

Morphology and classification of the main stem Bagmati River, Central Nepal

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ABSTRACT

Rivers are significant geomorphic agents which can carry huge amounts of sediments and water from their catchments to depositional basins. Due course of flow they can bring various hazards such as flooding, inundation of flood plains, erosion of banks and trigger various slope movements. To understand nature and behavior of the Bagmati River, which is a perennial, storm and spring-fed, eight order river of central Nepal, the planiform morphological parameters of this river were analysed and river segments along the main stem stretches were classified into various stream-types, using topographic maps, aerial photographs, and satellite imageries.

The Bagmati River is an 8th order perennial river. The Bagmati River basin comprises 39 sub-basins of 4th order and higher. The averages of meander wavelengths (L_m), meander belt width (W_{blt}), radius of curvature (R_c) and sinuosity (K) of the 7th order main stem Bagmati River are 598.27 m, 164.07 m, 252.35 m and 1.38, respectively. Similarly, the averages of L_m , W_{blt} , R_c , and K of the 8th order main stem rivers are respectively, 496.77, 126.58 m, 286.13 m, and 1.55. All these parameters reflect fluctuating trends of variation along the downstream stretch. However, the portion of the 7th order river shows abrupt increase of L_m after the Bagmati River crosses the Main Boundary Thrust. The R_c also indicates slight increase in this region. The sinuosity reflects overall increase from the 7th to the 8th order rivers. This increase in sinuosity is attributed to the decrease in slope and competency of the river. There exists a moderate degree of correlation between K and W_{blt} showing that the W_{blt} of the Bagmati River tends to increase as the sinuosity increases.

The stream segments of the Bagmati River fall on A-, B-, C-, G- and D-type rivers. All the segments of the Bagmati River, lying within the Kathmandu Valley and having substrate of the fluvio-lacustrine valley-fill sediments, fall on C-type stream because of low entrenchment and high width/depth ratio. Similarly, A-type streams are developed at segments which flow through the Tistung Formation of the granite terrain of the Lesser Himalaya most probably due to entrenched and gorged valley and high slope. Likewise, B- and G-type streams are developed in terrains of the Lesser Himalaya and the Sub-Himalaya. The B-type streams are moderately entrenched with sinuous to meandering and wide channels. The D-type stream segment which is a multi-thread channel is characteristically developed within the terrain of the Sub-Himalaya presumably due to the change in slope caused by thrusting, and greater input of sediments from the Siwaliks in relation to weak and loosely consolidated lithology.

Key words: Stream order, Sinuosity, Meandering River, Bagmati River, Kathmandu Basin, Sub-Himalaya

INTRODUCTION

Rivers are significant geomorphological agents that exhibit diversity of pattern and behavior (Selby, 1983). The nature and the rate of development of different patterns probably depend on weathering and tectonic

condition. In tectonically uplifting landscapes, the mass movements and valley floor aggradations are prominent (Marutani et al., 2001). The Nepal Himalaya is geologically young, tectonically active and inherently fragile, thus causing development of different morphological features and patterns of the river. The river patterns thus developed are indicative of dynamism of the river system.

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Determination of the morphological parameters and assignment of the river stretches to a classification scheme is the preliminary task, which is made to understand the river types. These data are applicable to evaluation of river condition and stability. The dynamism of the river is necessary to understand to develop strategies for management of flood plain and control bank erosions. Understanding of river dynamism and its related processes, and river stability condition are very important for watershed management, wetland management, flooding mitigation, reservoir sedimentation management and sustainable development of infrastructures.

Hazard analysis and mapping of the Bagmati River Basin (BRB; Fig. 1) initiated after the disaster of 1993 (DWIDP, 2005). ICIMOD and DPTC carried out preliminary disaster assessment in the BRB and adjacent areas after the extreme events of 1993. DWIDP (2009) prepared hazard maps of the BRB, and identified the

area prone to landslides, debris flow, flooding inundation and bank cutting. Riverbank erosion and bank failure may produce a significant amount of bed load (Rosgen, 1976). Shrestha and Tamrakar (2007a) evaluated the Manahara River, a tributary of the Bagmati River, in terms of its bank erosion and lateral instability hazard. Shrestha and Tamrakar (2007b) reported relative bank material loss potential of the Manahara River Basin (83 km²) to be 1243 tons per year and average bank recession rate to be 0.33 m/yr. Bhusal (1998) interpreted that the sediment loss from the Siwaliks is the highest in Nepal and this was about 5000 to 15000 tons/km²/yr. The sediment yield from the middle mountains ranges from 3000 to 8000 tons/km²/yr. This means about 50% of the sediment was yielded by the Siwaliks alone. According to Ghimire et al. (2006), large gullies in the headwater catchments of the Siwaliks are the major sediment sources which account for 20 to 60% of the total erosion in the Siwaliks. The rivers in the Siwalik Range are competent enough to carry significant amount of sediments available in the source (Shrestha et al., 2008). Tamrakar and Shrestha (2008) suggested that rivers originating from the Lesser Himalaya with unstable slope are even more capable to flush out sediment compared to the rivers of the Siwaliks. Thus depending on the terrains, dynamism of rivers may alter as reflected by some changes of various morphological attributes such as slopes, sinuosity, entrenchment ratio, width/depth ratio, etc. This study yields morphological parameters and classifies the main stem Bagmati River.

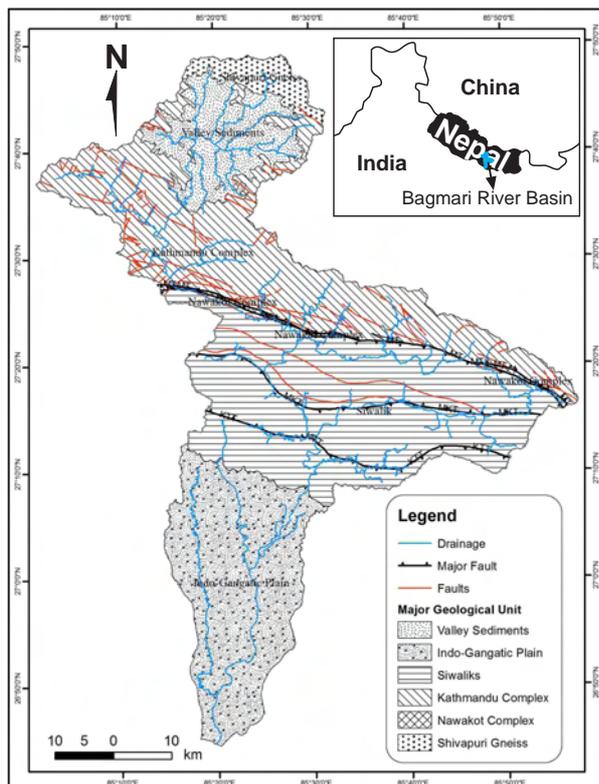


Fig. 1 Location of the study area with Bagmati River Basin showing major geological units and tectonic lines (based on Stöcklin and Bhattarai (1977), Stöckline (1980), Adhikari and Rimal (1996)

GEOLOGICAL OUTLINES OF THE BAGMATI RIVER BASIN

The BRB is characterized from the south to the north by the following geological units (based on Stöcklin and Bhattarai, 1977; Stöcklin, 1980; Adhikari and Rimal, 1996; DWIDP, 2005): (a) Indo-Gangetic Plain, (b) Sub-Himalaya, and (c) Lesser Himalaya (Fig. 1).

Indo-Gangetic Plain

It consists of the Pleistocene to the Recent alluvium of gravel, sand, silt and clay deposited by the rivers originating within the Himalayas or beyond. The average thickness of the sediments is about 1500 m.

There is a gradation from the coarser to the finer sediment from the northern to the southern parts of the plain (Table 1).

Sub-Himalaya

The Sub-Himalaya (Siwalik Group) is thrust over the sediments of the Indo-Gangetic Plain along the Main Frontal Thrust (MFT). It is separated from the Lesser Himalaya by the Main Boundary Thrust (MBT). The whole Siwaliks consist of alternating sequences of mudstone, sandstone and conglomerate. Based on grain size and facies assemblages, the Siwaliks are divisible into the Lower, Middle and Upper Siwaliks (Table 1).

Within the Siwalik terrain, there also lies a thrust slice of the Pre-Siwaliks which are characterized by fine- to medium-grained, ripple laminated, pink sandstone and minor green and purple shale (Adhikari and Rimal, 1996 ; DWIDP, 2005). The Siwaliks in the BRB are intersected by two north dipping east-west extending thrusts, viz. Marin Khola Thrust (MKT) and Kamala Tawa Thrust (KTT). The MKT has brought the Lower Siwaliks over the Upper Siwaliks. The KTT extends through the Chiruwa Khola in the western

part, crosses the Bagmati River, and extends roughly through the Kyan Khola in the eastern part.

Lesser Himalaya

The Lesser Himalaya comprises the autochthonous Nawakot Complex and the allochthonous Kathmandu Complex. The Nawakot Complex lies immediately north of the MBT, and consists almost exclusively of low-grade metasedimentary rocks, and is regionally subdivided into the Lower and the Upper Nawakot Groups (Stöcklin, 1980). However, the Lower Nawakot Group is completely absent in the BRB. Among the three units of the Upper Nawakot Group (Table 1), the Benighat Slates is continuous throughout the BRB, but the Malekhu Limestone and the Robang Formation exist only as narrow strips in the eastern part of the BRB.

The Kathmandu complex overlies the Nawakot Complex along the Mahabharat Thrust (MT). The Kathmandu Complex is subdivided into the Precambrian Bhimphedi Group consisting relatively high-grade metamorphic rocks such as garnetiferous schist, biotite schist, marble and quartzite, and the Phulchoki Group of unmetamorphosed to weakly

Table 1: Geological information of the Bagmati River (based on Stocklin, 1980; Gautam and Rösler, 1999)

Terrain	Complex	Group	Formation	Lithology	Age
Indo-Gangetic Plain				Gravel, sand, silt and clay	Quaternary
Siwalik Group			Upper Siwaliks	Cgl., mst., sst.	Early Pliocene
			Middle Siwaliks	Coarse-grained sst., mst.	Mid Pliocene to Late Pliocene
			Lower Siwaliks	Fine-grained sst., mst., slst.	Mid-Miocene to Early Pliocene
Lesser Himalaya	Kathmandu Complex	Phulchoki Group	Godavari Limestone	Limestone	Devonian
			Chitlang Formation	Slate	Silurian
			Chandragiri Formation	Limestone	Ordovician
			Sopyang Formation	Calc. phyllite, qzt.	Cambrian
			Tistung Formation	Meta-sst., phy, meta-slst., shale	Early Cambrian
		Bhimphedi Group	Markhu Formation	Calc. sch., lst., qzt.	Precambrian
			Kulekhani Formation	Biotite sch., quartzose schist, qzt.	Precambrian
			Chisapani Quartzite	White quartzite	Precambrian
			Kalitar Formation	Biotite schist, quartzite	Precambrian
			Bhainsedovan Marble	Marble	Precambrian
	Nawakot Complex	Upper Nawakot Group	Raduwa Foramtion	Garnetiferous schist	Precambrian
			Robang Formation	Phyllite, sericite quartzite, basic rocks	Post Early Paleozoic
			Malekhu Limestone	Limestone, dolomite	Post Early Paleozoic
		Benighat Slate	Slate, phyllite, lst.	Post Early Paleozoic	

Cgl.=conglomerate, sst.=sandstone, mst.=mudstone, slst.=siltstone, lst.=limestone, phy. = phyllite, qzt.=quartzite, sch.=schist, calc.=calcareous

metamorphosed sedimentary rocks such as metasandstone, limestone, shale, slate and phyllite of Early to Middle Paleozoic age (Stocklin, 1980) (Table 1). Besides, the BRB comprises granitic and gneissic rocks in the Kathmandu Complex.

The Lesser Himalaya also comprises Pliocene-Pleistocene basin-fill sediments as: Unconsolidated Sediments (Recent Alluvial Soil, Residual Soil, Colluvial Soil, and Alluvial Fan Deposit) and Consolidated Sediments (Tokha Formation, Gokarna Formation, Chapagaon Formation, Kalimati Formation, Kobgaon Formation and Basal Boulder Beds), in the midland zone. The basin-fill sediments overlie the basement rocks of the Pre-Cambrian to Devonian ages (Stöcklin, 1980; Yoshida and Igarashi, 1986). The lithology of the basement rocks as classified based on DMG (1998) is shown in Table 1.

PHYSIOGRAPHIC SUBDIVISION OF THE BAGMATI RIVER BASIN

From the south to the north of the BRB there are distinct topographic breaks characterized by various physiographic zones: (a) Terai Plain, (b) Siwaliks (Chure Range) with Dun Valleys, (c) Mahabharat Range and (d) Midlands (Fig. 2).

Terai Plain

The Terai Plain is the southernmost physiographic unit, and is a depositional landform with floodplains and recent and old river terraces. The altitude of the Terai Plain in the BRB varies from 75 to 150 m. The Terai Plain can be distinguished into three major landforms as Upper Piedmont, Lower Piedmont and Active Alluvial Plain. The Upper Piedmont is produced by coalescing fans adjacent to the Siwaliks.

Siwaliks with Dun Valleys

The Siwalik Range rises abruptly from the Terai Plain upto an altitude of about 1500 m, and produces the foothills of the Himalayas. The Siwaliks generally have a rugged topography with deeply dissected gullies and steep slopes formed by questas. The Siwaliks contain wide valleys of the Bagmati River and the Marin Khola. Low to high terraces adjacent to the river, alluvial fans, badlands and thin sandy soil covers are features found in this zone.

Mahabharat Range

The Mahabharat Range rises abruptly from the Siwalik Hills, and approaches the maximum altitude of about 3000 m. The Mahabharat Range exhibits a youthful topography often characterized by mountains, deep gorges and rugged landforms. The entire Mahabharat Range in the BRB, except for its southern edge that is made up of the rocks of the Nawakot Complex, is composed of the rocks of the Kathmandu Complex.

Midlands

The Midlands locate north of the Mahabharat Range and is characterized by lowering of the altitude up to 1000 m. The topography is mild with lower hills and wider valleys with recent and old terraces. The Kathmandu Valley is located in this zone and is characterized by dendritic, sub parallel and centripetal drainage systems. The entire Midlands and the BRB are composed of the rocks of the Kathmandu Complex.

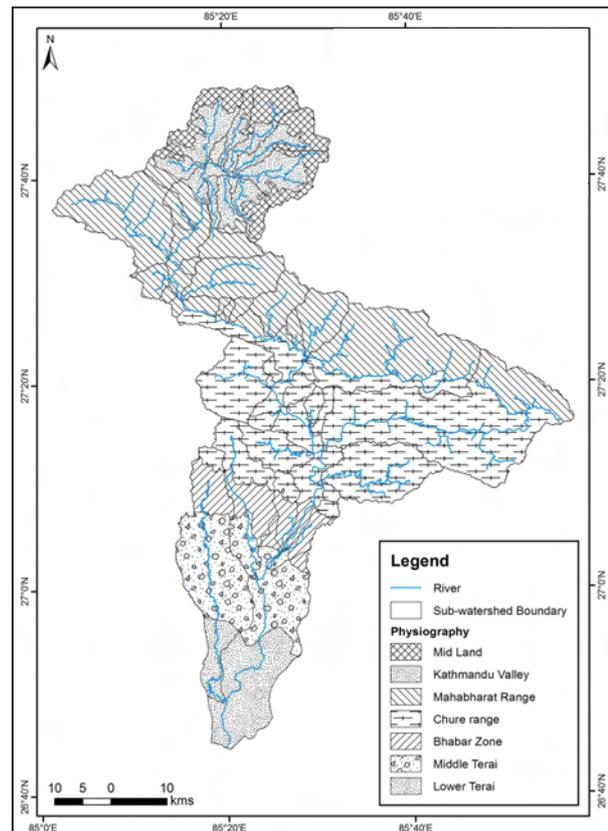


Fig. 2 Physiography of the Bagmati River Basin (based on Hagen's (1956) subdivision)

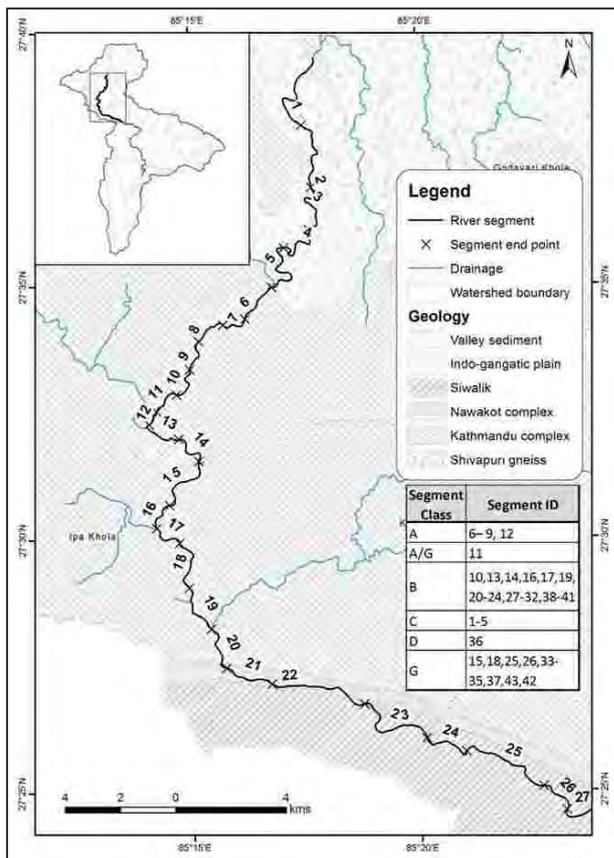
MORPHOLOGICAL CRITERIA FOR LEVEL I CLASSIFICATION

The stream system variables were utilized in the level I hierarchical inventory. This broad level classification allowed for rapid initial morphological delineation of stream types and organization of river information and amount of river types, A through G, to be determined within a basin. It also assisted in setting for condition of more detail assessment. The morphological context of the planform, profile and shape of the river provided: an indication of the general channel slope, shape (W/D ratio), channel pattern (single versus multi-thread channel), and delineation of general degree of confinement or lateral containment of the river. Level I classification was based on geomorphic features which can be interpreted from aerial photograph, satellite images, topographic maps, etc. The satellite imageries from Google Earth is very helpful for broad level stream classification as it

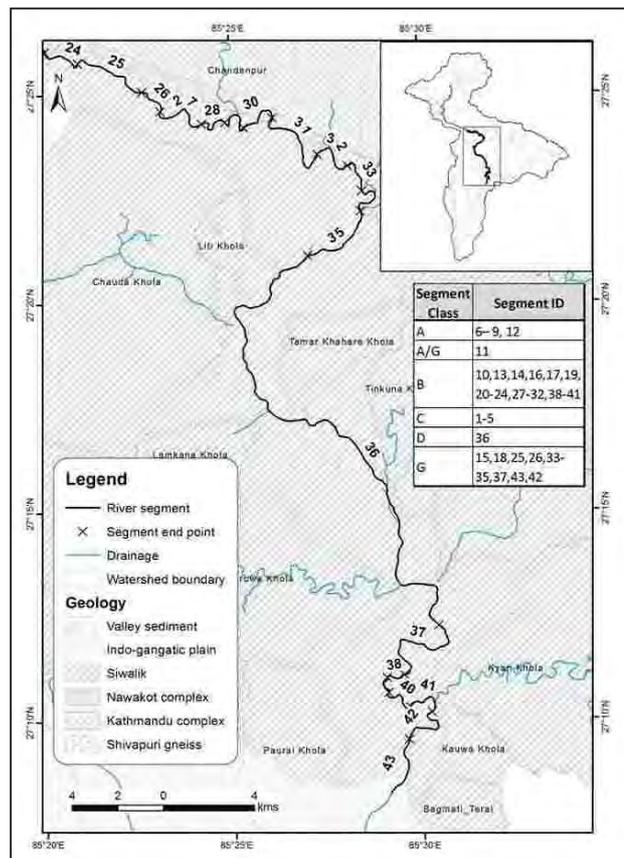
provides detail features of terrains up to about 2 m depth. Then, the information acquired from the satellite imagery and topographic maps was then analysed into the ArcGIS environment using spatial analysis tools combined with geo-processing and geostatistical tools. For this classification, the Bagmati River up to the Siwaliks was considered. Then the river corridor was fragmented into 43 segments (38 segments beyond and 5 segments within the Kathmandu Valley) considering one complete meandering cycle as one segment for single thread channel and the all the multi-thread channel was grouped into one segment (Fig. 3 a, b). The morphologic parameters required for broad level classification was measured and calculated for each segments.

Valley types

Delineation of the pertinent valley types provides a logical stratification with which to identify the



(a)



(b)

Fig. 3 Location of the river segment ID and distribution of stream types along the main stem Bagmati River: (a) Upstream portion and (b) Downstream portion continued

potential number of stream types within a broad area. The types of river valleys present at the segments along the Bagmati River course were delineated from topographic map, DEM and satellite imageries.

Stream ordering

A river basin consists of its several branches (segments) having different positions in the basin area and they have their own morphometric characteristics and, therefore it becomes necessary to locate the relative position of a segment in the basin, so that the hierarchical organization of stream can be visualized (Leopold, Wolman and Miller, 1969). In this study, the drainage order was determined using the method proposed by Strahler (1969). It may be mentioned that the hierarchical order increases only when two stream segments of equal order meet and form a junction. The stream order was computed from the digital layers acquired from the Department of Survey and by using ArcGIS software.

Plan-view morphology

Plan views of river patterns are grouped as: relatively straight ('A' stream type), low sinuosity ('B' stream type), meandering ('C' and 'F' stream types), tortuously meandering ('E' stream types), and the complex stream patterns such as braided ('D' stream types) and anastomosed ('DA' stream type).

The plan-view morphology is well attributed by various parameters: meander wavelength (L_m), meander belt width (W_{blt}), radius of curvature (R_c) and sinuosity (K). Meander wavelength (L_m) of the river is the distance between two successive crests or two successive trough of the curved channel (Fig. 4). W_{blt} is a straight line between the crest of the bend to the

crest of the next bend lying downstream, or is the distance between lines defining the confinement of the lateral boundaries of the channel.

R_c is the radius of a circle drawn through the apex of the bend and the two crossover midpoint of river, and is defined as the curved surface formed by the meandering stream channel. It is calculated by using the formula as:

$$R_c = (C^2/8M) + (M/2)$$

Where, C = Chord length between inflection points, and M = Middle ordinate distance between the curve crest and the chord. The radius of curvature relationship is used to evaluate channel resistance to erosion and a meander migration rate.

Channel sinuosity, which is the ratio of stream channel length to down-valley distance, was measured from satellite imageries, aerial photographs and topographic maps. With the exception of the large rivers, if sinuosity were computed for smaller stream systems using only topographic maps, significant underestimations would have been occurred in the process of map configuration. The channel sinuosity that is a primary indicator of types of stream is also an indication of how stream channel slope is adjusted to that of the valley slope. When it is measured accurately from aerial photographs, channel sinuosity may also be used to estimate channel slope (valley slope/sinuosity). All the planform parameters for the Bagmati River were measured and obtained from topographic map of 1:25,000 (scale) and the satellite imagery from Google Earth. The obtained values of the meander width ratio of different segments of the river are shown in Table 2.

Cross-section morphology

The broad level inventory was also based on interpretation of channel cross-section shapes that would distinguish narrow and deep streams from wide and shallow stream types. Channel systems characteristics which are important for the Level I scheme are: (a) degree of channel incision within the parent valley, (b) the location and extent of floodplains, (c) the occurrence and position of terraces, (d) the prevalence of colluvial slopes, (e) the presence of

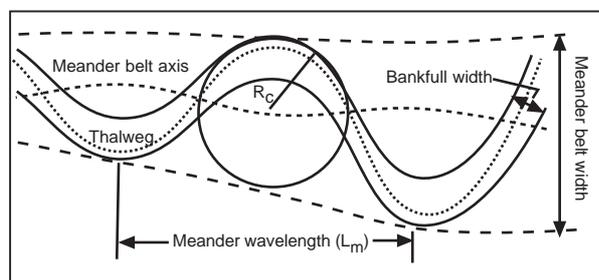


Fig. 4 Planform parameters of the river channel

Table 2: Morphological details of different segments of the Bagmati River

Segment ID	Stream order	Segment length, km	Segment length (L _m), m	W _{bit} , m	R _c , m	Sinuosity (K)*		
1	7th	3.64	1115.80	336.34	473.57	1.57	MC	
2	7th	2.76	803.68	175.49	301.51	1.21	SC	
3	7th	2.36	595.14	219.73	256.98	1.53	MC	
4	7th	2.21	1115.80	336.34	176.85	1.98	MC	
5	7th	2.94	527.67	310.22	180.97	1.9	MC	
6	7th	1.67	594.90	77.61	290.04	1.07	SC	
7	7th	1.05	556.29	148.03	174.36	1.26	SC	
8	7th	1.23	381.10	57.14	165.06	1.08	SC	
9	7th	1.25	701.86	161.25	268.91	1.15	SC	
10	7th	1.31	559.08	190.12	211.51	1.28	SC	
11	7th	1.13	393.65	70.52	166.12	1.18	SC	
12	7th	0.55	312.04	42.41	206.16	1.04	SC	
13	7th	1.56	298.27	94.74	331.11	1.31	SC	
14	7th	1.46	627.08	266.17	229.15	1.36	SC	
15	7th	2.41	633.64	161.75	231.92	1.26	SC	
16	7th	1.15	545.25	151.44	205.26	1.19	SC	
17	7th	1.22	586.57	166.48	183.61	1.24	SC	
18	7th	2.07	633.72	131.82	221.19	1.24	SC	
19	7th	1.91	654.25	104.29	288.9	1.13	SC	
20	7th	1.8	629.51	174.25	199.86	1.68	MC	
21	7th	1.84	596.37	83.49	363.56	1.06	SC	
22	7th	3.67	945.60	114.60	433.32	1.07	SC	
23	7th	3.46	469.80	85.88	479.97	1.35	SC	
24	7th	1.91	522.77	127.70	274.42	1.25	SC	
25	7th	3.5	619.26	116.20	368.99	1.14	SC	
26	7th	1.4	704.35	183.82	223.82	1.18	SC	
27	7th	2.79	494.16	162.96	193.8	1.48	SC	
28	7th	1.61	417.23	253.01	155.89	1.56	MC	
29	7th	1.91	521.31	379.38	151.67	2.27	MC	
30	7th	1.92	616.73	140.33	193.88	1.44	SC	
31	7th	4.18	701.75	177.60	255.74	1.64	MC	
32	7th	2.13	454.64	132.33	168.12	1.51	MC	
33	7th	1.6	603.53	134.59	257.4	1.25	SC	
34	7th	2.05	372.66	186.30	139.04	2.31	MC	
35	7th	3.55	634.06	88.10	409.46	1.16	SC	
36	7th		Multi-thread channel					
Mean		2.09	598.27	164.07	252.35	1.38		
Standard deviation		0.88	181.75	81.01	91.14	0.32		
37	8th	5.24	562.25	155.85	238.6	1.97	MC	
38	8th	0.88	419.17	105.85	149.6	1.14	SC	
39	8th	0.87	334.47	110.97	121.86	1.3	SC	
40	8th	1.7	390.89	158.83	128.06	1.49	SC	
41	8th	1.88	653.89	174.95	208.46	1.94	MC	
42	8th	2.86	375.52	60.09	193.52	1.82	MC	
43	8th	2.75	741.18	119.50	456.9	1.19	SC	
Mean		2.31	496.77	126.58	213.86	1.55		
Standard deviation		1.40	144.91	36.61	106.96	0.33		

*Sinuosity: MC = Meandering Channel (K>1.50), SC = Sinuous Channel (K = 1.05 to 1.50) based on Leopold and Wolman (1957)

structural control features, (f) the degree of channel confinement and entrenchment, and (g) the overall valley versus channel macro-dimensions.

The channel cross-sectional shape of all the segments of the Bagmati River was distinguished from the satellite imagery from Google Earth which had sufficient fine resolution to 2 m for this study.

Bed features

The longitudinal profile, which can be generally inferred from topographic maps, changes with channel sinuosity in the down-valley direction, and serves as the basis for delineating stream reaches into general slope categories that reflect morphology of the channel profile. Bed features are also related to channel slope, and both parameters are integral to delineation of stream types.

MORPHOLOGY AND CLASSIFICATION OF THE BAGMATI RIVER

The results of analyses of all the morphological parameters and the resulting classification of the Bagmati River are presented in Tables 2 and 3.

Stream order

The main stem Bagmati River originates from the eastern hill, Nagarkot in Kathmandu Valley within the catchment of the Hanumante River. The latter is a 6th order river that stretches for 18.30 km. It confluences with another 6th order Godawori River (channel length 16.08 km) near Balkot and forms a 7th order main stem Bagmati River. The Bagmati River that flows in the Kathmandu Valley stretches for about 51 km and comprises catchment area of about 678 square km. The 7th order main stem Bagmati River further stretches towards the south for about 50 km beyond the Kathmandu valley, through the Mahabharat Range and becomes 8th order stretch in the Sub-Himalayan zone where it further extends for about 104.18 km within the territory of Nepal. The total catchment area of the Bagmati River Basin approaches 3761 square km.

As soon as the Bagmati River drains out from the Kathmandu Valley, it starts incising the rocks of the Lesser Himalaya and flows through the Siwaliks receiving flows from several lower order drainages along its stretch. But at Sikere Dobhan, which lies in the Middle Siwalik zone, the seventh order Kokhajor Khola confluences with the Bagmati River that then

Table 3: Result of broad level classification of the Bagmati River

Segment ID	Stream order	*Entrenchment ratio	Sinuosity (K)	Geological Formation	Stream type
1	7th	ME to SE	1.57	Fluvio-lacustrine valley-fill sediment	C
2	7th	ME to SE	1.21	Fluvio-lacustrine valley-fill sediment	C
3	7th	ME to SE	1.53	Fluvio-lacustrine valley-fill sediment	C
4	7th	ME to SE	1.98	Fluvio-lacustrine valley-fill sediment	C
5	7th	ME to SE	1.90	Fluvio-lacustrine valley-fill sediment	C
6	7th	E	1.07	**Lesser Himalaya (LH): Tistung Formation	A
7	7th	E	1.26	(LH): Tistung Formation	A
8	7th	E	1.08	(LH): Tistung Formation	A
9	7th	E	1.15	(LH): Tistung Formation	A
10	7th	ME	1.28	(LH): Tistung and Markhu Formations	B
11	7th	E	1.18	(LH): Granite	A
12	7th	E	1.04	(LH): Granite	A
13	7th	ME	1.31	(LH): Granite	B
14	7th	ME	1.36	(LH): Granite + Quaternary Terrace Deposit (QTD)	B
15	7th	E	1.26	(LH): Chisapani and Kulekhani Formations	G
16	7th	ME	1.19	(LH): Kulekhani and Markhu Formations	B
17	7th	ME	1.24	(LH): Kulekhani and Markhu Formations	B
18	7th	E	1.24	(LH): Kulekhani, Chisapani and Markhu Formations	G
19	7th	ME	1.13	(LH): Kalitar, Bhainsedovan, Raduwa and Benighat Formations	B
20	7th	E/ME	1.68	LH: Benighat Slate, and Middle Siwaliks	B
21	7th	ME	1.06	Middle Siwaliks	B
22	7th	ME	1.07	Upper and Middle Siwaliks	B
23	7th	ME/SE	1.35	Upper and Middle Siwaliks	B
24	7th	ME	1.25	Upper and Middle Siwaliks	B
25	7th	ME	1.14	Upper and Middle Siwaliks	G
26	7th	ME	1.18	Upper and Middle Siwaliks	G
27	7th	E/ME	1.48	Upper and Middle Siwaliks	B
28	7th	E/ME	1.56	Upper and Middle Siwaliks	B
29	7th	E/ME	2.27	Upper and Middle Siwaliks + (LH): Benighat Slate	B
30	7th	E/ME	1.44	(LH): Benighat Slate, and Middle Siwaliks + QTD	B
31	7th	E/ME	1.64	Middle Siwaliks	B
32	7th	E/ME	1.51	Middle Siwaliks	B
33	7th	E/ME	1.25	Middle Siwaliks	G
34	7th	E	2.31	Middle, Lower and Pre-Siwaliks	G
35	7th	E	1.16	Middle Siwaliks + QTD	G
36	7th			Pre-, Lower, Middle and Upper Siwaliks	D
37	8th	SE	1.97	Middle Siwaliks	G
38	8th	ME	1.14	Middle Siwaliks	B
39	8th	E/ME	1.3	Middle Siwaliks	B
40	8th	ME	1.49	Middle Siwaliks	B
41	8th	ME	1.94	Middle Siwaliks	B
42	8th	E/ME	1.82	Middle Siwaliks	B
43	8th	E	1.19	Lower Siwaliks	G

*Entrenchment ratio: E = Entrenched, SE = Slightly entrenched, ME = Moderately entrenched
 ** LH = Lesser Himalaya

becomes the 8th order main stem Bagmati River. The River then follows the course towards the south through the rest of the Siwaliks and the Indo-Gangetic Plain.

The major tributaries contributing to the main stem Bagmati River and their highest stream orders and lengths are listed in Table 4. There are altogether thirty-nine sub-basins in the Bagmati River Basin. There are one 8th order, two 7th order, twelve 6th order, sixteen 5th order, seven 4th order, and one 2nd order sub-

basins. The length of the 8th order stream alone is 104.18 km.

Meander wavelength

Meander wavelength shows a fluctuating and slightly diminishing trend of variation from the upstream segments to the downstream segments of the Bagmati River. The average L_m of the seventh order and eighth order river segments are respectively 598.27 m

Table 4: Stream order, length, total number of sub-basin and physiography of the Bagmati River Basin

Stream order	Sub-basin name	Stream length, km	Total number of basin	Physiography
8th	Main stem Bagmati River	104.18	1	MZ, MR, S, TP
7th	Marin Khola	51.94	2	MR and S
	Kokhajor Khola	22.89		MR and S
6th	Bagmati River	20.82	12	MZ
	Hanumante River	10.24		MZ
	Bishnumati River	6.07		MZ
	Godvari River	3.43		MZ
	Balkhu Khola	6.64		MZ
	Kulekhani Khola	30.04		MR
	Ipa Khola	1.88		MR
	Khani Khola	8.14		MR
	Khani Khola 1	5.06		MR
	Kyan Khola	28.72		MR
	Chauda Khola	7.00		S
	Chiruwa Khola	13.30		S
	5th	Manahara River		21.31
Dhobi Khola		12.44	MZ	
Nakhu Khola		14.32	MZ	
Kodku Khola		10.68	MZ	
Chaimale Khola		7.39	MR	
Chandanpur Khola		13.43	MR	
Khor Bhanjyang Khola		2.49	MR	
Paurai Khola		7.73	MR	
Tinkuna Khola		5.20	MR	
Chandi Khola		37.63	TP	
Jhajh Nadi		74.38	TP	
Lamkane Khola		1.98	S	
Budhi Bagmati Bhangalo		12.72	S	
Shrighari Khola		0.18	S	
Mahadev Khola		0.69	S	
Akasedanda Khola	0.97	S		
4th	Sokan Khola	10.29	7	S
	Tamar Khahare Khola	7.51		S
	Deuta Khola	5.49		S
	Subhane Khola	3.33		S
	Bhalu Khola	3.10		S
	Liti Khola	4.63		S
2nd	Kauwa Khola	3.49	1	S
	Tukucha Khola	5.27		MZ

MZ=Midland Zone; MR= Mahabharat Range; S=Siwaliks; TP=Terai Plain

(Standard deviation (SD) = 181.75 m) and 496.77 (SD=141.91 m). There seems to be weak relationship between geological terrains and the meander wavelength. However, it is true that the portion of the seventh order river flowing over the substrate of the fluvio-lacustrine valley-fill sediment in the Kathmandu Valley possess higher meandering wavelength (the highest being 1115.80 m at segment IDs 1 and 4), and L_m suddenly increases after the Bagmati River crosses the MBT (Fig. 5a).

Meander belt width

The meandering belt width (W_{blt}) of the 7th order main stem river varies from 379.38 to 42.41 m. For the 8th order river it ranges from 174.95 to 60.01 m. Here, the highest value indicates the highest magnitude of river wandering and lowest value indicates lowest magnitude of river wandering. The averages of the W_{blt} for 7th and 8th order main stem rivers are respectively, 164.07 m (SD=181.75 m) and 126.58 m (SD=36.61 m). The meandering belt width shows a fluctuating trend along the stream (Fig. 5a).

Radius of curvature

The radius of curvature (R_c) of the seventh order main stem river varies from 479.97 to 139 m and that for the eight order river from 456.90 to 121.86 m. The averages for the 7th and the 8th order rivers are 252.35 m (SD=91.14 m) and 286.13 m (SD=36.61 m), respectively. The variation trend of the R_c indicates a fluctuating trend (Fig. 5a). However, slightly increasing values can be observed between the terrains of the Mahabharat Range and the Siwalik Range.

Sinuosity

Sinuosity refers to deviation of actual channel path from expected theoretical (straight) path. River sinuosity indicates how a river has adjusted its slope to that of its valley. The degree of sinuosity also related to channel dimensions, sediment load, stream flow, and the bed and bank materials (Rosgen, 1996). Leopold and Wolman (1957) divided river channels basically into 3 types on the basis of sinuosity index, as straight channel ($K < 1.05$), sinuous channel ($K = 1.05$ to 1.5), and meandering channel ($K > 1.5$).

The studied segments of the main stem Bagmati River have varying sinuosity showing a fluctuating trend though it shows overall increase (Fig. 5b). Out of 43 segments, 29 are sinuous channels and 13 are meandering channels. Considering the 7th order stream, about 71% are sinuous and 29% are meandering channel segments. In 8th order stream, about 57% are sinuous and 43% are meandering channels. The average sinuosity of the seventh order main stem Bagmati River is 1.38 (SD=0.32). Similarly, the average sinuosity of the eight order segment is 1.55 (SD=0.33). The eighth order Bagmati River is more sinuous than the seventh

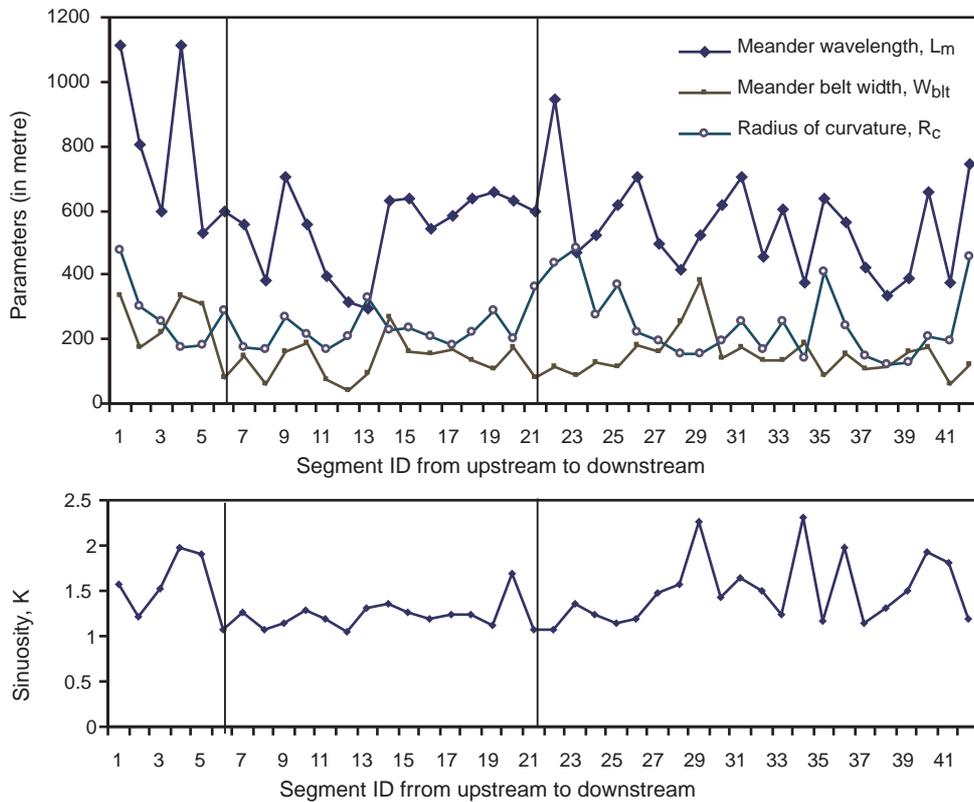


Fig. 5 Downstream variation of planform parameters: (a) Fluctuating trends of meander wavelength, meander belt width and radius of curvature, and (b) Slightly increasing trend of sinuosity though it has a fluctuating pattern.

order segment. This increase in sinuosity is attributed to the decrease in slope and competency of the river.

RELATIONSHIPS AMONG MORPHOLOGICAL PARAMETERS

The planform parameters when correlated and regressed themselves using bivariate analysis (Fig. 6), have yielded moderate degree of correlation to no correlation. The sinuosity indicates positive and extremely weak degree of correlation with meander wavelength (Fig. 6a), but moderate degree of correlation with meander belt width (Fig. 6b). There are also positive and moderate degree of relationships between meander wavelength and meander belt width (Fig. 6c), and between meander wavelength and radius of curvature (Fig. 6d). The relationships such as K versus R_c and W_{blt} versus R_c are very weak and negative (Figs. 6e and f). Therefore, among the relationships, the one of sinuosity versus meander belt width is somehow satisfactory, and suggests that when sinuosity increases meander belt width of the Bagmati River also tends to increase.

LEVEL I CLASSIFICATION

The stream segments of the Bagmati River fall on A, B, C, G and D classes. Here, all the segments of the Bagmati River, lying within the Kathmandu Valley and having substrate of the fluvio-lacustrine valley-fill sediments, fall on C-type stream. Similarly, A-type streams are developed at segments which flow through the Tistung Formation and granite terrain of the Lesser Himalaya. Likewise, B- and G-types streams are developed in terrains of the Lesser Himalaya and the Sub-Himalaya. The D-type stream segment is characteristically developed within the terrain of the Sub-Himalaya (Fig. 3 a, b).

The C-type streams are meandering with width channels compared to the depth and are less entrenched compared to A-, B-, and G-types. The B-type stream segments which are more frequent compared to the other types of stream, possess moderate entrenchment, wide channels compared to depth and are sinuous to meandered channels. The A-type streams are localized in the terrain composing metasandstones and granite of the Lesser Himalayas, and are narrow channels with

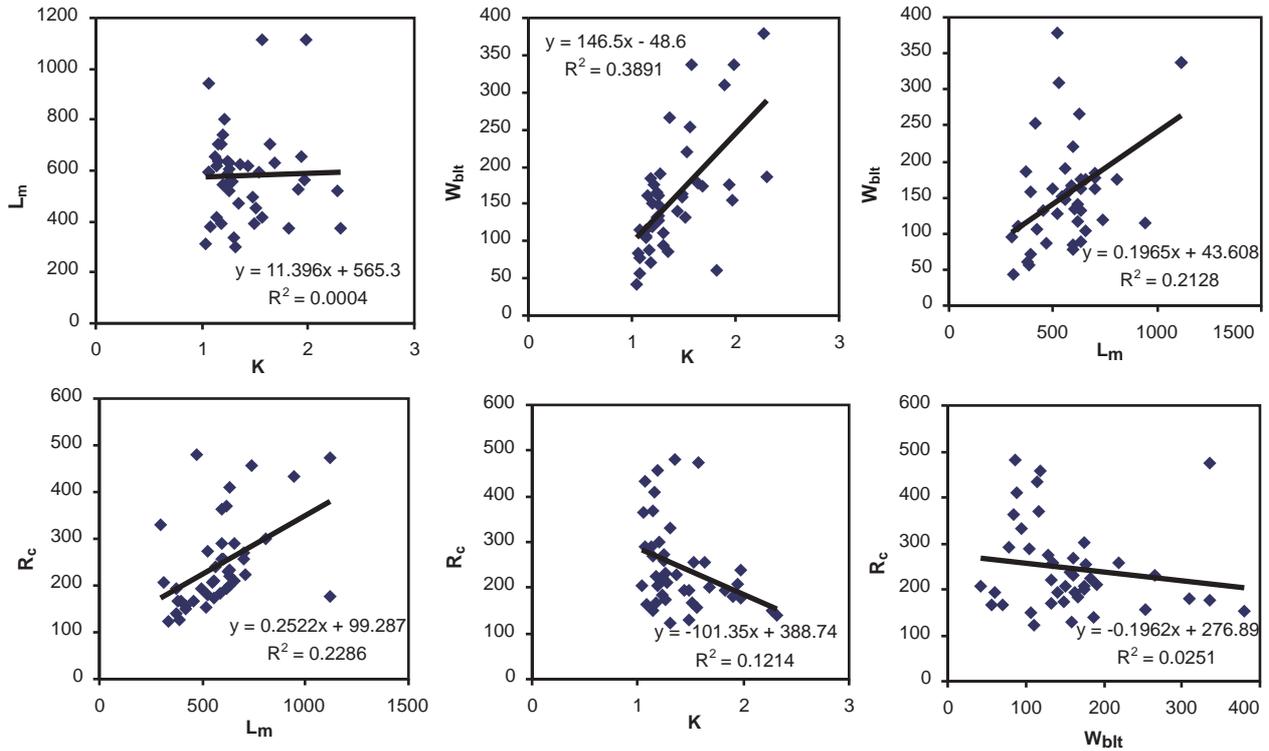


Fig. 6 Relationships between various morphological parameters: (a) K versus L_m , (b) K versus W_{bit} , (c) L_m versus W_{bit} , (d) L_m versus R_c , (e) K versus R_c , and (f) W_{bit} versus R_c . The relationships in (b), (c), and (d) are moderately positive, in (a) is almost no correlation, and in (e) and (f) are weakly negative.

greater degree of entrenchment, low width of the channel compared to the depth, low degree of sinuosity and with steeper slope compared to the rest of the stream types. The multi-thread channel, D-type stream is found in the Siwalik region, where it is influenced by large input of sediments from the south-north flowing tributaries from the relatively young loosely consolidated conglomerates of the Upper Siwaliks, and thrusting.

CONCLUSIONS

The drainage order analysis of the Bagmati River results that, the main stem Bagmati River originates from eastern hill, Nagarkot in Kathmandu Valley within the catchment of the Hanumante River. The main stem Bagmati River of the Central Nepal Himalaya is an eighth order perennial river that comprises 39 sub-basins of fourth order and higher within catchment of 3761 sq km, and stretches for about 206 km incising fluvio-lacustrine sedimentary deposits of Kathmandu Valley, Lesser Himalaya, Siwaliks and Indo-Gangetic Plain within the territory of Nepal.

The result of morphological analysis of Bagmati River reveals that meander wavelength, meander belt width and radius of curvature show fluctuating trend of variation from upstream to downstream segments along the main stem river. There seems to be weak relationship between geological terrains and morphological parameters. However, the portion of the seventh order river flowing over the substrate of the fluvio-lacustrine valley-fill sediment in the Kathmandu Valley possesses higher meandering wavelength; and slightly increasing values of radius of curvature can be observed between the terrains of the Mahabharat Range and the Siwalik Range.

The sinuosity of the main stem Bagmati River shows fluctuating trend though it shows overall increase. Out of 43 segments, 29 are determined to be sinuous channels and 13 meandering channels. The eighth order segment is more sinuous than the seventh order segments. This increase in sinuosity is attributed to the decrease in slope and competency of the river as it emerges out from the Mahabharat Range to the Sub-Himalayan (Siwalik) Range.

The stream segments of the Bagmati River fall on A-, B-, C-, G- and D-type categories. The segments of the main stem Bagmati River flowing over the substrate of the fluvio-lacustrine valley-fill sediment in the Kathmandu belong to C-type stream. A-type streams are developed at segments which flow through the Tistung Formation and granite terrains of the Lesser Himalaya (Mahabharat Range). Likewise, B- and G-type streams are developed in terrains of the Lesser Himalaya and the Sub-Himalaya. D-type stream segment is characteristically developed within the terrain of the Sub-Himalaya (Siwaliks).

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