Bank erosion and lateral instability hazard status of Kodku Khola, southeast Kathmandu, central Nepal

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ABSTRACT

The northward flowing fifth order Kodku Khola confluences with the Manahara River in the southeast of Kathmandu, and has about 16.49 km stretch with 35.67 sq km watershed area. Many large civil engineering structures such as irrigation canals, bridges, highways and roads are under construction, and are located along and around the river in the urbanizing Kodku Khola valley. Some sections of the river are of high erosion potential due to various reasons. Many human activities together with natural processes have led to bank erosion and channel shifting of the Kodku Khola. Thus, study of the river bank erosion and lateral instability is of great concern as unstable segments of the river may pose threat on civil engineering structures and adjacent agricultural lands. The river bank hazard potential and its variations were assessed in terms of its bank erosion and lateral instability (BELI) hazard indices by considering four parameters namely, bank erosion hazard index (BEHI), near bank stress index (NBSI), lateral instability hazard index (LIHI), and anthropogenic disturbance factors (ADF). For this, thirty nine locations were surveyed throughout the river and assessed the BELI hazard levels. This paper evaluated the BELI hazard levels and channel shifting condition of the Kodku Khola.

Key words: Bank erosion, Planform geometry, Flood prone areas, Channel shifting

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INTRODUCTION

Stream bank erosion is a natural process, however, in many places the rate of stream bank erosion accelerates noticeably because of poor hydraulic and geotechnical processes (Rosgen 2001). Stream bank erosion can be taken as the sum of bank erodibility and bank erosivity. The former is directly related to material properties, slope protection against gravitational and lateral force, whereas the latter to near bank stress and boundary stress, which are hydraulic properties. Stream bank erosion removes the lateral toe support of the slope and generates slope instability (Shrestha and Tamrakar 2007). Many human activities together with natural processes have led to bank erosion and channel shifting of the Kodku Khola. The extensive bank erosion in the river basin has led to numerous social and economic consequences such as loss of agricultural land, settlement and other essential engineering infrastructures. High human intrusion on the natural landscape of the river corridor can also extends erosion rate in the river basin.

The Kodku Khola originating from Majhgau is one of the major tributaries of the Manahara River from southern part of the Kathmandu Valley (Fig. 1).
KODKU KHOLA BASIN

Most of the floodplains areas are used for farming and settlement. Some parts are covered by forest and some of the parts are used for quarry sites for brick industries. Due to rapid urbanisation of the Kodku valley the land used pattern has been changed around the river corridor. The water quality has been highly degraded due to contamination of sewer and solid waste disposed to the lower portion of the Kodku Khola.

Relative relief is extremely high in the Majhgau and Badikhel, high in the Muldol area and moderate to moderately low in the Taukhel, Dhapakhel, Harisidhi and Khumaltar. Relative relief decreases from south to north of the Kodku Khola watershed.

The Kodku Khola is the fifth order river. There are altogether twenty two 2nd order, six 3rd order and two 4th order streams in the watershed. The third order main stem stretches for about 3,440 m from Majhgau up to the confluence of the Kodku Khola with the Guhe Khola. The fourth order main stem river stretches for 793 m up to Tasinchok where it confluences with the major tributaries extending from the Muldol sub-watershed. The fifth order main stem river stretches for about 11,886 m and finally confluences with the Manahara River.

Planform geometry of the river is controlled by various parameters. Sinuosity (K), meander wavelength (Im), meander belt with (Wblt), and radius of curvature (Rc). All these parameters were calculated from the topographic map enlarge to 1:10,000 scale. The results of these parameters are calculated for 3rd and 5th order stream. Sinuosity indices of the third, fourth and fifth order main stem stretches of the Kodku Khola are 1.13, 1.29, and 1.36, respectively showing sinuous nature according to the classification of Leopold and Wolman (1957). The Meander wavelength, belt width and radius of curvature of the fifth order main stem river are 161.2 m, 223.1 m, and 53.3 m, respectively. Both Lm and Wblt gradually increase from the 3rd to the 4th order stream, but increase drastically to the 5th order stream. Radius of curvature however slightly diminishes and increases again from the 3rd to the 5th order stream. Increasing size of the 5th order stream possibly has caused increase in Planform parameters.

Geologically, the Kodku watershed comprises three types of sediments and rocks; Cambro-Ordovician bedrocks and Plio-Pleistocene fluvial-lacustrine sediments, Quaternary sediment (after DMG 1998) (Fig. 2). The Kodku watershed comprises Cambro-Ordovician metasedimentary rocks of the Phulchoki Group i.e., the Sopyang and the Chandragri formations in the southernmost portion. The Sopyang Formation comprises dark to yellowish brown thinly bedded calcareous slate, argillaceous limestone and grey metasiltstone. It is well exposed at the left bank of the Kodku Khola near the Badikhel. The Chandragiri Formation comprises bluish grey to brown, finely crystalline limestone, phyllite and metasandstones. The beds extend NW-SE, and dip southwestward in the southern portion and northeastwards in the northern portion, thus forming the portion of the anticline. A ridge forming bedrock of the Chandragiri Limestone also exists at Jharuwarasi, where river incises forming a hanging valley towards the south. Adjacent to the bedrocks of the above two formations are distributed the colluvial sediments and the alluvial fan deposits. The western half portion of the watershed is occupied by the Chapagaon Formation. It comprises of subrounded to rounded silty sandy gravel occasionally intercalated with silty sand, clayey silt, and boulder beds. The portion of the western part of the watershed is occupied by the Lukukdol Formation characterised by sandy clayey silt interbedded with gravel, sand, and peat layers. The majority of the northeastern or the eastern half portion of the watershed constitutes the Kalimati Formation.

BANK EROSION AND LATERAL INSTABILITY HAZARD ASSESSMENT

Stream bank erosion is basically controlled by two parameters which influence erodibility and erosivity of the banks. These parameters are respectively Bank Erosion Hazard Index (BEHI) and Near Bank Shear Stress Index (NBSI). Six parameters of bank features; bank height ratio (BHR), bank angle (BA), root depth ratio (RDR), root density (RD), surface protection (SP) and bank material characteristics (BMC) are considered for BEHI (Rosgen 2001). Similarly near bank maximum depth (D_{max}), bankfull depth (D_{bcf}), near bank slope...
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(S_{\text{act}}) and average slope (S_{\text{avg}}) are considered in terms of NBSI. Shrestha and Tamrakar (2007) proposed some other parameters which are responsible for lateral instability of channels. These parameters are expressed in terms of lateral instability hazard index (LIHI) and anthropogenic disturbance (AD). Altogether these four parameters, i.e., BEHI, NBSI, LIHI and AD were assessed to generate a bank erosion and lateral instability (BELI) hazard indices for the Kodku Khola.

To generate the BELI hazard map, thirty nine locations at the Kodku Khola were surveyed. The Ushikata theodolite and staff were used to measure the cross-section and the longitudinal section of the Kodku Khola. Planform geometry and hydraulic parameters were assessed from the field survey and topographic map. Eventually, BEHI, NBSI, LIHI, and AD were determined and their values were transformed into corresponding ratings based on Rosgen (2001) and Shrestha and Tamrakar (2007) using the Table 1. The BELI rating for a given location was then determined by summing up of the corresponding values of the four parameters. Finally, it was further classified in to very low, low, moderate, high, very high, and extreme hazard categories based on these categories, and then BELI hazard indices were obtained for the river corridor within the flood prone width.

Table 1: Criteria for evaluating bank erosion and lateral instability hazard levels.

| Parameters                          | Attributes          | Hazard levels             |
|-------------------------------------|---------------------|----------------------------|
|                                     | Value               | Very high | low | Moderate | High | Very high | Extreme |
| Bank height ratio                   | Value               | 1.0-1.1  | 1.1-1.2 | 1.2-1.5 | 1.5-2 | 2.2.8     | >2.8    |
|                                     | Index               | 1-2       | 2-4     | 4-6     | 6-8   | 8-9       | 10      |
| Root depth ratio (%)                | Value               | 100-80    | 80-55   | 55-30   | 30-15 | 15-5      | <5      |
|                                     | Index               | 1-2       | 2-4     | 4-6     | 6-8   | 8-9       | 10      |
| Root density (%)                    | Value               | 100-80    | 80-55   | 55-30   | 30-15 | 15-5      | <5      |
|                                     | Index               | 1-2       | 2-4     | 4-6     | 6-8   | 8-9       | 10      |
| Bank angle (degree)                 | Value               | 0-20      | 20-60   | 60-80   | 80-90 | 90-120    | >120    |
|                                     | Index               | 1-2       | 2-4     | 4-6     | 6-8   | 8-9       | 10      |
| Surface protection (%)              | Value               | 100-90    | 90-50   | 50-30   | 30-15 | 15-5      | <5      |
|                                     | Index               | 1-2       | 2-4     | 4-6     | 6-8   | 8-9       | 10      |
| Total BEHI                          | <10                 | 10-20     | 20-30   | 30-40   | 40-45 | >45       |
| Near bank stress index (NBSI)       | Value               | <0.8      | 0.8-1.05| 1.06-1.14| 1.15-1.19| 1.20-1.60 | >1.60   |
|                                     | Index               | <2        | 2-4     | 4-6     | 6-8   | 8-9       | >9      |
| Sinuosity (K)                       | Value               | <2.1      | 2.1-1.4 | 1.4-1.6 | 1.6-1.8| 1.8-2.0   | >2.0    |
|                                     | Index               | 1-2       | 2-4     | 4-6     | 6-8   | 8-9       | >9      |
| Meander width ratio                 | Value               | <2        | 2-5     | 5-10    | 10-15 | 15-20     | >20     |
|                                     | Index               | 1-2       | 2-4     | 4-6     | 6-8   | 8-9       | >9      |
| Meander length ratio                | Value               | <10       | 10-15   | 15-20   | 20-25 | 25-30     | >30     |
|                                     | Index               | 1-2       | 2-4     | 4-6     | 6-8   | 8-9       | >9      |
| W/D ratio                           | Value               | <1.4      | 1.4-2.0 | 2-10    | 10-20 | 20-40     | >40     |
|                                     | Index               | 1-2       | 2-4     | 4-6     | 6-8   | 8-9       | >9      |
| Total LIHI                          | <8                  | 8-16      | 16-24   | 24-32   | 32-36 | >36       |
| Anthropogenic disturbance           | Value               | <5        | 5-10    | 10-15   | 15-20 | 20-25     | >25%    |
|                                     | Index               | 1-2       | 2-4     | 4-6     | 6-8   | 8-9       | >9      |
| Total rating                        | <22                 | 22-44     | 44-66   | 66-88   | 88-99 | >99       |
River itself shows dynamic nature by shifting its channel in space and time. The shifting of channel can however be aggravated by effects of natural and human activities. The channel shifting of the Kodku Khola was determined by comparing the topographic map of 1999 and satellite image of 2013 of the Kodku watershed (Fig. 3). The river channel is more shifted in Imadol and Khumaltar.

Bank erosion hazard index

Five parameters of stream bank features were assessed following the Rosgen. The variables includes Bank height ratio (BHR), bank angle (BA), root depth ratio (RDR), root density (RD), surface protection (SP) (Table 2). The assessed stream bank variables were transformed in to their corresponding rating by using the Table 1. Hazard rating ranges from 0-10 corresponding to very low, low, moderate, high, very high and extreme. Apart from the above five parameters according to the Rosgen (1996) bank material type, its stratification, texture and stiffness were also considered for determining the BEHI. Bank height ratio, bank angle and root depth ratio were calculated quantitatively in the field at each location. But root density and surface protection percentage were obtained qualitatively by estimating the vegetation present on banks of the Kodku Khola throughout thirty nine locations.

The status of erosion is largely controlled by the steepness of the slope of the stream bank. Vertical and cantilever banks often show high erosion rates. Generally, higher BHR value represents greater susceptibility to stream bank erosion Rosgen (2001). In the Kodku Khola, BHR ranges from low value 1 to high value 8. The lowest values observed were repeatedly throughout the river whereas the highest values were observed from Jharuwarasi near the gorge. The Badikhel, Thaiba, Dasghare and Gwarko sites of the Kodku Khola fall on moderate to high hazard level. Majgau and Jharuwarasi sites of the river fall on extreme hazard level.

The result of BEHI is indicated in Table 2 and Fig. 4. The result shows that Erosion potentiality of the Kodku Khola banks fall on low to very high hazard level. The Harishidhi (BE26, BE27, and BE28) and Thaiba (BE20) areas exhibit very high potential of stream erosion. More than half of the sample stations exhibit the high to very high hazard level. The hazard level increases towards downstream region.

Near bank stress index

Near bank stress index (NBSI) is the ratio of near bank shear stress and boundary shear stress. To find NBSI each stream width at a selected station was divided into three equal parts. The near bank shear stress was estimated by taking the depth and slope of near bank region.

$$\tau_{nb} = \gamma d_{nb} S_{nb}$$  \hspace{1cm} (1)

Where $\tau_{nb}$ = near bank shear stress (kN/m$^2$), $\gamma$ = unit weight of water (kN/m$^2$), $d_{nb}$ = near bank maximum depth (m), $S_{nb}$ = near bank slope

Boundary shear stress ($\tau$) was calculated using the following expression of Shields (1936).

$$\tau = \gamma RS$$ \hspace{1cm} (2)

Where $\tau$ = boundary shear stress, $\gamma$ = Unit weight of water, R = Hydraulic radius of the riffle cross-section at bank full stage and S = Average stream slope.

Finally NBSI was calculated, and the values of NBSI were then transformed into their corresponding hazard rating based on Table 1. The greater values of NBSI indicate greater power of stream flow to erode the stream banks (Table 3).
The banks of the Kodku Khola are subject to very high to extreme near bank stresses (Table 3 and Fig. 5). Sample stations around the Majhga area (BE1, BE2, and BE3), Thapagau (BE7), Jharuwarasi (BE16) and Harishidhi areas are subject to very high hazard level and the remaining sample stations fall on extreme hazard level.

**Lateral instability hazard index**

Sinuosity (K: Sinuosity is the ratio of the channel length to the distance of the valley), meander width ratio (MWR: the ratio of the meander length to bank full depth of the river), meander length ratio (MLR: ratio of the meander length to bank full depth of the river) and width depth ratio (W/D: ratio of meander width to the bank full depth of the river) are the hazard indices which influence the lateral instability of the river. Laterally unstable stream banks have higher values of all above indices. The sinuosity of the river is progressively developed by the result of the bank erosion. MWR and MLR represent lateral containment of the river. Higher values of W/D indicate unstable stream banks. The cross-section survey and Planform results were used to calculate the above all lateral instability hazard indices of all study sites.

The result (Table 4 and Fig. 6) shows that lateral instability condition of the banks of the Kodku Khola fall on low to moderate hazard levels. Moderate LIHI is due to high

**Table 2: Field data of BEHI and their corresponding hazard ratings.**

| Sample Station | Field measured values | Bank erosion hazard index rating |
|---------------|-----------------------|--------------------------------|
|               | BHR | RD | BA | SP | BHR | RDR | RD | BA | SP | Adjustment | Total BEHI | BEHI Level |
| BE1           | 5   | 0.14 | 95 | 30 | 95 | 10   | 8  | 1  | 3  | 1         | -10   | BEHI 13    |
| BE2           | 1.5 | 0.5  | 80 | 85 | 50 | 6    | 6  | 8  | 9  | 4         | -10   | BEHI 13    |
| BE3           | 1.3 | 0.31 | 20 | 110 | 50 | 6    | 6  | 8  | 9  | 4         | -10   | BEHI 21    |
| BE4           | 1.4 | 0.33 | 22 | 120 | 20 | 6    | 6  | 7  | 10 | 8         | -10   | BEHI 17    |
| BE5           | 1.2 | 0.29 | 70 | 90 | 75 | 6    | 6  | 3  | 8  | 3         | 5     | BEHI 31    |
| BE6           | 1.7 | 0.16 | 70 | 85 | 40 | 6    | 7  | 3  | 7  | 5         | -10   | BEHI 18    |
| BE7           | 3   | 0.27 | 85 | 75 | 60 | 10   | 6  | 2  | 6  | 4         | -10   | BEHI 18    |
| BE8           | 1.9 | 0.19 | 45 | 80 | 60 | 7    | 7  | 4  | 6  | 4         | -5    | BEHI 23    |
| BE9           | 1   | 0.88 | 50 | 95 | 80 | 1    | 2  | 4  | 8  | 2         | 5     | BEHI 21    |
| BE10          | 2.7 | 0.31 | 40 | 70 | 70 | 9    | 6  | 5  | 5  | 3         | 5     | BEHI 33    |
| BE11          | 1   | 0.55 | 20 | 85 | 25 | 1    | 4  | 7  | 7  | 7         | 5     | BEHI 31    |
| BE12          | 1.3 | 0.47 | 15 | 110 | 25 | 4    | 4  | 8  | 9  | 7         | 5     | BEHI 37    |
| BE13          | 1   | 0.56 | 30 | 110 | 70 | 1    | 4  | 6  | 9  | 3         | 0     | BEHI 23    |
| BE14          | 1.2 | 0.75 | 30 | 85 | 55 | 4    | 3  | 6  | 7  | 4         | 0     | BEHI 24    |
| BE15          | 1   | 0.5  | 20 | 110 | 10 | 1    | 4  | 8  | 9  | 9         | 5     | BEHI 36    |
| BE16          | 1.1 | 0.79 | 25 | 83 | 60 | 2    | 2  | 7  | 7  | 4         | 2     | BEHI 24    |
| BE17          | 1.5 | 0.17 | 60 | 105 | 50 | 6    | 7  | 4  | 9  | 4         | 0     | BEHI 30    |
| BE18          | 8   | 0.03 | 45 | 78 | 60 | 10   | 10 | 5  | 7  | 4         | 0     | BEHI 36    |
| BE19          | 1   | 0.85 | 40 | 75 | 75 | 1    | 2  | 5  | 6  | 3         | -5    | BEHI 12    |
| BE20          | 1.3 | 0.4  | 20 | 110 | 10 | 4    | 5  | 8  | 9  | 9         | 10    | BEHI 45    |
| BE21          | 1   | 0.42 | 20 | 105 | 10 | 1    | 5  | 8  | 8  | 9         | -2    | BEHI 30    |
| BE22          | 1   | 0.3  | 60 | 105 | 75 | 1    | 6  | 4  | 8  | 3         | -5    | BEHI 20    |
| BE23          | 1.4 | 0.34 | 35 | 105 | 40 | 4    | 6  | 5  | 8  | 5         | 5     | BEHI 33    |
| BE24          | 1.4 | 0.33 | 50 | 100 | 55 | 4    | 6  | 4  | 8  | 4         | -5    | BEHI 21    |
| BE25          | 1.9 | 0.2  | 65 | 95 | 45 | 8    | 7  | 3  | 8  | 4         | 5     | BEHI 35    |
| BE26          | 1.5 | 0.35 | 68 | 85 | 90 | 6    | 6  | 3  | 7  | 2         | 0     | BEHI 24    |
| BE27          | 1   | 0.38 | 20 | 105 | 10 | 1    | 5  | 8  | 8  | 9         | 5     | BEHI 36    |
| BE28          | 1.2 | 0.13 | 10 | 87 | 10 | 2    | 8  | 9  | 8  | 9         | 5     | BEHI 41    |
| BE29          | 1.5 | 0.1  | 10 | 95 | 20 | 6    | 8  | 9  | 8  | 8         | 5     | BEHI 44    |
| BE30          | 1   | 0.1  | 10 | 105 | 5  | 1    | 8  | 9  | 9  | 10        | 5     | BEHI 42    |
| BE31          | 1.4 | 0.17 | 80 | 85 | 85 | 4    | 7  | 2  | 7  | 5         | 5     | BEHI 30    |
| BE32          | 1.9 | 0.14 | 75 | 85 | 80 | 7    | 8  | 2  | 7  | 5         | 5     | BEHI 34    |
| BE33          | 1.3 | 0.32 | 25 | 95 | 8  | 4    | 6  | 6  | 8  | 9         | 5     | BEHI 38    |
| BE34          | 1.8 | 0.15 | 78 | 65 | 86 | 6    | 8  | 2  | 5  | 2         | 5     | BEHI 28    |
| BE35          | 2.7 | 0.14 | 65 | 88 | 70 | 9    | 8  | 3  | 7  | 3         | 5     | BEHI 35    |
| BE36          | 2.5 | 0.09 | 40 | 90 | 55 | 9    | 8  | 5  | 8  | 4         | 5     | BEHI 39    |
| BE37          | 1.9 | 0.12 | 40 | 90 | 55 | 8    | 8  | 5  | 8  | 4         | 5     | BEHI 38    |
| BE38          | 2.3 | 0.09 | 45 | 80 | 55 | 8    | 8  | 5  | 6  | 4         | 5     | BEHI 36    |
| BE39          | 2.5 | 0.13 | 40 | 90 | 60 | 9    | 8  | 5  | 8  | 4         | 5     | BEHI 34    |

**Fig. 5: NBSI hazard status of the Kodku Khola.**
values of almost all the Planform parameters. Sinuosity (K), meander width ratio (MWR) and meander length ratio (MLR) of the river largely influence the value of LIHI, and hence its fluctuation. The result shows that the area of Badikhel and the downstream sites from the Harishidhi to the Manahara River Bridge fall on low lateral instability hazard index level. The low values of LIHI are due to the extreme channelisation and human encroachment of the river. The channelisation directly affects the K, MWR and MLR of the river. Such planform parameters are frequently altered due to many anthropogenic disturbances and discharge variation of the river.

Table 3: Result of the near bank stress index (NBSI).

| Sample Station | Near bank max. depth, \(D_{nb}\) (m) | Bankfull depth, \(D_{bf}\) (m) | NBSI = \(D_{nb}/D_{bf}\) | Rating | NBS hazard level |
|----------------|--------------------------------------|--------------------------------|--------------------------|--------|-----------------|
| BE1            | 1.3                                  | 0.9                            | 1.44                      | 8.55   | VH              |
| BE2            | 1.2                                  | 0.9                            | 1.33                      | 8.2    | VH              |
| BE3            | 1.3                                  | 0.8                            | 1.60                      | 9      | VH              |
| BE4            | 1.7                                  | 1.0                            | 1.70                      | 9.1    | E               |
| BE5            | 1.4                                  | 0.6                            | 2.33                      | 9.2    | E               |
| BE6            | 1.5                                  | 0.7                            | 2.14                      | 9.2    | E               |
| BE7            | 1.6                                  | 0.7                            | 2.29                      | 9.5    | E               |
| BE8            | 1.2                                  | 0.8                            | 1.5                       | 8.8    | VH              |
| BE9            | 1.6                                  | 0.8                            | 2.00                      | 9.1    | E               |
| BE10           | 1.3                                  | 0.5                            | 2.60                      | 9.3    | E               |
| BE11           | 1.5                                  | 0.6                            | 2.50                      | 9.3    | E               |
| BE12           | 1.6                                  | 0.7                            | 2.29                      | 9.18   | E               |
| BE13           | 1.1                                  | 0.5                            | 2.20                      | 9.2    | E               |
| BE14           | 1.0                                  | 0.6                            | 1.73                      | 9.02   | E               |
| BE15           | 1.3                                  | 0.5                            | 2.60                      | 9      | E               |
| BE16           | 1.0                                  | 0.4                            | 1.25                      | 8.1    | VH              |
| BE17           | 1                                    | 0.5                            | 2                          | 9.01   | E               |
| BE18           | 1.3                                  | 0.6                            | 1.83                      | 9.04   | E               |
| BE19           | 1.2                                  | 0.6                            | 2.00                      | 9.01   | E               |
| BE20           | 1.0                                  | 0.5                            | 2.00                      | 9.01   | E               |
| BE21           | 1.3                                  | 0.6                            | 2.17                      | 9.03   | E               |
| BE22           | 1.3                                  | 0.5                            | 2.60                      | 9.3    | E               |
| BE23           | 2.0                                  | 0.6                            | 3.33                      | 9.6    | E               |
| BE24           | 1.5                                  | 0.6                            | 2.50                      | 9.3    | E               |
| BE25           | 1.1                                  | 0.6                            | 1.83                      | 9.04   | E               |
| BE26           | 0.8                                  | 0.6                            | 1.33                      | 8.5    | E               |
| BE27           | 1.0                                  | 0.3                            | 3.33                      | 9.7    | E               |
| BE28           | 1.1                                  | 0.5                            | 2.20                      | 9.2    | E               |
| BE29           | 1.2                                  | 1.0                            | 1.20                      | 8      | VH              |
| BE30           | 1.2                                  | 0.9                            | 1.33                      | 8.4    | VH              |
| BE31           | 1.5                                  | 0.9                            | 1.67                      | 8.9    | E               |
| BE32           | 1.5                                  | 0.8                            | 1.88                      | 9      | E               |
| BE33           | 2.3                                  | 0.9                            | 2.56                      | 9      | E               |
| BE34           | 2.5                                  | 1.0                            | 2.50                      | 9.3    | E               |
| BE35           | 2.3                                  | 1.1                            | 2.09                      | 9.1    | E               |
| BE36           | 2.9                                  | 1.2                            | 2.42                      | 9.4    | E               |
| BE37           | 2.5                                  | 1.0                            | 2.50                      | 9.3    | E               |
| BE38           | 2.7                                  | 1.3                            | 2.08                      | 9.02   | E               |
| BE39           | 2.4                                  | 1.2                            | 2.00                      | 9.01   | E               |

Anthropogenic disturbances

The river bank erosion is also influenced by natural as well anthropogenic factors. Flood and landslide are main natural factors that directly affect the river bank stability condition. The major anthropogenic activities such as bank encroachment, river channel excavation and unplanned cultivation on the river corridors are also responsible for bank erosion hazard. Disturbance percentage of each location was assessed qualitatively from the field and rating was assigned from 1 to 10 into six hazard classes from very low to extreme by using the Table 2.

At the Majhgau area, banks of the Kodku Khola have been less disturbed by human activities whereas natural factors moderately affect stability condition of river banks (Fig. 7 and Table 5). Some areas of the Thaiba and Harishidi belong to very high hazard levels. The sample stations located downstream from the Harishidhi to the Gwarko areas are highly disturbed by human activities. River has extremely lost its natural status by extreme channelization and pollutions in these areas. The Taukhel, Jharuwarasi, Dasghare and Imadol areas fall on high hazard levels. The sample station downstream from the Thapa Gau to Dashgare areas are seriously affected by the anthropogenic disturbances such as unplanned cultivation, disposal of sewage and livestock.
### Table 4: Result of lateral instability hazard indices and their corresponding ratings.

| Location | Rating | MWR | Rating | MLR | Rating | W/D ratio | Rating | Total rating | Hazard level |
|----------|--------|-----|--------|-----|--------|-----------|--------|--------------|--------------|
| BE1      | 1      | 10.77 | 7.1    | 30.77 | 9      | 7.22      | 5.1    | 22.2         | M            |
| BE2      | 2      | 13.33 | 7.8    | 30.00 | 9      | 5.00      | 4.9    | 23.7         | M            |
| BE3      | 2      | 6.04  | 4.5    | 7.99  | 0.8    | 12.34     | 6.5    | 13.8         | L            |
| BE4      | 2      | 5.52  | 4      | 7.30  | 0.7    | 10.10     | 6.1    | 12.8         | L            |
| BE5      | 2      | 5.98  | 4.1    | 7.91  | 0.8    | 10.79     | 6.2    | 13.1         | L            |
| BE6      | 2      | 7.00  | 4.9    | 9.26  | 1.9    | 12.42     | 6.5    | 15.3         | L            |
| BE7      | 5      | 12.33 | 6.9    | 13.70 | 3.1    | 10.43     | 6.5    | 21.5         | M            |
| BE8      | 2      | 8.65  | 5.6    | 27.16 | 8.5    | 10.13     | 6.1    | 22.2         | M            |
| BE9      | 3      | 8.66  | 5.7    | 11.73 | 2.2    | 12.03     | 6.2    | 17.1         | L            |
| BE10     | 1      | 13.83 | 7.2    | 18.73 | 5.1    | 10.00     | 6      | 21.3         | M            |
| BE11     | 3      | 14.67 | 7.3    | 19.88 | 5.9    | 8.45      | 5.5    | 21.7         | M            |
| BE12     | 3      | 13.83 | 7.3    | 18.73 | 5.1    | 7.03      | 4.9    | 20.3         | M            |
| BE13     | 7      | 13.36 | 7.2    | 19.44 | 5.8    | 13.58     | 6.4    | 26.4         | M            |
| BE14     | 7      | 9.72  | 5.8    | 14.14 | 3.8    | 15.71     | 7.1    | 23.7         | M            |
| BE15     | 7      | 12.83 | 6.9    | 18.67 | 5.5    | 13.89     | 6.6    | 26            | M            |
| BE16     | 7      | 12.49 | 6.8    | 18.18 | 5.3    | 17.50     | 7.4    | 26.5         | M            |
| BE17     | 4      | 10.25 | 5.9    | 16.95 | 4.7    | 11.80     | 6.2    | 20.8         | M            |
| BE18     | 3      | 8.63  | 5.6    | 13.04 | 2.9    | 23.00     | 8.1    | 19.6         | L            |
| BE19     | 2      | 11.99 | 7.1    | 17.81 | 4.8    | 13.83     | 6.6    | 20.5         | M            |
| BE20     | 2      | 14.63 | 7.4    | 21.74 | 6.4    | 14.47     | 6.9    | 22.7         | M            |
| BE21     | 2      | 8.36  | 5.2    | 12.42 | 2.7    | 19.51     | 7.9    | 17.8         | L            |
| BE22     | 2      | 13.63 | 7.2    | 20.25 | 6.2    | 13.77     | 6.5    | 21.9         | M            |
| BE23     | 8      | 18.37 | 8.5    | 19.41 | 5.6    | 16.33     | 7.5    | 29.6         | M            |
| BE24     | 2      | 11.46 | 6.7    | 8.34  | 1.8    | 32.00     | 8.6    | 26.1         | M            |
| BE25     | 7      | 8.5   | 4.8    | 9.53  | 1.9    | 26.33     | 8.4    | 23.6         | M            |
| BE26     | 6      | 2.77  | 2      | 5.23  | 1.3    | 41.67     | 9      | 18.3         | L            |
| BE27     | 2      | 4.23  | 1.7    | 4.80  | 1.2    | 73.00     | 9.5    | 14.4         | L            |
| BE28     | 2      | 8.58  | 5.1    | 9.74  | 1.8    | 20.38     | 8.4    | 17.3         | L            |
| BE29     | 2      | 4.66  | 3.3    | 5.29  | 1.4    | 20.52     | 8.4    | 15.1         | L            |
| BE30     | 2      | 8.28  | 5.1    | 9.40  | 1.7    | 12.17     | 6.2    | 15            | L            |
| BE31     | 1      | 8.24  | 4.9    | 18.74 | 5.5    | 10.11     | 6.1    | 17.5         | L            |
| BE32     | 2      | 6.86  | 4.7    | 7.60  | 1.8    | 18.13     | 7.6    | 16.1         | L            |
| BE33     | 5      | 6.03  | 4.6    | 3.62  | 1.3    | 33.58     | 8.8    | 19.7         | L            |
| BE34     | 2      | 5.81  | 3.4    | 2.64  | 1.2    | 39.50     | 8.9    | 15.5         | L            |
| BE35     | 3      | 3.33  | 2.9    | 4.14  | 1.5    | 24.64     | 8.5    | 15.9         | L            |
| BE36     | 0      | 9.64  | 5.6    | 11.87 | 2.3    | 11.25     | 6.3    | 14.2         | L            |
| BE37     | 0      | 2.97  | 2.8    | 7.92  | 1.9    | 15.20     | 7.4    | 12.1         | L            |
| BE38     | 0      | 10.61 | 6.1    | 20.81 | 6.1    | 8.08      | 5.8    | 18            | L            |
| BE39     | 3      | 6.76  | 4.6    | 4.88  | 1.6    | 15.42     | 6.5    | 15.7         | L            |
Table 5: Result of anthropogenic disturbance.

| Sample station | Average values | AD ratings | Hazard level |
|----------------|----------------|------------|--------------|
| BE1            | 10.7           | 4          | M            |
| BE2            | 11.7           | 4          | M            |
| BE3            | 11.0           | 4.5        | M            |
| BE4            | 3.0            | 2          | L            |
| BE5            | 11.3           | 4          | M            |
| BT6            | 7.5            | 3          | L            |
| BE7            | 9.6            | 3.5        | L            |
| BE8            | 18.8           | 7.2        | H            |
| BE9            | 8.3            | 3          | L            |
| BE10           | 4.2            | 2          | L            |
| BE11           | 6.7            | 3          | L            |
| BE12           | 10.0           | 4          | M            |
| BE13           | 12.5           | 5.5        | M            |
| BE14           | 15.0           | 6          | H            |
| BE15           | 12.3           | 4.6        | M            |
| BE16           | 10.0           | 4          | M            |
| BE17           | 14.3           | 5          | M            |
| BE18           | 9.3            | 3.5        | L            |
| BE19           | 7.1            | 3          | L            |
| BE20           | 13.3           | 5.8        | M            |
| BE21           | 12.5           | 5.5        | M            |
| BE22           | 8.8            | 3.2        | L            |
| BE23           | 12.3           | 3.2        | L            |
| BE24           | 11.9           | 5          | M            |
| BE25           | 14.4           | 5.5        | M            |
| BE26           | 15.0           | 6          | H            |
| BE27           | 16.9           | 6.5        | H            |
| BE28           | 15.0           | 6          | H            |
| BE29           | 15.0           | 6          | H            |
| BE30           | 16.1           | 6.2        | H            |
| BE31           | 14.7           | 5.8        | M            |
| BE32           | 12.3           | 4.8        | M            |
| BE33           | 12.7           | 4.8        | M            |
| BE34           | 13.7           | 5          | M            |
| BE35           | 13.7           | 5.5        | M            |
| BE36           | 16.0           | 7          | H            |
| BE37           | 16.3           | 7          | H            |
| BE38           | 17.0           | 7.5        | H            |
| BE39           | 17.7           | 7.5        | H            |

**BANK EROSION AND LATERAL INSTABILITY HAZARD STATUS**

Above mentioned four major parameters namely BEHI, NBSI, LIHI, AD were combined to prepare the BELI hazard map (Fig. 8) of the Kodku Khola. This shows that the river has moderate to high hazard level except in one sample station (BE4) near Badikhel. The stream bank with high hazard are observed near Taukhel (BE12, BE15), Gorge (BE18), Thaiba (BE20), Dashghare (BE23), Harishidhi (BE25, BE28, BE29, BE30) and downstream from Los Angel School (BE33, BE36, BE37, BE38, BE39). The remains out stations indicate the stream banks are moderately hazardous (Table 6, Figs. 8 and 9).

Table 6: Result of the bank erosion and lateral instability hazard.

| Locations | Distance | BEHI | LIHI | NBSI | BELI | Hazard |
|-----------|----------|------|------|------|------|--------|
| BE1       | 0.65     | 4    | 13   | 22.2 | 8.55 | 48.2   | M      |
| BE2       | 1.15     | 4    | 13   | 23.7 | 8.2  | 49.7   | M      |
| BE3       | 1.71     | 4.5  | 21   | 13.8 | 9    | 48.3   | M      |
| BE4       | 1.9      | 2    | 17   | 12.8 | 9.1  | 40.8   | L      |
| BE5       | 1.96     | 4    | 31   | 13.1 | 9.2  | 57.1   | M      |
| BE6       | 2.08     | 3    | 18   | 15.3 | 9.2  | 45.3   | M      |
| BE7       | 3.29     | 3.5  | 18   | 21.5 | 9.5  | 52     | M      |
| BE8       | 3.75     | 7.2  | 23   | 22.2 | 8.8  | 61.4   | M      |
| BE9       | 4.32     | 3    | 21   | 17.1 | 9.1  | 50.1   | M      |
| BE10      | 4.44     | 3    | 33   | 21.3 | 9.3  | 65.3   | M      |
| BE11      | 4.57     | 3    | 31   | 21.7 | 9.3  | 64.7   | M      |
| BE12      | 4.57     | 4    | 37   | 20.3 | 9.18 | 70.3   | H      |
| BE13      | 5.06     | 5.5  | 23   | 26.4 | 9.2  | 63.9   | M      |
| BE14      | 5.17     | 4.6  | 36   | 26   | 9    | 75.6   | H      |
| BE15      | 5.37     | 4    | 24   | 26.5 | 8.1  | 63.5   | M      |
| BE16      | 6.12     | 5    | 30   | 20.8 | 9.01 | 64.8   | M      |
| BE17      | 7.05     | 3.5  | 36   | 19.6 | 9.4  | 68.1   | H      |
| BE18      | 7.15     | 3    | 12   | 20.5 | 9.01 | 44.5   | M      |
| BE19      | 7.25     | 5.8  | 45   | 22.7 | 9.01 | 82.5   | H      |
| BE20      | 7.32     | 5.5  | 30   | 17.8 | 9.03 | 62.3   | M      |
| BE21      | 8.02     | 3.2  | 20   | 21.9 | 9.3  | 54.1   | M      |
| BE22      | 8.52     | 3.2  | 33   | 29.6 | 9.6  | 74.8   | H      |
| BE23      | 9.02     | 5    | 21   | 26.1 | 9.3  | 61.1   | M      |
| BE24      | 9.55     | 5.5  | 35   | 23.6 | 9.04 | 73.1   | H      |
| BE25      | 10.16    | 6    | 24   | 18.3 | 8.5  | 57.3   | M      |
| BE26      | 10.56    | 6.5  | 36   | 14.4 | 9.7  | 65.9   | M      |
| BE27      | 10.71    | 6    | 41   | 17.3 | 9.2  | 73.3   | H      |
| BE28      | 10.85    | 6    | 44   | 15.1 | 8    | 73.6   | H      |
| BE29      | 11.2     | 6.2  | 42   | 15   | 8.4  | 71.6   | H      |
| BE30      | 11.83    | 5.8  | 30   | 17.5 | 8.9  | 62.3   | M      |
| BE31      | 12.38    | 4.8  | 34   | 16.1 | 9    | 63.9   | M      |
| BE32      | 12.94    | 4.8  | 38   | 19.7 | 9    | 71.5   | H      |
| BE33      | 13.56    | 5    | 28   | 15.5 | 9.3  | 57.5   | M      |
| BE34      | 14.11    | 5.5  | 35   | 15.9 | 9.1  | 65.4   | M      |
| BE35      | 14.74    | 7    | 39   | 14.2 | 9.4  | 69.2   | H      |
| BE36      | 15.39    | 7    | 38   | 12.1 | 9.3  | 66.1   | H      |
| BE37      | 15.93    | 7.5  | 36   | 18   | 9.02 | 70.5   | H      |
| BE38      | 16.49    | 7.5  | 34   | 15.7 | 9.01 | 66.2   | H      |
| BE39      | 17.7     | 7.5  | 34   | 15.7 | 9.01 | 66.2   | H      |
CONCLUSIONS

The Kodku Khola falls in a moderate to high level of BELI hazard. The hazard level is found higher while moving from the upstream (Badikhel) to the downstream. BELI hazard level is moderate in the Majhgau, Badikhel and Taukhel areas. From Arubot to Los Angel School, the hazard levels fall in moderate to high level. The river has more hazardous in the Thaiba, Harishidi and Gwarko areas. BEHI and AD plays great roles for increasing the BELI hazard levels in the Kodku Khola. Minimising the hazard level of the Kodku Khola is very essential for the peoples, infrastructures around river corridors and to keep the river's natural beauty. Minimising the human disturbance such as by prohibiting channelisation, encroachments, direct sewage input and mining are best way to minimise the hazard levels in the Kodku Khola. To reduce stream bank erodibility, riparian vegetation buffer zones with suitable bioengineering measures should be established soon.

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