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MORPHO-HYDRAULIC CHARACTERISTICS AND SEDIMENT DYNAMICS OF TWO GRAVELLY STREAMS FLOWING OVER THE SIWALIK TERRAIN, CENTRAL NEPAL SUB-HIMALAYA

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ABSTRACT:
The Pantale Khola and the Thado Khola both are the fourth order streams originating from the Churia Hills and flowing on the gravelly terrain towards the north and ultimately mixing to the Rapati Nadi. The total area of the study area is 64 km^2. The fluvial condition of these streams originating from the Churia Hills along with their characteristics, sediment transport and sediment dynamics were studied. Geomorphic characterization of both the streams were accomplished using the help of topographic maps and satellite imageries. Five stream transects on each of the stream were surveyed for cross-sections and longitudinal profiles. Samples were collected from the thalweg of each transect for suspended sediment concentration and Wolman's pebble counting method was applied for establishing grain size distribution. The Rosgen classification of streams was applied to classify the stream reaches. Manning's roughness coefficient was calculated on the features as seen on the field and hence discharge was calculated. The streams have been classified as F4 type for the Pantale Khola and F4, F4b types for the Thado Khola. The bed load was calculated and hence total sediment load was also calculated. Both the streams show the eroding potential as found out from the stream power.

KEYWORDS:
Fluvial morphology, hydraulic parameters, stream classification, sediment load, stream power

INTRODUCTION

Rivers and streams are the systems in dynamic equilibrium, which means it balances water flow and sediment transport by the process of erosion and deposition. The Rosgen stream classification categorizes streams according to the channel morphology [1] so that the consistent and quantitative descriptions can be made. In the Sub-Himalayas, the huge sedimentation within the basins here could be because of fluvial characteristics [2] and fragile lithology [3, 4]. The fluvial characteristics are in turn influenced by topography and climate [5], tectonics and weathering [6], composition of source area and riverbed materials. Therefore, understanding of sediment dynamics of the region is important concern in order to mitigate and control in the future the sediment related disasters [7]. Due to the higher discharge of a stream on the proposed study area during monsoon, it may cause stream to become wider and deeper and also the sediment yield on the stream will be progressively high due to higher rainfall rate on its source area.

Stream power, which is the product of stream discharge, stream slope, and the specific weight of water, has a direct relationship with sediment transport. This relationship has been used to characterize sediment transport and investigate

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geomorphic questions across a range of time and spatial scales, from the instantaneous rate of sediment transport at a river cross section [8] to the evolution of river long profiles across mountain ranges over geologic time [9]. Stream power has been shown to influence channel pattern and form [10, 11, 12], riffle and pool characteristics [13], channel migration [14, 15], channel aggradation and degradation [16], floodplain dynamics [17], extreme geomorphic changes in floods [18, 19], stream bed grain size [20], abundance of landslides [21], and bedrock incision rates [22, 23, 24]. This relationship between stream power and sediment load has been utilized in engineering-style studies to quantify sediment loads and erosion/deposition budgets and also in geomorphology research to explain landscape form and processes [25]

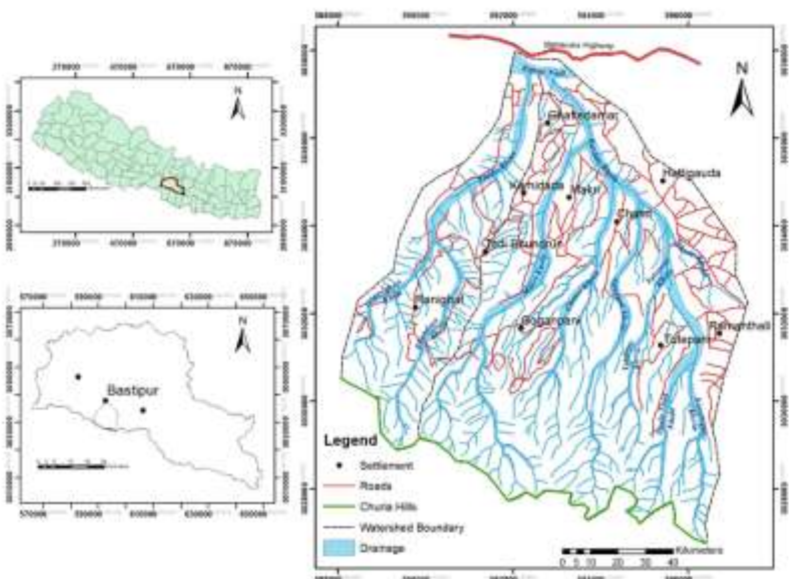

Figure 1 Location map of the study area.

The present study has been concluded on the Pantale Khola and Thado Khola (Figures 1) which are both fourth order streams flowing from the Siwalik (Churia) Range over the gravelly siliciclastic terrain. As the stream classification is needed to predict the behavior of the streams and also to develop specific hydraulic and sediment relationship for the given stream type, an attempt has been made to understand the flow dynamics of both streams along with the basic geomorphic parameters.

Geological Setting

The study area lies in the Siwalik Group of central Nepal, the age of which ranges from Middle Miocene to Early Pleistocene [26]. The study area comprises portions of both the southern and northern Siwalik Belts extending roughly NW-SE. The Upper Siwalik Subgroup of the southern part is thrust over by the Lower Siwalik Subgroup of the northern part, therefore creating a Dun Valley, and thus the thrust is known as the Main Dun Thrust (MDT) (Figure 2). The Lower Siwalik subgroup is mainly made up of variegated mudstones and shales with thin interbedded layers of sandstone while the Upper Siwalik Subgroup consists of loosely consolidated pebble and cobble conglomerates

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with the subangular clasts of quartzite, sandstone, phyllite, slate and granite along with minor intercalation of sandstone and mudstones. The study area also consists of the Late Quaternary Deposits such as gravel, sand and mud.

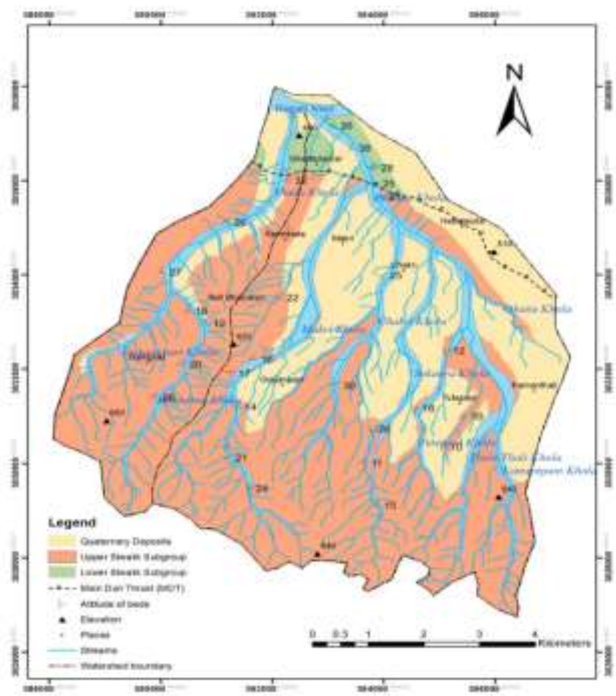

Figure 2 Geological map of the study area.

Topography and drainage

The study area comprises of steeper terrain in the southern boundary which is demarcated by the Churia Range while the northern and central parts consist of flatter fluvial terraces (Figure 2). The altitude ranges from 402 m (near mouth of the Thado Khola) to 849 m (at southern boundary or the Churia Hills). The study area covers an area of about 64 km2. The streams, the Pantale Khola and the Thado Khola considered during the study originate from the Churia Range and contribute to the Rapati Nadi, which is at the northern boundary of the study area. Various other ephemeral streams act as tributaries for the two major streams. The major tribiutaries of the Pantale Khola are Chakri Khola, Makri Khola, Sukaura Khola, Tutepani Khola, Kamerepani Khola and Ghatte Khola. Also, the tributaries of the Thado Khola are Goganghari Khola and Bhundrun Khola. Most of the tributaries originate from the Churia Hills. Both of the streams under study are of 4th order and the drainage patterns observed in both of the streams are dendritic and parallel drainage pattern.

MATERIALS AND METHODS

The morphological characteristics along with the sediment transport within the channel was studied. The morphological characteristics were studied to classify the streams as according to the Rosgen Stream Classification.

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- Level I classification of the streams is the geomorphic characterization of the streams which is an integral result of basin relief, landform and valley morphology. The parameters such as stream ordering [27, 28], valley types were determined using topo-maps of the scale 1:25,000 while the planform parameters of streams such as meander belt width, meander wavelength, radius of curvature and sinuosity which reflects the stability condition of the streams were measured using topo-maps of scale 1:10,000.
- Level II classification consists of the cross-sectional survey for determining the hydraulic parameters of the streams and longitudinal survey for determining the stream channel slope and water surface slope. For this, five segments on each stream were selected (Figure 3). The survey was carried out using levelling instrument, staffs and measuring tape.

Wolman's pebble counting method [29] was adopted across all the five transects on each stream. The particle distribution curve was used to calculate the D50 and D84 values.

The entrenchment ratio (ER), width-depth (W/D) ratio, sinuosity was used to classify the streams. The stream type was further classified detailly using the slope of the channel and particle size.

The calculation of the bed-load of both the streams were done using Hassanzadeh equation [30]. The relation was used to calculate the rate of bedload in volume per unit width and per unit time (q_b), and rate of bedload in weight per unit time (Q_b).

$$q_b = 24f^{2.5}(agd^3)^{1/2}$$
$$\tau_b = \gamma R_h S$$
$$a = \gamma_s\text{-}\gamma/\gamma$$
$$f = \tau_b/(\gamma_s\text{-}\gamma)d$$

where, q_b = bedload in (m^2/s), g = acceleration due to gravity = 9.80 m/s^2, d = median grain diameter (d_{50}), f = hydrodynamic immersed gravity force ratio, R_h = hydraulic radius, γ = specific weight of water = 9.807 KN/m3, γ_s = specific weight of sediment = 26.5 KN/m^3, a = immersed sediment specific gravity, γ_s -γ = submerged specific weight of sediment, KN/m^3, τ_b = boundary shear stress

$$Q_b = \gamma_s W q_b$$

where, Q_b = bedload in KN/s, W = width in (m)

The Suspended Sediment Concentration (SSC) in the streams is mainly due to erosion on the banks and watershed. It determines the concentration of solid particles present in the surface water and is expressed as mg/l. It was measured by filtration method. The dry weight of the sediment is thus obtained from known volume of the sample water.

The shear stress on the stream channel was calculated using Shield's equation [31] which determines whether the stream is competent or incompetent to erode the channel materials.

For boundary shear stress (Shields 1936),

$$\tau_b = \rho g R S$$

Critical shear stress (τ_c) for d_{50} were calculated using the following relation: $\tau_c = \theta_c*(s-1)\,\rho g*d_{50}$, where, τ_b = boundary shear stress, (N/m^2), R = Hydraulic radius (m), S = Average stream slope (m/m), θc = Shields parameter for critical dimensionless shear stress taken from shields curve, s = specific gravity of the partcals and is calculated as the ratio of the specific weight of the sediments (γ_s) to the specific weight of water (γ), g = gravitational constant, d_{50} = median diameter of particles, ρ_c = density of sediments and ρ = density of water.

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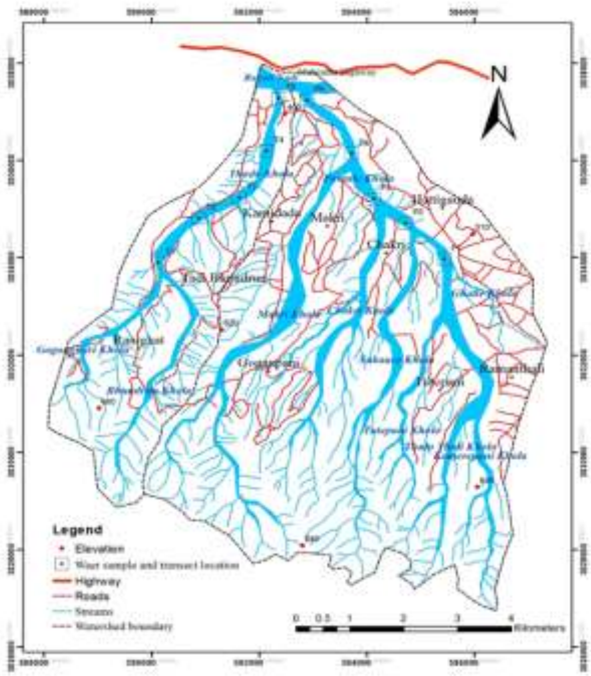

Figure 3 Water sampling and transects location.

RESULTS AND DISCUSSION

Morpho-hydraulic parameters

The stream cross-sections were taken at various places (Figure 3, 4, 5 and 6) of the both the streams for the determination and calculation of various hydraulic parameters. The measured parameters are bankfull cross-sectional area, width/depth of the channel, hydraulic radius, slope, etc.Varying bankfull cross-sectional area and the channel cross sectional area were found at the different survey locations (Table 1). As both the streams are somewhat braided, the cross-sectional area at bankfull flow are greater in number. The bankfull channel cross-section area has its highest value along the transect P2 of the Pantale Khola and transect T3 of the Thado Khola with the values of 169.53 m^2 and 108.07 m^2 respectively. Transect P3 and T1 has the lowest cross-sectional area of 93.59 m^2 and 27.5 m^2. The discharge varies from location to location. The highest value of hydraulic radius on the Pantale Khola as calculated is 0.91m in transect P2 and the lowest value is 0.55 m in transect P5 (Table 1). Similarly, the highest value of hydraulic radius in the Thado Khola is 0.94 m in transect T5 and the lowest value is 0.36 m in transect T4. The data obtained from the Wolman's pebble count (Table 2) were plotted so that D_{50} and D_{84} values were obtained from the grain size distribution curve (Figure 7 and 8). Both the streams have the almost same textured sediments, which is also shown by the graph (Figure 9). As the geology is the governing factor for the slope of the area, the gradient of the both streams are higher at the source areas (southern part) and decreases further downstream. Slope was measured using a levelling instrument. The value was highest at the transect P4 of the Pantale Khola which is 0.0118 and also at transect T4 of the Thado Khola which is 0.0248. The highest velocity in the Pantale Khola is 1.735 m/s which is measured at transect P4 and in the Thado Khola is 2.810 m/s which is measured at transect T5. The hydraulic geometry relation of the Pantale

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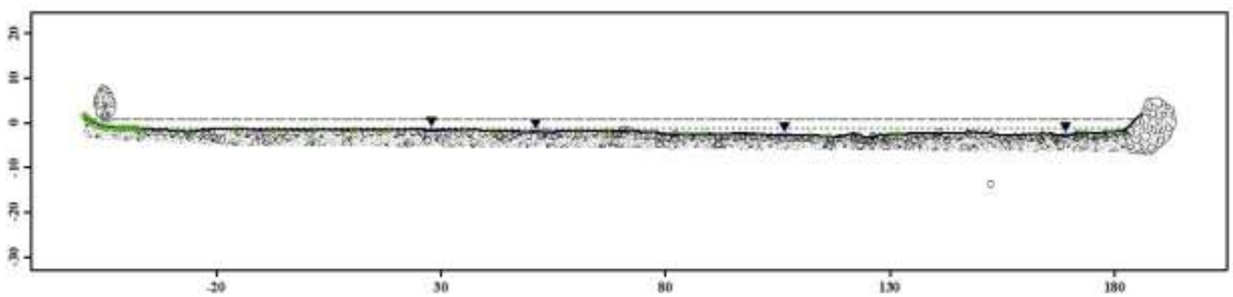
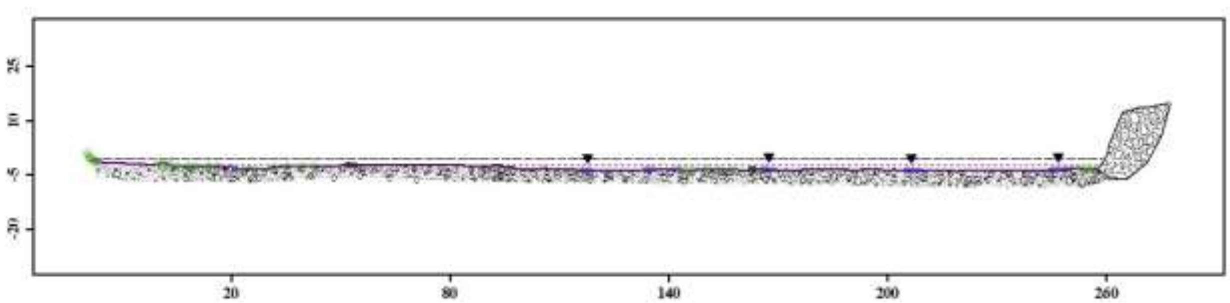
Khola shows almost same discharge and velocity trend on going towards downstream except for the transect P3 which is due to low slope (Figure 10), while the velocity and discharge trend shows increasing pattern in case of the Thado Khola but eventually it has its greater value on the downstream point (Figure 11).

The Pantale and the Thado Khola both are the fourth order streams originating from the southern Churia hills. The stream segments of both the Pantale and Thado Khola falls under A, B categories. A-type streams can be observed in the southern part near the source areas, while B-type streams are flowing on the middle and the northern part of the study area over the Quaternary deposits of both the Lower Siwalik and the Upper Siwalik.

The A-type streams are developed on the first order of both streams which are narrow channels with greater degree of entrenchment, lower width to depth, lower sinuosity and steeper slopes as compared to the other streams. Similarly, the B-type streams are developed on the 2nd, 3rd and 4th order which have moderate to varying entrenchment, wide channel to depth ratio (W/D ratio).

The higher value of n is calculated at the downstream portions of the Pantale Khola while the Thado Khola has almost similar n-values. Ramser collected data and computed roughness coefficients for drainage channels before and after dredging or straightening, and during growing- and non-growing-season conditions [32]. Cowan used Ramser's data to compute roughness coefficient adjustment values for five primary factors of energy loss for open channel flows [33]. As the basin area increases, the sources contributing the streams also increases which is the main reason for the increase of discharge of river downstream. In case of the Pantale Khola, there is a sudden decrease in the discharge of the river at some P3 which may be due to the less slope and velocity of the channel. Also, discharge is also affected significantly by cross-section area of the stream, resulting in higher discharge volume at transects with higher sectional area. Tamrakar calculated the river discharge of the Bishnumati River was 10.53 m^3/s in six-order stretch of the river which is much less than the Pantale and Thado Khola [34].





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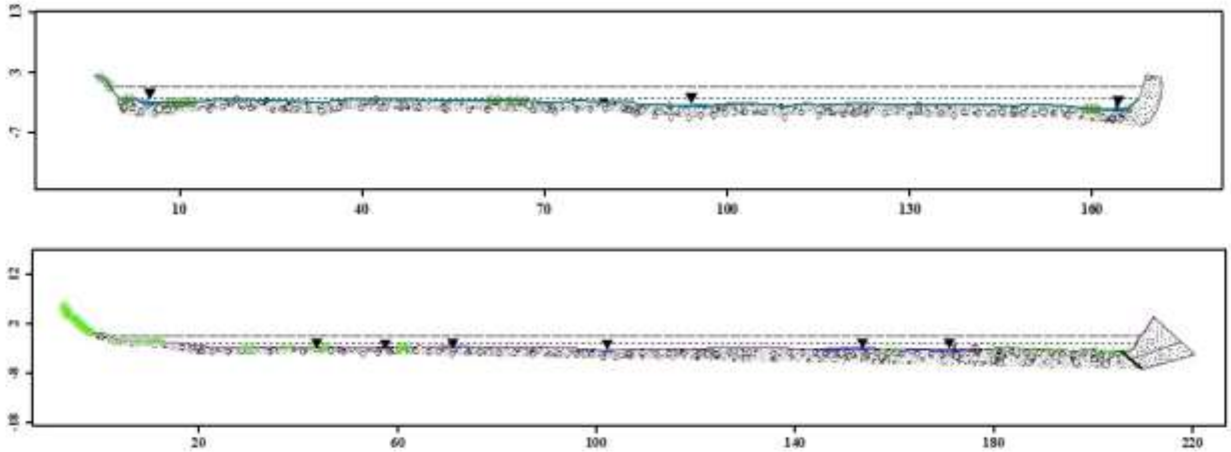
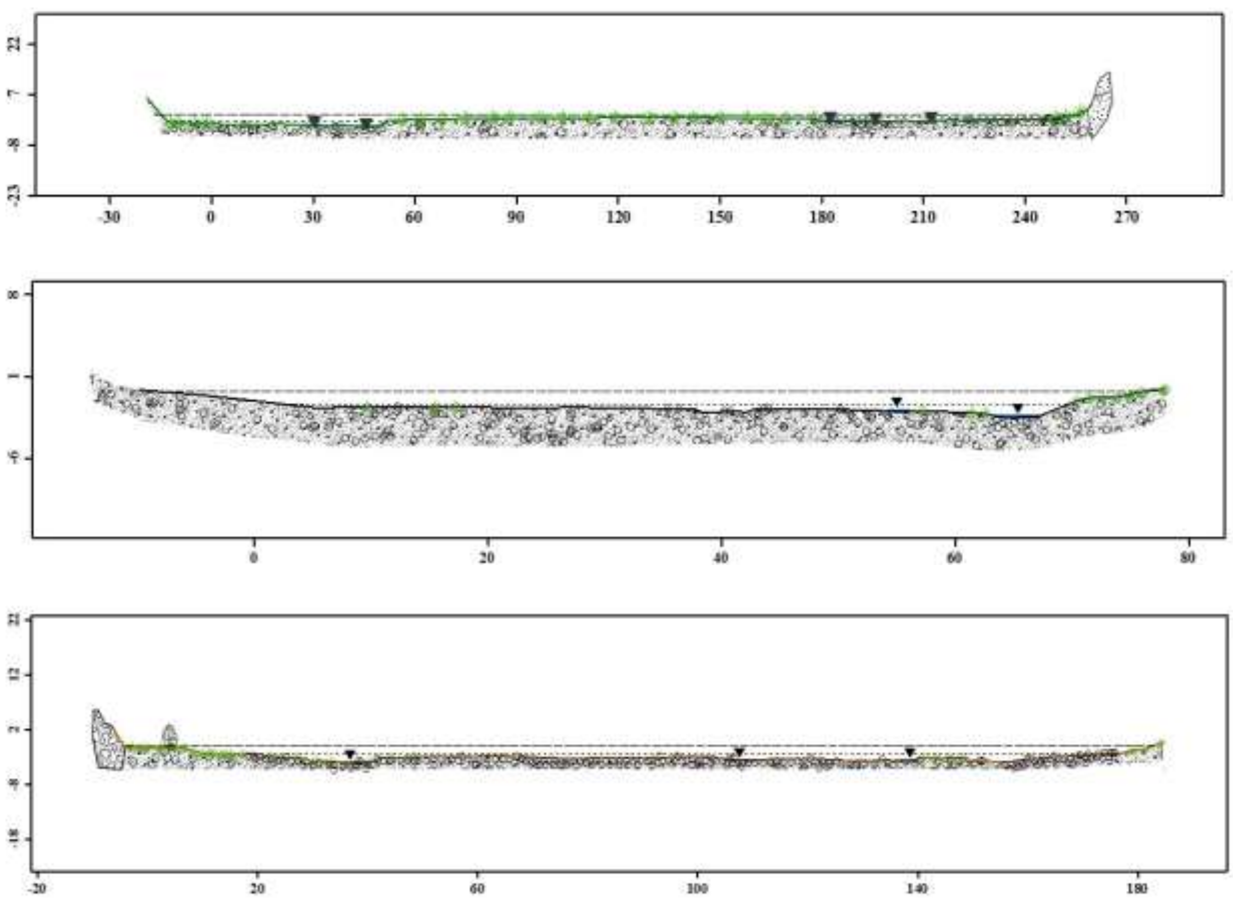


Figure 4 Cross-sections of transect P1, P2, P3 and P4 of the Pantale Khola respectively.



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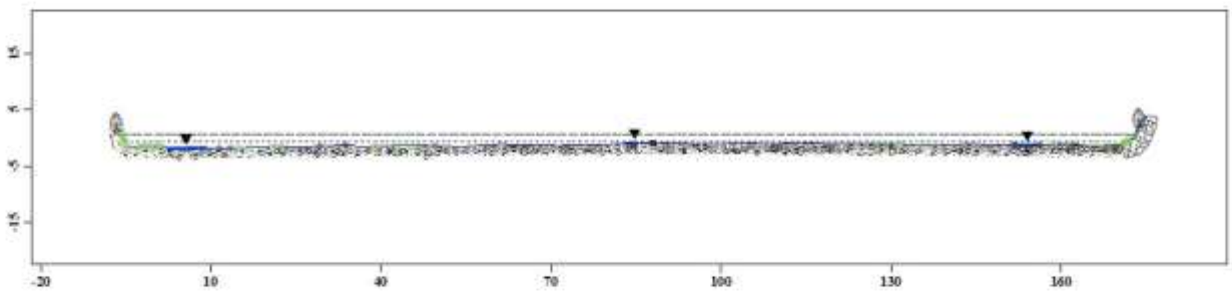

Figure 5 Cross-sections of P1, T1, T2 and T3 transects respectively.

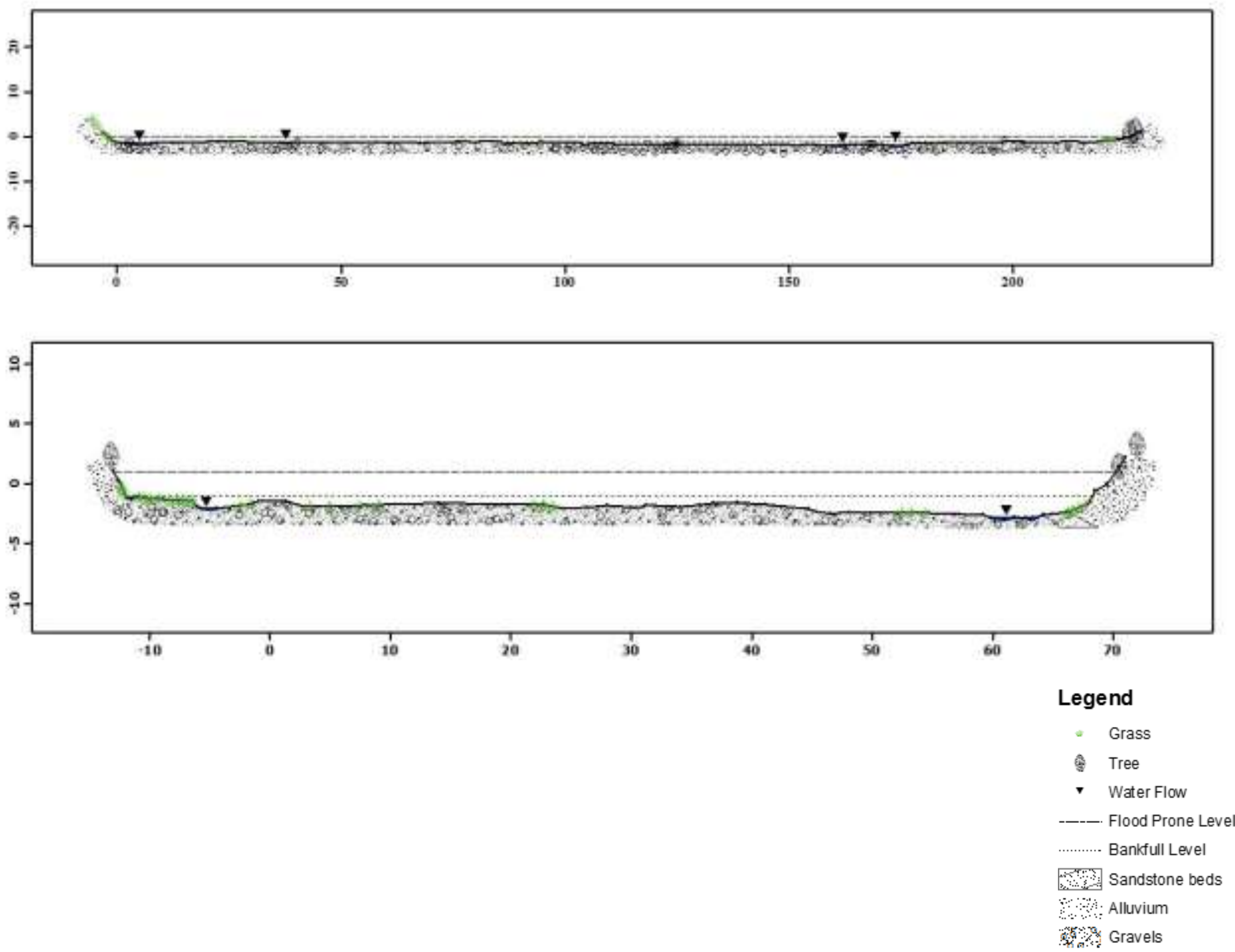

Figure 6 Cross-section of transect T4 and T5 of the Thado Khola respectively.

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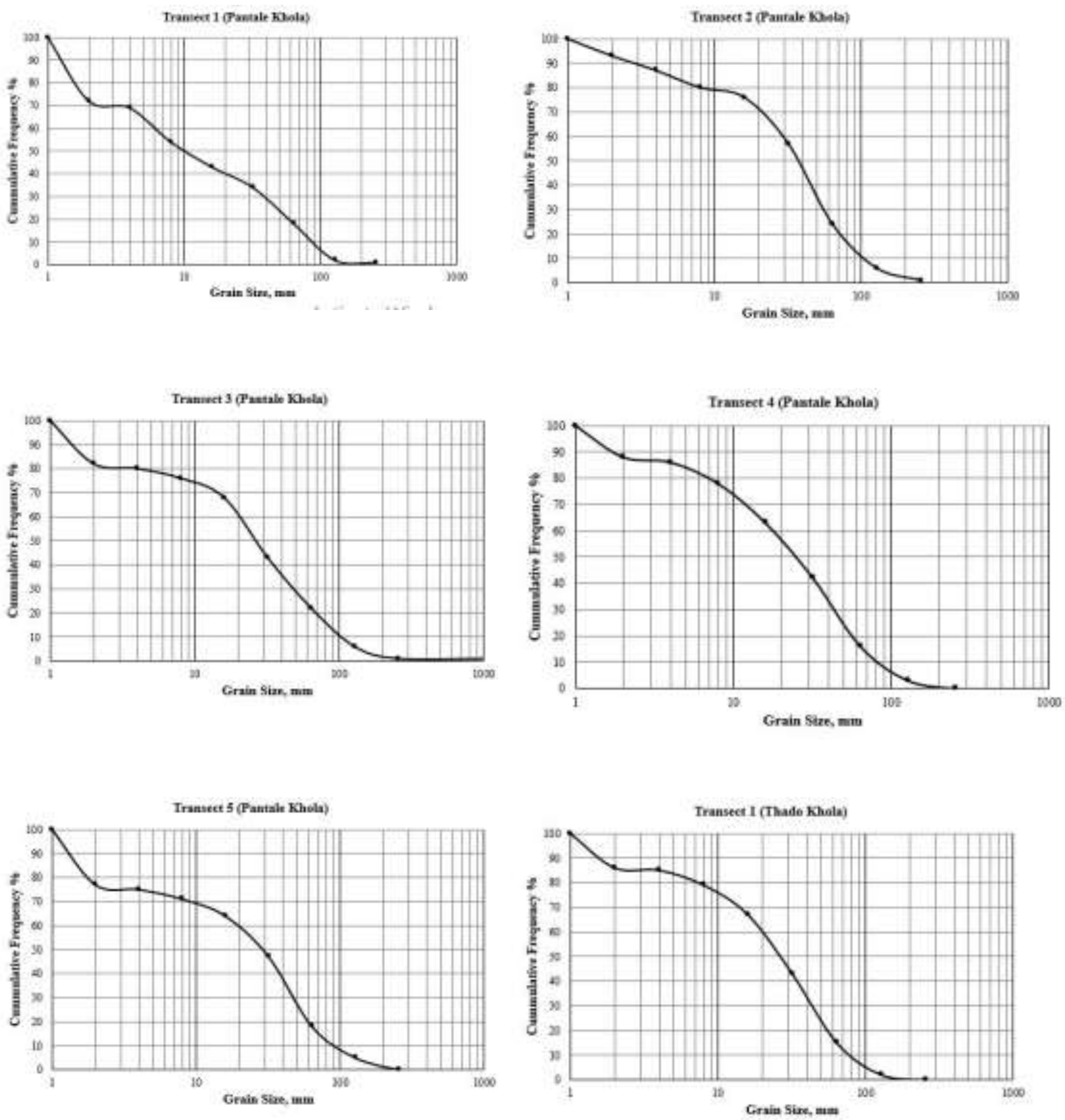

Figure 7 Grain size distribution curves of the Pantale and Thado Khola.

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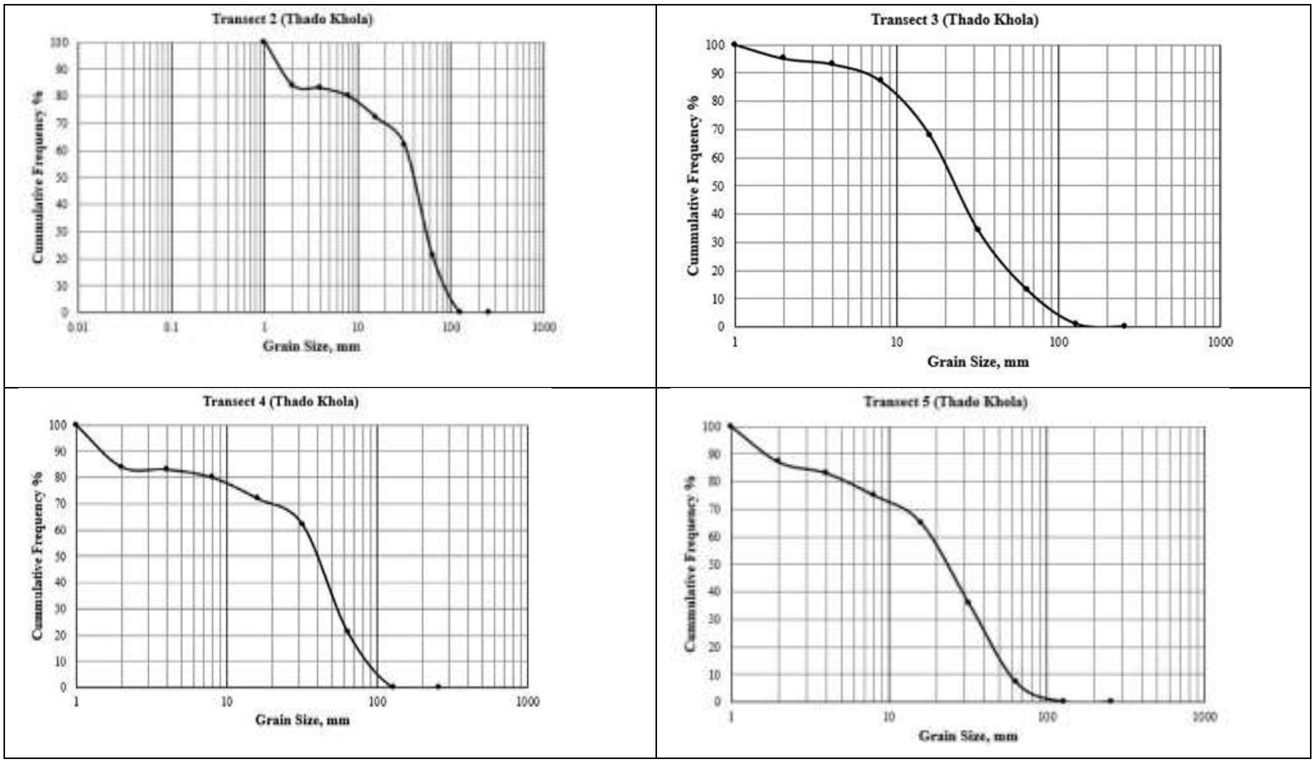

Figure 8 Grain size distribution curves of the Pantale and Thado Khola.

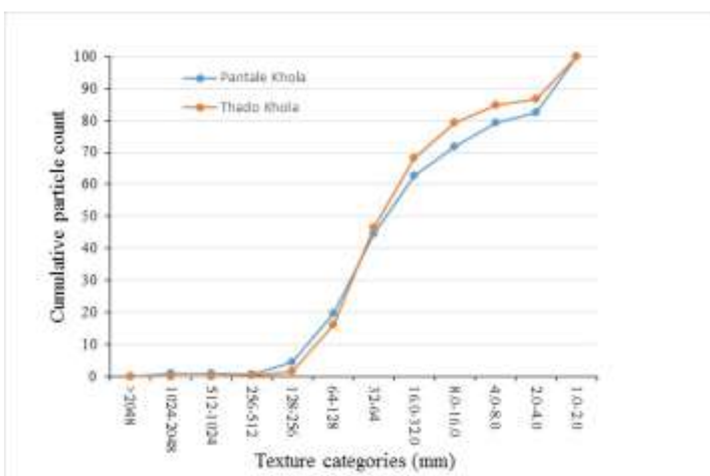

Figure 9 Output of pebble count on Pantale and Thado Khola (Wolman, 1954).

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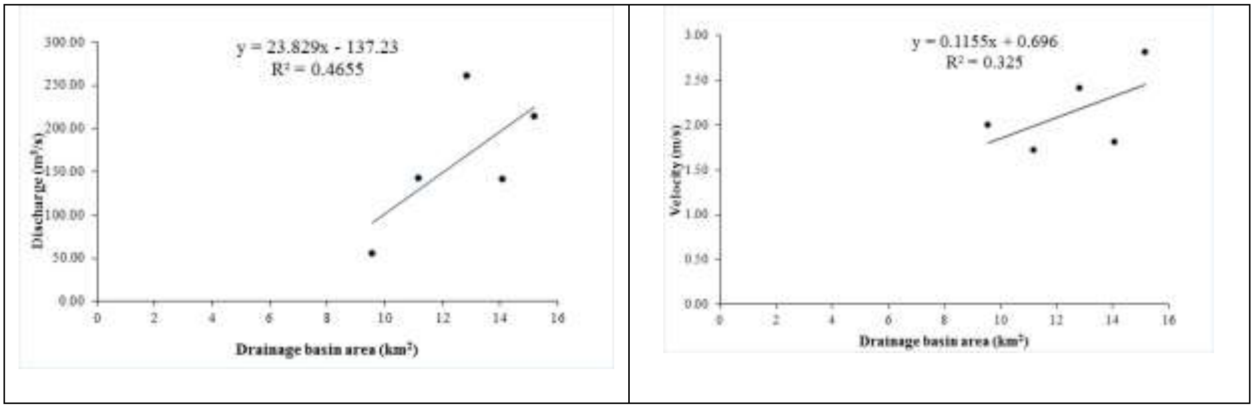

Figure 10 Hydraulic geometry relations of the Pantale Khola.

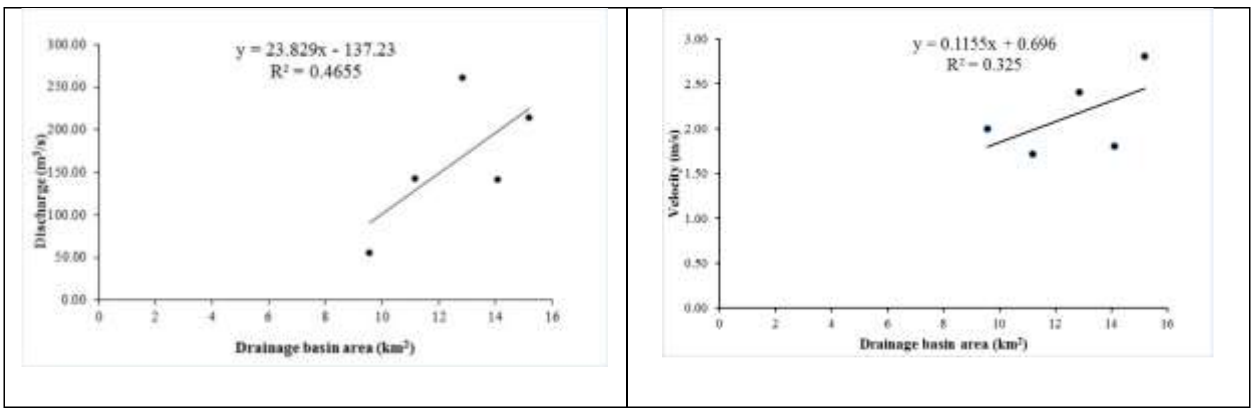

Figure 11 Hydraulic geometry of the Thado Khola.

Stream classification

The level I classification or the geomorphic characterization of the streams, which is done on the basis of Rosgen's classification of streams shows that the streams are of A and B types on both the Pantale and Thado Khola. The A and B type streams are present in the first order tributaries on the source areas while the B type of streams are present in the downstream regions. The hydraulic geometry relation of the Pantale Khola shows increasing discharge and velocity trend on going towards downstream, while the velocity and discharge trend fluctuates in case of the Thado Khola but eventually it has its greater value on the downstream point. As the geology is the governing factor for the slope of the area, the gradient of the both streams are higher at the source areas and decreases further downstream (Table 1). The level II classification is done on the basis of measured hydraulic parameters of the streams. The stream segments of the Pantale Khola are classified as F4 for all the segments and for the Thado Khola, the segments have been classified as F4 and F4b for the segments T1, T3, T4 and F4 for T2 and T5 segments (Table 3). The F-type channels are generally widening type, entrenched and there is no any bankfull floodplain connection. These types of channels consist of riffle-pool sequences.

Table 1 Morpho-hydraulic parameters of the Pantale and Thado Khola.

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Transect no.	Watershed area, km^2	Manning's n value	Bankfull cross-sectional area (m^2)	Slope	Max bkf depth, D_{max} (m)	Bkf width, W_{bkf} (m)	Mean depth at bkf, D_{bkf}= A_{bkf}/W_{bkf}, (m)	Hydraulic radius, R (m)	D_{50} (mm)	Velocity (m/s)	Bankfull Discharge (m^3/s)
P1	15.61	0.043	149.85	0.0082	2.1	212.8	0.704	0.70	10.909	1.649	247.06
P2	22.99	0.047	169.53	0.0051	1.7	186.3	0.910	0.91	38.788	1.428	242.05
P3	32.46	0.056	93.59	0.0044	2	164.1	0.570	0.57	27.520	0.818	76.52
P4	46.36	0.051	137.43	0.0118	1.5	189.6	0.725	0.72	22.154	1.735	238.48
P5	48.82	0.053	142.75	0.0115	1.9	260.9	0.547	0.55	29.176	1.366	194.96
T1	9.56	0.041	27.50	0.0235	1.1	69.8	0.394	0.39	27.333	1.996	54.88
T2	11.19	0.046	82.50	0.0141	1.6	153.0	0.539	0.54	39.758	1.719	141.78
T3	12.85	0.047	108.07	0.0142	1.3	117.1	0.923	0.92	24.471	2.409	260.39
T4	14.10	0.044	78.30	0.0248	1.1	219.5	0.357	0.36	41.366	1.809	141.64
T5	15.18	0.042	76.00	0.0148	2	80.8	0.941	0.94	24.276	2.810	213.55

Table 2 Frequency of partical sizes from different transects of the Pantale and Thado Khola.

Trans ects	Particle	Bedrock	Boulder			Cobble		Gravel					Sand				
	Descriptio n	Bedrock	Large	Medium	Small	Large	Small	Very coarse	Coarse	Medium	Fine	Very fine	Very coarse	Coars e	Medium	Fine	Very fine
	Size (mm)	>2048	1024-2048	512-1024	256-512	128-256	64-128	32-64	16.0-32.0	8.0-16.0	4.0-8.0	2.0-4.0	1.0-2.0	0.5-1.0	0.25-0.5	0.125-0.25	0.062-0.125
P1	TF				1	1	16	16	9	11	15	3	28				
	%F				1	1	16	16	9	11	15	3	28				
	%CF				1	2	18	34	43	54	69	72	100				
P2	TF				1	5	18	33	19	4	7	6	7				
	%F				1	5	18	33	19	4	7	6	7				
	%CF				1	6	24	57	76	80	87	93	100				
P3	TF		1	0	0	5	16	21	25	8	4	2	18				
	%F		1	0	0	5	16	21	25	8	4	2	18				
	%CF		1	1	1	6	22	43	68	76	80	82	100				
P4	TF				0	3	13	26	21	15	8	2	12				
	%F				0	3	13	26	21	15	8	2	12				
	%CF				0	3	16	42	63	78	86	88	100				
P5	TF				0	5	13	29	17	7	4	2	23				
	%F				0	5	13	29	17	7	4	2	23				
	%CF				0	5	18	47	64	71	75	77	100				
T1	TF				0	2	13	28	24	12	6	1	14				
	%F				0	2	13	28	24	12	6	1	14				
	%CF				0	2	15	43	67	79	85	86	100				

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T2	**TF**				1	3	21	33	12	5	5	2	18				
	%F				1	3	21	33	12	5	5	2	18				
	%CF				1	4	25	58	70	75	80	82	100				
T3	**TF**				0	1	12	21	34	19	6	2	5				
	%F				0	1	12	21	34	19	6	2	5				
	%CF				0	1	13	34	68	87	93	95	100				
T4	**TF**				0	0	21	41	10	8	3	1	16				
	%F				0	0	21	41	10	8	3	1	16				
	%CF				0	0	21	62	72	80	83	84	100				
T5	**TF**				0	0	7	29	29	10	8	4	13				
	%F				0	0	7	29	29	10	8	4	13				
	%CF				0	0	7	36	65	75	83	87	100				

Table 3 Summary of stream classification of the Pantale Khola and Thado Khola.

Attributes	**Pantale Khola**										**Thado Khola**									
	Transects																			
	P1		**P2**		**P3**		**P4**		**P5**		**T1**		**T2**		**T3**		**T4**		**T5**	
Entrenchment Ratio, ER	1.05	F	1.50	F	1.04	F	1.10	F	1.04	F	1.172	F	1.24	F	1.013	F	1.030	F	1.037	F
Width/depth ratio, $W/D=W_{bkf}/D_{bkf}$	302	F	205	F	288	F	262	F	476	F	177	F	284	F	127	F	615	F	86	F
Sinuosity, $K=L_{thalweg}/L_{valley}$ (m/m)	1.01	B	1.01	B	1.03	B	1.02	B	1.01	B	1.008	F	1.05	F	1.02	F	1.005	F	1.06	F
Slope of channel, (m/m)	0.008	F4	0.005	F4	0.004	F4	0.012	F4	0.012	F	0.024	Fb	0.014	F	0.014	F	0.025	Fb	0.015	F
Channel material, D_{50} (mm)	10.91	F4	38.79	F4	27.5	F4	22.15	F4	29.18	F4	27.33	F4b	39.76	F4	24.47	F4	41.37	F4b	24.28	F4
Dominant channel material	medium gravel		coarse gravel		coarse gravel		coarse gravel		coarse gravel		coarse gravel		very coarse gravel		coarse gravel		very coarse gravel		coarse gravel	
Rosgen stream type	F4		F4		F4		F4		F4		F4		F4b		F4		F4		F4b	

Sediment transport

The total sediment transported by a river or a stream is also known as the sediment load. The total load includes all the particles moving along with a river or a stream as bedload and suspended load. The calculation of bed load transport was done using the Hassenzadeh bed load equation (Table 4).

The maximum bed load transport calculated in the Pantale Khola is 126.553 million tonnes/year from the transect P4 and the minimum is 4.115 million tonnes/year from the transect P3. Similarly, the maximum bedload transport in the

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Thado Khola is calculated to be 203.163 million tonnes/year from the transect T3 and the minimum is 42.431 million tonnes/year from the transect T2 (Table 4).

Table 4 Calculation of bed load using Hassanzadeh (2007) relation.

Transect	D_{50} (m)	f = (γRS)/(γs-γ)d	Width of wetted perimeter	$(agd^3)^{1/2}$ $*10^{-5}$	$24f^{2.5}$	$q_b * 10^{-5}$	Q_b (KN/s)	Q_b (tonnes/year)	Qb (million tonnes/year)
P1	0.011	0.309	214.2	465.34	1.274	0.006	33.642	108186327	108.186
P2	0.039	0.070	188.1	3119.89	0.031	0.001	4.775	15354213	15.354
P3	0.028	0.053	165.2	1864.51	0.016	0.000	1.280	4115447	4.115
P4	0.022	0.225	191.0	1346.70	0.577	0.008	39.354	126553077	126.553
P5	0.029	0.127	141.1	2035.31	0.137	0.003	10.438	33565620	33.566
T1	0.027	0.197	70.6	1845.54	0.412	0.008	14.239	45788198	45.788
T2	0.040	0.112	154.1	3237.65	0.100	0.003	13.195	42430760	42.431
T3	0.024	0.310	118.9	1563.40	1.282	0.020	63.177	203162694	203.163
T4	0.041	0.125	221.0	3436.04	0.133	0.005	26.819	86244416	86.244
T5	0.024	0.329	82.7	1544.75	1.493	0.023	50.542	162531123	162.531

Table 5 Total sediment yield of Pantale and Thado Khola.

Transect no	Total suspended sediment load (tons/year)	Total bed load (tons/year)	Total Sediment concentration (tons/year)	Watershed area (km^2)	Total SY ($tons/km^2/year$)	Total SY (million tons/km2/year)
P1	63887	108186327	108250215	15.61	6934671	6.935
P2	47326	15354213	15401539	22.99	669923	0.670
P3	14237	4115447	4129684	32.46	127224	0.127
P4	83478	126553077	126636555	46.36	2731591	2.732
P5	132805	33565620	33698426	48.82	690259	0.690
T1	119773	45788198	45907971	9.56	4802089	4.802
T2	162305	42430760	42593065	11.19	3806351	3.806
T3	289049	203162694	203451743	12.85	15832821	15.833
T4	12507	86244416	86256923	14.1	6117512	6.118
T5	52528	162531123	162583652	15.18	10710385	10.710

The sediment discharge or sediment load in the channel was calculated by multiplying the main concentration of sediment in water at each cross-section by the average discharge. The sediment yield pattern shows variation along the stream in both cases of the Pantale and Thado Khola. The highest value of the sediment yield in case of the

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Pantale is 6.935 million tons/km^2/year at the transect P1 and 15.833 million tons/km^2/year for the T3. The Pantale Khola has high yield in the upstream region though the value also fluctuates in downstream location while the value of yield is fluctuating throughout the stream in case of the Thado Khola (Table 5). Variation in the data of sediment yield along the river profile in both streams can be seen which is due to the contributing tributaries near the higher sediment yielding locations along with the land erosion occurring at the banks due to various anthropogenic activities. The sediment yield of both the streams has greater values in the downstream regions which indicates that the stream sediments get transported to the Rapati Nadi rather than deposited at the channel.

Stream competence evaluation

Competency is the maximum particle size a river or a stream is able to transport which increases as the velocity increases, whereas capacity is the measure of volume of sediments a river or a stream can transport. Dimensionless boundary shear stress and dimensionless critical shear stress from the different transects of both the streams are calculated during, to analyze the competency of the stream. Boundary shear stress (τ) and critical shear stress (τ_c) at bankfull stage for d_{50} were obtained using Shield's equation. The dimensionless boundary shear stress if exceeds the dimensionless critical boundary shear stress which is the maximum force required to make median sized sediment of the channel into motion than the river is termed competent if not then incompetent.

Here, in case of both the streams the dimensionless boundary shear stress exceeds the dimensionless critical boundary shear stress in all transects. So, both the streams are competent enough to carry the bed material distributed on the streambed (Table 6).

Stream capacity evaluation

The capacity of a stream or river is the total amount of sediment a stream is able to transport. This measurement usually corresponds to the stream power and the width integrated bed shear stress across section along a stream profile. The capacity of any river is dependent on channel gradient, discharge and the presence and absence of fines or large particles in fluid. The stream power is highest at the P2 and T3 transects and lowest at P1 and T5 transects of the Pantale Khola and Thado Khola respectively (Table 6).

In general, the source areas of the streams or rivers have high gradient and have competency of transporting sediments of larger size compared to the river/stream segment of low gradient. In both cases of the Pantale and Thado Khola, the streams are competent enough to transport the sediment. The mountain and hilly rivers are competent enough to transport their sediments as the dimensionless boundary shear stress exceeds the critical dimensionless shear stress [35, 36]. The stream power is fluctuating which is mainly due to changing slope and stream pattern. The stream power in case of the Pantale Khola ranges from 3.3 KNm/s to 27.58 KNm/s and for the Thado Khola, the value ranges from 12.64 KNm/s to 36.24 KNm/s. The stream power fluctuates throughout the stream length as the slope of the channel varies on different places. Shallow streams seem to commence particle motion at lesser shear stresses than anticipated by Shield's hypothesis. Thus, braided streams and single channel streams with fairly wide, shallow channels would be most suited to transporting coarser bedload materials [37].

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Table 6 Calculation of Dimensionless Boundary shear stress, Dimensionless critical shear stress using Shields (1936) relations. and stream power using Bagnold (1960; 1966).

Transect no.	Distance from the catchment (km)	Hydraulic Radius, R	Slope	D_{50} (m)	Boundary Shear Stress (τ_b),(KN/m^2	Dimensionless boundary shear stress (τ_b*)	U	Rep*=U*(D/V), (m/s)	Critical shear stress (τ_c*)	Competancy of stream.	Discharge (m3/s)	Stream Power, Ω (kg.m^2/s^3)	Stream Power (KNm/s)
P1	6.51	0.70	0.0082	0.011	0.056	0.309	0.0075	81.467	0.042	Competent	247.056	19853.414	19.853
P2	7.54	0.90	0.0051	0.039	0.045	0.070	0.0067	259.279	0.055	Competent	242.047	12097.512	12.098
P3	8.31	0.57	0.0044	0.028	0.024	0.053	0.0049	135.460	0.048	Competent	76.517	3299.432	3.299
P4	9.39	0.72	0.0118	0.022	0.083	0.225	0.0091	201.252	0.052	Competent	238.476	27577.359	27.577
P5	10.82	0.55	0.0115	0.029	0.062	0.127	0.0079	228.194	0.057	Competent	194.965	21972.503	21.973
T1	5.63	0.39	0.0235	0.027	0.090	0.197	0.0095	257.870	0.055	Competent	54.884	12639.851	12.640
T2	6.82	0.54	0.0141	0.040	0.074	0.112	0.0086	340.619	0.059	Competent	141.781	19591.355	19.591
T3	7.69	0.91	0.0142	0.024	0.126	0.310	0.0112	274.065	0.057	Competent	260.389	36235.748	36.236
T4	8.8	0.26	0.0248	0.041	0.062	0.090	0.0079	324.475	0.059	Competent	141.642	34424.581	34.425
T5	9.91	0.92	0.0148	0.024	0.133	0.329	0.0115	279.184	0.057	Competent	213.547	30972.871	30.973

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CONCLUSION

The conditions that can be drawn from the present study are:

- Rosgen level II classification concludes that the stream segments are of the F type. The F-stream types are characterized by very high channel width/depth ratios at the bankfull stage, and bedform features occurring as a moderated riffle/pool sequence. These channels can develop very high bank erosion rates, lateral extension rates, significant bar deposition and accelerated channel aggradation and/or degradation while providing for very high sediment supply and storage capacities. The Pantale and Thado Khola flowing on the gravel bed terrain are further classified as bedload dominated low sinuosity F4-type and F4b-type streams.
- The sediment yield of both streams is seen high on the downstream region and are fluctuating throughout the stream. The sediment transport study resulted that the Pantale Khola yields 6.935 million tons/km^2/year to 0.127 million tons/km^2/year and the Thado Khola yields 15.833 million tons/km^2/year to 4.802 million tons/km^2/year. It suggests that the tributaries of both the streams highly contribute for the sediment yield than the yield from the source areas. Also, the geology of the area consists of the conglomerate bed of the Upper Siwalik Subgroup, the first order streams flowing directly into the main stream channel easily erodes the strata due to high gradient causing the high yield of the sediments. The sediments are transported and deposited into the Rapati Nadi eventually.
- Both the Pantale Khola and the Thado Khola possess high boundary shear stress making the stream competent to erode and transport the river bank and river bed materials.
- The rivers flowing across the gravelly terrains are competent enough to transport their sediments as the dimensionless boundary shear stress exceeds the critical dimensionless shear stress. Considering the streams competency and capacity, and sediment yields of both Pantale Khola and the Thado Khola, these streams are potential to transport and bring the sediment to downstream reaches.

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