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JEHLUM & TAWI
FLOOD RECOVERY PROJECT

Consultancy Services for Preparing Feasibility and Detailed Project Report for Flood Mitigation and Comprehensive River Management Measures for Tawi Basin

PRELIMINARY MORPHOLOGY REPORT

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FEASIBILITY AND DETAILED PROJECT REPORT FOR FLOOD MITIGATION AND COMPREHENSIVE RIVER MANAGEMENT MEASURES FOR TAWI BASIN

PRELIMINARY MORPHOLOGY REPORT

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1 INTRODUCTION

Preliminary river morphological study has involved the use of satellite images to understand the regional scale physiography of the entire basin, particularly the hinterland, as they influence the downstream processes. We have used the Landsat and Sentinel satellite data to map the morphology of the entire basin to start with and this report primarily focuses on this. Detailed geomorphic mapping has focused on delineation of various geomorphic features in the basin based on visual mapping from False Color Composites (FCCs), and the various image processing techniques to delineate their boundaries precisely. We have also mapped the planform of the alluvial reaches in detail including the channel belt and active floodplain of the river in different stretches to get a first order assessment of the flood risk.

Since the main purpose of geomorphic mapping is for flood risk evaluation, it was decided during the kick off meeting to focus on the part of the Tawi river between Udhampur and confluence with the Chenab. The main source of data for mapping are Landsat and Sentinel data, the best possible scale from this is 1: 25,000 and 1: 10,000 respectively as per requirements included in ToR. **However, it is important to note that high resolution data such as Sentinel may not be available for the entire historical period and hence the resolution of the maps will vary as per the available data.**

The detailed morphological report will be prepared within the scope of the *Task 4 - Prepare River Hydrology and Morphological Report* and will include the reconstruction of planform changes using historical satellite images including the declassified Corona data of 1965 to reconstruct a baseline condition for fluvio geomorphological changes. We will use the pre-monsoon satellite images to reconstruct the river morphology and planform dynamics for the last ~50 years. Starting with Corona data set, we will produce river morphology maps for different years between 1965 (Landsat MSS) and 2018 (Landsat 8) at appropriate time intervals. We will use a time interval of around 10 years for the first four decades and then of 5 years for the last 15 years. We can also include some specific years such as 2014 and 2015 to document the river morphological changes due to the large flood. The specific years would be finalized after checking the data availability in consultation with PMU and I&FC officials.

2 MORPHOLOGY STUDY METHODOLOGY AND TECHNICAL APPROACH

2.1 TECHNICAL APPROACH FOR MORPHOLOGICAL MAPPING

Multispectral satellite image and digital elevation model (DEM) have emerged as the primary data sources for the mapping of landforms. They offer an opportunity to gain important insight into the morphology of an area through landform identification using spatial, temporal, spectral and radiometric resolution of satellite images, and through the synergetic approach using DEM derivatives such as profile, slope, hill shading, aspect and 3-D flythrough visuals

A detailed geomorphic map of whole Tawi river basin and planform mapping of the river within active flood plain has been prepared, depicting the current settings of the river and landform units. Planform mapping of the river has been performed as per the guidelines developed by the Consortium of all IITs for the Ganga basin (GRBEMP report, 2010, 2011).

Geomorphic features in the channel belt as well as active floodplain were delineated using satellite images and some index derived from it such as Normalised Difference Water Index (NDWI) and Normalised Difference Vegetation Index (NDVI). These features, have been mapped to record the river character and behavior for understanding the distinctive physical processes operating in different stretches. Topographic characteristics of entire Tawi basin were studied with the help of available ALOS PALSAR DEM (12.5 m) data and various DEM derivatives obtained from it followed by the correction and validation by recent sentinel-2 and Landsat data.

2.1.1 Data used

Toposheets are used for qualitative comparison of the geomorphic features. Satellite data of the pre-monsoon month have been used in the study to avoid the effect of the rain as well as of the ice melt. ALOS PALSAR DEM have been advantageous as it provides finer resolution in comparison to SRTM DEM. Advanced Land Observing Satellite (ALOS) was launched from Tanegashima, Japan, on 24 January 2006 aiming to advance land-observing technology, to contribute to cartography, regional observation, disaster monitoring, and the Earth resources surveying. PALSAR an enhanced version of the Japanese Earth Resources Satellite (JERS-1) SAR instrument (Rosenqvist et al., 2007). It has a center frequency of 1270 MHz (23.6 cm, i.e., L-band), and a chirp bandwidth of 14 MHz and 28 MHz. Phased Array type L-band Synthetic Aperture Radar (PALSAR) is an active microwave sensor which use L-band frequency to achieve cloud-free and day-and-night land observation (Osawa 2004). Table 2.1 lists all the available data for the study area that have been for this work.

Table 2.1 – Data used and their description.

Data Type	Resolution/ Scale	Aquisition time	Data source
Topographic sheet NI 43-14, NI 43 15, NI 43-11	1: 2,50,000	1915-44	US army map service
Landsat images LC08_L1TP_149037_20180209_20180221_01_T1 LC08_L1TP_148037_20180218_20180307_01_T1 LC08_L1TP_149037_20140926_20170419_01_T1	30 meter	9-2-2018 18-2-2018 26-9-2014	USGS
Sentinel-2 S2A_MSIL1C_20180217T053911_N0206_R005_T43SDS_20180217T092458 S2A_MSIL1C_20180217T053911_N0206_R005_T43SES_20180217T092458 S2A_MSIL1C_20180707T053641_N0206_R005_T43SDS_20180707T082817	10 meter	17-2-2018 17-2-2018 7-7- 2018	Copernicus Open Access Hub
ALOS-PALSAR DEM AP_12569_FBD_F0640 AP_12569_FBD_F0650 AP_12576_FBD_F0640 AP_12576_FBD_F0650	12.5 meter	2009	Alaska satellite facility https://vertex.daac.asf.alaska.edu

2.2 METHODOLOGY

The delineation of landforms was done using on screen image interpretation techniques. Geomorphic features were interpreted based on elements of interpretation such as shape, tone or colour, pattern, shadow, association and texture. Different band combinations of satellite data were used to generate a false colour composite (FCC) for image interpretation and manual mapping. In hilly areas, identification of the landforms is very challenging and hence visualisation of the terrain is an important component. Digital Elevation Model (DEM) which represents the spatial variations of the surface, is very helpful in identification of landforms specially in hilly areas. In the study ALOS PALSAR DEM was used to generate various topographic index. Planform mapping was performed in ArcGIS with Projection -UTM and datum-WGS-84 and various DEM derivates were calculated in SAGA-GIS and Q-GIS.

2.2.1 DEM Derivatives

Terrain roughness is a key property to measure the variability or heterogeneity of a topographic surface. There are various ways to calculate the calculate roughness of an area. In this work, we have used Terrain Ruggedness Index (TRI) after Riley (1999) and Topographic Position Index (TPI) after Jenness (2002).

Terrain Ruggedness Index (TRI) calculates the change in elevation between each grid cell and the mean of 8-cell neighborhood in a moving window. TRI is always ≥ 0 m, where 0 represents the minimum roughness.

Topographic Position Index (TPI) calculates the difference between the elevation of a cell and the mean elevation in a neighbourhood surrounding that cell. Neighbourhood means that elevation is calculated using a moving window centred on the cell of interest. The positive values of TPI, indicate that the cell is higher than its neighborhood, while negative values of TPI indicate the cell is lower than its neighbourhood cells.

TPI is a scale-dependent index and is sensitive to local differences from regional elevations. It helps to identify the upslope areas or ridges (where TPI is positive) from lower slopes or depressions (where TPI is negative). This index is useful for identifying landscape patterns that correspond with different rock type, dominant geomorphic process, soil characteristics, vegetation, or air drainage. In our study area, It has helped in mapping the spatial distribution of ridges and depressions in our study area but does not provide data on the relative depth of depressions. Both the indices are calculated in open source software called, SAGA-GIS.

Normalized height: The morphometric indices that controls the way the maximum values of the slope are taken over into the cell in the neighborhood (considering the local slope between the cells). It works on the principle that smaller the slope, the more of the maximum value is taken over into the cell that results in the smoothening or generalization. Whereas, the higher the slope, the less value is taken over into the cell and will result in a more irregular pattern caused by small changes in elevation between the cells.

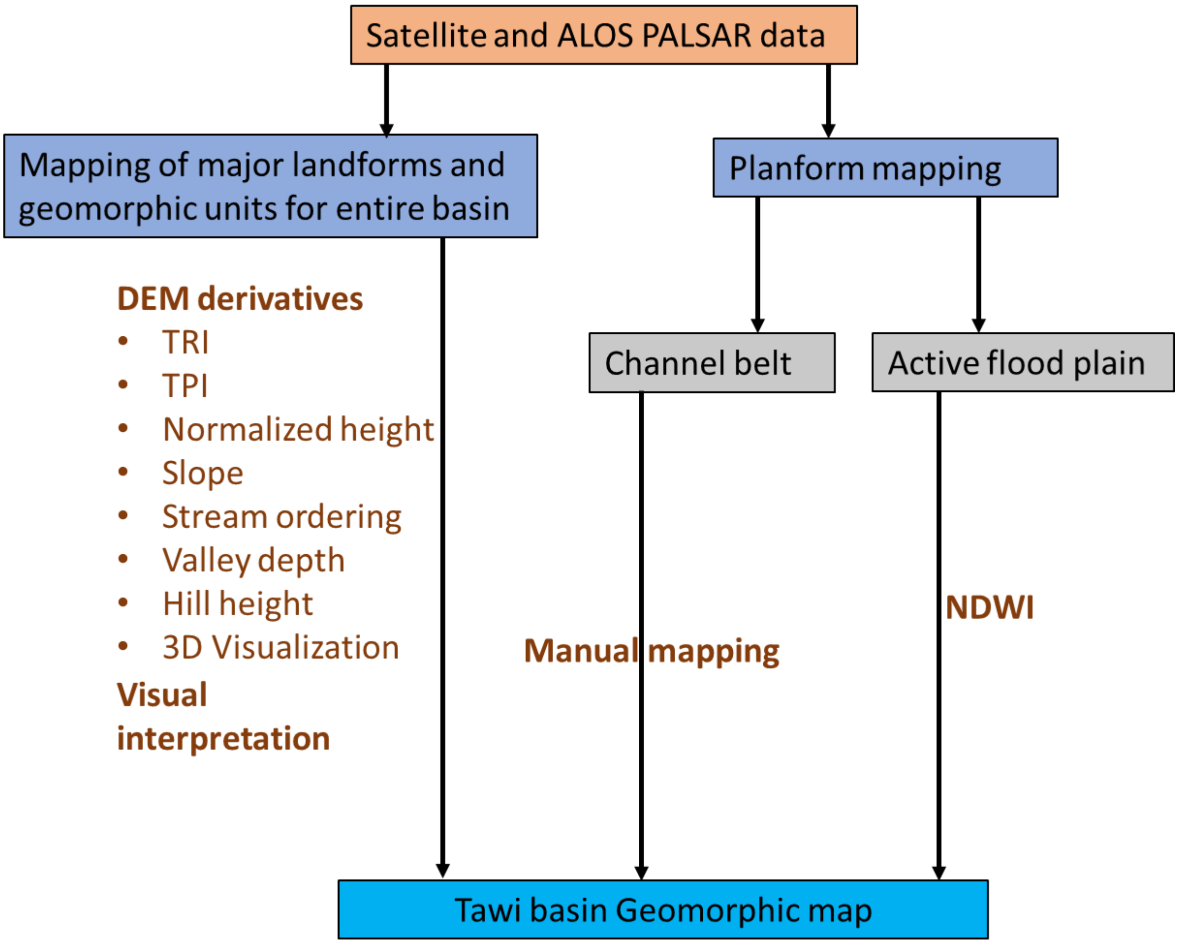


Figure 2.1: Flow chart showing methodology used for morphological study.

Stream order: ALOS PALSAR has helped to map the stream order with higher spatial resolution as compared to SRTM 30/90 m. An Arc-Hydro tool (an ARC-GIS software) has been used in the delineation of the stream order. Stream order and the drainage pattern reflects the influence of slope, lithology, and structural controls on the drainage basin.

3D visualization: With the help of high-resolution ALOS PALSAR and Landsat imageries, a 3-D view of the study area enabled us to identify the major landform units.

Visual Interpretation: Further, the present day geomorphic units were mapped using the spectral signature of the available satellite images (Sentinel and Landsat images). The elements of interpretation (such as tone, texture, shape, etc.) were used to map the different geomorphic units.

2.2.2 Planform mapping

Channel belt features were mapped by visual interpretation of satellite imageries. Active flood plain boundary was demarcated by calculating the NDWI from the Landsat image of 26th September 2014 (after flood event) and post-monsoon Sentinel-2 image of 2018. Both these images (Figure 2.2 a, b) have a distinct tone for high moisture area. This method presents a first order assessment of the active floodplain of the Tawi river based on satellite data which needs to be validated through field checks. Tables 2.2 and 2.3 present a complete list of morphological features and landforms that have been mapped for this project.

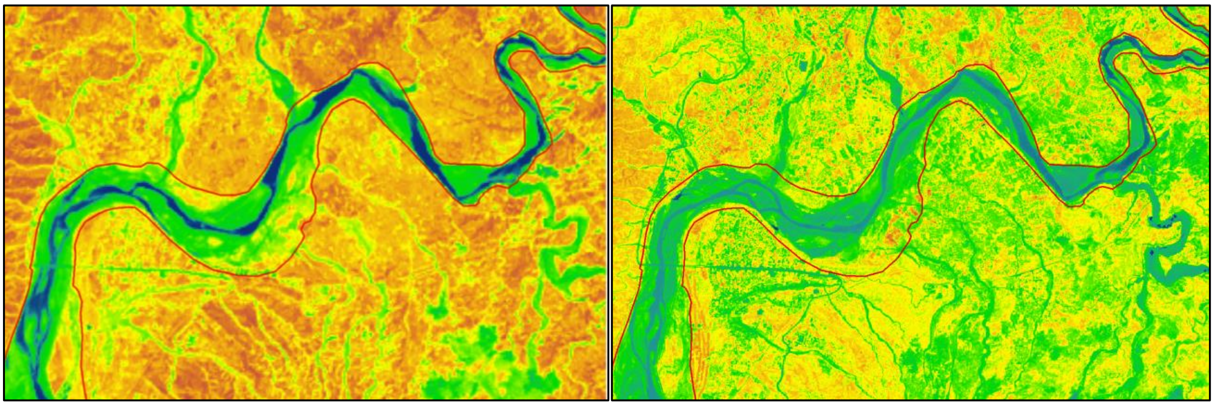


Figure 2.2: Color coded NDWI images showing sharp extent of moisture content (Dark green color), a) Image taken after the flood event in 2014, b) Post monsoon sentinel-2 image.

Table 2.2 – Channel belt and Floodplain geomorphic features (GRBEMP report, 2010).

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.

Feature	Definition and characteristics
Secondary channel	Pattern of co-existing 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.
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 plan view, reflecting the morphology of the former channel bends with water.
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.
Meander cut off	Channel depressions of arcuate or sinuous planform (generally one meander loop). Horse show or semi-circular in plan view, 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; coalescence 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
Active flood plain	It 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.

Table 2.3 – Major Landforms mapped in the study area (Roy e al., 2010).

Feature	Definition and characteristics
Mountains and Hills	There is no specific elevation criteria to differentiate both these units. Generally mountains are characterized by steep slopes and well defined summit. In the study these features are qualitatively separated by their elevation difference.
Intermontane basin	A generic term for wide structural depressions between mountain ranges that are partly filled with alluvium and called "valleys" in the vernacular. Intermontane basins may be drained internally (bolsons) or externally (semi-bolson).
Piedmont alluvial plain	Lying or formed at the base of a mountain or mountain range dominated by alluvium deposits; e.g., a piedmont terrace or a piedmont pediment. An area, plain, slope, glacier, or other feature at the base of a mountain; e.g., a foothill or a bajada.
Alluvial plain	A large assemblage of fluvial landforms (braided streams, terraces, etc.,) that form low gradient, regional ramps along the flanks of mountains and extend great distances from their sources (e.g., High Plains of North America).
Mountain valley	Any small, externally drained V-shaped depression (in cross-section) cut or deepened by a stream and floored with alluvium, or a broader, U-shaped depression modified by an alpine glacier and floored with either till or alluvium, that occurs on a mountain or within mountains. Several types of mountain valleys can be recognized based on their form and valley floor sediments (i.e., V-shaped valley, U-shaped valley).
Ridge	A long, narrow elevation of the land surface, usually sharp crested with steep sides and forming an extended upland between valleys. The term is used in areas of both hill and mountain relief.

2.3 SOFTWARE USED

Apart from using the Arc GIS for mapping and ERDAS for image processing, we have used an open source software, SAGA, for morphological analysis. This was helpful in generating several maps for terrain analysis and also for generating hypsometric curve. We also plan use the Analytical Hierarchy Process (AHP) model for the flood risk assessment developed by Saaty (1980). This model will be built in a GIS framework using a multi criteria decision making algorithm.

3 REVIEW OF NATIONAL AND GLOBAL STUDIES

One of the first geomorphological maps of the Gangetic basin was compiled by Geddes (1960) using topographic surveys techniques. A series of cones and intercone areas were mapped by Geddes (1960) along the Himalayan front, and he demonstrated that sediment load and discharge of a river is related to the size of the alluvial fans. Satellite data and toposheets were also used for delineating major geomorphic units such as uplands, ravines, floodplains, paleo channels, etc. (e.g., Bajpai, 1989; Bajpai and Gokhale, 1986). Based on the disposition of various geomorphic elements, Sinha et al. (2005) distinguished seven mega-geomorphic units for geomorphic characterization of Gangetic plains namely-Active channel belt, Active flood plain, minor channels and flood plain, inactive flood 18 plain, slightly dissected surface, highly dissected surface, and piedmont plain. To understand reach scale morphology within channel belt, meandering and braiding parameters were developed by (Friend and Sinha, 1993). Sinuosity (P) and braid channel ratio (B) for different rivers allow us to characterize reach scale morphology of channels and their spatial variability. Based on remote sensing and GIS data, Parua (2002) and Thakur et al. (2012) observed the morphological changes of the Lower Ganga river for pre and post-Farakka. Sinha and Ghosh (2012) observed remarkable dynamics of the river both upstream and downstream of the Farakka. The meandering and the braiding nature of the river is dependent on the size and amount of sediment load, slope of the basin, bank material and vegetation.

The rivers originating in the Himalayas are braided due to their high sediment load and the rivers originating in plains are meandering because of their low sediment load. The general belief is that slope and discharge influence the sinuosity and braiding nature of the river but Sinha and Friend (1994) observed that the availability of bed load sediment relative to suspended load sediments has a much stronger influence on the same.

The capability of the channel to alter its planform depends on the balance between the erosional forces exerted by the flowing water and the resistance to erosion of the material present on the channel's bed and banks. Channel planform changes by erosional and depositional processes results into meandering and braiding of the channels and/or by cut-offs and avulsions that involve switching of channel position (Brook and Luft, 1987). This balance is a function of the slope of channel bed, discharge of the channel, sediment load, size of bed material, and the composition of bank material (Richards, 1982b; Robert, 2014). A change in any of these variables disturbs the equilibrium and leads to aggradation or degradation.

Figure 3.1 shows that when the channel pattern changes from 1 to 5, other morphologic aspects of the channel also change; that is, for a given discharge, both the gradient and the width-depth ratio increase. In addition, peak discharge, sediment size, and sediment load probably increase from pattern 1 to pattern 5. With such geomorphic and hydrologic changes, hydraulic differences can be expected, and flow velocity, tractive force, and stream power also increase from pattern 1 to 5. Therefore, the stability of a graded stream decreases from pattern 1 to pattern 5, with patterns 4 and 5 being the least stable.

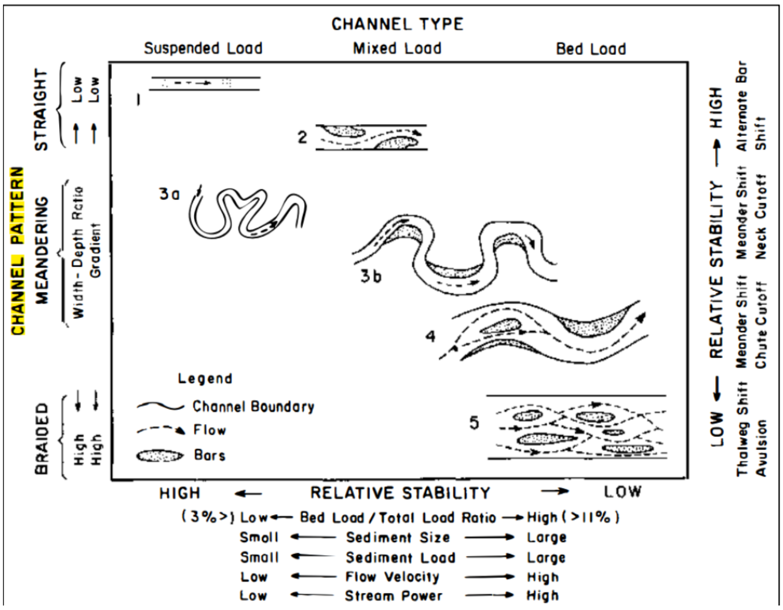


Figure 3.1: Channel classification based on pattern and type of sediment load, showing types of channels, their relative stability, and some associated variables (Schumm, 1981).

The migratory behavior of the river is a natural process, but many times, this is triggered or amplified by human interventions. The assessment of the migration behavior of the river is very essential for urban planning, and to prepare river management schemes. It is also useful for the studies associated with the river bank erosion, flood hazard, and slope failure (avulsion). Conventional methods for studying planform changes are ground survey using Plane table method, Theodolite survey, etc. However, these methods are very tedious and time-consuming and requires repetitive field-visits. Therefore, because of their high temporal resolutions and easy availability, planform mapping using satellite images can be very useful in reconstructing and delineating the spatio-temporal changes in the streams (Philip et al., 1989). Several efforts have been done to reconstruct and understand the planform migration of the channel and evolution of the dynamic geomorphic processes (e.g., Gupta et al., 2013; Leopold and Wolman, 1957; Sinha et al., 2014; Stølum, 1998).

Leopold and Wolman (1960) analyzed and integrated what appears to be the most prevalent essential characteristics of meandering channels in nature. He gave the general idea that large river has large bends and smaller rivers have smaller bends and also presented the pattern and behavior of the meander formed by melt river on the surface of glaciers.

Schumm and Lichty (1963) carried out work on flood-induced channel migration in Cimarron river in south western Kanas. The flood destroyed the meander bend, point bars and eroded the protective bank vegetation; the average width of the river was 50 feet in 1874. During and after the major flood of 1914, the river widened until an average width of 1,200 feet was reached in 1942. Parker (1976) performed a stability analysis of the meandering and braiding patterns in a model alluvial river. The analysis indicates that if the slope and the width-depth ratio at formative discharges are sufficiently low, meandering is favored. However, if the slope and the width-depth are sufficiently high, braiding is favored. Schumm (1985) documented that the pattern of any river is related to its hydrology, sediment yield characteristics, and geologic history of the drainage basin. He also mentioned that the river pattern itself provide the information of river characteristics. Based on the material on which the river flows, he detected three categories of stream channel: bedrock, semi-controlled, and alluvial. Friend and Sinha (1993) proposed modifications to braiding and meandering parameters to include both single and multiple channels. Sinuosity (P) is defined as, $P = L_{cmax}/L_R$, where L_{cmax} is the length of the midline of the channel (in single-channel rivers), or the widest channel (in multi-channel rivers), and L_R is the overall length of the reach. 'Braid-channel ratio' (B) has been defined as, $B= L_{ctot}/L_{cmax}$, where L_{ctot}, is the total of the mid-channel lengths of all the channels in a reach.

Surian (1999) documented the channel change of the Piave river in the eastern Alps, Italy in response to human interventions and analyzed that the river dynamics was affected by the bank protection structures and hydroelectric dams. He performed the historical analysis using maps and aerial photographs and documented that the presence of the dam has reduced the flow and sediment supply which results into reduction of channel width to 35 percent of its initial value while the braiding index has decreased from 3 to 1.5. The author also predicted that this trend would continue until the channel attains an equilibrium condition. Hudson and Kesel (2000) analyzed the channel migration and meander-bend curvature in the Lower Mississippi river between the time-period of 1877 and 1924 and developed a relation between meander bend curvature and migration. They documented that the highest migration rates were observed in channels with meander bend radius to channel width ratio between 1 and 2.

Kummu et al. (2008) documented the bank erosion and deposition rates along the left and right banks, change in alluvial islands of the Mekong river China between Vientiane–Nong Khai in the span of 44 years (1961-2005) and found that the average annual erosion rates in left banks were higher than that of the right bank and thus, increased bank protection on the right side (Thailand side) has decreased the erosion rates. The authors also documented that the presence of the Dam has made the river ‘hungry’ i.e., river water devoid of sediments, (Kondolf, 1997) in the downstream resulting in the river bank erosion and the erosion rates in the islands were higher than the erosions rates in the river banks. Rutherfurd et al. (1996) made a similar study using the 1961 and 1992 hydrographic atlases to estimate the bank erosion and accretion rates in the Vientiane–Nong Khai reach of the Mekong river.

4 DATA AVAILABILITY ANALYSIS

Table 4.1 identifies the data available for the study area that are being used for this project. We are currently using a variety of remote sensing data products for morphological study. For this report, the Sentinel data of February 2018 have been used for basin scale mapping of morphological features. For mapping planform dynamics of the lower alluvial reaches, we will be using the satellite data for the years 1968, 1977, 1989, 2000, 2005, 2010, 2014, 2015 and 2018. The Landsat MSS and TM data can produce maps at a resolution of 1: 50,000 and 1:25,000 scale respectively and the sentinel data can provide the best possible resolution of 1: 10,000 (see Table 4.1).

Table 4.1 – Data availability.

Year	Data	Spatial resolution	Suggested scale for mapping	Availability
1965, 67	CORONA	~4-5m	1: 10,000	Only post monsoon data available, to be purchased
1968	CORONA	~4-5m	1: 10,000	Pre-monsoon data available, to be purchased
1977	Landsat 2 MSS	60m	1: 50,000	Yes
1989	Landsat 5 TM	30m	1:25,000	Yes
2000	Landsat 5 TM	30m	1:25,000	Yes
2002-09	Landsat 7 ETM	30m	1:25,000	Not available, problems of Scan line
2010	Landsat 5 TM	30m	1:25,000	Yes
2014	Landsat 8	30m	1:25,000	Yes
2015	Landsat 8	30m	1:25,000	Yes
2018	Landsat 8 Sentinel 2	30m 10m	1:25,000 1:10,000	Yes

As per the TOR and comments from the I&FC department, they would like to have the planform maps at a scale of 1:25,000 for the river between Udhampur and confluence and at 1: 10,000 for selected reaches. As per the Table 4.1, the best possible scale at which these maps can be produced is 1:10,000 from Sentinel data that is available only since June 2015. All other maps have to be based on the Landsat data from which only 1: 25,000 scale maps are possible. Additionally, high resolution orthophotos for the present day scenario can be obtained from which maps at 1:10,000 scale can be easily created. Further, for computing morphometric parameters and mapping flood risk in the alluvial reaches, high resolution DEM would also be required. In addition, we need several data sets for flood risk assessment. Table 4.2 shows the data required for carrying out high resolution mapping and flood risk analysis.

Table 4.2 – Data required for high resolution morphological mapping.

Data	Spatial resolution	Suggested scale for mapping	Possible source and Remarks
CORONA images	**4-5 m**	1: 10,000	USGS, one mission carried out between 1965-67; data available for Jammu is for 1967
High resolution DEM	Variable, < 10 m	1: 10,000	To be acquired
High resolution ortho images	0.5 m	1: 10,000	To be acquired
LULC maps	1: 10,000	1: 10,000	NRSC Hyderabad
District and block boundaries	**NA**	**NA**	District officials
Population data	Block level	NA	Census office, Landscan data
Major infrastructure in the basin	As available	NA	I&FC department
Rainfall data	Point data	NA	IMD

It is relevant to mention here that the earliest satellite data available is for 1965/1967 from the Corona Mission and this was a one-time mission. The Landsat MSS data (79 m resolution) is available from 1977 onwards and Landsat TM data (30 m resolution) is available from 1989 onwards. Therefore, the earliest time we can go back to with the available satellite data is 50 years (1967). If there are maps or any other data available (e.g. air photos) for the time period beyond 1967, this has to be provided.

5 MORPHOLOGICAL AND PHYSIOGRAPHIC CHARACTERIZATION

The Tawi river basin is a sub basin of the Chenab basin, and a major part of this basin falls in the State of Jammu and Kashmir, India, and nearly 5% falls in Pakistan. The Tawi river originates from Kali Kundi glacier and covers 141 km before its confluence with Chenab in Pakistan. The elevation of the entire basin varies between 189 m at confluence of Chenab and Tawi to 4295 meters near Kailash-Kund glacier from mean sea level (Figure 5.1). The upper portion of the river basin is characterized by rugged mountainous topography, the middle part consists of low hills followed by piedmonts and alluvial plains. Total basin area of the Tawi basin is about 2897 km^2 out of which 1390 km^2 and 1372 km^2 area falls in Udhampur and Jammu districts respectively and the lower most portion with 135 km^2 area in upstream of the confluence of Chenab and Tawi falls in Pakistan (Figure 5.1).

The Udhampur district lies in the mighty Himalayan Range and it is situated in south eastern part of Jammu and Kashmir state. Physiographically, the district is characterized by mountain ranges trending NW-SE direction, the district is covered partly by Pir Panjal ranges and partly by Outer Himalayas. Major slope of the terrain is towards south and southwest. The gentle terrain occurs in southern and southwestern part while in northern part is covered by complex and high mountainous terrain. Majority of the district is occupied by the rocks belonging to Murree and Siwalik formations of tertiary period, CGWB (2014).

The district of Jammu shares the border with Pakistan in the west and ranks among the most populous city in the state. It falls in sub-mountainous region at the foothills of the Himalayas. Jammu district can be divided in two major units viz. Siwalik ranges (Hilly area) and outer plains. Siwalik range rises gradually in the north part of the district and outer plains merges with the Indo-Gangetic plains in the south CGWB (2013).

The drainage network was extracted from the ALOS PALSAR DEM with appropriate thresholding to remove the spurious drainage. Stream order was calculated using the DEM data in Arc GIS using arc hydro tool. Stream upto 7th order has been found in the basin (Figure 5.2). Drainage texture and patterns are quite variable in the basin depending upon the geomorphic setting and specific landform; this has described later in conjunction with major geomorphic units. A strong structural control on drainage pattern is apparent in the mountainous part of the basin.

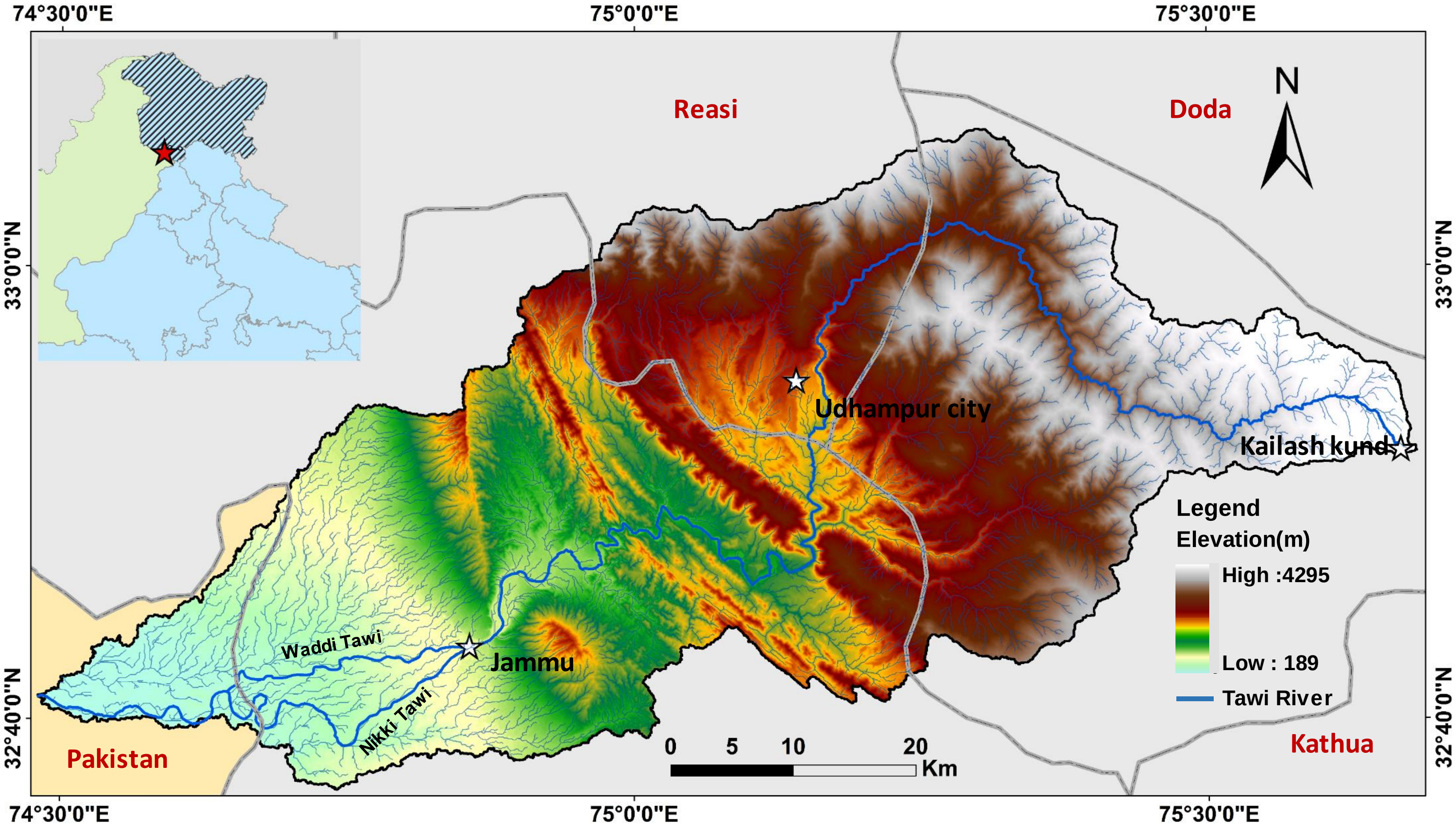


Figure 5.1: Physiographic and Topographic characterization of Tawi River Basin.

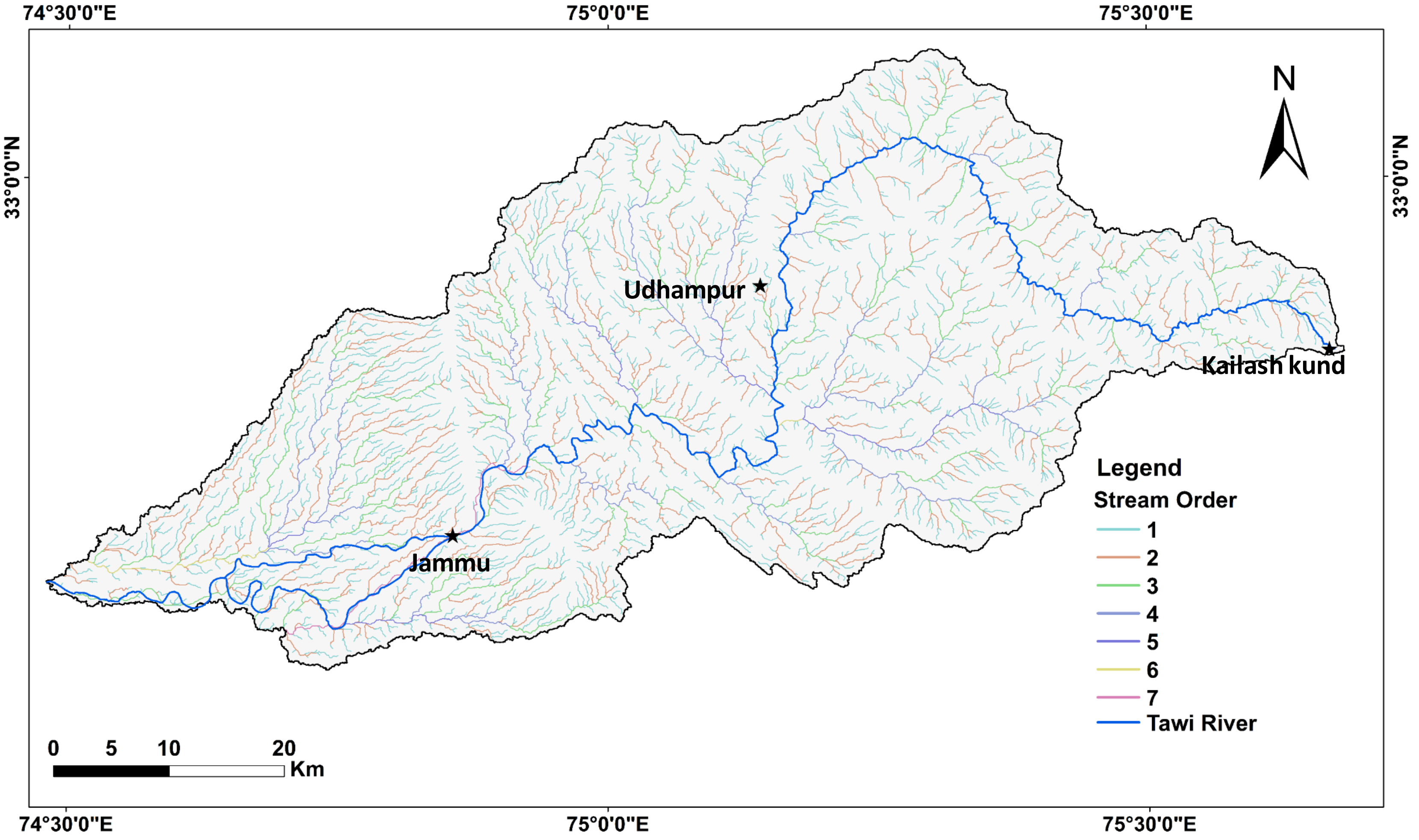


Figure 5.2: Drainage network and Stream order of Tawi River Basin.

The hypsometric curve for Tawi River Basin reveals a gradual sloping pattern increasing towards a steeper curve. The shape of a hypsometric curve is an indicator of dominant geomorphic processes at work in a river basin (Figure 5.3). A convex curve indicates more of the watershed's area (or volume of rock and soil) is held relatively high in the watershed. In this case, diffusive hill slope processes such as land-sliding, rain-splash, inter-rill erosion, soil creep, etc., play a larger role. A concave curve indicates the bulk of the basin's area (or volume of rock and soil) resides at relatively low elevation. More material has been removed from higher areas and either transported to lower areas or advected out of the basin completely. Concave curves indicate channelized/linear/fluvial/ alluvial processes dominate (Talampas et. al, 2015). These hypsometric curve shapes describe the stages of the landscape evolution, which also provides an indication of erosion status of watershed.

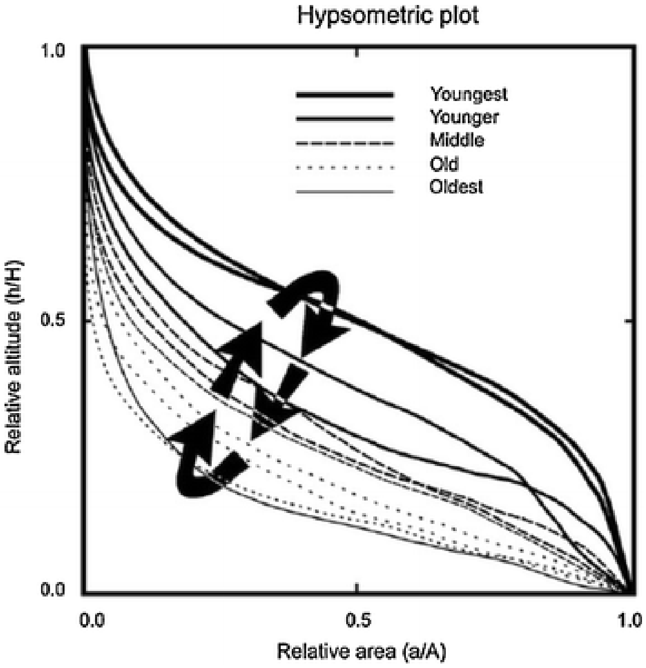
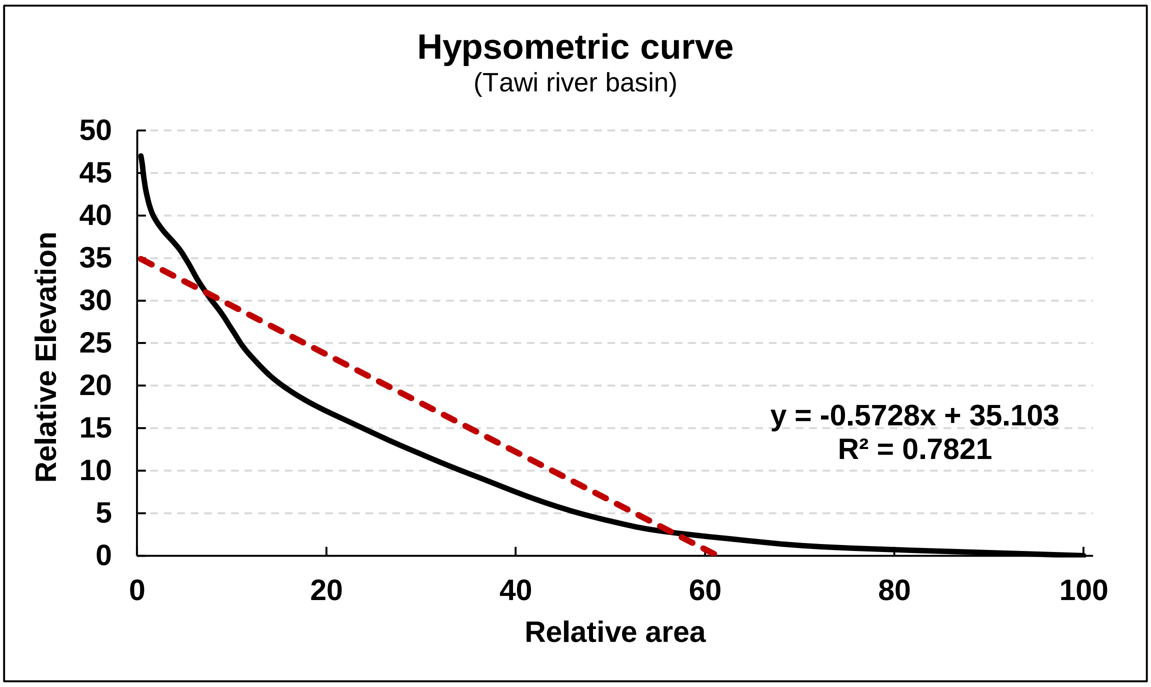


Figure 5.3: Interpretation of different hypsometric curves: convex curves represent youthful stages, s-shaped and concave curves represent mature and old stages. This behavior depends on variation in orogenic elevation during a geomorphic cycle (Perez-Pena et al. 2009).

Figure 5.4 shows the hypsometric curve for Tawi River Basin using relative area as well as absolute area. The hypsometric curve of the Tawi River is a S-shaped feature displaying a concave upward profile suggesting proneness of the watershed to erosional processes. The hypsometric curve shows that ~55% of the basin has less than ~180 m of elevation (<5% of relative elevation) suggesting a very flat terrain in the alluvial reaches. However, about 20% of the basin area has > 1000 m of elevation which is quite significant in terms of erosional processes and this also explains the concave up profile. Our analysis suggests that the Tawi basin has a very active erosional hinterland and the slope are quite steep in the high mountainous area. This results in a high sediment flux from the hinterland particularly during the high monsoon period.



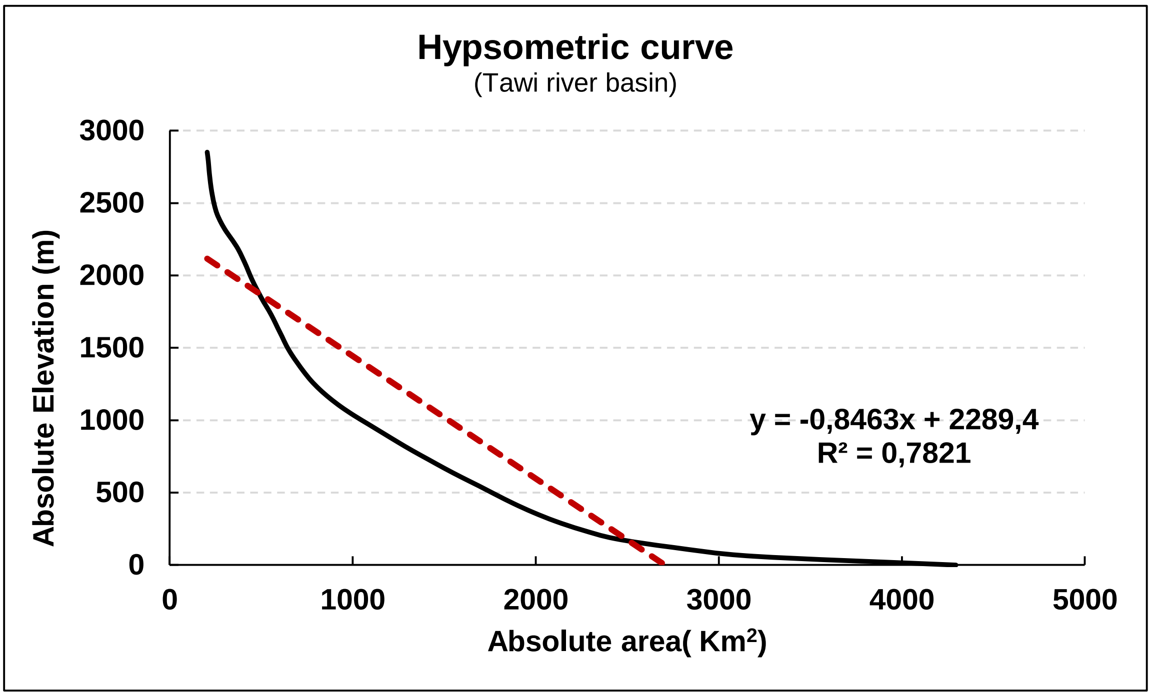


Figure 5.4: Hypsometric curves for Tawi river basin using (a) relative area and (b) absolute area.

6 GEOMORPHIC MAPPING AND PLANFORM DYNAMICS ANALYSIS

6.1 GEOMORPHIC UNITS

On the basis of digital elevation model (Figure 5.1), 3D visualisation (Figure 6.1) we have observed seven major landform units in Tawi river basin (Figure 6.2) namely, (1) Highly rugged mountain (HRM), (2) Moderately rugged mountain (MRM), (3) Moderately rugged hills (MRH), (4) Low rugged hills (LRH), (5) Intermontane basin (IB), (6) Piedmont (PD), and (7) Alluvial plains (AP).

Further, with the help of different DEM derivatives (Section 2.2.1), we have characterised the basin characteristics e.g.

a) Topographic ruggedness index(TRI): This index provides the heterogeneity in the elevation among different landform units (Figure 6.3 a)
b) Topographic position index (TPI): It has helped in mapping the spatial distribution of ridges and depressions in our study area but does not provide data on the relative depth of depressions. It has also helped in identifying the drainage pattern within the different landform units (Figure 6.3 b).
c) Normalized height: It has helped in demarcating the outer boundary of piedmont alluvial plain with alluvial plain. This index also highlighted the ridges and valleys. (Figure 6.3 c)
d) Hill height: This index has highlighted specifically ridges present in the basin (Figure 6.3 d)
e) Valley depth: This index highlighted the major valleys present in the basin (Figure 6.4 a)
f) Standardized height: has produced a sharp boundary between mountains and other landform units (Figure 6.4 b)
g) Slope map: A slope map (Figure 6.4 c) was also prepared from the DEM and mean slope of each landform units was computed (discussed later).

Table 6.1 describes the landform units based on the above parameters and other geomorphic features.

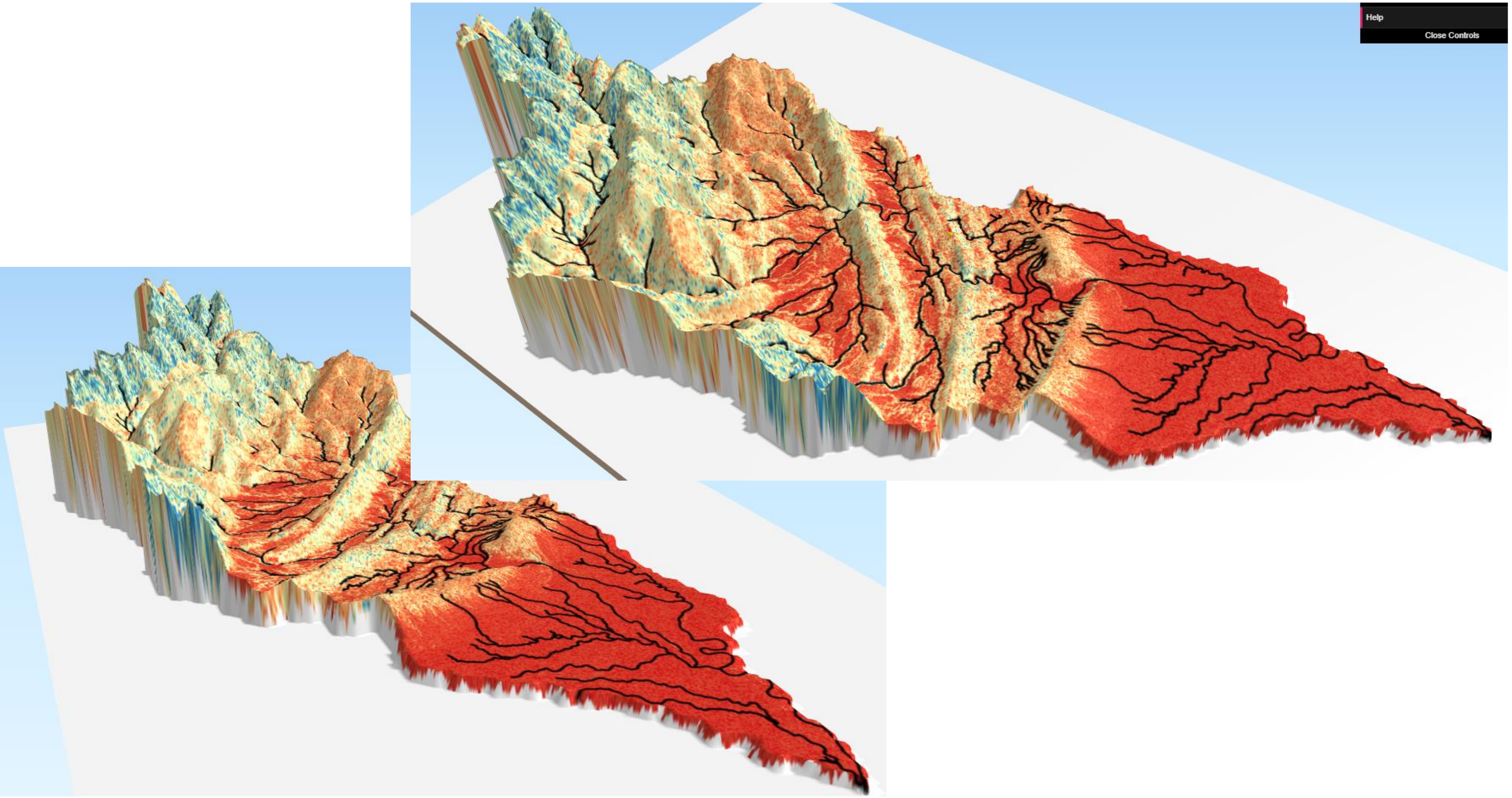


Figure 6.1: 3D view of Tawi basin generated by draping the Sentinel FCC over the DEM.

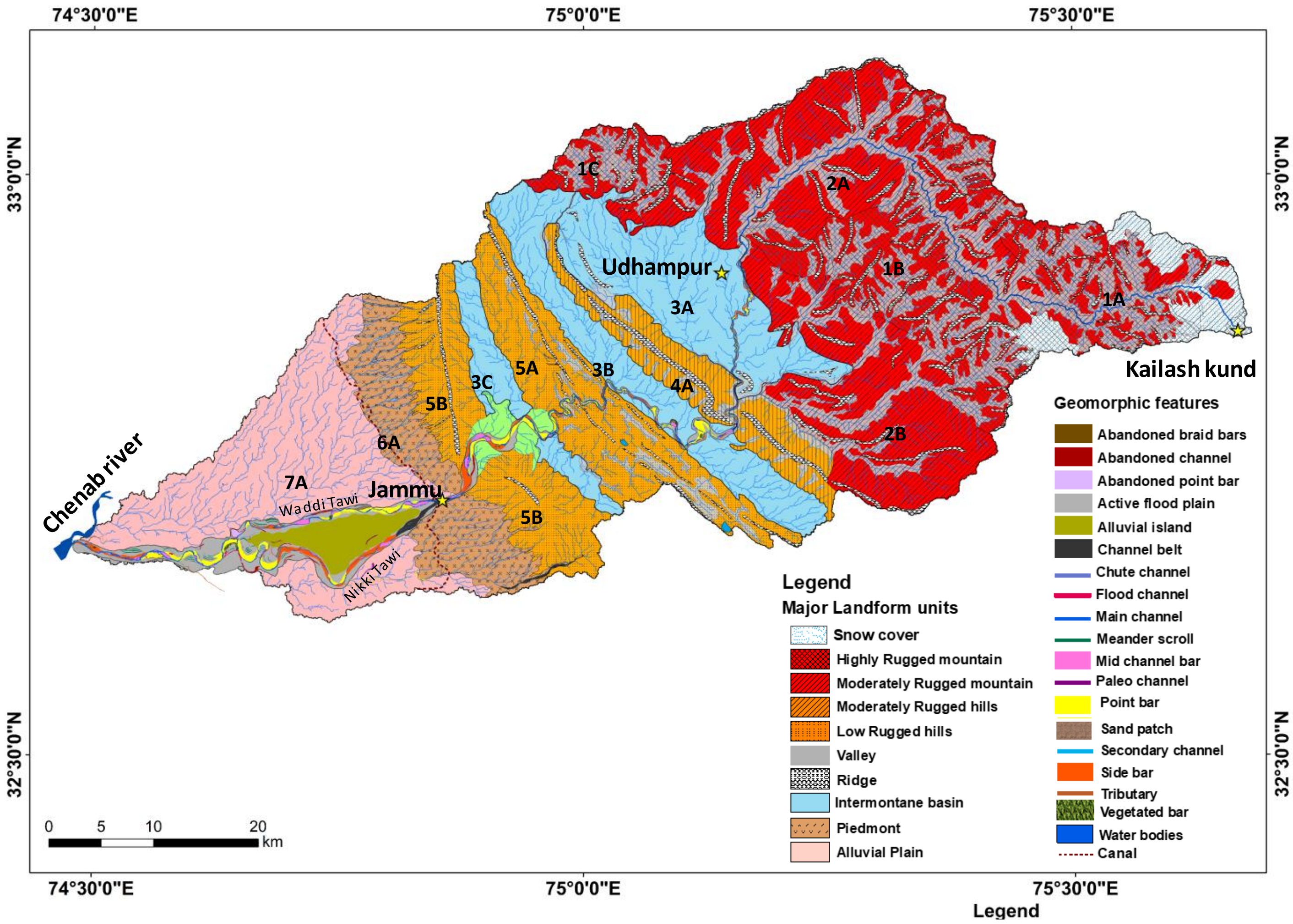


Figure 6.2: Geomorphic map of Tawi River Basin prepared from Sentinel data of 2018.

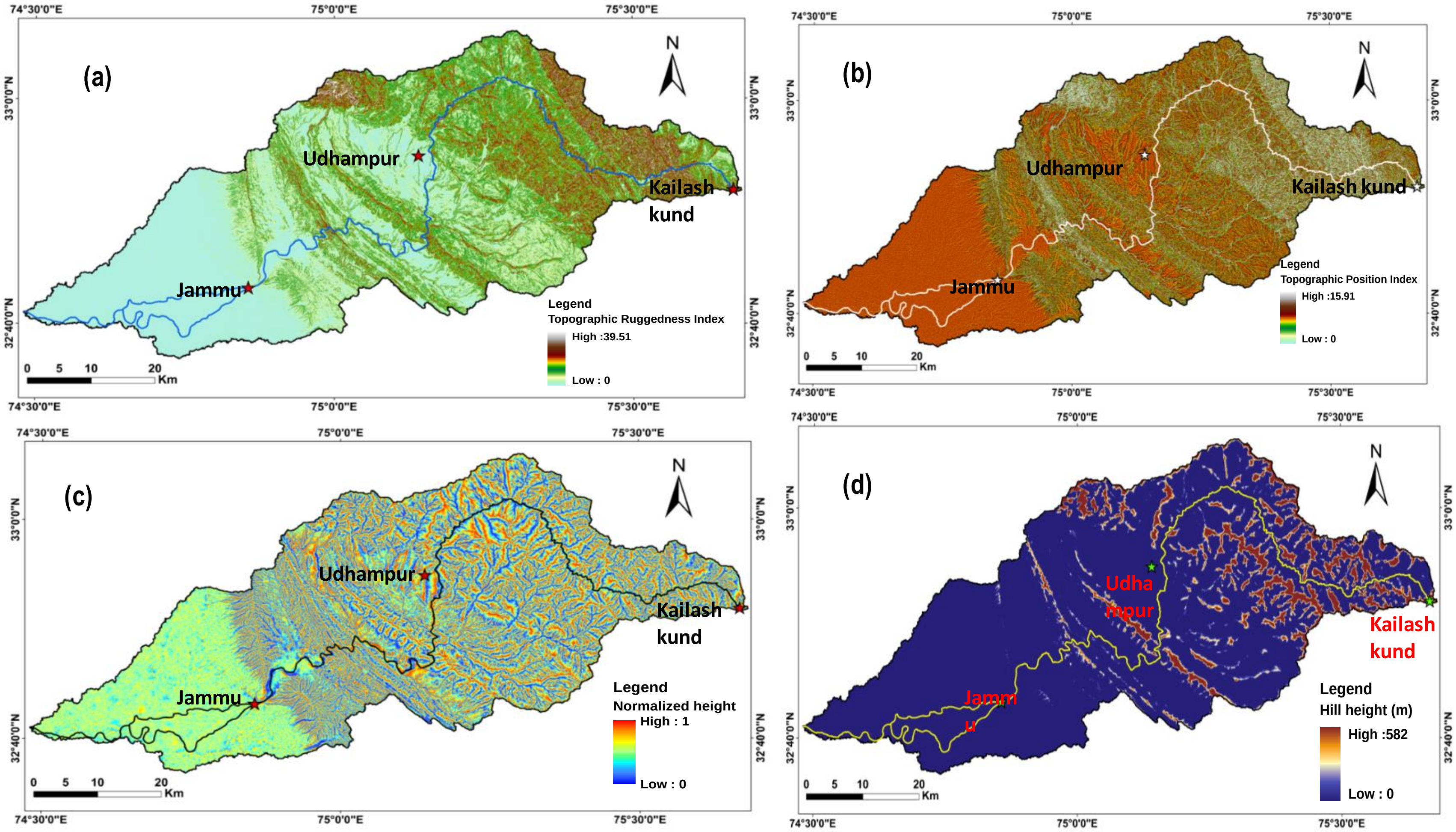


Figure 6.3: DEM derived for the Tawi River Basin: (a) Topographic Ruggedness Index map, (b) Topographic Position Index map, (c) Normalized height map, (d) Hill height map.

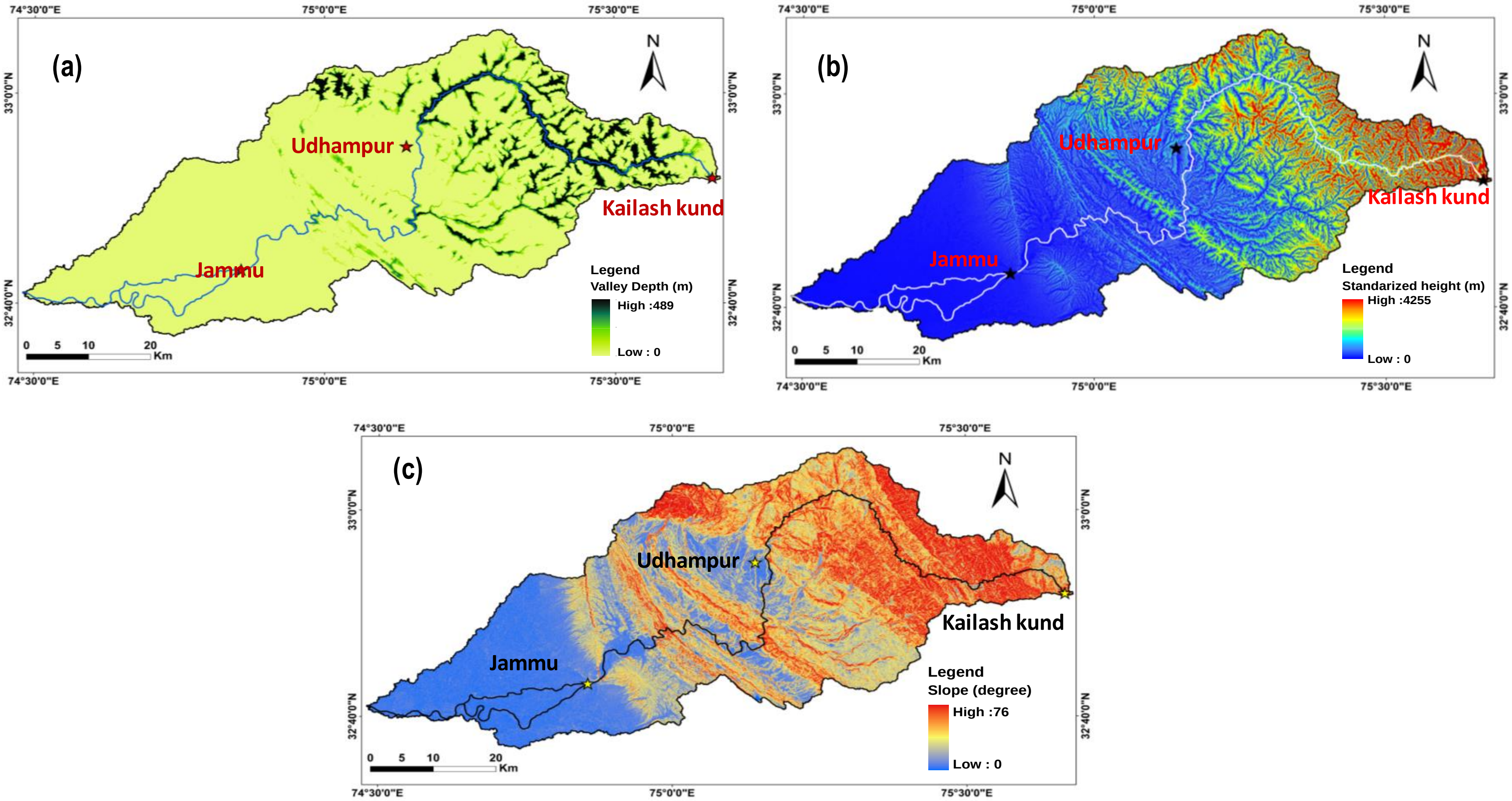


Figure 6.4: DEM derivatives for the Tawi basin: (a) Valley Depth map, (b) Standardized height map, (c) Slope map.

Table 6.1 – Major landform units in the Tawi basin and their characteristics.

Landform units	Characteristics
Unit 1: Highly rugged mountain (HRM)	The highly rugged mountains mostly lie in the north eastern part of the Tawi basin but a few patches are also present in the north west of Udhampur city. The HRM is characterized by high mean elevation ~1979 m with as well as high average slope gradient ~28° with in the basin. It is characterized by high ruggedness index (mean TRI 4.95) than that of the other major landforms in the Tawi basin which defines the high heterogeneity of this landform units. Due to this, the ridge and valley topography is also very prominent in this part of the basin (Hill height and valley depth Index. These landform units have parallel drainage pattern due to steep slope gradient (as high as ~76°). (See Unit 1A, B, C).
Unit 2: Moderately rugged mountain (MRM)	The moderately rugged mountains have a mean elevation of 1485 m and average slope of $18.64^{0.}$ This unit is mainly characterized by parallel drainage with lesser drainage density. Most of the streams in the SE region (Unit 2B) show bending at 90° which reflects the major structural control in this part. As heterogeneity decreases (TRI~3.09), the valleys and ridges topography decreases (See Unit 2A, B, C).
Unit 3: Moderately rugged hills (MRH)	The mean elevation in this landform units is 787m which characterized them as hills. But, the heterogeneity of the basin corresponds to (TRI ~3.38) similar to that of MRM, hence named as moderately rugged hill. Most of the stream are straight and parallel to each other due to high mean slope gradient~20.32^{0}. A prominent ridge runs along the strike of the hill. The main Tawi river exits from the high mountain in this unit where an offset of the hill as well as the ridge marks the presence of a Tear Fault.
Unit 4: Low rugged hills (LRH)	The low rugged hills flank the intermontane basins (See Unit 5A, B) and are characterized by low mean elevation of 503 m and a mean slope of 14.43^{0}. The Tawi river channel is crossing the low rugged hills with a low mean TRI~ 2.38. Some of the streams in the LRH shows trellis pattern which indicates surface crumbling or folding due to tectonic activity (See Unit 4A). The LRH at the foothills (See Unit 4B) shows a radial drainage pattern with a prominent ridge that acts as a drainage divide.
Unit 5: Intermontane basin (IB)	This unit is expressed as bowl shaped valleys between the two mountain ranges. Most parts of this unit are flat as reflected from the low mean elevation of 576 m. Dendritic pattern is most prominent in these areas (See Unit 5A), they are mostly flat plains with a mean slope of 8.72^{0}. Some parts also show sub parallel drainage pattern (See Unit 5B, C) with sharp bends reflecting structural control, In general, thus unit has very low gradient, and the Mean TRI also very low 1.47.
Unit 6: Piedmont (PD)	This unit occurs at the foot of the low rugged hills and marks a major break in slope with a mean elevation of 316 m and mean slope of 3.04^{0}. The TRI is also very low (TRI ~ 0.58) The low slope gradient controls the drainage pattern in these regions which is mainly sub-parallel. As the Piedmont and alluvial plain shares almost similar elevation profile, normalized height index helped to clearly demarcate the boundary between the two units.
Unit 7: Alluvial plains (AP)	The piedmont extends further with low slope gradient (~2^{0}) to form Alluvial plain. This unit is dominated by sub-dendritic drainage pattern due to low elevation as well as slope, Mean TRI 0.4 is also low. The main channel in this unit forms braided channels due to sediment deposition in the travel path.

6.2 CHANNEL PLANFORM ANALYSIS OF TAWI RIVER BASED ON 2018 SENTINEL DATA

Channel plan form analysis has been carried out for the stretch between Udhampur to the confluence point between Tawi and Chenab. In the upstream reaches, the channel is very narrow and planform features are limited. Further, for the sake of clarity, we have divided the stretch into seven reaches (I-VII) hence to show/highlight fluvial features we have produced reach wise maps for the section between Udhampur and confluence of Tawi and Chenab.

Passing through different topographic indifferences river Tawi has shown a diverse planform from narrow channels in the mountainous reaches to meandering channel in the alluvial plains. From upstream to downstream it is evident form the planform maps that between Udhampur city and Hansooh (Reach I, Figure 6.5) the river is almost straight and has very few depositional features. Downstream of Hansooh, a few point bars and side bars start to appear and they become much more prominent by the river reaches Jaganoo. The river in reaches I is guided primarily by the valley setting and the floodplain is generally quite narrow with a few wide patches around Jaganoo. Downstream of Jagnanoo (reach II), the river is again confined within narrow valleys down to Dchhapar (reach III). Downstream of Dchhapar, the river channel as well as floodplain start to widen reaching a maximum width of ~1 km. A number of mid channel bars and side bars also appear in this part of reach III. In all these three reaches (I, II, and III), the river flowing in a nearly north-south direction.

Further downstream of Dchhapar and close to Pingar (reach IV), the active flood of the river increases due to wider valleys and a large meander has formed giving rise to a large point bar (Figure 6.6). Several smaller meander appear further downstream and some of the point bars are vegetated as well. The river is again confined in downstream of Sahan but not as much as it was in upstream reaches (I, II and III). The river between Sahan to Kanalah is structurally controlled but form several side bars and point bars. A number of nallahs joint around Kanalah that bring in significant sediments from the upslope regions and this could explain a sudden increase in the lateral bar formation in this section.

Downstream of Chak-Chilah (reach V), the morphology of the river changes significantly and a remarkable widening is noted between Nagrota and Narain (Figure 6.7). A large number of nallahs join in this stretch and large lateral bars and point bars are particularly noted reflecting significant sediment flux through these nallahs. Before entering into alluvial plains, the Tawi river becomes a little narrow in just upstream of Jammu city partly due to the presence of the extension of the hills on both the sides of the river and probably also because of embankments.

Several interventions are noted in the reach VI, downstream of the Jammu and these have influenced the river morphology significantly. There are several bridges and a few canals in the river around Jammu city. Immediately downstream of the Jammu city, the river bifurcates into two major streams (Figure 6.8). The right branch is called Waddi Tawi while the left branch is called Nikki Tawi. There is a very large alluvial island between these two rivers, which is completely modified by humans. No remnant of any fluvial feature is there in this part as most of this is either used for residence or for cultivation purpose. At present, the channel belt of the Nikki Tawi is wider than the Waddi Tawi but presumably the flow and morphology of these branches have changed through time and this will be documented in our planform dynamics analysis. Both these rivers have formed large side bars and point bars. The river flows are very wide in monsoon seasons while the river channel is very narrow in pre-monsoon period thereby developing having very wide active flood plains. Since the urban density is quite high in this stretch, the active flood plain of both the rivers is heavily occupied by urban settlements and the river is forced to flow in very narrow channel within the embankments along the river. Several meander scrolls in this reach were mapped from satellite images suggesting frequent shifts of the meander bends particularly in the Nikki Tawi around Chumbian. The Waddi Tawi also shows several meander scrolls just before its confluence with Nikki Tawi. It is also noted that the confluence point of the Waddi Tawi and Nikki Tawi has also been very dynamic and have shifted upstream and downstream through time. This will also be documented in our planform dynamics analysis.

The most downstream reach VII of the Tawi river between Chumbian and the Chenab-Tawi confluence point (Figure 6.8) flows generally westward and is marked by meandering channel with frequent meander scrolls throughout. Well-developed point bars are common except in the most downstream stretch before the confluence. In general, we characterise the river to have a very dynamics regime and this will be captured in the planform dynamics analysis through mapping of thalweg position and changes in channel morphology. The section between Ahmalpur and the confluence of the Tawi with Chenab is relatively less disturbed and few older meander scrolls present in the Northward part shows that the river has shifted to the south with time.

It can be concluded that the Tawi river shows significant morphological diversity between Udhampur and its confluence point with Chenab. The morphology in the upper reaches is controlled by hills and mountains manifested narrow channels and relatively stable form. In the alluvial plains, it is relatively wider and dynamic is controlled by alluvial processes along with significant human interventions.

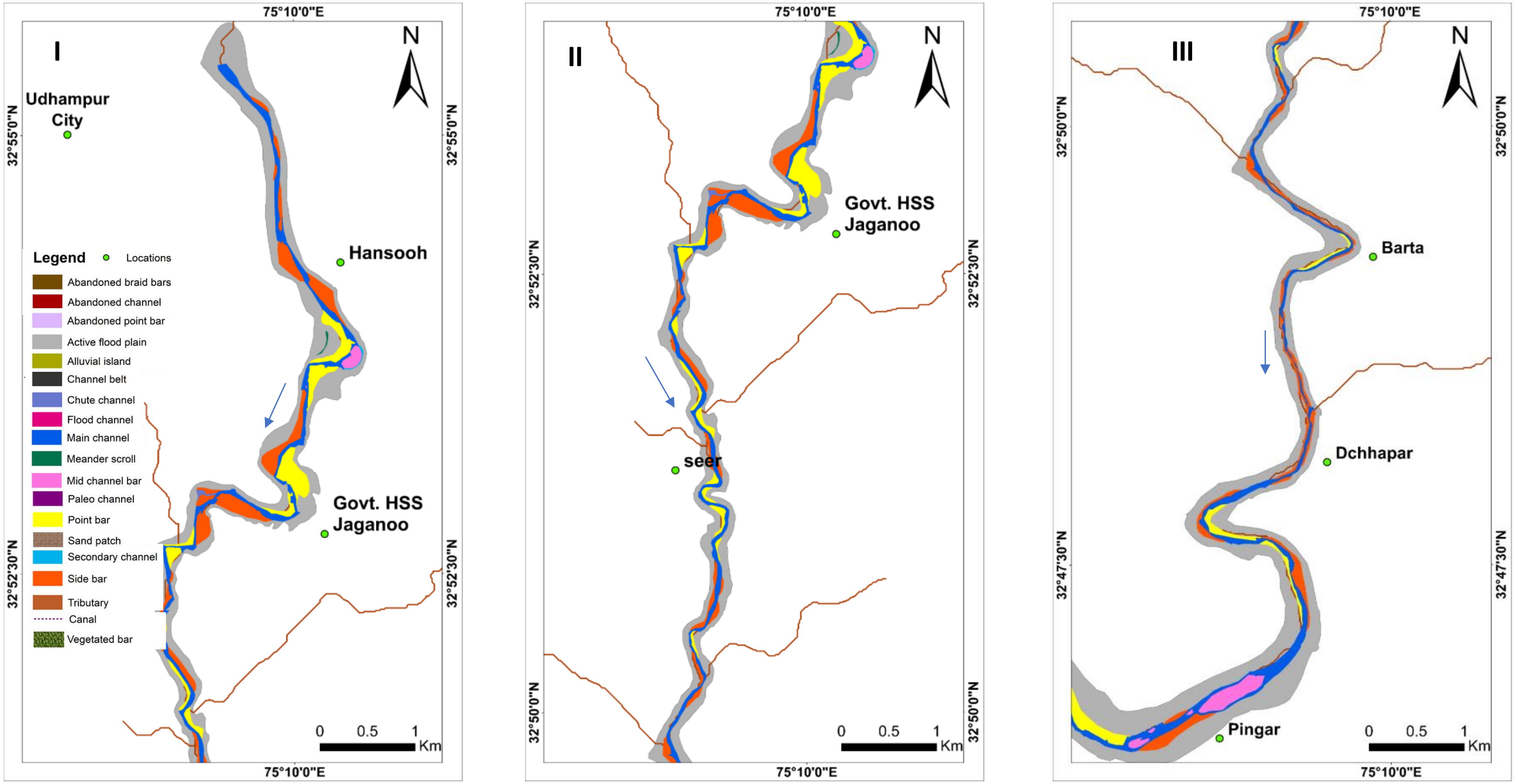


Figure 6.5: Planform map of Tawi River between Udhampur and Pingar (reaches I, II and III) showing narrow river channel and floodplain confined by mountainous valleys.

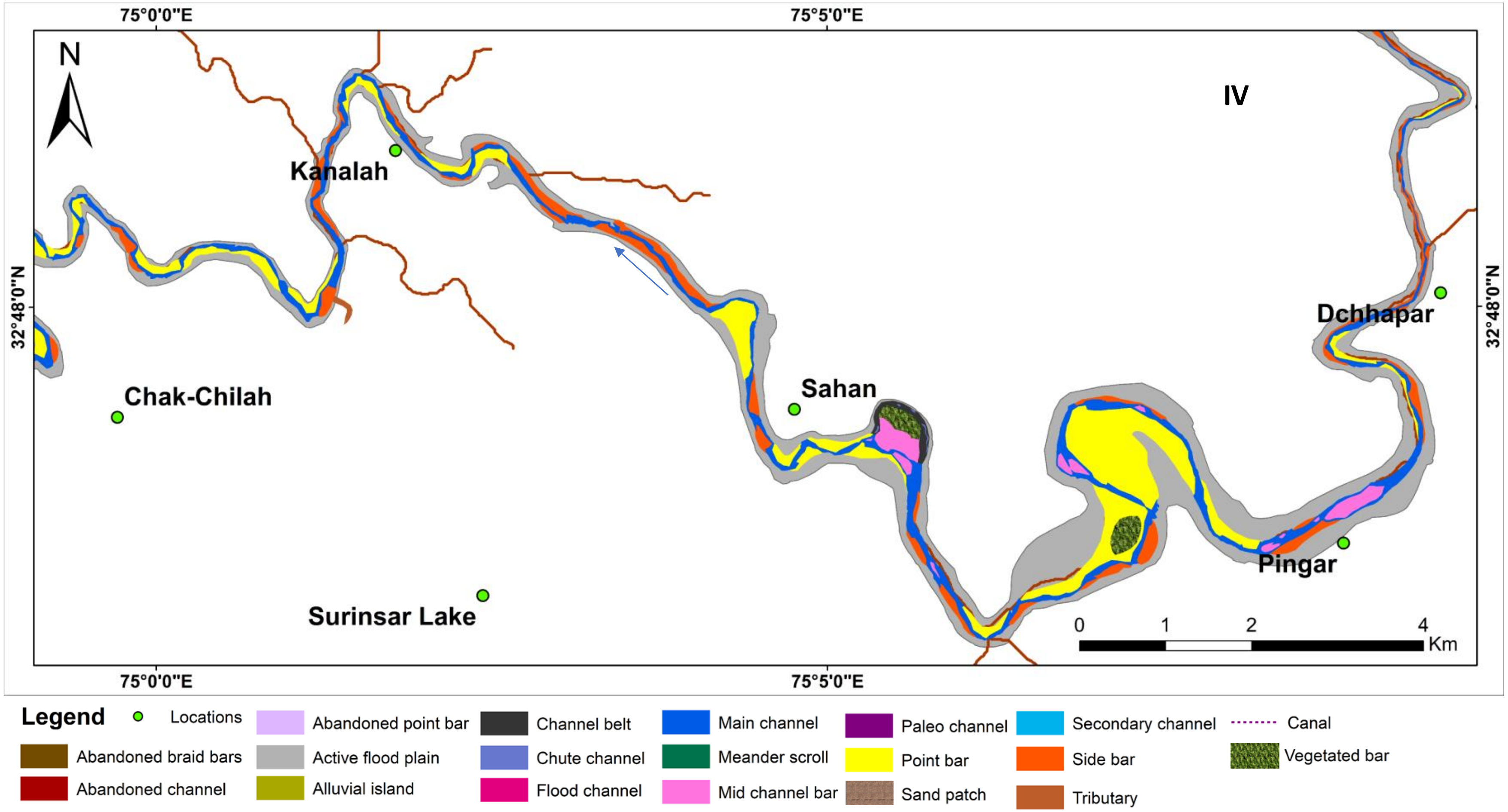


Figure 6.6: Planform map of Tawi River between Pingar and Chak-Chilah (Reach IV) showing structurally controlled meandering river confined by mountainous valleys.

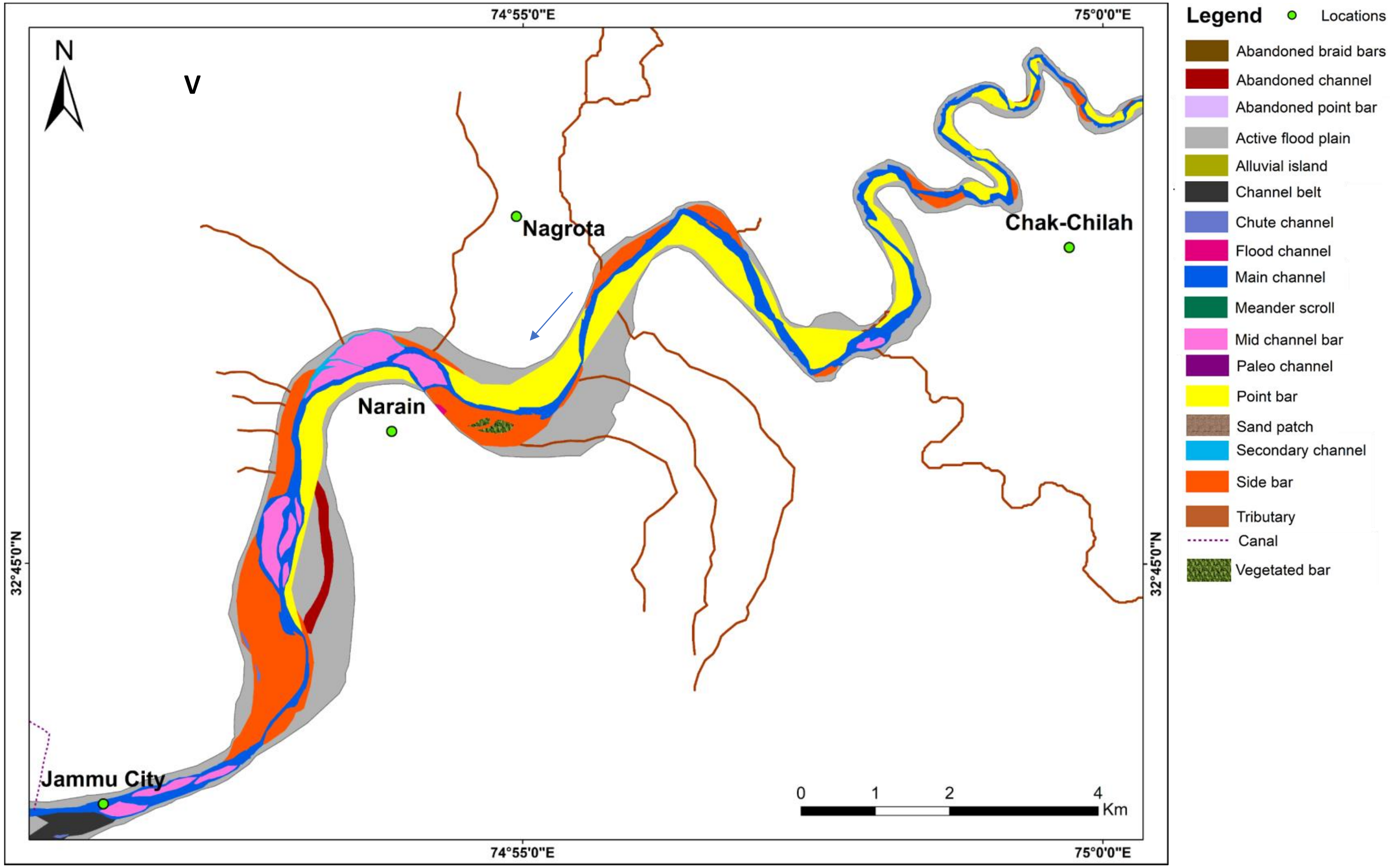


Figure 6.7: Planform map of Tawi River between Chak-Chilah and Jammu city.

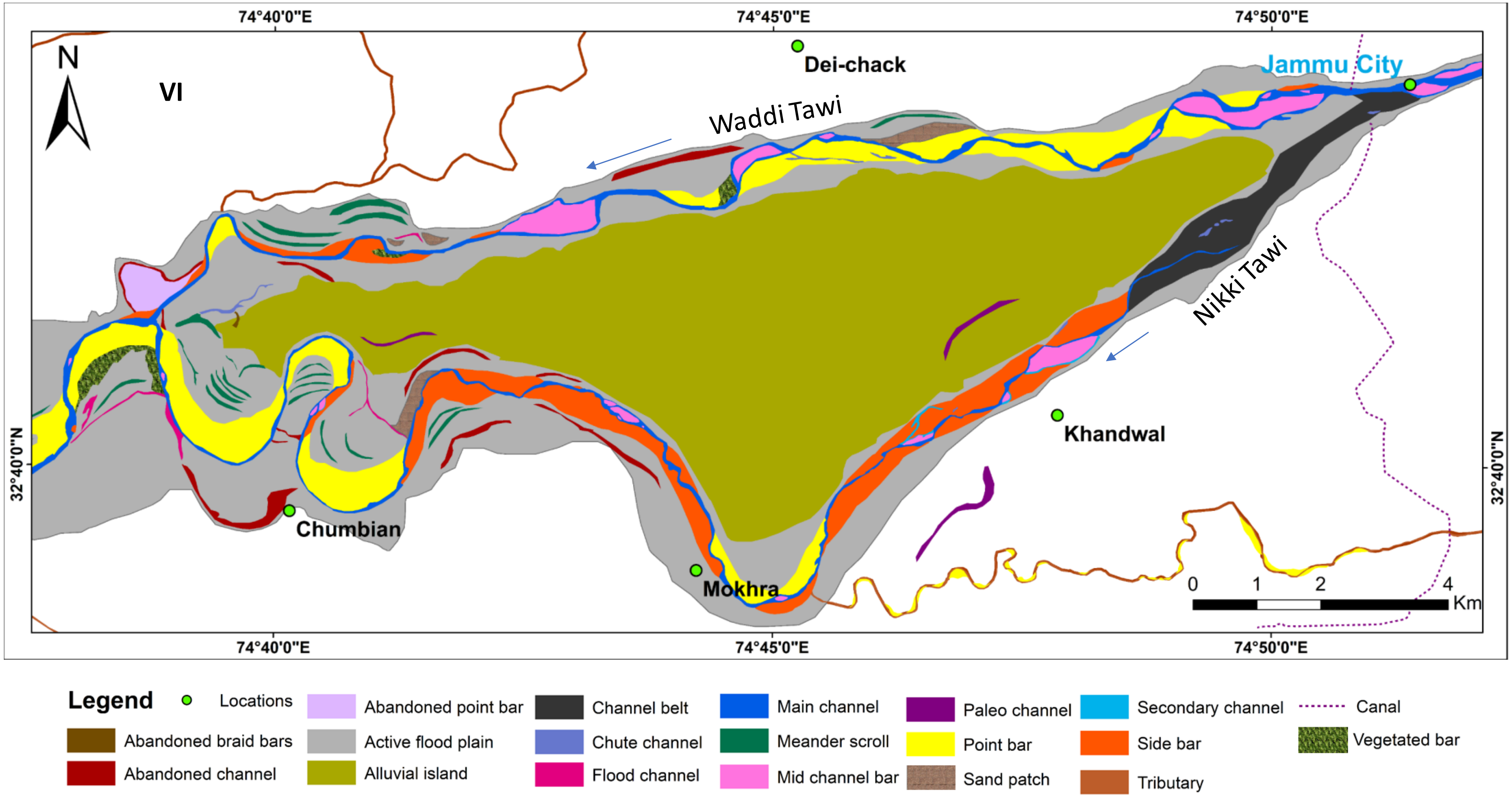


Figure 6.8: Planform map of Tawi River between Jammu city and Chumbian.

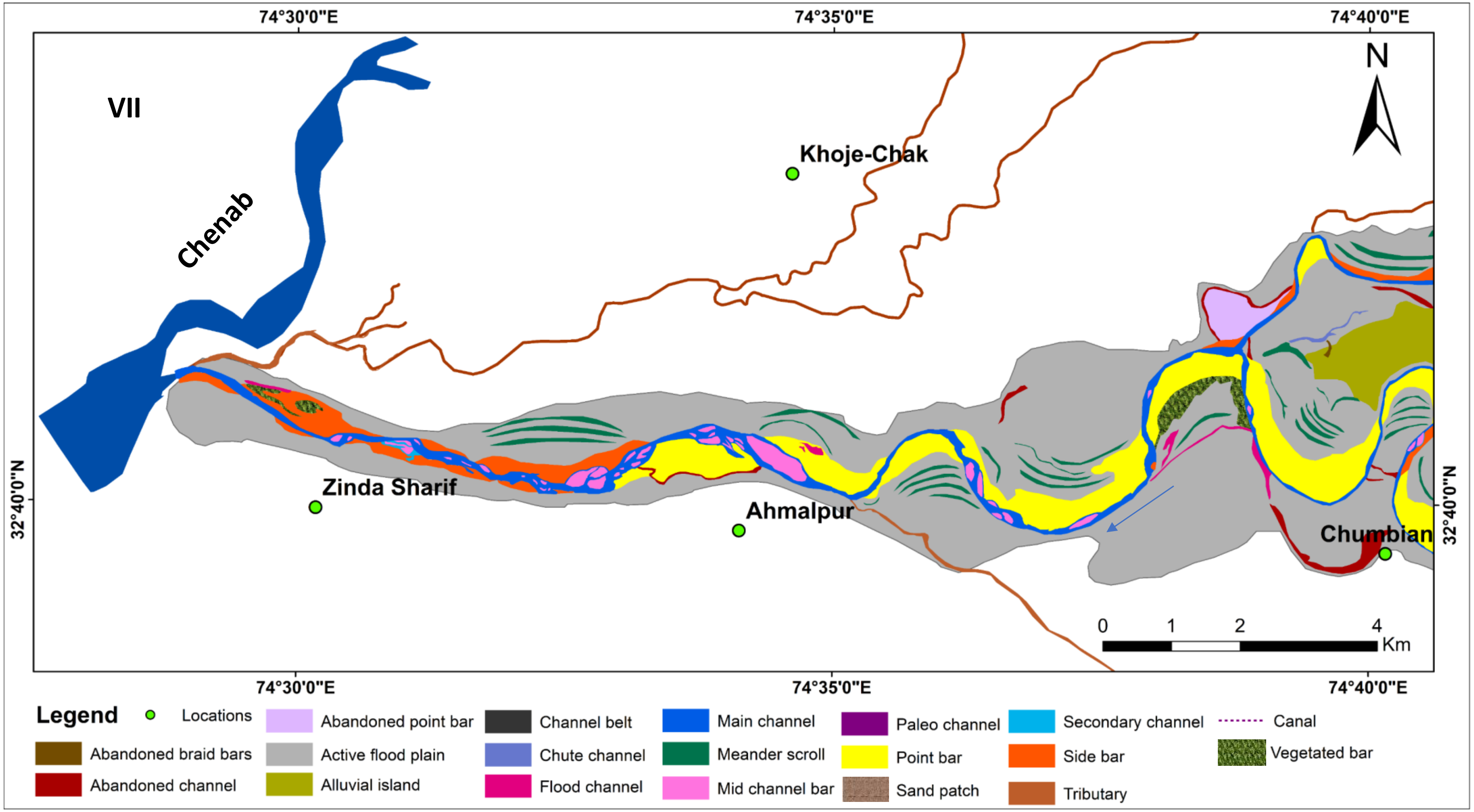


Figure 6.9: Planform map of Tawi River between Chumbian and Chenab-Tawi confluence.

7 PRELIMINARY MORPHOLOGICAL ANALYSIS

Our morphological mapping so far has focused on characterising the Tawi river in terms of its basin characteristics and channel morphology in the alluvial reaches. At this stage, our assessment suggests that:

The morphometric analysis of the Tawi basin suggests that the hinterland is tectonically active as manifested by drainage anomalies and morphological elements.

A major effect of an active hinterland is the high sediment flux from the fragile slopes that affects the channel morphology downstream. The small nallahs seem to contributing significant sediment flux owing to their steep slopes and sharp changes in channel morphology of the Tawi river is noted downstream of their confluences.

The channel morphology in the upstream mountainous reaches is fairly stable being confined by narrow valleys. Not many depositional or erosional features are documented and the river is primarily guided by the valley settings. At places, the valley widening results in some morphological complexity.

The alluvial reaches particularly those downstream of Jammu are fairly dynamic and frequent migration of meanders are documented. The thalwegs of the main channel as well as confluence point of Waddi Tawi and Nikki Tawi have also moved through time. A detailed documentation of such dynamic behaviour will be presented in the detailed morphological report.

The future studies that would be carried out as a part of this project would include:

- Temporal analysis of planform dynamics to document changes in channel position and form during the period 1967-2018.
- Identification of hotspots of siltation and planform dynamics through planform dynamic analysis
- Analytical Hierarchy Process (AHP) analysis for flood risk assessment in a GIS framework incorporating all physical factors influencing the flood hazard and socio-economic factors affecting flood vulnerability
- Field validation for confirming the hotspots of planform dynamics as well as flood risk areas.
- Site specific suggestions for flood management based on the morphological analysis and flood risk assessment.

8 PRELIMINARY FLOOD RISK ASSESSMENT

Our preliminary morphological maps suggest that the active floodplain of the Tawi river in the alluvial reaches downstream of Udhampur is fairly constricted. Major parts of the active floodplain has been occupied for agriculture and urban settlements. Downstream of Jammu city, the river splits into two branches, called Waddi Tawi and Nikki Tawi, that re-join ~20 km downstream. The area between the two anabranches, the maximum width is ~10 km, is also heavily occupied by agricultural lands and urban settlements. In addition, there are a number of bridges along the river in this stretch and the river is also embanked in stretches. A barrage is also under construction downstream of Jammu city. The barrage is flanked by two bridges, upstream and downstream of the barrage, and the one downstream of the barrage is barely 100 m from the barrage.

It is also important to note that the river brings in large amount of sediments from its fragile slopes and significant aggradation is noted in the alluvial reaches that has probably raised the bed level of the river significantly over the years. This is also manifested in frequent bars in most parts of the alluvial reaches and was also documented during the field visit. At this stage, our preliminary assessment is that flood risk in Tawi river can be attributed to the following factors:

1. Several stretches of the river in the alluvial part are highly dynamic and they have been shifting their courses very often. Our preliminary assessment suggests that the most vulnerable stretches are Chumbian-Ahmalpur and downstream stretch of Waddi Tawi ~5 km upstream of its confluence with Nikki Tawi (Figure 6.9). A detailed analysis of planform dynamics would be able to identify the hotspots more precisely and we will present the results in the detailed report.

Several stretches of the river are highly aggrading due to large sediment flux and this has made them vulnerable to avulsion and flooding. The stretch of the Nikki Tawi river near Balole Nallah confluence is a good example where large aggradation on the left bank pushed the river to the right bank and this in turn eroded the spurs and has vulnerable to flooding. Large sediment flux from the Balole nallah could have contributed to this shift. Several other bends show a similar pattern and these vulnerable stretches would be mapped using historical images.

The interventions such the barrage in construction and several bridges have also contributed to trapping of sediments upstream. The embankments have further restricted the river flow and have aggravated the siltation. This has resulted in instability of the channel and these reaches have become vulnerable to breaches and flooding.

While the construction of embankments may have been necessary in some stretches particularly around the major cities such as Jammu. Apart from restricting the flow and inducing siltation, this also generated a false sense of security amongst the people and as a result, the urban settlements have mushroomed very close to the embankments. This has increased the vulnerability to floods enormously.

9 REVIEW FOR SELECTED FLOOD AND RIVER MANAGEMENT OPTIONS

Flood protection and river management strategies in the Tawi basin have so far focused mostly on structural interventions including embankments, revetments and spurs. While these interventions may have been necessary in certain stretches, they have influenced the flow and sediment transport characteristics of the river adversely inducing siltation and channel instability. They have also increased the vulnerability to floods as these embankments are prone to breaches. The other proposed steps for river/flood management such as watershed management and identification of low lying areas affected during floods, flood retention basins are welcome steps. At this stage, we offer the following suggestions:

1. The embankments and bunds are not the ideal options for Himalayan rivers charged with large sediments and hence this option should be taken up only when absolutely necessary for the safety of people and important infrastructure. If they have to be constructed, the spacing between the left and right embankments should be based on scientific analysis of flood inundation and mapping of active floodplain. Further, an embankment health monitoring program must be initiated for the existing as well as new embankments so that the points vulnerable to breaching can be identified well in advance and necessary protection measures can be taken.
2. Sediment management should become an essential part of flood management strategies in such sediment charged rivers such as the Tawi. This strategy would require the identification of hotspots of siltation and regular dredging to maintain the channel conveyance capacity. Our detailed planform analysis using historical images would provide such hotpots and we may be able to provide site specific suggestions in this regard later.
3. A GIS based analysis of flood hazard and vulnerability should provide the identification of flood risk areas including the low-lying areas that are frequently inundated by floods. High resolution DEM would particularly facilitate this analysis and we may be able to identify the areas where flood water storages can be created. As detailed in the Inception Report, it may be ideal to use the natural depressions as floodwater storage rather than creating any major dam. Actually, besides being not permitted as per Indus Waters Treaty-1960 in the Tawi River, the creation of flood storage dams could increase the risk of dam failure and flooding.
4. Flood zoning strategy should be promoted as a non-structural flood management strategy instead of structural interventions as also highlighted in the Inception Report. This should be based on river space concept (also known as the river corridor concept) wherein the active channel belt and active floodplain of the river must be preserved. Accordingly, the Inception Report details some potential applicable nature-based solutions for floodplain and wetland restoration and management.

10 SUMMARY AND RECOMMENDATIONS

This report has presented the basin scale morphological analysis of the Tawi wiver basin based the satellite image (Sentinel 2018 data) and regional scale DEM (PALSAR data). Several DEM derivatives were also used to understand the terrain characteristics and morphometric analysis. Downstream of Udhampur, we have also carried detailed channel morphological mapping at 1: 10,000 scale for 2018 and the planform maps have been generated for different stretches to illustrate the spatial variability in channel morphology and to provide a first order understanding of channel dynamics and flood risk.

Some of the major recommendations at this stage are as follows:

1. Flood risk and channel dynamics in the alluvial reaches are closely linked processes and they need to be looked at in an integrated way. Our planform dynamics analysis will attempt to characterise the ‘hotspots’ of channel dynamics and they will also be taken into considerations for flood risk analysis.
2. Sediment dynamics seems to be an important factor influencing channel morphology and behaviour and several hotpots are mappable in our first order analysis. More precise mapping of these hotspots would be provided in the detailed morphology report. Sediment dynamics and sediment management must form an integral part of flood management in the Tawi river.
3. Human interventions such as embankments and bridges have influenced the channel morphology of the Tawi river significantly and suitable measures will have to designed for such reaches to reduce these impacts particularly in relation to flood risk.
4. A GIS based flood risk assessment should provide the most susceptible areas. A non-structural flood management based on a sound understanding of river processes (including river dynamics and sediment dynamics) may provide long term solutions. As also highlighted in the Inception Report, the structural interventions may be recommended only where they are absolutely necessary to safeguard human population and major infrastructure and they should be planned on the basis of scientific understanding of channel dynamics.
5. Floodplain zoning based on river space concept may be a sustainable strategy for flood management from an environmental perspective and this can generate multiple benefits apart from disaster risk reduction.

11 REFERENCES

Brook, G.A. and Luft, E.R., 1987. Channel pattern changes along the lower Oconee River, Georgia, 1805/7 to 1949. Physical Geography, 8(3): 191-209.

Davis WM (1909) The Mountain Ranges of the Great Basin, in Geographical Essays (pp 725-772), Boston (New York, Dover reprint 1954, originally issued 1903), Bulletin - Museum of Comparative Zoology. Harvard College 42: 129-177.

Friend, P. and Sinha, R., 1993. Braiding and meandering parameters. Geological Society, London, Special Publications, 75(1): 105-111.

Geddes, A., 1960. The alluvial morphology of the Indo-Gangetic Plain: Its mapping and geographical significance. Transactions and Papers (Institute of British Geographers)(28): 253-276.

Ground water information booklet (2014), Central Ground Water Board, Government of India Ministry of Water Resources Udhampur District, Jammu & Kashmir.

Ground water information booklet (2013), Central Ground Water Board, Government of India Ministry of Water Resources Udhampur District, Jammu & Kashmir.

Gupta, N., Atkinson, P.M. and Carling, P.A., 2013. Decadal length changes in the fluvial planform of the River Ganga: bringing a mega-river to life with Landsat archives. Remote Sensing Letters, 4(1): 1-9.

Gupta, N., Atkinson, P.M. and Carling, P.A., 2013. Decadal length changes in the fluvial planform of the River Ganga: bringing a mega-river to life with Landsat archives. Remote Sensing Letters, 4(1): 1-9.

Hudson, P.F. and Kesel, R.H., 2000. Channel migration and meander-bend curvature in the lower Mississippi River prior to major human modification. Geology, 28(6): 531-534.

Kummu, M., Lu, X., Rasphone, A., Sarkkula, J. and Koponen, J., 2008. Riverbank changes along the Mekong River: remote sensing detection in the Vientiane–Nong Khai area. Quaternary International, 186(1): 100-112.

Kondolf, G.M., 1997. PROFILE: hungry water: effects of dams and gravel mining on river channels. Environmental management, 21(4): 533-551.

Leopold, L.B. and Wolman, M.G., 1957. River channel patterns: braided, meandering, and straight. US Government Printing Office.

Parker, G., 1976. On the cause and characteristic scales of meandering and braiding in rivers. Journal of fluid mechanics, 76(3): 457-480.

Osawa, Yuji. 2004. "Optical and Microwave Sensors on Japanese Mapping Satellite – Alos." Japan Aerospace Exploratium Agency (JAXA): 22–25.

Parua, R., 2002. Fluvial geomorphology of the river Ganga around Farakka. Journal of the Institution of Engineers. India. Civil Engineering Division, 82(FEV): 193-196.

Perez-Pena JV, Azanon JM, Azor A (2009) CalHypso: an ArcGIS extension to calculate hypsometric curves and their statistical moments. Applications to drainage basin analysis in SE Spain. Comput Geosci 35(6):1214–1223

Report Code: 021_GBP_IIT_FGM_DAT_02_Ver1_Dec 2011; Delineation of valley margin and Geomorphic mapping of Channel Belt and Active Floodplain of the Ganga river.

Report Code: 005_GBP_IIT_FGM_DAT_01_Ver 1_Dec 2010; Active Floodplain Mapping: Defining the "River Space

Richards, K., 1982b. Rivers: forms and process in alluvial channels, London: Methuen and Co. Ltd.

Robert, A., 2014. River processes: an introduction to fluvial dynamics. Routledge.

Rosenqvist et al., 2007.A. Rosenqvist, M. Shimada, N. Ito, M. Watanabe ALOS PALSAR: A Pathfinder mission for global-scale monitoring of the environment IEEE Transactions on Geoscience and Remote Sensing, 45 (11) (2007), pp. 3307-3316.

Rutherfurd, I., Bishop, P., Walker, M. and Stensholt, B., 1996. Recent channel change in the Mekong River near Vientiane: implications for the border between Thailand and Lao PDR, Development Dilemmas in the Mekong Subregion: Workshop Proceedings, Melbourne, Australia.

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. International journal of services sciences, 1(1), 83-98.

Sinha, R. and Ghosh, S., 2012. Understanding dynamics of large rivers aided by satellite remote sensing: a case study from Lower Ganga plains, India. Geocarto International, 27(3): 207-219.

Schumm, S.A., 1985. Patterns of alluvial rivers. Annual Review of Earth and Planetary Sciences, 13(1): 5-27.

Schumm, S.A. and Lichty, R.W., 1963. Channel widening and flood-plain construction along Cimarron River in southwestern Kansas. US Government Printing Office.

Stølum, H.-H., 1998. Planform geometry and dynamics of meandering rivers. Geological Society of America Bulletin, 110(11): 1485-1498.

Sinha, R., Sripriyanka, K., Jain, V. and Mukul, M., 2014. Avulsion threshold and planform dynamics of the Kosi River in north Bihar (India) and Nepal: A GIS framework. Geomorphology, 216: 157-170.

Surian, N., 1999. Channel changes due to river regulation: the case of the Piave River, Italy. Earth Surface Processes and Landforms, 24(12): 1135-1151.

Sinha, R. and Friend, P.F., 1994. River systems and their sediment flux, Indo-Gangetic plains, Northern Bihar, India. Sedimentology, 41(4): 825-845.

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

Schumm, S.A., 1981. Evolution and response of the fluvial system, sedimentological implications. In: Ethridge, F.G., Flores, R.M. (Eds.), Recent and 760 Geomorphic Classification of Rivers Nonmarine Depositional Environments. SEPM (Society for Sedimentary Geology), Special Publication 31, Tulsa, OK, pp. 19–29.

Talampas, Wendell D., and Ruel R. Cabahug. "Catchment Characterization to Understand Flooding in Cagayan De Oro River Basin in Northern Mindanao, Philippines." MINDANAO JOURNAL OF SCIENCE AND TECHNOLOGY 13 (2015): 213-227.

Thakur, P.K., Laha, C. and Aggarwal, S., 2012. River bank erosion hazard study of river Ganga, upstream of Farakka barrage using remote sensing and GIS. Natural Hazards, 61(3): 967-987.

Perez-Pena JV, Azanon JM, Azor A (2009) CalHypso: an ArcGIS extension to calculate hypsometric curves and their statistical moments. Applications to drainage basin analysis in SE Spain. Comput Geosci 35(6):1214–1223