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Study on gross streambank sediment erosion from the Godavari Khola, southeast Kathmandu Valley, Central Nepal

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ABSTRACT

The fifth order Godavari Khola is flowing from the South to the North direction and is one of the major tributaries from the southern part of the Kathmandu Valley. As the urbanization is growing in the Kathmandu Valley the banks of the streams are being targeted for the housing and roads, therefore it is important to know the characteristic of the river behavior, nature of erosion and sediment production along its banks. This study accesses the stream bank erosion characteristics and sediment production by erosion along the Godavari Khola. It was conducted by surveying and accessing hydraulic parameters, Bank Erosion and Lateral Instability status, streambank recession rates and gross sediment erosion from the bank.

The Godavari Khola has high bank erodibility and lateral instability as the hazard level of Bank Erosion and Lateral Instability (BELI) and width/depth ratio are quite high. Since the slope and the bankfull depth exceed the critical slope and critical depth values, respectively, the Godavari Khola is competent enough to mobilize its sediments. The apparent recession rate of the banks of the Godavari Khola is 0.66 m per year yielding 85 m^3 volume of the displaced material which weighs 141 tonnes. The estimated bank erosion rate is in between 0.02 to 0.235 m/y and the gross erosion is estimated to be 320 tonnes per year. Similar to the other river of the Kathmandu Valley, the Godavari Khola is very disturbed by the anthropogenic activities. Riparian vegetation clearing and bad agricultural practice is one of the major causes for the high bank erosion and instability of the Godavari Khola.

Keywords: Stream bank erosion, Godavari River, Bank Erosion Hazard Index, Bank erosion rate, Sediment budget

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INTRODUCTION

Stream bank erosion is a natural process caused by running water involving the loss of valuable farmland and recreational land. Infrastructure may be threatened by accelerated stream bank erosion. Due to rapid pace infrastructure development in the Kathmandu valley, the river corridors are already full of settlement and road. There are problem of river encroachment and high anthropogenic activities. Bank protections like gabion walls and retaining walls are being used haphazardly along the rivers and have caused the disturbance in the natural flow of the river. The Godavari Khola which is situated at the Southeast of the Kathmandu valley is now targeted to fulfill the demand of the increasing population for the settlement. So the study on stream bank erosion helps to protect and conserve the river and helps in planning the infrastructure development along the river corridor.

The Godavari Khola is a fifth order stream and a perennial stream which is flowing from the south to north direction. It is one of the major tributary of the Hanumante Khola. The Godavari Khola shows the dendritic type drainage pattern. The Godavari Khola is highly accessible from Sadobato and Gwarko of the Lalitpur District and also from Lokanthali and Kaushaltar of the Bhaktapur district. Most of the length of the river corridor has road so it is very easy to access. The study area is shown in Fig 1.

Various researchers have conducted study on the stream bank erosion throughout the world. Shrestha and Tamrakar (2007 a) had estimated the recession rate of the Manahara River and also measured the volume of the displaced material and tons of displaced material. Likewise, Shrestha and Tamrakar (2007 b) had studied the bank erosion and lateral instability hazard by considering bank erodibility hazard index, near bank stress index, lateral instability hazard index, anthropogenic disturbances, riparian vegetation and environment status. Rosgen (2001) observed that the bank erodibility is a function of two components; a) bank erosion hazard index and b) near bank stress index.

Prosser et al. (2001) had described the method to represent the erosion of sediment from riverbanks and the propagation of gully, hill slope and river bank sourced sediment through a river network. They develop a relation for the sediment by including the factors like proportion of riparian vegetation, stream power and bank erosion rate.

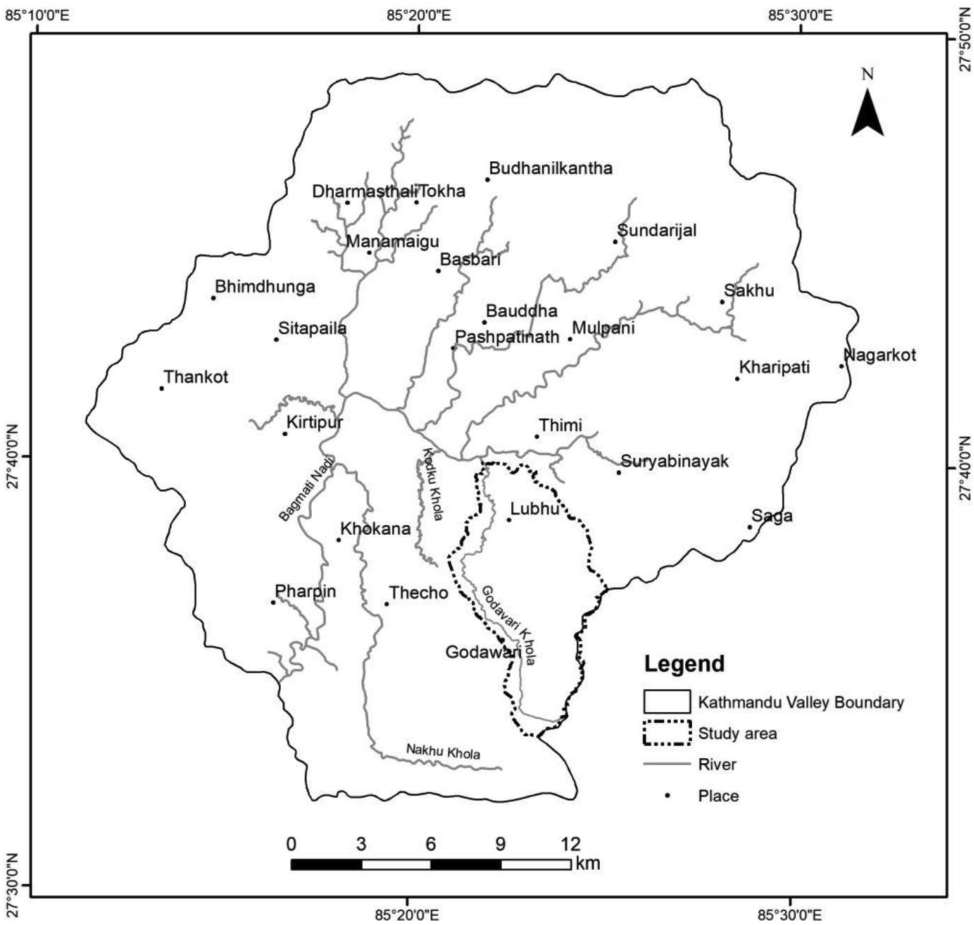

Fig. 1: A map showing the study area

Hughes and Prosser (2003) have produced a new methodology for the prediction of a mean annual rate of sediment production from bank erosion, incorporating the proportion of riparian vegetation and formulating the empirical relation for the bank erosion rate. They also expressed the exponential relationship that describes the increasing proportion of erodible bank as a function of floodplain width.

METHODOLOGY

The 13 transects were designed systematically covering the entire river and various parameters and assessments have been studied. Fig. 2 shows the location of transect. Six assessments were conducted in the present study and are given in following sections:

River morpho-hydrologic assessment

This was conducted by studying the regional water scale parameters, cross sectional and longitudinal surveys, bar material grain size analysis and riparian vegetation mapping. Wolman's pebble counting was also conducted for the quantitative description of the river bed material (Wolman, 1954). In Wolman's pebble counting, the pebble is selected randomly along the edge of the stream and measure the b-axis. In general about 100 measurements are required in order to accurately quantify pebble distributions. The data is then plotted by size class and frequency to determine the distributions.

Bank erosion potential assessment

This assessment was sub-divided in Bank erosion hazard index (BEHI), Near bank stress index (NBSI), Lateral instability hazard index (LIHI), and Anthropogenic disturbance (AD) to obtain a Bank erosion and lateral instability hazard index (BELI) rating. Rosgen (1996) developed a method for Bank erosion hazard index, including variables which are bank height ratio, ratio of root depth to bank height, bank angle and surface protection. Near bank stress index is a method given by Rosgen (2001) which uses the parameters such as near bank maximum depth, bankfull depth, near bank slope and average slope. Near bank stress index (NBS) was conducted by two methods, they are NBS of method 5 (NBS = D_{nb}/D_{bkf}) and of method 6 (NBS = $\sigma s_{nb}/\sigma_{bkf}$, where, σ_{nb} = near bank shear stress and σ_{bkf} = boundary shear stress). LIHI and AD developed by Shrestha and Tamrakar (2007 b) were used in this study. LIHI uses the categories such as meander width ratio, sinuosity, width/depth ratio and meander length ratio (Shrestha and Tamrakar (2007b).

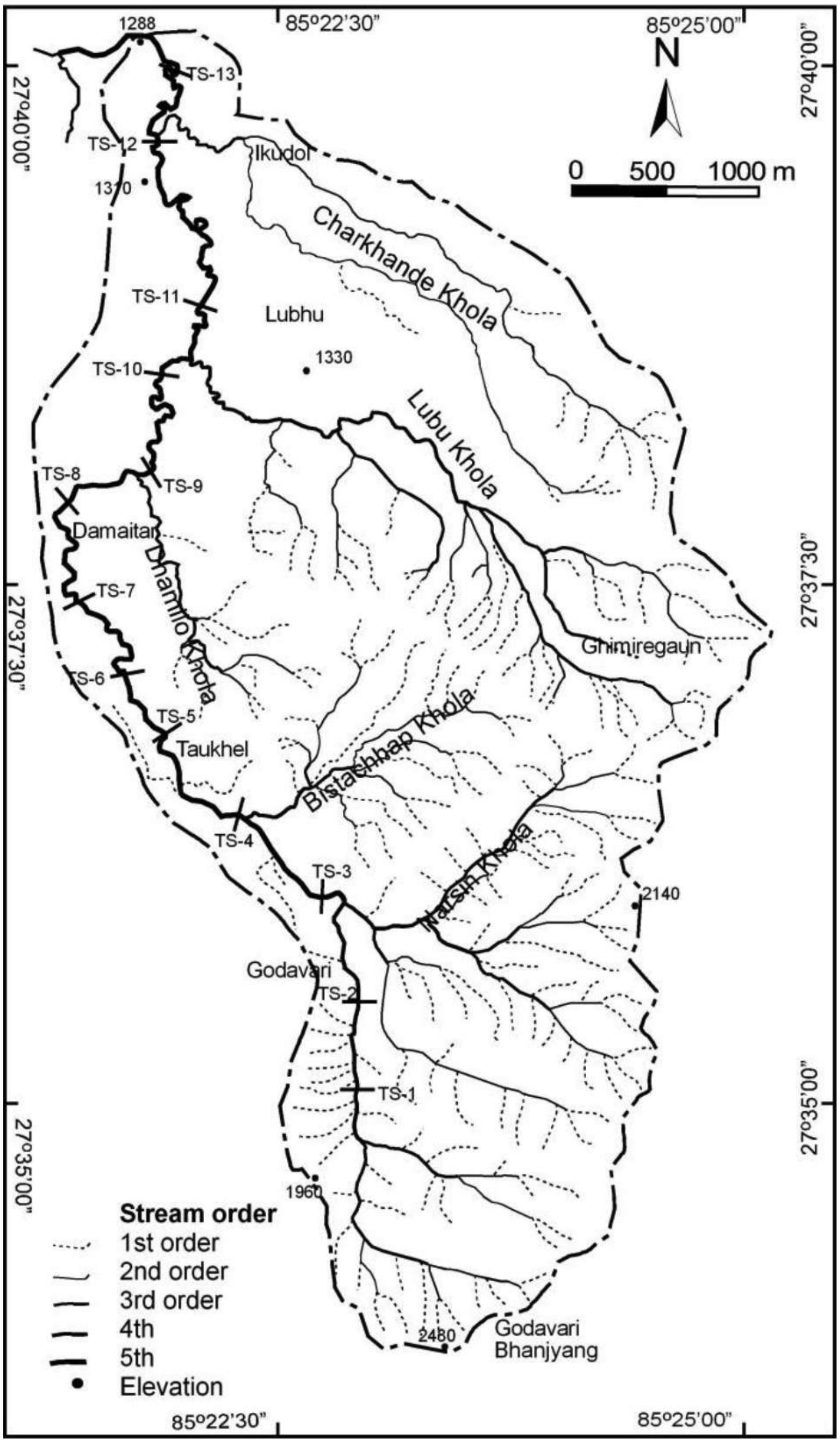

Fig. 2: A map showing stream order of the Godavari watershed and the thirteen transects studied

Anthropogenic disturbance (AD) were also rated low, medium and high according to the disturbances present (Shrestha and Tamrakar, 2007 b). After getting all the ratings of BEHI, NBS, LIHI, and AD, the rating of four parameters are summed and finally get the Bank erosion and lateral instability hazard index (BELI).

Stream competence

Shields (1936) equation was used to calculate boundary shear stress:

$$\tau = \gamma R S \quad (1)$$

where, τ = boundary shear stress (N/m^2), γ = unit weight of water (N/m^3), R = hydraulic radius (m), and S = Channel slope (m/m).

The critical shear stress was computed following equation of Andrew (1983):

$$\tau_{ci} = 0.0834 (d_i/d_{s50})^{-0.872} \quad (2)$$

where, τ_{ci} = critical shear stress, d_i = diameter of interest of riffle sample (usually coarse fraction d_{10}), and d_{s50} = mean diameter of bar sample.

Critical depth and critical slope from the Shield's criteria were computed using the following relations:

$$D_c = (1.65 . \tau_{ci} . d_i)/S \quad (3)$$

$$S_c = (1.65 . \tau_{ci} . d_i)/D_{bkf} \quad (4)$$

where, D_c = critical depth (m), S_c = bankfull slope required, 1.65 = sediment density (g/m^3), S = water surface slope at bankfull stage, and d_i = diameter of interest of riffle sample.

Stream power per unit length of channel was calculated using the relation of Brookes (1990):

$$\Omega = \gamma Q S \quad (5)$$

where, Ω = stream power (N/s), γ = unit weight of water (N/m^3), Q = bankfull discharge (m^3/s), and S = water surface slope (m/m).

Aggrading/ degrading potential

Schumm's (1963) relationship was used to determine the aggrading/degrading potential of the Godavari Khola.

$$F = 255 M^{-1.08} \quad (6)$$

$$\text{where, } F = W_{bkf}/D_{bkf} \quad (7)$$

$$M = [(S_r . W_{bkf}) + (S_b . D_{bkf})]/(W_{bkf} + 2D_{bkf}) \quad (8)$$

where, S_r is % silt and clay in wetted perimeter of a riffle cross-section and S_b is % silt and clay in a bar material. S_r and S_b are derived from the Wolman pebble count of the channel cross-section and bar material, respectively.

Relative bank material loss potential and bank erosion rate

Relative bank material loss

Shrestha and Tamrakar (2007a) has assessed relative bank material loss considering six major parameters: soil texture, stream alignment, vegetation at top of the bank, bank slope, slope of inside depositional bar, and stream gradient. For the estimation of recession rate, it was initially assumed that the maximum loss was 0.3 m per year. This assumption was based on the figure of 1 ft of recession taken in common practice (Shrestha and Tamrakar, 2007 a)

$$RRs = T.S.V.G.B1.B2 \quad (10)$$

where, T = soil texture, S = stream alignment, V = vegetation at top of bank, G = stream gradient,B1 = bank slope, and B2 = slope of inside depositional bar.

Then, the volume of displaced materials (V_d) in m^3 and tons of erosional loss per year has beenas calculated using the following formula (Shrestha and Tamrakar, 2007a),

$$V_d = RRs . L. H \quad (11)$$

where, V_d = Volume of displaced material (m^3), RRs = recession rate, L = length of eroding bank (m), and H = height of eroding bank (m). Then the tons of depleted material (TDM) was calculated as:

$$TDM = (V_d . \rho)/1000 \quad (12)$$

where, V_d = volume of displaced material (m^3), and
ρ = Average density of material (kg/m^3).

Bank erosion rate

The bank erosion rate was calculated in a segment wise basis. The segments were differentiated by joining the two neighbor midpoints of the transects. The bank erosion rate was calculated by three empirical relations. The empirical rule for meander and bank erosion proposed by Rutherfurd (2000) is:

$$BE = 0.016 Q^{0.60} \quad (13)$$

where, BE = the bank erosion rate in meters of recession per year, and Q = the discharge (m^3/s) of the 1.58 year recurrence interval flood event, assumed to represent bankfull discharge.

Later Rutherford (2000) modified his relation by including proportion of riparian vegetation:

$$BE_x = 0.008(1 - PR_x)(Q\ 1.58)^{0.60} \quad (14)$$

where, PR_x = the proportion of bank with intact native riparian vegetation. The lastest relation was developed by Hughes and Prosser (2003) incorporating the factors like riparian vegetation, stream power, and the proportion of erodible material.

Hughes and Prosser (2003) included the which is given below:

$$BE_x = 0.00002.\rho.g.Q_{bkf}\ S(1\text{-}PR_x)\ .\ (1\text{-}e^{-0.008Fx}) \quad (15)$$

where, Q_{bkf} = bankfull discharge in m^3/s, g = acceleration due to gravity (9.81 m/s^2), and Fx is the floodplain width in m.

Sediment budget (B_{Cx})

Prosser et al. (2001) predicted the mean annual supply of sediment from bank erosion by assuming bank height of 3m and sediment bulk density of 1.5 t/m^3 and purposed the following empirical relation:

$$BC_x = 18(1\text{-}PR_x)\ (Q1.58)0.6\ L_x \quad (16)$$

where BC_x = sediment budget (t/y) and L_x = the length of the link (km).

RESULTS

Morpho-hydrology of the Godavari Khola

The Godavari Khola is the fifth order river and its major tributaries like the Narsin Khola, Bistachhap Khola and Lubhu Khola are fourth order streams, and the Dhamilo Khola and the Charkhande Khola are third order stream. Among thirteen transects, TS-11 has the highest sinuosity value of 1.57 and rest of transects have values less than 1.5 indicating low sinuosity. As the river flows through the downstream the sinuosity increases and decreases randomly (Table 1).

Meander belt width (W_{blt}) ranges from 38.1 to 121.8 m. The transect TS-8 has the highest value and TS-4 has the lowest value. TS-8 is more unstable than the rest of transects. Channel width (W_{bkf}) of the Godavari Khola ranges from 3.2 to 28 m (Table 1). The lowest width is of TS-1 and the highest is of TS-13. Stream bed slope varies from 0.02 to 0.12. The lowest slope is of TS-13 and two transect have the highest value i.e. TS-1 and TS-5. Slope of a river is directly related with sinuosity. Stream with steep slope has low sinuosity whereas stream with gentle slope has high sinuosity. Longitudinal profile (Fig. 3) also shows the change in elevation which is concave upward in shape.

The bankfull discharge is highest in the TS-13 (4.37 m3/s) and lowest in the TS-1 transec (0.54 m^3/s). Decrease in roughness and increase in slope, hydraulic radius and cross-sectional area increases discharge. Discharge increases from upstream to downstream due to decrease in roughness and contribution of its tributaries at downstream. The bankfull velocity is greatest at TS-5 which is 0.5 m/s followed by 0.44 m/s (TS-7), 0.42 m/s (TS-4), and 0.40 m/s (TS-6 and TS-11). Bank erosion is the major problem caused by high velocity in the TS-4 to TS-6. Velocity is directly proportional to the discharge and indirectly proportional to the cross sectional area of channel. TS-5 has the high velocity due to high slope. TS-3 has the least velocity due to least slope and high roughness.

The results obtained from the pebble count data show that the sediment of the Godavari Khola are composed of pebble, sand and silt/clay in each of the transect, whereas boulders are present at transects TS-1, TS-2, TS-4, TS- 6 and TS-8. In the stream bed, TS-2 has the highest and TS-8 has the lowest d_{50} values (Table 2). Cobble is decreasing towards the downstream but gravel is increasing.

Table 1: Morpho-hydrological parameter of the Godavari Khola

Morpho-hydrological data	Transects												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Sinuosity, K	1.00	1.00	1.15	1.00	1.15	1.15	1.15	1.00	1.15	1.00	1.30	1.15	1.15
Belt width, W_{blt} (m)	47.2	56.1	105	38.1	111	53.4	76.9	122	84.8	82.7	98.7	60.8	98
Meander wavelength, L_m (m)	426	717	693	300	433	326	321	439	348	438	663	441	366
Width at bankfull, W_{bkf} (m)	3.2	6.1	11.4	8.0	6.3	14.3	7.5	11.4	21.8	13.2	11.2	18.5	28.0
Width of flood prone area, W_{fpa} (m)	10.6	10.3	13.5	9.7	12.9	31.3	57	35	62.5	112	100	56.1	123
Max. depth bankfull, D_{max} (m)	0.6	0.7	0.7	0.8	0.9	1.1	1.1	1.2	1.0	0.7	1.2	0.7	1.0
Mean depth at bankfull, D_{bkf} (m)	0.43	0.48	0.3	0.54	0.51	0.61	0.57	0.53	0.35	0.44	0.9	0.36	0.66
Bankfull cross-section area, A_{bkf} (m^2)	1.37	2.93	3.41	4.32	3.21	8.77	4.27	6.01	7.6	5.79	10	6.66	18.5
Hydraulic radius, R (m)	0.34	0.41	0.28	0.48	0.44	0.56	0.49	0.48	0.34	0.41	0.77	0.35	0.63
Width-depth ratio, W/D	17.7	12.7	38	14.8	12.4	22.3	13.2	21.6	62.6	30.1	12.5	51.4	42.4
Entrenchment ratio, ER	3.31	1.69	1.18	1.21	2.05	2.19	7.6	3.07	2.87	8.49	8.95	3.03	4.38
Meander wavelength ratio, MLR	133	117.5	60.8	37.5	68.7	22.8	42.8	38.5	16	33.2	59.2	23.8	13.1
Meander width ratio, MWR	14.7	9.2	9.2	4.8	17.6	3.7	10.3	10.7	3.9	6.3	8.8	3.3	3.5

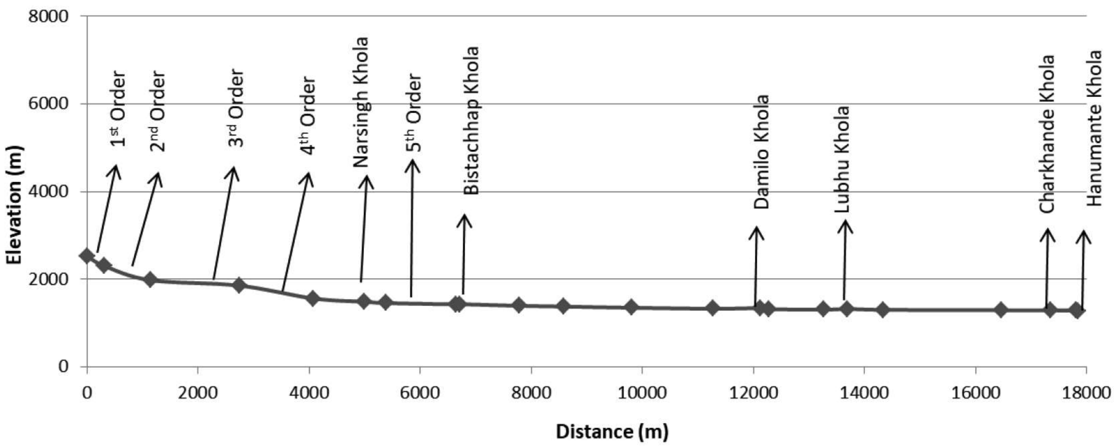

Fig. 3: Longitudinal profile of the Godavari Khola

The stream bar material grain size distribution was accounted same as the stream bed material grain size distribution. The boulder was only found on TS-1, whereas TS-9 transect consisted only of silt/clay. The percentage of the silt/clay were increasing from TS-1 to TS-9 and decreases rapidly having no silt/clay in TS-13. Percentage of sand is very high in TS-11 transect (46.42%) and there were no sand in TS-4, TS-6, TS-8 and TS-9 transect. The percentage of gravel is very high in TS-13 transect (91.25%).

Bank erosion potential assessment

Bank erodibility is a function of mainly two components, i.e., BEHI and NBSI which consider bank erosivity and bank erodibility, respectively. To these are added lateral instability hazard index parameter and anthropogenic disturbance parameters for overall bank erosion and lateral instability hazard of a river.

Bank erosion hazard index (BEHI)

The bank erosion hazard index was evaluated at the same location where cross-sections were prepared. From the result, most of the transects along the Godavari Khola has high bank erosion hazard index. The BEHI is seen high from TS-9 to TS-13 because in these locations, bank angles are high, whereas root depth ratio, root density, surface protection and riparian vegetation all are low (Table 3). The banks of TS-9 to TS-13 consist of materials like cohesionless sand and gravel which are erodible. Mostly, the southern part of the river has good riparian vegetation, low sand and gravel at banks, low bank angle, high root depth and root density, hence the riverbanks therein have moderate bank erosion potential.

Near bank stress (NBS)

Near bank stress ranges from 1.40 to 5.89, obtained from the method 5. These two values were observed at the TS-1 and TS-5 transect. The method 5 is a depth related parameter. The NBS is low in TS-1 and TS-2 transect, moderate in TS-3, TS-6, TS-7 and TS-11, high in TS-4, TS-8, TS-10 and TS-13 transect, very high in TS-9 transect only and extreme in TS-5 and TS-12 transect (Table 4).

Based on the method 6, NBS varies from 0.40 to 6.42. The lowest value obtained from the TS-1 transect and the highest was from the TS-12 transect. When NBS derived from the method 6 is compared, it is found that almost all the sites have shown extreme except TS-1, TS-2 and TS-3 transect. These extreme NBS implies that there is a great potential of bank erosion in all transect of the Godavari Khola.

Lateral instability hazard index (LIHI)

All transects show very high unstable bank height ratio, meander width ratio (MWR) and width/depth ratio (W/D). High W/D ratio associated with bank erosion and channel widening (Rosgen 1996). High MWR reflects greater degree of channel accretion compared to low MWR. The transects TS-2, TS-6, TS-9, TS-12 and TS-13 were leveled moderately unstable while other transect were leveled highly unstable (Table 5).

Table 2: d_{50} of the stream bed and stream bar

Transect	Stream bed d_{50} (mm)	Stream bar d_{50} (mm)
TS-1	40	0.8
TS-2	85	23
TS-3	28	0.25
TS-4	26	0.018
TS-5	28	0.6
TS-6	25	0.022
TS-7	40	0.03
TS-8	0.65	0.015
TS-9	30	0.03
TS-10	9	0.7
TS-11	20	0.15
TS-12	28	0.25
TS-13	35	40

Table 3: Stream bank characteristics used to develop bank erosion hazard index (BEHI) (the rating system is after Rosgen, 1996)

Transect	Bank Angle		Bank Height Ratio (BHR)				Root Depth Ratio (RDR)			Root Density		Surface Protection %		Adjustment	Total	
	Value (deg.)	Score	BH (m)	BKFH (m)	*BHR	Score	RD (m)	**RDR	Score	Value (%)	Score	Value (%)	Score		BEHI	
TS-1	105-119	9	1	0.43	2.33	8	-	1	1	>90	1	<5	10	0	29	M
TS-2	30-50	3	2	0.48	4.17	10	-	1	1	75-90	2	10-20	8	-10	14	L
TS-3	87-105	8	0.5	0.30	1.67	6	-	0.75-0.6	3	60-75	3	45-60	4	-1.7	22.3	M
TS-4	83-87	7	1.16	0.54	2.15	10	-	1	1	45-60	4	75-90	2	-2	22	M
TS-5	83-87	7	3	0.51	5.89	10	-	0.95-0.75	2	60-75	3	60-75	3	5	30	H
TS-6	83-87	7	1.1	0.61	1.79	6	-	1	1	75-90	2	<5	10	1.75	27.8	M
TS-7	>120	10	0.86	0.57	1.51	6	0.3	0.45-0.35	5	10-20	8	>90	1	0	30	H
TS-8	105-119	9	1	0.53	1.90	7	0.4	0.6-0.45	4	<5	10	<5	10	-4	36	H
TS-9	105-119	9	1	0.35	2.87	10	0.4	0.6-0.45	4	<5	10	<5	10	1.5	44.5	VH
TS-10	>120	10	1	0.44	2.28	8	0.25	0.35-0.25	6	05-10	9	<5	10	6	49	E
TS-11	105-119	9	1	0.90	1.12	2	0.45	0.6-0.45	4	25-35	6	10-20	8	0	29	M
TS-12	>120	10	1.1	0.36	3.06	10	0.35	0.35-0.25	6	10-20	8	20-25	7	5	46	E
TS-13	87-105	8	1.3	0.66	1.97	7	0.45	0.35-0.25	6	05-10	9	45-60	4	7.6	41.6	VH

*BHR=BH/BKFH **RDR=RD/BH L=low M=moderate H=high VH=very high E=extreme

Anthropogenic disturbances index (AD)

As the river flows downstream the anthropogenic disturbance increases. The disturbances include human encroachment of river banks for: (i) settlement, cultivation, and mining; (ii) alteration of channel for protection against erosion; and (iii) deforestation and clearing of riparian vegetation zone. The vegetation clearing, altered hydrology and alteration of channel are the major disturbances in the Godavari Khola. Gabion walls and check dams are the structure used wildly along the river which caused the alteration of the channel. For

Table 4: Result of NBS assessment in the Godavari Khola (the rating system is after Rosgen, 2001)

	Near Bank Stress Level III (5)				Near Bank Stress Level III (6)							
Transect	Near bank max depth, D_{nb} (m)	Bankfull depth, D_{bkf} (m)	Ratio, D_{nb}/D_{bkf}	NBS	Near bank max depth, D_{nb} (m)	Near bank slope, S_{nb}	Near bank stress, τ_{nb} (N/m^2)	Bankfull depth, D_{bkf} (m)	Average slope, S_{avg}	Boundary shear stress, τ_{bkf} (N/m^2)	Ratio τ_{nb}/τ_{bkf}	NBS
TS-1	0.60	0.43	1.40	Low	0.60	0.04	206.01	0.43	0.12	518.85	0.40	Very Low
TS-2	0.70	0.48	1.46	Low	0.70	0.04	240.35	0.48	0.07	310.78	0.77	Very Low
TS-3	0.50	0.30	1.67	Moderate	0.50	0.04	171.68	0.30	0.05	153.04	1.12	Moderate
TS-4	1.16	0.54	2.15	High	1.16	0.07	796.57	0.54	0.06	312.55	2.55	Extreme
TS-5	3.00	0.51	5.89	Extreme	3.00	0.11	3090.15	0.51	0.12	618.17	5.00	Extreme
TS-6	1.10	0.61	1.79	Moderate	1.10	0.07	755.37	0.61	0.05	312.70	2.42	Extreme
TS-7	0.86	0.57	1.51	Moderate	0.86	0.05	438.70	0.57	0.06	356.61	1.23	Very High
TS-8	1.00	0.53	1.90	High	1.00	0.04	343.35	0.53	0.03	149.93	2.29	Extreme
TS-9	0.95	0.35	2.73	Very High	0.95	0.04	326.18	0.35	0.05	160.45	2.03	Extreme
TS-10	1.00	0.44	2.28	High	1.00	0.04	343.35	0.44	0.04	176.17	1.95	Extreme
TS-11	1.50	0.90	1.67	Moderate	1.50	0.04	647.46	0.90	0.03	290.06	2.23	Extreme
TS-12	1.10	0.36	3.06	Extreme	1.10	0.11	1133.06	0.36	0.05	176.58	6.42	Extreme
TS-13	1.30	0.66	1.97	High	1.30	0.05	663.16	0.66	0.05	336.68	1.97	Extreme

Table 5: Result of LIHI assessment of the Godavari Khola (the rating system after Shrestha and Tamrakar, 2007b)

Transect	Sinuosity, k		Meander width ratio, MWR		Meander length ratio, MLR		Width/depth ratio,W/D		Total LIHI rating	*Hazard level
	value	rating	value	rating	value	rating	value	rating		
TS-1	1.02	1	17.80	8.5	72.43	9.42	17.67	7.5	26.42	High
TS-2	1.09	1	12.04	7	38.89	9.08	12.71	6.5	23.58	Moderate
TS-3	1.13	1	9.43	5.5	33.33	9.03	38.00	8.9	24.43	High
TS-4	1.08	1	16.05	8	66.34	9.36	14.81	6.9	25.26	High
TS-5	1.25	2	20.90	9	54.86	9.24	12.37	6.4	26.64	High
TS-6	1.48	4	10.83	6	16.79	4.5	22.33	8.1	22.60	Moderate
TS-7	1.31	3	15.71	8	31.77	9.01	13.20	6.6	26.61	High
TS-8	1.45	4	10.97	6	39.17	9.09	21.63	8.05	27.14	High
TS-9	1.43	4	6.48	4.5	12.42	3	62.64	9.3	20.80	Moderate
TS-10	1.64	6	15.24	8	16.37	4	30.14	8.5	26.50	High
TS-11	1.33	3	15.37	8	31.56	9.01	12.50	6.5	26.51	High
TS-12	1.56	5	7.65	7	11.70	2.5	51.39	9.2	23.70	Moderate
TS-13	1.86	8	5.60	4	7.68	1	42.42	9.1	22.10	Moderate

the agriculture the farmer made small dam of stone in the river to collect water and to pump the water to the field which causes the alteration in the channel. It was observed that from TS-7 the disturbance level is high up to the confluence of the Hanumante Khola (Table 6).

Bank erosion and lateral instability hazard index (BELI)

The four parameters: BEHI, NBS, LIHI and AD were combined to calculate the total rating (Table 7) and were categorized with different hazard zones. TS-10 lies within the Very high hazard consisting 92.2 rating while TS-2 consist 44.38 rating which is the lowest rating which lies in moderate hazard. Very high to high hazard are owing to loose sediments, lack of riparian vegetation zone and human encroachments. The riverbanks having moderate hazard (TS-1 to TS-4) are located upstream from the confluence of the Bistachhap Khola and the Godavari Khola. The riverbanks with very high hazard (TS-10) are observed in the Siddhipur area. From TS-7 to TS-13, the riverbanks have high bank erodibilty and lateral instability hazard.

Stream competence

According to Shields (1936), at condition of critical motion of the sediment particle of size (d) on the bed, the drag force on the particle caused by fluid flow is equal to the force required to move the particle. The boundary shear stress is the shear stress generated by flowing stream over its substrate. In order to evaluate the flow competence of the Godavari Khola, boundary shear stress of all the thirteen transect were calculated (Table 8). The boundary shear stress of the TS-5 transect is the highest (407.91 N/m^2) whereas TS-8 transect is the lowest (139.71 N/m^2).

Critical shear stress is the measure of force required to mobilize and transport a given grain sized particle resting on the channel bed. Critical shear stress is a threshold dimensionless shear stress required to entrain di of the riverbed material.

Critical depth (D_c) and critical slope (S_c) are useful in determining whether the given size particle are transported during the bankfull flow only or even during normal flow. D_c and S_c are the minimum depth and minimum slope required to mobilize and transport the large particles made available annually

Table 6: Result of Anthropogenic disturbance of the Godavari Khola (the rating system is after Shrestha and Tamrakar, 2007 b)

Transect	Average values of disturbance	AD ratings	Hazard level
TS-1	7.0	3.0	Low
TS-2	12.0	5.0	Moderate
TS-3	10.7	4	Moderate
TS-4	12.1	5	Moderate
TS-5	15.0	6	High
TS-6	7.3	3	Low
TS-7	13.1	5.5	Moderate
TS-8	14.0	5.5	Moderate
TS-9	15.0	6.0	High
TS-10	18.8	7.5	High
TS-11	19.4	7.5	High
TS-12	20.7	8	Very high
TS-13	21.4	8	Very high

Table 7: Bank erosion and lateral instability hazard rating of the Godavari Khola

Location	BEHI	NBS	LIHI	AD factor	Total BELI rating	Hazard level
TS-1	29	1	26.42	3	59.42	Moderate
TS-2	14	1.8	23.58	5	44.38	Moderate
TS-3	22.3	5.5	24.43	4	56.23	Moderate
TS-4	22	9.2	25.26	5	61.46	Moderate
TS-5	30	9.5	26.64	6	72.14	High
TS-6	27.75	9.2	22.6	3	62.55	Moderate
TS-7	30	8.1	26.61	5.5	70.21	High
TS-8	36	9.3	27.14	5.5	77.94	High
TS-9	44.5	9.2	20.8	6	80.5	High
TS-10	49	9.2	26.5	7.5	92.2	VH
TS-11	29	9.2	26.51	7.5	72.21	High
TS-12	46	9.6	23.7	8	87.3	High
TS-13	41.6	9.1	22.1	8	80.8	High

to the channel. These were calculated in all transect (Table 8). Critical depth value ranges between 0.00001 m and 0.11 m, and he critical slope value ranges between 0.000002 and 0.0091. The critical depth and the critical slope are less than the existing slope and the bankfull depth on channel which indicates that stream is competent enough to mobilize the riverbed materials currently distributed in river.

The result of the stream power is shown in Table 8. TS-5 has the highest stream power (3435.61 N/s) and TS-3 has the lowest stream power (318.54 N/s). The flow capacity of the Godavari Khola is contrastingly high and bears potential towards streambed scouring.

Aggrading/Degrading potential of the Godavari Khola

If the rate at which sediment enters a given channel of a stream is greater than the rate at which it goes out, the channel bed experiences deposition of sediment, this is known as aggradation. If the rate at which sediment entering a given channel is less than that at which it is going out, the excess sediment will be picked up from the bed and banks, and there will be lowering of bed level, this is known as degradation.

The transect TS-2 does not consist of silt-clay, therefore the M-factor is zero and does not take part in the logarithmic plot between F-factor and M-factor. But if we consider very

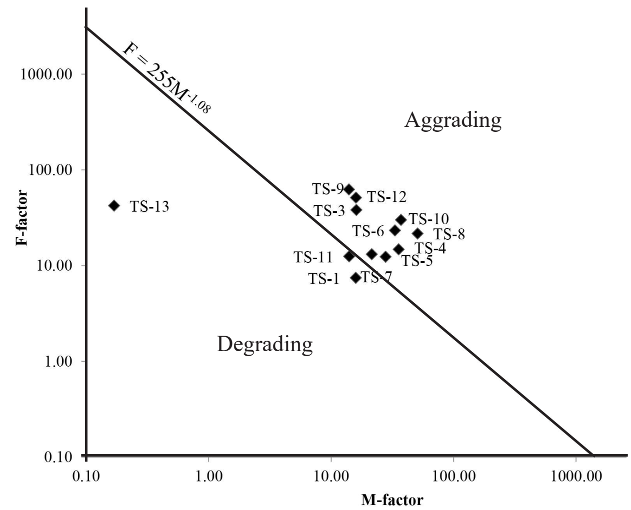

Fig. 4: Aggrading/degrading potential of the the Godavari Khola transects

Table 8: Morpho-hydroogical and hydraulic data of the Godavari Khola

Morpho-hydrological and Hydraulic data	Transects												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Hydraulic radius, R (m)	0.34	0.41	0.28	0.48	0.44	0.56	0.49	0.48	0.34	0.41	0.77	0.35	0.63
Stream water surface slope, S (m/m)	0.12	0.66	0.52	0.06	0.12	0.05	0.06	0.03	0.05	0.04	0.03	0.05	0.02
Boundary shear stress, τ (N/m^2)	407.9	268.7	145.69	274.1	532.4	289.9	310.2	139.71	154.2	164.1	247	170.1	321.4
Critical shear stress, τ_{cr^*}, (N/m^2)	7.79	91.49	4.92	0.39	12.38	0.29	0.86	0.47	0.04	22.1	3.92	4.92	585.6
Bankfull discharge, Q_{bkf}	0.54	0.96	0.68	1.83	3.21	3.52	1.86	1.98	1.92	1.51	4.01	1.84	4.37
Stream power, Ω (N/s)	614.6	651	318.54	1094	3436	1731	1076	621.18	930.7	624.2	1114	1441	1456
d_{s50} bar x 10^{-3} (m)	0.8	23	0.25	0.018	0.6	0.022	0.03	0.015	0.001	0.7	0.15	0.25	40
$d_{10} = d_i$, riffle (m)	0.17	0.29	0.09	0.12	0.08	0.2	0.08	0.08	0.08	0.05	0.07	0.09	0.06
d_{50}, riffle (m)	0.04	0.085	0.028	0.026	0.028	0.025	0.04	0.0007	0.03	0.009	0.02	0.028	0.035
Critical bankfull depth, D_c (m)	17.8	66.33	1.4	0.13	1.24	0.19	0.18	0.21	0.01	4.03	1.39	1.46	111.5
Critical bankfull slope, S_c (m/m)	5	91.2	0.24	0.01	0.3	0.01	0.02	0.01	0	0.37	0.05	0.2	8.78

low value of the percent silt-clay in the riffle then it belongs to degrading condition. The plot of F-factor versus M-factor is shown in Fig. 4. Here, Fig. 4 shows that the transects TS-1, TS-2, TS-11 and TS-13 are in degradation condition and the rest of transects are in aggradation condition. In overall, the Godavari Khola is identified as an aggrading river.

Relative bank material loss potential and bank erosion rate

Bank recession rate (BRR)

The recession rate (RRs) is an estimation of the number of meter the bank likely to recede in a year. It is only a relative recession rate. The six parameters were assessed for the recession rate (eq. 10). The result of the recession rate of the Godavari Khola is shown in Table 9.

a) Soil texture (T): Most of the banks of the Godavari Khola are composed of non-cohesive silt, sand, gravel and cobbles. Only TS-11 consists of clay to silty clay soil.

b) Stream alignment (S): At the upper part of the stream (up to TS-4), the Godavari Khola has straight alignment. And after that the stream alignment changes from straight to meander as depending on the slope, bank material, riparian vegetation and bankfull discharge. At the lowest part (TS-12 and TS-13) of the Godavari Khola the alignment is sharply curved.

c) Vegetation at top of the bank (V): The trees are only found up to third order stream that is near to the Godavari. Most of the banks of the fourth and the fifth order stream are covered by grass, shrub and crops. Road are constructed along the banks of the Godavari Khola. Vegetation of the banks is cleared for agriculture, shelters, clay mining for brick industry, animal farm house and animal grazing. Hence, due to low vegetation at the top of banks, there is high risk of bank erosion.

d) Stream gradient (G): Higher the stream gradient, greater the rate of flow and the greater the potential for the stream bank erosion. The slope gradient is high having rating 1 from the origin of the stream to TS-4 transect (near the confluence of the Bistachhap Khola). After the TS-4, the stream gradient slowly decreases. At the lowest part of the stream (i.e. after the TS-10) there are many long and deep pools, and few riffles which make the ratings of 0.3.

e) Bank slope (B1): The slope of an eroding bank is an indicator of erosion rate. A vertical slope or undercut bank generally means a high rate of erosion. The lesser the eroding bank lower the erosion potential. Slope of eroding bank assessed is very steep. Undercutting banks are highly present at the Godavari Khola, indicating high susceptibility of bank erosion. Most of the ratings of the bank slope fall in 1 because they are steep to vertical. Only TS-1 has 3:1 (Horizontal to Vertical ratio) or less which means that bank slope is low and rated 0.3. And TS-2 has 0.6 rating because its bank slope is in between the 3:1 and 1:1 (Horizontal to Vertical ratio) (Shrestha and Tamrakar, 2007 a).

f) Slope of inside depositional bar (B2): As erosion occurs on the outside edge of a bend in a stream, deposition occurs on the inside portion. The slope of depositional bar is

Table 9: Result of relative bank material loss assessment

Transect	T	S	V	G	B1	B2	Recession rate, RRs	RRs, m/yr	Length of Eroding Bank, L (m)	Height of Eroding Bank, L (m)	Volume of displaced material, V_d (m^3)	Tons of Displaced Material (TDM)
TS-1	1	0.3	0.3	1	0.3	1	0.027	0.008	30	1.00	0.243	0.467
TS-2	1	0.3	0.3	1	0.6	1	0.054	0.016	25	2.00	0.810	1.557
TS-3	1	0.3	0.6	1	1	0.6	0.108	0.032	120	0.50	1.944	3.736
TS-4	1	0.3	1	1	1	1	0.300	0.090	87	1.16	9.083	11.644
TS-5	1	0.6	1	0.6	1	1	0.360	0.108	80	3.00	25.920	45.671
TS-6	1	1	0.6	0.6	1	0.6	0.216	0.065	72	1.10	5.132	9.864
TS-7	1	0.3	0.6	0.3	1	1	0.054	0.016	75	0.86	1.045	1.340
TS-8	1	0.3	0.6	0.3	1	1	0.054	0.016	115	1.00	1.863	2.388
TS-9	1	0.6	0.6	0.6	1	1	0.216	0.065	30	1.00	1.944	2.989
TS-10	1	0.6	0.6	0.6	1	1	0.216	0.065	55	1.00	3.564	5.253
TS-11	0.3	0.3	0.6	0.3	1	1	0.016	0.005	275	1.00	1.337	1.713
TS-12	1	1	1	0.3	1	1	0.300	0.090	200	1.10	19.800	32.446
TS-13	1	1	1	0.3	1	1	0.300	0.090	110	1.30	12.870	22.039
									Total Sediment Displaced		85.554	141.108

indicative of the rate of erosion and other indicator is the presence or absence of vegetation on the depositional bar. Absence of vegetation signifies a rapid erosional rate. The risk ratings for this factor fall on rating 0.6 to 1, indicating rapid rate of erosion. Only two transect (TS-3 and TS-6) has 0.6 rating because the slope of inside depositional bar falls in between 3:1 and 1:1 (Horizontal to vertical ratio) and rest of the transect have slope of inside depositional bar less than 10:1 (Horizontal to vertical ratio) so they were rated 1 (Shrestha and Tamrakar, 2007 a).

Table 9 shows the ratings of all six parameters with the result of the relative bank material loss. The result shows that at most of the locations the bank material texture (T) has value 1 and at one location this value is 0.3. Stream alignment has value 0.3 at most of the locations and at some locations this value ranges between 0.6 and 1.0. Vegetation present at banks of river (V) falls on 0.3 to 1.0 ratings. The value 0.6 has the highest frequency. The results of recession rate, volume of depleted material (V_d) and total depleted material, and TDM is given in Table 9. The total apparent recession rate of the bank is 0.66 m per year, which exhibits the volume of displaced material to be 85 m^3 which weigh 141 tons.

Bank erosion rate (BE_x)

Riverbank erosion is the most uncertain of the sediment source in the river. For the calculation of the bank erosion rate riparian vegetation map was prepared and from this map proportion of riparian vegetation was estimated. The buffer of 3 times the bankfull width was created using GIS. The area of the riparian vegetation inside the buffer of a segment is taken and then divided by the area of a buffer of the segment, and then the result is proportion of riparian vegetation.

From Fig. 5, it is seen that most of the area of the buffer is covered by non-riparian vegetation and bank erosion is likely to happen. The result of the proportion of riparian vegetation and BE_x is presented in Table 10.

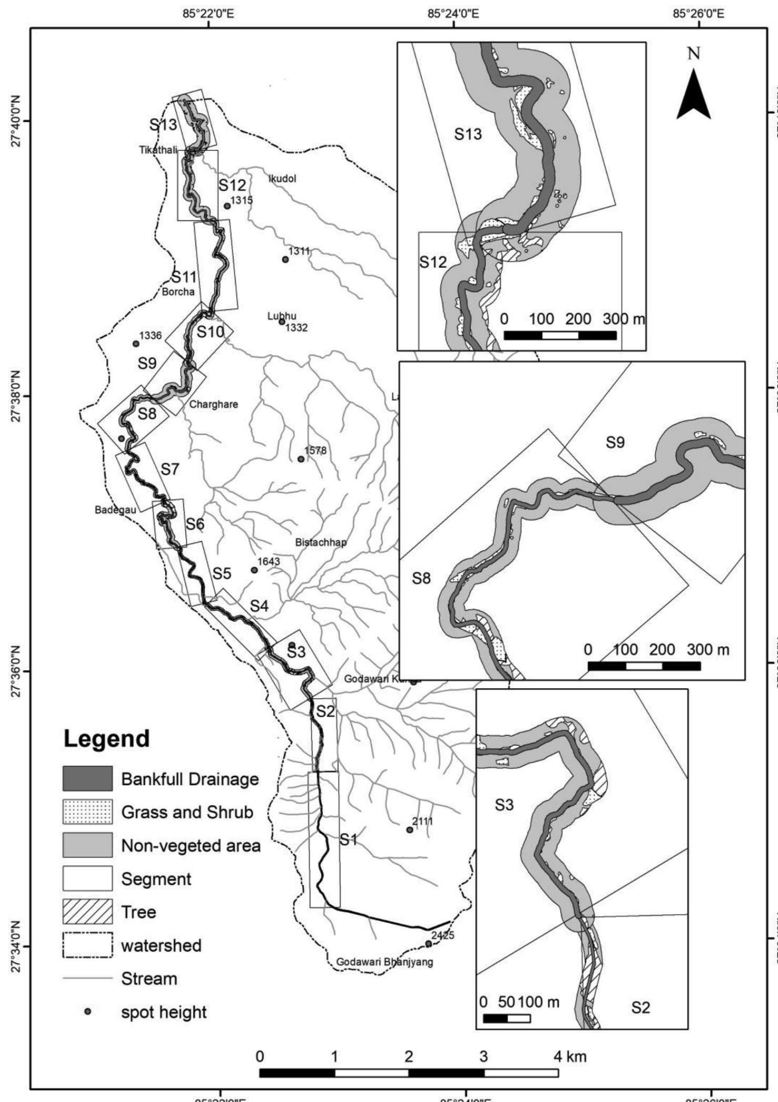

Fig. 5: Map of the native riparian vegetation along the Godavari Khola corridor and showing the segment S1 to S13

Table 10: Result of proportion of riparian vegetation, bank erosion rate and sediment budget

Segment	Length (km)	W_{bkf} (m)	Buffer $3*W_{bkf}$ (m)	Area of $3*W_{bkf}$ buffer (m^2)	Vegetated area (m^2)	Proportion of riparian vegetation	Q_{bkf} (m^3/s)	BE* (Rutherford 2000) (m/y)	BE_x** (Modified) (m/y)	BC_x (Sediment Budget) (t/y)	Density of water, ρ (kg/m^3)	g (m/s^2)	River bed slope (m/m)	Flood plain width (m)	BE_x*** (m/y)
S1	3.26	3.2	9.6	39428.01	31945	0.81	0.54	0.01	0.001	7.66	1000	9.8	0.12	10.6	0.002
S2	0.82	6.1	18.3	39889.07	33331	0.84	0.96	0.02	0.001	2.37	1000	9.8	0.07	10.3	0.002
S3	1.31	11.4	34.2	87125.61	26133.4	0.30	0.68	0.01	0.004	13.02	1000	9.8	0.05	13.5	0.005
S4	1.16	8	24	58946.55	13042.5	0.22	1.83	0.02	0.009	23.33	1000	9.8	0.06	9.7	0.012
S5	1.24	6.3	18.9	39286.80	8404.43	0.21	3.21	0.03	0.013	35.23	1000	9.8	0.12	12.9	0.060
S6	0.80	14.3	42.9	89205.91	31477.1	0.35	3.52	0.03	0.011	19.79	1000	9.8	0.05	31.3	0.052
S7	1.23	7.5	22.5	61004.15	15782.7	0.26	1.86	0.02	0.009	23.83	1000	9.8	0.06	57	0.063
S8	1.46	11.4	34.2	86641.58	15089.6	0.17	1.98	0.02	0.010	32.76	1000	9.8	0.03	35	0.023
S9	1.00	21.8	65.4	136997.73	13719.5	0.10	1.92	0.02	0.011	23.84	1000	9.8	0.05	62.5	0.062
S10	1.00	13.2	39.6	84668.29	15858	0.19	1.51	0.02	0.008	18.79	1000	9.8	0.04	112.1	0.058
S11	1.06	11.2	33.6	106822.01	11906.1	0.11	4.01	0.04	0.016	38.88	1000	9.8	0.03	100.2	0.126
S12	2.14	18.5	55.5	167788.36	23356.6	0.14	1.84	0.02	0.010	47.75	1000	9.8	0.05	56.1	0.056
S13	0.88	28	84	166511.23	25552.2	0.15	4.37	0.04	0.016	32.58	1000	9.8	0.05	122.6	0.235

where, $BE^* = 0.016*Q_{bkf}^{0.6}$ (meter of recession per year); $BE_X^{**} = 0.008*(1-PR_x)*Q_{bkf}^{0.6}$ (meter of recession per year); $BE_X^{***} = 0.0002*\rho*g*Q_{bkf}*S*(1-PR_x)*(1-e^{-0.008Fs})$ (meter of recession per year); $BC_X = 18*(1-PR_X)*Q_{bkf}^{0.6}*L_X$ (tonne per year)

Bank erosion after Rutherfurd (2000) (BE) is the bank erosion rate in metres of recession per year, and is found to range between 0.01 m/y and 0.04 m/y. BE_X values are lesser than BE due to riparian factor used in BE_X. The value of BE_X ranges between 0.001 m/y and 0.016 m/y. BEx calculated based on eq. (15) ranges between 0.002 m/y and 0.235 m/y (Table 10).

Sediment budget (BC_x)

Sediment budget refers to the balance between sediment added to and removed from the fluvial system. The study focused on the bank erosion, therefore the sediment budget was calculated to estimate how much sediment was being eroded along the length of the stream in a year. Prosser et al (2001) assumed a mean bank height of 3 m, and a sediment bulk density of 1.5 t/m^3, and given a relation as shown in eq. 16. The calculated result of sediment budget is shown in Table 10. The Maximum sediment is eroded from S12 segment having the value of 47.75 t/y because this segment has high length and low proportion of riparian vegetation. The total sediment produced from S1 to S13 segment from the bank of the Godavari Khola is 320 tons of sediment per year which it deposit to the Hanumante Khola.

DISCUSSION

The Godavari Khola is originating from south-east hills of the Kathmandu Valley with rock belonging to Kathmandu Complex. The central part of the watershed contains alluvial deposit and northern part is comprised of the Kalimati Formation. The result of planform parameters shows the increasing of meandering as soon as the river enters to the valley fill sediment. The Width/depth ratio shows that it is unstable and prone to near bank erosion. The Godavari Khola is entrenched at the south part and slightly entrenched at the north part. For the bank erosion status of the Godavari Khola BEHI, NBSI, LIHI and AD were evaluated. The BEHI is moderate to extreme at places were the riparian vegetation is poor and high bank height. Due to erodible materials at the banks (silt, sand, gravel), bank failure is seen at the meandered channel. The high to extreme near bank stress (NBS) implies that there is great potential of bank erosion along the river. LIHI is moderate to high, which shows that the river is laterally unstable. An anthropogenic disturbance (AD) is high. The ratings of the BEHI, NBS, LIHI and AD are summed to get the bank erosion and lateral instability hazard index, which range moderate to very high. The river bank from Thaiba to the confluence of the Godavari Khola and Hanumante Khola are characterized by high bank erodibility and lateral instability hazard. The soil texture, vegetation at top of bank, bank slope and slope of inside depositional bar shows positive towards the bank erosion. In most of transects, the bank slope is steep and slope of inside depositional bar is low. Therefore, the Godavari Khola has the bank recession rate of 0.66 m/y and the total volume of displaced material is 85 m^3. The total weight of the displaced material is 141 tons. Bank erosion is estimated by different empirical relations. Rutherfurd (2000) give a relation in which bank erosion is governed by bankfull discharge but later it was modified because native riparian vegetation controls the erosion of the bank. Hughes and Prosser (2003) noticed stream power and floodplain width which governs the erosion of the bank. The result of the bank erosion shows that the bank erosion rate range between 0.001 m/y and 0.235 m/y. The sediment that was eroded at the bank of the Godavari Khola supply it to the Hanumante Khola is 320 tons per year.

CONCLUSIONS

The Godavari Khola is an aggrading river which produces 320 tons of sediment per year and have bank erosion rate up to 0.235 m/y. The apparent recession rate of the bank is 0.66 m/y which exhibit volume of the displaced material to be 85 m^3 which weigh 141 tons. The riparian vegetation decreases as the river flows towards north. The anthropogenic disturbances are high. The bank erosion and lateral instability (BELI) is moderate to very high; indicating that stream banks are very unstable. The Godavari Khola has very high temporal variation of the channel which indicates that there is high bank erosion rate.

REFERENCES

Andrew, E.D., 1983, Entrainment of gravel from natural sorted riverbed material. Geol. Soc. America Bull., v. 94, pp. 1225–1231.

Brookes, A. 1990. Restoration and enhancement of engineered river channels: some European experiences. Regulated Rivers: Research and Management v. 5, no. 1, pp. 45–56

Hughes, A.O., and Prosser, I.P., 2003, Gully and riverbank erosion mapping for the Murray-Darling Basin. Technical Report 03/03, CSIRO Land and Water, Canberra.

Prosser, I., Rustomji, P., Young, P., Moran, C. and Hughes, A., 2001, Constructing River Basin Sediment Budgets for the National Land and Water Audit. 15/01, CSIRO Land and Water, Canberra.

Rosgen, D.L., 1996, *Applied river morphology, Wildland Hydrology*, Pasoga, Springs, Colorado, 390p.

Rosgen, D.L., 2001, A stream channel stability assessment methodology. In proceedings of the seventh International Sedimentation Conference, Reno, Nevada, pp. 25–28.

Rutherfurd, I., 2000, Some Human Impacts on Australian Stream Channel Morphology. In: S. Brizga and B. Finlayson (Eds.), River Management (The Australasian Experience). John Wiley and Sons, England, pp. 11–50

Schumm, S.A., 1963, A tentative classification system of alluvial rivers. Circular 477, U. S. Geological survey, Washington, D. C.

Shields, A., 1936, *Application of similarity principles and turbulence research to bed-load movement.* In: W.P. Ott and J.C. Uchelen (translators), Mitt. Preuss. Verschsanst., Berlin. Wasserbau Schiffbau. California Institute of Technology, Pasadena. CA, Report No. 167, 43p.

Shrestha, P. and Tamrakar, N.K., 2007 a, Bank erosion process and bank material loss potential in Manahara River, Kathmandu, Nepal. Bulletin of the Department of Geology, Tribhuvan University, Kathmandu, Nepal., v. 10, pp. 35–44.

Shrestha, P. and Tamrakar, N.K., 2007 b, Streambank erodibility and lateral instability hazard in the Manahara River, Kathmandu basin, Nepal. Jour. Nepal Geol. Soc., vol. 35, pp. 55–65.

Wolman, M.G., 1954. A method of sampling coarse river-bed materials. Trans. Am. Geophys, Union, v. 35, pp. 951–956.