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Estimation of Total and Unit Stream Power along Bhagirathi River, Uttarakhand, India

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ABSTRACT
Stream power is mostly used as an indicator for investigating engineering structures along the river banks. It has a considerable influence on forms and processes of the river system. It also provides information regarding the potential of a river to move sediments. The objective of this study is to estimate the total and unit stream power of Bhagirathi River and thereby to find the relationship of average unit stream power with landslides along the river. In this study, the longitudinal profile of the Bhagirathi River has been drawn using filled ASTER DEM in GIS environment. The smoothed longitudinal profile has been further used for the computation of slope at 1 km interval. The power function relationship has been established between peak discharge and drainage area to estimate peak discharge for ungauged points along the Bhagirathi River at 1 km interval. Channel slope, the specific weight of water and discharge are vital parameters for stream power computation. Total and unit stream power have been estimated at 1 km interval along the Bhagirathi River. The slope is found to be 0.04 and 0.0014 mm^{-1} along the extreme upper and lower reaches of the Bhagirathi River, respectively. Due to the steep slope, the total and unit stream power profiles show high peaks in the mid-stream of the Bhagirathi. The fluctuations in the total stream power along the Bhagirathi River signify the variation in sub-regional slope as well as in discharge contributing areas. The unit stream power is high in the upper reaches of the river, and it shows decreasing trend in downstream. Unit stream power mainly governs the bar deposition in the active channel of the Bhagirathi River. The association between average unit stream power and number of exposures/landslides has been found to be statistically significant at the 0.01 level of significance.

Keywords: Longitudinal profile, Total stream power, Unit stream power, Bhagirathi River, ASTER DEM, GIS, Polymodal distribution.

INTRODUCTION

Stream power is a product of stream slope, discharge, and weight of water that influence sediment transport (Rhoads, 1987; Gartner, 2016). The geomorphic impacts of the running water in an open channel and sediment transportation are assessed regarding the distribution of stream power per unit channel area over time (Jain et al., 2006; Kale, 2007). River develops a broad range of channel shapes during young, mature and old stages with respect to the available energy distribution in each stage. Potential or position energy is the main force, driving the river system (Fonstad, 2003). The potential energy is gradually transformed into kinetic energy when the river flows along the slope. Thus, kinetic energy is an essential factor for erosional and transportation functions to make the fluvial system active (Knighton, 1999). The total and unit stream power are significant predictors of geomorphic response to a flood event (Yochum et al., 2017).

Rhoads (1987) argued that the stream power can be used in a conceptual context rather than specific quantitative measures of power. An actual measurement of energy expenditure is not possible in the river system (Rhoads, 1987). Hence, various alternative methods (e.g., total stream power and cross-sectional stream power) can be used for measuring the true stream power of the rivers (Fonstad, 2003). Bagnold (1966) termed the cross-sectional stream power as unit stream power. He applied unit stream power for calculation of sediment transport rate and for the prediction of the competence of a river. Bagnold (1966) used stream power as a theoretical basis for evaluating the bedload transport in a channel. Phillips (1989) also observed that the sediment transport capacity in a channel depends on the unit stream power. A few field studies of stream power have predicted downstream energy expenditure trends using hydraulic geometry principle (Knighton, 1999; Kale, 2007; Bawa et al., 2014; Righini et al., 2017; Wicherski et al., 2017; Yochum et al., 2017). Graf (1983, 1998) observed that the lithological dissimilarity could be responsible for the variation in stream power.

In the fluvial system, the morphology of an open channel evolves from equilibrium between the energy exerted by the running water in a channel and the resistance of sediments of the channel perimeter against entrainment (Lecce, 1997). The stream power has been studied as a vital factor that influences components of the river system, including channel shape (Mosley, 1981), sediment transport rates (Bagnold, 1966), sediment delivery

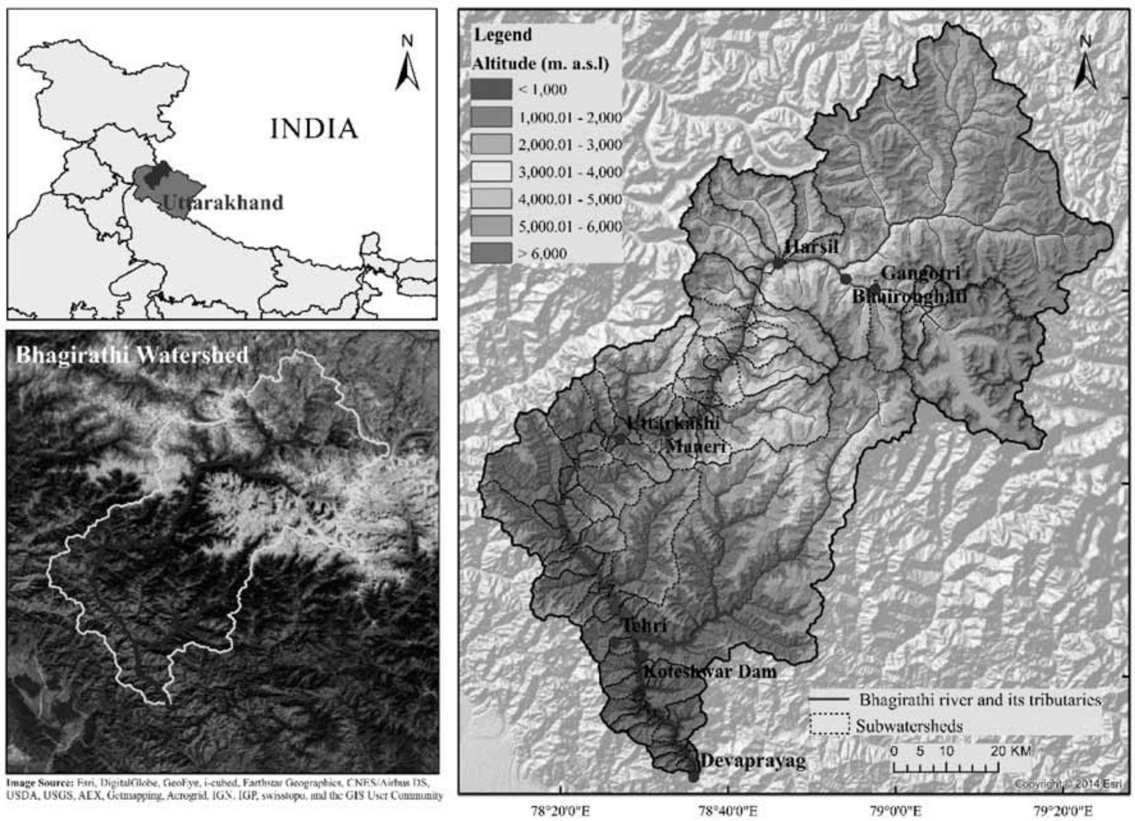

Figure 1. Location map of the study area.

ratios (Phillips and Slattery, 2006), channel migration (Nanson and Hickin, 1986; Kumar et al., 2013), channel pattern (Schumm and Khan, 1972), bedload movement (Petit et al., 2005), aggradation/ degradation threshold (Bull, 1979), riffle and pool characteristics (Wohl et al., 1993), genetic classification of floodplain (Nanson and Croke 1992), floodplain initiation processes (Jain et al., 2008) and geomorphic effectiveness of floods (Kale, 2007).

The spatial pattern of stream power expenditure has been possibly applied to correlate the longitudinal distribution of geomorphic features within a channel with stream energy. However, modeling of the river system is a challenging task because the physically-based relationship between channel geomorphic features within a channel and processes are not well established (Fonstad, 2003). The morphological structure and behavioral attributes of streams are controlled by the variables such as catchment hydrology, sediment character, degree of channel confinement, sediment supply, channel gradient, flood history, vegetation and human impact (Leopold et al.,1964; Kale, 2008; Ortega et al., 2014). Generally, in the tropical regions, the gradient decreases with an increase in discharge from upstream to downstream. Hence, channels do lateral expansion as they enter flat alluvial plains. Geological controls propel considerable local discontinuities in longitudinal profile of a river. However, the downstream variations in slope and elevation produce a striking change in channel shape and morphology (Graf, 1983; Reinfelds et al., 2004).

Uttarakhand state is highly prone to flood and landslides. After June 2013 flood event, it became necessary to know the total and unit stream power of all Uttarakhand Rivers. Jack (2010) estimated total and unit stream power for Ganga and Yamuna River. Furthermore, he selected a small reach along the Ganga River, starting from Rishikesh to Balawali. Against the backdrop of studies mentioned above, this research is focused on the total and unit stream power estimation along the Bhagirathi River. Such a study will significantly help engineers and planners to manage and construct engineering structures along or across the Bhagirathi River.

STUDY AREA

The Bhagirathi is a major source stream of the Ganga river system in the state of Uttarakhand. The holy Bhagirathi River is a major river of the Gangetic plain of northern India. The headwater of the Bhagirathi River originates from Gamukh (snout of Gangotri glacier) at an elevation of 4255 meters a.m.s.l. Its principal tributaries join river at different locations; these are Kedar Ganga at Gangotri, Jadh Ganga at Bhaironghati, Kakora Gad, and Jalandhari Gad near Harsil, Siyan Gad near Jhala, Asi Ganga near Uttarkashi, Bhilanga River near old Tehri at an elevation of 1,750 m a.m.s.l. (Figure 1).

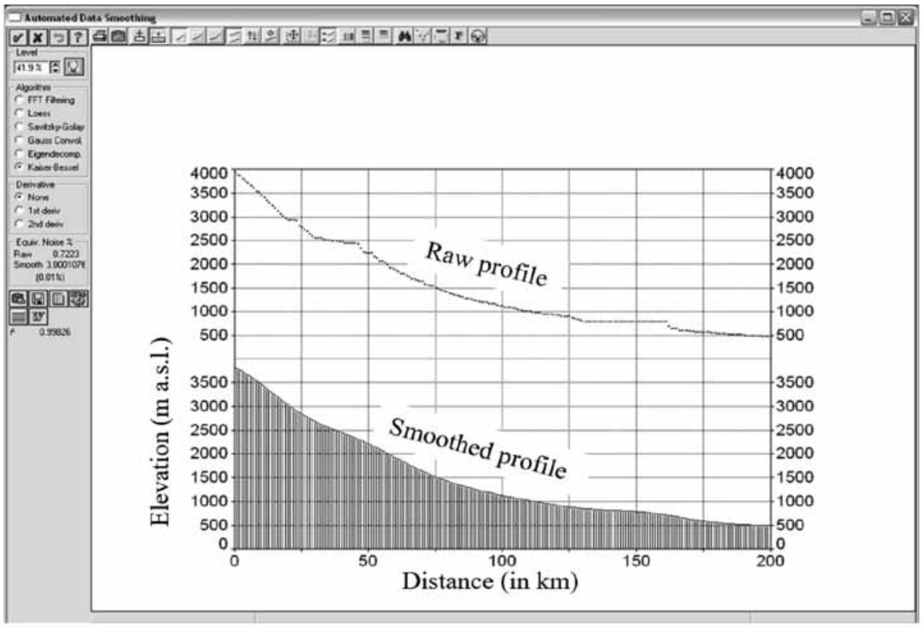

Figure 2. Raw and smoothed longitudinal profile of the Bhagirathi River.

The Bhagirathi River is 205 km long and the Alaknanda River joins it at Devprayag (elevation of 465 m, a.m.s.l). Downstream of the confluence, the Bhagirathi is known as the holy Ganga River. In the Bhagirathi River basin, the Chaukhamba-I is the highest peak. There are several human-made dams along the Bhagirathi River, some are functional, but some are under construction or planned. The total catchment area of the Bhagirathi River is 8846.64 km^2, distributed in Uttarkashi and Tehri Garhwal districts of Uttarakhand.

DATA AND METHODOLOGY

Geomorphic mapping was completed using Google Earth satellite images of 2014. The Advanced Spaceborne Thermal Emission and Reflection Radiometer Digital Elevation Model (ASTER DEM), Global Digital Elevation Model Version 2 (GDEM V2) released in 2011 at 30 m spatial resolution were obtained from the USGS Global Visualization Viewer (GloVis). In this study, Spatial analyst tool (hydrology) of ESRI ArcGIS 10 was used for watershed demarcation, calculation of river profile and estimation of channel slope. ASTER DEM data were used for delineation of Bhagirathi watershed at 1 km interval and its major rivers using D-8 flow algorithm of ArcGIS 10. Subsequently, the trunk stream (Bhagirathi) was selected to extract the bed elevation values from the filled ASTER DEM using 3D Analyst of ArcGIS 10. The raw longitudinal profile contains many unrealistic kinks that are due to noise in DEM data. These unrealistic kinks were removed to compute the slope (Bawa et al., 2014). The smoothening of river profile was performed in Table 2D Curve software. In trial version of Table 2D Curve software automated data smoothening method, 'Kaiser-Bessel' was used to eliminate the unrealistic kinks from the raw profile (Figure 2) (e.g. Thomson and Emery, 2014). The association of raw and smoothed profile is strong as the r^2 value is 99.82. Further, the smoothed profile was used to compute slope. A 200 km long longitudinal profile and slope (m/m) were derived for the Bhagirathi river.

Channel slope is an essential component for estimation of discharge and velocity of the river. Channel slope was computed at 1 km interval using smoothed longitudinal profile of the Bhagirathi River. Channel slope was calculated using Eq. (1):

$$S = \Delta H / \Delta L \qquad \ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

S= slope, the ΔH=Height difference (m), the ΔL=Channel length between two successive points (m). The slope was calculated for 1 km interval. Step-wise flowchart of creation of longitudinal profile and slope estimation at an equal interval of 1 km are shown in Figure 3.

Hydrological data (Table 1) were obtained from the thesis of Jack (2010). These data were used to establish a power function relationship between discharge and drainage area (Eq. 2) (Jain et al., 2006). The discharge data are available for a few sites in the Bhagirathi and Alaknanda basins (Table 1).

A continuous distribution of discharge (Q) is necessary for stream power estimation, based on discharge-area relationship along the Bhagirathi River (Eq.2):

$$Q = a * A^b \qquad \ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

Where A is the contribution catchment area in km^2, Q shows discharge (m^3s^{-1}), the a and b coefficients are equal to 0.580 and 0.841, respectively. The coefficient of determination (r^2) of the power function relationship is 0.893. Here, discharge is a dependent while the drainage

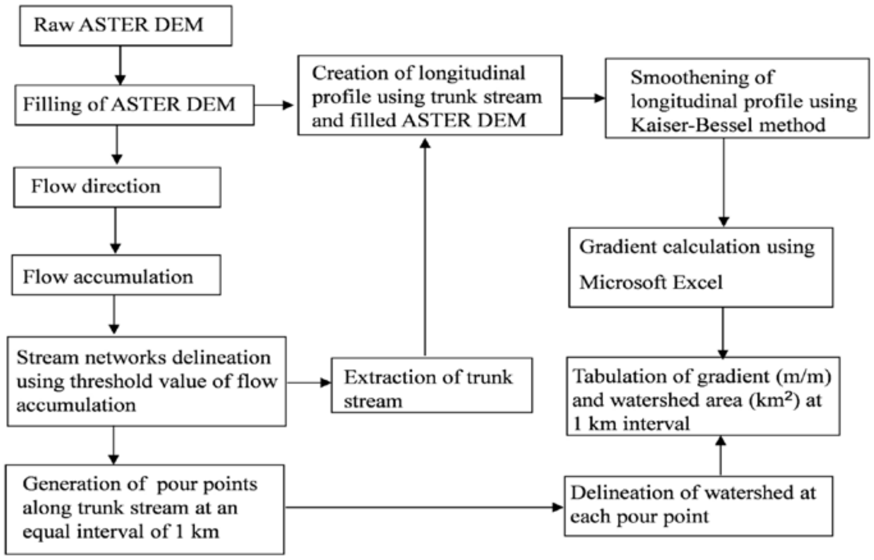

Figure 3. Flow chart depicting: a) procedures for delineation of the watershed, b) creation of the longitudinal profile, c) its smoothening and d) slope estimation at an equal interval of 1 km.

Table 1. Drainage area and peak discharge (1985-1997).

Location	Area (km^2)	Average peak monthly discharge
Rudraprayag (Alaknanda)	1647.991	287
Devaprayag (Alaknanda)	10141.81	1008
Devaprayag (Ganges)	10919.77	2269
Rishikesh (Ganges)	21467.67	2283

Source: Jack (2010).

area is an independent variable. The average peak monthly discharge data were used for the calculation of stream power because it is widely related to the river dynamics and a huge amount of sediment load is transported during the period of highest flow (Jack, 2010). Therefore, by using peak monthly discharge, a value of peak stream power was calculated and used to explain the bar formation and toe-cutting induced exposures/landslides. The mean peak discharge of the Bhagirathi watershed is 670.5 m^3s^{-1}.

The total stream power was calculated using Eq. (3) (Bagnold, 1966):

$$\Omega = yQS \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where Ω is total stream power per unit length of the channel (W m^{-1}), y is the specific weight of water (9800 Nm^{-2}), Q is discharge (m^3s^{-1}), and S is the energy slope (m/m) of the flow within a given reach. We took channel slope (m/m) as a proxy for energy slope of the flow. Reinfelds et al. (2004) defined total stream power as "the total rate of energy expenditure per unit length of the channel". Hence, it appears to be an suitable factor for longitudinal connectivity in the channel.

Unit stream power confers a measurement of the rate of energy expenditure per unit area of a river channel width. Unit stream power was calculated using Eq. (4) (Kumar et al., 2013):

$$\text{Unit stream power} = \text{Total stream power/ the width of active channel} \quad \ldots.. (4)$$

RESULTS AND DISCUSSION

Longitudinal River profile and channel slope

The work carried out in the badlands of Henry Mountains by Gilbert, (1877) showed that "if we draw the profile of the river on paper, we produce a curve concave upward and with the greatest curvature at the upper end." The concavity of the longitudinal profile of rivers is mainly produced by vertical erosion and removal of bed materials, the balance between aggradation and bed subsidence, and sediment and discharge added by tributaries to the main river (Sinha and Parker, 1996). The slope of a river is primarily influenced by its discharge and sediment size distribution (Snow and Slingerland, 1987). Thus, river longitudinal profile is an outcome of its interplay with the basin topography, land cover, soil and precipitation that control the supply of water and sediment to the river.

The hierarchy of geomorphic features of the channel and valley within the Bhagirathi watershed is influenced by dissimilarity in lithology and slope. In the upstream of the river, the slope is high. It is more than 0.04 m/m at

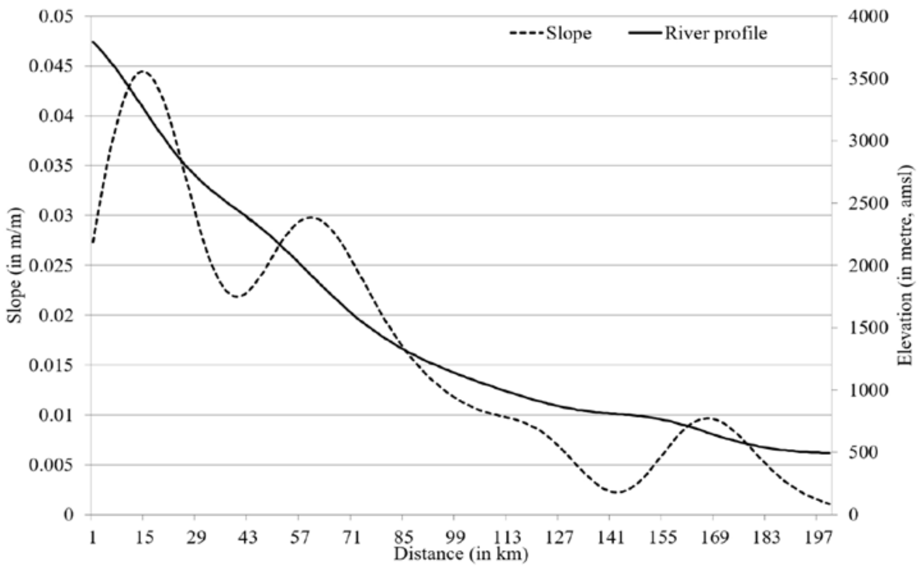

Figure 4. Longitudinal profile and slope of the Bhagirathi River.

Table 2 Overall **s**tatistics of slope, discharge, bar area, elevation, channel width, total and unit stream power

Parameters	Average	Minimum	Maximum
Slope (m/m)	0.016643	0.00106	0.04444
Discharge (cumecs)	670.46494	114	1076
Bar Area (km^2)	0.1195	0	1.147
Elevation (m)	1497.26	492.46	3793.84
Channel width(m)	156.74	11.098	1818.49
Total Stream power (wm^{-1})	79869.192	11169	167822
Unit stream power (wm^{-2})	1701.86	10	9850

an elevation of 3600 m (Reach 1), and after that, it shows decreasing trend. In the middle reach, slope shows an increasing trend (0.03 m/m at an altitude of 2400m). After that altitude the slope is continuously decreasing (Figure 4). Downstream near the distance of 140 km (Reach 16), the slope is only 0.002 m/m. This lowest slope is due to the Tehri dam.

Total stream power

In Bhagirathi river, total stream power shows a direct relationship between slope and discharge. The channel slope of the entire Bhagirathi River varies between 0.00106 and 0.04444 m/m. The total stream power varies from 11169 to 167822 Wm^{-1} with an average total stream power of 799869.2 (Wm^{-1}) (Table 2).

Along the Bhagirathi River, a high total stream power has been found in the mid-stream due to the influx of discharge by tributaries and sub-tributaries (reach 3-7) (e.g., Knighton, 1999). In the upstream, the slope is steep as a consequence; a sharp increase in the total stream power has been observed (reach 1-1). With the decrease of the slope, the total stream power also shows a decreasing trend (Figure 5a). Overall, the total stream power mimics the slope of the channel.

At the origin point of Bhagirathi River, few tributaries debouch with it, so discharge is low in the upper reach but when Bhagirathi reaches Bhaironghati; Jadh Ganga, Jalandhri Jad near Harsil, Siyan Gad near Jhala debouch with it. Hence, a large amount of discharge has been added to the river. Thus, the influence of tributaries is visible on the downstream increase in discharge. In the downstream of middle reach of the river, no major tributary joins the Bhagirathi River. Therefore, no significant changes occur in total stream power as well as in discharge in this reach (Figure 5b). In the lower reaches, Bhilangna River joins the Bhagirathi near old Tehri and adds a considerable amount of water to Bhagirathi, resulting in an increase in the total stream power. The headwater peak of the total stream power is sharp and narrow. But in midstream and downstream of Tehri dam, the peaks in total stream power are broad and flattened. The sharp and narrow headwater peak is due to local variation in slope and addition of high discharge at one point. The significant broad and flattened peaks in the midstream and downstream of the Tehri dam is due to the diminishing slope and relatively

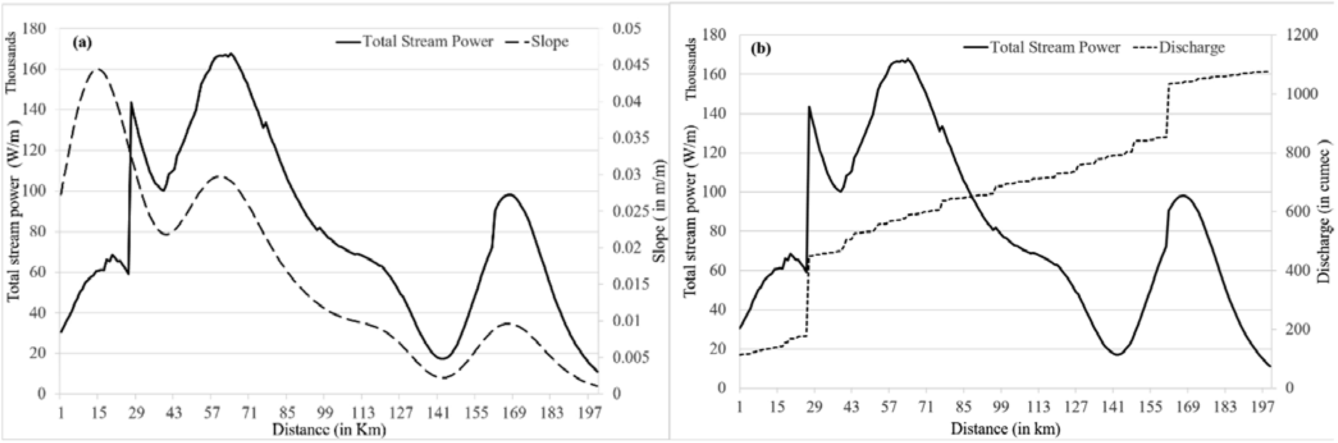

Figure 5. Relationship between **(a)** total stream power and slope and **(b)** total stream power and discharge in the Bhagirathi River.

high discharges, compared to headwater reaches. It is observed that the reach-scale variability in total stream power distribution is influenced by the discharge influxes from tributaries and change in channel slope (e.g., Fonstad, 2003; Jain et al., 2006).The river stretch between Maneri and Tehri dams is highly influenced by anthropogenic activities. Hence, the total stream power is relatively low as compared to upstream stretch. Thus, it is inferred that there are nonlinear downstream changes in the total stream power in the Bhagirathi watershed (e.g., Lecce, 1997; Jain et al., 2006). This study does not consider the stream power, estimated in the reservoirs of Maneri, Tehri, and Koteshwar dams.

Unit stream power and geomorphic characterisation of the Bhagirathi River

Unit stream power has been plotted against distance and slope of the Bhagirathi River. Interactions among channel width, discharge, slope, and stream power provide a reach-wise capacity of a river to perform geomorphic work. If the channel width is wide, the relatively low amount of sediments is carried out by the river. Hence, most of the sediment would store as valley-fill deposits. It means that if channel width is more, the unit stream power will be less when other factors remain the same. In general, the trend shows a fluctuating active channel width along the longitudinal profile of the Bhagirathi basin. The active channel width is narrow in the upstream of Harsil, where the river passes through deep gorges. After that, the width of active channel begins to widen slightly. In detail, the channel width is the maximum at the upstream reach of the Tehri dam as this dam breaks the longitudinal connectivity of the Bhagirathi River. The channel width varies between 11.1 (reach-1) and 1818.5 m (reach-16) (Figure 6).

Unit stream power is also associated with bar area in the channel belt. Presence of high bar area in the channel belt signifies the low unit stream power (Harsil reach) while the low bar area indicates (Figure 6) high unit stream power (reach 1 starting from Gomukh). Hence, bar area in the channel belt is negatively associated with the unit stream power.

The unit stream power varies from 10 (reach-16) to 9850 Wm^{-2} (upstream of Harsil). The reach-16 is a dead reach due to Tehri dam because the Bhagirathi River is not performing any geomorphic work in this reach. In the Bhagirathi watershed, unit stream power is high in the upstream, and it is decreasing in downstream due to increase in channel width (Figure 7).The reason for this high unit stream power in the upper stretch is the steep slope and narrow channel width as compared to the lower reaches. Despite a large amount of discharge added by the Bhilangana River to the Bhagirathi River near the old Tehri, the unit stream power is 1282 Wm^{-2}. But the unit stream power is not considered for the two dams namely, Maneri and Tehri dam that caused a break in longitudinal connectivity of the river as a consequence, ponding occurs in the reservoirs. On the basis of the unit stream power, the virgin stretches of the Bhagirathi river are located upstream of the Maneri dam and downstream of the Tehri and Koteshwar dams. A polymodal distribution in unit stream power has been observed.

The Bhagirathi River channel was divided into twenty-one distinct reaches on the basis of the geomorphic features and valley configuration (Figure 6). Geomorphic features like confluence bar, channel lag, mid-channel bar, point bar, and side bar have been mapped (Figure 8). Seventy-four significant exposures/landslides have been mapped along Bhagirathi River. The relationship of average unit stream power with landslides shows that the high stream power is one of the primary reasons for exposures/landslides (Figure 9). The Pearson correlation coefficient (r) and coefficient of determination (r^2) between average unit stream power and number of exposures/landslides are 0.586 and 0.3447, respectively. The correlation is significant at the 0.01 level of significance. The primary

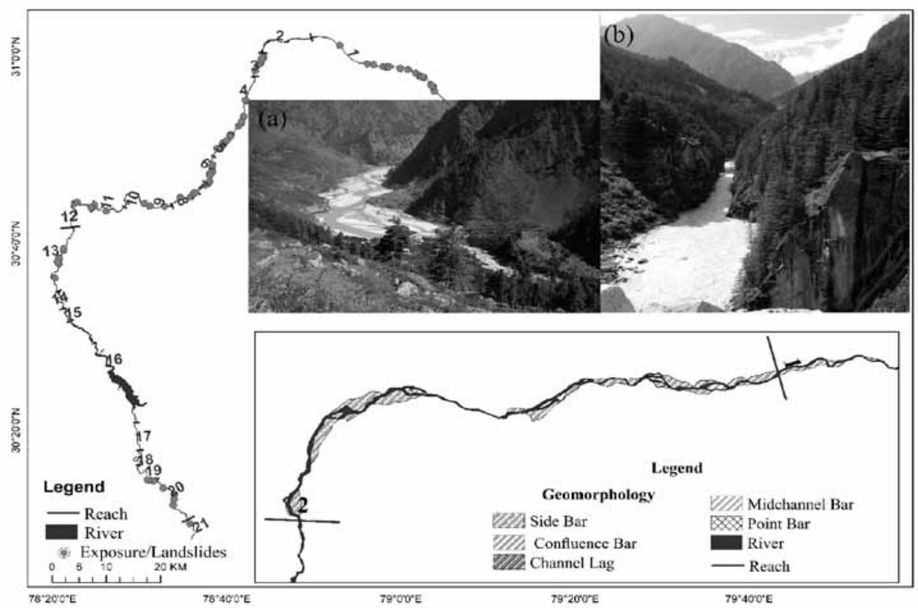

Figure 6. Bhagirathi River has been divided into twenty-one reaches and landslides have been mapped in each reach. Field photographs depict the Bhagirathi River near (**a**) Jhala village with a high bar area to channel ratio (**b**) Awe-inspiring box-shaped gorge and interlocking spurs are visible near Jangla village, and Gangotri channel is entrenched and confined. (**Courtesy**: Field photographs were obtained from Prof. Milap Chand Sharma, CSRD, Jawaharlal Nehru University, New Delhi). **Inset:** Detailed Geomorphic features of reach 2.

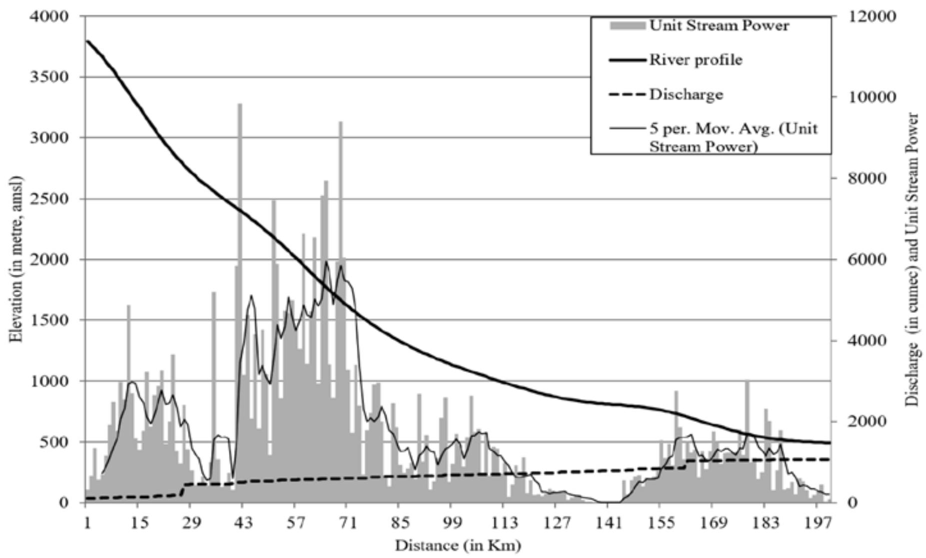

Figure 7. Unit stream power of the Bhagirathi River.

reasons behind exposures/landslide along the Bhagirathi River are down cutting, removal of basal materials and resultant slope failure. Out of seventy-four landslides, eighteen landslides (24 %) were found in part of above the average unit stream power of 5×10^{3}Wm^{-2}. Number of landslides and exposures are observed along the river with an average unit stream of <1300 Wm^{-2}. Hence, along the Bhagirathi River, the highest number of exposures/ landslides has been found in the reaches of the highest average unit stream power.

CONCLUSIONS

In the Bhagirathi river, tributaries provide a considerable discharge leading to increase in the upper and lower basin. The upper basin is characterised by the steep headwater slope and high peak in the total and unit stream power. But the lower basin is mostly influenced by the anthropogenic activities (damming of the river). The highest unit stream power was observed in reach 2 to reach 6. Along the dam sites, the total and unit stream power is low. The polymodal

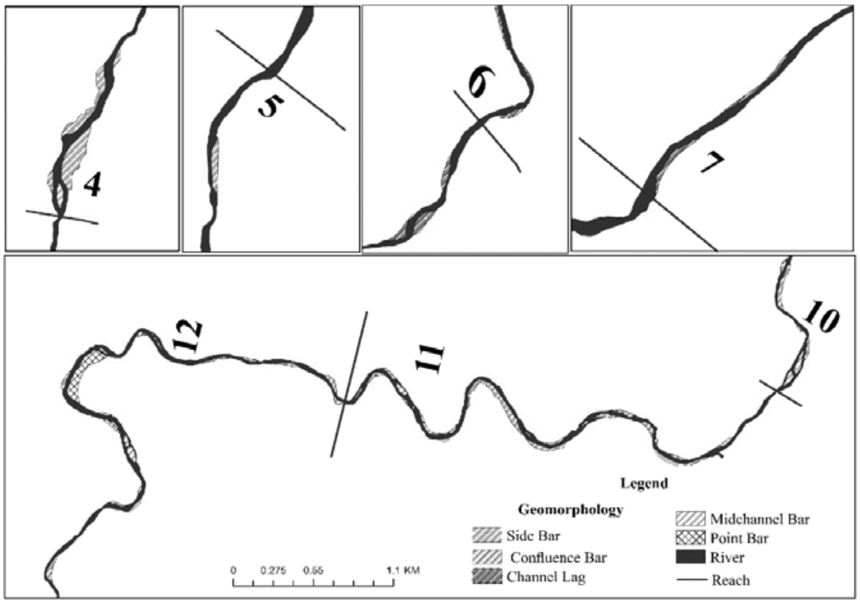

Figure 8. Geomorphic features of the Bhagirathi River in the selected reaches (4, 5, 6,7,10 and 11).

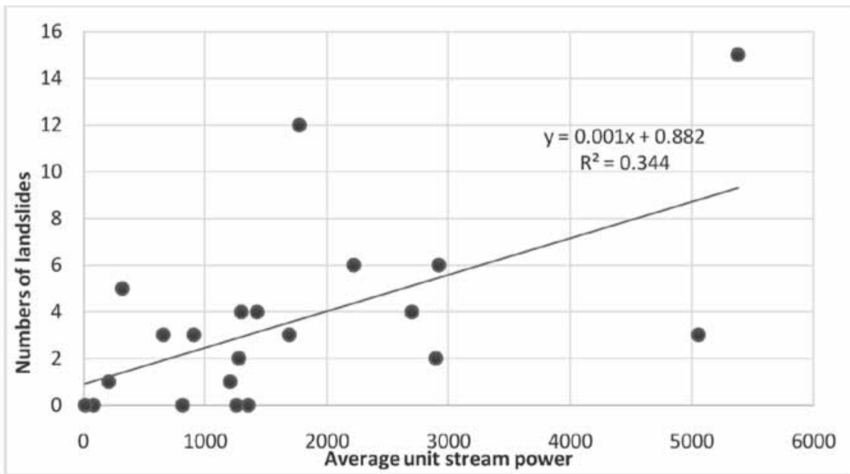

Figure 9. Relationship between exposures/landslides and average unit stream power.

distribution patterns are observed in total and unit stream power. The average unit stream power is 1701.9 Wm^{-2} that signifies downcutting without any floodplain formation along the Bhagirathi River. The presence of large boulders, cobbles, pebbles and coarse sand also signifies a high energy environment without any floodplain pocket.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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