

Stream Power Distribution Pattern of the Ganga River and its Tributaries

GRBMP : Ganga River Basin Management Plan

by

Indian Institutes of Technology



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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.

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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) –

$$\Omega = \gamma \cdot Q \cdot s \quad \dots (1)$$

Where γ -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 cgiar website (<http://seamless.usgs.gov/> or <http://srtm.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.

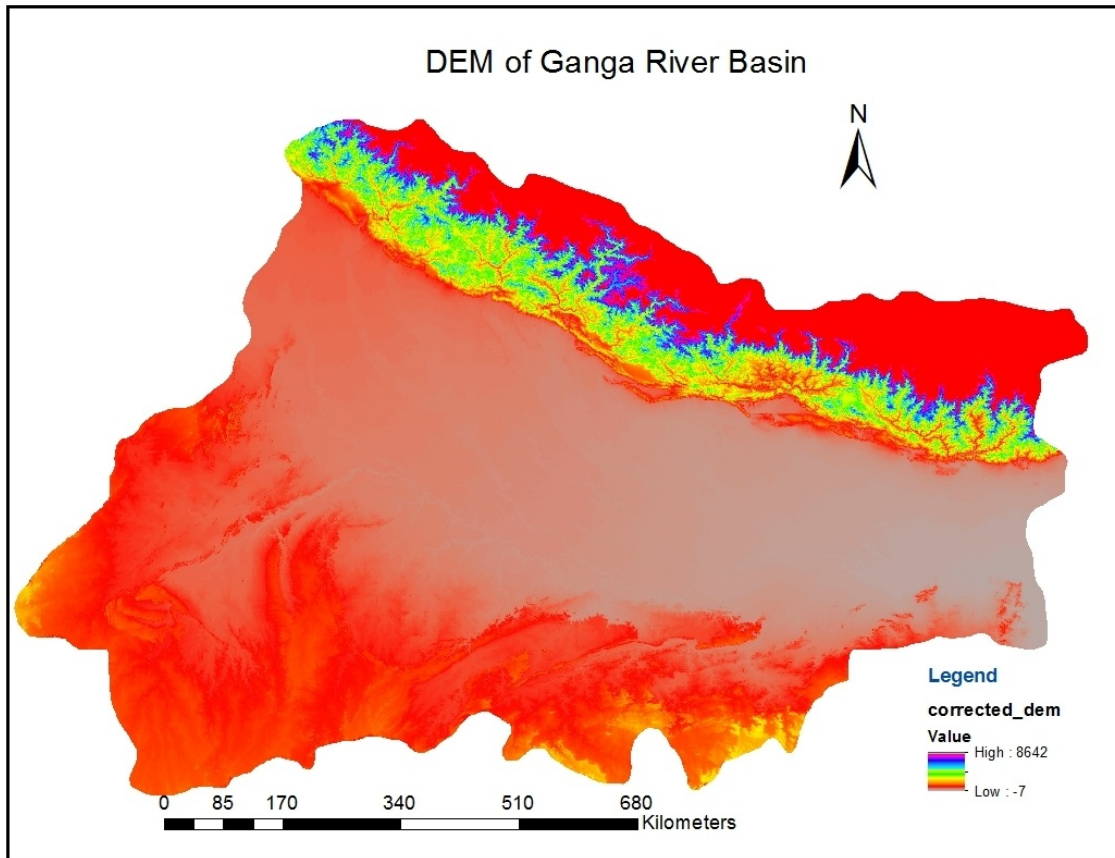


Figure 1: Raw DEM (SRTM) of Ganga River Basin with Spatial Resolution of 90m

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 through the curve smoothing method and superimposed over the discharge profile to generate stream power distribution pattern (Jain et al., 2006).

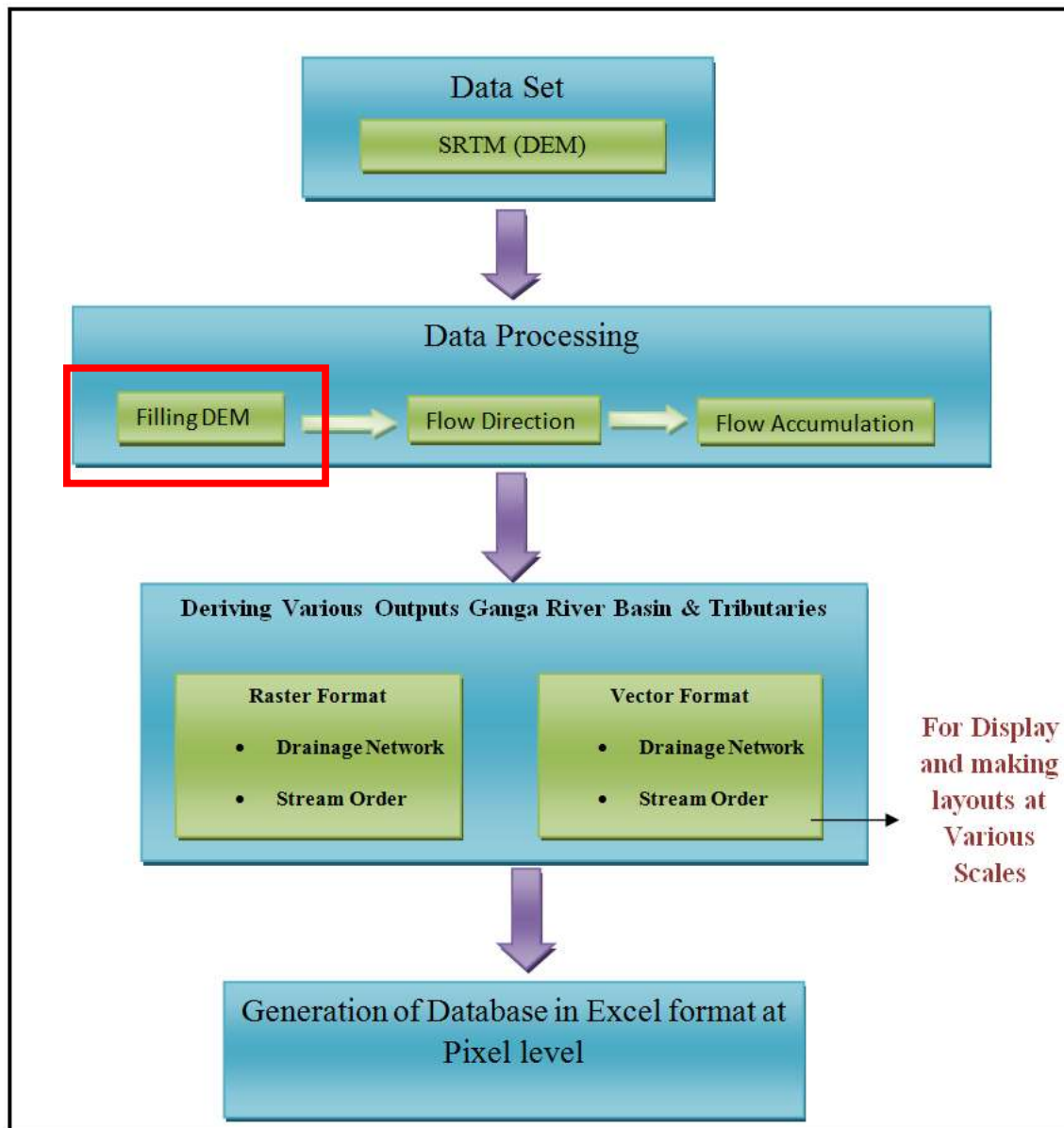


Figure 2: Flow Diagram Showing the various Steps of Methodology

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.

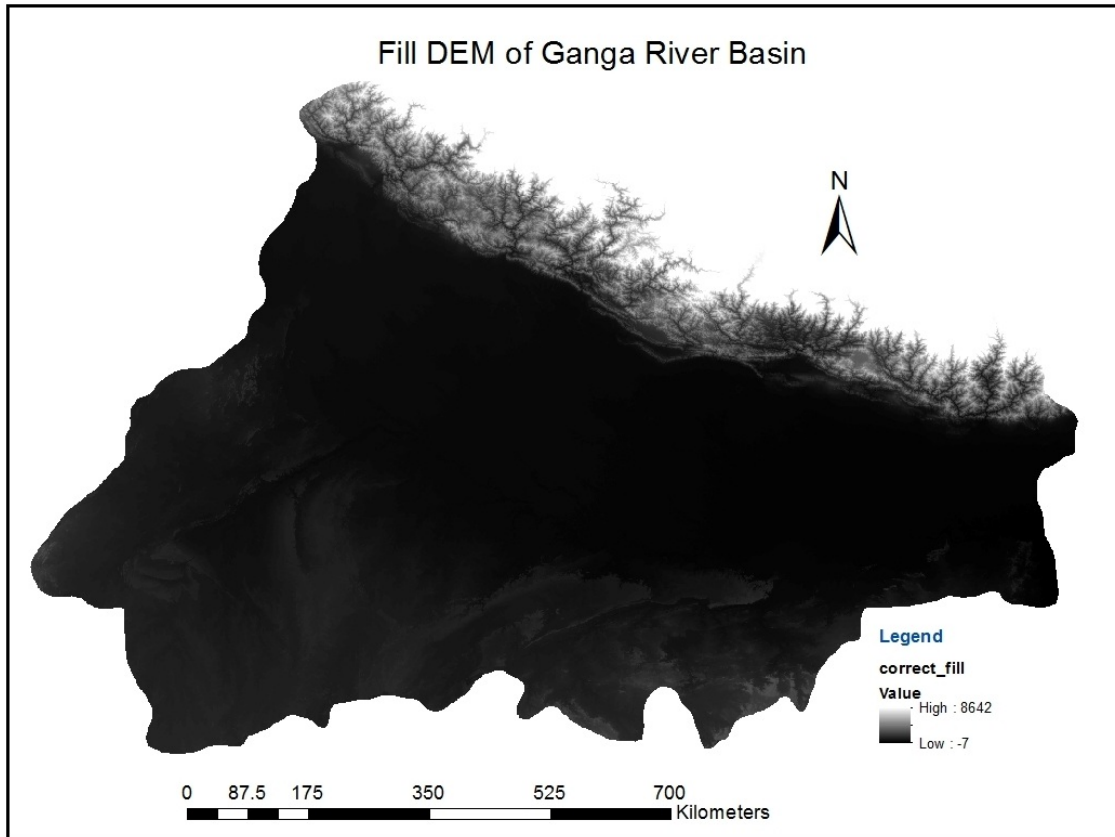


Figure 3: Filled Dem Generated from Raw Dem

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 , $d = \sqrt{2}$.

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

$(\text{Flow Direction FD})[i, j] = [\text{Value of the cell } C(i, j) - \text{Value of the neighboring cell}] / [\text{Distance to the neighboring cell}]$

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 $-(1 \times 10^{-4})$
(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).

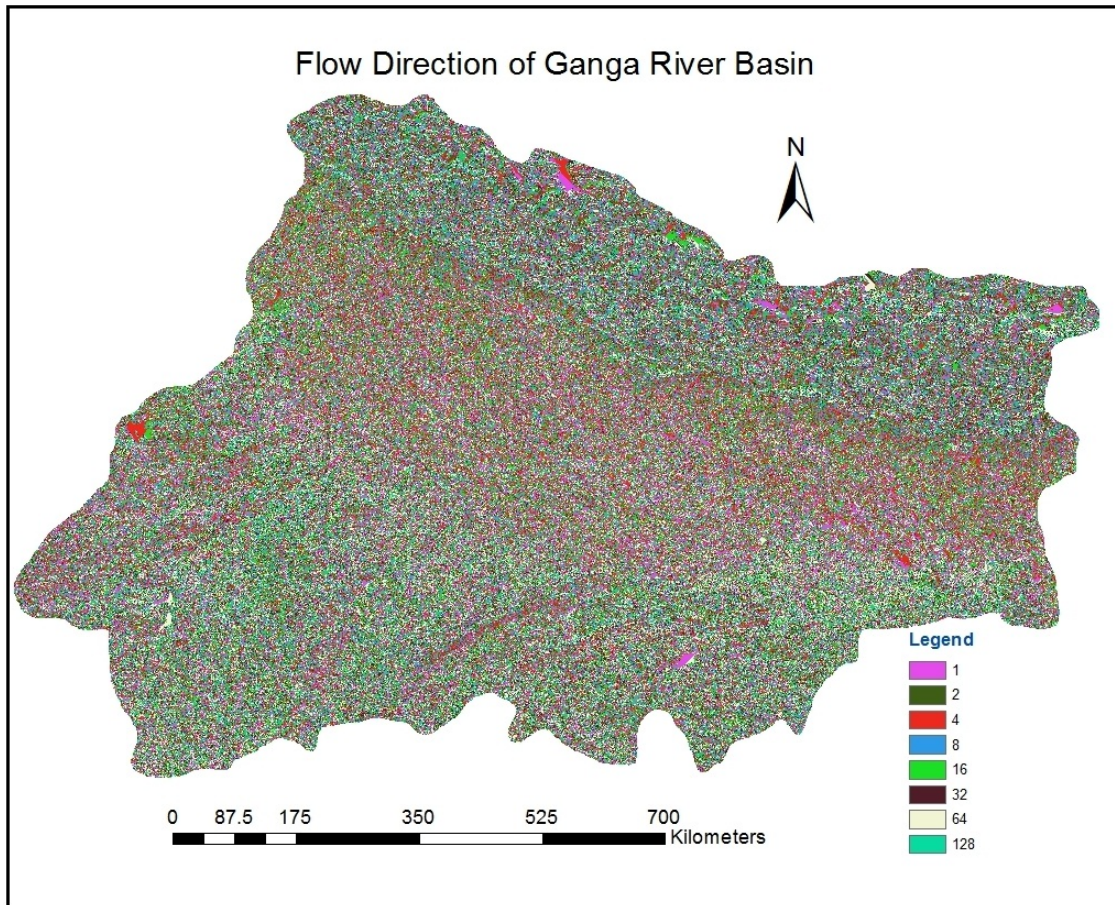


Figure 4: Flow Direction map of the Ganga river basin

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.

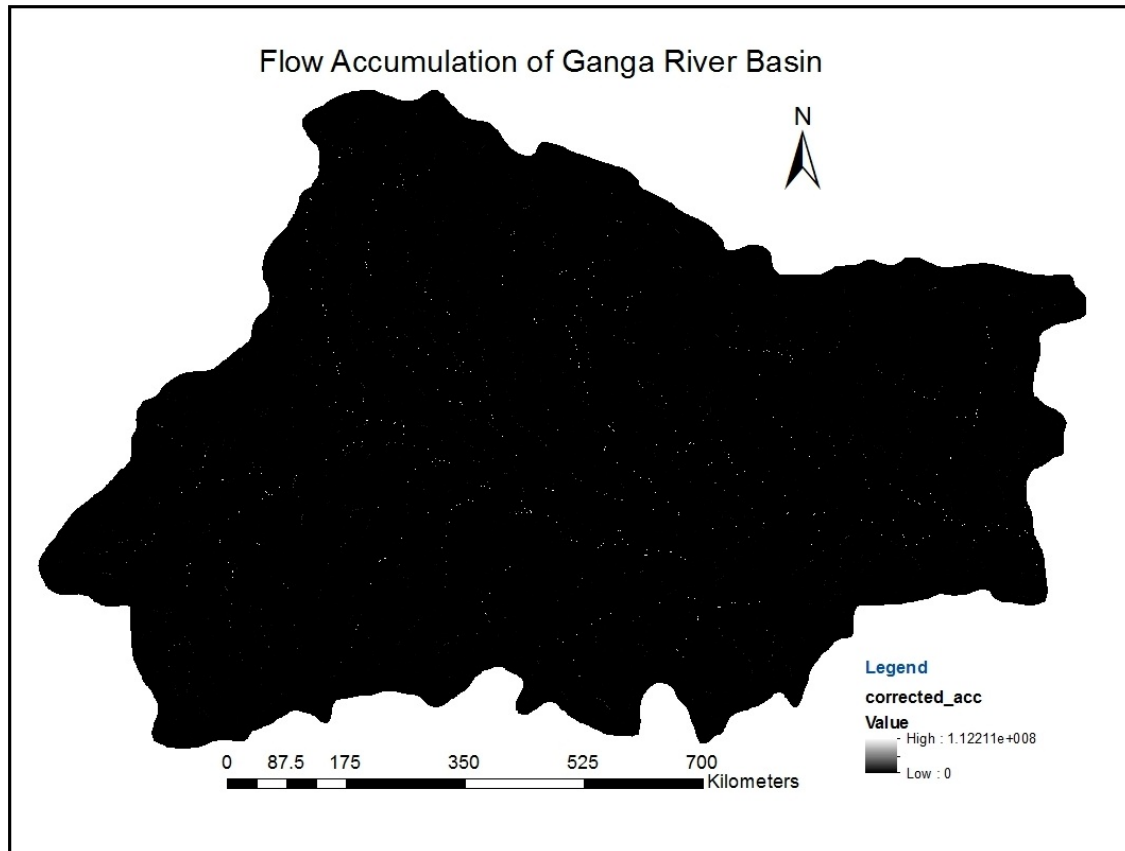


Figure 5: Flow Accumulation Map of the Ganga River Basin

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. 6 shows stream order of the Ganga river.

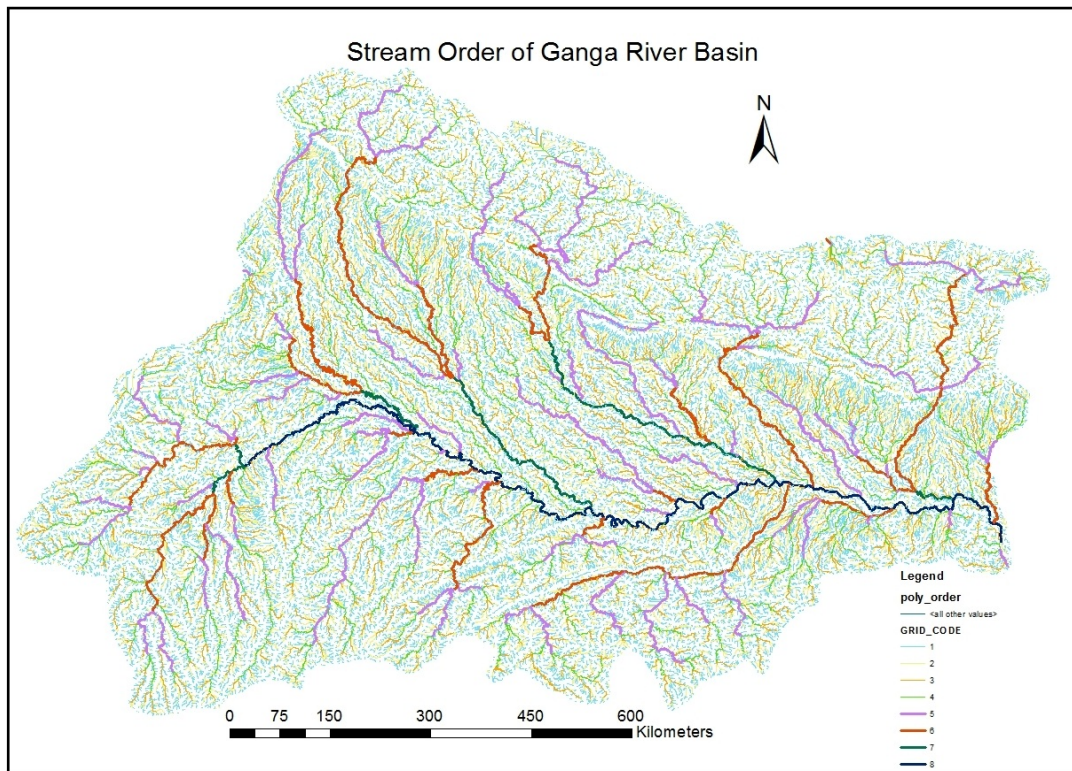


Figure 6: Stream Ordering Structure of the Ganga River Basin

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.

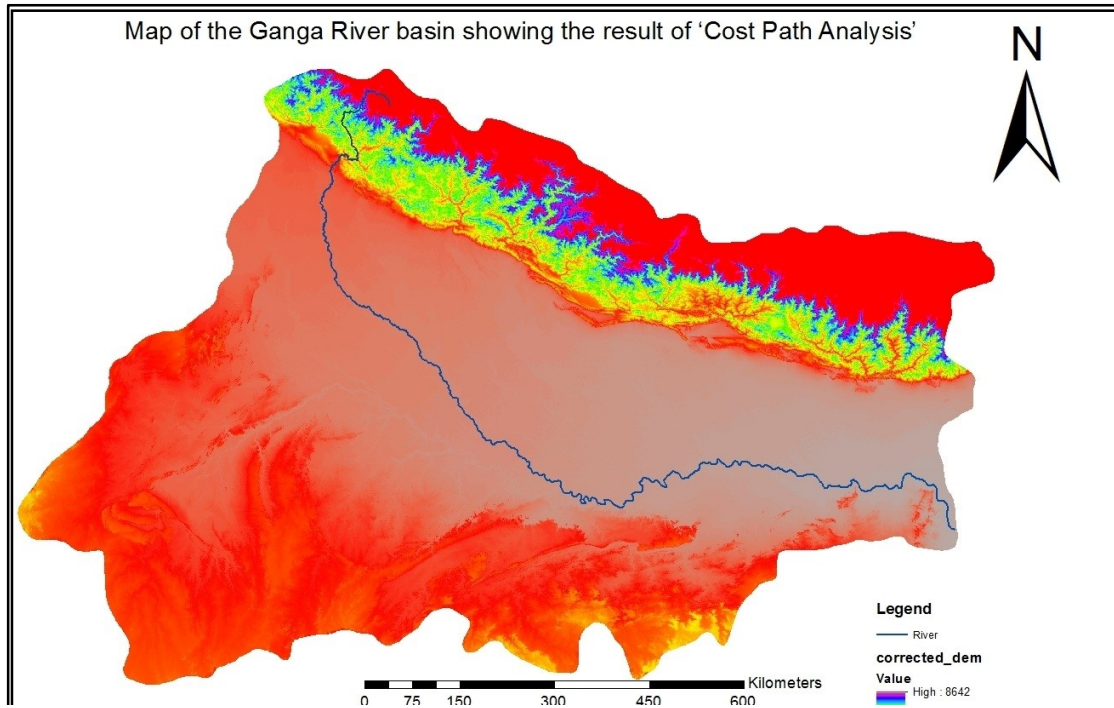


Figure 7: Map of the Ganga River Basin Showing the Result of 'Cost Path Analysis'

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 and its 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 –

$$\begin{aligned} Q &= 361A^{0.72} & (\text{WGP}), & R^2 = 0.58 \\ Q &= 2.78 A^{0.71} & (\text{EGP}), & R^2 = 0.65 \end{aligned}$$

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 pattern following the methodology after Jain et al. (2006). This data will provide a coarse resolution distribution of stream power for 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.

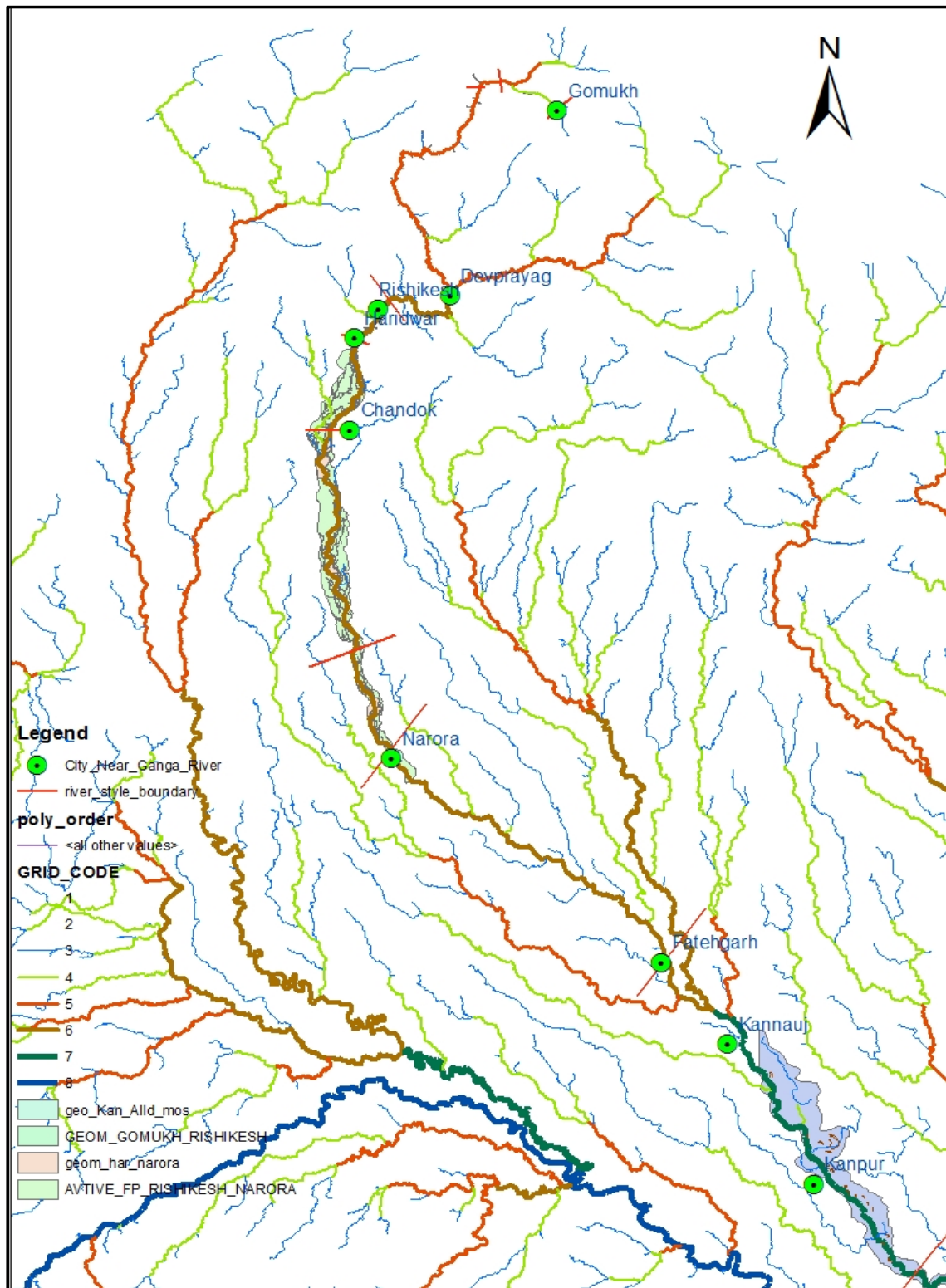


Figure 8(a): Comparison of the Drainage Map of the Ganga River with the Digitized Geomorphic Map from Landsat Data Between Reach of Gomukh to Kanpur. Polygons Defines the Digitized Geomorphic Map of the Channel Area.

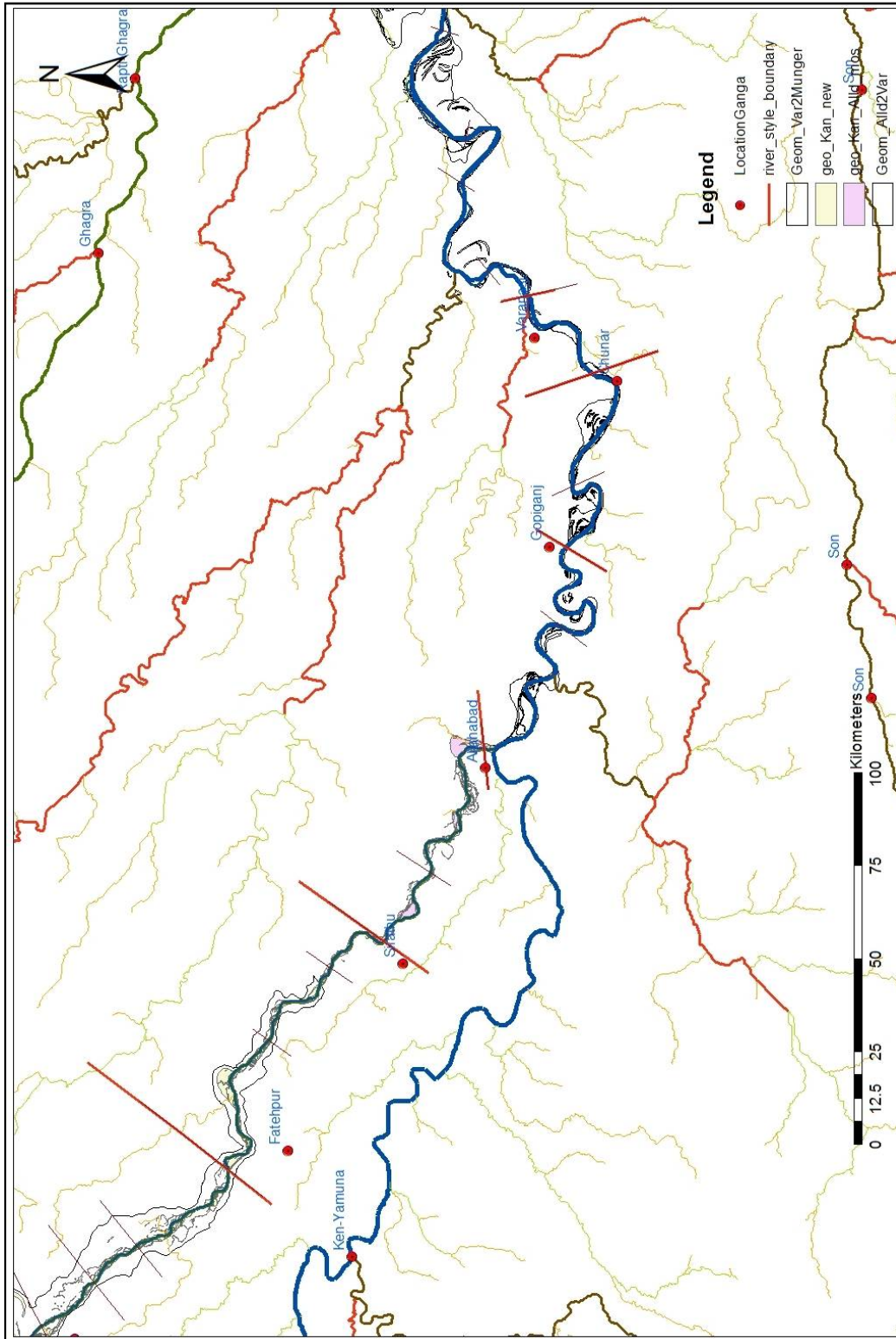
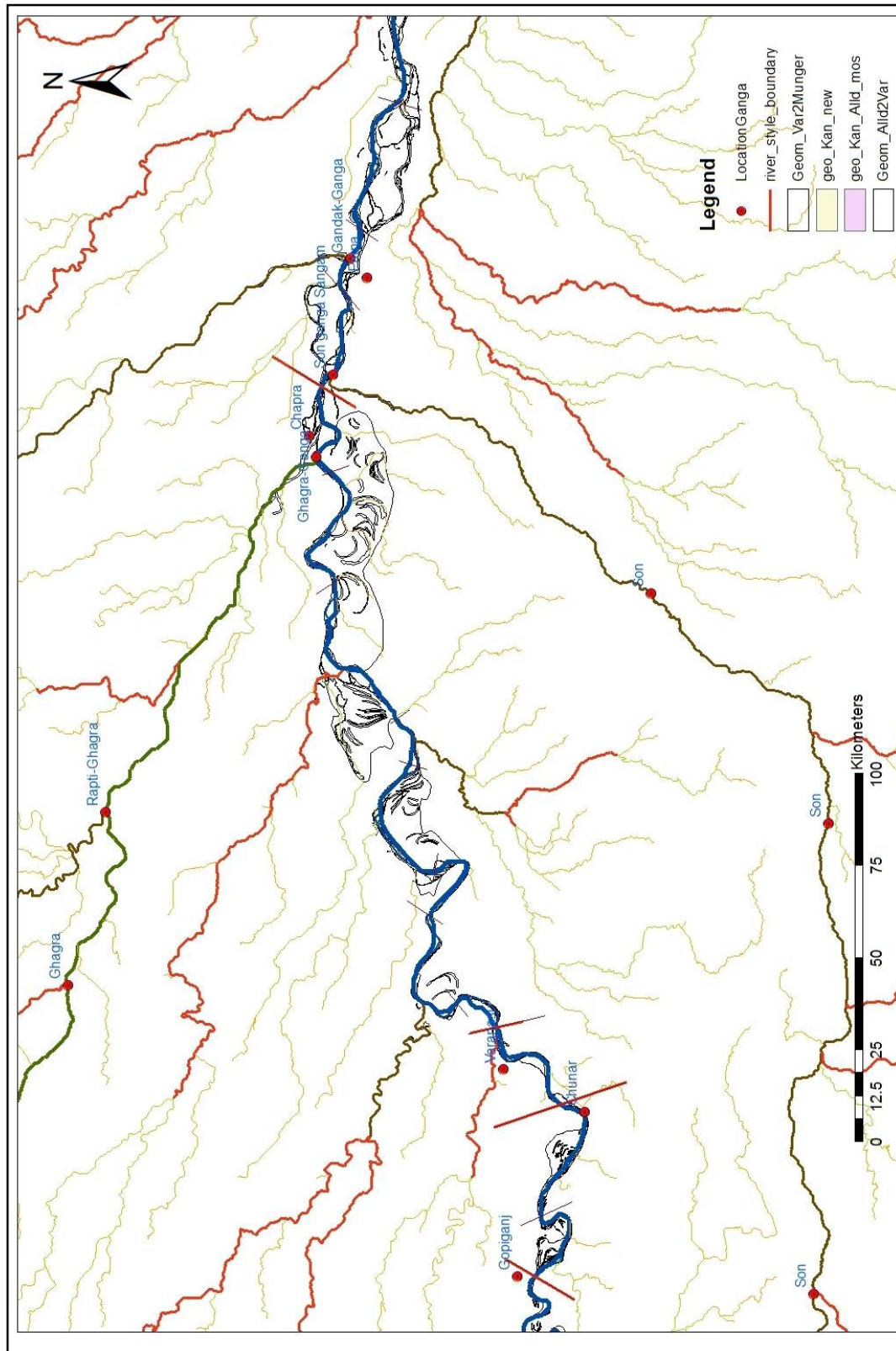


Figure 8(b): Comparison of the Drainage Map of the Ganga River with the Digitized Geomorphic Map from Landsat Data Between Reach of Kanpur to Gopiganj



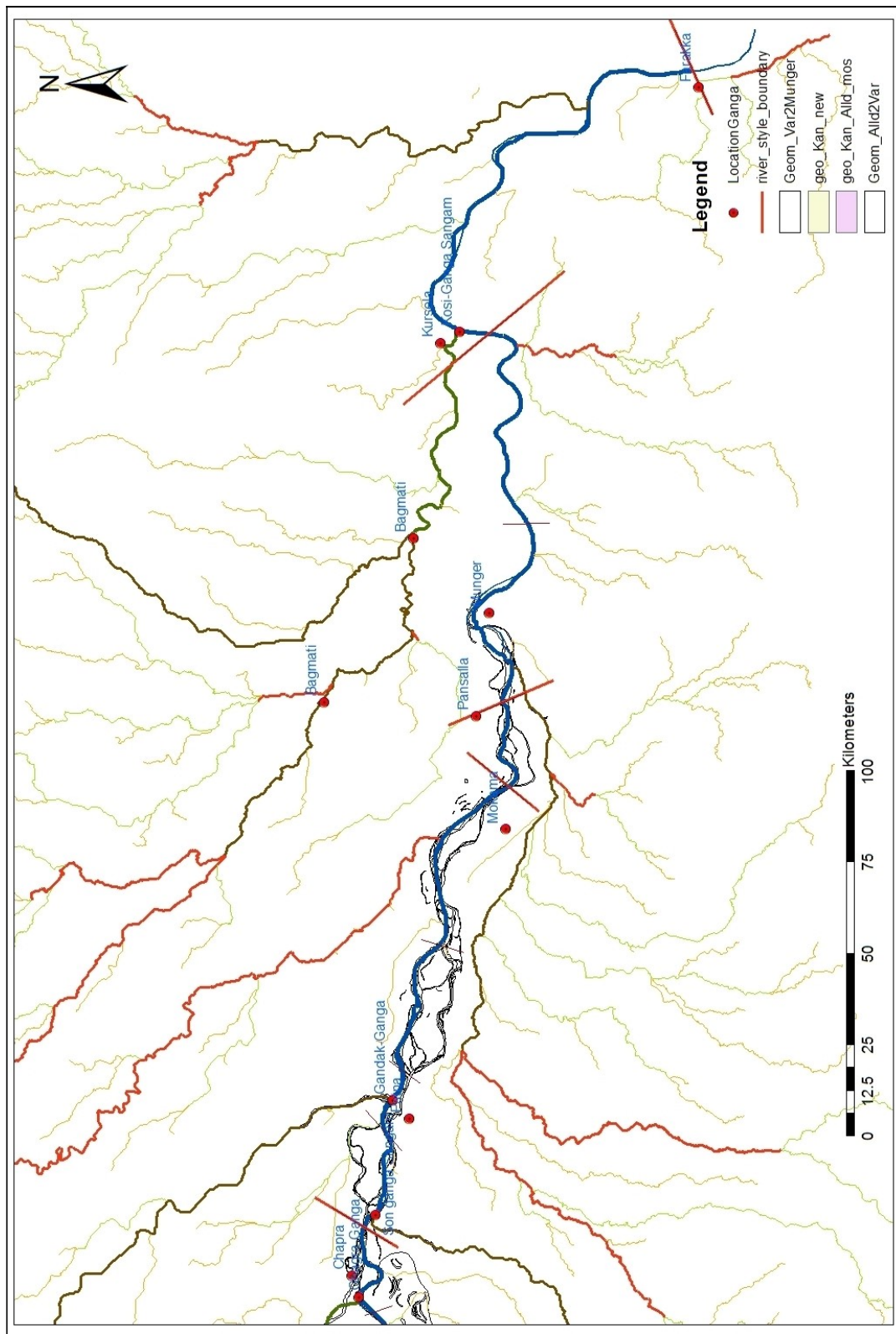


Figure 8(d): Comparison of the Drainage Map of the Ganga River with the Digitized Geomorphic Map from Landsat Data Between Reach of Patna to Farakka

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 River has 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 lie 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, Baghmata 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.

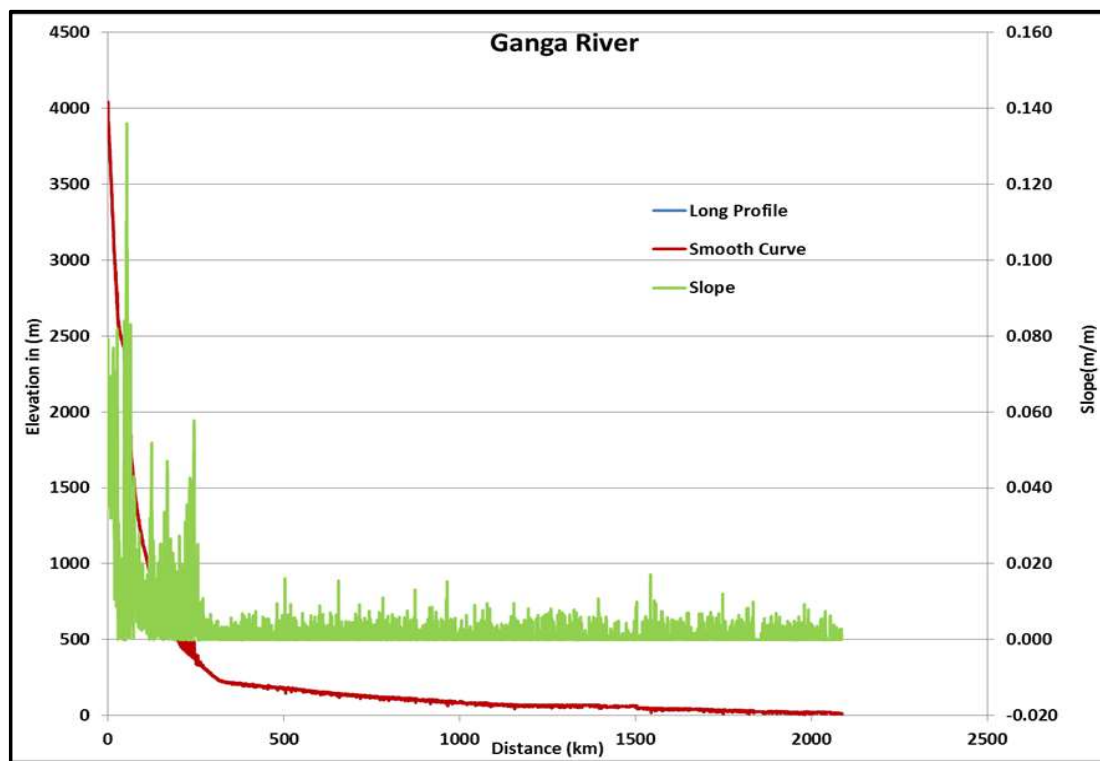


Figure 9: Shape of Long Profile of the Ganga River and its Effect on Slope Distribution along the River.

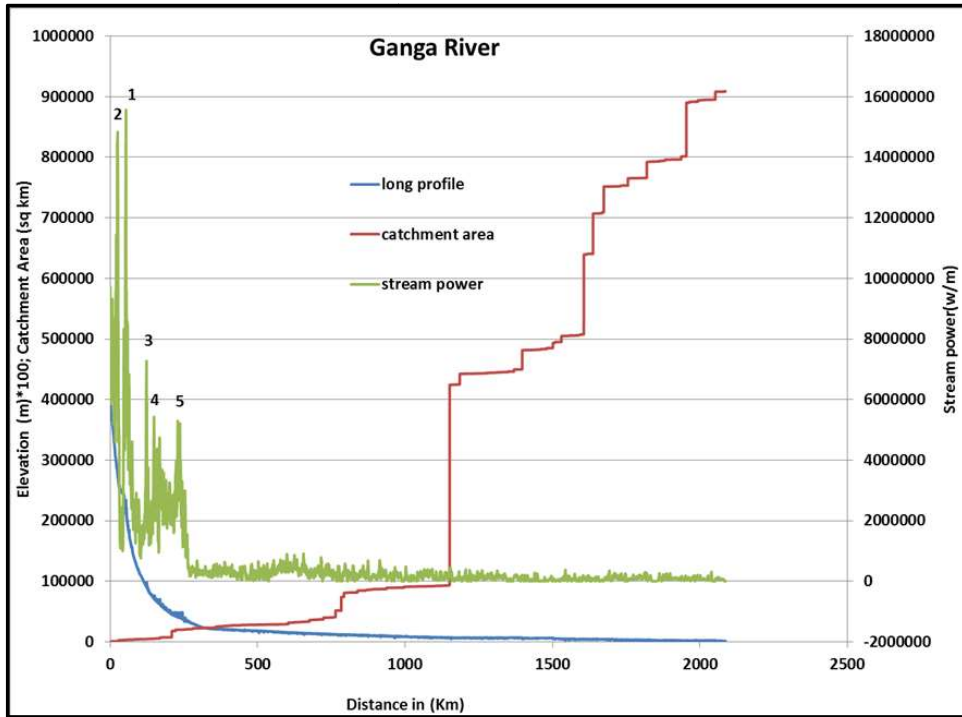


Figure: 10: Stream power distribution pattern in the Ganga river.

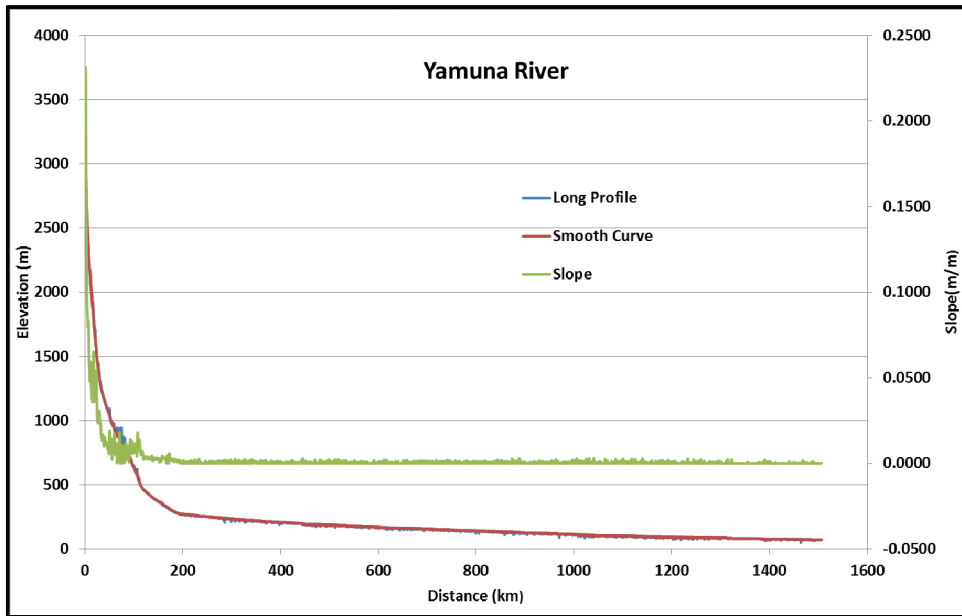


Figure: 11: Shape of Long Profile of the Yamuna River and its Effect on Slope Distribution along the River.

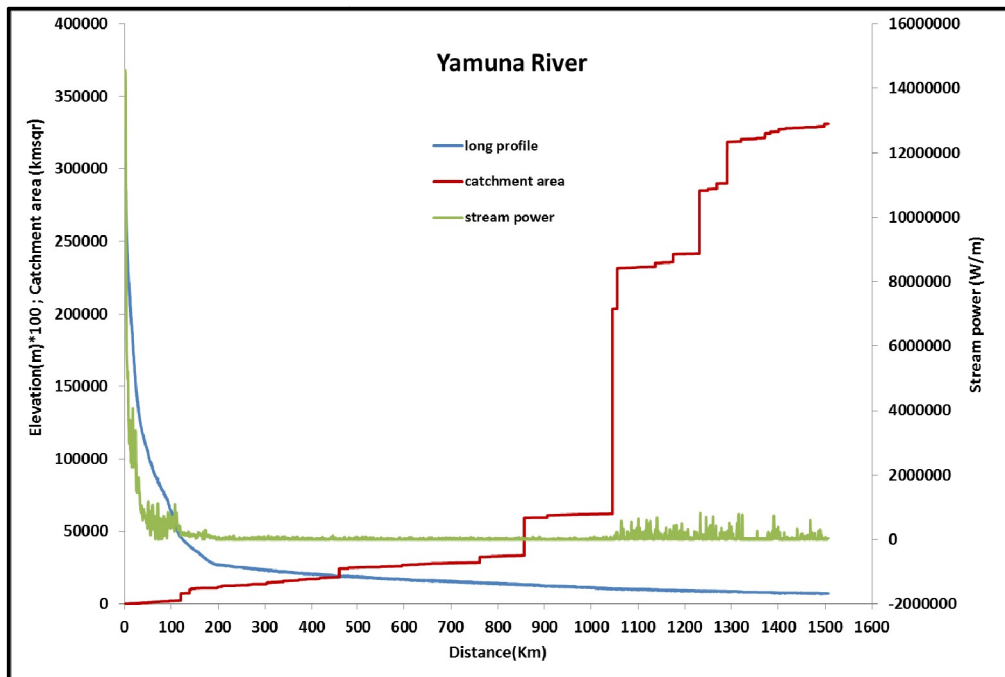


Figure 12: Stream Power Distribution Pattern in the Yamuna River. The Figure Also Shows the Distribution Pattern of the Long Profile and Contributing Catchment Area

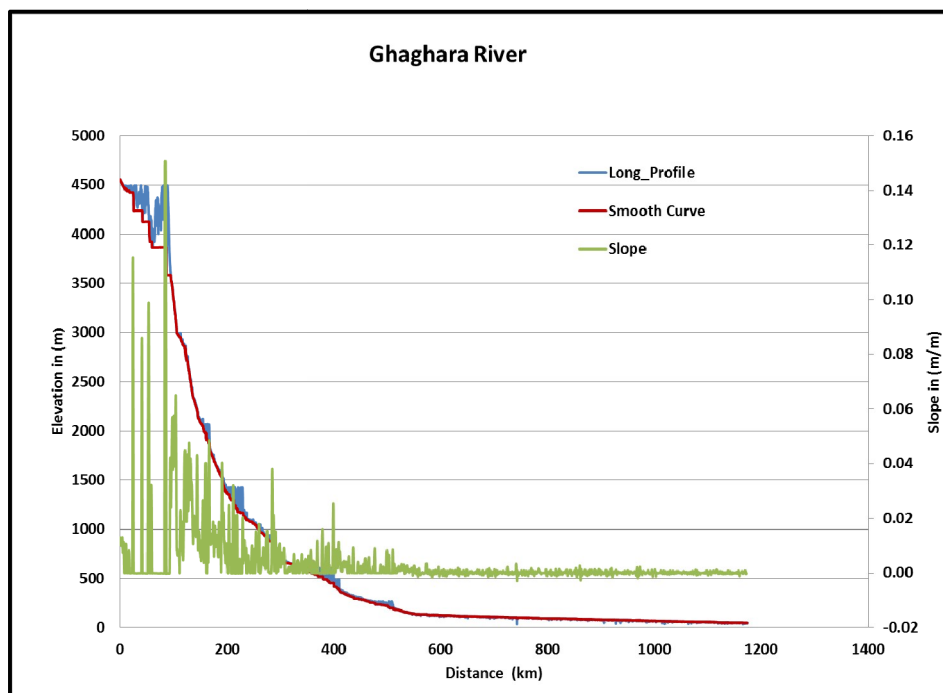


Figure 13: Shape of Long Profile of the Ghaghara River and its Effect on Slope Distribution along the River.

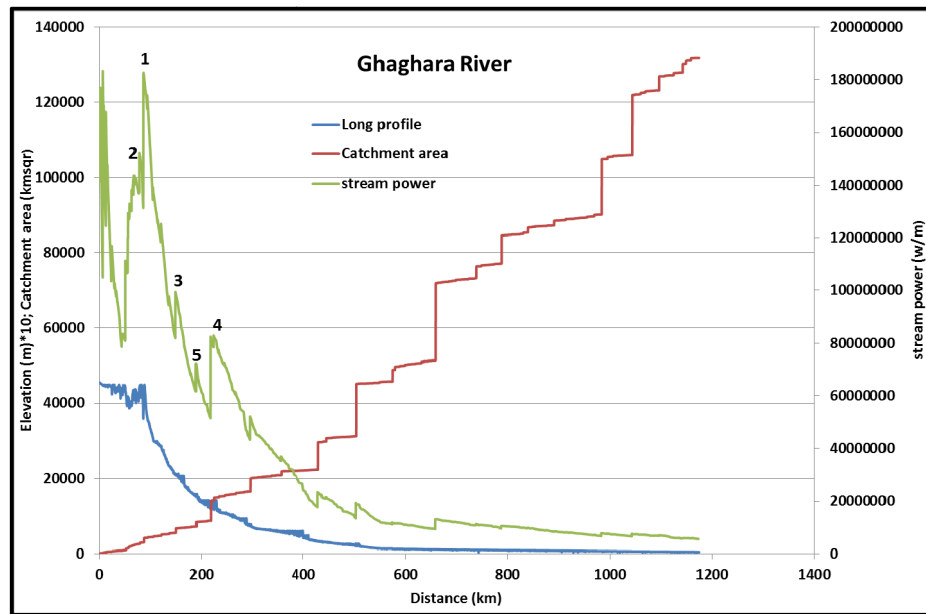


Figure 14: Stream Power Distribution Pattern in the Ghaghara River. The Figure also Shows the Distribution Pattern of the Long Profile and Contributing Catchment Area.

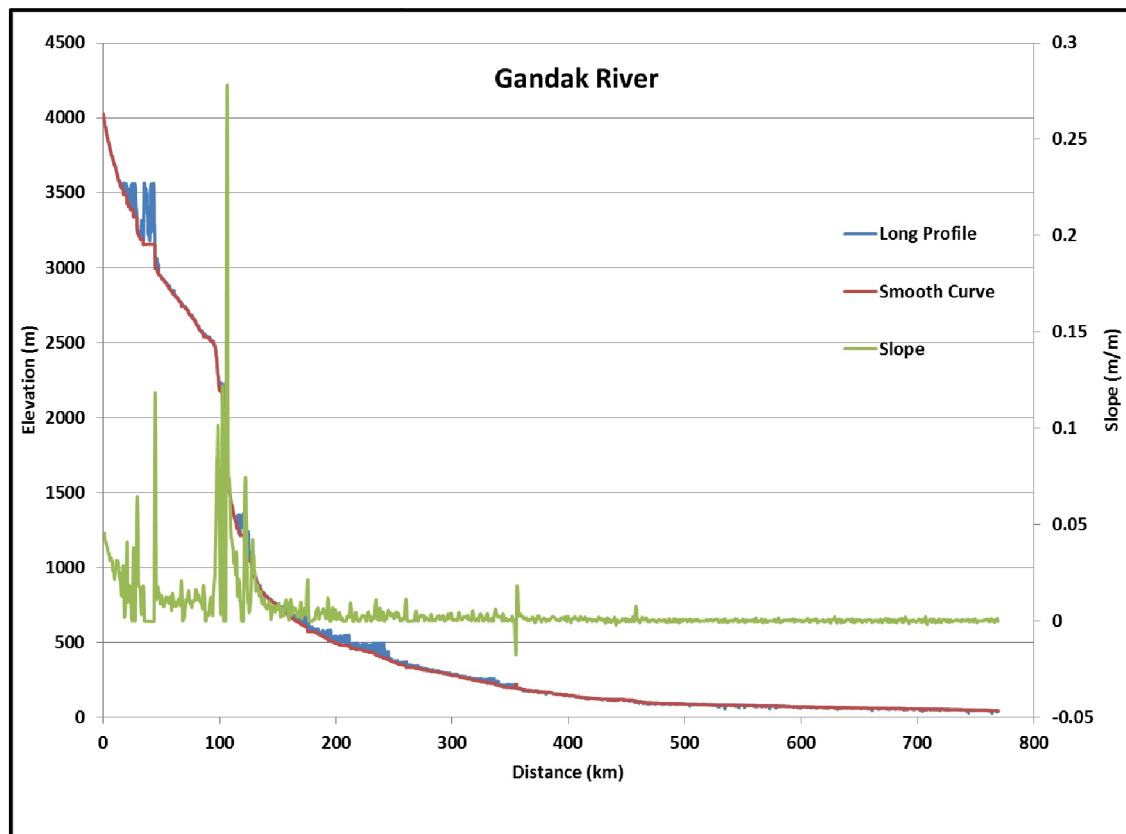


Figure 15: Shape of Long Profile of the Gandak River and its Effect on Slope Distribution Long the River.

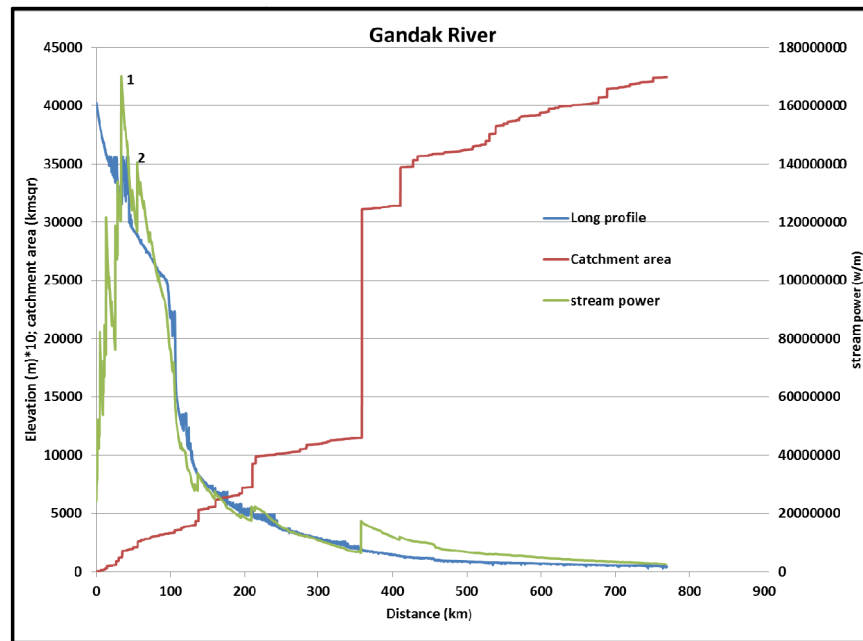


Figure 16: Stream Power Distribution Pattern in the Gandak River. The Figure also Shows the Distribution Pattern of the Long Profile and Contributing Catchment Area.

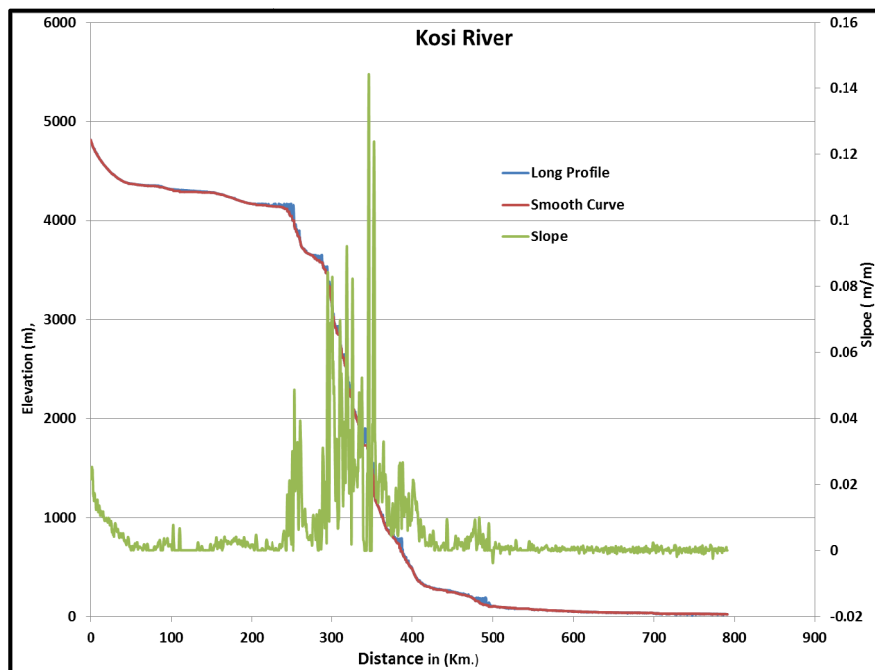


Figure 17: Shape of Long Profile of the Kosi River and its Effect on Slope Distribution along the River.

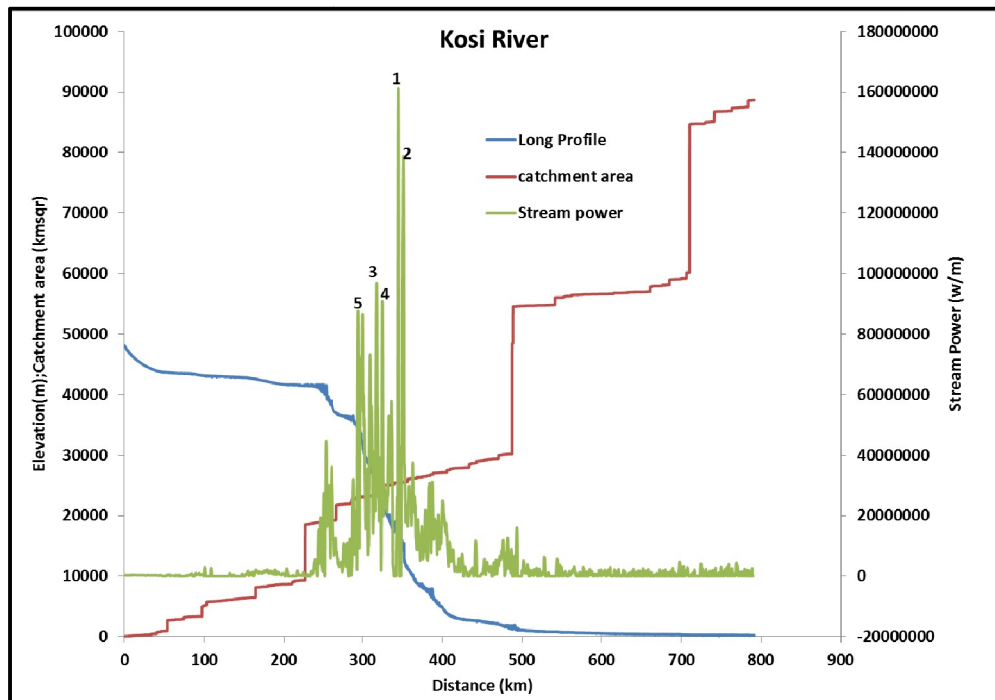


Figure 18: Stream Power Distribution Pattern in the Kosi River. The Figure also Shows the Distribution Pattern of the Long Profile and Contributing Catchment Area.

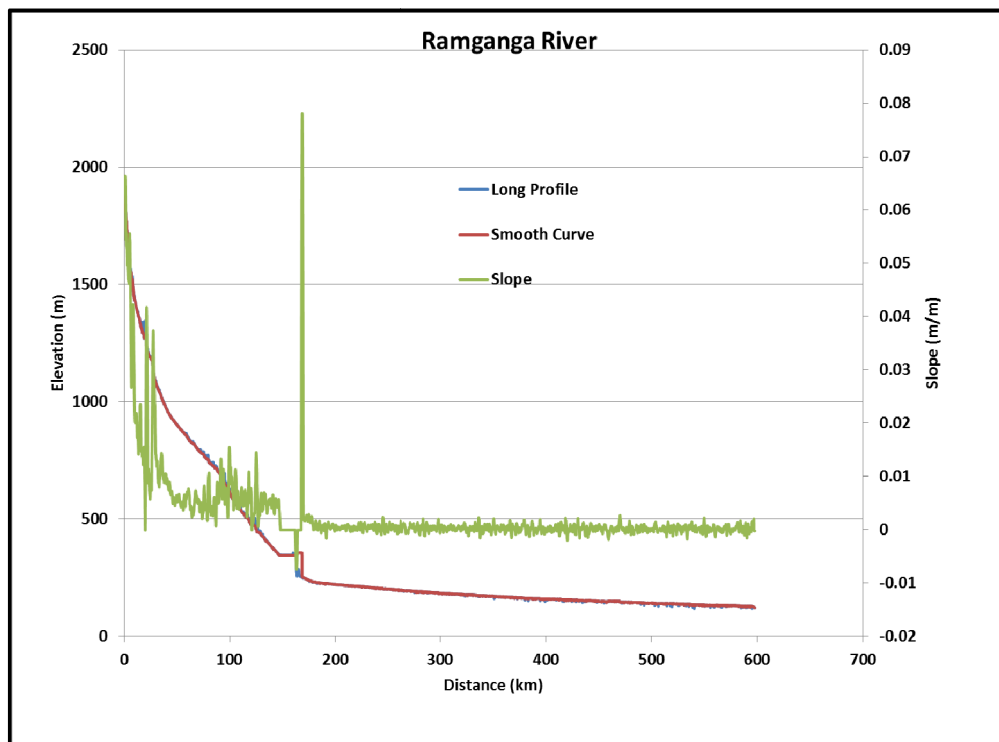


Figure 19: Shape of Long Profile of the Ramganga River and its Effect on Slope Distribution Along the River.

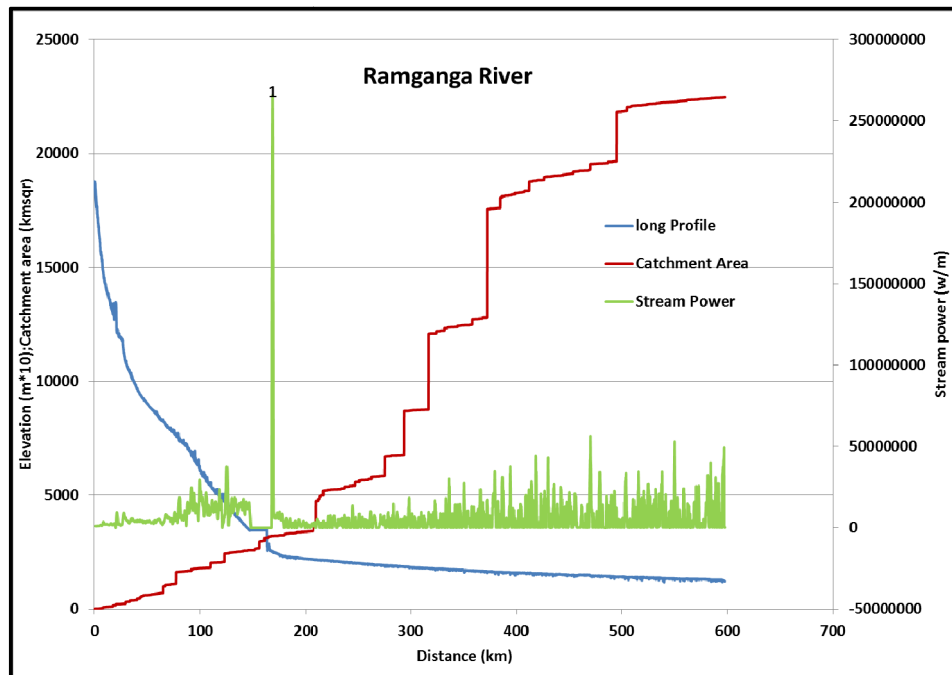


Figure 20: Stream Power Distribution Pattern in Ramganga River. The Figure also Shows the Distribution Pattern of the Long Profile and Contributing Catchment Area.

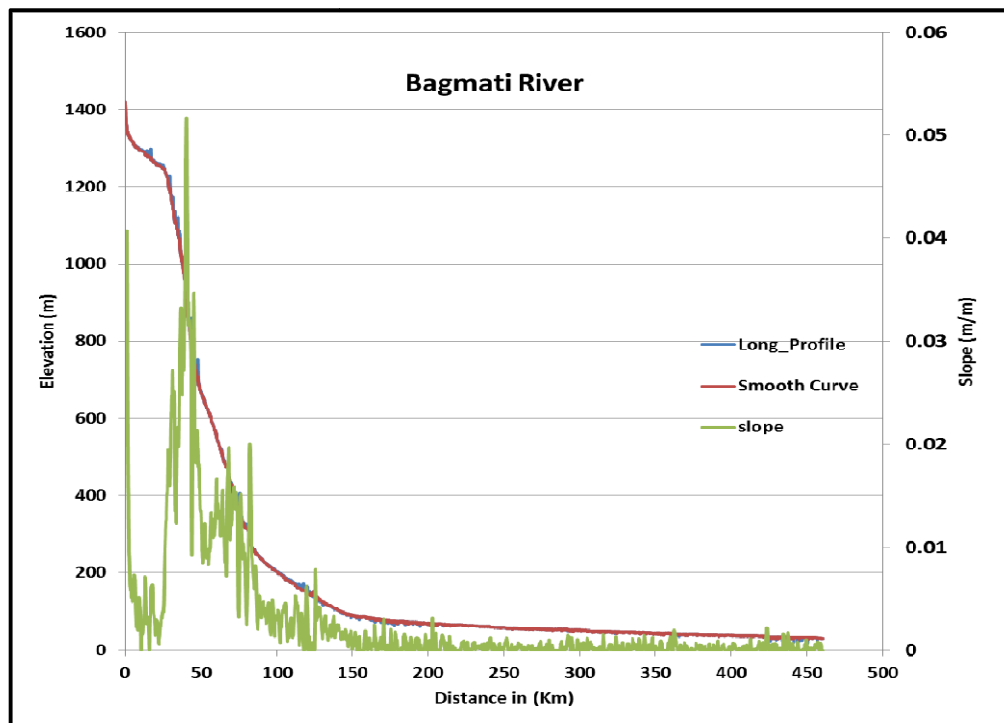


Figure 21: Shape Of Long Profile Of The Bagmati River and its Effect on Slope Distribution along the River.

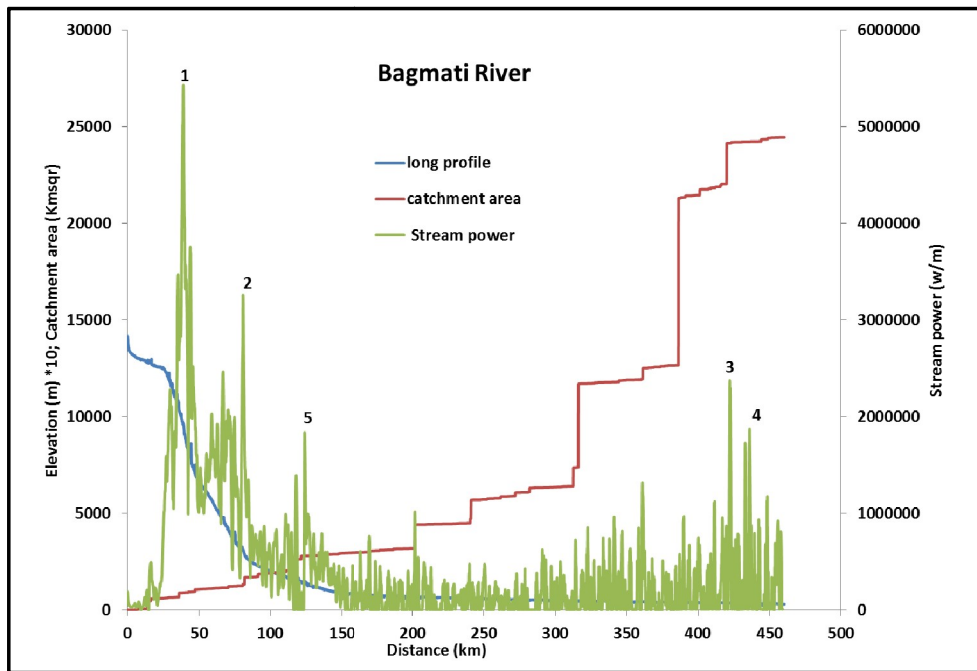


Figure 22: Stream Power Distribution Pattern in Bagmati River. The Figure also Shows the Distribution Pattern of the Long Profile and Contributing Catchment Area.

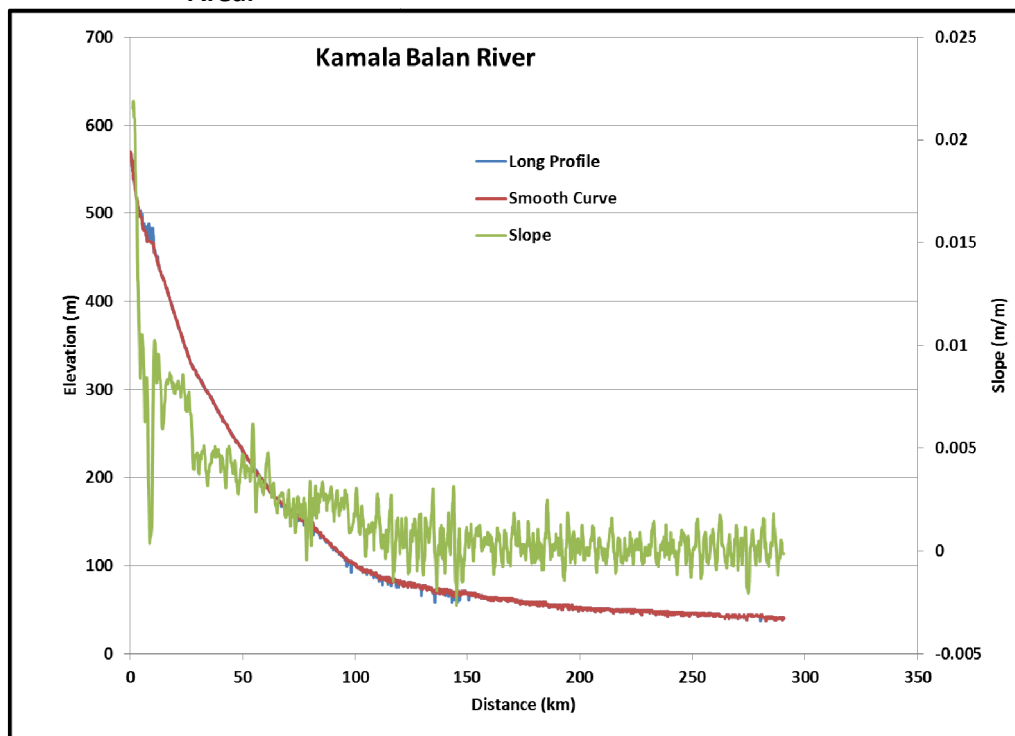


Figure 23: Shape of Long Profile of Kamla-Balan River and its Effect on Slope Distribution along the River.

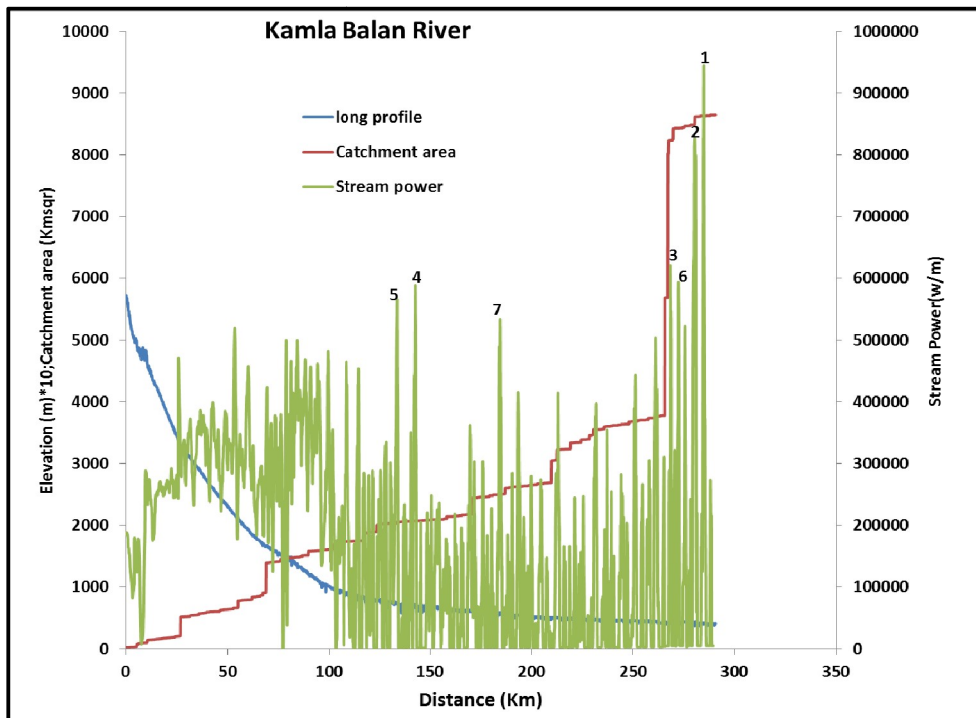


Figure 24: Stream Power Distribution Pattern in Kamla-Balan River. The Figure also Shows the Distribution Pattern of the Long Profile and Contributing Catchment Area.

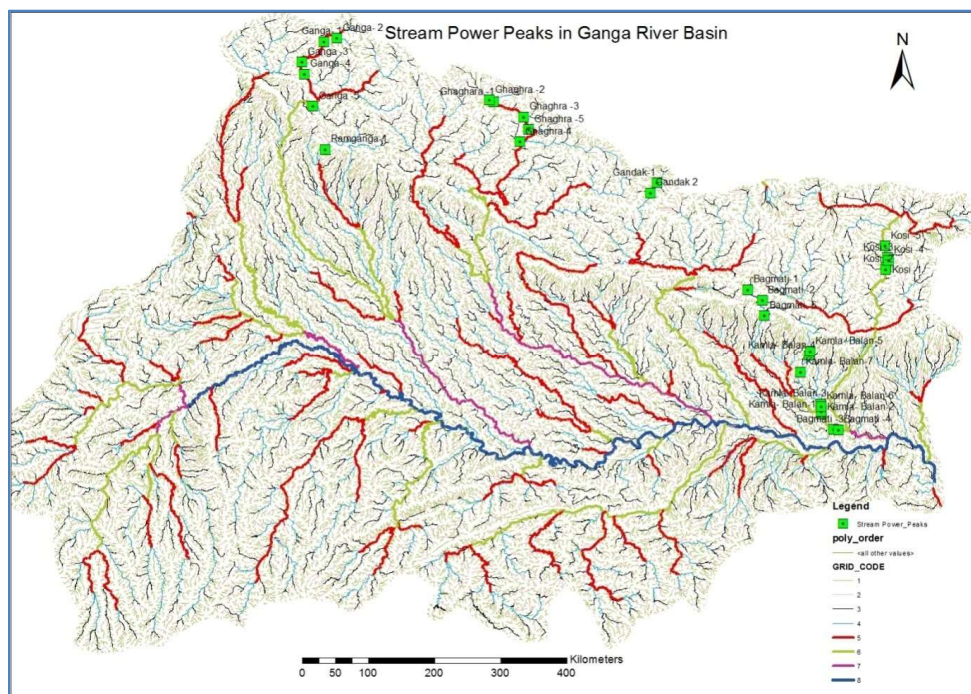


Figure 25: Location of Stream Power Peaks in the Planform Map. The Most of the Stream Power Peaks Lies it the Higher Himalayan Areas, which is also the Major Sources of Sediment Supply in Downstream Reaches.

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.

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