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Morphometry and geomorphic development of the Bagmati River Basin, Nepal Himalaya

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ABSTRACT

Morphometric analysis of a watershed provides a quantitative description of the drainage system which is an important aspect of characterization of watershed. The analysis requires measurement of linear features, aerial aspects, gradient of channel network and contributing ground slopes of the drainage basin. The morphometric characteristics at the watershed-scale may contain important information regarding its formation and development because all hydrologic and geomorphic processes occur within the watershed. In this study morphometric property of the Bagmati River Basin (BRB) was investigated using different morphometric attributes and hypsometric analysis in order to investigate geomorphic development of the river basin, in an active tectonic zone. DEM has been prepared from the contour and spot height data using digital topographic maps of 1:25000-scale acquired from the Department of Survey, Nepal. The main stem Bagmati River is the eighth order perennial river that stretches for 206 km with an elongated catchment of area 3761 sq km. It consists of 39 sub-basins of fourth order and higher. The study shows that the drainage system of the BRB is attaining a mature stage from a youth stage from lower order streams to the higher order streams in geomorphic development process. Some exceptions occurred at higher order stream segments, where drainage development seems to control by structure and lithology. According to the analytical results, erosional stage and level of tectonic activity of sub-basins differ from each other. Generally, the lithology and geological structure seems to control the drainage texture and relief of the BRB. The river system within the Kathmandu Valley is attaining maturity having meandering channels with wide flood plains, whereas rivers of the Lesser Himalaya and the Siwaliks are at youth stage with erosional potential. The downstream part of higher order stream segments are in mature stage having potential for lateral erosion and meander migration. Therefore, the Bagmati River stretch, especially the eight order one poses vulnerability to bank erosion.

Key words: Bagmati River Basin, geomorphology, morphometry, hypsometry, river dynamics, GIS

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INTRODUCTION

Morphometric analysis of a watershed provides a quantitative description of the drainage system which is an important aspect of the characterization of watershed (Strahler 1964). The analysis requires measurement of linear features, aerial aspects, gradient of channel network and contributing ground slopes of the drainage basin (Nautiyal 1994). Pioneering work on the drainage basin morphometry has been carried out by Horton (1932, 1945), Miller (1953), Smith (1950), Strahler (1964) and others. Geomorphic development of streams within watershed is characterized by evolutionary changes in the landform geometry with different cycle of erosion. Hence streams within a watersheds generally follow the sequential changes in landforms through youth (higher energy landforms; fairly straight channel and steep gradient, flows in V-shaped valley, in highland or mountainous area, high velocity and actively lowering its channel through down cutting in order to reach base level), mature (medium energy landforms; has a moderate gradient and velocity, has eroded its bed downward and is closer to base level, has slowed down velocity and the stream begins to meander. While it is still eroding downward carving out a valley floor between valley walls, the stream will flood all or a part of its valley, depositing alluvium on its developing floodplain) and old (low but equal energy landforms; nearly reached its base level, gradient and velocity are very low, has lost its ability to erode downward, it deposits as much material as it erodes, meanders greatly in its nearly flat valley, has a wide, well-developed floodplain marked with oxbow lakes) as classified by Davis (Chorley et al. 1985).

The Bagmati River Basin (BRB) of Nepal Himalaya lies between 26°42’ and 27°50’ north latitude, and 82°02’

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and 85°58' east longitude. It covers an area of 3761square kilometers. It is a perennial river fed by storm and springs. The BRB extends from the north towards the south for 206 km (Fig. 1). It has a centripetal drainage pattern in the Kathmandu Valley (Bajracharya 1991; 1992), and exhibits dendritic to sub parallel drainage patterns further downstream. The river basin has been analyzed through different morphometric parameters for finding out basin geomorphic development and contribution of such morphometric parameters to understand main stem river dynamism.

PHYSIOGRAPHIC SUBDIVISIONS

The BRB can broadly be divided into four morpho-tectonic units: Terai Plain, Chure Range, Mahabharat Range, and Midlands, from the south to the north (Hagen 1969). The Terai Plain (with altitude 75-150 m) is a depositional landform characterized mainly by floodplains and river terraces. The Chure Range rises abruptly from the Terai Plain up to an altitude of about 1000 m and displays a very rugged topography with dissected gullies and steep slopes. The Mahabharat Range displays a rather youthful topography characterized by towering hills, deep gorges, and rugged landforms. The Midlands (altitude 1000-3000 m) are characterized by comparatively a matured topography consisting of subdued hills, wide river valleys, and tectonic basin (Kathmandu Valley in the BRB). Climate of BRB can be divided into three regions: tropical, warm and cool temperate, extending from the south to the north of the basin. The monsoon rainfall in the BRB is mainly concentrated between the months of June to September. The annual average rainfall in BRB and the adjacent area is 1800 mm, whereas the monsoon average rainfall is 1500 mm (calculated from rainfall gauging stations data from 1983 to 2010).

GEOLOGY AND TECTONICS

The BRB broadly covers four major laterally continuous and approximately parallel tectonic zones. Geologically, BRB consists of the Indo-Gangetic Plain (Terai), the Siwaliks, the Nawakot Complex and the Kathmandu Complex (Fig. 2). The Indo-Gangetic Plain (Terai) consists of Pleistocene to Recent alluvium deposited by the rivers originating within the Himalayas or beyond. The Middle Miocene to Early Pleistocene Siwaliks consists of an alternation of mudstone, sandstone, and conglomerate at varying proportions and textures. The Late Precambrian to the Paleozoic Nawakot Complex consists almost exclusively of low grade

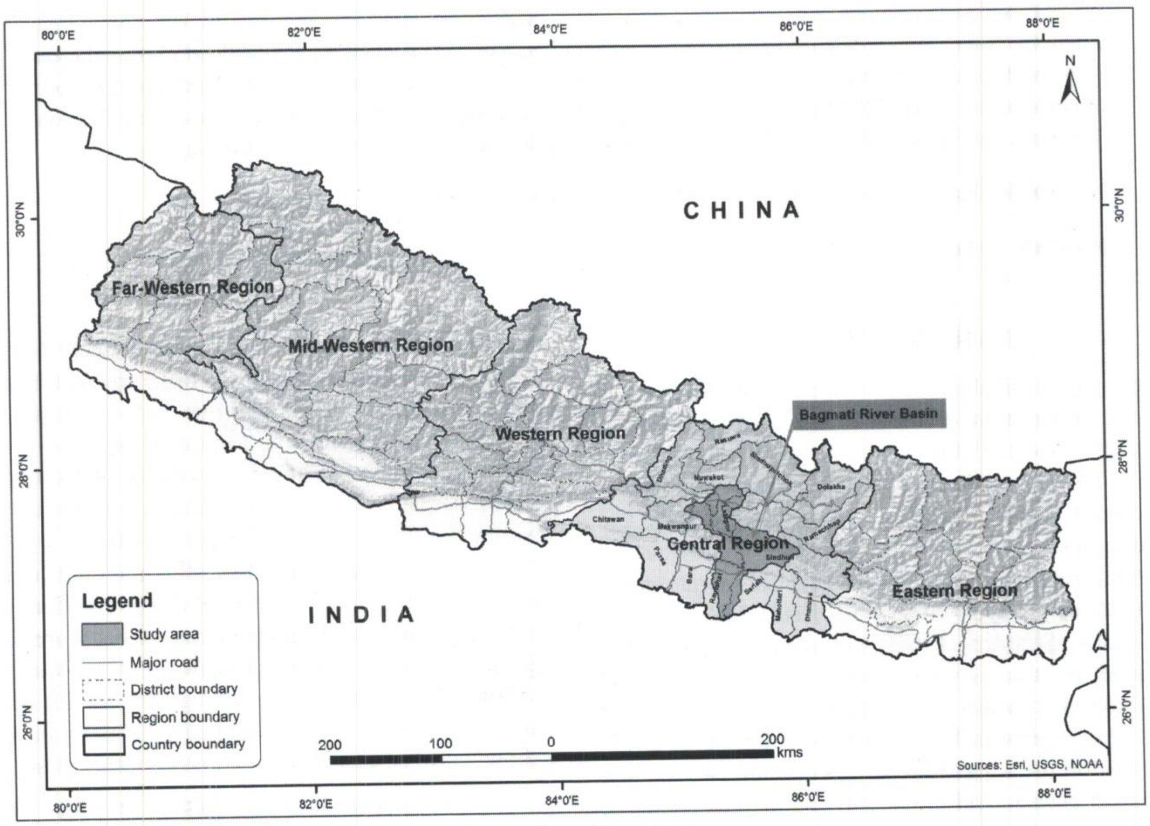

Fig. 1: Location of the study area.

metasediments. The characteristic rocks are slate, phyllite, quartzite, limestone, and dolomite. The Precambrian to Devonian Kathmandu Complex consists of low- grade metasediments to high-grade metamorphic rocks, i.e., slate, phyllite, schist, gneiss, sandstone, quartzite, limestone, and marble (Stocklin and Bhattarai 1981; Stocklin 1980). The Main Frontal Thrust (MFT), the Main Boundary Thrust (MBT), and the Main Central Thrust (MCT), respectively, separate the Terai from the Siwaliks, the Siwaliks from Nawakot Complex, and the Nawakot Complex from the Kathmandu Complex. Besides these major Himalayan Thrusts, the rocks of BRB have been cut by several parallel and transverse thrusts and faults developed as an archive of the Himalayan uplift (DMG 1987; Adhikary and Rimal 1996). The Kathmandu Valley comprises the Pliocene to the Recent fluvio-lacustrine sediments (Yoshida and Igarashi 1984), which are resting over the basement rocks of the Phulchoki and the Bhimphedi Groups, which occupy the large core of the Mahabharat synclinorium (Stocklin and Bhattarai 1977). The fluvio-lacustrine sediments are divided into two series, the Quaternary unconsolidated sediments and the Pleo-Pleistocene slightly consolidated sediments (DMG

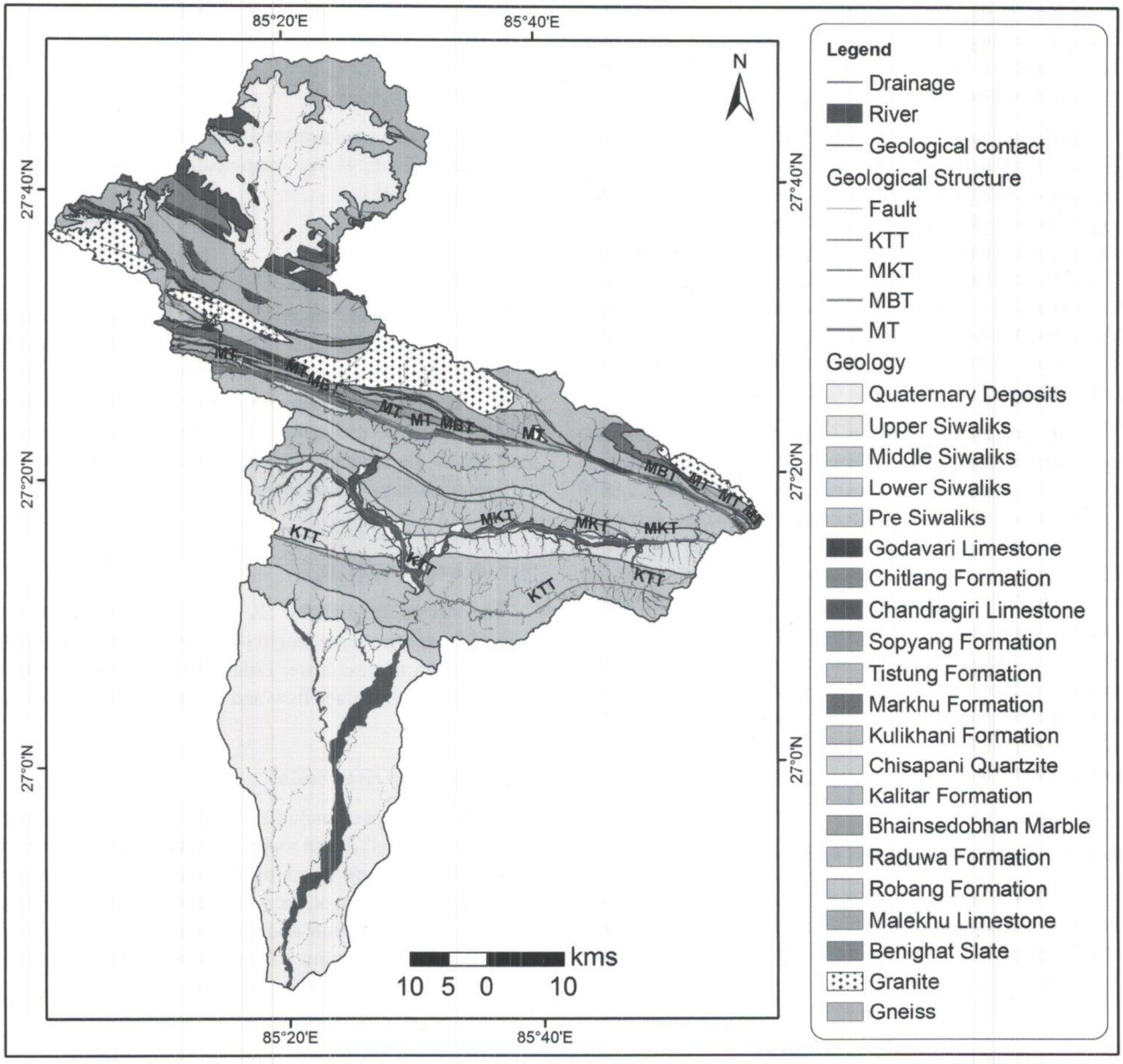

Fig. 2: Geological map the Bagmati River Basin (compiled from Stöcklin and Bhattarai 1981; Stöcklin 1980)

1998). The Quaternary unconsolidated sediments comprise clay, silt, sand, gravel and boulder layers. Similarly, Pleo-Pleistocene sediments are composed of layers of clay, silt, sand, gravel, boulders and lignites.

MATERIALS AND METHODS

Morphometric studies involve evaluation of streams through the measurement of various stream properties. Analysis of various drainage parameters namely ordering of the various streams and measurement of length of drainage channels, number of streams, bifurcation ratio, basin area, perimeter of basin, length of drainage channels, drainage texture, circulatory ratio, elongation ratio, form factor, relative relief, relief ratio, hypsometric curve and hypsometric integral values, etc..

A Digital Elevation Model (DEM) was used to calculate spatial variables in GIS environment in this study. The DEM was prepared from the contour and the spot height data using digital topographic maps of 1:25000 scale. In total thirty nine topographic sheets have been used. The preparation of DEM from the acquired topographic sheets includes i) conversion of contours polyline into point data merged with spot height point data to minimize the error in DEM at flat terrain, and ii) creation of the DEM by interpolating the merged height data with 20 m cell size using spatial analysis tool.

The processes used to extract the morphometric parameters from DEM was based on the tools available in the ArcGIS environment, in particular ArcHydro and Spatial analyst tools was used to generate the stream networks, stream order and delineation of watershed boundary. Geoprocessing and geostatistical tools were used for calculating other morphometric parameters, such as; stream number, mean stream length, stream length ratio, bifurcation ratio, form factor, circularity ratio, elongation ratio, drainage texture, relative relief, relief ratio, hypsometric curve and hypsometric integral. All of these morphometric variables were computed using standard methods and formulae presented in Table 1.

Linear aspect of the channel system

The linear aspect includes the stream order (u), stream number (Ln), stream length (L_u), bifurcation ratio (R_b), mean stream length (L_{sm}) and stream length ratio (RL) of stream segments.

Stream order (u)

The designation of stream order is the first step in drainage basin analysis. It expresses the hierarchical relationship between stream segments, their connectivity and discharge arising from contributing catchments (Leopold, Wolmen and Miller 1969). In present study, the stream ordering has been carried out using widely accepted method for stream ordering developed by Strahler (1964).

Bifurcation ratio (R_b)

The bifurcation ratio is an index of relief and dissection (Horton 1945; Schumm 1956), and was calculated from the ratio of the number of stream segments of given order to the number of segments of next higher order.

Stream length (L_u)

Stream length was measured from the mouth of a river to the drainage divide. It was computed based on the Horton's Law (Horton 1945).

Mean stream length (L_{sm})

The law of stream length states that: "the average length of the streams of each order of the stream in a basin closely approximate a direct geometric series in which the first term is the average length of streams of the first order" (Strahler 1964). The mean stream length (L_{sm}) was calculated from the ratio of the total stream length of a given order to the number of streams of that order.

Stream length ratio (R_L)

The stream length ratio (R_L) was calculated from the ratio of the mean stream length of a given order to the mean stream length of next lower order . It possessed important relationship with surface flow and discharge (Horton 1945).

Aerial aspect of river basin

The aerial aspect includes the discussion of drainage texture, basin length, basin shape, elongation ratio, circularity ratio, form factor and length of overland flow. Basin area is hydrologically important because it directly affects the size of the storm hydrograph and the magnitudes of peak and mean runoff. The maximum flood discharge per unit area is inversely related to size (Chorley et. al. 1957).

Drainage texture (Dt)

The drainage texture shows the relative spacing of

Table 1: Methodology adopted for the computation of morphometric parameters.

S.N.	Morphometric Parameters	Formula/Definition	Reference
I	**Aerial Aspect of the Basin**		
1	Stream Order (μ)	Hierarchical Rank	Strahler (1964)
2	Bifurcation Ratio (R_b)	$R_b = \frac{N_\mu}{N_{\mu+1}}$ Where N_μ = number of streams of a given order $N_{\mu+1}$ = number of stream of the next higher order	Schumn (1956)
3	Stream Number (N_μ)	$N_\mu = R_b^{(K-\mu)}$ Where, N_μ = number of stream segment of a given order R_b = constant bifurcation ratio μ = basin order K = highest order of the basin	Horton (1945)
4	Stream Length (L_μ)	Length of the stream	Horton (1945)
5	Mean Stream Length (L_{sm})	$L_{sm} = \frac{L_\mu}{N_\mu}$ Where, Lμ = total stream length of order μ Nμ = total number of stream segment of order μ	Strahler (1964)
6	Length Ratio (R_L)	$R_L = \frac{L_\mu}{L_{\mu-1}}$ Where, L_μ = cumulative mean length of the given order	Horton (1945)
7	Length of Overland Flow (L_g)	$L_g = \frac{1}{D_d - 1}$ Where, D_d= drainage density	Horton (1945)
II	**Aerial Aspects of the Basin**		
8	Form Factor (R_f)	$R_f = \frac{A}{L_b^2}$ Where, R_f = form factor indicating elongation of the basin shape A= area of the basin L_b^2 = maximum basin length	Horton, (1932)
9	Circularity Ratio (R_c)	$R_c = \frac{4\pi A}{\rho^2}$ Where, A = area of the basin Π = 3.14 ρ = perimeter of the basin	Miller (1953)
10	Elongation Ratio (R_e)	$R_e = \frac{2\sqrt{A/\pi}}{L_b}$ Where, A = area of the basin L_b = maximum basin length Π = 3.14	Schumm (1956)
11	Drainage Texture (D_t)	$D_t = \frac{1}{(t+\rho)/2}$ Where, D_t= drainage texture	Singh (1998)
III	**Relief Aspects of the Basin**		
12	Relative relief (R_R)	Difference between the highest and the lowest points (height) in a unit area	Singh (1998)
13	Relief Ratio (R_h)	$R_h = \frac{R_R}{L_b}$ Where, R_R = total relief (relative relief) of basin L_b = maximum basin length	Schumn (1956)
14	Hypsometric Curve (HC)	Curve represents the relative proportions of a basin area that lies below a given height	Hurtrez et. al. (1999);
15	Hypsometric Integrals (HI)	$HI = \frac{Elev_{mean} - Elev_{min}}{Elev_{max} - Elev_{min}}$ Where, $Elev_{mean}$= weighted mean elevation $Elev_{max}$= maximum elevation $Elev_{min}$= minimum elevation	Pike and Wilson (1971)

drainage lines (Horton 1945). The drainage texture of BRB was derived according to method proposed by Singh (1998). Here drainage texture on regional scale was calculated by dividing the basin into grid squares. Spatial distribution of Dt was revealed through generation of isopleths with Dt category- extremely coarse, very coarse, coarse, moderate, fine, very fine drainage textures.

Form factor (R_f)

The form factor, which is a qualitative expression of drainage outline, was computed from the ratio of basin area to square of the basin length.

Circularity ratio (R_c)

The circularity ratio expresses the degree of circularity of basin, and was calculated from the ratio of the basin area to the area of a circle having the same circumference perimeter as the basin.

Elongation ratio (R_e)

Elongation ratio was computed from the ratio of diameter of a circle of the same area as the drainage basin and the maximum length of the basin according to Schumn (1956).

Relief aspect of river basin

The relief aspect of the drainage basins are related to the study of three dimensional features of the basins involving area, volume and altitude of vertical dimension of landforms wherein different morphometric methods are used to analyze terrain characteristics, which are the result of basin processes. Thus relief aspect includes the analysis of relationships between area and altitude, altitude and slope angle, average ground slope through relative relief and relief ratio.

Relative relief (R_R)

Relative relief is the difference between highest and lowest points (heights) in a unit area (Singh 1998). RR is used for overall assessment of degree of dissection. The relative relief of the river basin was calculated by grid square method, and were classified after (Singh 1998) into categories as:- extremely low (0-15 m), moderately low (15-30 m), low (30-60 m), moderate (60-120 m), high (120-240 m), moderately high (240-480 m), very high (480-860 m) and extremely high (>860 m) RR.

Relief ratio (R_h)

Relief ratio was calculated after Schumn (1956) from the ratio of the maximum relief to horizontal distance along the longest dimension of the basin parallel to the principle drainage line. Relief ratio measures overall steepness of a drainage basin and is an indicator of the intensity of erosion processes operating on the slopes of the basin. Relief ratio has direct relationship between the relief and channel gradient.

Hypsometric analysis

Hypsometry is the graphical representation of the area/elevation function of a drainage basin or the integral of a basin's surface area with respect to its elevation (Langbein 1947; Strahler 1952). Hypsometric analysis aims at developing a relationship between horizontal cross-sectional area of the watershed and its elevation in a dimensionless form that permits comparison of watersheds irrespective of scale issue (Dowing et al. 1998). A hypsometric curve (an S-shaped line graph) and a hypsometric integral (a value) are important indicators of watershed conditions and are watershed health indicators (Ritter et al. 2002). Awasthi et al. (2002) studied hypsometric curves and integrals to explain the watershed health of two watersheds in Nepal and revealed that the watershed had undergone through sever erosion during the past and are susceptible to surface erosion and soil degradation.

Hypsometric curve (HC)

The hypsometric curve is related to the volume of the soil mass in the basin and the amount of erosion that had occurred in a basin against the remaining mass (Hurtrez et al. 1999). It is a continuous function of non-dimensional distribution of relative elevations with the relative area of drainage basin (Strahler 1952). Strahler (1952) interpreted the shape of the hypsometric curves by analyzing numerous drainage basins and classified the basins as young (convex upward curves), mature (S-shaped hypsometric curves) and old (concave upward curves). Shapes of these hypsometric curves describe the stage of the landscape evolution, which also provide indication of erosion status of the watershed. There is frequent variation in the shape of the hypsometric curve during the early geomorphic stages of development followed by minimal variation after the watershed attains a stabilized or mature stage (Singh and Sarangi 2008). The hypsometric curves which have been used to infer the stage of development of the drainage network are also powerful tools to differentiate between tectonically active and inactive areas (Keller and Pinter 1996).

Hypsometric curve of the BRB was obtained by plotting the relative area along the abscissa and relative elevation along the ordinate. The relative area is obtained as a ratio of the area above a particular contour (a) to the total area (A) of the watershed encompassing the outlet. Similarly, the relative elevation is calculated as the ratio of the height of a given contour (h) from the base plane to the maximum basin elevation (H) (up to the remote point of the watershed from the outlet).

Hypsometric Integral (HI)

The hypsometric integral is an indication of 'cycle of erosion' (Strahler 1952). The 'cycle of erosion is defined as the total time required for reduction of a land topological unit to the base level, i.e., the lowest level. This entire period or the 'cycle of erosion' can be divided into three stages viz. monandnock (old) (HI $\leq$0.3), in which the watershed is fully stabilized; mature or equilibrium (HI <0.3-0.6>), in which

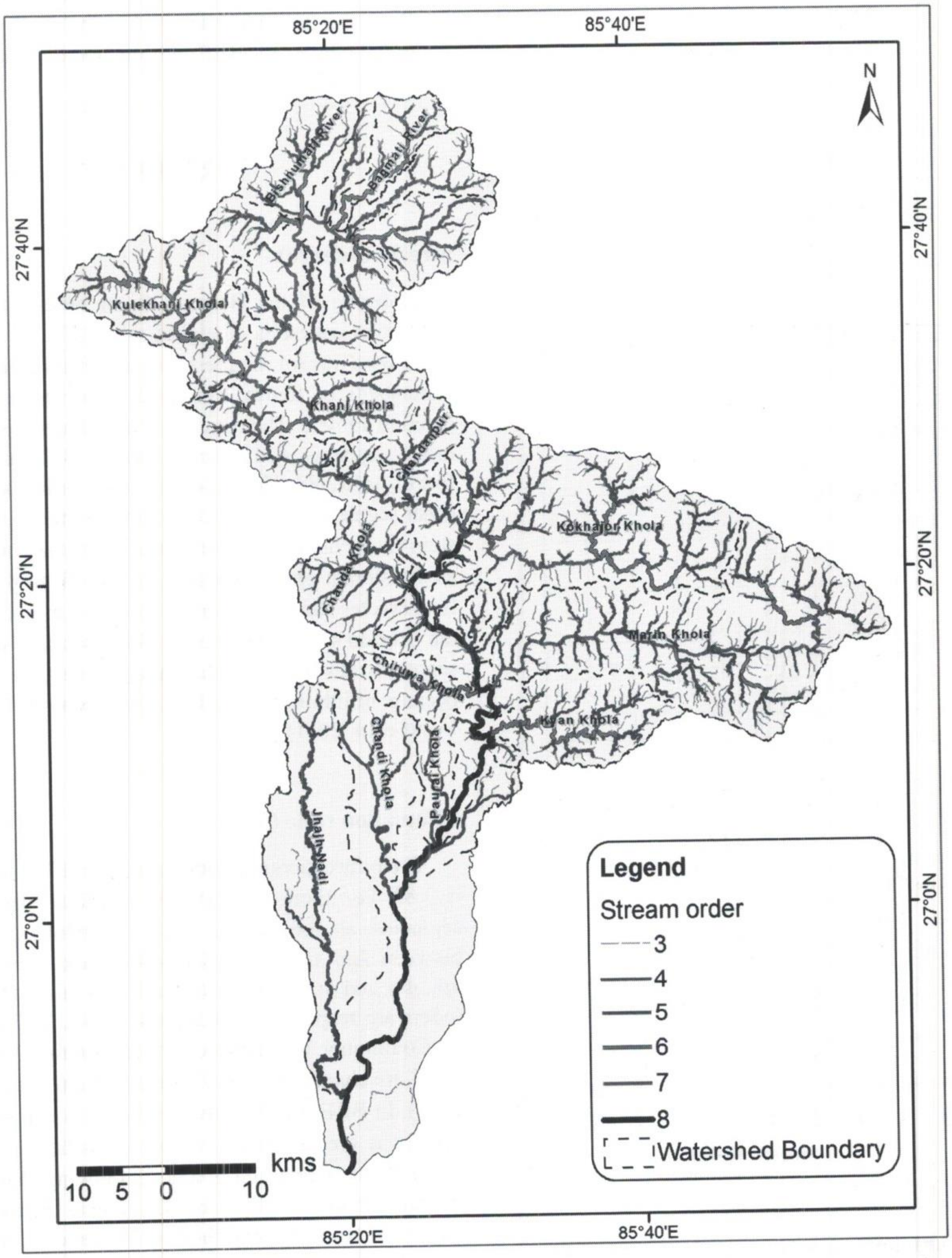

Fig. 3: Map showing drainage order of the BRB (first and second order streams are removed for clarity of map view).

Table 2: Order wise stream number and bifurcation ratio between different orders of the BRB

Stream Order (u)	Stream Number	Bifurcation Ratio (R_b)
First	23726	
Second	6219	3.82
Third	1462	4.25
Fourth	335	4.36
Fifth	88	3.81
Sixth	20	4.40
Seventh	3	6.67
Eighth	1	3.00
Total/Mean	31854	4.33

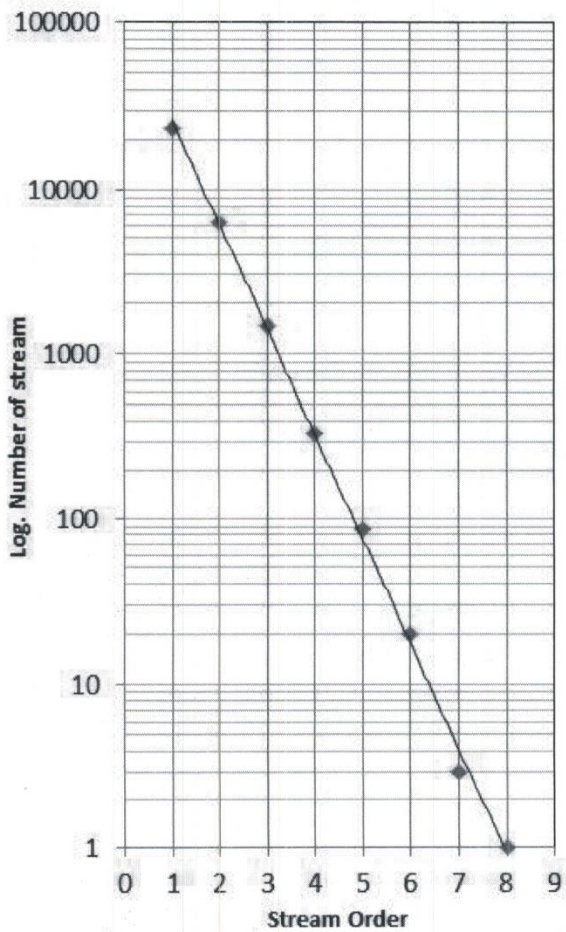

Fig. 4: Log numbers of stream versus stream order.

the watershed is in a steady state; and inequilibrium or young stage (HI ≥0.6), in which the watershed is highly susceptible to erosion (Strahler 1952). The hypsometric integral helps in explaining the erosion that had taken place in the watershed during the geological time scale due to hydrologic process and land degradation factors (Bishop et al. 2002). Besides, it also provides a simple morphological index with respect to relative height of the elevation distribution within the area considered, which can be used in surface runoff and sediment yield prediction from watershed (Sarangi and Bhattacharya 2000). The hypsometric integral of the BRB was generated using the elevation-relief ratio method as proposed by Pike and Wilson (1971).

RESULTS

Stream order (u)

Ordering of the Bagmati River reveals that the main stem river course is of eighth order (Fig. 3, Table 2). The order wise stream numbers and length including of 39 sub-watersheds of fourth order and higher were counted and listed in Table 2. The result indicates that there is 31854 first order segments, 6219 second order, 1462 third order, 335 fourth order, 88 fifth order, 20 sixth order, and 3 seventh order segments that contribute to form the eighth order main stem river course. The number of stream segment decreases as the stream order increases, as seen from the Fig. 4, and is characteristic of a normal basin, as in accordance with the Horton's Law (Horton 1945). But the seventh order segments deviate from the straight line (Fig. 4), probably because of lithological and structural controls (Horton 1945; Yusuf et al. 2011).

Bifurcation ratio (R_b)

The bifurcation ratio between 1st and 2nd order segment is 3.82, i.e., there are just 3.82 times as many first order segments as the second order segments. Similarly, Rb between 2nd and 3rd order is 4.25 and between 3rd and 4th, 4th and 5th, 5th and 6th, 6th and 7th, and 7th and 8th orders are respectively, 4.36, 3.81, 4.40, 6.67 and 3 (Table 2). Commonly, the values of bifurcation ratio fall between 3 and 5 are characteristics of natural stream systems (Strahler 1975). In BRB, the R_b between the sixth and seventh order streams is greater than 5, whereas this ratio for the rest of the streams is between 3 and 5, showing that the former streams are structurally controlled due to recent tectonics in the Lesser Himalaya and the Siwaliks, and the latter streams lie within the natural stream system.

Stream length (L_u)

The drainage network of BRB shows that the total length of stream segments is maximum in the first order stream, and decreases with increased stream order (Table 3). Longer lengths of stream are generally indicative of flatter gradients. This suggests that the drainage network in the study area is being developed as in normal river basins.

Mean stream length (L_{sm})

The L_{sm} value of BRB progressively increases form the first order (0.25) to the eighth order streams (104.18) (Table 3). The relationship of log value of stream length and stream order plot gives a straight line (Fig. 5), which indicates that the drainage network of BRB is developed as in normal river basins.

Stream length ratio (R_L)

The stream length ratio between different orders is approximately constant with variable trend of values (i.e., R_L value changes from one order to another) for present drainage system (Table 3). This fact indicates that the drainage system is at late youth to mature stage of geomorphic development (Singh and Singh 1997).

Drainage texture (D_t)

The spatial distribution of drainage texture of BRB ranges from extremely coarse to fine D_t (Fig. 6). Extremely coarse drainage texture is broadly distributed at unconsolidated sedimentary deposit at center of the Kathmandu Valley, and at the Indo-Gangetic Plain. Very coarse to coarse Dt distributes at upper parts of the Indo-Gangetic Plain and at lower part of the Siwaliks presumably due to good permeability of sub-surface material. Likewise, moderate to fine D_t distributes at terrains surrounding the Kathmandu Valley, the Lesser Himalayas and at the Siwaliks. Such distribution pattern of drainage texture suggests that the drainage development in BRB seems to governed by lithology and structure of the area (Fig. 7). Because extremely coarse to coarse D_t broadly concentrate at areas with soft and unconsolidated sedimentary deposits at the center of Kathmandu Valley and at the Terai Plain having low drainage density and frequency. Coarse D_t is present at areas just uphill sides of very coarse D_t and as patches at flood plains along the main steam rivers. Moderate to low D_t is present at formations having indurated rocks of the Lesser Himalaya and the Siwaliks.

Table 3: Stream length, mean stream length and stream length ratio between different orders of the BRB.

Stream Order (u)	Stream Length (km)	Mean Stream Length (L_{sm}); km	Stream Length Ratio (R_L)
First	6008.40	0.25	
Second	2726.92	0.44	0.45
Third	1467.54	1.00	0.54
Fourth	790.53	2.36	0.54
Fifth	508.59	5.78	0.64
Sixth	201.10	10.06	0.40
Seventh	155.88	51.96	0.78
Eighth	104.18	104.18	0.67
Average Length Ratio			0.57

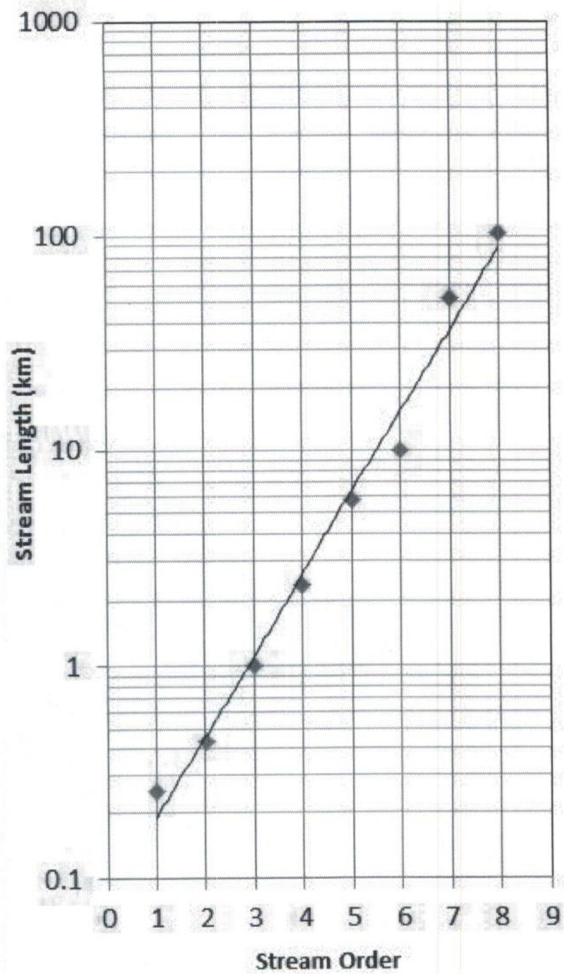

Fig. 5: Mean stream length versus stream order.

Form factor (R_f)

The form factor (R_f) value in BRB ranges from 0 to 1. The value of 0 indicates a highly elongated shape with flatter peak flows for longer duration and 1 indicates a perfect circular shape with high peak flows for short duration (Horton 1932). The Bagmati River Basin covering 3761 sq km area with basin length of 156.4 km achieves form factor value of 0.15 reveals that the river basin is highly elongated with flatter peak flows for longer duration. Hence, flood flows in such basin are easier to manage than circular basin (Christopher et al. 2010).

Circularity ratio (R_c)

The circularity ratio (R_c) values ranges from 0 (a line) to 1 (a circle). R_c indicates the tendency of small drainage basin in homogenous geologic material to preserve geometrical similarity (Miller 1953). Rc is also influences by length and

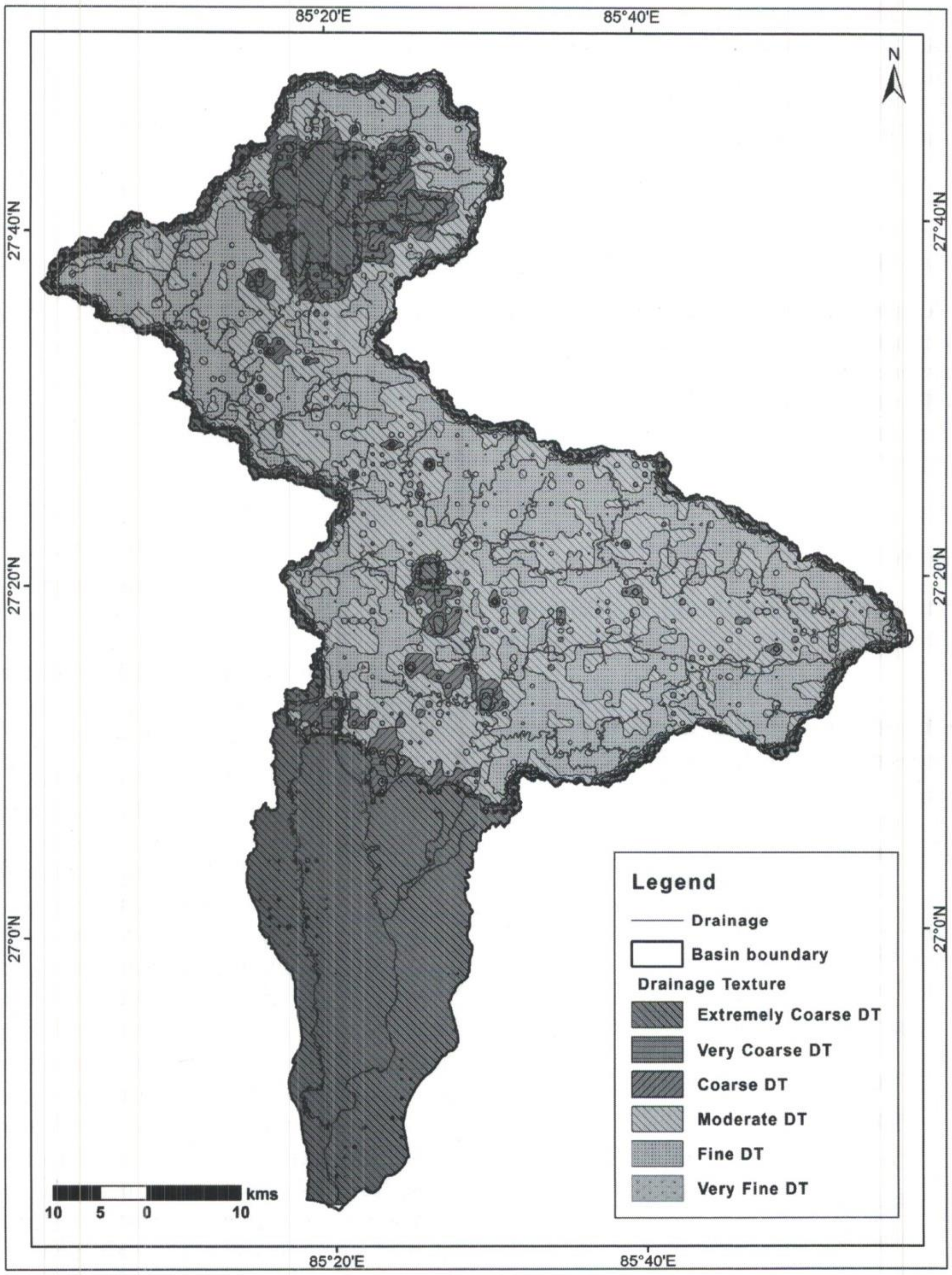

Fig. 6: Isopleths map showing spatial distribution of drainage texture in BRB.

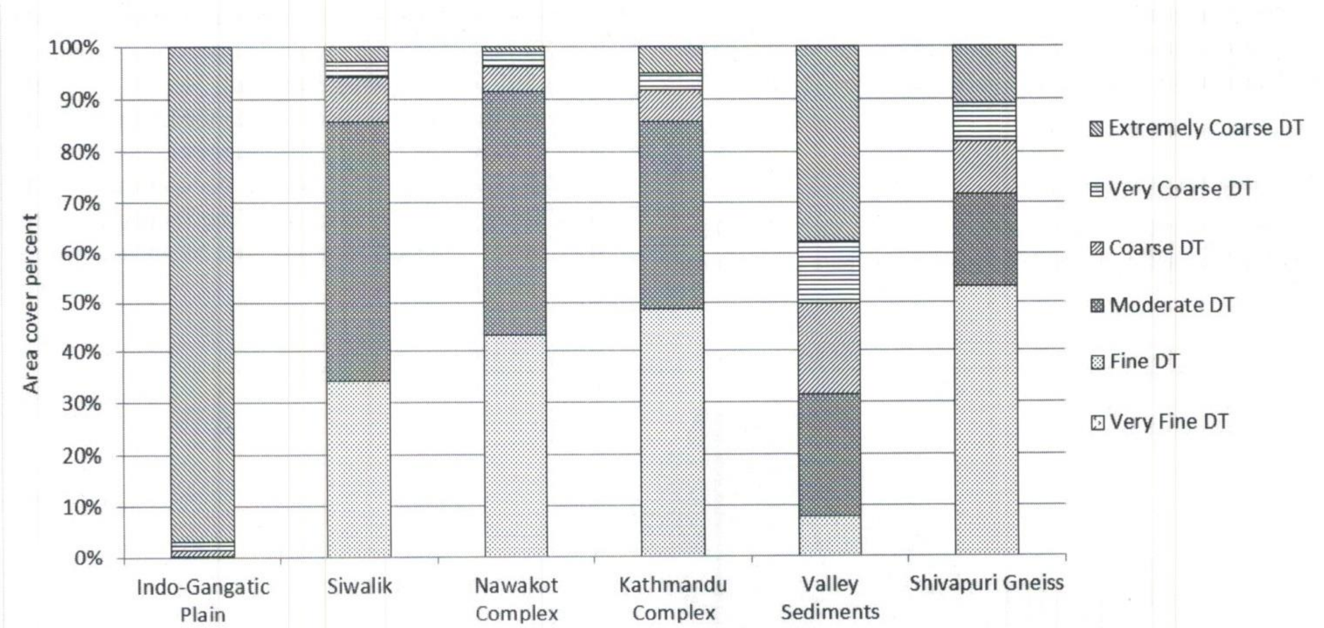

Fig. 7: Bar diagram showing drainage texture distribution with respect to geological terrains.

frequency of streams, geological structure, land use / land cover, climate and shape of basin (Javed et. al. 2009). The higher the value of Rc, the more circular shape of the basin and vice versa (Miller 1953). The R_c value of the BRB is 0.18 having area of 3761sq km and perimeter 510 km indicates that the basin is strongly elongated in shape.

Elongation ratio (R_e)

The Re values generally ranges between 0.6 and 1.0 over a wide variety of climate and geological types. Values near to 1.0 are the characteristics of the region of very low relief, while values range of 0.6 to 0.8 usually occur in the areas of high relief and steep ground slope (Strahler 1964). Circular basins appear more efficient in the discharge of run-off than that of elongated basins (Singh and Singh 1997). The elongation ratio of BRB is 0.22 resulting the basin is highly elongated having high relief and steep slope.

Relative relief (R_R)

The spatial variation of relative relief (RR) in the BRB is revealed through generation of isopleth map from DEM (Fig. 8). The R_R of the BRB ranges from 57.53 to 310.16 which reveal that the land surface has gentle to very steep slope. The extremely low R_R is broadly distributed at the center part of the Kathmandu Valley and at the Indo-Gangetic Plain where soft and unconsolidated sedimentary deposits present. Moderately low and low R_R respectively surrounds center of the Kathmandu Valley and upper part of Indo-Gangetic Plain. Similarly, moderate R_R is distributed at outer margin of sedimentary deposits of the Kathmandu Valley, upper part of Indo-Gangetic Plain, and is broadly distributed at the upper and the middle part of the Siwaliks surrounding the area with low R_R. Likewise, moderately high to high R_R is distributed at the regions of the Lesser Himalaya and the Siwaliks where metamorphic to meta-sedimentary rocks present (Fig. 8 and 9). In the middle of the Siwaliks (Fig. 8) there is continuous band of low relief area bounded by moderate relief and then by high relative relief, this is the area covered by lower, middle and upper Siwaliks bounded between two major thrusts (MKT and KKT) developed within the Siwaliks (Fig. 2). Hence such distribution pattern of RR on the study area suggests that the relief of the study area is being governed by geology (lithology and structure) of the area. The distribution pattern of relative relief of BRB shows positive correlation with lithology and tectonic zonation of area (compare Fig. 8 and Fig. 2). Which provide a strong evidence of geological control on geomorphic development of river basin.

Relief ratio (R_h)

The Rh value of BRB is 1.01. The R_h values of sub-basins vary from 0.20 to 84.31 suggesting that the rivers have high to very high gradient. Such gradient-gain from relief aspect, fragile nature of land surface and active monsoon rainfall possess high risk of land degradation and other mass wasting phenomenon in the BRB. This might be the reason for high input of sediment load to main stem river. This study also shows that the R_h value of sub-basins increases with decreasing drainage area and size of the sub-basins.

Hypsometric curve (HC)

The generated hypsometric curve of the BRB has concave upward shape at the head ward part (upstream) and there is distinct nick point at the middle of curve with convex upward shape and then again gets concave upward shape at tell ward (downstream) part. Hence, the overall shape of the hypsometric curve is deformed S-shaped curve (Fig. 10). Here, the shape of hypsometric curve can be relate with geology of river basin. At the upstream part, the Bagmati River originates in terrain of the Tistung Formation of the Lesser Himalaya characterized by metasandstones

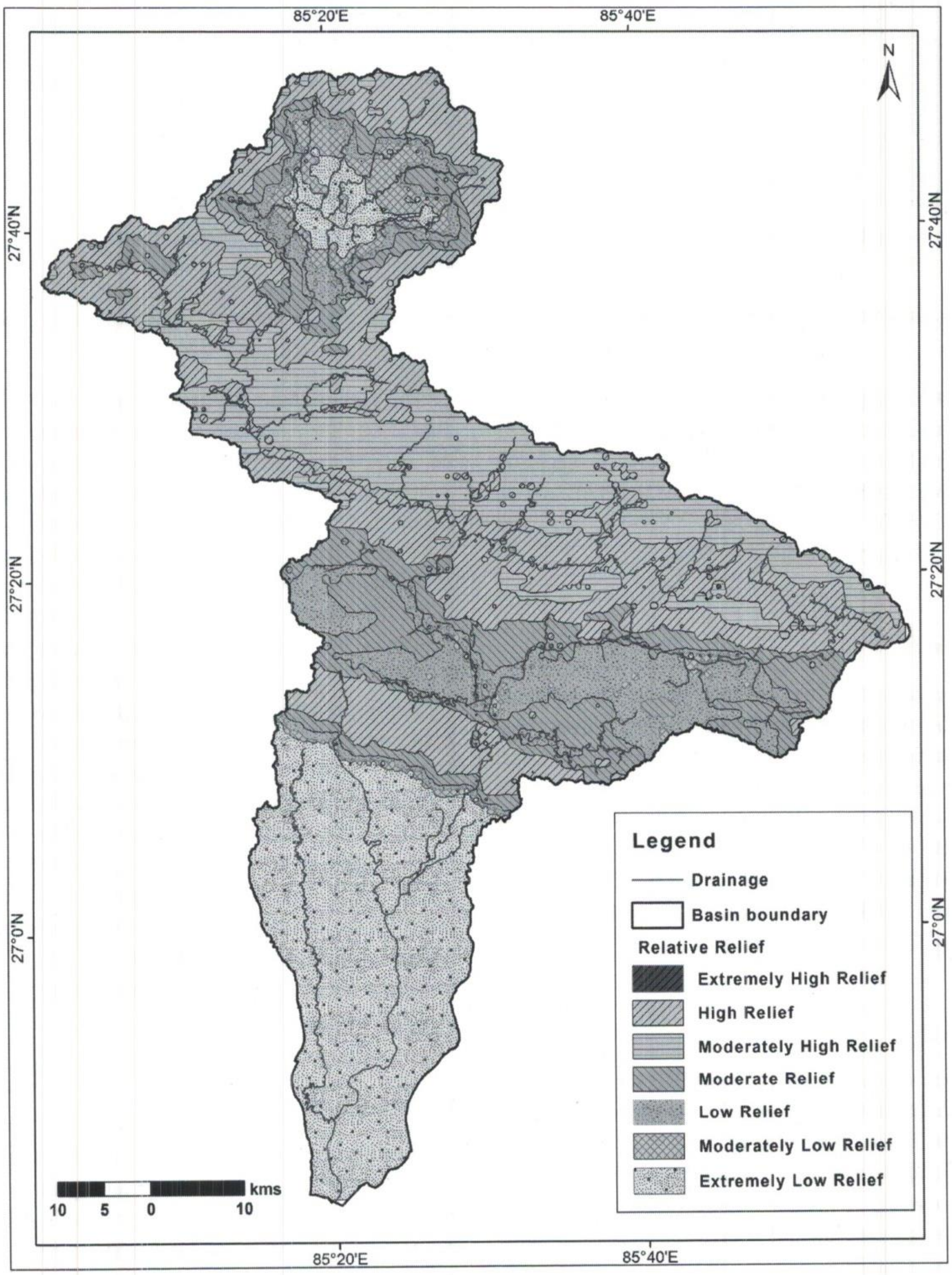

Fig. 8: Isopleths map showing spatial distribution of relative relief in BRB.

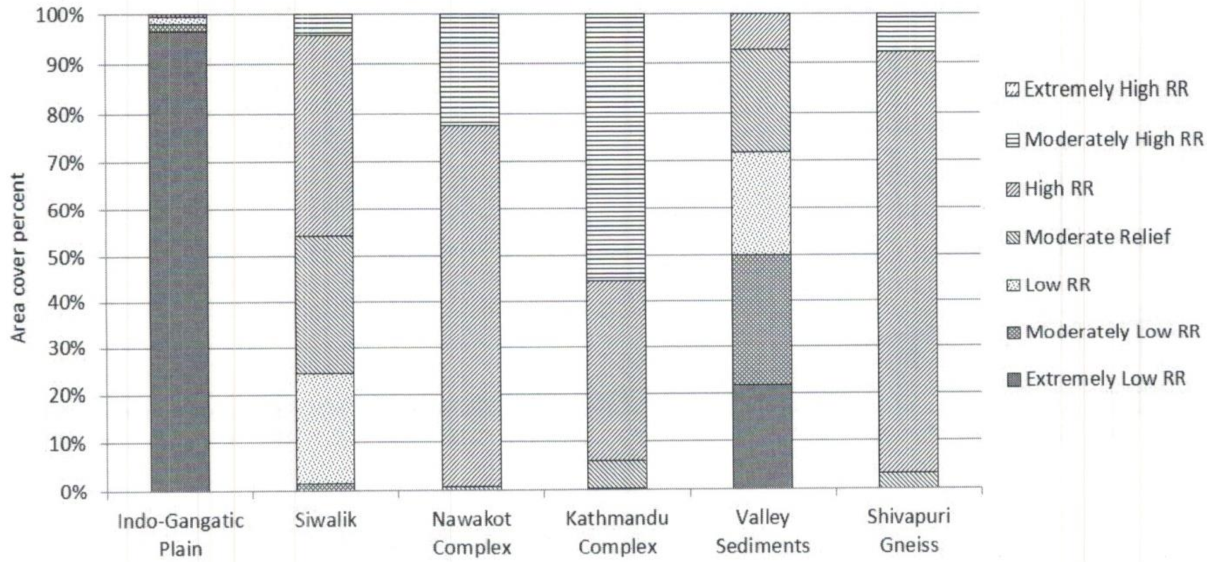

Fig. 9: Bar diagram showing relative relief distribution with respect to geology of terrains.

and phyllitic rocks, then it flows over the fluvio-lacustrine sedimentary deposits of the Kathmandu Valley. After the fluvio-lacustrine sedimentary deposits the river gets rejuvenated and starts incising the Lesser Himalayan rocks forming distinct nick point. Then the river flows through the Siwaliks and then spread over the Terai Plain (Fig. 11). Hence, the head ward convex shape of hypsometric curve shows that the river within the Kathmandu Valley is attaining its maturity. The convex upward shape at the middle of the curve replicates the river at the Lesser Himalaya and the Siwaliks where river is at youth stage with potential of erosion, and then gradually enter towards maturity when flows through the Terai Plain. Similar result is also shown by the longitudinal profile along the Bagmati River (Fig. 11). There is a nick point where river gets rejuvenated after departing from fluvio-lacustrine sediment and entered to basement rock of the Lesser Himalaya near Katuwal Daha. Hence, the hypsometric curve indicates that the drainage development within the BRB is in varying stage from youth to mature.

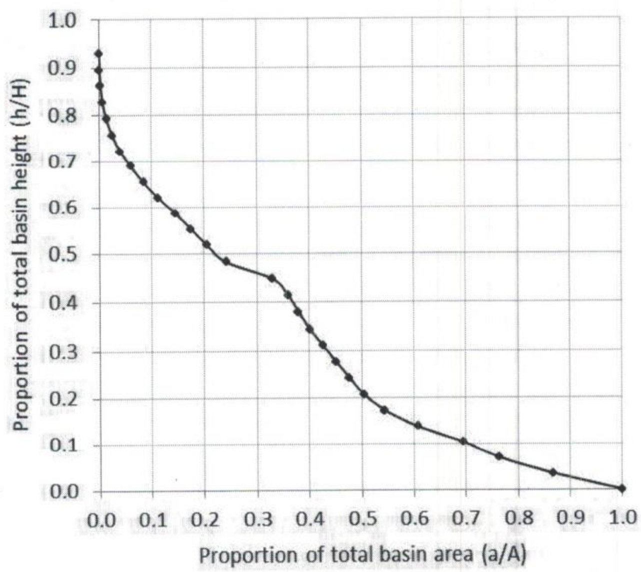

Fig. 10: Hypsometric curve of the Bagmati River Basin.

Hypsometric Integral (HI)

Theoretically, hypsometric integral values range from 0 to 1, as value close to 0 suggests significant incision, slope movement, and erosion of soil mass since the formation of watersheds (Bishop et al. 2002). In this study HI of sub-basin of BRB ranges from 0.29 (8th order main stem river) to 0.53 (fourth order stream segment). Average HI of main stem catchment is 0.44. Low HI values indicate old and more eroded areas and evenly dissected drainage basins. High values of HI indicate that most of the topography is high relative to mean, such as a smooth upland surface cut by deeply incised streams indicating young and less eroded areas.

DISCUSSION

The analysis and interpretation of various linear attributes indicates that the drainage system and basin development

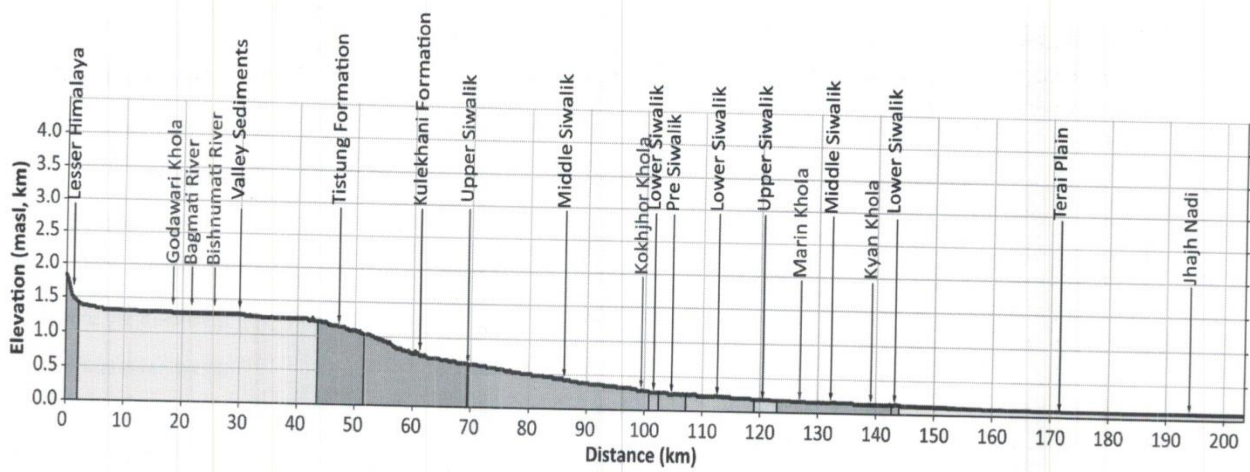

Fig. 11: Longitudinal profile along the Bagmati River.

within the Bagmati River Basin have been undergone through geomorphic development processes trending towards youth to late youth stage in lower order streams to maturity in the higher order streams. Such nature of basin development is probably because of nature of geological processes, climatic trend and lithological variation of rock formations. At sixth and seventh order segments morphological development seems to be controlled by lithology and geological structures of area.

The evaluation of BRB through aerial aspects of the morphometric parameters revealed that the BRB achieved highly elongated shape analyzed from form factor (value 0.15), circularity ratio (value 0.18) and elongation ratio having value of 0.8. The result shows not only main stem river basin but also all of the sub-basins of BRB have elongated to highly elongated shape, which indicates that the terrain of the BRB is characterized by high relief and steep slope. Another important aerial attribute drainage texture results variable spatial distribution pattern within the basin depending on characteristics of the area. And such distribution pattern of drainage texture indicates that the drainage development in the BRB is controlled by geology (lithology and structures) of area. In addition climate (hydro-meteorology) and tectonic might also have influenced in such development. Similar result is obtained by analysis of relative relief, the attribute of aerial aspect. The spatial distribution pattern of relative relief varies from gentle to very high. Extremely low to low RR is distributed at unconsolidated sedimentary deposits of Kathmandu Valley, Indo-Gangetic Plain and recent alluvial deposits. And the value of R_R progressively increases with increasing strength of host rock. For Instance, high to very high R_R is distributed around strong formations of Lesser Himalaya and Siwaliks. Likewise, overall R_R of the BRB varies from low to very high indicating the river basin is characterized by gentle to very steep slope. Furthermore the average relief ratio value of river basin is 1.01 and ranges from 0.20 to 84.31. This fact also suggests that the streams of BRB flow through very high gradient to gently sloping lands.

According to generated result the shape of hypsometric curve, the BRB has a concave upward shape with a convex portion at the middle replicating a deformed S-shaped curve (Fig. 10) showing the fact of river rejuvenation, and lithological and tectonic control on geomorphic development of BRB. The hypsometric curve indicates that the drainage system is attaining a mature stage from the youth which is true for most of the Himalayan watershed system (Awasthi et al. 2002). This could be due to the soil erosion from the watershed resulting from the incision of channel beds, down slope movement of top soil and bedrock material, washout of the top soil mass and cutting of the stream banks. The HI values indicate that the sub-basins lower than fourth order observed to be in youth stage and is still under geologic development. Sub-basins of fourth order and higher are progressively approaching towards mature stage. The river sub-basins under youth stage of growth exhibit possibility of further vertical erosion and degradation of landmass, thus contributing huge volume of sediments to the Bagmati River. Such sediment yields may have direct impact on the dynamics of the river. The seventh and the eighth order main stem stretches of the Bagmati River, which are tending to mature stage, show potentiality of lateral erosion because of dominance of huge meandering and braided segments therein. According to the result in the area, erosional stage and level of tectonic activity of sub-basins differ from each other.

CONCLUSION

1. The drainage system within the Bagmati River Basin is attaining a mature stage from the youthful stage forming elongate basin shape, which is true for most of the Himalayan watershed system.

2. The drainage system and basin development is in normal geomorphic development, in which low order streams have been attaining youth to late youth stage and the high order streams have been heading towards maturity though some exceptions occur at higher order stream segments such as the Ipa Khola, and the Chauda Khola. The mature stage river segments as Kokhajhor Khola, Marin Khola, and main stem Bagmati River at downstream segment (seventh and eighth order main stems) show high potential of lateral erosion. Because these sub-basins are highly elongated in shape which supports flatter peak flows for longer duration, and relative relief also decreases progressively towards higher order segments. Hence, stream velocity at such segments become moderate and sediment load from upstream causes the stream to deposit alluvium developing floodplain, and flood all parts of its valley. This supports the stream to form meander pattern providing energy for lateral erosion and meander migration.

3. The hypsometric curve shows that the river within the Kathmandu Valley is attaining maturity with meandering channels having wide floodplains. Flowing down from the Kathmandu valley it regains its energy at the Lesser Himalaya and the Siwaliks attending the youth stage showing high potential of river erosion at lower order. Further flowing down, it gradually gains maturity with increasing order up to the seventh and eighth, where it develops wide floodplains with meandering patterns. And before escape out from the hills to the depositional zone (Terai plain) it forms the braided patterns.

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REFERENCES

Adhikary, T. P. and Rimal, L. N., 1996, Stratigraphy and structural framework of the Sub-Himalaya, Bagmati River region, Central Nepal. Journal of the Nep. Geol. Soc., v. 13, pp. 37-50.

Awasthi, K. D., Sitaula, B. K., Singh, B. R. and Bajracharya, R. M., 2002, Land-use changes in two Nepalese watersheds: GIS and geomorphometric analysis. Land Degrd. & Dev., 13, pp. 495–513.

Bajracharya, S. R., 1991, Drainage pattern and its evolution in the Kathmandu Valley. Journal of Nep. Geol. Soc., v. 7, pp. 101-110.

Bajracharya, S. R., 1992, An evaluation of geomorphometry and geoenvironment of Kathmandu Valley, central Nepal. Bull. Dept. Geology, Tribhuvan Univ. , v. 2. pp. 163-172.

Bishop, M. P., Shroder, J. F., Bonk, R. and Olsenholler, J. 2002, Geomorphic change in high mountains: a western Himalayan perspective. Global & Planet. Change, 32, pp. 311-329.

Chorley, R. J., Donald, E. G., Malm, and Pogorzelski, H. A., 1957, A new standard for estimating drainage basin shape. Amer. Jour. Sci., 255, pp. 138-141.

Chorley, R. J., Schumm, S. A. and Sugden, D. E.,1985. *Geomorphology*. Methuen and Co. Ltd., London, New York

Christopher, O., Idown A. O. and Olugbenga A. S., 2010, Hydrological Analysis of Onitsha North East Drainage Basin using Geoinformatic Techniques. World Applied Science Journal 11 (10), pp. 1297-1302.

Clark, I. J., 1966, Morphometry from maps. In Essays in Geomorphology (edited by G. H. Dury), Heinmann, London, pp. 235–274.

DMG, 1998, Engineering and Environmental Geological Map of the Kathmandu Valley, Scale 1:50000. Department of Mines and Geology, Lainchaur, Kathmandu, Nepal.

Dowing, T. I., Richardson, D. P., O'Sullivan, A., Summerell, G. K. and Walker, J. 1998, Application of the hypsometric integral and other terrain based metrices as indicators of the Catchment helth: A preliminary analysis. CSIRO Land and Water, Technical Report 20/98. Canberra.

Hagan, T., 1969, Report on the Geological Survey of the Nepal Preliminary Reconnaissance. Zurich: Memories de la Soc. Helvetique des Sci. Naturelles.

Horton, R. E., 1932, Drainage basin characteristics. Trans. Am. Geophysc. Union 13, pp. 350–361.

Horton, R. E., 1945, Erosional development of streams and their drainage basins: Hydrophysical approach to quantitative morphology. Geol. Soc. Am. Bul. v. 56, pp. 275-370.

Hurtrez, J. E., Sol, C. and Lucazeau, F. 1999, Effect of drainage area on hypsometry from an analysis of small-scale drainage basins in the Siwalik hills (Central Nepal). Earth Surface Processes and Landform, 24, 799–808.

Javed, A., Khanday, M. R. and Ahmed, R., 2009, Prioritization of Sub-watersheds based on Morphometric and Land Use Analysis using Remote Sensing and GIS Techniques. J. Indian Soc. Remote Sens., v. 37, pp 261–274.

Keller, E. A. and Pinter, N., 1996, Active tectonics: Earthquakes Uplift and Landscapes; Prentic Hall, New Jersey.

Langbein, W. B., 1947, Topographic characteristics of drainage basins, USGS Water Supply Paper 968-B, pp. 25–157.

Leopold, L. B., Wolmann, M. G. and J. P. Miller, 1964, Fluvial

Process in Geomorphology. WH Freeman and Company; San Fransisko and London.

Miller, V. C., 1953, A quantitative geomorphic study of drainage basin characteristics on the Clinch Mountain area, Virgina and Tennessee, Proj. NR 389-402, Tech Rep 3, Columbia University, Department of Geology, ONR, New York.

Nautiyal, M. D., 1994, Morphometric analysis of drainage basin, district Deharadun, Uttar Pradesh. J. Indian Soc. Remote Sensing, v. 22(4), pp. 252–262.

Pike, R. J. and Wilson, S. E., 1971, Elevation-relief ratio, hypsometric integral and geomorphic area-altitude analysis. Geological Soc. Am. Bull., v. 82, pp. 1079–1084.

Ritter, D. F., Kochel, R. C. and Miller, J. R., 2002, Process Geomorphology. McGraw Hill, Boston.

Sarangi, A. and Bhattacharya, A. K., 2000, Use of geomorphological parameters for sediment yield pridction from watersheds. J. Soil & Water Cons. India, v. 44, pp. 99–106.

Schumm, S. A., 1956, Evolution of drainage system and slope in badlands of Perth Amboy, New Jersy. Bull. Geo. Soc. Am, v. 67, pp. 597–46.

Singh, O. and Sarangi, A., 2008, Hypsometric analysis of the lesser Himalayan watersheds using geographic information system. Indian J. Soil Cons., v. 36 (3), pp. 148–154.

Singh, S. and Singh, M. C., 1997, Morphometric Analysis of Kanhar River Basin. National Geographical Jour. of India, v. 43 (1), pp. 31–43.

Singh, S., 1998, Geomorphology. Prayag Pustakbhawan Allahabad.

Smith, K. G., 1950, Standards for grading textures of erosional topography. Am. Jour. Sci., v. 248, pp. 655–668.

Stocklin, J. and Bhattarai, K. D., 1977, Geology of Kathmandu area and central Mahabharat Range, Nepal. Report of Department of Mines and Geology Kathmandu Nepal/UNDP (Unpublished Report), pp. 86.

Stocklin, J. and Bhattarai, K. D., 1981, Geology of Kathmandu area and central Manabharat Range, Nepal Himalaya. United Nations Mineral Exploration, Technical Report Nepal, 64+ p.

Stocklin, J., 1980, Geology of Nepal and its regional frame. Journal of the Geological Society of London, v. 137, pp. 1–34.

Strahler, A. N. and Strahler A. H., 2002, A Textbook of Physical Geography. John Wiley and Sons, New York.

Strahler, A. N., 1952, Hypsometric (area-altitude) analysis of erosional topography. Geologic. Soc. Am. Bull., v. 63, pp. 1117–1141.

Strahler, A. N., 1957, Quantitative analysis of watershed geomorphology, Trans. Am. Geophys. Union, v. 38, pp. 913–920.

Strahler, A. N., 1964, Quantitative geomorphology of drainage basins and channel networks, In: VT Chow (ed), Handbook of Applied Hydrology. McGrew Hill Book Company, New York, Section, pp. 4–11.

Strahler, A. N., 1975, Physical Geography. Fourth Edition, ch. 27p.

Yoshida, M. and Igarashi, Y., 1984, Neogene to Quaternary Lacustrine Sediments in the Kathmandu Valley, Nepal. Jr. Nepal. Geol. Soc., Sp. Issue, v. 4, pp. 73-100.

Yusuf, A., Rao, L. A. K. and Ansari Z. R., 2011, Int. J. Res. Chem. Environ. v. 1(2), pp. 36–45.