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.

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.
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 \( NBS = \frac{D_{nb}}{D_{bkf}} \) and of method 6 \( NBS = \frac{\sigma_{nb}}{\sigma_{bkr}} \) where, \( \sigma_{nb} \) = near bank shear stress and \( \sigma_{bkr} \) = 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, 2007b). 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:

\[ \tau = \gamma R S \]  

where, \( \tau \) = boundary shear stress (N/m\(^2\)), \( \gamma \) = 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):

\[ \tau_{ci} = 0.0834 \left( \frac{d_i}{d_{50}} \right)^{0.872} \]  

where, \( \tau_{ci} \) = critical shear stress, \( d_i \) = diameter of interest of riffle sample (usually coarse fraction \( d_{10} \)), and \( d_{50} \) = mean diameter of bar sample.

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

\[ D_c = \frac{(1.65 \cdot \tau_{ci} \cdot d_i)}{S} \]  

\[ S_c = \frac{(1.65 \cdot \tau_{ci} \cdot d_i)}{D_{bkf}} \]  

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):

\[ \Omega = \gamma Q S \]  

where, \( \Omega \) = stream power (N/s), \( \gamma \) = 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.

\[ F = 255 M^{-1.08} \]  

where, \( F \) = \( W_{bkf}/D_{bkf} \) and \( M \) = \( [S_r \cdot W_{bkf}] + (S_b \cdot D_{bkf})]/(W_{bkf} + 2D_{bkf}) \)

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, 2007a).

\[ RRs = T.S.V.G.B1.B2 \]  

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 been calculated using the following formula (Shrestha and Tamrakar, 2007a),

\[ V_d = RRs \cdot L \cdot H \]  

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:

\[ TDM = \frac{(V_d \cdot \rho)}{1000} \]  

where, \( V_d \) = volume of displaced material (m\(^3\)), and \( \rho \) = 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 Rutherford (2000) is:

\[ BE = 0.016 Q^{0.60} \]  

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:
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Table 1: Morpho-hydrological parameter of the Godavari Khola

| Morpho-hydrological data          | Transsects |
|----------------------------------|------------|
|                                  | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 |
| Sinuosity, K                     |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Belt width, W₆₈ (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, Lₘ (m)       | 426 | 717 | 693| 300 | 433| 326 | 321 | 439| 348 | 438 | 663 | 441 | 366 |
| Width at bankfull, Wₐ₝ (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, Wₚₘ (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, Dₚₜ (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, Dₚₑ (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, Aₚₑ (m²) | 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 |
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                      |
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 widely 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)** |
| Bankfull depth, $D_{bf}$ (m) | Bankfull depth, $D_{bf}$ (m) | Bankfull depth, $D_{bf}$ (m) | Average slope, $S_{avg}$ | Boundary shear stress, $t_{bs}$ (N/m²) | Ratio $t_{bs}/t_{bf}$ |
| trans | $D_{bf}$ | $D_{bf}$ | $t_{bs}$ | $S_{avg}$ | $t_{bs}$ | $S_{avg}$ |
|-----------------|-----|-----|-----|-----|-----|-----|
| 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 |
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 erodibility 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/m²) whereas TS-8 transect is the lowest (139.71 N/m²).

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

| Transect | Sinuosity, k value | Meander width ratio, MWR rating | Meander length ratio, MLR value | Width/depth ratio, W/D rating | Total LIHI rating | Hazard level |
|----------|-------------------|---------------------------------|---------------------------------|-------------------------------|------------------|-------------|
| TS-1     | 1.02              | 1                               | 17.80                           | 8.5                           | 72.43            | 9.42        | 26.42       | High        |
| TS-2     | 1.09              | 1                               | 12.04                           | 7                             | 38.89            | 9.08        | 23.58       | Moderate    |
| TS-3     | 1.13              | 1                               | 9.43                            | 5.5                           | 33.33            | 9.03        | 24.43       | High        |
| TS-4     | 1.08              | 1                               | 16.05                           | 8                             | 66.34            | 9.36        | 25.26       | High        |
| TS-5     | 1.25              | 2                               | 20.90                           | 9                             | 54.86            | 9.24        | 26.64       | High        |
| TS-6     | 1.48              | 4                               | 10.83                           | 6                             | 16.79            | 4.5         | 22.33       | Moderate    |
| TS-7     | 1.31              | 3                               | 15.71                           | 8                             | 31.77            | 9.01        | 26.61       | High        |
| TS-8     | 1.45              | 4                               | 10.97                           | 6                             | 39.17            | 9.09        | 27.14       | High        |
| TS-9     | 1.43              | 4                               | 6.48                            | 4.5                           | 12.42            | 3           | 20.80       | Moderate    |
| TS-10    | 1.64              | 6                               | 15.24                           | 8                             | 16.37            | 4           | 26.50       | High        |
| TS-11    | 1.33              | 3                               | 15.37                           | 8                             | 31.56            | 9.01        | 26.51       | High        |
| TS-12    | 1.56              | 5                               | 7.65                            | 7                             | 11.70            | 2.5         | 23.70       | Moderate    |
| TS-13    | 1.86              | 8                               | 5.60                            | 4                             | 7.68             | 1           | 22.10       | Moderate    |

**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   |
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Critical depth value ranges between 0.00001 m and 0.11 m, and the 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.

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

| Location | BEHI | NBS | LIHI | AD factor | Total BEHI 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).

**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

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

| Morpho-hydroogical and Hydraulic data | Transcets | 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, t (N/m²)     |           | 407.9 | 268.7 | 145.69 | 274.1 | 532.4 | 289.9 | 310.2 | 139.71 | 154.2 | 164.1 | 247.0 | 170.1 | 321.4 |
| Critical shear stress, t_cr+ (N/m²) |           | 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, Qbar             |           | 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 |
| d0.0 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 |
| d₁₀ = dᵣ, riffle (m)                |           | 0.17 | 0.29 | 0.09 | 0.12 | 0.08 | 0.2 | 0.08 | 0.08 | 0.05 | 0.05 | 0.07 | 0.09 | 0.06 |
| dᵣ₀, 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, Dₑ (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_e (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 |

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

| 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, V4 (m^3) | Tons of Displaced Material (TDM) |
|----------|----|----|----|----|-----|-----|---------------------|-----------|-------------------------------|----------------------------------|----------------------------------|-----------------------------------|
| TS-1     | 1  | 0.3| 0.3| 1  | 1   | 1   | 0.027               | 0.008     | 30                            | 1.00                             | 0.243                            | 0.467                             |
| TS-2     | 1  | 0.3| 0.3| 0.6| 1   | 0.6  | 0.054               | 0.016     | 25                            | 2.00                             | 0.810                            | 1.557                             |
| TS-3     | 1  | 0.3| 0.3| 1  | 1   | 0.6  | 0.108               | 0.032     | 120                           | 0.50                             | 1.944                            | 3.736                             |
| TS-4     | 1  | 0.3| 1  | 1  | 1   | 0.300 | 0.090               | 87        | 1.16                          | 9.083                            | 11.644                           |                                   |
| TS-5     | 1  | 0.6| 1  | 0.6| 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   | 0.216 | 0.065               | 30        | 1.00                          | 1.944                            | 2.989                             |
| TS-10    | 1  | 0.6| 0.6| 0.6| 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.
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 values are lesser than BE due to riparian factor used in BE. The value of BE 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 (BCx)

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/m³, 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 where 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, NBSI, 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 transsects, 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 m³. 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.

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

| Segment | Length (km) | Wref (m) | Buffer 3°xwaf (m) | Area of 3°Wref buffer (m²) | Vegetated area (m²) | Proportion of riparian vegetation | Qwaf (m³/s) | BE* (Rutherford 2000) (m/y) | BE* (Modified) | BCx (Sediment Budget) (t/y) | Density of water, ρ (kg/m³) | River bed slope (m/m) | Floodplain width (m) | BE*** |
|---------|------------|----------|------------------|--------------------------|-------------------|-------------------------------|-------------|--------------------------|----------------|-----------------------------|--------------------|----------------------|------------------|--------|
| 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  |
| S2      | 0.82       | 6.1      | 18.3             | 39889.07                 | 33331             | 0.84                          | 0.96        | 0.02                     | 0.002          | 2.17                        | 1000               | 9.8                  | 0.07  | 10.3  |
| S3      | 1.31       | 11.4     | 34.2             | 87125.61                 | 26334.4           | 0.30                          | 0.68        | 0.01                     | 0.004          | 13.02                       | 1000               | 9.8                  | 0.05  | 13.5  |
| 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   |
| 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  |
| 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  |
| 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    |
| 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    |
| 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  |
| 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 |
| S11     | 1.06       | 11.2     | 33.6             | 106822.01                | 11066.1           | 0.11                          | 4.01        | 0.04                     | 0.016          | 38.88                       | 1000               | 9.8                  | 0.03  | 100.2 |
| S12     | 2.14       | 18.4     | 55.5             | 167788.36                | 23356.6           | 0.14                          | 1.84        | 0.02                     | 0.010          | 47.75                       | 1000               | 9.8                  | 0.05  | 56.1  |
| 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 |

where, BE* = 0.016*Qwaf (meter of recession per year); BE** = 0.008*(1-PR)°Qwaf/ (meter of recession per year); BE*** = 0.0002*gs*(Qwaf)°*Qwaf*(1-PR)°*(1-c°0.008v) (meter of recession per year); BCx = 18°(1-PR)*Qwaf*°*(1-c°0.008v) (tonne 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.

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