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Dry season discharge and sediment yield of the northern tributaries of the Kathmandu Valley, Central Nepal

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ABSTRACT

Population growth, urbanization and improper land use practice cause change in natural behavior of the river system. In this point soil erosion and sediment deposition in the river channel adversely bring environmental problems like variation in discharge, surface water physical quality, sediment transportation capacity, sediment yield and stream power. In lack of proper research and planning, disasters like flooding, failure of engineering structure, bank erosion and imbalance in aquatic ecosystem can be seen. To better understand the stream, present work was carried out to determine the discharge, sediment transportation capacity, sediments yield and stream power of northern major tributaries of the Bagmati River. Subsequent to this, relations between the two or more than two morpho-hydraulic parameters with the discharge and sediments load were evaluated.

The northern Bagmati River basin occupies an area of 3750 sq. km and lies within $26^0 42'$ and $27^0 50'$ N latitude and $85^0 02'$ and $85^0 58'$ E longitude. The Bagmati River, non-glacial perennial river, consists of four main tributaries contributing from the northern part of the Bagmari River basin. They are the Manahara River, Bagmati River, Dhobi Khola and the Bishnumati River. The four major tributaries including the Bagmati River were upto sixth stream order. The study revealed that water discharge varied from 0.033 to 1.983 m^3/s and the grain size distribution d_{50} ranged from 0.0002 to 0.0250 m. The study found that the suspended load for dry season varied from 5.93 to 916 mg/L and the bed load from 6 to 393711 tonnes/day. The total sediment yield ranged from 0.58 to 22029.64 tonnes/km^2/day. The boundary shear stress and critical shear stress ranged from 0.03 to 30.87 N/m^2 and 0.05 to 0.06 N/m^2, respectively. The stream power per unit channel width was found to vary from 0.001 to 0.06 KNm/s/m^2 for tributaries. Except at few sites, the rest of the sites of the studied river exhibit competency and good capability of sediment transport of the rivers. This study helps to implement proper engineering hydraulic practices around the river corridors.

Key words: Stream discharge, boundary shear stress, critical shear stress, sediment yield, stream power, Bagmati River

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INTRODUCTION

River system is a natural and dynamic process which carries sediments generated due process of weathering, mass wasting and erosion of rocks and soils present in the nature. In this point, on the basis of the characteristics of the river system, particular system of the river has its own capacity of transporting sediment and yielding sediment from the river basin. The sediment yield and the amount of sediment load depend upon hydraulic regime, geological setting, land use and human influences. When sediment load increases due to high erosion rate than sediment yield rate, the normal range exceeds resulting problems to mankind and manmade structures, and reduce environmental quality and elements of rivers. Therefore, to overcome such situations it is important to study estimation of sediment yield and sediment transport capacity of the rivers. According to Tamrakar and Shrestha (2008) rivers in the Lesser Himalaya are capable to flush out sediment compared to such in the Siwaliks because of unstable slope. Various studies have shown that the rivers in the

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northern Kathmandu Valley are far from the equilibrium and there existed various bank erosion problems (Tamrakar, 2004a, 2004b; Shrestha and Tamrakar, 2007a, 2007b; Tamrakar et al., 2011). Guzman et al. (2013) displayed the suspended sediment concentration–discharge relationships in which concentration of suspended sediment is high for low flow and sediment concentration is low for high flow. Wolman and Miller (1960) proposed that the amount of sediment transported by flows of a given magnitude depends on the form of the relationship between discharge and sediment load and on the frequency distribution of the discharge events. Ashmore and Day (1988) studied drainage areas ranging from 10 to over 100,000 km^2 and for the duration between 5 and 29 years, and found that the effective discharge was less than 0.1% in some cases and over 15% in others, with the majority of stations having values between 1 and 10%. Similarly, Powell et al. (1996) studied the bed load contribution and represented a mean annual bed load yield of 39 tonnes km^{-2} year^{-1}. Although bed load contributed up to 13% of the sediment load during individual events, on average it constituted only 8% of the total sediment yield of 472 tonnes km^{-2} year^{-1}.

This study aims to provide piece of information on sediment transport, stream competency, stream power, and sediment yield across northern main tributaries of the Bagmati River basin. Data acquired after analysis help to improve understanding of sediment transport relations, provide information for designing stream restoration, and flood mitigation. Different transects

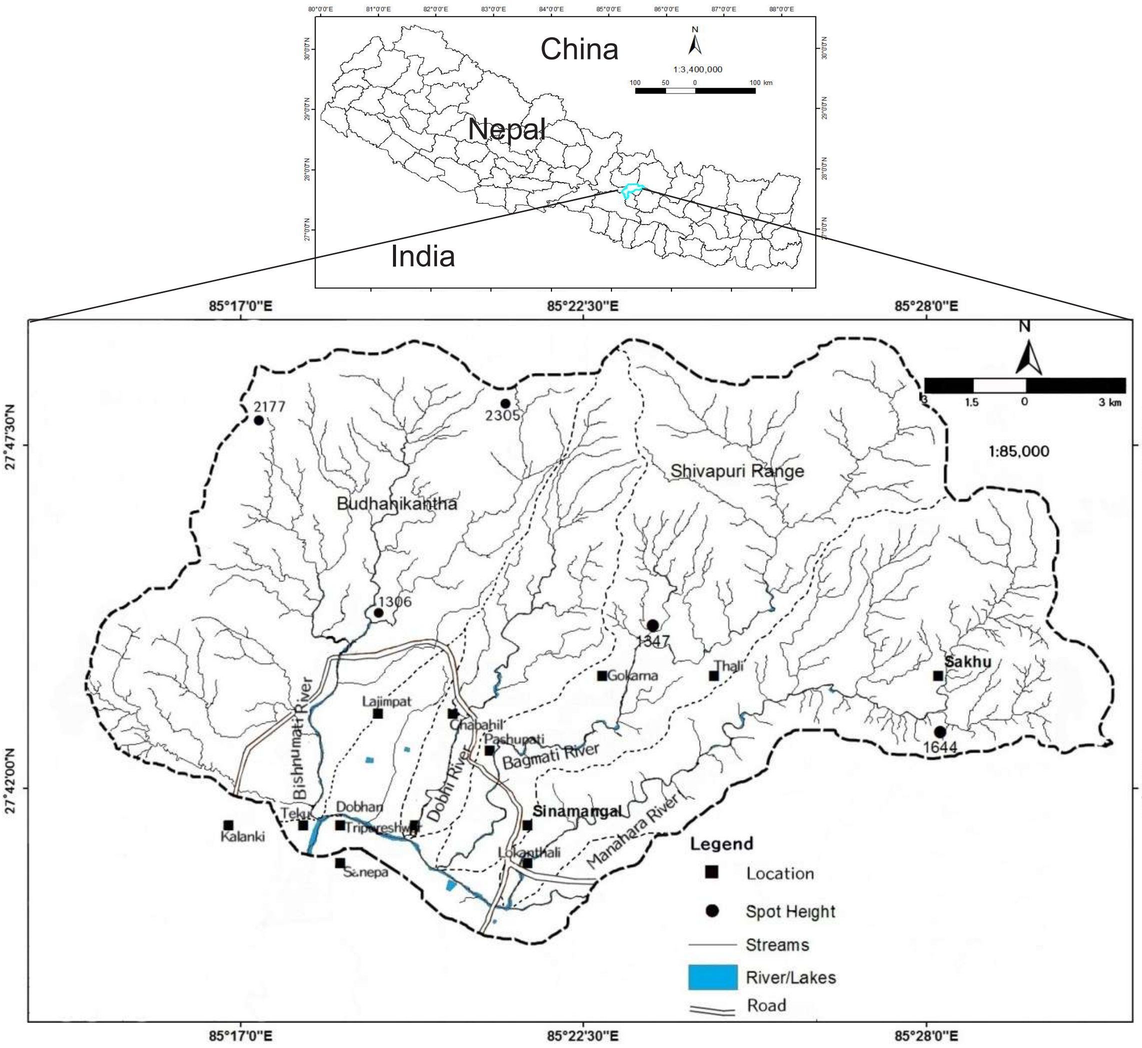

Fig. 1 Location and drainage map of the study area.

(ten in each) were selected at main tributaries of the Bagmati River basin (Fig. 1) for dry season only to examine suspended sediment concentration, sediment loads, particle size distribution, stream power and sediment yield for particular season.

Geologically, the Kathmandu Valley basin comprises fluvio-lacustrine sediments which overlies the basement rocks of Pre-Cambrian to Devonian age (Table 1). The basement rocks mainly consist of phyllite, sandstone, slate, meta-sandstones, quartzite, siltstone, shale and crystalline limestone in the east, west and the south of the valley. Similarly, in the north and the northeast, basement rocks comprise gneiss, schist and granite (Stöcklin and Bhattarai, 1977; Stöcklin, 1980).

Furthermore, the basin fill sediments are divided into two series; they are Quaternary Unconsolidated Sediments and Plio-Pliestocene slightly consolidated sediment (DMG, 1998) as shown in Fig. 2. Present study was conducted on the northern part of the Bagmati River basin, located in the Kathmandu Valley. The watershed occupies 99.34 sq. km area including partly the, Lalitpur and Bhaktapur Districts. The latitude and longitude of the watershed is $74^{0}53'$ to $74^{0}75'$ N and

Table 1: Geology of the study (a) Stratigraphic column of the Kathmandu Complex (Stöcklin, 1980), and (b) Stratigraphic column of the basin-fill sediments (after Yoshida and lgarashi, 1984).

Table 1(a)

Stratigraphic unit	Composition	Distribution	Age
Recent Flood Plain	Sand, silt and clay	Along the Bagmati River and its tributaries	Holocene
Lower Terrace deposits	Micaceous sand and gravel	Along the Bagmati River and its tributaries	
Patan Formation	Laminated arkosic sand, silt clay and peat layers	Mainly around Patan and Kathmandu cities	Pleistocene
Thimi Formation	Arkosic sand, silt clay, peat and gravel	Around Kathmandu at Pashupati, Airport, Thimi and Bhaktapur	
Gokarna Formation	Laminated arkosic sand, silt, clay and peat	North part of the Kathmandu Valley around the Gokarna area	
Boregaon Terrace Deposit	Rounded gravel with laminated silt and sand	Southern area of the Kathmandu Valley near the Chapagaon and the Boregaon Villages	
Chapagaon Terrace Deposit	Subrounded gravel of phyllite and metasandstone	Southern area of the Kathmandu Valley near the Chapagaon Village	
Pyangaon Terrace Deposit	Sub rounded gravel of meta-sandstone and phyllite	Southern areas of the Kathmandu Valley near the Pyangaon and the Godavari Village	
Lukundol Formation	Weakly consolidated clay, silt and beds with lignite layers	Along terrace, scarps near the Chapagaon Village, probabably widely distributed in the subsurface of the Kathmandu Valley	Pliocene

Table 1(b)

Complex	Group	Formation	Main Lithology	Thickness (m)	Age
KATHMANDU COMPLEX	Phulchauki Group	Godavari Formation	Limestone, Dolomite	300	Devonian
		Chitlang Formation	Slate	1000	Silurian
		Chandragiri Formation	Limestone	2000	Ordovician
		Sopyang Formation	Slate, Calcareous Phyllite	200	Cambrian?
	………..…………………….........	….Transitional Zone		……………	………………….
	Bhimphedi Group	Tistung Formation	Metasandstone, Phyllite, Schist	3000	Late Paleozoic
		Markhu Formation	Marble, Schist	1000	Precambrian
		Kulekhani Formation	Quartzite, Schist	2000	Precambrian
		Chisapani Quartzite	White Quartzite	400	Precambrian

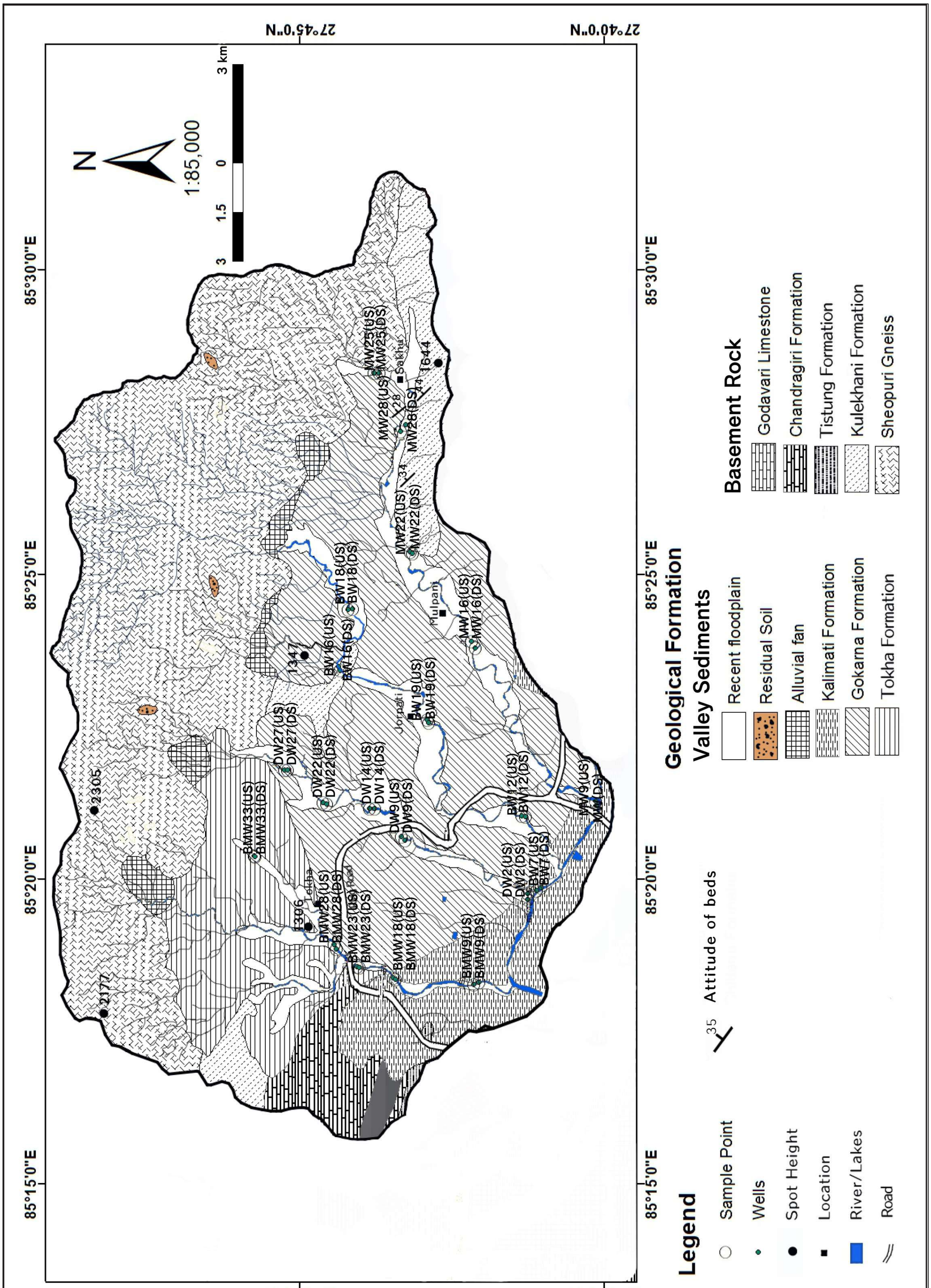

Fig. 2 Geology and sampling transects of the northern Bagmati basin.

$21^0 54'$ to $21^0 62'$ E. The temperature of this area varied from 9^0C to 48^0CE. The watershed received 552 mm average rainfall per year.

METHODOLOGY

Stream discharge calculations

During the study, the stream discharge of four rivers; the Bishnumati River, the Dhobi Khola, the Bagmati River, and the Manahara River were calculated for different ten transect of each river. The area-velocity method was used to calculated cross-sectional area and velocity. Velocity was recorded by using a current meter. Discharge (Q) was the volume of water flowing through a stream channel cross-section per unit time (Chow, 1986). Discharge was calculated using the continuity equation:

$$Q = VA \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where, V = Velocity of stream flow (m/s), A = cross-sectional area (m^2), Q = Discharge (m^3/s).

Slope (s)

Slope of the stream was the ratio of elevation difference to distance of river. Although slope is partly imposed by geological constraints, rivers are nevertheless free to change slope substantially by means of aggradation and degradation. Data from topographic maps were used to calculate slope here.

Suspended sediment concentration (SSC)

Measurement of suspended sediment was done by using a filtration method (ASTM D3977-97, 2002). This is simple, laboratory analytical method to estimate suspended solid which quantifies concentrations of suspended solid material in the surface water. SCC data were obtained by measuring the dry weight of all the sediment from known volume of water-sediment mixture collected from depth integrated sampling of water from stream cross-sections. Usually, SSC is expressed in (mg/L).

Bed load and suspended load calculation

Bed load is defined as part of sediment within the bed layer moved by saltation (jumping), rolling, or sliding. It is the clastic material that moves through the channel fully supported by the channel bed itself. These materials are mainly sand and gravels which are kept in motion by the shear stress acting at the boundary. The diameter of bed and bar substrate is routinely measured using some variation of the Wolman pebble count method (Wolman, 1954). Pebble counts involve measuring the B-or intermediate axis of 100 to 400 individual bed particles collected from the channel bed by hand using some type of ruler or template (Bunte and Abt, 2001). Typically, pebble diameter measurements were made in millimeters. Bed substrate classes generally followed those in Rosgen (1994).

For the bed load calculation, slope and stream sediment characters were assessed to characterize grain size of each of segments in the reach-scale and in the cross-section scale, Wolman's (1954) pebble counting was adopted in numbers of transects including pools during the cross-section survey. The particle size distribution was used to obtain the d_{50}.

The Hassanzadeh (2007) bedload equation which agrees closely with the measured data is expressed as follows:

$$\{q_b/(agd^3)^{0.5}\} = 24\ f^{2.5} \ldots\ldots\ldots\ldots (2)$$

$$f = \tau_0/(\gamma_S - \gamma)d \ldots\ldots\ldots\ldots (3)$$

and

$$a = (\gamma_S - \gamma)/\ \gamma \ldots\ldots\ldots\ldots (4)$$

where, q_b = bed load in (m^2/s), g = acceleration due to gravity, d = median grain diameter (d_{50}), f = hydrodynamic-immersed gravity force ratio, τ_0 = boundary shear stress = γR_h S, Rh = hydraulic radius, S = stream slope, a = immersed sediment specific gravity, γ_S = specific weight of sediment = 2650 kg/m^3, γ = specific weight of water =1000 kg/m^3 (which may be varied depending on water temperature), and γ_S-γ = submerged specific weight of sediment, kg/m^3.

Bed load in the present study was estimated using Hasanzadeh's (2007) empirical equation. Then the bed load transport capacity (Q_b) in kg/s was calculated using the following relation:

$$Q_b\ (kg/s) = \rho_S\ W\ q_b. \ldots\ldots\ldots\ldots (5)$$

The bed load transport capacity (Qb) in kg/s was then converted into the tonnes/day using the following expression:

Q_b (tonnes/day) = ρ_S W q_b. 86.4…(6)

Where, conversion factor is 86.4, W is width of channel, and q_b is bed load in m^2/s.

Shear stress

It is related to sediment mobilization and transport in many theoretical and empirical treatments of sediment transport. Following relation wass used to obtain boundary shear stress (Shields, 1936):

$$\tau = \gamma RS \text{……………………(7)}$$

Critical shear stress (τ_c) for d_{50} were calculated using following relation

$$\tau_c = \theta_c \,.\, g\,(\rho_c - \rho) * d_{50} \text{………(8)}$$

where, τ = boundary shear stress, (N/m^2), γ = specific weight of water (N/m^3), R = Hydraulic radius (m), S = Average stream slope (m/m), θ_c = Shields parameter for critical dimensionless shear stress was taken from the Shields curve, g = gravitational constant, d_{50} = median diameter of particles, ρ_c = density of sediments, ρ = density of water.

Stream power

Bagnold (1966) defined stream power concept as the available power supply, or time rate of energy supply, to unit length of a stream is clearly the time rate of liberation in kinetic form of the liquids potential energy as it descends the gravity slope. The available stream power supply can be expressed as:

$$\Omega = \gamma QS \text{……………………..(9)}$$

Where, Ω = stream power (KN/s/m), γ = unit weight of water (KN/m^3), Q = hydraulic discharge of the stream (m^3/s), and S = stream slope (m/m).

Stream power per unit of bed area (Bagnold, 1966) was calculated using the following relation:

$$\omega = \tau_b V \text{……………………..(10)}$$

RESULTS AND DISSCUSION

Stream order and profile

The Bishnumati river, one of major tributary of Bagmati River from the northern valley, is a sixth order stream that has 16.344 km length and the total watershed area of 102.26 sq. km. The Manahara River is a fifth order river having major contribution for the Bagmati has length of 25.24 km and watershed area of 74.26 sq. km (Fig. 3). The Dhobi Khola is a fifth Order River which has minor contribution for the Bagmati Basin, and has length of 17.81 km and watershed area of 30.74 sq. km. Similarly, the Bagmati River is a sixth order, before the mixing with another major tributary, and has 26.94 km length (Fig. 3) and catchment area of 74.13 sq. km in the northern territory of the Kathmandu Valley.

Morpho-hydraulic parameters

The calculated hydraulic parameters values vary from upstream to downstream in each stream (Table 2). Slope (m/m) is 0.002–0.240, 0.001–0.020, 0.001–0.027 and 0.001–0.035 in the Manahara River (maximum), the Bagmati River (minimum), the Dhobi Khola and the Bishnumati River, respectively. Entire values randomly changed in each sampling point of individual river. W/D ratio is maximum at the Bagmati River with 16.60–163.04, minimum at the Bishnumati River with 8.21–34.04 followed by the Manahara River i.e. 17.05–57.97 and 9.39–153.47 in the Dhobi Khola. Hydraulic radius ranges are 0.07–0.28 m, 0.12–0.30 m, 0.03–0.17 m and 0.09–0.63 m in the Manahara River, the Bagmati River, Dhobi Khola and the Bishnumati River, respectively.

The result shows that variation is large for the Bishnumati River and low for the Dhobi Khola. The hydraulic radius is increasing towards downstream of all streams with slight fluctuation but in the sampling points like DW2(DS) and BMW9(DS) values suddenly decrease, which can be due to anthropogenic activities near dense settlement areas. Velocities of the individual stream are 0.27–0.63 m/s, 0.12–0.50 m/s, 0.18–0.46 m/s and 0.19–0.62 m/s in the Manahara River, the Bagmati River, the Dhobi Khola and the Bishnumati River, respectively. Discharge ranged between 0.06–0.717 m3/s in the Manahara River which is minimum discharge recorded compared to other studied rivers. Discharge of surface water measured in the Bagmati River (0.294–1.983 m^3/s) is maximum discharge during dry period among four rivers studied. Discharge of Dhobi Khola (0.033–1.974 m^3/s) is nearly equal to that of the Bagmati River, however in the initial point of

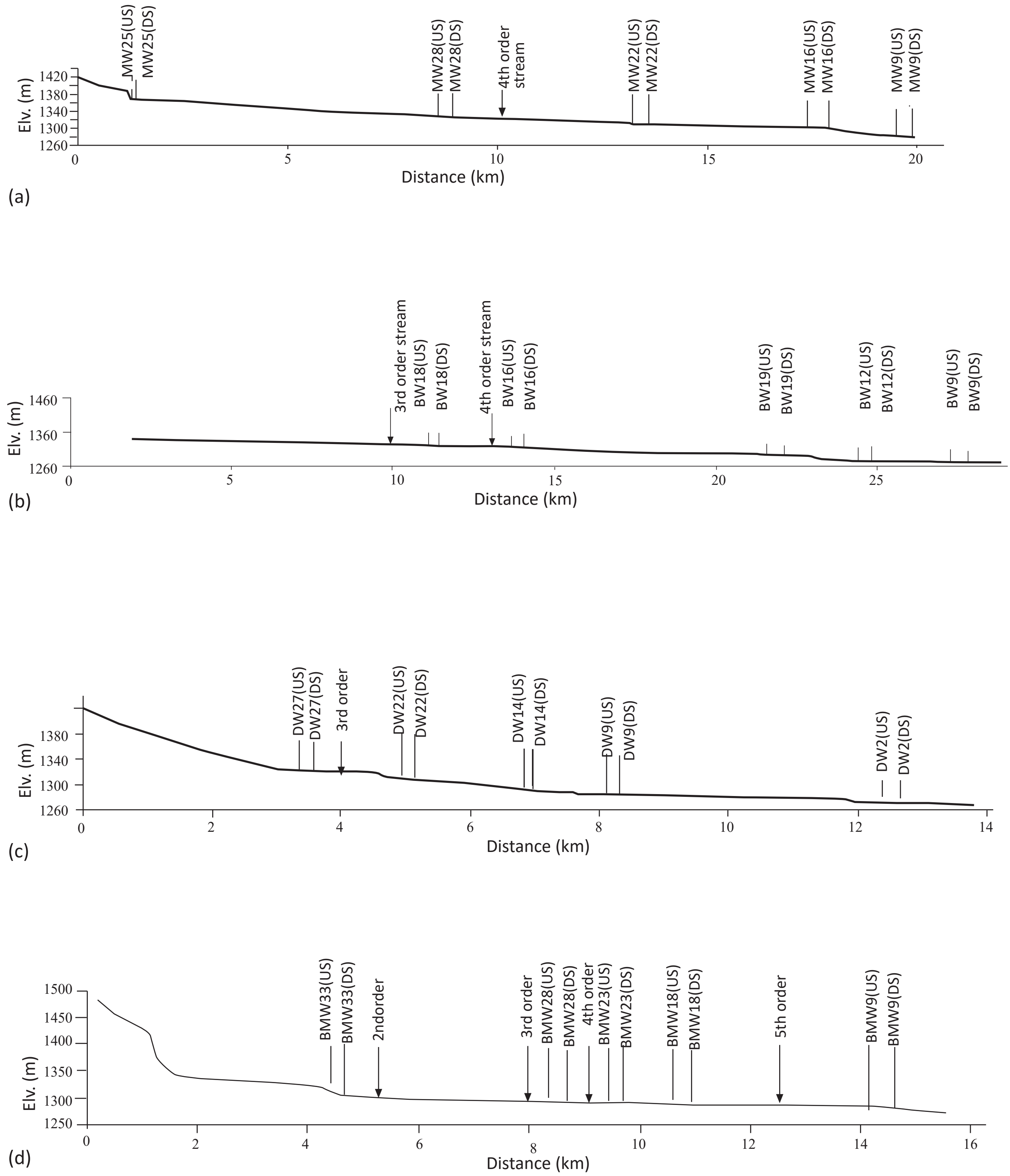

Fig. 3 Longitudinal profies of rivers. (a) Manahara River, (b) Bagmati River, (c) Dhobi Khola and (d) Bishnumati River

Table 2: Morpho-hydraulic parameters of different rivers.

River	Location	Distance (km)	Slope (m/m)	Width (m)	Area (m^2)	Depth (m)	W/D	WP (m)	R_h (m)	V (m/s)	Q (m^3/s)
Manahara River	MW25(US)	1.20	0.022	2.30	0.18	0.08	29.39	2.46	0.07	0.32	0.060
	MW25(DS)	1.30	0.240	2.50	0.23	0.09	27.17	2.68	0.09	0.30	0.059
	MW28(US)	8.54	0.003	5.30	0.74	0.14	37.86	5.58	0.13	0.27	0.193
	MW28(DS)	8.61	0.040	5.50	0.54	0.10	56.12	5.70	0.09	0.36	0.204
	MW22(US)	13.16	0.004	8.00	1.10	0.14	57.97	8.28	0.13	0.63	0.711
	MW22(DS)	13.23	0.043	7.40	1.29	0.17	42.52	7.75	0.17	0.35	0.443
	MW16(US)	17.69	0.002	6.00	1.03	0.17	34.95	6.34	0.16	0.27	0.286
	MW16(DS)	17.76	0.013	5.60	0.90	0.16	34.84	5.92	0.15	0.30	0.293
	MW9(US)	19.71	0.008	5.10	0.89	0.17	29.22	5.45	0.16	0.48	0.481
	MW9(DS)	19.74	0.033	5.40	1.71	0.32	17.05	6.03	0.28	0.41	0.717
Bagmati River	BW18(US)	4.53	0.002	8.00	1.03	0.13	62.14	8.26	0.12	0.33	0.386
	BW18(DS)	4.59	0.010	6.50	2.16	0.33	19.56	7.16	0.30	0.12	0.294
	BW16(US)	8.33	0.001	6.00	1.58	0.26	22.78	6.53	0.24	0.37	0.628
	BW16(DS)	8.40	0.008	5.30	1.13	0.21	24.86	5.73	0.20	0.43	0.571
	BW19(US)	9.50	0.002	10.10	1.48	0.15	68.93	10.39	0.14	0.22	0.422
	BW19(DS)	9.58	0.020	4.50	1.22	0.27	16.60	5.04	0.24	0.32	0.473
	BW12(US)	10.65	0.004	12.00	2.44	0.20	59.02	12.41	0.20	0.30	0.756
	BW12(DS)	10.68	0.013	10.50	2.06	0.20	53.52	10.89	0.19	0.50	1.076
	BW7(US)	14.15	0.001	24.00	6.00	0.25	96.00	24.50	0.24	0.28	1.703
	BW7(DS)	14.21	0.008	30.00	5.52	0.18	163.04	30.37	0.18	0.33	1.983
Dhobi Khola	DW27(US)	3.03	0.023	1.10	0.09	0.08	13.44	1.26	0.07	0.34	0.033
	DW27(DS)	3.12	0.011	1.30	0.18	0.14	9.39	1.58	0.11	0.32	0.062
	DW22(US)	4.61	0.008	2.20	0.36	0.16	13.44	2.53	0.14	0.23	0.085
	DW22(DS)	4.72	0.027	2.60	0.32	0.12	21.13	2.85	0.11	0.25	0.087
	DW14(US)	6.34	0.015	2.20	0.37	0.17	13.08	2.54	0.15	0.18	0.086
	DW14(DS)	6.45	0.009	2.30	0.27	0.12	19.59	2.53	0.11	0.43	0.116
	DW9(US)	7.59	0.005	6.50	0.98	0.15	43.11	6.80	0.14	0.28	0.292
	DW9(DS)	7.69	0.020	5.40	0.19	0.04	153.47	5.47	0.03	0.27	0.245
	DW2(US)	11.75	0.001	13.00	2.29	0.18	73.80	13.35	0.17	0.53	1.458
	DW2(DS)	11.9	0.027	8.00	1.44	0.18	44.44	8.36	0.17	0.46	1.974
Bishnumati River	BMW33(US)	11.13	0.018	3.20	0.30	0.09	34.04	3.39	0.09	0.30	0.104
	BMW33(DS)	11.23	0.035	4.00	0.50	0.13	31.75	4.25	0.12	0.23	0.116
	BMW28(US)	13.58	0.003	5.50	1.30	0.24	23.31	5.97	0.22	0.25	0.359
	BMW28(DS)	13.70	0.013	5.20	1.99	0.38	13.61	5.96	0.33	0.19	0.376
	BMW23(US)	21.23	0.001	7.20	1.66	0.23	31.30	7.66	0.22	0.30	0.522
	BMW23(DS)	21.33	0.013	5.00	0.98	0.20	25.51	5.39	0.18	0.47	0.507
	BMW18(US)	24.05	0.001	6.00	2.42	0.40	14.85	6.81	0.36	0.36	1.007
	BMW18(DS)	24.20	0.001	5.40	3.19	0.59	9.16	6.58	0.48	0.24	0.932
	BMW9(US)	26.68	0.001	6.40	4.99	0.78	8.21	7.96	0.63	0.33	1.715
	BMW9(DS)	26.80	0.008	4.80	1.75	0.36	13.17	5.53	0.32	0.62	1.256

stream of both rivers, values have wide difference. Lastly, discharge calculated at the Bishnumati River is 0.104–1.256 m^3/s, which gradually diminishes towards downstream, perhaps due to human influence such as river training activities, channel improvement work, and due to loss through substrates.

Grain size analysis

To calculated median grain size (d_{50}), Wolman Pebble counting method was adopted and graphical method was used. On the basis of grain size, streams are classified into sand bed and gravel bed with value ranged from 0.0001 m to 0.0008 m and 0.01 m to 0.2 m, respectively. The d_{50} at the Manahara River, the Bagmati River, the Dhobi Khola and the Bishnumati River varies from 0.0007 m to 0.025 m, 0.0002 m to 0.02 m, 0.0002 m to 0.013 m and 0.0002 m to 0.004 m, respectively. The range of d_{50} is similar in the Bagmati River and the Dhobi Khola but in the Manahara River and the Bishnumati River, it is quite different. Generally, grain size becomes finer towards downstream during normal runoff period of the stream. But, the trend line of the Dhobi Khola is increasing towards downstream of the river. This can be due to change in streambed sediment brought about by the river training s during study time. Since, all the range is in between 0.01 m to 0.2 m, all streams are gravel bed stream.

Suspended load and transport capacity

Sediment load in the main tributaries at the northern part of the Kathmandu Valley was calculated by multiplying the main suspended sediment concentration (SSC) in water at each cross-section by average discharge in the same cross-section. SSCs on the Manahara River, the Bagmati River, the Dhobi Khola and the Bishnumati River ranged from 12 to 588 mg/L, 21 to 163 mg/L, 82 to 600 mg/L, and 44 to 916 mg/L, respectively (Table 3). Among all streams, the Bishnumati River contributed maximum amount of SSC whereas the Dhobi Khola contributed minimum SSC. The sediment rating curve i.e., discharge versus suspended sediment concentration shows that negative correlation in the Bagmati River and the Dhobi Khola but anomalous result can be seen at DW22(US) of the Dhobi Khola. Similarly, at studied transects like MW22 (US and DS) and BW16(DS) and BW19(US), values increased exceptionally in the Manahara River and decrease in the Bagmati River. But the positive correlation could be seen in both streams. Anomalous results at individual transect could be resulted due to human influence near river channel; agriculture practice, deforestation etc.

Bed load and transport capacity

The calculation of rate of bed load was done using the Hassanzadeh (2007) type of common dimensionless formulas on the hydraulics of sediment transport. The existing relations were used to determine the rate of bedload in volume per unit time and unit width (qs) and rate of bedload in weight per unit time (Q_b). The rate of bed load transport (Q_s) has though increased (Fig. 4) from upstream portion of all major northern tributaries of the Bagmati River towards the downstream portion, the trend is fluctuating.

Bed load transport at the Manahara River is minimum (6 tonnes/day) at MW28(US) and maximum (393711 tonnes/day) at MW9(DS). At the Bagmati River it is minimum (15 tonnes/day) at BW18(US) and maximum (43124 tonnes/day) at BW19(DS). Similarly, at the Dhobi Khola it is minimum (6 tonnes/day) at DW2(US) and maximum (44071 tonnes/day) at DW22(DS). In the Bishnumati River, the minimum bedload is 23 tonnes/day at BMW9(US) and maximum is 40203 tonnes/day at BMW28(DS).

Total sediment yield

Total Sediment Yield (tonnes/km^2/day) at the Manahara River ranged from 0.53 Tonnes/km^2/day (MW28(US)) to 22029.64 tonnes/km^2/day (MW25(DS)) (Table 3). At the Bagmati River it ranged from 0.59 tonnes/km^2/day (BW18(US)) to 710.70 tonnes/km^2/day (BW19(DS)). At the Dhobi Khola the total sediment yield varies between 0.70 tonnes/km^2/day (at DW2 (US)) and 2493.22 tonnes/km^2/day (at DW22(DS)). Likewise, total sediment yield varied from 0.58 tonnes/km^2/day (at BMW9(US)) to 227.01 tonnes/km^2/day (at BMW33(DS)).

Stream power

Stream power (ω) is a measurement of the energy transfer (Bagnold, 1966) and is a stream power per unit

Table 3: Total sediment yield from different transects

River	Location	Distance (km)	Suspended Load, SSD (Tonnes/day)	Bedload, Q_b (Tonnes/day)	Total load (Tonnes/day)	Basin area contributing to site (km^2)	Total SY ($Tonnes/km^2/day$)
Manahara River	MW25(US)	1.20	27.36	123	150	7.10	21.16
	MW25(DS)	1.30	17.57	178423	178440	8.10	22029.64
	MW28(US)	8.54	8.06	6	15	27.33	0.53
	MW28(DS)	8.61	5.93	1420	1426	27.86	51.20
	MW22(US)	13.16	66.23	15	81	52.20	1.55
	MW22(DS)	13.23	114.68	232219	232334	52.48	4427.10
	MW16(US)	17.69	7.85	30	38	59.28	0.64
	MW16(DS)	17.76	18.58	7584	7602	59.61	127.53
	MW9(US)	19.71	9.70	103	113	73.79	1.53
	MW9(DS)	19.74	14.82	393711	393726	74.23	5304.14
Bagmati River	BW18(US)	4.53	9.29	15	25	42.00	0.59
	BW18(DS)	4.59	16.75	21286	21303	42.12	505.77
	BW16(US)	8.33	6.33	162	168	52.62	3.19
	BW16(DS)	8.40	3.18	155	158	52.70	3.00
	BW19(US)	9.50	5.73	140	146	59.90	2.44
	BW19(DS)	9.58	15.53	43124	43140	60.70	710.70
	BW12(US)	10.65	5.71	1230	1236	69.70	17.73
	BW12(DS)	10.68	3.41	1859	1862	69.90	26.64
	BW7(US)	14.15	3.45	265	268	73.65	3.65
	BW7(DS)	14.21	7.10	14231	14238	74.20	191.89
Dhobi Khola	DW27(US)	3.03	521.02	197	718	10.60	67.73
	DW27(DS)	3.12	235.51	162	397	10.76	36.91
	DW22(US)	4.61	609.88	3210	3820	17.46	218.77
	DW22(DS)	4.72	134.07	44071	44205	17.73	2493.22
	DW14(US)	6.34	82.38	1923	2005	19.13	104.81
	DW14(DS)	6.45	97.57	39	137	19.27	7.10
	DW9(US)	7.59	39.65	440	480	23.37	20.52
	DW9(DS)	7.69	51.13	168	219	23.48	9.32
	DW2(US)	11.75	14.04	6	20	28.78	0.70
	DW2(DS)	11.9	15.23	6094	6109	29.26	208.79
Bishnumati River	BMW33(US)	11.13	36.55	459	496	14.00	35.40
	BMW33(DS)	11.23	64.80	31843	31908	14.05	2271.01
	BMW28(US)	13.58	25.03	697	722	37.05	19.48
	BMW28(DS)	13.70	55.61	40203	40259	37.23	1081.36
	BMW23(US)	21.23	94.51	115	209	63.23	3.31
	BMW23(DS)	21.33	156.10	5669	5825	63.42	91.85
	BMW18(US)	24.05	37.15	78	115	71.22	1.62
	BMW18(DS)	24.20	31.24	253	284	71.34	3.99
	BMW9(US)	26.68	28.77	23	52	89.34	0.58
	BMW9(DS)	26.80	26.14	11032	11058	90.64	122.00

Table 4: Discharge and stream powers of the northern rivers in the Kathmandu Valley

River	Location	Distance (km)	τ_b (KN/m^2)	Area (m^2)	V (m/s)	Total discharge (m^3/s)	Slope (m/m)	$\Omega = \gamma QS$ (KN/s/m)	$\omega = \tau_{b*}V$ (KN/ms/m^2)
Manahara River	MW25(US)	1.20	0.016	0.18	0.32	0.060	0.022	0.013	0.005
	MW25(DS)	1.30	0.201	0.23	0.30	0.059	0.240	0.139	0.060
	MW28(US)	8.54	0.005	0.74	0.27	0.193	0.003	0.007	0.001
	MW28(DS)	8.61	0.037	0.54	0.36	0.204	0.040	0.080	0.013
	MW22(US)	13.16	0.006	1.10	0.63	0.711	0.004	0.030	0.004
	MW22(DS)	13.23	0.070	1.29	0.35	0.443	0.043	0.186	0.024
	MW16(US)	17.69	0.003	1.03	0.27	0.286	0.002	0.005	0.001
	MW16(DS)	17.76	0.020	0.90	0.30	0.293	0.013	0.038	0.006
	MW9(US)	19.71	0.013	0.89	0.48	0.481	0.008	0.038	0.006
	MW9(DS)	19.74	0.092	1.71	0.41	0.717	0.033	0.234	0.038
Bagmati River	BW18(US)	4.53	0.002	1.03	0.33	0.386	0.002	0.008	0.001
	BW18(DS)	4.59	0.030	2.16	0.12	0.294	0.010	0.029	0.004
	BW16(US)	8.33	0.002	1.58	0.37	0.628	0.001	0.006	0.001
	BW16(DS)	8.40	0.015	1.13	0.43	0.571	0.008	0.045	0.007
	BW19(US)	9.50	0.003	1.48	0.22	0.422	0.002	0.008	0.001
	BW19(DS)	9.58	0.047	1.22	0.32	0.473	0.020	0.093	0.015
	BW12(US)	10.65	0.008	2.44	0.30	0.756	0.004	0.030	0.002
	BW12(DS)	10.68	0.024	2.06	0.50	1.076	0.013	0.137	0.012
	BW7(US)	14.15	0.002	6.00	0.28	1.703	0.001	0.017	0.001
	BW7(DS)	14.21	0.014	5.52	0.33	1.983	0.008	0.156	0.005
Dhobi Khola	DW27(US)	3.03	0.016	0.09	0.34	0.033	0.023	0.007	0.005
	DW27(DS)	3.12	0.012	0.18	0.32	0.062	0.011	0.007	0.004
	DW22(US)	4.61	0.011	0.36	0.23	0.085	0.008	0.007	0.003
	DW22(DS)	4.72	0.030	0.32	0.25	0.087	0.027	0.023	0.008
	DW14(US)	6.34	0.022	0.37	0.18	0.086	0.015	0.013	0.004
	DW14(DS)	6.45	0.009	0.27	0.43	0.116	0.009	0.010	0.004
	DW9(US)	7.59	0.007	0.98	0.28	0.292	0.005	0.014	0.002
	DW9(DS)	7.69	0.007	0.19	0.27	0.245	0.020	0.048	0.002
	DW2(US)	11.75	0.002	2.29	0.53	1.458	0.001	0.021	0.001
	DW2(DS)	11.9	0.045	1.44	0.46	1.974	0.027	0.516	0.020
Bishnumati River	BMW33(US)	11.13	0.015	0.30	0.30	0.104	0.018	0.018	0.005
	BMW33(DS)	11.23	0.040	0.50	0.23	0.116	0.035	0.039	0.009
	BMW28(US)	13.58	0.006	1.30	0.25	0.359	0.003	0.011	0.002
	BMW28(DS)	13.70	0.043	1.99	0.19	0.376	0.013	0.049	0.008
	BMW23(US)	21.23	0.002	1.66	0.30	0.522	0.001	0.005	0.001
	BMW23(DS)	21.33	0.024	0.98	0.47	0.507	0.013	0.066	0.011
	BMW18(US)	24.05	0.003	2.42	0.36	1.007	0.001	0.009	0.001
	BMW18(DS)	24.20	0.005	3.19	0.24	0.932	0.001	0.010	0.001
	BMW9(US)	26.68	0.004	4.99	0.33	1.715	0.001	0.010	0.001
	BMW9(DS)	26.80	0.023	1.75	0.62	1.256	0.008	0.092	0.014

of bed area. The stream power per unit of bed area is shown in the Table 4 for major tributaries of the Bagmati River in the northern part. The stream power ranged from 0.001 to 0.060 KN/ms/m^2 in the Manahara River, 0.001 to 0.15 KN/ms/m^2 in the Bagmati River, 0.001 to 0.020 KN/ms/m^2 in the Dhobi Khola and 0.001 to 0.014 KN/ms/m^2 in the Bishnumati River. The stream power was very high at MW25(DS) of the Manahara River, and its linear trend was continuously decreasing towards downstream (Fig. 5). The Bagmati and the Bishnumati Rivers had stream power almost constant throughout studied transects. However, in case of the Dhobi Khola, it was gradually increasing towards downstream.

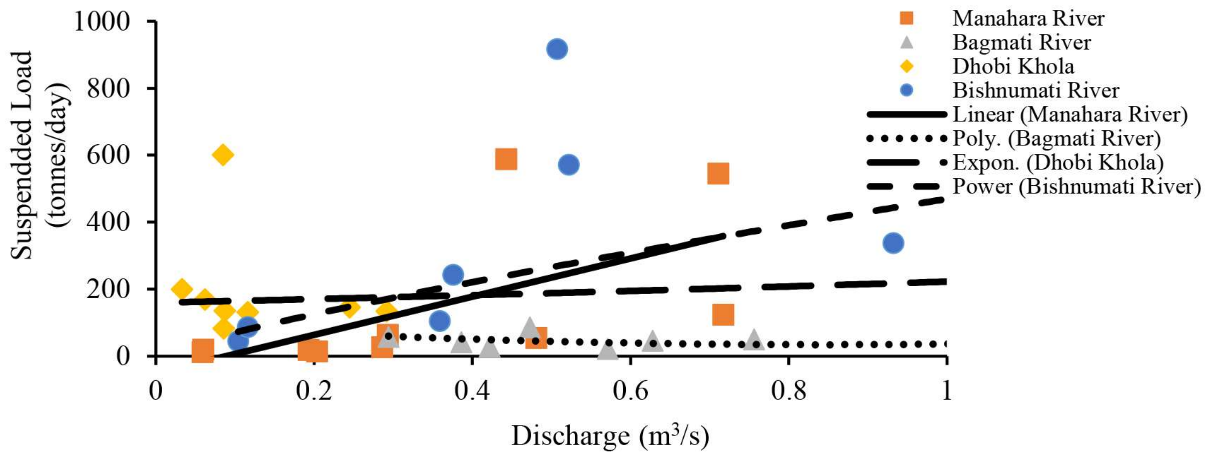

Fig. 4 Sediment rating curves: (a) Sediment load and (b) bed load for different rivers

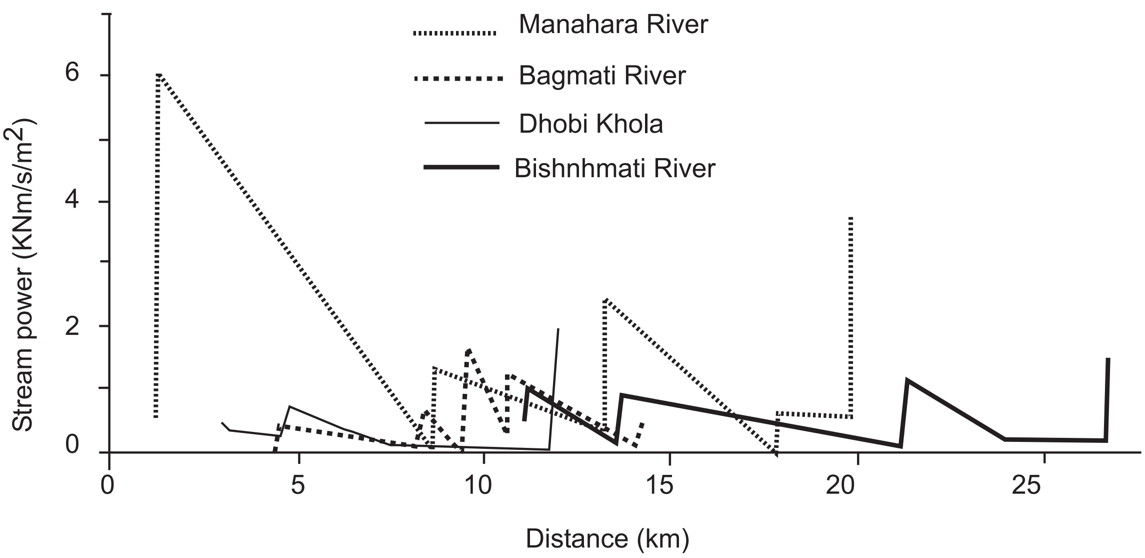

Fig. 5 Trends of stream power of different rivers in the northern Kathmandu Valley

Table 5: Shear velocity, particle Reynolds number, shear stresses and dimensionless shear stresses

River	Location	Distance (km)	Water temp	d_{50}, m	γ, KN/m^3	R_h, m	S, m/m	τ_b, KN/m^2	τ_b^*	μ, . 10^{-6}, m^2/s	ρ, Kg/m^3	$U^* = (\tau_b/\rho)^{0.5}$, m/s	$R_{ep}^* = (U^* d_{50})/\mu$	τ_c^*	$\tau^*/\tau_c^*{}_b$
Manahara River	MW25(US)	1.20	27.20	0.012	9.777	0.07	0.022	0.045	0.2254	0.893	995.7	0.212	2845	0.060	3.76
	MW25(DS)	1.30	26.10	0.005	9.777	0.09	0.240	0.537	6.5064	0.893	995.7	0.734	4111	0.060	108.44
	MW28(US)	8.54	28.90	0.022	9.765	0.13	0.003	0.013	0.0368	0.800	995.7	0.116	3186	0.060	0.61
	MW28(DS)	8.61	28.90	0.020	9.765	0.09	0.040	0.109	0.3315	0.800	995.7	0.331	8286	0.053	6.25
	MW22(US)	13.16	30.50	0.025	9.765	0.13	0.004	0.017	0.0422	0.800	995.7	0.132	4132	0.060	0.70
	MW22(DS)	13.23	30.00	0.001	9.765	0.17	0.043	0.214	16.1916	0.800	995.7	0.463	463	0.060	269.86
	MW16(US)	17.69	30.00	0.002	9.765	0.16	0.002	0.009	0.3113	0.800	995.7	0.094	199	0.060	5.19
	MW16(DS)	17.76	29.50	0.001	9.765	0.15	0.013	0.060	4.5290	0.800	995.7	0.245	245	0.060	75.48
	MW9(US)	19.71	26.50	0.018	9.777	0.16	0.008	0.035	0.1166	0.893	995.7	0.186	3759	0.060	1.94
	MW9(DS)	19.74	25.10	0.001	9.777	0.28	0.033	0.237	20.531	0.893	995.7	0.488	383	0.060	342.18
Bagmati River	BW18(US)	4.53	22.40	0.0030	9.789	0.12	0.002	0.006	0.1129	1.003	998.2	0.075	224	0.052	2.17
	BW18(DS)	4.59	22.90	0.0009	9.789	0.30	0.010	0.069	4.6491	0.893	998.2	0.263	265	0.042	110.69
	BW16(US)	8.33	22.90	0.0002	9.789	0.24	0.001	0.006	1.6799	0.893	998.2	0.075	17	0.032	52.50
	BW16(DS)	8.40	22.70	0.0200	9.789	0.20	0.008	0.036	0.1086	0.893	998.2	0.189	4244	0.060	1.81
	BW19(US)	9.50	24.50	0.0006	9.777	0.14	0.002	0.007	0.7291	0.893	998.2	0.084	54	0.038	19.19
	BW19(DS)	9.58	24.70	0.0010	9.777	0.24	0.020	0.120	7.2440	0.893	998.2	0.346	388	0.056	129.36
	BW12(US)	10.65	22.60	0.0010	9.789	0.20	0.004	0.018	1.0775	0.893	998.2	0.133	149	0.050	21.55
	BW12(DS)	10.68	23.10	0.0100	9.789	0.19	0.013	0.057	0.3442	0.893	998.2	0.239	2671	0.060	5.74
	BW7(US)	14.15	24.80	0.0005	9.777	0.24	0.001	0.006	0.7362	0.893	998.2	0.078	44	0.032	23.01
	BW7(DS)	14.21	25.00	0.0010	9.777	0.18	0.008	0.036	2.2033	0.893	998.2	0.191	214	0.050	44.07
Dhobi Khola	DW27(US)	3.03	30.90	0.0035	9.765	0.07	0.023	0.050	0.8711	0.800	995.7	0.225	983	0.060	14.52
	DW27(DS)	3.12	31.00	0.0027	9.765	0.11	0.011	0.039	0.8825	0.800	995.7	0.199	671	0.060	14.71
	DW22(US)	4.61	32.00	0.0002	9.765	0.14	0.008	0.038	11.9917	0.800	995.7	0.194	46	0.050	239.83
	DW22(DS)	4.72	29.90	0.0002	9.765	0.11	0.027	0.092	30.8699	0.800	995.7	0.303	68	0.053	582.45
	DW14(US)	6.34	29.70	0.0016	9.765	0.15	0.015	0.067	2.5248	0.800	995.7	0.259	517	0.060	42.08
	DW14(DS)	6.45	29.50	0.0100	9.765	0.11	0.009	0.029	0.1731	0.800	995.7	0.169	2117	0.060	2.89
	DW9(US)	7.59	27.90	0.0011	9.765	0.14	0.005	0.019	1.0674	0.800	995.7	0.139	192	0.050	21.35
	DW9(DS)	7.69	28.20	0.0024	9.765	0.03	0.020	0.020	0.4947	0.800	995.7	0.140	421	0.058	8.53
	DW2(US)	11.75	26.40	0.0130	9.777	0.17	0.001	0.007	0.0312	0.893	995.7	0.082	1193	0.060	0.52
	DW2(DS)	11.9	27.50	0.0110	9.765	0.17	0.027	0.126	0.6960	0.893	995.7	0.356	4387	0.060	11.60
Bishnumati River	BMW33(US)	11.13	20.80	0.0040	9.789	0.09	0.018	0.033	0.4938	1.003	998.2	0.181	721	0.060	8.23
	BMW33(DS)	11.23	23.50	0.0008	9.789	0.12	0.035	0.096	7.3047	0.893	998.2	0.311	278	0.060	121.74
	BMW28(US)	13.58	22.90	0.0005	9.789	0.22	0.003	0.015	1.8009	0.893	998.2	0.122	68	0.040	45.02
	BMW28(DS)	13.70	25.10	0.0010	9.777	0.33	0.013	0.111	6.7555	0.893	995.7	0.335	375	0.058	116.47
	BMW23(US)	21.23	26.50	0.0002	9.777	0.22	0.001	0.005	1.5782	0.893	995.7	0.072	16	0.045	35.07
	BMW23(DS)	21.33	26.30	0.0015	9.777	0.18	0.013	0.064	2.5751	0.893	995.7	0.253	425	0.055	46.82
	BMW18(US)	24.05	27.80	0.0009	9.765	0.36	0.001	0.009	0.6200	0.800	995.7	0.096	108	0.040	15.50
	BMW18(DS)	24.20	28.40	0.0009	9.765	0.48	0.001	0.016	1.0580	0.800	995.7	0.126	141	0.060	17.63
	BMW9(US)	26.68	28.50	0.0040	9.765	0.63	0.001	0.010	0.1559	0.800	995.7	0.102	508	0.060	2.60
	BMW9(DS)	26.80	28.90	0.0007	9.765	0.32	0.008	0.069	5.9396	0.800	995.7	0.262	230	0.052	114.22

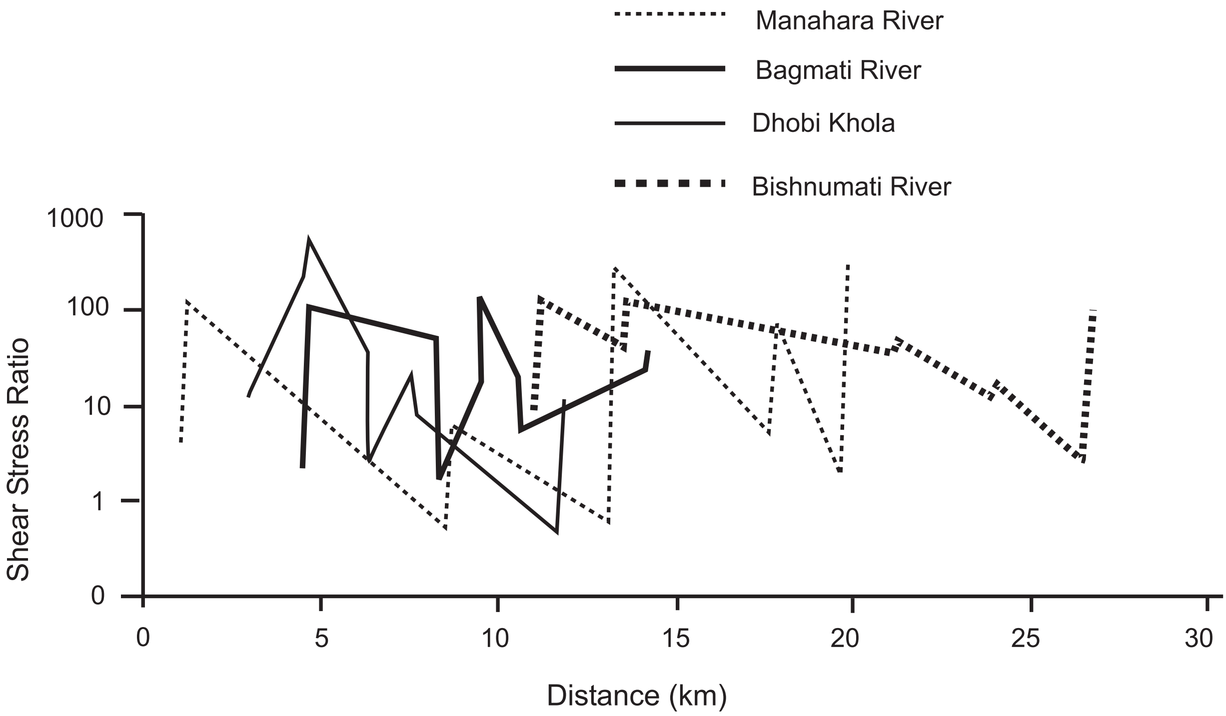

Fig. 6 Variation of the shear stress ratio of different rivers in the northern Kathmandu Valley

Stream competence

Stream competence evaluation in the main tributaries of the Bagmati River in the northern part was evaluated with boundary shear stress and critical boundary stress ratio in each transects of the rivers. The shear stress ratio of all the transects of the Bagmati River was higher than 1 (Table 5). It referred to that the studied transects have erosivity which was competent to erode sediments from the stream transects. The shear stress ratio gradually increased towards the downstream (Fig. 6) although the trends are fluctuating. The same trend was followed by the Bishnumati River and other streams, however, the shear stress ratio gradually diminished towards downstreams. Two transects MW28(US) and MW22(US) of the Manahara River and transect DW2(US) of the Dhobi Khola had the shear stress ratios less than unity and showed their incompetency.

CONCLUSIONS

The Bagmati River basin is non-glacial river basin, in which discharge mainly is dependent upon rain fall. The Bagmati River basin in the northern Kathmandu Valley consists of four main tributaries the Manahara River, Bagmati River, the Dhobi Khola and the Bishnumati River. The four major tributaries including the Bagmati River were upto sixth stream order. Fluvial geomorphology of the Bagmati River in its northern part is influenced by the mass wasting, flooding, bank erosion, sediment erosion, transport and deposition, and vegetation growth phenomena as well as the dominant anthropogenic activities. Increasing population and changing in land use pattern have affected the stream discharge and sediment transport capacity of the river that ultimately has influenced the river sediment dynamics.

The study revealed that the water discharge was varying from location to location and river to river. The minimum water discharge was 0.033 m^3/s at Tankal of the Dhobi Khola and maximum (1.983 m^3/s) at Sankhamul of the Bagmati river. The lowest median grain size distribution (d_{50}) was 0.0002 m at Gokarneshor Temple area of the Bagmati River and the highest was 0.0250 m at Changunarayan of the Manahara River. The study found that suspended load for dry season varied from the 916 (Naya bus park area) to 12 mg/L (Sankhu of the Manahara River) and bed load 6 Tonnes/day (Sankhu and Salmutar) to 393711 Tonnes/day (Narephat of the Manahara River). The total sediment yield was ranging from 0.53 (Sankhu, Salmutar of the Manahara River) to 22029.64 Tonnes/km^2/day (Sankhu of the Manahara River). The boundary shear stress and the critical shear stress were ranging from 0.0312 to 30.87 N/m^2 and 0.032 N/m^2 to 0.06 N/m^2, respectively. The stream power was found to range from 0.001 to 0.06 KNm/s/m^2. The study was carried out during the dry season therefore the results only represent the outcomes for the dry period only, and the study helps to proper engineering hydraulic practices around the tributaries corridor.

Some sites for instance, Salmutar (Sankhu) and Changunarayan of the Manahara River had more erodibility. Such sites need river training to protect from the scouring of river during particular season. Thus, spotted sensitive area which is highly erodible; Bhuddhanagar of the Dhobi Khola, Dalanepul of the Dhobi Khola, Nayabasti (Jorpati), Tinkune (Gairigaun) of the Bagmati River should be channel improved using favorable techniques such as gabion wall construction, riprap, etc.

Sand mining and quarry at channel and bank areas reduced the stability of area and supported the channel shifting. Therefore, mining should be done in a scientific way. Year-wise monitoring of rivers by installing the river gauge stations in the channel in different locations should be done to study the anthropogenic influence on the stream characteristics.

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