics* etc. Conservation issues of some wetlands of Ganga river basin are reported in Table 7.

Various threats on wetlands of this basin are:

a) Removal of vegetation (deforestation) and its consequence as erosion.
b) Shifting of wetlands to paddy fields.
c) Pressure due developmental activities like industry or residential areas.
d) Pollution due to industrial and domestic waste dumping.
e) Overfishing and unregulated fishing.
f) Poaching of birds and other animals.
g) Introduction of exotic plant and animal species.
h) Pollution due agricultural runoff.

Table 7: Conservation issues of some wetlands of Ganga River Basin

Name of the wetland	State	Conservation issues
Banganga wetland	Uttarakhand	Agricultural encroachment Human settlement Weed infestation Silt deposition Livestock grazing
Jhilmil Jheel	Uttarakhand	Livestock grazing Poaching Road kill Invasive plant species Encroachmen
Lakh Bahosi wildlife sanctuary	Uttar Pradesh	Grazing Grass collection Hunting and Bird trapping
Samaspur Bird Sanctuary	Uttar Pradesh	Fishing Drainage Livestock grazing Siltation Pesticides
Surha Taal Wildlife Sanctuary	Uttar Pradesh	Excessive fishing Irrigation Weed infestation Over exploitation
Gogabil Pakshi Vihar, Bhagar Beel and Baldia Chaur	Bihar	Poaching Bird trading

		Land disputes Fisheries
Kursela River Course and Diyara Flood plain	Bihar	Bird trapping Poaching Less scientific investigations Poor administration Agricultural runoff
Mokama Tal	Bihar	Poaching Construction of thermal power plants Agricultural runoff
Vikramshila Gangetic Dolphin Sanctuary	Bihar	Agricultural runoff Fishing Transportation
Khabar Tal	Bihar	Poaching of birds Weed infestation Agricultural encroachment Eutrophication Agricultural run off Livestock grazing
Mora Mahananda Tal	Bihar	Threatened by eutrophication and weed infestation
Udhuwa Lake Bird Sanctuary	Jharkhand	Illegal settlement Agriculture Poaching Illegal fishing Fertilizers and pesticides
Naya Bandh Wetland complex	West Bengal	Aquaculture activities Bird trapping Pesticides Land reclamation
Naroradam and adjoin areas	Uttar Pradesh	Over fishing Poaching Agricultural activities Pesticides Industrial pollution
Farakka Barrage and Adjoining Areas	West Bengal	Agricultural infestation Fisheries Obstruction of *T. ilisha* migration

5. Management and conservation of wetlands

(a) Developing conservation strategies

Due to the rapid increase of human population, the wetlands as well as the other aquatic systems are facing constant stress because of shifting of water bodies into agricultural land. The marginal areas of wetlands are used for agriculture and consequently the wetland area shrinks. This compels the dependent water birds to congregate in a smaller place that makes them susceptible to poaching. Shrinkage of wetland area reduces the food sources for birds. As a result birds move to agricultural lands that increases the conflict of farmers with the birds. The non cultivable marshy patches of wetlands are to be protected and managed. The nesting grounds of the birds are to be protected. Community conservation programmes and indulge of traditional relation of human with animal would decrease the human animal conflicts. Some wetlands in the Ganga basin are directly used for aquatic plant cultivation that provides edibles. The extensive cultivation of aquatic plants in the wetlands decreases the access ground of birds and restrict their feeding habits. Thus the wide cultivation of aquatic plants in the wetlands is to be regulated.

(b) Wetland vegetation management

The vegetation around the wetlands is very important. These provide nesting and resting place for many water birds. These vegetation are generally removed. Tall trees are cut for timber. Plantation of tall trees should be encouraged around the wetlands; these are used for nesting by bird like storks. Engineered vegetated treatment systems especially effective at removing suspended solids and sediment from non point source (NPS) pollution before the runoff reaches natural wetlands

(c) Reforestation and flood and siltation control

Deforestation accelerates the erosion and consequently heavy siltation and sediment deposition in the wetlands. Siltation and flooding destroys the sandbank colonies of many birds. Fringe area forest protection and programmed reforestation should be taken into consideration for flood and siltation control.

(d) Regulation of developmental activities

Many anthropogenic activities are due the rapid urbanization and the developmental activities around the wetlands. Excavations for soil, stone quarry, brick industry around the wetlands are to be regulated to prevent the siltation problem.

(e) Pollution

Wetlands are highly polluted by the industrial, municipal and agricultural waste. Fertilizers and pesticides are immensely used in the agricultural lands. Toxic chemicals may induce bio-magnifications of toxicants. Waste disposal at the wetlands are to be strictly regulated and use of organic fertilizers should be encouraged in place of toxic fertilizers and chemicals.

(f) Regulation of overexploitation

Change of fringe human population should be recorded time to time by the concerned authority. This would reveal the dependency on the wetland and the stress on the wetland. Overexploitation of bio-resources should be checked. Mesh size of the fishing net should be regulated so that juvenile cannot be caught. Catch of brooder fish should be banned. Similarly fishing through poison and dynamite should be banned.

(g) Community conservation and mass involvement

Fringe people are directly dependent on wetland resources. Their active participation in the conservation programme is most important. Indulge of traditional knowledge and conservation strategy induces the management of wetlands. Cage culture and pen culture fish practices can be introduced depending upon conditions to have more fish yield from the wetlands. Public awareness would lead to the sustainable development.

(h) Identification of wetlands

Major criteria for prioritizing wetlands are birds by the international conventions. The points of considerations are total number of species, total number of birds (abundance), number of threatened species, number of threatened birds, number of rare or near threatened species and number of species of raptor as they are predatory and often on the top of the food chain. Wetlands can also be identified on the basis of their type, location and area. Other biological factors may be included for the identification of wetlands, such as-

-Presence of endemic fish.
-Number of water birds
-Important aquatic vegetation
-Life cycle of any important flora or fauna
-Flagship species
-Presence of threatened species

(i)Analysis of biotic elements

Information on biotic elements is essential. Species diversity, growth of vegetation, biomass estimates, etc. are items to be described in biologically relevant terms, to define the ecological value of the biotic elements as well as that of the whole ecohydrological study. The various biotic communities are

(j)Identification of species

Conservation programmes, the first question comes “what to conserve”. Identification of threatened species is important, because they are the visible form of biodiversity loss. The more degraded ecosystems are to be conserved first and the most threatened species are to be protected first. Molecular tools and techniques can be used to reduce the ambiguity in the conventional taxonomic procedures.

(k)Biomonitoring

Invertebrates and lower vertebrates are important bioindicators of wetlands. Insect, fish and amphibians play significant role in healthy ecosystems. Insect is very crucially integrated in the lentic water food web and well linked to both fish and amphibians as food source. Fish is very vital bioindicator of confined water ecosystem.

(l) Energy transformation in wetland

Energy dynamics for

-Transformation and storage of solar energy into chemical energy by the producers.

-Flow of energy through different trophic levels

(m) Mapping and Modelling for wetland management

Topographical maps and geospatial techniques like GPS and GIS can be used for the mapping of wetlands. Information regarding catchment area, connections with the river stem, water table change, ecohydrology can be achieved through the mapping. Mapping may lead to restoration of linkage and sediment removal. Ecohydrology models can be designed by coupling an ecological model with a conceptual hydrological model (Arnold *et al.* 2009). Such models are pattern oriented based on a good number of parameters as water balance, biotic species, etc. Some of the important models currently employed in the field of Ecohydrology are Soil and Water Assessment Tool (SWAT), Soil and Water Integrated Model (SWIM), Integrated Quantity Quality Model (IQQM), River and Stream Water Quality Model (QUAL2K), etc. In general modelling in wetlands involves linear models. Monitoring, modeling and management of wetland exist together. Vegetation change, hydrology, plankton variation, thermal conditions are the monitoring of wetlands, whereas outflow control, denitrofication and restoration are the management activities through the ecohydrological modelling, nutrient modelling or flow pattern modeling.

(n) Legal Framework:

Wetlands conservation in India is indirectly influenced by an array of policy and legislative measures (Parikh & Parikh 1999). Some of the key legislations are given below:

- The Indian Fisheries Act - 1857
- The Indian Forest Act – 1927
- Wildlife (Protection) Act - 1972
- Water (Prevention and Control of Pollution) Act - 1974
- Territorial Water, Continental Shelf, Exclusive Economic Zone and other Marine Zones Act - 1976
- Water (Prevention and Control of Pollution) Act - 1977
- Maritime Zone of India (Regulation and fishing by foreign vessels) Act - 1980

- Forest (Conservation act) – 1980
- Environmental (Protection) Act - 1986
- Coastal Zone Regulation Notification - 1991
- Wildlife (Protection) Amendment Act - 1991
- National Conservation Strategy and Policy Statement on Environment and Development – 1992
- National Policy And Macro level Action Strategy on Biodiversity-1999
- Tribal Forest protection Act of 2004

In summary, mapping and modelling utilizing topographical maps and geospatial techniques like GIS and Remote Sensing can establish change in water table of wetlands, their connections with the nearby rivers and other water bodies and other ecohydrological parameters. Monitoring, modelling and management co exist and they are interdisciplinary. Monitoring may include analysis of thermal condition, vegetation pattern change, hydrology and plankton variation. Modelling may include eco hydrological model, nutrient retention model or flow pattern model. Monitoring and modelling would light the pave for the management of outflow control, denitrification, sediment removal or restoration of wetlands. Proper identification of wetland is very important from the management point of view. Identification on the basis of type and location would give the general information of the wetlands. As already mention identification on the basis of biotic community is necessary. Water bird and fish biodiversity analysis is to be done primarily for the wetland management. Status analysis and management of threatened, endemic and special key species is mandatory because these are the most visible symbol of biodiversity loss. Biological study of these biotic community as well as lower groups (Invertebrates: e.g. insects and lower vertebrates: e.g. herpetofauna) is to be done for biomonitoring of wetlands and invasive species management of the wetlands. Simultaneously, mass involvement and public awareness is necessary for sustainable development.

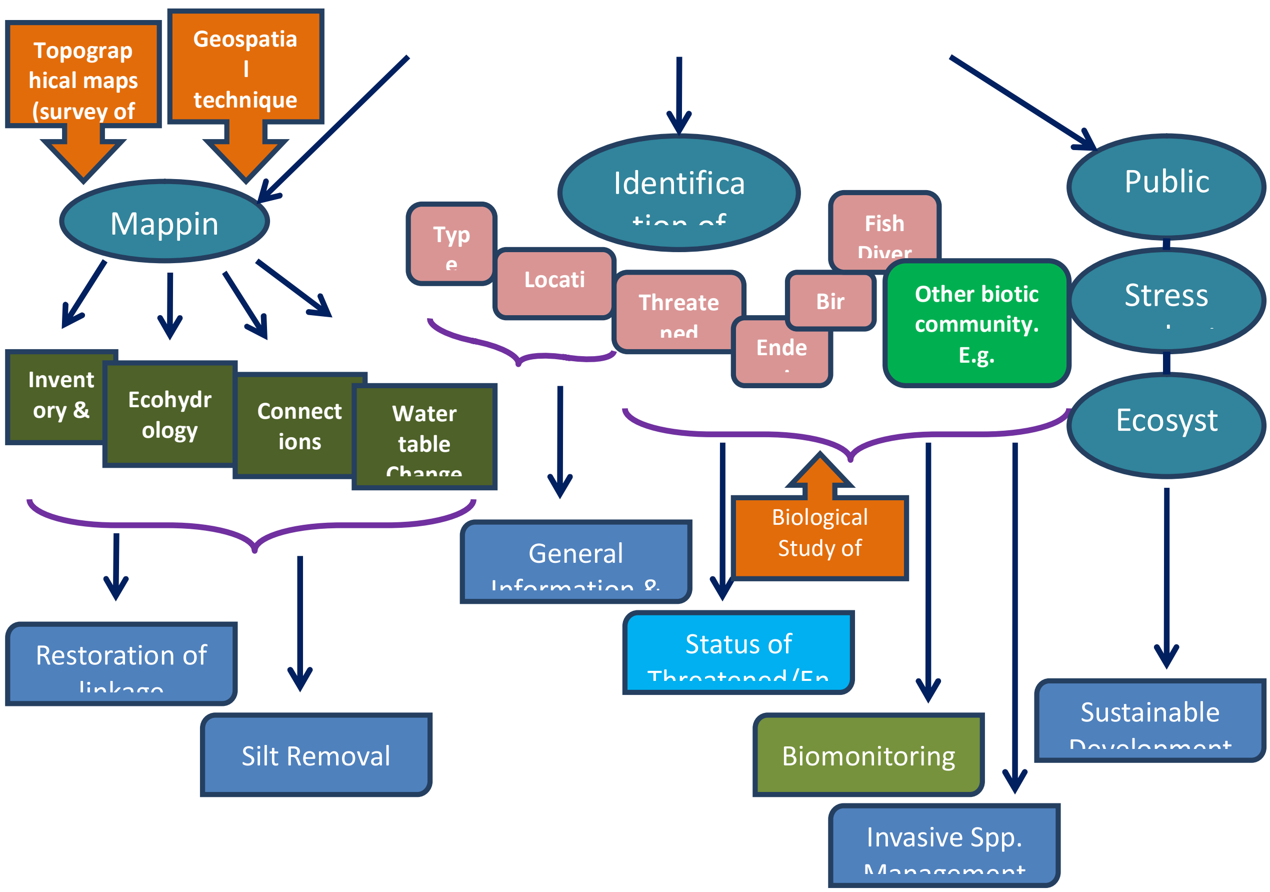


Fig. 11 Line Diagram of the Management Plan

6. Conclusion

A prime need of hour to protect wetlands is to understand the human wetland interaction. Estimation of fringe human population, their historical change and their dependence on the wetlands for the resources can find out the stress on the wetland. Public awareness and mass involvement are necessary for the protection of the wetlands. Total ecological change of wetlands due to cleaning, weed removal or embankment for tourism is not advisable. However, weed control and cleaning of wetland may be some management tool depending upon the necessity. Threatened wetlands are to be prioritized and managed first. Engineered vegetated treatment systems (VTS) are especially effective at removing suspended solids and sediment from non point source (NPS) pollution before the runoff reaches natural wetlands. Wetlands are the breeding ground for many fishes. Wetlands support many amphibians, invertebrates and plant species. Amphibians and lower organisms are the indicator of healthy wetlands. Their habitat protection is most important which would ensure the survival of higher fauna.

References

Arnold, S., Attinger, S., Frank, K. and Hildebrandt, A. (2009) Parameterization and uncertainty in coupled ecohydrological models*, Hydrol. Earth Syst. Sci. Discuss*, **6:**4155-4207.

Adhikari, B.S. and Babu, M.M. (2008). Floral diversity of Baanganga Wetland, Uttarakhand, India. Check List **4(3):**279–290.

Ahmed, A. and Rahmani, A.R. (2002). Illegal trade of waterbirds in northern India. *In*: Birds of wetlands and grasslands: Proceedings of the Salim Ali centenary seminar on conservation of avifauna of wetlands and grasslands. Eds: Rahmani, A.R. and G. Urga. Bombay Natural History Society. pp. 65-68.

Conservation of Wetlands in India (2007): A Profile: Approach and Guidelines. MoEF, Govt. of India.

Chowdhury, S and Driver, P. (2007). An ecohydrological model of waterbird nesting events to altered floodplain hydrology, in MODSIM 2007 International Congress on Modelling and Simulation, Eds. L Oxley and D Kulasiri, Modelling and Simulation Society of Australia and New Zealand. pp. 2896–2902.

Das, A.P. and Mishra, S. (2009). Hexavalent Chromium [Cr (VI)]: Yellow water Pollution and its Remediation. Sarovar Saurabh. ENVIS Newsletter on wetland ecosystem. Salim Ali Centre for Ornithology and Natural History. Vol. 5, No. 2.

DeAngelis, D.L.., Trexler, J.V., Cosner, C., Obaza, A. and Jopp, F. (2010). Fish population dynamics in a seasonally varying wetland. *Ecological Modelling*, **221:**1131–1137.

Environmental and Social Management Framework (2011). Volume-I - Environmental and Social Analysis. National Ganga River Basin Authority. MoEF, Govt. of India.Prepared by The Energy and Resources Institute Consultant.

Ghosh, A.K., Bose, N., Singh, K.R.P. and Sinha, R.K. (2004). Study of spatio-temporal changes in the wetlands of north Bihar through remote sensing. 13th International Soil Conservation Organisation Conference – Brisbane.

Golley, F.B. (1960). Energy dynamics of a food chain of an old-field, *Ecolo. Monograph*, **30:**187-206.

Gururaja, K.V. and Aravind, N.A. Inland Waters Biodiversity. www.gururajakv.net.

Hattermann, F.F., Krysanova, V. and Hesse, C. (2010). Modelling wetland processes in regional applications. *Hydrological Sciences Journal*, **53(5):**1001-1012.

Isaiah, (2008). The Flow of Energy: Primary Production to Higher Trophic Levels, the Regents of the University of Michigan.

Islam, M.Z. and Rahmani, A.R. (2008). Potential and Existing Ramsar Sites in India/ Indian Bird Conservation Network: Bombay Natural History Society, Bird Life International and Royal Society for the Protection of Birds. Oxford University Press.

Inland waters biodiversity. www.cbd.int.

Jin, C. (2008). Biodiversity dynamics of freshwater wetland ecosystems affected by secondary salinization and seasonal hydrology variation: a model-based study. *Hydrobiologia,***598**:57-270

Lindeman, R L.(2008). The Trophic-Dynamic Aspect of Ecology, *Ecology*,**23(4):**399-417.

National Wetland Atlas (2010): Bihar. MoEF, Govt. of India. Space Applications centre, Indian Space Research Organization.

National Wetland Atlas (2010): Uttar Pradesh. MoEF, Govt. of India. Space Applications centre, Indian Space Research Organization.

National Wetland Atlas (2010): Uttarakhand. MoEF, Govt. of India. Space Applications centre, Indian Space Research Organization.

National Wetland Atlas (2010): West Bengal. MoEF, Govt. of India. Space Applications centre, Indian Space Research Organization.

National Wetland Conservation Programme Guidelines for Conservation and Management of Wetlands in India. (2009). Ministry of Environment and Forests Government of India

North Indian wetlands: www.birdlife.org

Odum, W. E. (1971) Pathways of energy flow in a south Florida estuary, Sea Grant Technical Bulletin no. 7. University of Miami, USA.

Pathak, V., Tyagi, R.K., and Singh, B. (2004). Ecological status and production dynamics of wetlands of Uttar Pradesh. Central Inland Fishery Research Institute. Bull. No.131.

Prasad, S.N., Ramachandra, T.V., Ahalya, N., Sengupta, T., Kumar, A., Tiwari, A.K., Vijayan, V.S. and Vijayan, L. (2002). Conservation of wetlands of India – a review. *Tropical Ecology*,**43(1)**: 173-186.

Ramsar Convention: www.ramsar.org

Sarovar Saurabh (2010). ENVIS Newsletter on wetland ecosystems and inland wetlands. Salim Ali Centre for Ornithology and Natural History. Vol-6.

Ton, S., Odum, H.T. and Delfino, J.J. (1988). Ecological-economic evaluation of wetland management alternatives. *Ecological Engineering,* 11:291-302.

Whitten, S M., and Bennett, J. A bio-economic model of wetland protection on private lands. National Wetlands Research and Development Program funded by Environment Australia (now the Australian Government Department of Environment and Heritage) and Land and Water Australia.

Wetlands of India: www.wwfindia.org

PROJECT MANAGEMENT BOARD [PMB]

Expert Members:

- Sri Swami Avimukteshwaranand Saraswati
- Dr Madhav AChitale
- Dr Bharat Jhunjhunwala

PROJECT IMPLEMENTATION AND COORDINATION COMMITTEE [PICC]

Representatives from IIT Consortium:

- Dr ShyamAsolekar, IIT Bombay
- Dr A K Mittal, IIT Delhi
- Dr Mohammad Jawed, IIT Guwahati
- Dr Vinod Tare, IIT Kanpur
- Dr D J Sen, IIT Kharagpur
- Dr Ligy Philip, IIT Madras
- Dr I M Mishra, IIT Roorkee

Thematic Group Leads:

- Dr Purnendu Bose, Environmental Quality and Pollution (EQP)
- Dr A K Gosain, Water Resources Management (WRM)
- Dr R P Mathur, Ecology and Biodiversity (ENB)
- Dr Rajiv Sinha, Fluvial Geomorphology (FGM)
- Dr Vinod Tare, Environmental Flows (EFL)
- Dr S P Singh, Socio Economic and Cultural (SEC)
- Dr N C Narayanan and Dr Indrajit Dube, Policy Law and Governance (PLG)
- Dr Harish Karnick, Geospatial Database Management (GDM)
- Dr T V Prabhakar, Communication (COM)

COMPOSITION OF

1. Environmental Quality and Pollution (EQP)
Lead: Purnendu Bose, IIT Kanpur

Members: Shyam R Asolekar, Suparna Mukherjee (IIT Bombay); A K Mittal, A K Nema, Arun Kumar, T R Sreekrishanan (IIT Delhi); Ajay Kalmhad (IIT Guwahati); Saumyen Guha, Vinod Tare (IIT Kanpur); A K Gupta, M MGhangrekar, Sudha Goel (IIT Kharagpur); Ligy Philip, Mukesh Doble, R Ravi Krishna, S M Shivnagendra (IIT Madras); A A Kazmi, B R Gurjar, Himanshu Joshi, Indu Mehrotra, I M Mishra, Vivek Kumar (IIT Roorkee); Anirban Gupta (BESU Shibpur); P K Singh (IIT BHU); Rakesh Kumar (NEERI Nagpur); S K Patidar (NIT Kurukshetra); Sanmit Ahuja (ETI Dynamics, New Delhi)

2. Water Resources Management (WRM)
Lead: A K Gosain, IIT Delhi

Members: Rakesh Khosa, R Maheswaran, B R Chahar, C T Dhanya, D R Kaushal (IIT Delhi); Subashisa Dutta, Suresh Kartha (IIT Guwahati); Shivam Tripathi, Gautam Rai, Vinod Tare (IIT Kanpur); Anirban Dhar, D J Sen (IIT Kharagpur); B S Murty, Balaji Narasimhan (IIT Mdras); C S P Ojha, P Perumal (IIT Roorkee); S K Jain (NIH, Roorkee); Pranab Mohapatra (IIT Gandhi Nagar); Sandhya Rao (INRM, New Delhi)

3. Fluvial Geomorphology (FGM)
Lead: Rajiv Sinha, IIT Kanpur

Members: Vinod Tare (IIT Kanpur); Vikrant Jain (IIT Gandhi Nagar); J K Pati (Allahabad University); Kirteshwar Prasad, Ramesh Shukla (Patna University); Parthasarthi Ghosh, Soumendra Nath Sarkar, TapanChakarborty (ISI Kolkata); Kalyan Rudra (WBPCB); S K Tandon, Shashank Shekhar (University of Delhi); Saumitra Mukherjee (JNU Delhi)

4. Ecology and Biodiversity (ENB)
Lead: R P Mathur, IIT Kanpur

Members: A K Thakur, Vinod Tare (IIT Kanpur); Utpal Bora (IIT Guwahati); M D Behera (IIT Kharagpur); Naveen Navania, Partha Roy, Pruthi Vikas, R P Singh, Ramasre Prasad, Ranjana Pathania (IIT Roorkee); Sandeep Behera (WWF-India)

THEMATIC GROUPS

5. Socio Economic and Cultural (SEC)
Lead: S P Singh, IIT Roorkee

Members: Pushpa L Trivedi (IIT Bombay); Seema Sharma, V B Upadhyay (IIT Delhi); P M Prasad, Vinod Tare (IIT Kanpur); Bhagirath Behera, N C Nayak, Pulak Mishra, T N Mazumder (IIT Kharagpur); C Kumar, D K Nauriyal, Rajat Agrawal, Vinay Sharma (IIT Roorkee)

6. Policy Law and Governance (PLG)
Lead: N C Narayanan, IIT Bombay and Indrajit Dube, IIT Kharagpur

Members: ShyamAsolekar, Subodh Wagle (IIT Bombay); Mukesh Khare (IIT Delhi); Vinod Tare (IIT Kanpur); Deepa Dube, Uday Shankar (IIT Kharagpur); G N Kathpalia, Paritosh Tyagi (IDC, New Delhi)

7. Geo-Spatial Database Management (GDM)
Lead: Harish Karnick, IIT Kanpur

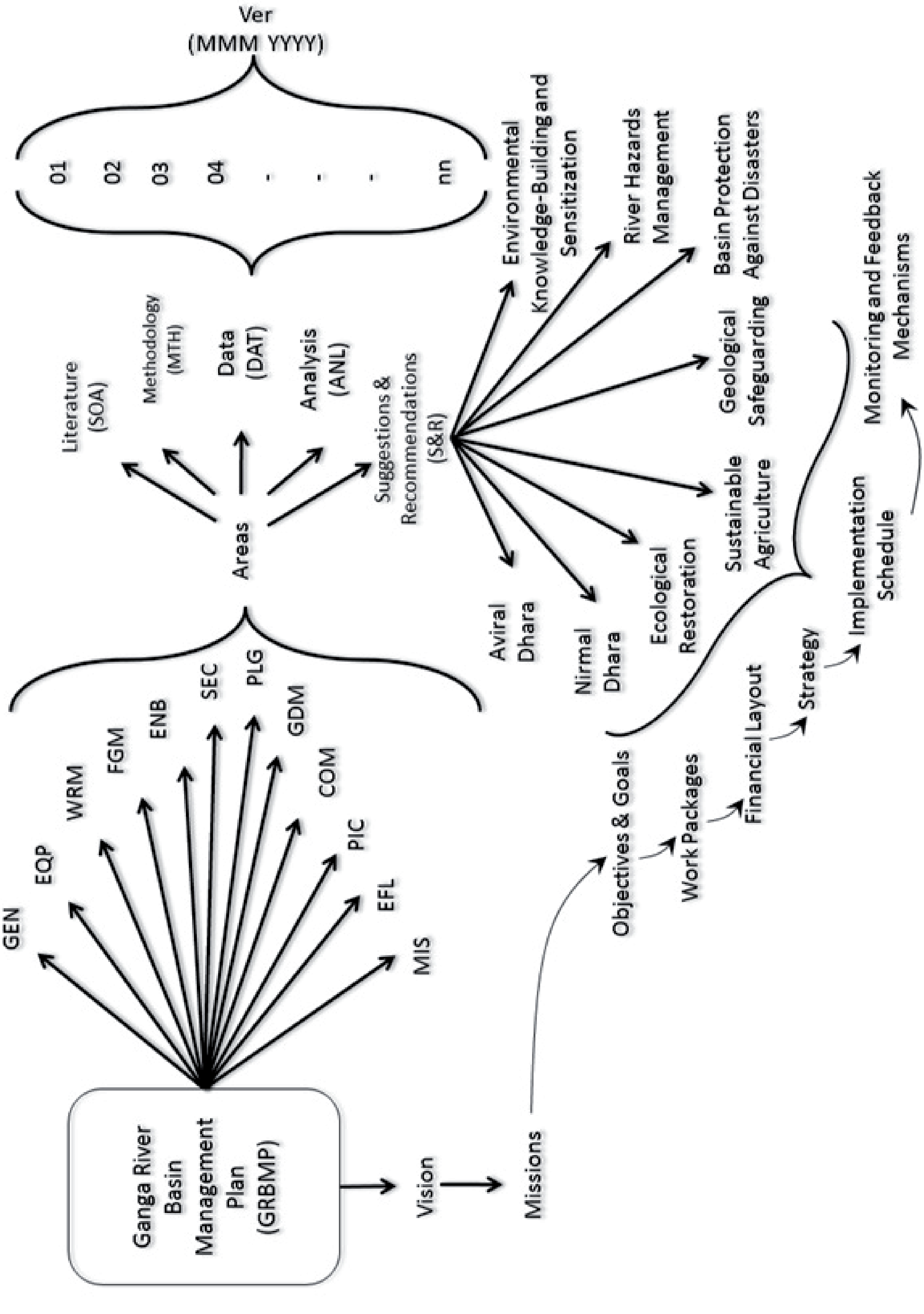
Members: N L Sharda, Smriti Sengupta (IIT Bombay); A K Gosain (IIT Delhi); Arnab Bhattacharya, Kritika Venkatramani, Rajiv Sinha, T V Prabhakar, Vinod Tare (IIT Kanpur)

8. Communication (COM)
Lead: T V Prabhakar, IIT Kanpur

Members: Purnendu Bose, Rajiv Sinha, Vinod Tare (IIT Kanpur)

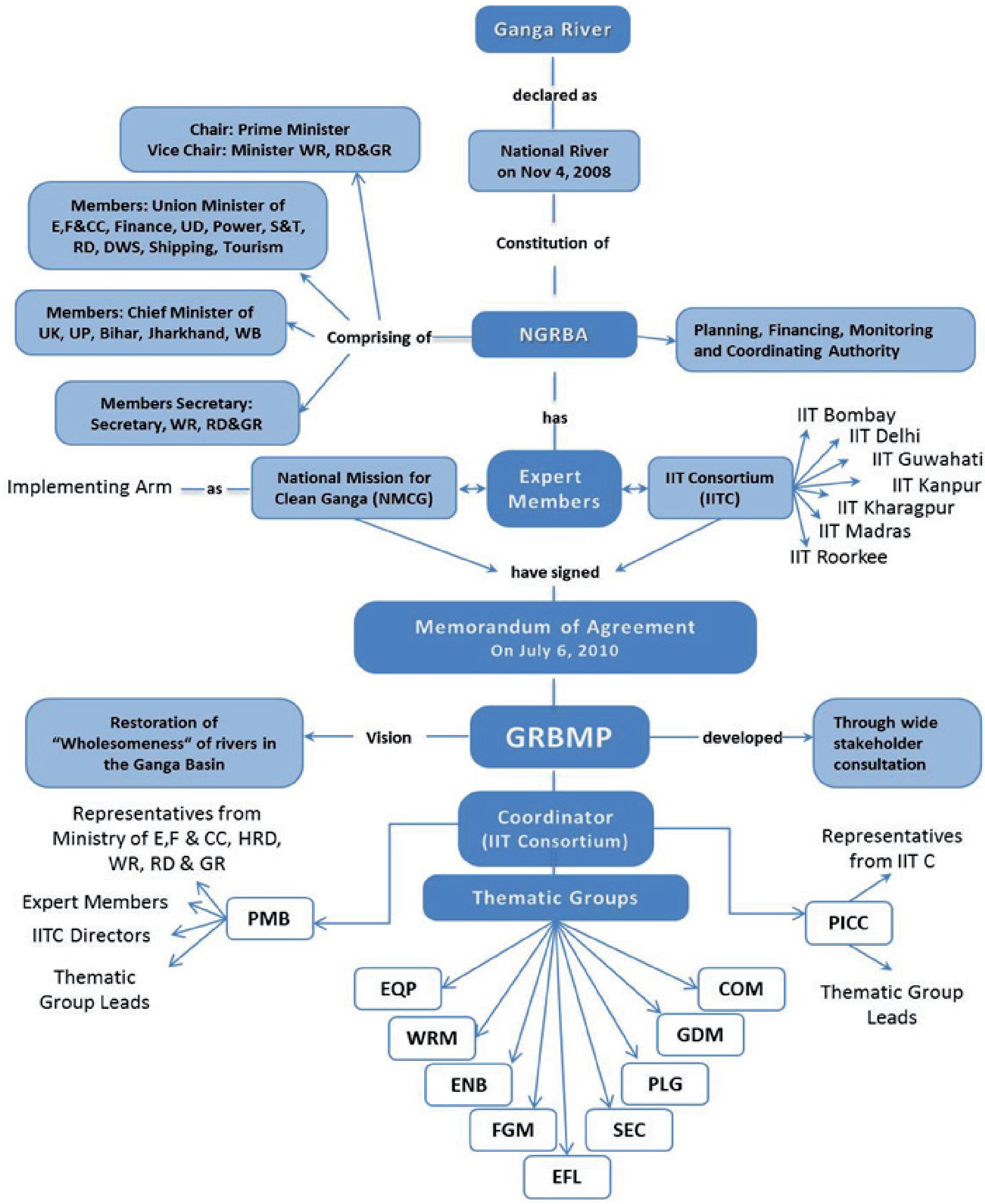
9. Environmental Flows (EFL)
Lead: Vinod Tare, IIT Kanpur

Members: ShyamAsolekar (IIT Bombay); A K Gosain (IIT Delhi); P M Prasad, R P Mathur, Rajiv Sinha, Shivam Tripathi (IIT Kanpur); M D Behara (IIT Kharagpur); B S Murthy, N Balaji (IIT Madras); Pranab Mohaparta, Vikrant Jain (IIT Gandhinagar); S K Jain (NIH Roorkee); Nitin Kaushal (WWF-India, New Delhi); Sandeep Behera (NMCG, MoWR, RD & GR, New Delhi); A P Sharma K D Joshi (CIFRI, Barrackpore); Ravindra Kumar (SWaRA-UP); Ravi Chopra (PSI, Dehradoon); Paritosh Tyagi, (IDC, New Delhi)



GRBMP WORK STRUCTURE

ORGANIZATIONAL STRUCTURE FOR PREPARING GRBMP



NGRBA: National Ganga River Basin Authority
NMCG: National Mission for Clean Ganga
MoEF: Ministry of Environment and Forests
MHRD: Ministry of Human Resource and Development
MoWR, RD&GR: Ministry of Water Resources, River Development and Ganga Rejuvenation
GRBMP: Ganga River Basin Management Plan
IITC: IIT Consortium
PMB: Project Management Board
PICC: Project Implementation and Coordination Committee

EQP: Environmental Quality and Pollution
WRM: Water Resources Management
ENB: Ecology and Biodiversity
FGM: Fluvial Geomorphology
EFL: Environmental Flows
SEC: Socio Economic and Cultural
PLG: Policy Law and Governance
GDM: Geospatial Database Management
COM: Communication

Centre for Ganga River Basin Management and Studies