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Geomorphic Classification and Mapping of Rapti River System Using Satellite Remote Sensing Data

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Abstract

Rapti river system in India has been selected for the form and process based geomorphic classification and mapping through modern techniques i.e. satellite remote sensing data, digital elevation model data, survey of India topographical maps, and GIS. The high-resolution satellite remote sensing data and GIS has provided very precise and relatively complex information about the rivers specifically focused on fluvial geomorphic features / units. More than 100 research articles have been critically reviewed for form and process based geomorphic classification. Various geomorphologists have tried to map the river based on form and process, more of them, mapped the river on them own thought, some of geomorphic features are commonly mapped, but some geomorphic features, they were mapped differently means geomorphic features are same, but they have given the name different as no match with each-other. Total 57 different geomorphic classifications have been obtained from these studies and have been grouped into four geomorphic classification i.e. Rosgen classification system, river styles framework, natural channel classification, and statistical classification. For this study we have used 1: 2000 mapping scale to identify various in-channel geomorphic features, and out-of-channel geomorphic features at micro level. A total of 44 specific morphology features have been identified, out of which 21 specific morphology features have been identified in "out-of-channel (active floodplain)", 5 specific morphology features have been identified in "out-of-channel inactive floodplain (terrace)" and 18 specific morphology features have been identified in "in-channel".

Keywords

Geomorphic Classification, Remote Sensing, DEM, GIS, Rapti River

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1. Introduction

The geomorphic classification of a river is a repeated subject by professionals from an extensive scope of disciplines including both environmentalists and geomorphologists [1]. Geomorphic Classification is the categorization and description of the nature, origin and development of landforms. The fundamental framework of this classification scheme is that a geomorphic unit can be classified based collectively on its origin and development (process), on its general structure and shape (landform), on measurements of its dimensions and characteristics (morphometry), and on the presence and status of process overprinting (geomorphic generation) [2]. The classification of river has varied widely, from the desire of geomorphologists to improve their understanding of river behavior and morphology, with the characterization of basic attributes of river types [3]. The classification of fluvial systems remains in a developmental stage because of the dynamic changes that happen over wide spatial and temporal scales [4], and because classification systems only reflect the current state of knowledge on river function [5]. Geomorphic classification of a river has been attempted by numerous scientists, researchers, environmentalists and geomorphologists from

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different disciplines who have used several variables at different spatial scales. Brussock has proposed a river classification system based on three different sedimentological settings i.e. a cobble and boulder bed channel, a gravel bed channel, or a sand bed channel, this classification has classified the running water habitats into longitudinal classes based on their channel form [6]. He was chosen three physical aspects i.e. relief, lithology and runoff as state factors that control all other connecting parameters related with channel form such as temperature, depth, velocity and substrate. The above stated work has confirmed a significant part of the prior work of Leopold that stream channel- form can be predicted along the length of the river within geographic regions [7].

Various geomorphologists have tried to map the river based on form and process, more of them, mapped the river on them own thought, some of geomorphic features are commonly mapped, but some geomorphic features, they were mapped differently means geomorphic features are same, but they have given the name different as no match with each-other [1]. These river maps can be considered as raw information showing the river. In the current era, we have an emerging technologies i.e. aerial photographs, high-resolution satellite remote sensing data, geographic information system, LiDAR, digital elevation model, drone survey data, etc. which provide massive opportunities to produce more accurate and detailed topographic and geomorphic maps [8-10]. Morphometric analyses and field mapping present a critical template for a range of toolkits for integrative river science [11-13].

Recently, Wyrick has provided one of the most favourable developments at fluvial landform and presented strong hydraulic definitions, they have used morphological units as term, which is based on the automatic landform classification, and combinations of velocity and depth, and this is a very useful approach [14]. They have presented that many of the units persist with their hydraulic definitions at different flow stages, with minimal adjustment of their boundaries. This approach can be applied only in in-channel, out-of-channel, and floodplain area mapping, but it cannot be applied to areas outside the valley bottom that do not experience flow. Due to these limitations of Wyrick approach, we struggle that an even more generic, topography-centric landform mapping framework for rivers would be more transferable and universally applicable. It needs to raise important questions about the explanation of how we classify these geomorphic features [15]. A variation classification schemes that are used for different purposes is possibly predictable. We trust the exertion of researchers i.e. Wyrick who try for uniformity and more demanding definitions [14]. Still, the collectively literature on fluvial geomorphic features is uneven in its descriptions of fluvial landforms. To resolve the confusion, we have critically reviewed more than 100 research articles and case studies for form and process based geomorphic classification and generate a uniform geomorphic classification and mapped the various geomorphic features of Rapti river system.

2. About the Study Area

The Rapti river system in India is extends from 26°17'22"N to 27°55'01"N and 81°43'08"E to 83°49'19"E. The Rapti river is originate from Hanpaldhuri hill (Nepal) with an altitude of 3,388 m amsl. The Rapti river is a principal tributary of the Ghaghra River, which in turns is a major tributary of the Ganges river system. After flowing through the mountainous and steep path in Nepal region, it enters in India at Holiya village and flows in 9 districts of U.P. before merging into the Ghaghra river at Kaparwaa Ghat. Rapti river is also known as Gorakhpur Sorrow. In this study the river margin areas have been selected as 2.5 km both side buffer of Rapti river and its 16 major tributaries, and areas between two embankments, morphologically active area over the years (1999-2019), and active floodplains (Figure 1). For this study we have used 1: 2000 mapping scale to identify various in-channel geomorphic features, and out-of-channel geomorphic features at micro level and covers an area of 5,069.73 km^2. The detail of Rapti river system including river length and mapping area is shown in Table 1.

Table 1. Rapti River and its 16 Major Tributaries.

S. No.	River Name	River Length (Km)*	Mapping Area (Km^2)
1	Rapti River	566.01	1,955.48
2	Ami River	237.45	749.93
3	Burhi Rapti River	168.74	608.77
4	Rohin River	129.67	412.86
5	Jamuaar Nala	52.16	162.75
6	Chandan River	45.59	136.82
7	Gurra River	45.58	134.45
8	Ghonghi River	45.13	136.85
9	Kondara River	44.89	127.17
10	Ph-Ghonghi River	41.28	99.60
11	Mahwa Nala	38.65	94.55
12	Pharend Nala	38.46	132.20
13	Bahela River	29.54	86.73
14	Bathwa Nala	25.88	78.20
15	Ban-Ganga River	23.42	90.77

S. No.	River Name	River Length (Km)*	Mapping Area (Km^2)
16	Teler Nala	16.97	38.34
17	Payas River	11.75	24.26
		Total Area (Km^2)	5,069.73

* River length is based on Landsat-8 OLI satellite imagery, 2019

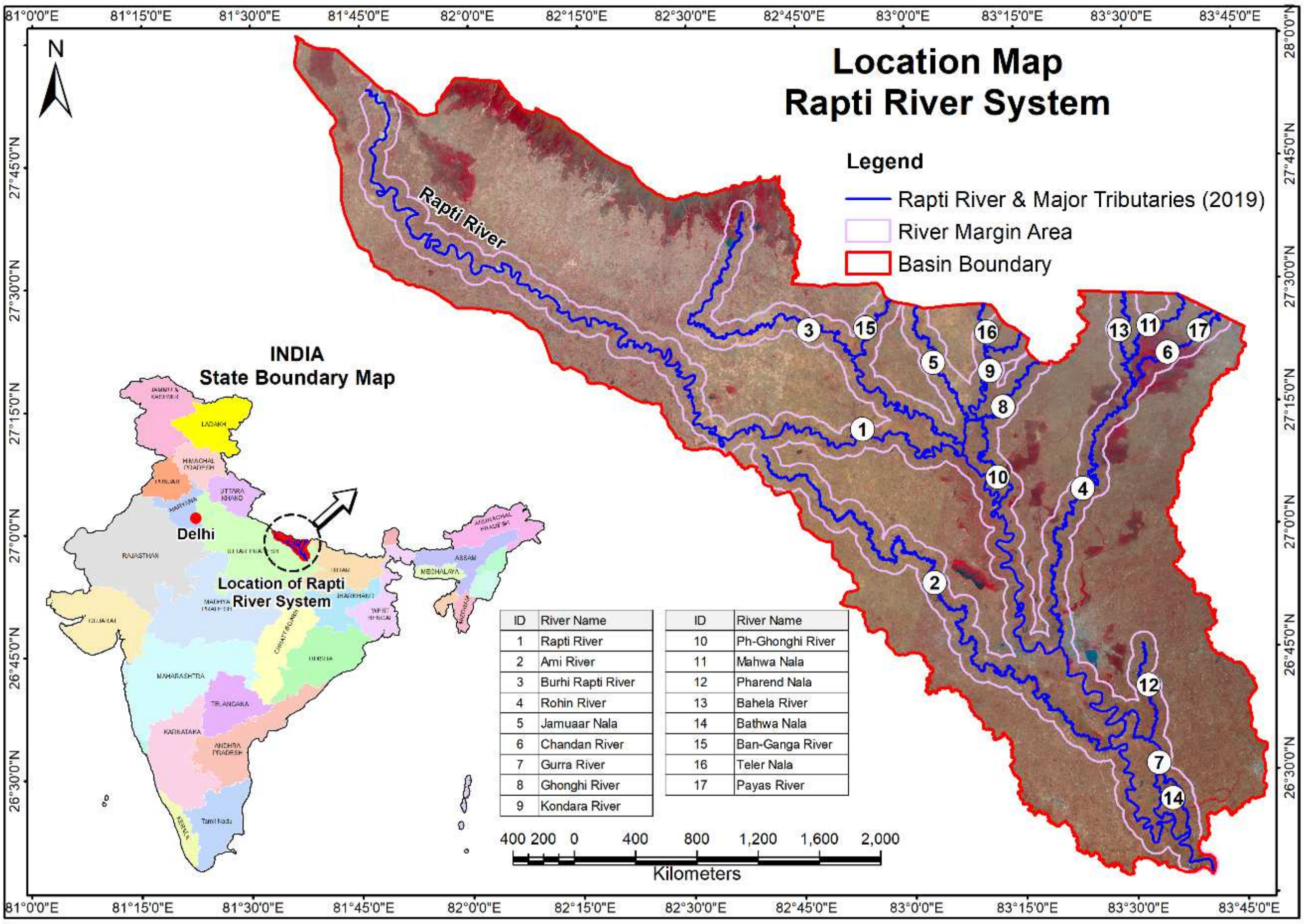


Figure 1. Location Map of Rapti River System.

3. Data Used and Sources

Landsat-8 OLI (Operational Land Imager) and PAN sharpening satellite remote sensing data (Level-1) with 15 m spatial resolution has been downloaded from Earth Explorer, Earth Resources Observation and Science (EROS) Center, United States Geological Survey (USGS) [16]. Acquisition date: 15th March 2019. https://earthexplorer.usgs.gov/

ALOS PALSAR Terrain-Corrected (RTC) DEM data with 12.5 m spatial resolution, radiometrically and terrain-corrected geocoded GeoTiff image has been downloaded from Alaska Satellite Facility, Fairbanks (AK) [17]. Acquisition date: 16th April 2010. https://search.asf.alaska.edu/

Survey of India Topographical Maps Open Series Maps (OSM) on 1:50,000 scale, No. 63 E / 09, 10, 13, 14; 63 I / 02, 03, 07, 08, 10, 11, 12, 15, 16; 63 J / 11, 12, 13; 63 M / 01, 02, 03, 04, 05, 06, 07, 08, 09, 10, 11 have been downloaded from Survey of India, Nakshe Portal [18]. Dated: 2003-2004. http://soinakshe.uk.gov.in/

ArcGIS Online Satellite Imagery A very high-resolution satellite imagery with 1 m spatial resolution available through ArcGIS Online [19]. http://www.arcgis.com/home/webmap/viewer.html

4. Form and Process BASED Geomorphic Classification

Classification is the ordering of objects into groups based on common characteristics and attaching labels to the groups. A wide range of classification schemes have been developed for fluvial systems, reflecting the intended purpose of the classification, different disciplines involved, and the characteristics of the systems being classified i.e. the studied environment, as per Gurnell [20]. We have critically reviewed more than 100 research articles and case studies for form and process based geomorphic classification. These classifications (57 in total) have been grouped into four classifications i.e. (A) Rosgen classification system (total 16), (B) river styles framework (total 17), (C) natural channel classification (total 19), and (D) statistical classification (total 5). Some of the popular geomorphic classification is shown in Table 2. This table is summarizing many classifications based on geomorphic criteria, classification method, classification objective, classification scale, and year of classification.

Table 2. Examples of Geomorphic-based River Classifications.

S. No.	Year	Classification Method	Classification Objective	Classification Scale	References	Remarks
A	Classification Framework: Natural Channel Classification (NCC)					
1	1877	Bed material and mobility. Substrate	Occurrence of alluvial vs. bedrock rivers as a function of bed load supply relative to transport capacity as modulated by wood jams.	Reach to valley	[21-23]	Small-to-medium-sized, alluvial & bedrock rivers, with very steep to moderate slopes & variable confinement; concepts generalizable to any environment.
2	1936	Channel - floodplain interactions	Floodplain formation by lateral accretion, vertical accretion or braiding processes.	Reach to valley	[24]	Large, alluvial, floodplain rivers of various slope; unconfined to partly confined.
3	1957	Alluvial channel patterns	Describe (or predict) alluvial channel patterns.	Channel pattern	[25-26]	-
4	1963	Bed material and mobility. Bed mobility	Recognizes the difference between live-bed (sand / silt) rivers and threshold (gravel / cobble) channels.	Reach to valley	[27]	Sand-bed irrigation canals (India), gravel / cobble-bed canals & small to large, floodplain rivers.
5	1973	Valley bottom	Characterize valley bottom or floodplain dynamics.	Valley bottom, floodplain	[26, 28, 29]	-
6	1975	Channel - floodplain interactions: Aerial photographs	Recognizes 67 channel types as a function of the degree & character of sinuosity, braiding, & anabranching.	Reach to valley	[30]	Medium to large alluvial rivers of various slope, grain size & floodplain extent.
7	1977	Process domain	Sediment production, transfer & deposition zones.	Basin	[31]	Source to sink (head waters to lowland depositional zone); generally applicable to any river environment.
8	1978	Channel pattern. quantitative relationships: S-Q-D	S-Q domains for braided vs. meandering channels, stratified by grain size & sinuosity.	Reach to valley	[32]	Sand-to-gravel-bed rivers of various size, with moderate to low slopes.
9	1982	Channel pattern. quantitative relationships: S-Q	S-Q threshold for braided vs. meandering channels, with degree of sinuosity & frequency of islands indicated.	Reach to valley	[33]	Small to large, gravel / cobble-bed rivers, with moderate to low slopes.
10	1990	Channel units	Visual classification of steep channel units and associated processes based on topography, hydraulics, grain size and water-surface slope.	Channel unit	[34-35]	Small, very steep to moderate gradient, cobble & boulder-bed channels. Concepts generalizable to other environments.
11	1992	Hydrologic regimes	Classify and characterize hydrologic regimes	Basin	[36]	-
12	1999	Process domain	Interaction between disturbance processes, and channel morphology	Valley	[37]	Mountain rivers (headwaters to alluvial plains), but concepts applicable to any environment.
13	2002	Bed material and mobility. Bed mobility	Recognizes 6 channel types as a function of bankfull Shields stress, grain size, mode of transport, reach morphology & channel stability.	Reach to valley	[38-39]	Applicable to most types of alluvial rivers (boulder-to-silt-bed, confined headwaters to unconfined lowlands).
B	Classification Framework: River Styles Framework (RSF)					
14	1945	Stream order	Network structure.	River network	[40-41]	Any river networks.
15	1975	Stream hierarchical	Provide a theoretic hierarchical framework for river classification.	All scales	[31, 42]	-
16	1976	Morpho-dynamic processes of river	Classify streams on the basis of their morpho-dynamic processes and adjustments.	Channel reach; often viewed in the basin context	[31, 43]	-
17	1985	Channel pattern. quantitative relationships: (u/(u*c)) & channel form index at bankfull stage	Extension of Ikeda framework to bar formation & reach type in mountain rivers	Reach	[44]	Small-to-medium-sized, gravel / cobble-bed rivers, with variable confinement & steep to moderate slopes.

S. No.	Year	Classification Method	Classification Objective	Classification Scale	References	Remarks
18	1986	Hierarchical	Describes physical conditions & processes across multiple spatial & temporal scales to assess aquatic habitat.	Micro to reach, viewed within a basin context	[5]	Small-to-medium-sized streams in mountain basins; headwater streams to low-order floodplain channels; steep to moderate slopes.
19	1992	Channel - floodplain interactions	Genetic sequences.	Reach to valley	[29, 45]	Synthesis of alluvial floodplain rivers from around the world; silt to boulder-bed rivers of various size, and slope.
20	1993	Channel pattern. quantitative relationships: S-Q	S-Q domain for anastomosed channels added to data reported by Ferguson [55]	Reach to valley	[46]	Silt-to-gravel-bed anastomosed rivers of various size, with moderate to low slopes.
21	1996	Hierarchical	Uses channel morphology to assess channel condition and stability as a function of sediment supply.	Reach; viewed within a valley & basin context	[47-49]	Small, headwater streams to large, lowland rivers; alluvial rivers with boulder to sand beds, steep to low slopes.
22	1997	Hierarchical	Recognizes eight channel types and their response potential within the context of fluvial processes associated with each channel type.	Reach to valley, viewed within a basin context	[50-52]	Alluvial, bedrock & colluvial channels from headwaters to lowlands; small to large rivers, with steep to low slopes, boulder to sand beds.
23	2000	Hierarchical	Divides a basin into different river styles, which are used together with genetic models to assess channel condition and to inform restoration actions.	Reach to valley, viewed within a basin context	[53]	Broad range of process domains for alluvial & bedrock rivers of various size, slope, substrate & confinement, mountain basins; but concepts are generalizable to other environments.
24	2002	Channel units	Visual classification of obstruction-forced pools and their associated hydraulics and scour mechanisms	Channel unit	[54]	Small-to-medium-sized, gravel / cobble-bed rivers, with moderate slopes & unconfined to partially confined valleys.
25	2003	Channel pattern. quantitative relationships: (u/(u*c)) & channel form index at bankfull stage	Domains for Montgomery alluvial channel types, including braided rivers	Reach to valley	[52]	Small to large rivers, with boulder to gravel beds, steep to low slopes and variable confinement.
26	2006	Channel pattern. quantitative relationships: S-Q	S-Q thresholds for meandering vs. island-braided vs. braided channels, with critical width for channel migration.	Reach to valley	[56]	Small-to-medium-sized rivers, with boulder to gravel beds, & steep to low slopes.
C	Classification Framework: Rosgen Classification System (RCS)					
27	1899	Drainage network	Describe valley geomorphology, quantify drainage network	Basin, valley, drainage network	[41, 57]	-
28	1957	Channel pattern. quantitative relationships: S-Q	S-Q threshold for braided vs. meandering channels.	Reach to valley	[25]	Small to large rivers, with cobble to sand beds, & moderate to low slopes.
29	1963	Channel pattern. quantitative relationships: S-Q-D	S-QD threshold for braided vs. meandering & straight channels (latter two share a common space).	Reach to valley	[58-59]	Alluvial floodplain rivers (unconfined to partly confined): Re-analysis of Leopold [25].
30	1972	Channel pattern. quantitative relationships: Other discriminators	Straight, meandering & braided channels as a continuous function of S vs. bed load transport rate, or shear stress.	Reach to valley	[60-62]	Moderate-slope, laboratory sand-bed channels.
31	1973	Channel pattern: conceptual frameworks	Modification of Schumm's framework; recognizes six major channel types.	Reach to valley	[63-64]	Medium to large rivers, with cobble to silt beds & various slopes; concepts generally applicable to floodplain rivers.
32	1976	Channel pattern. quantitative relationships: Other discriminators	Domains for straight vs. meandering vs. braided channels as a function of bankfull Froude number & channel form index.	Reach to valley	[65]	Data compilation, using laboratory sand-bed channels, sand & gravel irrigation canals & sand to cobble, floodplain rivers of various size & slope (India).
33	1982	Channel units	classification of bar types & processes.	Channel unit	[66]	Large, gravel / cobble, floodplain rivers of various slope, with unconfined to partially confined valleys.
34	1984	Channel pattern:	Domains for braided vs. wandering vs.	Reach to	[67-69]	Small to large rivers, with cobble /

S. No.	Year	Classification Method	Classification Objective	Classification Scale	References	Remarks
		conceptual frameworks	meandering channel types as a function of bank strength.	valley		gravel beds, & moderate slopes; concepts generally applicable.
35	1994	Hierarchical	Four hierarchical scales of analysis to assess channel condition and develop data for natural channel design.	Micro to valley.	[70-72]	Alluvial & bedrock rivers from headwaters to lowlands; small to large rivers, with steep to low slopes, boulder to silt beds & variable confinement.
36	1995	Channel reach	Regionalize channel morphology and dynamic.	Channel reach; often viewed in the basin context	[73-74]	-
37	2015	Stream-reach taxonomy	For geomorphic units, at tiers 1 and 2 they focus on topographic definitions that will facilitate development of tractable algorithms based on topography for automating the derivation of these features.	Margins area.	[75]	Within each reach, geomorphic units and structural elements were classified. Classifications provide the legend labels of a geomorphic map/units. The simplicity or complexity of the map then reflects the degree of heterogeneity of that riverscape and provides useful clues as to its histories and the processes that shape it.
D	Classification Framework: Statistical Classification (STC)					
38	1983	biological resources	Manage biological resources.	All scales	[76]	-
39	1984	Channel reach	Sectorize streams in reach having homogeneous geomorphic features.	Channel reach; often viewed in the basin context	[28, 77]	-
40	1996	Channel reach	Identify reaches producing / storing LWD.	Channel reach	[78]	-
41	1997	Channel reach	Identify reaches sensitive to erosion.	Channel reach	[79]	-

4.1. Rosgen Classification System (RCS)

This classification is based on field-collected empirical data that classifies the geomorphic stream to identify stream types by numerically constrained physical metrics [80]. The field surveys are based on the ecological aspects, on a basin context, or on the degree of modification [81]. Such means spotlight unmodified rivers, and data collected have be used to categorize channels [31, 50]. For instance, Rosgen's formed-based classification of natural rivers Rosgen [82] attached lots of attention on dimensional properties to define eight primary stream types [83]. This stream type classifications provide inferences into the sensitivity of stream reaches to natural channel changes [84]. It is arguably the most commonly used stream classification system in the world.

4.2. River Styles Framework (RSF)

This classification is focuses on channel change using thresholds, stability analysis, degree of disturbance, or/and site-based analysis [83]. River styles classification is describing river character and behavior and can be used to understand river condition, recovery potential and prioritize management [80]. Use threshold to identify the stability limit through a field method [85]. Olsen [86] evaluated channel stability thresholds for stream reach, which if the bankfull flow is sufficient to move large particles, the stream is considered instable and the threshold of stream has been reached. For this classification, field data, remote sensing and GIS data on geology, hydrology, and stream geomorphic is required to identify broad-scale to local controls on river character and behavior [80].

4.3. Natural Channel Classification (NCC)

This classification is a model-based stream classification using a machine-learning (support vector machine) algorithm to group reaches based on their historic, undisturbed planform [80]. The ocular system stability rating is developed to predict which streams are likely to perturbation in natural forests [87-89] used sediment budgets, developed for individual reaches of the urbanizing Menomonee river in Wisconsin to score channel segments. Approach on the basis of potential for recovery is exampled by the study classifying river conditions at different positions within the catchment into five categories [53]. Those five categories are intact reaches, restoration reaches, degraded reaches, turning point reaches, creation reaches. Remotely-sensed channel slope, discharge, valley confinement, sediment supply, and sediment size are used as predictors of channel planform in a modeling framework [80].

4.4. Statistical Classification (STC)

Statistical classification refers to any classification methods used to differentiate, or group stream reaches, watersheds, etc.

based on multiple physical, chemical, and/or biological attributes [80]. Attributes are often selected for their role in driving or responding to dominant processes within a catchment. Requires remote sensing and GIS data to classify reaches from the top-down or correlate classified reaches to larger-scale environmental or physical processes.

5. Form and Process based Geomorphic Mapping

The physical form of a river is the result of the coupled climatic, biotic and hydro-geomorphic processes acting upon it [57]. Accordingly, the classification of rivers into reach types based on their physical characteristics lends insight into both the formative processes that shape rivers and the diversity of rivers that occur across an area of interest [52]. There are numerous frameworks for classifying streams, many of which have diverse spatial and temporal output scales [45, 51, 90]. Classification applications range from river maintenance and flood control to channel and riparian protection from land use. More broadly it helps to disentangle natural and anthropogenic influences on channels, determine current channel condition and forecast response to future disturbance [52]. We have used the form and process-based geomorphic classification proposed by Wheaton [75] in 2015.

For geomorphic mapping of a river, it is required to define the margin area. A margin represents a border or edge between distinct regions, and it may be an expression of river form; alternatively, it may constrain river behavior. Margins can be differentiated as margins of anthropogenic origin or natural origin. Margins of anthropogenic origin include embankments, dyke, fences, hedgerows, constructed levees, canal, drains, railway line, roads and walls [91]. Margins of natural origin include valley margins, valley bottom margins and channel margins. In this study the river margin areas have been defined as a 2.5 km both side buffer of river center line with area between two embankments, morphologically active area over the years (1999-2019), and active floodplains.

The geomorphic features are identified and mapped is dependent on the minimum mapping unit (area and resolution) and the purposes for which the map will be used e.g. broad-scale description vs. detecting changes in unit assemblage through time [8]. For this study we have used 1: 2000 mapping scale to identify various in-channel geomorphic features, and out-of-channel geomorphic features at micro level.

5.1. Identification of Fluvial Geomorphic Units

A geomorphic unit is a landform that is a by-product of the deposition of sediment and/or erosion of sediment or bedrock. Fryirs define geomorphic units as the building blocks of rivers, each with its own form-process association. Fluvial geomorphic units are commonly differentiated based on their position with respect to the channel and by differentiating instream, floodplain, inactive floodplain, hillslope and fan units [92]. Wheaton has proposed a four-tiered hierarchical taxonomy for geomorphic units, which are based on (i) vertical position or flow stage relative to channel bed, (ii) their shape, (iii) specific morphology type and (iv) sub-categories of sedimentological and vegetative characteristics [75].

The order of this proposed hierarchy is critical because it emphasizes a primary topographic definition of geomorphic units in tiers 1 and 2 that explicitly ties it to the flow regime and relative magnitude of events responsible for creating, maintaining and/or sculpting these features. Secondarily, the first tier is tied explicitly to broader scale controls on reach types, valley setting and to the natural capacity for adjustment [45, 93]. The further into the tiered system a specific geomorphic unit is classified, which is to identify the relative topographic stage position of the geomorphic unit of interest e.g., in-channel geomorphic units or out-of-channel geomorphic units in tier-1, then, from the perspective of the center of that geomorphic units e.g., the deepest part of a pool, the crest of a riffle in tier-2.

Tier 3 includes a plurality of geomorphic unit names that many geomorphologists use e.g. unit bars, meander cutoff, paleo channel, piedmont plain, etc. More detailed mapping of instream geomorphic units at tier 3 may be warranted to differentiate features that make up a broader scale geomorphic unit. For example, in some cases, when mapping a macroscale feature like a large bar that is fundamentally a mid-channel bar but has a number of unit bars and smaller bank attached bars pasted on to it, it may be simplest to denote the bar as a bar complex or to map individual geomorphic units that make up compound features, e.g. ramps, ridges, chute channels, bar platforms, etc. [75]. The third tier uses the same specific morphology names used in morphological investigations, however the key attributes that help differentiate different types of geomorphic units (68 in total) are more easily defined.

Whereas tiers 1 through 3 are all based on topographic definitions and geographic attributes, tier 4 are modifiers based on vegetation. Sedimentological characteristics and vegetation associations (e.g., bare, vegetating, forested) are additional attributes that are helpful for further differentiating tier 3 geomorphic units into tier 4 subcategories. These attributes are not readily identifiable from most topographic data sets. Determining sedimentological characteristics requires either field measurements (e.g., Wolman pebble counts) or very high-resolution point data of bare surfaces.

5.2. Mapping of Specific Morphology of Rapti River System

The specific morphology mapping of Rapti river system was performed using a combination of high-resolution satellite imagery (available in ArcGIS online), nationally available 12.5 m DEM (ALOS PALSAR) in Alaska Satellite Facility's and Google Earth and cover an area around 5069.73 km^2. The scale of mapping is most general and has been done from broadly available data sets for which there are generally national coverages. Out of the 68 units defined by Wheaton [75], only 28 specific morphology features have been identified from their classification system and 16 specific morphology features have been suggested by us in the Rapti river system using advance satellite remote sensing data. A total of 44 specific morphology features have been identified, out of which 21 specific morphology features have been identified in "out-of-channel (active floodplain)", 5 specific morphology features have been identified in "out-of-channel inactive floodplain (terrace)" and 18 specific morphology features have been identified in "in-channel". The details of specific morphology features are shown in Table 3. Figure 2 is showing the low-resolution map of specific morphology features of Rapti river system. The greater details of specific morphology features at a specific location (can be seen as rectangle shapes with number e.g. 01, 02, 03, … 32 in Figure 2) is shown in Figure 3, that can be obtained in higher resolution mapping form the GIS database.

Table 3. List of Specific Morphology Features in Rapti River System [92].

S. No.	Specific Morphology	Form	Process Interpretation
A	Out-of-Channel - Active Floodplain - Geomorphic Features		
A (I)	Concave Geomorphic Features		
1	Anabranch (Abh)*	Pattern of coexistent channels that repeatedly bifurcate and re-join. Channels have low width / depth ratio.	Formed during high flow conditions events when flow reoccupies and reactivates former channels. These channels are dominated by low-energy, suspended-load deposits.
2	Secondary Channel (Sch)*		
3	Backswamp (Bsm)	The lowest area of the valley floor. Morphology is flat with depressions. Ponds, wetlands and swamps commonly form where lower order tributaries drain directly onto the floodplain.	Forms when the reduction in energy gradient from the proximal to distal floodplain only allows suspended-load materials to be transferred to the backswamp.
4	Back Channel (Bch)*	Low-sinuosity subsidiary channel with a defined bed and banks. Commonly observed at valley margins.	Flow alignment along the valley floor short-circuits the channel during high discharge events, steepening the down-valley flow trajectory and inducing scour.
5	Chute Cutoff (Cco)*	Straight / gently curved channel that dissects the convex bend of the primary channel. This may occur through a point bar. Chute cutoffs have a straighter planform than meander cutoffs.	Short-circuiting of the primary channel reduces sinuosity and stream length, steepening the water slope at flood stage. Chute cutoffs generally occur in higher energy settings than meander cutoffs.
6	Meander Cutoff (Mco)	A meander bend that has been cut through the neck, leaving an abandoned meander loop on the floodplain. May host standing water (i.e. oxbow lake) or be infilled with fine-grained materials.	Formed by the channel breaching the meander bend or through the development of a neck cut-off during high flow conditions. As the palaeo-meander loop becomes plugged with instream materials the abandoned meander becomes isolated from the main channel.
7	Neck Cutoff (Nco)		
8	Oxbow Lake (Obl)		
9	Paleo-Channel (Pch)*	An old, inactive channel on the floodplain. May be partially or entirely filled. Extends over more than one meander wavelength.	Caused by a sudden shift in channel position (avulsion), generally to a zone of lower elevation, abandoning a channel on the floodplain.
10	Swale (Swl)	Ridges are scroll bars that have been incorporated into the floodplain. Ridge and swale topography may indicate phases of palaeo-migration paths, palaeo-curvature and palaeo-widths of channel bends.	During bankfull conditions the high-velocity filament of flow is located along the concave bank of a bend.
11	Ridge and Swale Topography (Rst)*		
12	Dendritic Ridge (Drg)		
A (II)	Convex Geomorphic Features		
13	Crevasse Splay (Csl) (Crevasse Channel-Fill)	A sediment tongue fed by a crevasse channel that breaches the levee. Crevasse splays have a lobate or fan-shaped planform with distal thinning away from the levee.	Crevasse channels breach and erode the levee, taking bedload materials from the primary channel and conveying them onto the floodplain at high flood stage.
14	Flood-Out (Fot)	Fan-shaped sand body that radiates downstream from an intersection point of a discontinuous channel. Tend to have a convex cross-profile, and fine in a downstream direction.	Formed when a discontinuous channel supplies sediment to an unincised valley fill surface.
15	Island (Isl)	Vegetated mid-channel bar. Can be emergent at bankfull stage. They are commonly elongate in form, aligned with flow direction	Generally, form around a bar core that has been stabilised by vegetation. This induces further sedimentation on the island.

S. No.	Specific Morphology	Form	Process Interpretation
		scaling to one or more channel widths in length.	
16	Natural Levee (Nlv)	Raised elongate asymmetrical ridge that borders the channel. Levee crests may stand several metres above the floodplain surface.	Levee form is influenced by, and in turn influences, the channel-floodplain linkage of biophysical processes, influencing the lateral transfer of water, sediment, organic matter, etc.
A (III)	Planar Geomorphic Features		
17	Valley Fill (Vfl)	Relatively flat unincised surface. May have ponds and discontinuous channels or drainage lines. Organic-rich deposits may develop around swampy vegetation.	These sediment storage features are typically formed by flows which lose their velocity and competence as they spread over an intact valley floor and deposit their sediment load.
18	Beaver Meadow (Bmd) (Swamp, Swampy Meadow)		
19	Active Flood Plain (Afp)*	Flat, tabular laterally extensive sheets in non-levee settings with massive, often poorly sorted facies.	Associated with rapid sediment-charged bedload deposition on the floodplain during extreme flood events. Common in sandy ephemeral streams.
20	Old Flood Plain (Ofp)*		
21	Older Alluvial Plain (Oap)	Lies adjacent to or between active or abandoned channels and the valley margin.	Floodplain form reflects the contemporary arrangement of out-of-channel sediment build-up and reworking at flood stage. Formed from lateral accretion (with-in-channel) and vertical accretion (overbank) deposits.
B	Out-of-Channel - Inactive Floodplain (Terrace) - Geomorphic Features		
B (I)	Planar - Geomorphic Features		
22	Alluvial Terrace (Atc) (Fill Terrace)	Typically, a relatively flat (planar), valley marginal feature that is perched above the contemporary channel and/or floodplain.	Initially formed by lateral and vertical accretion processes under prior flow conditions. Tectonic uplift, a change to base level or shifts in sediment-load and discharge regime prompt downcutting into valley floor deposits, abandoning the former floodplain.
23	Strath Terrace (Stc)	A relatively flat. These erosional surfaces have a bedrock core, often with a thin alluvial overburden. Strath terraces often confine the channel, analogous to valley margins.	Reflect incision and valley expansion associated with downcutting into bedrock, abandoning terrace surfaces.
B (II)	Hillslope / Upland - Geomorphic Features		
24	Concave Bank Bench (Cbb) (Convex Bar)	Bank-attached unit, often with a low ridge across the central portion parallel to the primary channel. Located along the upstream limb i.e. along the concave bank.	Associated with flow separation and generation of secondary currents at high flood stage. Sedimentation occurs in sheltered backwater zones of relatively low flow velocity.
25	Piedmont Plain (Pdp)*	Piedmont surface relief is characterized by relatively low, rolling hills. Its geology is complex, consisting of several rock formations of different materials and duels interchangeably.	Piedmont, in geology, is the terrain formed at the bottom of a mountain or mountains by debris deposited by the flow of rivers.
26	Piedmont (Pdm)*		
C	In-Channel - Geomorphic Features		
C (I)	Convex - Geomorphic Features		
27	Boulder Berm (Bbm) (Boulder Bench)	Elongate, bank-attached stepped feature. Can have a convex cross-section. Comprised of course, boulder bedload materials with limited finer grained matrix.	Formed from bedload deposition in a single event under high-velocity conditions. Materials are accreted along the bank where flow velocity decreases substantially.
28	Compound Bar (Cmb). Compound Bank-Attached Bar*	Bank-attached bar that is comprised of an array of smaller scale geomorphic units. Generally composed of laterally accreted sand or gravel but may include silt or boulders.	Development of compound lateral or point bar forms is dependent on channel alignment (and associated implications for the distribution of flow energy over the bar surface at different flow stages) and associated patterns of reworking by flood events.
29	Confluence Bar (Cfb). Tributary Confluence Bar (Channel Junction Bar, Eddy Bar)	Formed at, and immediately downstream of, the mouth of tributaries. These delta-like features have an avalanche face. They generally comprise poorly sorted gravels and sands with complex and variable internal sedimentary structures.	Typically form at high flood stage in reaches where a comparatively minor tributary enters the trunk channel.
30	Diagonal Bar (Dgb). (Diamond Bar)	Mid-channel unit bar oriented diagonally to banks in gravel and mixed-bed channels. These bars commonly have an elongate, oval or rhomboid planform.	Formed where flow is oriented obliquely to the longitudinal axis of the bar. May indicate highly sediment-charged conditions or reworking of riffles.
31	Expansion Bar (Exb)	Coarse-grained (up to boulder size) mid-channel bar with a fan-shaped planform. Often occur downstream of a bedrock	As flow expands abruptly at high flood stage in high-energy depositional environments, it loses competence and induces deposition. These bars

S. No.	Specific Morphology	Form	Process Interpretation
		constriction that hosts a forced pool.	remain inactive between large floods, constraining processes at lower flow stages.
32	Forced Riffle (Frl)	Longitudinally undulating gravel or boulder accumulations that act as local steps. Irregular spacing is dictated by the distribution of bedrock outcrops, wood or hillslope sediment inputs along the river.	Flow is characterised by high-energy turbulence over lobate accumulations of coarse bedload materials, and bedrock outcrops.
33	Forced Pool (Fpl)*	These deeper areas along longitudinal profiles are scour features associated with irregularly spaced bedrock outcrops, wood and forced riffles. A backwater pool may form immediately upstream of a bedrock step.	These areas of tranquil flow within high-energy settings may accumulate finer grained materials at low-moderate flow stage, but they are flushed and possibly scoured during extreme events.
34	Point Bar (Pob)	Bank-attached arcuate-shaped bar developed along the convex banks of meander bends. The bar surface is typically inclined towards the channel, as are the sedimentary structures.	Result from lateral shift in channel position associated with deposition on the convex bank and erosion on the concave bank. Sand or gravel bedload material is moved by traction towards the inner sides of channel bends via helicoidal flow.
35	River Riffle (Rrl)	Topographic highs along an undulating reach-scale longitudinal profile. They occur at characteristic locations, typically between bends in sinuous alluvial channels.	Riffles are zones of temporary sediment accumulation which increase roughness during high flow stage, inducing deposition.
36	Pool (Pol)*	Pools may span the channel, hosting tranquil or standing flow at low flow stage. Alluvial pools are alternating deep areas of channel along an undulating reach-scale longitudinal bed profile.	At high flow stage, when flow converges through pools, decreased roughness and greater bed shear stresses induce scour and flushing of sediment stored on the bed.
37	Scroll Bar Ridge (Sbr)	Elongate ridge form developed along the convex bank of a bend. Commonly develop on point bars with an arcuate morphology.	Formed by two-dimensional flow paths on the inside of a bend. Adjacent to the thalweg, sand or gravel bedload material is moved by traction towards the inner sides of channel bends via helicoidal flow.
38	Sand Sheet (Sst)*	Relatively homogeneous, uniform, tabular sand deposits which cover the entire bed. May consist of an array of bedforms, reflecting riffle, dune or plane bed sedimentation.	Formed when transport capacity is exceeded, or competence is decreased, and bedload deposition occurs across the bed. Generally, reflect transport and capacity-limited conditions due to an oversupply of sediment.
39	Gravel Sheet (Gst) (Basal or Channel Lag)	Relatively homogeneous, thin / tabular bedload sheets that are deposited across the bed. Often coarse grained and poorly sorted.	Deposited under uniform energy conditions in highly sediment-charged rivers. Generally, indicates transport and capacity-limited or competence limited conditions due to oversupply of sediment.
40	Lateral Bar (Ltb) (Alternate or Side Bar)	Bank-attached unit bar developed along low-sinuosity reaches of gravel- and mixed bed channels. Bar surface is generally inclined gently towards the channel.	Flow along a straight reach of river adopts a sinuous path. Bar length and width are proportional to these flows. They generally migrate in a downstream direction.
41	Forced Mid-Channel Bar (Fmcb) (Pendant Bar, Wake Bar, Lee Bar)	A mid-channel bar form that is induced by a flow obstruction. The resultant bar form often has a downstream-dipping slip face as the bar extends downstream.	Perturbations in flow and subsequent deposition are induced by obstructions. These bars build in a downstream direction and may become vegetated.
42	Compound Mid-Channel Bar (Cmcb)*	A mid-channel bar that comprises an array of smaller scale geomorphic units. Variable morphology reflects material texture, flow energy and the history of flood events that induce formation and ramps or dissection features.	The assemblage of geomorphic units is dependent largely on channel alignment and patterns of reworking by flood events. Formed initially from the lag deposition of coarser sediments (a unit bar).
C (II)	Planar - Geomorphic Features		
43	Bench (Bnh). (Oblique-Accretion Bench)	A distinctly stepped, elongate, straight to gently curved feature that is inset along a bank. Sedimentary structures tend to be quite distinct from the floodplain.	Formed by oblique - and vertical accretion of bedload and suspended-load materials during small to moderate floods within widened channels. Oblique accretion benches represent low-energy falling-stage suspended-load deposition in sand-bed and mud-rich streams.
44	Point Bench (Pbnh)*	Distinctly stepped, bank attached unit developed along the convex bank of a sinuous channel. Typically has an arcuate planform with a planar surface that is elevated above the point bar.	Deposition along the convex bank via vertical and/or oblique accretion of interbedded sands and mud indicates slow lateral migration or lateral accretion within an over widened bend.

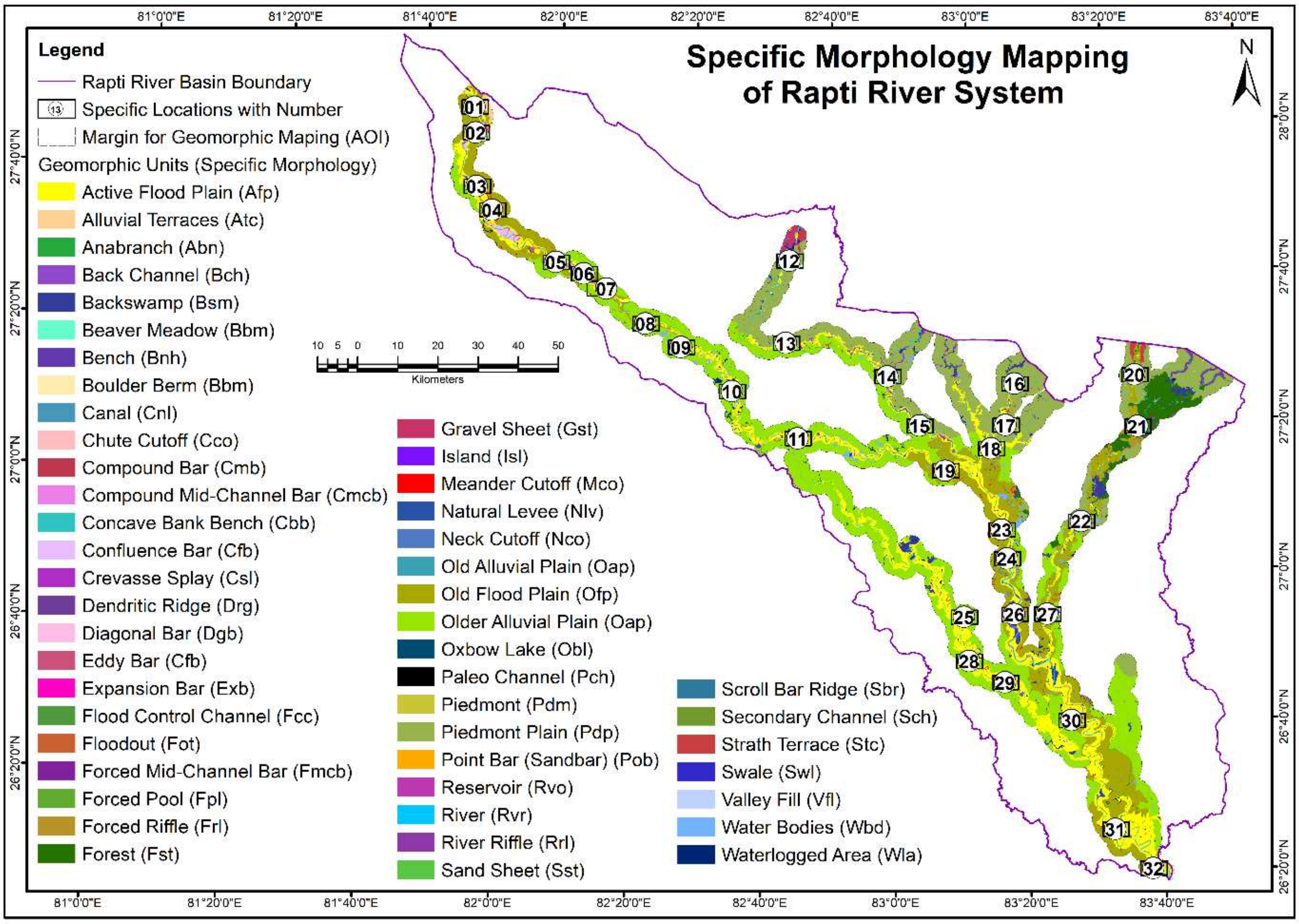
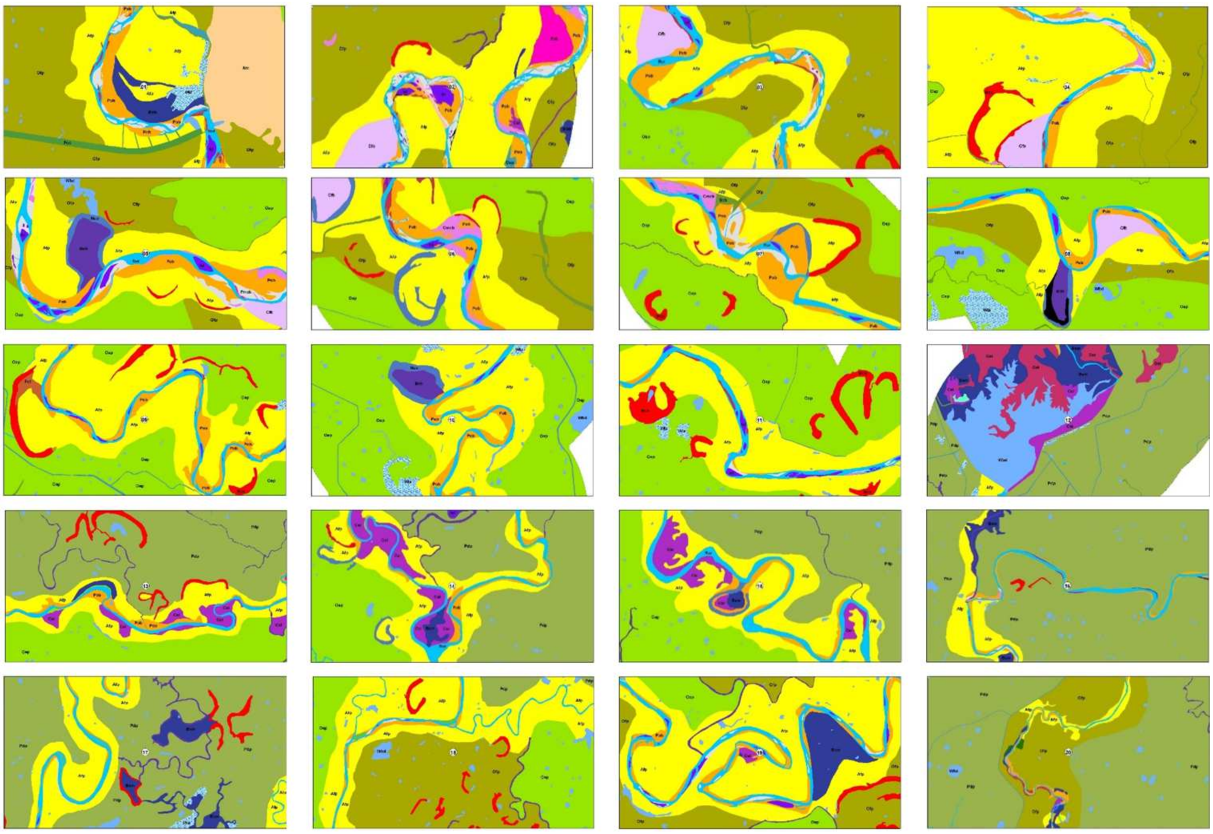


Figure 2. Specific Morphology Features in Rapti River System.



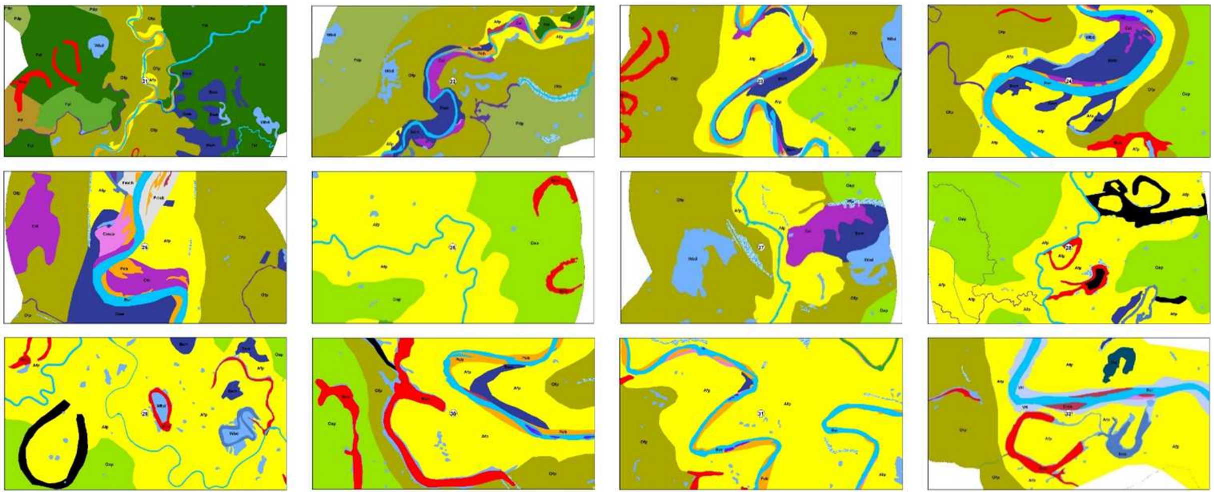


Figure 3. High-Resolution Map of Specific Morphology Features in Rapti River System.

6. Conclusion

This study is based on the interpretation of satellite remote sensing data and digital elevation data at a specific scale and/or spatial resolution. The high-resolution satellite remote sensing data and GIS has provided very precise and relatively complex information about the rivers specifically focused on fluvial geomorphic features / units. In addition, the input of satellite remote sensing data and GIS permits for integration of further info to improve the understanding of mechanisms that control the morphogenetic processes. Geomorphic units are the building blocks of river systems. The morpho-dynamic attributes of fluvial geomorphic features provide a fundamental basis to understand the river character and behaviour. Analysis of geomorphic features / units is a significant tool to read the landscape. Each geomorphic unit has a distinct form-process association. We have demarcated various geomorphic features / units of Rapti river system, based on geometry (shape and size), location and/or position within a landscape (i.e. In-channel geomorphic features, Out-of-channel geomorphic features), bounding surface (i.e. erosional or depositional boundaries) and sedimentological attributes based on satellite remote sensing data and field survey. A total of 44 specific morphology features have been identified in the study area, out of which 21 specific morphology features have been identified in “out-of-channel (active floodplain)”, 5 specific morphology features have been identified in “out-of-channel inactive floodplain (terrace)” and 18 specific morphology features have been identified in “in-channel”. We have also merge that collected informations by modern techniques (i.e. satellite remote sensing data and field survey), which is different from time-consuming traditional cartography. These steps have been saved the time and cost. This technique can be applied in other area, landscapes, location, river system and climatic zones, although there is still considerable work to be done before such mapping will become routine.

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