**Bulletin of the Department of Geology**

Bulletin of the Department of Geology, Tribhuvan University, Kathmandu, Nepal, vol. 17, 2014, pp. 1–41

# Riverbank erosion potential and channel stability status of the Kodku River, southern Kathmandu Basin, Central Nepal

*Naresh Kazi Tamrakar, Ramita Bajracharya, Sudarshon Sapkota, Ishwar Thapa, Prem Paudel and Niraj Bal Tamang

*Central Department of Geology, Tribhuvan University, Kathmandu, Nepal*

## ABSTRACT

The Kodku River is a southern tributary of the Manahara River and extends for about 15.86 km with 35.67 sq. km of watershed area. It is quite a potential linkage between the hilly, southern Kathmandu and the urban, inner Kathmandu. The river corridors are frequently subject to bank erosion, slope movements and flash flooding. Riverbank erosion is an important cause of toe erosion of slopes causing landslides and also posing threat on the infrastructures. Stream channel stability is crucial to understand overall river stability. Recognition of existing stability condition of river is to understand nature and behavior of the river, and is important in many ways: (a) to recognize the bank erosion and lateral instability hazard, (b) to develop infrastructure along or nearby the river corridor, (c) to start on where to restore the river, (d) to develop reservoir and exploit natural resources, and (e) to develop safe settlement areas. The Kodku River is a gravelly mixed-load meandering river. Level II classification distinguishes the Badikhel Segment as a 'B4c' type stream, the Taukhel Segment as a 'C6c' type, and the fifth order segments such as the Arubot, Thaiba and Harisidhi Segments as 'C4c' type streams. The 'B4c' type stream is entrenched and somewhat laterally confined by steep valley slopes and terrace landforms. It has the highest unit stream power (16.64 N-m/s/$m^2$), high potential of bed material scouring and tendency of vertical instability. The 'C6c' type stream is a meandering stream with shallow channel and wide valley. The 'C4c' type streams have shallow and wide meandering channels with well developed flood plains and lateral bars, and have the least unit stream power (in Harishiddi Segment 0.11N-m/s/$m^2$), low potential of river bed material erosion but have tendency of lateral instabilities. The bank erosion hazard map indicates that the upper third order stretch and few downstream stretches lie in low hazard zone, but the overall areas of the Harisidhi Segment, Gwarko, Imadol and some other areas lie in high to very high hazard zone because of devegetation, modification of channels and other anthropogenic activities in addition to the weak nature of the bank materials.

**Key words:** Streambank erosion, channel stability, Kodku River, Bank erosion hazard index, near bank stress

**Received:** 2 Feb, 2014 **Accepted:** 10 June, 2014

## INTRODUCTION

Rivers are dynamic and continuous systems having networks of tributaries, and are geomorphic agents showing diversity of form and behavior. Rivers tend to achieve their base level of erosion by incising the valley and changing their profile and morphology. According to Mackin (1948), the slope of an equilibrium river is adjusted over a period of years to provide velocity required for the transport of loads. Lane (1955) defined that discharge and slope of a river in equilibrium tend to balance bed material load and size.

The river which is able to transport sediment and water and maintain its dimension, pattern and profile without significant aggradation or degradation is regarded as the stable channel or graded channel (Rosgen 1996). However, several factors tend to disturb equilibrium of a river system, and when the river gets disturbed it reacts to reacquire equilibrium by series of adjustments, which are usually mirrored in aggradation, degradation (Schumm, 1963), or changes in planform (Leopold and Wolman, 1960).

Channel stability status can be assessed taking into account of competence (Andrew, 1983, 1984), aggrading/degrading relationship (Schumm, 1963), meander geometry relationship (Leopold and Wolman,

*Corresponding author:

E-mail address: ntamrakar@hotmail.com

1960), etc. Rosgen (2001) concluded that the parameters such as river-channel form, primarily streamflow, sediment regime, riparian vegetation, and direct physical modifications are related to stream channel instability. Rosgen's (1994) stream classification can be used taking in to account of various morpho-hydraulic parameters, and then assessing the bank erosion potential. Rosgen (1996) used streambank erodibility index and near bank stresses in the model. Streambank erodibility indices are developed by using the messurement of different parameters such as bank height, angles, materials, presence of layers, rooting depth, rooting density and percent of bank protection. Shrestha and Tamrakar (2007) added the parameters such as lateral instability hazard index (LIHI), and the disturbance index (DI) to these bank erodibility indices of Rosgen (1996).

Stability conditions of the Bishnumati and the Manahara Rivers were evaluated by Tamrakar (2004a, 2004b) Adhikari and Tamrakar (2005), Bajracharya and Tamrakar (2007) Shrestha and Tamrakar, (2007) and Tamrakar and Bajracharya (2009). Tamrakar (2004a and 2004b) studied disturbing factors influencing the Bishnumati River degradation problem and concluded that human-induced as well as natural factors were responsible for river environment degradation. The studies evaluated that the upstream segments of the Bishnumati River is laterally unstable while the downstream segments is vertically unstable. Adhikari and Tamrakar (2005) studied bank erosion hazard along the Bishnumati River corridor, and concluded that the mid to the lower segments of the river fall on high hazard zone.

Bajracharya and Tamrakar (2007) studied environmental status of the Manahara River. The study concludes that river environment is degrading due to human-induced as well as natural causes. This river is vertically as well as laterally unstable. The upstream segments of the river are in degrading condition whereas the downstream segments are in aggrading condition. The Manahara River course had shifted by 140 m in about 10 years (Tamrakar and Bajracharya, 2009). Tamrakar et al. (2011) calculated boundary shear stress and Shields number for five segments of the Manahara River. These exceed critical dimensionless shear stress of every segment of the Manahara River suggesting for enough competency of river segments in transporting their bed materials. Shrestha and Tamrakar (2007) studied stream bank condition, erosion process and bank erodibility and lateral instability hazard along the Manahara River. They concluded that unconsolidated channel, lack of riparian vegetation, rapid landuse change, lateral channel shifting, meander migration, and mining of construction material were the causes of lateral instability and bank erosion hazard along the river.

Maharjan and Tamrakar (2010) studied the existing condition of the Nakhu River. They classified the river into C5 and C4 types and concluded that the overall segments of the river are in aggrading condition and are capable of mobilizing the sediments as well as depositing its load also.

The Kodku River is one of the major tributaries of the Manahara River (Fig. 1), which confluences with the Bagmati River. The Kodku River originates from Majhgau and confluences with the Manahara River near Imadol from the southern part. The major tributaries of

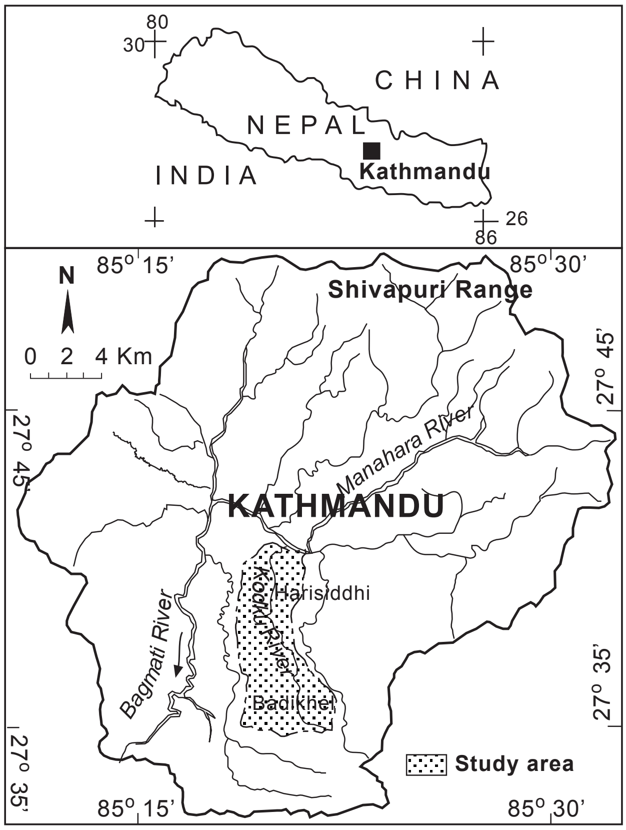



Fig. 1 Location map of the Kodku River Watershed

the Kodku River are the Guhe Khola, that contributes from south-east, and the Dhamilo Khola, which contributes from south-west of the watershed. The Kodku River Corridor is one of the most potential corridors for future development of roads which would link the southern remote areas of the Kathmandu Valley to the inner core areas. Highways and roads will be the major priority of Nepal if it has to develop its regions and economy. Transportation facility makes ease of people welfare, and helps to grow agricultural, industrial, and trading sectors. Extension of highways and roads are associated with establishment of number of large engineering structures and involvement of huge investment for these structures.

The river corridors are frequently subjected to river bank erosion, slope movements and flash flooding. There were many flash flooding that occurred in the Kodku River within 30-35 years (at Dhapakhel in 1979, at Gwarko and Imadol in1981, 2002, 2007). Riverbank erosion is an important cause of lateral erosion of toe of the slope and generates slope movements (Shrestha and Tamrakar, 2007; Shrestha et al. 2008; Tamrakar et al. 2007). Therefore, river bank erosion poses threat on the infrastructures. In other words, the stream channel stability should be well assessed to know channel stability condition of the river before establishing infrastructures and developing the river corridor as settlement areas.

Stream channel stability is reflected by the degree of various morphological and hydraulic parameters, from which lateral and vertical stability of the river can be understood, and aggrading/degrading potential of the river and competence can be evaluated. Recognition of existing stability condition of river is to recognize nature and behavior of the river, and is important in many ways: (a) to recognize the floodprone areas, (b) to recognize the bank erosion and lateral instability hazard, (c) to establish or develop infrastructure along or nearby the river corridor, (d) to start on where to restore the river, (e) to develop reservoir and exploit natural resources, and (f) to develop safe settlement areas.

Past study (Maharjan and Dangol, 2007) of engineering hydrology of the Kodku River suggests that this river is appreciable for drinking water source for Lalitpur city. But currently, the downstream segments of this river is suffering from channel encroachment and disposal of industrial and municipal wastes. Large numbers of built-up areas have been growing on the banks of the river, causing anthropogenic factors to be influential in environmental degradation of the river. Therefore, the main aims of this study are to (a) classify river segments and find stream channel condition, and (b) assess bank erosion hazard potential and stability of the river.

## METHODS

The elements of the Level I, Level II and Level III river inventory after Rosgen (1996) are :

1. Reconnaissance field survey,

2. Regional watershed parameters such as stream ordering (Level I) following the method of Strahler (1957, 1964), relative relief, and drainage texture after Horton (1945) were determined and reproduced in maps (1:25,000 scales).

3. Planform pattern of a river reflects several clues about the stability condition of the river, and is also a major component of the hierarchical inventory of river classification. Meander wavelength, meander belt width, radius of curvature and sinuosity were measured using 1:10,000 topographic map. River pattern of a single thread or multithread was determined.

4. Cross-sectional survey (Level II): Based on the planform, stream order and nature of channel disturbance, five stream segments were selected and surveyed for cross-sections and longitudinal profiles. The survey was made using an Ushikata Theodolite, staffs and a measuring tape. The cross-sectional survey resulted in the hydraulic parameters and dimensionless indices (MWR, MLR, RCR) of planform parameters for comparison purpose.

To characterize grain size of each of five segments in reach-scale and in cross-section scale, Wolman's (1954) pebble counting was adopted in eight transects including pools during the cross-section survey. The particle size distribution was used to obtain the $d_{50}$.

5. Longitudinal survey: The stream longitudinal survey was made for each of the stream segments. Longitudinal survey data was utilized to calculate stream channel slope, water surface slope, level of the banks, etc. These data were input into the classification

as well used in assessing the channel stability.

6. Stream classification: The parameters such as ER, W/D ratio, sinuosity (K), were used to classify river in to A through G. Further using the slope and sediment size of the stream, the stream type was further refined following the classification of Rosgen (1994).

The following methods were used as continuation of the methods, in the next step of the study:

7. Assessment of Stream state or condition (Level III parameters): In this level III study, the categories as (a) riparian vegetation, (b) flow regime, (c) size/order, (d) debris occurrence, (e) depositional pattern, (f) meander pattern, and (g) altered state due to disturbances were assessed following Rosgen (1996). These parameters give insight into the stream type being assessed.

8. Additional parameters for channel stability assessment: Stability condition of a river is explained by behavior of the river towards lateral and vertical components due to tendency of erosion. This is exhibited by aggrading or degrading potential and competency to entrain and transport the coarse sediments. Results of morpho-hydraulic analyses were used to evaluate competency, aggrading/degrading potential and stability of the river. Furthermore, the meandering geometry of the existing river was compared with the established relationships to diagnose stability of the river.

(a) Lateral stability/Streambank erosion potential: The categories used for lateral stability were: a) Meander Width Ratio (MWR), sinuosity (K), width/depth ratio (W/D ratio), and (b) Bank Erosion Hazard Index (BEHI) and Near-Bank Stress (NBS) (Rosgen, 1996; 2001). MWR provides insight into channel adjustment processes by stream type and degree of confinement.

(b) Vertical stability/aggradation/degradation potential: Field measurement of bank height and floodprone level, and observations on excessive erosion and/or deposition, were taken as basis for vertical stability of the stream reach. The BHR and ER as calculated before were used to compare the stability ratings according to Rosgen (2001). Stability ratings for BHR are: Stable (low risk of degradation) 1.0 –1.05; Moderately unstable 1.06–1.3; Unstable (high risk of degradation) 1.3–1.5; Highly unstable > 1.5. Stream with ER less than 1.4 plus minus 0.2, is designed as entrenched stream (Rosgen, 1994; 1996). Besides, the indicators of incision and degradation, such as decrease in W/D ratio corresponding with increase in BHR, scouring of depositional features, active streambank erosion, and mobilization of the largest size of bed material were recorded by field inspection. The aggradation was determined from the depositional patterns, coarse deposition on floodplain and very high to extreme W/D ratios. Based on W/D ratio, lateral stability of the stream was described as very stable 1.0; stable 1.0–1.2 and moderately unstable 1.21–1.4 (Rosgen, 2001). The aggrading or degrading condition of the river was assessed by means of the Schumm's (1963) F versus M relationship.

The grain size parameters, i.e., percentage of silt and clay in wetted perimeter of a riffle cross-section and percentage of silt and clay in a bar material were obtained. The former was obtained from the Wolman's pebble count, whereas the latter was obtained from the volumetric bar surface sampling and sieving.

(c) River profile features: Pool maximum depth ratio (maximum depth of pools/mean depth of channel), and riffle maximum depth ratio (maximum depth of riffles/mean bankfull depth) were obtained from cross-sectional data. Measurements taken on a thalweg survey provided data on maximum bankfull depths, the various bed features and any change in slope.

(d) Channel dimension parameters: Mainly the changes in the bankfull W/D ratio were taken to assess any departure of the surveyed stream segment from the stable stream. The W/D ratio of 1 being stable and >1.4 being unstable (Rosgen, 2001). The plots of W/D ratio vs. Meander Belt Width, and W/D ratio vs. Meander Wavelength provided stability condition or departure of stream channel stability from the standard curves.

(e) Stream competence: Critical dimensionless shear stress (Andrews (1984) and Andrews and Nankervis (1995)) was evaluated to determine the size of sediment particle that could be moved by the flow. For these computations apart from the hydraulic data, grain size data from the channel as well as bar samples were collected, analysed and used.

Subsequent calculations using a Shields relation were used to compare the existing slope and depth of a stream to be able to transport the largest size made available annually (during bankfull stage) to the channel. The following calculations were used to make the competence prediction:

$$\tau_{ci} = 0.0834\ (d_{50}/ds_{50})^{-0.872} \quad (1)$$

Where: $\tau_{ci}$ = critical dimensionless shear stress, $d_{50}$ = median diameter of pavement or bed material on riffle, and $d_{s50}$ = median diameter of bar sample (sub-pavement).

The following equation was used to predict the critical depth and critical slope to move the largest size of sediment made available to the channel on a frequent basis:

$$\tau_{ci} = (D_c S_c)/[(\gamma_s)\ (d_i)] \quad (2)$$

$$D_c = [(\tau_{ci})\ (\gamma_s)\ (d_i)]/S \quad (3)$$

$$S_c = [(\tau_{ci})\ (\gamma_s)\ (d_i)]/D \quad (4)$$

Where: $\gamma_s$ = submerged specific weight of sediment (1.65), $d_i$ = Largest diameter of particle on bar (mm), D = mean bankfull depth of the channel (m), S = water surface slope at the bankfull stage, $D_c$ = critical depth (m), and $S_c$ = critical slope

If the combination of depth and/or slope does not move the largest size, then potential aggradation or excessive deposition is anticipated. If the existing depth (D) and or slope (S) exceeds the critical depth ($D_c$) and or slope ($S_c$) required to transfer the largest size ($d_i$) of the bed, then potential degradation, or excess scour and incision lead to instability.

(f) Channel stability ratings: The modified Pfankuch (1975) channel stability rating method was followed to evaluate the upper and the lower banks and streambed for evidence of excessive erosion/deposition. In this method the risk rating of the classification was later converted to ratings by stream type after Rosgen (1996).

(g) Stream type evolutionary scenario: The data from the stability assessment and stream classification were incorporated to draw inference about evolution scenario based on the channel evolution model of Simon (1989).

Hence, the river inventory hierarchy of up to level III mentioned before, and additional channel stability assessment parameters were considered to finally distinguish the stability condition of the Kodku River.

## LEVEL I INVENTORY OF STREAM STABILITY ASSESSMENT

### Watershed-scale parameters

The Kodku River watershed is located in the southern part of the Kathmandu valley (Fig.1). The watershed area of this river lies in the Lalitpur district. Geographically, it lies between longitude 85°19’13”E to 85°22’39”E in upper reaches and 85°19’13”E to 85°21’5”E in lower reaches and lalitude 27°34’34” N to 27°40’25” N. It originates from the north facing Tileswor Dada and Chaughare Dada located on southern part of the Kathmandu Valley, and extends for about 15.86 km and covers an area of 35.67 $km^2$.

Level I inventory of stream stability assessment includes all the watershed-scale parameters.

#### *Basin Relative Relief*

The altitude in the Kodku River watershed ranges from 1960 m to 1290 m. Basin relative relief (BRR) is extremely high in Majhgau and Badikhel, high in Muldol area, and moderate to moderately low in Taukhel Dhapakhel, Harisiddhi and Khumaltar (Fig. 4.1). It is low in Imadol area. BRR diminishes from the south to the north of the watershed.

#### *Drainage Texture*

The drainage texture (DT) (Horton, 1945) of the Kodku River basin ranges from fine to very coarse. It is fine in the southern mountain area such as Badikhel, moderate in Majhgau and Muldol, coarse in Bulu and Khatrigau, and very coarse in Taukhel, Harisiddhi, Khumaltar and Imadol. Areas with bedrocks and relatively high relief constitute relatively fine DT. DT is controlled by distribution of bedrocks and soft sediments.

#### *Stream Order*

Stream order is ‘a measure of the position of a stream in the hierarchy of tributaries’ (Leopold,

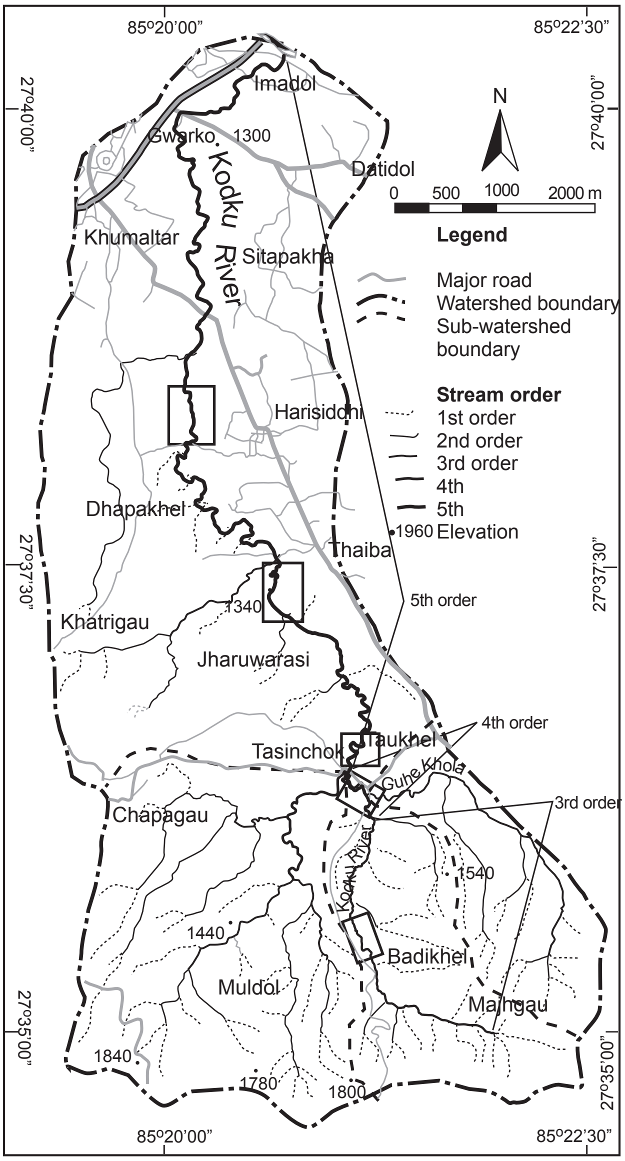



Fig. 2 Location map, drainage order and five surveyed segments of the Kodku River

Wolman and Miller, 1964). In this study, the drainage order was determined using the method proposed by Strahler (1957; 1964). The Kodku Watershed constitutes three sub-watersheds, of which the Kodku sub-watershed is contributed by the Guhe sub-watershed from the east and the sub-watershed (Muldol area) from the southwest. The Kodku mainstem River is the fifth order river (Fig. 2). The third order main stem stretches for about 3440 m from Majhgau up to the confluence of the Kodku River with the Guhe Khola (Fig. 2). 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 11886 m and finally contributes the Manahara River.

### *Landuse*

Most of the floodplains, the low-lying land and the gentle slope area are used for farming and settlement. The other parts are covered by forest, and some of the parts south of Thaiba by quarry sites for brick industries. Most of the steep to gentle slopes in the southern parts of watershed are covered by forest.

Most of the huge floodplains of the Kodku River from downstream of Thaiba, i.e., the northern half portion of the watershed, has been used for build-up, farm land and industrial areas. The water quality has been degraded due to sewer and solid waste disposed to the lower portion of the Kodku River lying north of Harisiddhi. With demand of growing population, the landuse pattern has been changed rapidly.

### *Geology*

The Kodku watershed comprises of basement rocks of the metasedimentary rocks of the Phulchoki Group, that includes the Sopyang and the Chandragiri Formations (Stöcklin 1981, Stöcklin and Bhattarai 1977) in the southermost portion (Fig. 3), while the Pleistocene to Pliocene valley fill sediments in the northern part. The Sopyang Formation comprises dark to yellowish brown (when weathered) thinly bedded calcareous slate, argillaceous limestone and grey metasiltstone. It is well exposed at the left bank of the Kodku River near Badikhel, where it is characterized by highly weathered, highly jointed, medium bedded argillaceous limestone and calcareous slate showing attitude: N50°W/38°SW. These lithologies are associated (at about 15 upstream) with moderately weathered laminated grey metasiltstone having attitude: N62°W/80°SW.

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 limestone also exists at Jharuwarasi, where river incises forming a

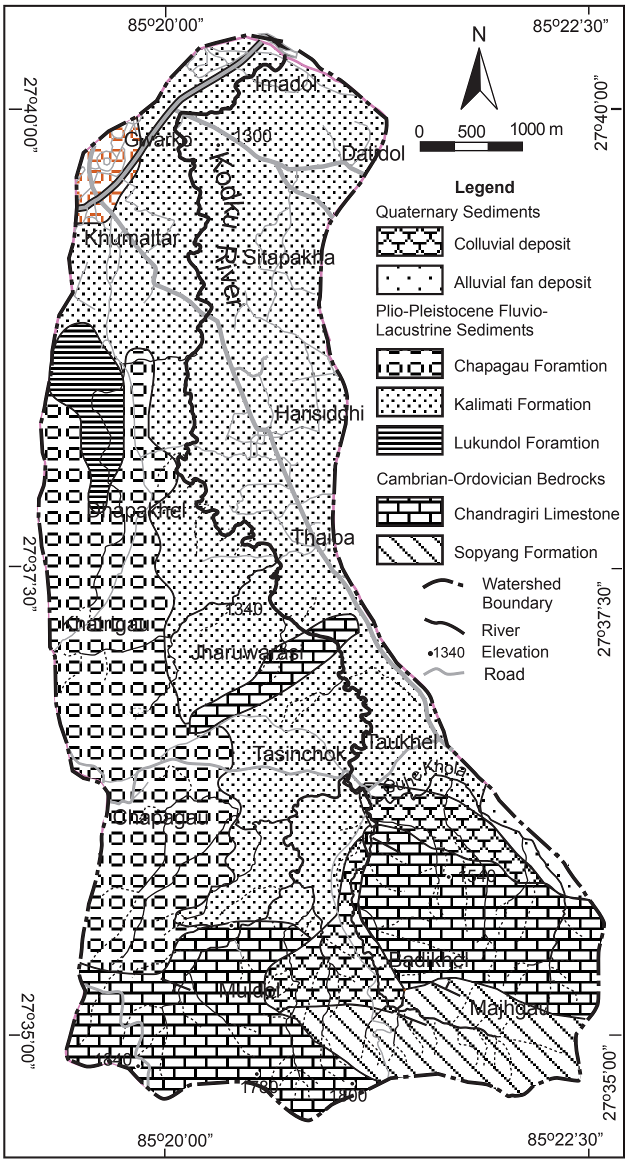



Fig. 3 Geological map of the Kodku watershed (after DMG, 1998).

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 colluvial sediment contains clay, silt, sand and some gravel, and mainly occurs adjacent to the footslope. The alluvial fan deposit consisting of gravel, sandy gravel, sands and silt occurs in extreme south-eastern part of the watershed. The western half portion of the watershed is occupied by the Chapagaon Formation. It comprises subrounded to rounded silty sandy gravel occassionally intercalated wtih silty sand, clayey silt, and boulder beds. The portion of the western part of the watershed is occupied by the Lukukdol Formation characterized by sandy-clayey silt interbedded with gravel, sand, and peat layers. The majority of the north-eastern or the eastern half portion of the watershed constitutes the Kalimati Formation. This formation consists of dark silty clay, clayey silt, fine sands and peat layers. Therefore, the Kodku River originates from the bedrocks of the Chandragiri Limestone and the Sopyang Formation, and traverses over the colluvial sediments and basin-fill sediments of the fluvio-lacustrine origin.

### *Planform*

The planform geometry is attributed by various parameters: sinuosity (K), meander wavelength ($L_m$), meander belt width ($W_{blt}$), and radius of curvature ($R_c$). Radius of curvature ($R_c$) is the radius of a circle drawn through the apex of the bend and the two crossover midpoint of river, and is defined as the curved surface formed by the meandering stream channel. All these parameters were calculated.

The results of planform parameters calculated for 3rd to 5th order stream streches are listed in Table 1. Sinuosity indices of the third, fourth and fifth order main stem stretches of the Kodku River are 1.13, 1.29, and 1.36, respectively showing sinuous nature according to classification of Leopold and Wolman (1957). The $L_m$, $W_{blt}$ and $R_c$ of the fifth order main stem river are 161.2 m, 223.1 m, and 53.3 m, respectively. Both $L_m$ and $W_{blt}$ gradually increase from the 3rd to the 4th order stream, but increase drastically to the 5th order stream. $R_c$ 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

Table 1: River morphological data of different stream order of the main stem Kodku River

| Parameters | Stream order | | |
|---|---|---|---|
| | Third | Fourth | Fifth |
| $L_m$, m | 95 | 95.7 | 161.2 |
| $W_{blt}$, m | 56.3 | 67.2 | 223.1 |
| $R_c$, m | 35.5 | 28.3 | 53.3 |
| $L_{Thalweg}$, m | 3440 | 793 | 11886 |
| $L_{Valley}$, m | 3046 | 614 | 8736 |
| Sinuosity (K) | 1.13 | 1.29 | 1.36 |

*Sinuosity (K): S = sinuous (1.05 to 1.5); St = straight (<1.05) based on Leopold and Wolman (1960)

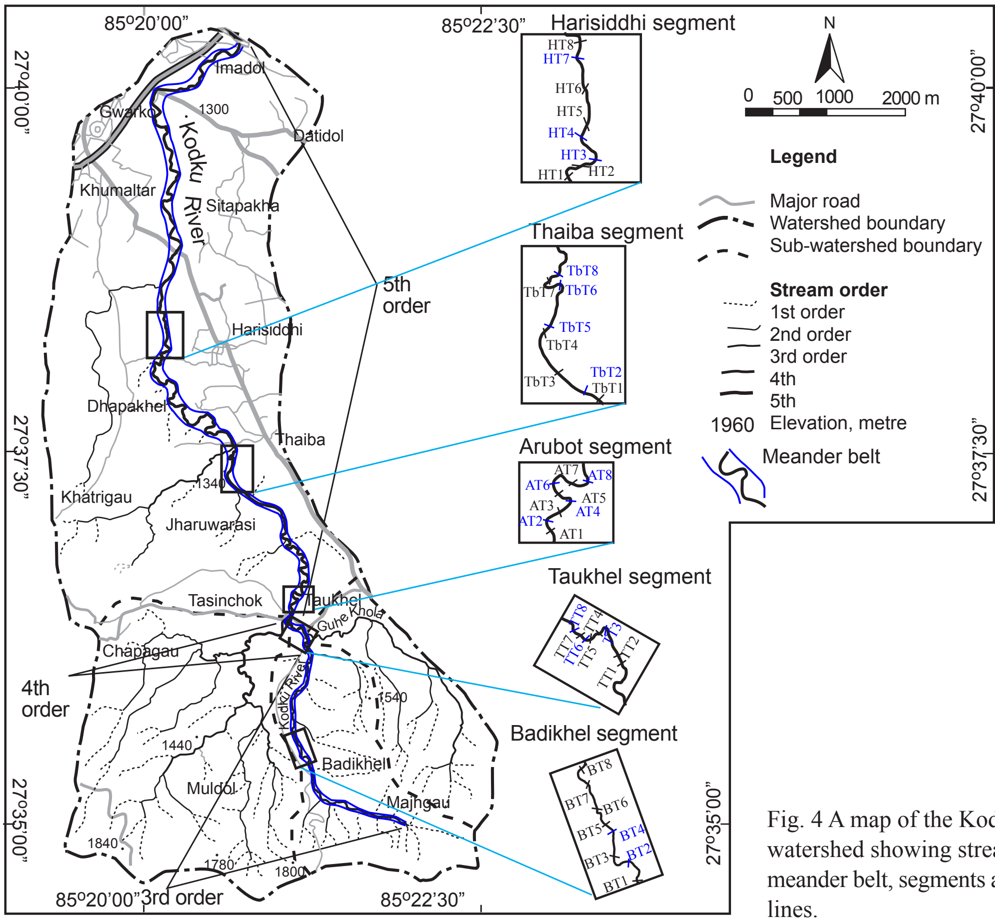


Fig. 4 A map of the Kodku watershed showing stream order, meander belt, segments and transect lines.

in planiform parameters.

The planform parameters of the five stream segments (Fig. 4) are incorporated in Table 2. All the five stream segments are sinuous and the Arubot Segment is the most sinuous one among them. Both $L_m$ and $W_{blt}$ increase with increasing stream order. But the fifth segment shows the diminishing trend probably due to anthropogenic alteration of the river. However, there is a good and high degree of positive correlation between meander length ratio (MLR) and meander width ratio (MWR) (Fig. 5).

### *Valley types and landforms*

The results of valley types and related stream types and landforms based on Rosgen (1996) are shown in Table 4.3, and are of the following kinds:

(1) Valley type I: It is a V-shaped alluvial valley, which is structurally confined and controlled by faults. The valley with bedrock is dissected and incised by the stream. It is found in the first and second orders of the

Table 2: Planiform parameters of the Kodku River

| | Badikhel Segment | Taukhel Segment | Arubot Segment | Thaiba Segment | Harisiddhi Segment |
|---|---|---|---|---|---|
| $L_{tw}$ (m) | 523.2 | 580.2 | 714.8 | 779.6 | 569.8 |
| $L_{valley}$ (m) | 419.6 | 450.7 | 419.6 | 650.1 | 486.9 |
| $K = L_{tw}/L_{valley}$ | 1.2 | 1.3 | 1.7 | 1.2 | 1.2 |
| $L_m$ (m) | 75.9 | 97.4 | 140.0 | 147.8 | 105.2 |
| $W_{blt}$ (m) | 57.4 | 71.9 | 96.2 | 99.5 | 92.7 |
| $R_c$ (m) | 24.7 | 27.5 | 36.8 | 72.8 | 34.9 |
| MLR= $L_m/W_{bkf}$ | 7.4 | 16.8 | 17.3 | 18.5 | 6.9 |
| MWR | 5.6 | 12.4 | 11.9 | 12.4 | 6.1 |

Length of thalweg, $L_{tw}$ Length of valley, $L_{valley}$
Sinuosity, K Meander wavelength, $L_m$
Meander belt width, $W_{blt}$ ; Radius of curvature, $R_c$
Meander length ratio, MLR; Meander width ratio, MWR

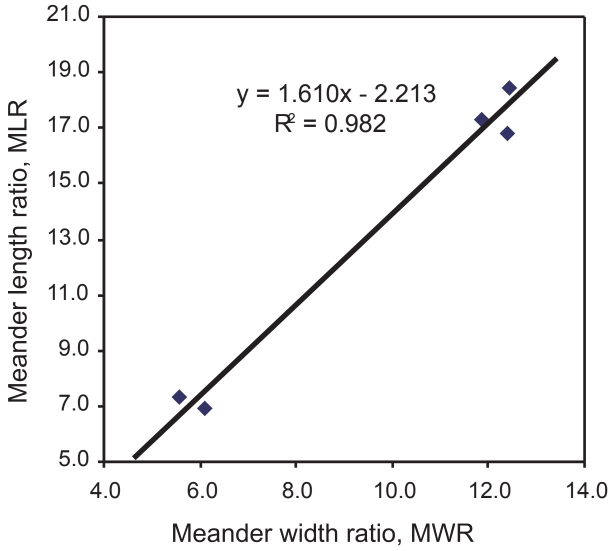



Fig. 5 Relationship between meander length ratio and meander belt width ratio.

Kodku main stem portion and at the gorge of the fifth order Kodku River where the river incises the bedrock of limestone. The later is probably uplifted due to associated faulting.

(2) Valley type II: This valley is located in the third order segment of the main stem Kodku River. It is characterized by fluvial valley slope with planated terraces. It consists of residual, colluvial, and alluvial slopes with few exposures of bedrocks.

(3) Valley type IV: The valley type IV is a classic meandering river valley incised in weathered rock and valley sediments, and is associated with tectonic upliftment of valley. It is distributed in the upstream portion of the fifth order main stem segment of the Kodku River, and is characterized by depositional landforms of alluvial terrace, flood plains and lateral bars.

(4) Valley type VI: This valley is structurally controlled and dominated by colluvial slopes, and is laterally confined. It is found in the starting segment of the third order main stem Kodku River.

(5) Valley type VIII: This valley is a multi-river terrace valley, which is a broad valley with gentle down valley elevation relief. It is associated with alluvial terrace, flood plains and lateral bars. This type of valley is observed in the mid to downstream portions of the fifth order main stem Kodku River.

## Level I Classification of River

Rosgen Level I provides a broad geomorphic characterization to start the classification process. Valley types, landform and fluvial characteristics are described and combined with channel relief, shape, and dimension profiles (Rosgen, 1994). Level I analysis requires rigorous map and areal photos to interprete valley features, and stream pattern and profile.

The characteristics in Level I (Table 3) are

(a) Channel pattern relative to single and multiple paths: Plan view morphology mainly the sinuosity of river system.

(b) Channel shape relative to width and depth: Cross section morphology: cross sections differ greatly from

Table 3: C riteria of Level I classification of stream segments (based on Rosgen (1996))

| Criteria | | Description | Stream type |
|---|---|---|---|
| Pattern | Relatively straight | K<1.2 | A, $A_{a+}$ |
| | Low sinuosity | K>1.2 | B, G |
| | Meandering | K>1.4 | C, F |
| | Torturously meandering | K>1.5 | E |
| | Complex: braided | K<1.2 | D |
| | Complex: anastomosed | K>1.2 | DA |
| Shape | Shallow/ wide | Highest W/D ratio | D |
| | Shallow/wide, entrenched meandering channel | | F |
| | Shallow/wide, low entrenched meandering channel | | C |
| | Deep/narrow | Narrow/deep channel but wider valley | E |
| | | Low W/D ratio more entrenched than E | $A^{a+}$, A, B, G |
| Valley slope | Extremely gentle | <0.5% | DA |
| | Gentle | <2% | C, E, F |
| | Moderately steep | <2-4% | B, G |
| | Steep | 4-10% | A |
| | Very steep | >10% | $A^{a+}$ |

Table 4: Level I classification of stream segments of the Kodku River

| Stream ID | Order | *Valley type | | Pattern: Sinuosity | | Shape | Channel slope | Bed features | Stream Type |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 3 | VI | Structural valley | 1.03 | Relatively straight | Narrow/deep | 2-4% | Riffles, rapids | B |
| 2 | 3 | VI | | 1.09 | Relatively straight | Narrow/deep | 2-4% | Riffles, rapids | B |
| 3 | 3 | VI | | 1.08 | Relatively straight | Narrow/deep | 2-4% | Riffles, rapids | B |
| 4 | 3 | II | Fluvial valley slope dominated by colluvial, alluvial and residual soil slopes | 1.01 | Relatively straight | Narrow/deep | 2-4% | Riffles, pools | B |
| 5 | 3 | II | | | Low sinuosity | Narrow/deep | 2-4% | Riffles, pools | B |
| 6 | 3 | II | | | Relatively straight | Narrow/deep | 2-4% | Riffles, pools | B |
| 7 | 3 | II | | | Relatively straight | Narrow/deep | 2-4% | Riffles, pools | B |
| 8 | 3 | II | | | Relatively straight | Narrow/deep | 2-4% | Riffles, pools | B |
| 9 | 3 | II | | | Low sinuosity | Narrow/deep | 2-4% | Riffles, pools | B |
| 10 | 4 | IV | Classic meandering river valley, structurally controlled and incised in weathered rocks, and or associated with tectonically uplifted valley | | Low sinuosity | Wide/shallow | <2% | Riffles, pools | C |
| 11 | 4 | IV | | | Low sinuosity | Wide/shallow | <2% | Riffles, pools | C |
| 12 | 5 | IV | | | Meandering | Wide/shallow | <2% | Riffles, pools | C |
| 13 | 5 | IV | | | Tortuously meandering | Wide/shallow | <2% | Riffles, pools | C |
| 14 | 5 | IV | | | Tortuously meandering | Wide/shallow | <2% | Riffles, pools | C |
| 15 | 5 | IV | | | Tortuously meandering | Wide/shallow | <2% | Riffles, pools | C |
| 16 | 5 | I | Structurally controlled | | Relatively straight | Narrow/deep | >10% | Vertical drop | $A^{a+}$ |
| 17 | 5 | VIII | Multi river terraces positioned laterally along broad vallyes with gentle downvalley elevation relief | | Relatively straight | Wide/shallow | <2% | Riffles, pools | C |
| 18 | 5 | VIII | | | Meandering | Wide/shallow | <2% | Riffles, pools | C |
| 19 | 5 | VIII | | | Tortuously meandering | Wide/shallow | <2% | Riffles, pools | C |
| 20 | 5 | VIII | | | Low Sinuosity | Wide/shallow | <2% | Riffles, pools | C |
| 21 | 5 | VIII | | | Low Sinuosity | Wide/shallow | <2% | Riffles, pools | C |
| 22 | 5 | VIII | | | Relatively straight | Wide/shallow | <2% | Riffles, pools | C |
| 23 | 5 | VIII | | | Low Sinuosity | Wide/shallow | <2% | Riffles, pools | C |
| 24 | 5 | VII | | | Low sinuosity | Wide/shallow | <2% | Riffles, pools | C |
| 25 | 5 | VIII | | | Low sinuosity | Wide/shallow | <2% | Riffles, pools | C |
| 26 | 5 | VII | | | Relatively straight | Wide/shallow | <2% | Riffles, pools | C |
| 27 | 5 | VIII | | | Meandering | Wide/shallow | <2% | Riffles, pools | C |
| 28 | 5 | VIII | | | Low Sinuosity | Wide/shallow | <2% | Riffles, pools | C |
| 29 | 5 | VIII | | | Low Sinuosity | Wide/shallow | <2% | Riffles, pools | C |
| 30 | 5 | VIII | | | Relatively straight | Wide/shallow | <2% | Riffles, pools | C |

*Valley type: I = Alluvial valley confined and is structurally controlled, II = Fluvial valley slope dominated by colluvial, alluvial and residual soil slopes, IV = Classic meandering river, structurally controlled and incised in weathered rocks, and or associated with tectonically uplifted valley, VI = Structurally controlled valley with dominated colluvial slopes, pattern controlled by confined laterally controlled valley, VIII = Multi river terraces positioned laterally along broad vallyes with gentle downvalley elevation relief.

deep and narrow to wide and shallow. The cross section morphology also describes the flood plain ranging from well-developed flood plains to virtually no flood plain.

(c) Channel Slope relative to Valley slope: the longitudinal profiles used to represent slope. Slope can be related to bed features and can be described as pools, riffles, rapids, cascades, and steps (Rosgen, 1994).

The Kodku River segments were classified based on the above mentioned criteria (Table 3) and are listed in Table 4 and shown in Fig. 6. The river segments are distinguished broadly into three types of rivers, i.e., B, Aa+, and C. All the third order stream segments of the main stem river are classified as "B' type river. The fourth and fifth order stream segments are clasified as 'C' type rivers. The fifth order segment at the gorge is classified as 'A' type river.

### *'B' Type Streams*

Two kinds of 'B' type streams are identified, i.e., one of the categories with VI valley type having bedforms of riffle and rapids, and the another with II valley type having bedforms of riffles and pools. The former is located in the upstream portion of the third order main stem Kodku River where bedrocks of limestone and metasiltstone exist, whereas the latter is located in the down stream portion of the third order mainstem where colluvial deposit is present. Both streams are characterized by low sinuosity and narrow/deep stream segments with slopes ranging from 2 to 4%.

### *'C' Type Stream*

The 'C' type streams commence with the initiation of the fourth order main stem river. These streams have IV type valleys, which are classic meandering river valleys that are structurally controlled and incised and associated with tectonically uplifted valley. These streams have variable degrees of sinuosity ranging from tortuously meandering to relatively straight segments, and shallow and wide channels with well develop riffles and pool bedforms. The channel slope in these streams is less than 2%. The overall 'C' type streams flow over the basin fill sediments of fluvio-lacustrine deposit of the Kalimati Formation.

### *'Aa+' Type Stream*

The 'Aa+' type stream is seen in fifth order main stem river at Jharuwarasi (Fig. 6), where the river incises a bedrock forming the hanging valley upstream of this location. The stream is more or less straight with narrow/deep channel and relatively very high channel slope (>10%). The incision is marked by presence of fall or a vertical drop of river, and presence of a gorge.

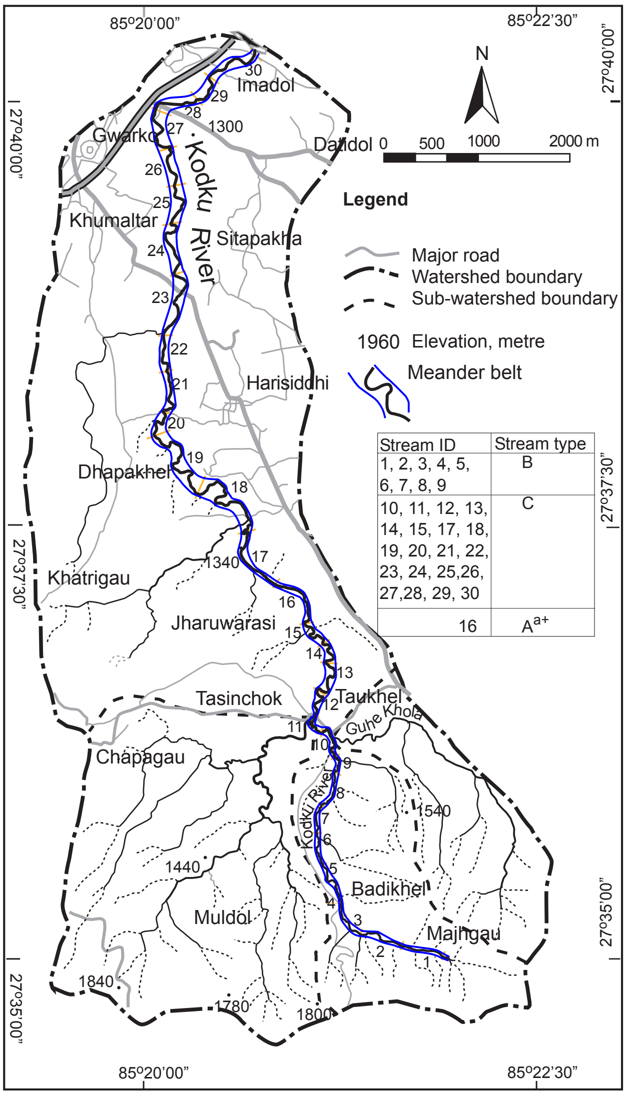



Fig. 6 A map of the Kodku watershed showing stream segment ID and stream type based on Level I classification.

## LEVEL II INVENTORY OF STREAM STABILITY ASSESSMENT

### Hydrologic Parameters

The bankfull width ($W_{bkf}$) is the highest in the Harisiddhi Segment (15.6 m), and is the lowest (5.8 m) in the Taukhel Segment (Table 5). Maximum depth at bankfull ($D_{max}$) is the highest in the Badikhel Segment (1.5 m), while it is the least in the Arubot and the Thaiba Segments (0.8 m). The mean depth at bankfull ($D_{bkf}$) varies between 0.5 and 0.8 m and is almost ranging narrowly. Hydraulic radius varies between 0.5 and 0.6 m. The cross-sectional area is relatively large in the Harisiddhi Segment (10 sq. m) and the Badikhel Segment (6.2 sq. m), whereas it is almost similar in the other segments (3.3 to 4.2 sq. m).

Width/Depth (W/D) ratio of the Taukhel Segments is the least (10.5). It is nearly similar for the Badikhel, Arubot and Thaiba segments (14.3–15.3), while it is nearly two times larger in the Harisiddhi Segments (29.5). W/D ratio exceeding 1.4 generally show lateral instability of the river.

The bank height ratio (BHR) increases from the Badikhel (1.6) to the Taukhel (2.2) and then diminishes to the Arubot Segment (1.8). It again increases towards the Harisiddhi Segments. Since BHR varies between 1.6 to 2.4 the banks are vertically unstable.

Table 5: Hydrologic parameters of the Kodku River

| | Badikhel Segment | Taukhel Segment | Arubot Segment | Thaiba Segment | Harisiddhi Segment |
|---|---|---|---|---|---|
| Width at bankfull, $W_{bkf}$ (m) | 10.3 | 5.8 | 8.1 | 8.0 | 15.2 |
| Max. depth at bankfull, $D_{max}$ (m) | 1.5 | 1.0 | 0.8 | 0.8 | 1.0 |
| Width of flood prone area, $W_{fpa}$ (m) | 16.8 | 40.7 | 50 | 42 | 53.2 |
| Max. depth at top of low bank, $D_{tob}$ (m) | 2.4 | 2.2 | 1.5 | 1.7 | 2.3 |
| Mean depth at bankfull, $D_{bkf} = A_{bkf}/W_{bkf}$ (m) | 0.8 | 0.6 | 0.5 | 0.5 | 0.7 |
| Entrenchment ratio, $ER = W_{bkf}/D_{bkf}$ | 1.7 | 7.1 | 6.3 | 5.4 | 3.7 |
| Hydraulic radius, $R = A_{bkf}/(2D_{bkf} + W_{bkf})$ (m) | 0.6 | 0.5 | 0.5 | 0.5 | 0.6 |
| Width/depth ratio, W/D ratio | 14.3 | 10.5 | 15.2 | 15.3 | 29.5 |
| Bank height ratio, $BHR = D_{tob}/D_{max}$ | 1.6 | 2.2 | 1.8 | 2.0 | 2.4 |
| Max depth ratio, $D_{max}/D_{bkf}$ | 1.9 | 1.8 | 1.6 | 1.6 | 1.6 |
| Bankfull cross-sectional area, $A_{bkf}$ ($m^2$) | 6.2 | 3.3 | 4.4 | 4.2 | 10 |
| Pool width, $W_{pool}$ (m) | 9.7 | 6.1 | 7.4 | 7.7 | 13.9 |
| Pool area, $A_{pool}$ ($m^2$) | 7.0 | 4.1 | 5.4 | 3.7 | 7.1 |
| Pool max depth, $D_{pool}$ (m) | 1.4 | 1.2 | 1.2 | 0.9 | 1.0 |
| Slope of channel , $S_{average} = \Delta Elv/\Delta L_{tw}$ (m/m) | 0.0055 | 0.0023 | 0.0007 | 0.0009 | 0.0002 |
| Bed material, $D_{50}$ (m) | 0.02 | 0.00003 | 0.001 | 0.002 | 0.003 |

Entrenchment ratio (ER), which is a parameter to determine if the stream has incised to the extent beyond the abandonment of its flood plain, ranges from 1.7 to 7.1, and the Badikhel Segment is relatively more entrenched (1.7) compared to the other segments while the Taukhel Segment is the least entrenched (7.1). Since ER is more than 1.6, the stream segments of the Kodku River are considered moderate to low entrenched.

## Longitudinal Profile

The average slopes of the 5th, 4th and 3rd order stretches are 0.83 m/m, 1.59 m/m and 5.86 m/m, respectively. The average slope of the Kodku River is 3.42 m/m. Two knick points, one close to the emergence of the 3rd order and another close to the emergence of the 4th order streams, are distinct (Fig. 7). The 3rd and 4th order main stem river stretches have tendency to erode their channel. Similarly, there is a knick point at about 1.6 km from the emergence of the 5th order stream, forming a water fall and a hanging valley to the upstream portion. There remains tendency of headward erosion at this location.

## Riverbed Material Size Distribution

The riverbed materials of individual segments were characterized using Wolman's (1954) pebble count. Eight transects in each segment were traversed for twentyfive counts. Fig. 8 shows plots from the cumulative frequency percent of clasts (Table 6). Based on median size, the sediments of the Badikhel Segment are coarse pebble, whereas those for Taukhel Segment are silt/clay mixture. The median sizes of the Arubot Segment and the Thaiba Segment both belong to very coarse sand. Very fine pebbles form the substrate of the Harisiddhi Segment. In the Badikhel and the Taukhel Segments, the size distribution of 0.1 to 4 mm range is almost absent while 0.1 to 1 mm size grades are actually missing in the rest of the segments showing gap graded distribution of the riverbed material and there are dominance of either gravel or silt/clay sediments.

The grain size of the riverbed materials of five representative segments is variable. The grain size is least (silt/clay) in Taukhel Segment and increases in downstream segments up to fine pebble. The decreasing and increasing trend in grain size of the riverbed materials indicates that the source of these materials depend on the geological formations of the area from

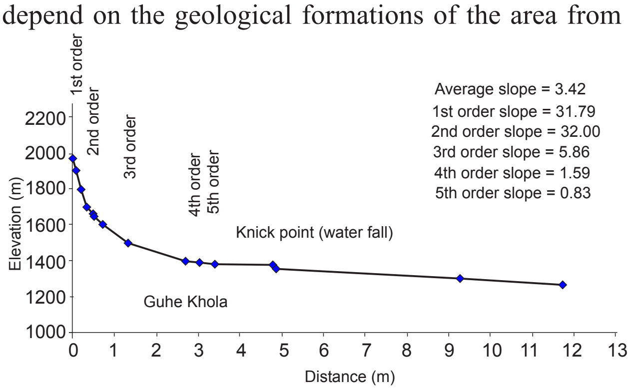
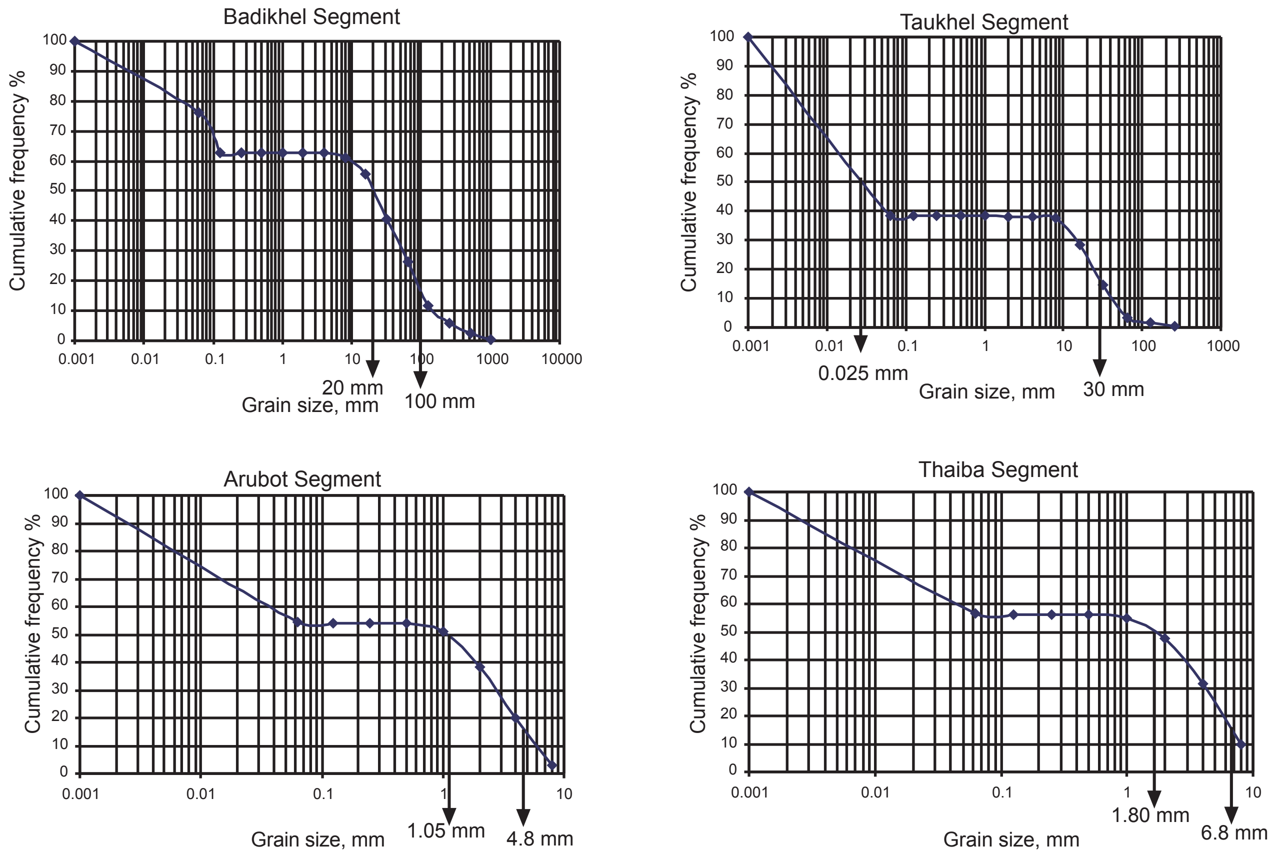



Fig. 7 A Longitudinal profile of the Kodku River.



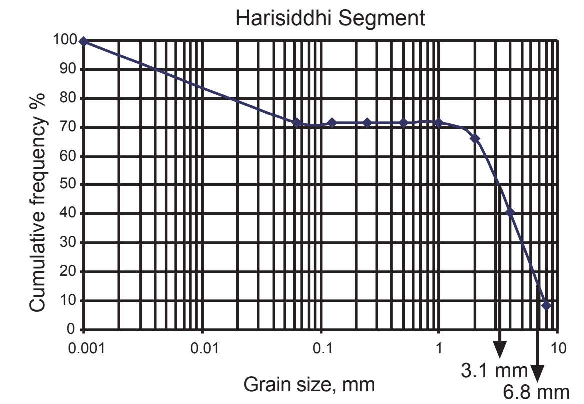




Fig. 8 Grain size distribution of the Kodku River.

where the river flows. The overall fourth and fifth segments flow over the Kalimati Formation (mainly silt/clay) but in the Harisidhi Segment, the pebbles have been brought from the nearby gravelly terrace deposit of the Chapagaun Formation.

## Stream Types

Morphological characteristics (Rosgen, 1994) viz ER, W/D ratio, K, slope and bed material were adopted for the classification of the stream. The Kodku River segments from the south to the north are classified as B4c, C6c-, C5c-, C5c- and C4c-streams, respectively (Table 7).

### *Badikhel Segment (B4c-type Stream)*

The Badikhel Segment is slightly entrenched (>2.2) with moderate W/D ratio (~12) (Fig. 9) and low sinuosity (K = 1.2) with bed material of gravel and silt/clay mixture. The slope is very low (0.006 m/m). Therefore, this segment is classified as C4c-type stream. Small point bars, point bars and side bars characterize the deposition pattern of this stream. Pools and riffles are present along with the presence of step pools. Riparian vegetation is poor, and constitutes mainly shrub and grass, and minorly few trees and bamboos

Table 6: Results of Wolman pebble count on segments of the Kodku River

| Particle | Description | Size Category (mm) | Badhikhel Segment | | | Taukhel Segment | | | Arubot Segment | | | Thaiba Segment | | | Harisiddhi Segment | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | *TF | % F | % CF | TF | % F | % CF | TF | % F | %CF | TF | % F | % CF | TF | % F | % CF |
| Bedrock | | 409 | | | | | | | | | | | | | | | |
| Boulder | Very Large | 2048-4096 | | | | | | | | | | | | | | | |
| | Large | 1024-2048 | 1 | 0.5 | 0.5 | | | | | | | | | | | | |
| | Medium | 512-1024 | 4 | 2 | 2.5 | | | | | | | | | | | | |
| | Small | 256-512 | 7 | 3.5 | 6 | 1 | 0.5 | 0.5 | | | | | | | | | |
| Cobble | Large | 128-256 | 11 | 5.5 | 11.5 | 2 | 1 | 1.5 | | | | | | | | | |
| | Small | 64-128 | 29 | 15 | 26 | 4 | 2 | 3.5 | | | | | | | | | |
| Pebble | Very coarse | 32-64 | 28 | 14 | 40 | 22 | 11 | 14.5 | | | | | | | | | |
| | Coarse | 16-32 | 30 | 15 | 55 | 28 | 14 | 28.5 | | | | | | | | | |
| | Medium | 8.0-16 | 11 | 5.5 | 60.5 | 18 | 9 | 37.5 | 6 | 3 | 3 | 20 | 10 | 10 | 17 | 8.5 | 8.5 |
| | Fine | 4.0-8 | 3 | 1.5 | 62 | 1 | 0.5 | 38 | 34 | 17 | 20 | 43 | 21.5 | 32 | 64 | 32 | 41 |
| | Very fine | 2.0-4.0 | 0 | 0 | 62 | 0 | 0 | 38 | 37 | 18.5 | 39 | 32 | 16 | 48 | 51 | 25.5 | 66 |
| Sand | Very coarse | 1.0-2.0 | 0 | 0 | 62 | 1 | 0.5 | 38.5 | 25 | 12.5 | 51 | 15 | 7.5 | 55 | 11 | 5.5 | 72 |
| | Coarse | 0.5-1.0 | 0 | 0 | 62 | 0 | 0 | 38.5 | 6 | 3 | 54 | 2 | 1 | 56 | 0 | 0 | 72 |
| | Medium | 0.250-0.500 | 0 | 0 | 62 | 0 | 0 | 38.5 | 0 | 0 | 54 | 0 | 0 | 56 | 1 | 0 | 72 |
| | Fine | 0.125-0.250 | 0 | 0 | 62 | 0 | 0 | 38.5 | 0 | 0 | 54 | 0 | 0 | 56 | 0 | 0 | 72 |
| | Very fine | 0.063-0.125 | 0 | 0 | 62 | 0 | 0 | 38.5 | 1 | 0.5 | 55 | 1 | 0.5 | 57 | 0 | 0 | 72 |
| Silt/Clay | | <0.063 | 76 | 38 | 100 | 123 | 61.5 | 100 | 91 | 45.5 | 100 | 87 | 43.5 | 100 | 56 | 28 | 100 |
| | | | 200 | 100 | | 200 | 100 | | 200 | 100 | | 200 | 100 | | 200 | 99.5 | |

*TF=Total frequency, CF = Cumulative frequency, F = Frequency

Table 7: Summary of classification of the Kodkhu River

| Attributes | Segments | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Badikhel | | Taukhel | | Arubot | | Thaiba | | Harisiddhi | |
| Entrenchment ratio, ER | 1.69 | B | 7.10 | E, C | 6.30 | E, C | 5.40 | E, C | 3.70 | E, C |
| Width/depth ratio, $W/D=W_{bkf}/D_{bkf}$ | 14.28 | B | 10.50 | E, C | 15.20 | C | 15.30 | C | 29.50 | C |
| Sinuosity, $K=L_{thalweg}/L_{valley}$ (m/m) | 1.20 | B | 1.30 | C | 1.70 | C | 1.20 | C | 1.20 | C |
| Slope of channel, $S_{average} = \Delta Elv/\Delta L_{thalweg}$ (m/m) | 0.006 | Bc | 0.002 | Cc | 0.0007 | C | 0.0009 | Cc | 0.0002 | Cc |
| Channel material, $D_{50}$ (m) | 0.020 | B4c | 0.00003 | C6c | 0.001 | C5c | 0.002 | C5c | 0.003 | C4c |
| Dominant channel material | Coarse pebble | | Silt/Clay | | Pebble to very coarse sand | | Pebble to very coarse sand | | Very fine pebble | |
| Rosgen Stream Type | | B4c | | C6c | | C4c | | C4c | | C4c |

(Fig 10) forming a discontinuous and linear distribution. Most of the reaches of the corridor are accompanied by cultivated and few houses. The river segment has been affected by clearing of the riparian vegetation, bank encroachment, and solid waste disposed from settlement areas.

### *Taukhel Segment (C6c-type Stream)*

The Taukhel Segment has a broad valley with terraces associated with well defined flood plains, and is slightly entrenched (ER= 7.10) (Fig. 11) with well defined meandering channel (K=1.3), moderate W/D ratio (10.5), and very low gradient (0.002 m/m). Silt/clay and subordinately coarse sand to cobble grade particles constitute bed materials. This river is therefore classified as C6c-type stream. Pools and riffles are present (Fig. 12). Deposition pattern is characterized by poorly developed small point bars. Riparian vegetation constitutes grass shrubs, and small trees, which occur more or less continuously along the both banks of the river.

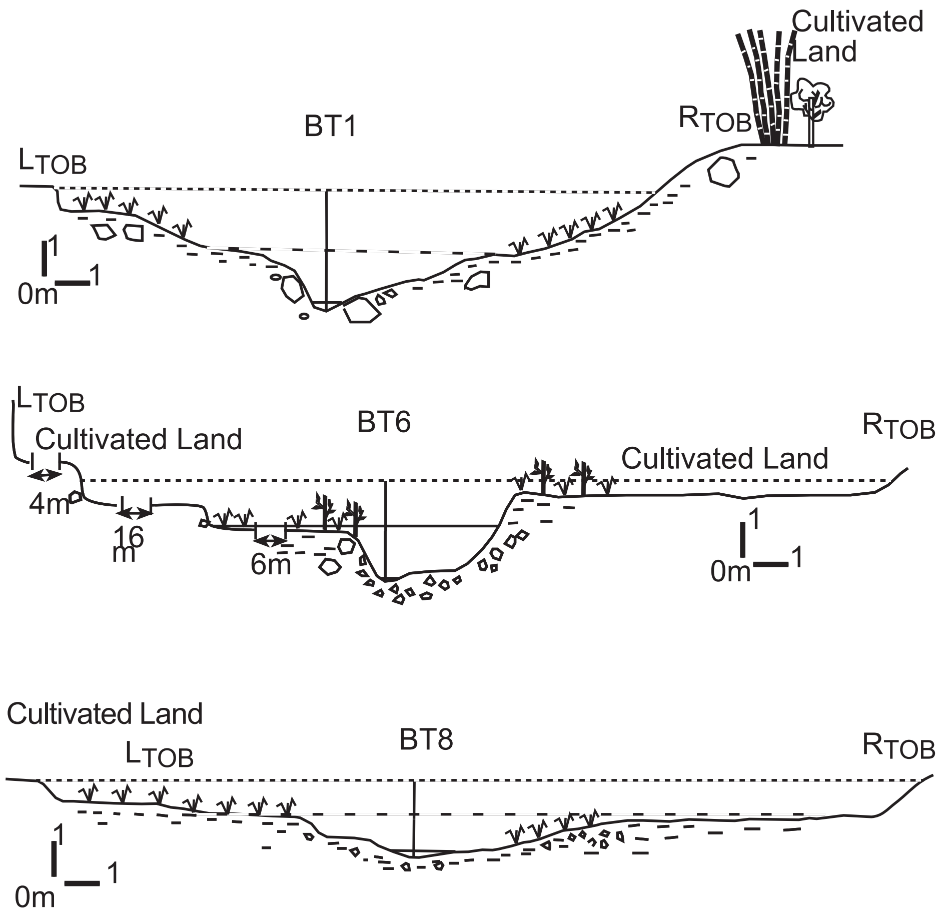



Fig. 9 Cross-sections of the Badikhel Segment.


Fig. 10 (a) Downstream view from the transect BT-1 in the Badikhel Segment and (b) Upstream view from the transect BT-3 in the Badikhel Segment.

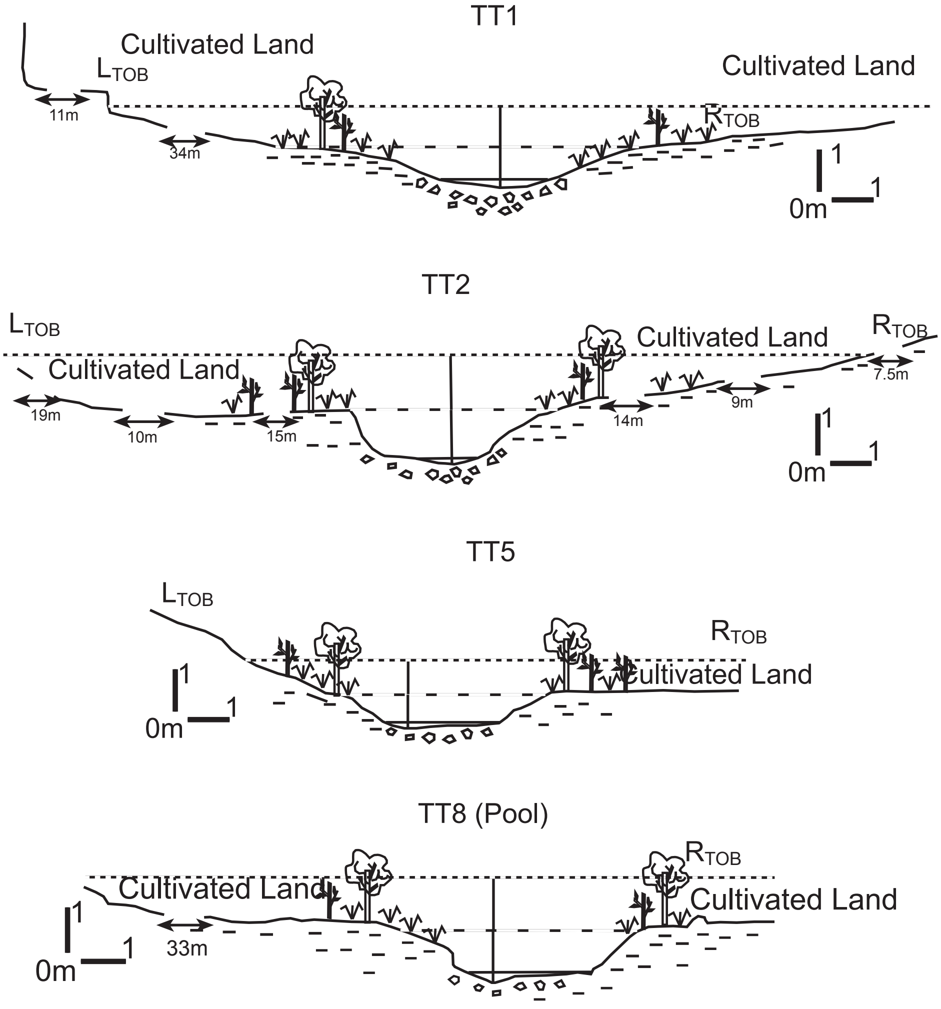



Fig. 11 Cross-sections of the Taukhel Segment


Fig. 12 (a) Transects in the Taukhel Segment and (b) Upstream view from the transect TT-3 in the Taukhel Segment.

### *Arubot Segment (C4c-type Stream)*

The Arubot Segment has a broad valley with terraces and is associated with well defined flood plains (Fig. 13). It is slightly entrenched (ER= 6.30) with very well defined highly sinuous meandering channel (K=1.7), moderate to high W/D ratio (15.2), and very low gradient (0.0007 m/m). The bed material comprises dominantly of pebbles to coarse sand and subordinately of clay/silt (Fig. 14). The river is classified as C4c-type stream. Point bars of muddy pebbly sediment are well developed. Pools and riffles are also present. Riparian vegetation is patchy and mostly poor, consisting of only shrubs and herbs (Fig. 14).

### *Thaiba Segment (C4c-type Stream)*

The Thaiba Segment possesses a broad valley with terraces and is associated with well defined flood plains (Fig. 15). It is slightly entrenched (ER= 5.40) with well defined sinuous channel (K=1.2), moderate to high W/D ratio (15.3), and very low gradient (0.0009 m/m). The bed material comprises dominantly of the pebbles to coarse sand and subordinately of clay/silt. Therefore, the segment is classified as C4c-type stream. There are well developed point bars of muddy pebbly sediment (Figs. 15 and 16), pools and riffles. The floodplains and lower terraces are used for cultivation. Riparian vegetation in the segment is poor, and patchy (Fig. 16). Mostly, it is composed of shrubs and herbs only, but in some instances contain sparse trees.

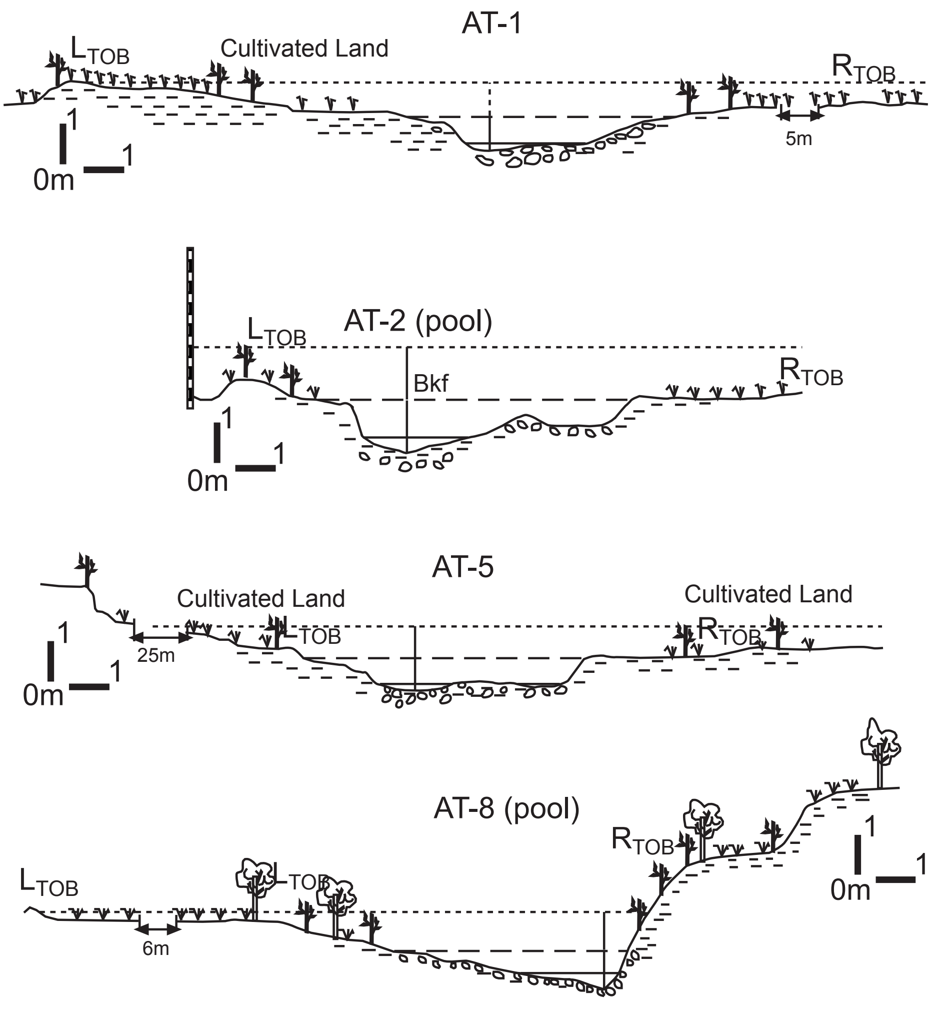



Fig. 13 Cross-sections of the Arubot Segment



Fig. 14 (a) Transects in the Arubot Segment. and (b) Upstream view from the transect AT-3 in the Arubot Segment.

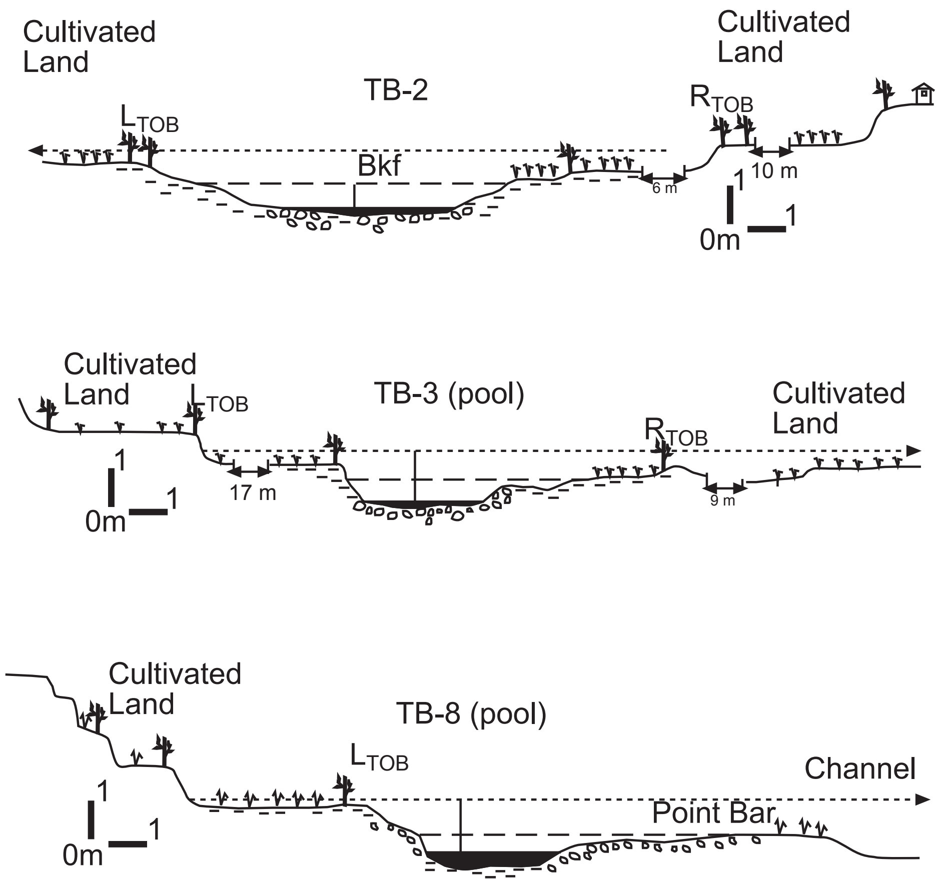



Fig. 15 Cross-sections of the Thaiba Segment

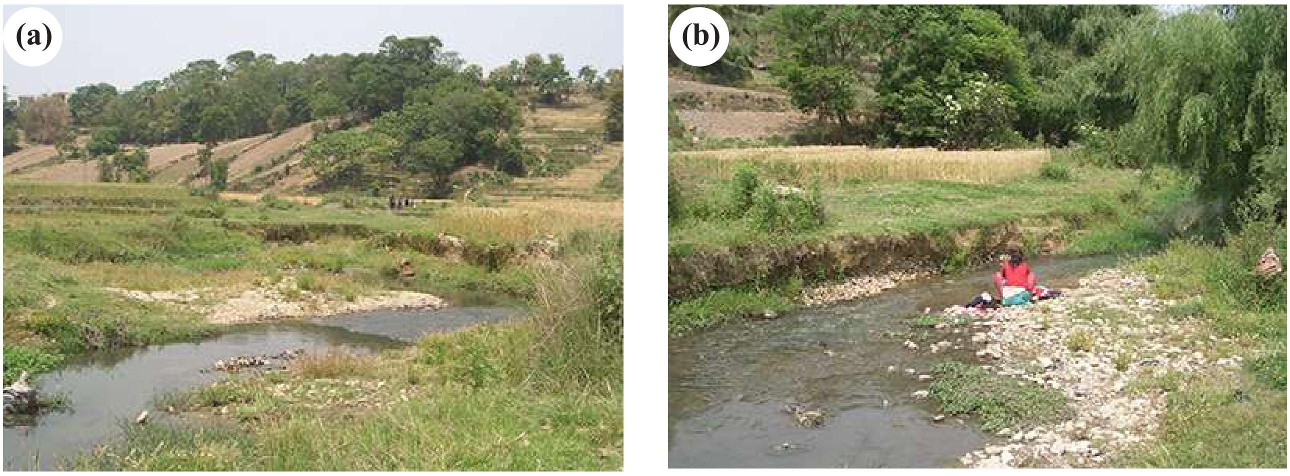



Fig. 16 Thaiba Segment: (a) Downstream view of the transect-1 and (b) Downstream view of the transect-4

### *Harishidi Segment (C4c-Typte Stream)*

The Harisiddhi Segment possesses a very wide valley with terraces and is associated with well defined very wide flood plains (Figs. 17, 18). It is slightly entrenched (ER= 3.70) with well defined sinuous channel (K=1.2), high W/D ratio (29.5), and very low gradient (0.0002 m/m). The bed material comprises dominantly of the pebbles to coarse sand and subordinately of clay/silt. Therefore, the segment is classified as C4c-type stream. There are well developed point bars of muddy pebbly sediment (Fig. 17), pools and riffles. The floodplains and lower terraces are used for cultivation as in the previous segments, but the floodplains are frequently encroached from builders. The riparian vegetation is very poor and frequently absent (Fig. 18), but when present, consists of only shrubs and herbs.

## LEVEL III CHANNEL STABILITY ASSESSMENT AND INTERPRETATION OF RESULTS

For the stream channel stability assessment at the Level III, several entities were determined for four transects of individual segment of the Kodku River by field survey. The results of analyses are listed in Table 8.

### Riparian Vegetation

Riparian vegetation ranges from perennial overstory to grass. The perennial overstory of trees and bamboos along with understory shrubs and high bush are preserved in the banks of the Badikhel (Fig. 19a) and the Taukhel Segments (Fig. 19b). In the former, trees are often more than 10 m tall. Shrubs are densely distributed. In the Taukhel Segment, the riparian vegetation is good in the upper reach while it becomes poor in the lower reach. In some transects of the Taukhel, Arubot (Fig. 19c) and the Thaiba segments (Fig. 19d), vegetation is diverse, containing perennial overstory, high bush and perennial/rhizomatous grass, whereas in the Harisiddhi Segment vegetation is very poor and contains mostly perennial grass only(Fig. 19e). In the Badikhel and the Taukhel Segments, the density of vegetation is moderate and they occur in linear and somewhat discontinuous pattern, but in the Arubot and the Thaiba Segments, riparian vegetation occurs in patches and discontinuous patterns. In the Harisiddhi Segment, it is scattering.

### Flow regime and stream size/order

The Kodku River is a perennial storm-fed river that has perennial stream channel, meaning that the surface water persists year long with seasonal variation in stream flow. The Badikhel and the Taukhel Segments are the third and the fourth order streams, respectively. The rest of the segments are fifth order channels. The

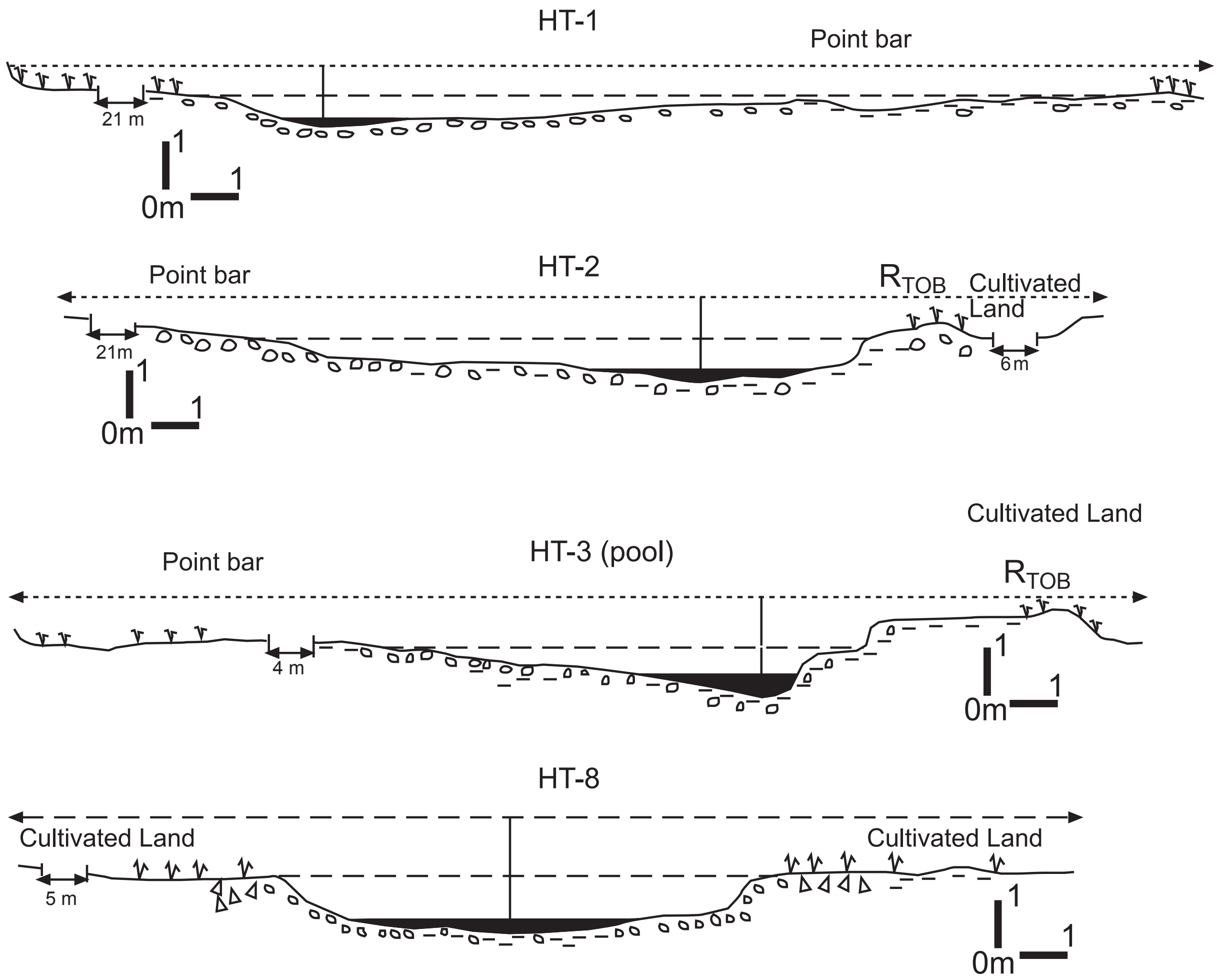



Fig. 17 Cross-sections of the Harisidhi Segment

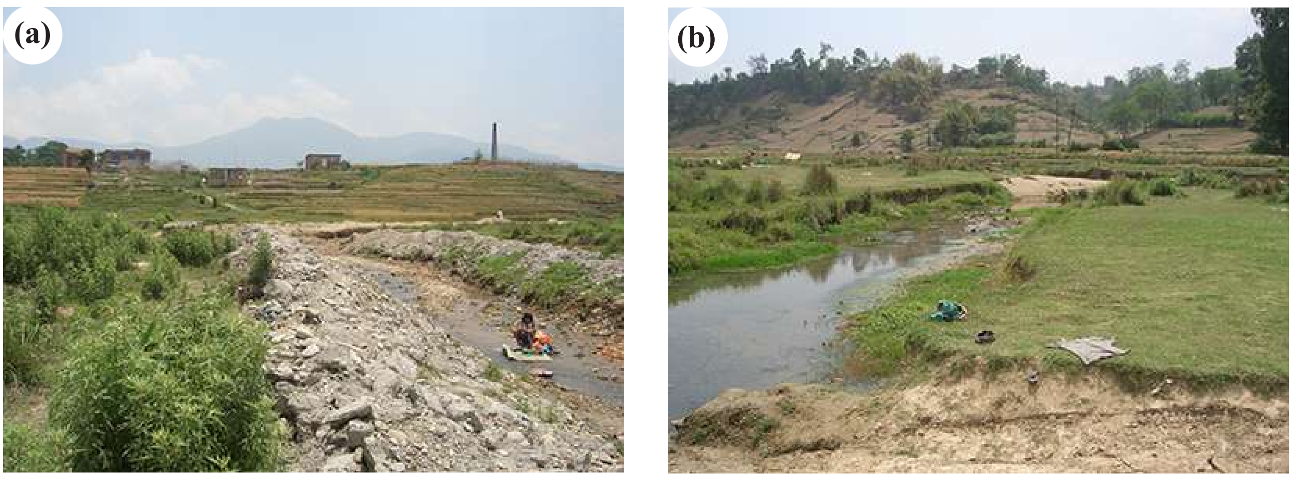



Fig. 18 Harisidhi Segment: (a) Downstream view from the transect HT-5 and (b) Upstream view from the transect HT-3

Table 8: Level III Stream channel stability evaluation

| | Stream type | [1]Riparian vegetation | [2]Flow regime | [3]Stream size/order | [4]Depositional features | [5]Meander patterns | [6]Debris and channel blockage | Streambank erosion potential [7]BEHI | [8]NBS | Pfankuch Channel [9]stability |
|---|---|---|---|---|---|---|---|---|---|---|
| Badikhel segment | B4c | | | | | | | | | |
| BT1 | | 10b | P2 | S-5, 3 | B-4 | M-6 | D3 | 21 (M) | 2.33 (E) | Fair |
| BT3 | | 10b, 11b | P2 | S-5, 3 | B-9 | M-6 | D1 | 27 (M) | 2.97 (E) | Fair |
| BT4 | | 7b, 11b | P3 | S-5, 3 | B-5 | M-1 | D1 | 31 (H) | 5.29 (E) | Fair |
| BT6 | | 7b, 11b | P4 | S-5, 3 | B-4 | M-6 | D1 | 18 (L) | 7.49 (E) | Fair |
| Taukhel segment | C6c | | | | | | | | | |
| TT2 | | 10b, 11b | P2 | S-5, 4 | B-1 | M-1, -2 | D1 | 21 (M) | 12.50 (E) | Good |
| TT4 | | 4b, 7b, 11a | P2 | S-4, 4 | B-4 | M-1 | D1 | 33 (H) | 11.00 (E) | Good |
| TT6 | | 7b, 11a | P2 | S-4, 4 | B-1 | M-1 | D1 | 31 (H) | 26.67(E) | Fair |
| TT8 | | 4b, 7b, 11a | P2 | S-4, 4 | B-4 | M-1 | D1 | 37 (H) | 8.72 (E) | Good |
| Arubot segment | C4c | | | | | | | | | |
| AT1 | | 8b | P2 | S-4, 5 | B-1 | M-1 | D1 | 23 (M) | 18.00 (E) | Fair |
| AT3 | | 4a, 6a | P2 | S-5, 5 | B-2 | M-1 | D1 | 24 (M) | 10.40 (E) | Good |
| AT5 | | 4b, 5b | P2 | S-5. 5 | B-1 | M-1 | D1 | 36 (H) | 18.00 (E) | Fair |
| AT7 | | 7b, 11b | P2 | S-5, 5 | B-1, -4 | M-1 | D1 | 24 (M) | 26.93 (E) | Good |
| Thaiba segment | C4c | | | | | | | | | |
| TbT2 | | 5a, 7a, 11a | P2 | S-5, 5 | B-4 | M-1 | D1 | 12 (L) | 18.67 (E) | Good |
| TbT3 | | 4a, 11a | P2 | S-5, 5 | B-4 | M-1 | D1 | 45 (VH) | 24.00 (E) | Fair |
| TbT4 | | 4a, 6a, 9a | P2 | S-5, 5 | B-9 | M-1 | D1 | 30 (H) | 10.01(E) | Fair |
| TbT5 | | 5a, 7a | P2 | S-5, 5 | B4 | M-1 | D1 | 20 (M) | 10.60 (E) | Good |
| Harisiddhi segment | C4c | | | | | | | | | |
| HT1 | | 4a, 7a | P2 | S-6. 5 | B-1 | M-1 | D1 | 36 (H) | 39.11 (E) | Fair |
| HT3 | | 4a | P2 | S-6. 5 | B-1 | M-1 | D1 | 41 (VH) | 37.00 (E) | Fair |
| HT5 | | 4a | P2 | S-6. 5 | B-2 | M-1 | D1 | 44 (VH) | 6.80 (E) | Fair |
| HT8 | | 4a | P2 | S-6. 5 | B-1 | M-1 | D1 | 42 (VH) | 9.60 (E) | Fair |

[1]Riparian vegetation: 4 = Perennial grass; 5 = Rhizomatous grass; 6 = Low brush; 7 = High brush; 8 = Combination grass/brush; 10 = Decidous with brush/grass understory; 11 = Perennial overstory; a = low, b = moderate

[2]Flow regime: P2 = Perennial stream channel, surface water persists year long with seasonal variation in stream flow dominated by storm flow

[3]Stream size/order: S-4 = 4.6-9 m; S-5 9-15 m; S-6 15-22.8 m; 3 = third order; 4 = forth order; 5 = fifth order

[4]Depositional features: B-1 = Point bars; B-2 = Point bars with few mid channel bars; B-4 = Side bars; B-5 = Diagonal bars; B-9 = channel

[5]Meander patterns: M-1 = Regular meander; M-2 = Tortous meander; M-6 = Confined meander scrolls

[6]Debris and channel blockage: D1 = None; minor amount of small floatable material

[7]BEHI: Bank erosion hazard index: VL, very low = 5-9.5; L, low = 10-19.5; M, moderate = 20-29.5; H, high = 30-39.5; VH, very high = 40-45; E, extreme = 46-50

[8]NBS: Near bank stress = $\tau_{nb}/\tau_{bkf}$(NBS method 6): VL, very low < 0.80; L, low = .8-1.05; M, moderate = 1.06-1.14; H, high = 1.15-1.19; VH, very high = 1.20-1.60, E, extreme > 1.60

[9]Pfankuch channel stability: B4 stream, Good = 40-64; Fair = 65-85; Poor = 85+; C6 stream, Good = 60-85; Fair = 86-105; Poor = 106+; C4 stream, Good = 70-90; Fair = 91-110; Poor > 111+

stream size of the Badikhel, Arubot, and the Thaiba Segments falls in S-5 category meaning the bankfull width of the river being 9–15 m. The Taukhel and the Harisiddhi Segments have this width respectively of 6–9 m and 15–22 m. Therefore, the Taukhel Segment is the narrowest channel while the Harisiddhi Segment is the widest one.

## Depositional Features

Depositional features provide insight into the effect of sediment supply and storage which is related to channel form and stability. Mostly four types of features are present in the Kodku River (Table 8). Side and diagonal bars are observed in the Badikhel and the Thaiba Segments, whereas point bars are dominant in the Taukhel, the Arubot and the Harisidhi Segments. Point bar with few mid channel bars are present in the Arubot and the Harisidhi Segments.

## Meander Patterns

The meander pattern of the channel depends on the size of sediment of channel and banks. The Kodku


Fig. 19 Photographs of stream segments of the Kodku River showing riparian vegetation condition. (a) Badikhel Segment, (b) Taukhel Segment, (c) Arubot Segment, (d) Thaiba Segment, and (e) Harisiddhi Segment.

River shows regular meander patterns in most of segments except the Badikhel Segment. The Badikhel segment shows confined meander scrolls.

## Debris and Channel Blockage

The materials which can create obstruction in flow of channel water and sediment are included in this parameter. Not any major material that can block the channel is observed in overall channel.

## Streambank Erosion Potential

Streambank erosion potential was accessed using two well known parameters which have influence of erodibility and erosivity of the banks. These parameters are respectively Bank Erosion Hazard Index (BEHI) and Near Bank Stress (NBS) after Rosgen (2001) (Tables 9 and 10). The former was determined using six parameters of bank features; bank angle (BA), bank height ratio (BHR), root depth ratio (RDR), root density (RD), surface protection (SP) and bank material characteristics (BMC), and these parameters were accessed at different sites along the Kodku River corridor and were assigned ratings to calculate BEHI (Table 11). Similarly, NBS was accessed at various sites along the river using the parameters such as near bank maximum depth ($D_{nb}$), bankfull depth ($D_{bkf}$), near bank slope ($S_{nb}$) and average slope ($S_{avg}$). From these the NBS of method 5 (NBS = $D_{nb}/D_{bkf}$) and of 6 (NBS = $\tau_{nb}/\tau_{bkf}$) were calculated (Table 12 ).

Table 9: Streambank characteristics used to develop Bank erosion Hazard Index (BEHI) (after Rosgen 2001)

| Adjective Hazard or risk rating categories | | Bank Height/ Bankfull Ht | Root Depth/ Bank Height | Root Density % | Bank Angle (Degrees) | Surface Protection% | Totals |
|---|---|---|---|---|---|---|---|
| VERY LOW | Value | 1.0-1.1 | 1.0-0.9 | 100-80 | 0-20 | 100-80 | |
| | Index | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 | 1.0-1.9 | 5-9.5 |
| LOW | Value | 1.11-1.19 | 0.89-0.5 | 79-55 | 21-60 | 79-55 | |
| | Index | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 | 2.0-3.9 | 10-19.5 |
| MODERATE | Value | 1.2-1.5 | 0.49-0.3 | 54-30 | 61-80 | 54-30 | |
| | Index | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 | 4.0-5.9 | 20-29.5 |
| HIGH | Value | 1.6-2.0 | 0.29-0.15 | 29-15 | 81-90 | 29-15 | |
| | Index | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 | 6.0-7.9 | 30-39.5 |
| VERY HIGH | Value | 2.1-2.8 | 0.14-0.05 | 14-5.0 | 91-119 | 14-10 | |
| | Index | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 | 8.0-9.0 | 40-45 |
| EXTREME | Value | >2.8 | <0.05 | <5 | >119 | <10 | |
| | Index | 10 | 10 | 10 | 10 | 10 | 46-50 |

For adjustments in points for specific nature of bank materials and stratification, the following is used:
Bank Materials: Bedrock (very low), Boulders (low), cobble (subtract 10 points unless gravel/sand>50%, then no adjustment), gravel (add 5-10 points depending on % sand), sand (add 10 points), silt/clay (no adjustment).
Stratification: Add 5-10 points depending on the number and position of layers.

Table 10: Near-bank stress rating (Rosgen 2001)

| Near bank stress rating | Ratio $D_{nb}/D_{bkf}$ | Near-bank stress/shear stress |
|---|---|---|
| Very low | <1.00 | < 0.8 |
| Low | 1.00-1.50 | 0.8 -1.05 |
| Moderate | 1.51-1.80 | 1.06 -1.14 |
| High | 1.81-2.50 | 1.15 - 1.19 |
| Very High | 1.51-3.00 | 1.20 -1.60 |
| Extreme | >3.00 | > 1.60 |

BEHI ranges from low value 12 to highest value 45. Both of these two values were observed from Thaiba segment. The calculated BEHI was categorized as low, medium, high, very high and extreme hazard based on the Rosgen (2001). BEHI is low to high in the Badikhel and the Thaiba Segments, moderate to high in the Taukhel and the Arubot Segments, and high to very high in the Harisidhi Segment.

It is often low to high in the upstream segments and is high to very high in the downstream segments showing that the higher order streams are potential to bank erosion. BEHI was mostly influenced by root density, surface protection and channel material. The upstream reach has high root density and surface protection with huge boulders. This condition helps to reduce the value of BEHI rating. But in the case of the downstream reach, vegetation is distributed in patches or discontinuous pattern and in some instance absence of vegetation, which reduces the proportion of root density and surface protection. These segments also contain high proportion of cohesionless sediments such as muddy gravel.

NBS ranges from 1.33 to 5.33, obtained from the method 5. These two values were observed from the Harisidhi Segment. This segment has variable values of bankfull depth and near bank depth. Based on the method 6, NBS varies form 2.33 to 39.11. The lowest value was obtained from the upper transects of the Badikhel Segment and the highest was from the Harisiddhi Segment. Comparatively, all the fourth and the fifth order river segments show high values because of low average slope compared to near bank slope, and the low bankfull depth compared to the near bank maximum depth in those segments.

Table 11: Results of BEHI assessment in the Kodku River

| | Bank Angle | | Bank Height Ratio (BHR) | | | | Root Depth Ratio (RDR) | | | Root Density | | Surface Protection % | | Adjust-ment | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Segment | Value (deg.) | Score | BH (m) | BKFH (m) | *BHR | Score | RD (m) | **RDR | Score | Value (%) | Score | Value (%) | Score | | BEHI |
| Badikhel | | | | | | | | | | | | | | | |
| BT1 | 110 | 9 | 1.6 | 1.2 | 1.33 | 6 | 0.5 | 0.31 | 6 | 20 | 8 | 50 | 4 | -10 | 21 (M) |
| BT3 | 120 | 10 | 2.1 | 1.5 | 1.40 | 6 | 0.7 | 0.33 | 6 | 22 | 7 | 20 | 8 | -10 | 17 (M) |
| BT4 | 90 | 8 | 1.7 | 1.4 | 1.21 | 6 | 0.5 | 0.29 | 6 | 70 | 3 | 75 | 3 | 5 | 31 (H) |
| BT6 | 85 | 7 | 2.5 | 1.5 | 1.67 | 6 | 0.4 | 0.16 | 7 | 70 | 3 | 40 | 5 | -10 | 18 (L) |
| Taukhel | | | | | | | | | | | | | | | |
| TT3 | 95 | 8 | 1.7 | 1.7 | 1.00 | 1 | 1.5 | 0.88 | 2 | 50 | 4 | 80 | 2 | 5 | 21 (M) |
| TT5 | 70 | 5 | 3.2 | 1.2 | 2.67 | 9 | 1 | 0.31 | 6 | 40 | 5 | 70 | 3 | 5 | 33 (H) |
| TT7 | 85 | 7 | 1.1 | 1.1 | 1.00 | 1 | 0.6 | 0.55 | 4 | 20 | 7 | 25 | 7 | 5 | 31 (H) |
| TT8 | 110 | 9 | 1.5 | 1.2 | 1.25 | 4 | 0.7 | 0.47 | 4 | 15 | 8 | 25 | 7 | 5 | 37 (H) |
| Arubot | | | | | | | | | | | | | | | |
| AT1 | 110 | 9 | 0.9 | 0.9 | 1.00 | 1 | 0.5 | 0.56 | 4 | 30 | 6 | 70 | 3 | 0 | 23 (M) |
| AT3 | 85 | 7 | 1.2 | 1.0 | 1.20 | 4 | 0.9 | 0.75 | 3 | 30 | 6 | 55 | 4 | 0 | 24 (M) |
| AT5 | 110 | 9 | 1.2 | 1.2 | 1.00 | 1 | 0.6 | 0.50 | 4 | 20 | 8 | 10 | 9 | 5 | 36 (H) |
| AT7 | 83 | 7 | 1.4 | 1.3 | 1.08 | 2 | 1.1 | 0.79 | 2 | 25 | 7 | 60 | 4 | 2 | 24 (M) |
| Thaiba | | | | | | | | | | | | | | | |
| TbT2 | 75 | 6 | 1.3 | 1.3 | 1.00 | 1 | 1.1 | 0.85 | 2 | 40 | 5 | 75 | 3 | -5 | 12 (L) |
| TbT3 | 110 | 9 | 1.0 | 0.8 | 1.25 | 4 | 0.4 | 0.40 | 5 | 20 | 8 | 10 | 9 | 10 | 45 (VH) |
| TbT4 | 105 | 8 | 1.2 | 1.2 | 1.00 | 1 | 0.5 | 0.42 | 5 | 20 | 8 | 10 | 9 | -2 | 30 (H) |
| TbT5 | 105 | 8 | 1.0 | 1.0 | 1.00 | 1 | 0.3 | 0.30 | 6 | 60 | 4 | 75 | 3 | -2 | 20 (M) |
| Harisiddhi | | | | | | | | | | | | | | | |
| HT1 | 105 | 8 | 1.3 | 1.3 | 1.00 | 1 | 0.5 | 0.38 | 5 | 20 | 8 | 10 | 9 | 5 | 36 (H) |
| HT3 | 87 | 8 | 1.5 | 1.3 | 1.15 | 2 | 0.2 | 0.13 | 8 | 10 | 9 | 10 | 9 | 5 | 41 (VH) |
| HT5 | 95 | 8 | 2.0 | 1.3 | 1.54 | 6 | 0.2 | 0.10 | 8 | 10 | 9 | 20 | 8 | 5 | 44 (VH) |
| HT8 | 105 | 9 | 1.0 | 1.0 | 1.00 | 1 | 0.1 | 0.10 | 8 | 10 | 9 | 5 | 10 | 5 | 42 (VH) |

*BHR = Bank height ratio = Bank height (BH)/Bankfull height (BKFH)    **RDR = Root depth (RD)/Bank height (BH)

Table 12: Results of NBS assessment in the Kodku River

| | | Near Bank Stress Levell III (5) | | | | Near Bank Stress Levell III (6) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Segment | Near bank max. depth, $D_{nb}$ (m) | Bankfull depth, D $D_{bkf}$ (m) | Ratio $D_{nb}/D_{bkf}$ | NBS | Near bank max. depth, $D_{nb}$ (m) | Near bank slope, $S_{nb}$ | Near bank shear stress, $\tau_{nb}$ (N/m$^2$) | Bankfull depth, $D_{bkf}$ (m) | Average slope, $S_{avg}$ | Boundary shear stress, $\tau_{bkf}$ (N/m$^2$) | Ratio $\tau_{nb}/\tau_{bkf}$ | NBS |
| Badikhel | BT1 | 1.3 | 0.8 | 1.60 | Moderate | 1.3 | 0.150 | 1883.52 | 0.8 | 0.103 | 808.3 | 2.33 | Extreme |
| | BT3 | 1.7 | 1.0 | 1.70 | Moderate | 1.7 | 0.180 | 3001.86 | 1.0 | 0.103 | 1010.4 | 2.97 | Extreme |
| | BT4 | 1.4 | 0.6 | 2.33 | High | 1.4 | 0.350 | 4806.90 | 0.9 | 0.103 | 909.4 | 5.29 | Extreme |
| | BT6 | 1.5 | 0.7 | 2.14 | High | 1.5 | 0.360 | 5297.40 | 0.7 | 0.103 | 707.3 | 7.49 | Extreme |
| Taukhel | TT3 | 2.0 | 0.8 | 2.50 | High | 2.0 | 0.140 | 2746.80 | 0.8 | 0.028 | 219.7 | 12.50 | Extreme |
| | TT5 | 1.4 | 0.5 | 2.80 | V. High | 1.4 | 0.110 | 1510.74 | 0.5 | 0.028 | 137.3 | 11.00 | Extreme |
| | TT7 | 1.6 | 0.6 | 2.67 | V. High | 1.6 | 0.280 | 4394.88 | 0.6 | 0.028 | 164.8 | 26.67 | Extreme |
| | TT8 | 1.9 | 0.7 | 2.71 | V. High | 1.9 | 0.090 | 1677.51 | 0.7 | 0.028 | 192.3 | 8.72 | Extreme |
| Arubot | AT1 | 1.5 | 0.5 | 3.00 | Extreme | 1.5 | 0.090 | 1324.35 | 0.5 | 0.015 | 73.6 | 18.00 | Extreme |
| | AT3 | 1.0 | 0.6 | 1.73 | Moderate | 1.0 | 0.090 | 918.22 | 0.6 | 0.015 | 88.3 | 10.40 | Extreme |
| | AT5 | 1.5 | 0.5 | 3.00 | Extreme | 1.5 | 0.090 | 1324.35 | 0.5 | 0.015 | 73.6 | 18.00 | Extreme |
| | AT7 | 1.7 | 0.4 | 4.25 | Extreme | 1.7 | 0.095 | 1584.32 | 0.4 | 0.015 | 58.9 | 26.92 | Extreme |
| Thaiba | TbT2 | 1.6 | 0.6 | 2.67 | V. High | 1.6 | 0.105 | 1648.08 | 0.6 | 0.015 | 88.3 | 18.67 | Extreme |
| | TbT3 | 1.0 | 0.5 | 2.00 | High | 1.0 | 0.180 | 1765.80 | 0.5 | 0.015 | 73.6 | 24.00 | Extreme |
| | TbT4 | 1.7 | 0.6 | 2.83 | V. High | 1.7 | 0.053 | 883.88 | 0.6 | 0.015 | 88.3 | 10.01 | Extreme |
| | TbT5 | 1.5 | 0.5 | 3.00 | Extreme | 1.5 | 0.053 | 779.90 | 0.5 | 0.015 | 73.6 | 10.60 | Extreme |
| Harisiddhi | HT1 | 1.6 | 0.3 | 5.33 | Extreme | 1.6 | 0.110 | 1726.56 | 0.3 | 0.015 | 44.1 | 39.11 | Extreme |
| | HT3 | 1.5 | 0.5 | 3.00 | Extreme | 1.5 | 0.185 | 2722.28 | 0.5 | 0.015 | 73.6 | 37.00 | Extreme |
| | HT5 | 1.5 | 1.0 | 1.50 | Low | 1.5 | 0.068 | 1000.62 | 1.0 | 0.015 | 147.2 | 6.80 | Extreme |
| | HT8 | 1.2 | 0.9 | 1.33 | Low | 1.2 | 0.108 | 1271.38 | 0.9 | 0.015 | 132.4 | 9.60 | Extreme |

NBS derived from the Method 5, which is a depth related parameter, is moderate to high in the Badikhel Segment, high to very high in the Taukhel Segment, moderate to extreme in the Arubot Segment, high to extreme in the Thaiba Segment and low to extreme in the Harisidhi Segment (Table 12). NBS range becomes wider in the last three downstream segments due to variability in near bank depth and bankfull depth ratio. It means that the scoured near bank regions frequently exist in the fifth order streams. When NBS derived from the Method 6 is compared, almost all the sites have shown extreme NBS except the two sites of the Thaiba Segment. These extreme NBS implies that there is a great potential of bank erosion in almost all the segments of the Kodku River as the near bank shear stresses there are more than 1.6 times the boundary shear stress.

### Channel Stability Evaluation

Pfankuch (1975) channel stability for the reach condition evaluation of each channel sample site, taking into account of the upper bank, the lower bank and the bottom portion of the stream channel, was assessed to score for various elements. For each of the element, four condition categories; excellent, good, fair and poor were scored, and the total of these categories as a total Pfankuch score was obtained. The scores were tallied with the chart after Rosgen (2001) to derive the stability of the reach condition by stream type.

Pfankuch stream stability is fair in the Badikhel and the Harisiddhi Segment, whereas it is good to fair in the Taukhel, Arubot and the Thaiba Segments (Table 13). In upstream segments, most of parameters such as mass wasting, cutting and scoring and deposition lie on good category and very few parameters such as aquatic vegetation at the bottom lie on poor category. Parameters of downstream segments show combined categories of good, fair and poor but mostly fair condition was obtained from the Harisidhi Segment.

Pfankuch stream stability rating varies from 65 to 108. The lowest rating was observed from the Badikhel Segment, whereas the highest was from the Harisidhi Segment. The wider range of rating in the upstream to the downstream segments is observed due to the variability in different parameters of upper bank, lower bank and stream bottom. The ratings of the Badikhel and the Harisidhi Segments were different but both of these segments fall on fair condition due to difference in stream types.

## ADDITIONAL STREAM STABILITY PARAMETERS

### River Profile Features

Pool maximum depth ratio (PMDR = maximum depth of pools/mean depth of channel), and riffle maximum depth ratio (RMDR = maximum depth of riffles/mean bankfull depth) are obtained from cross-sectional data. Measurements taken on a thalweg survey provided data on maximum bankfull depths, the various bed features and any change in slope.

The ranges of RMDR and PMDR are 1.89–1.62 and 1.84–1.92, respectively. The former diminishes downstream while the latter increases. From Fig. 20, it is apparent that PMDR widens and exceeds over RMDR in the downstream three segments of the fifth order stream. The wider the RMDR and PMDR for the segments, the greater the possibility of the increased instability due to higher near bank stress condition.

### Vertical and Lateral Channel Stabilities

Measures of morphological elements of stream are the fundamental criteria to evaluate vertical and lateral stabilities of the stream. Often Bank Height Ratio (BHR) and Entrenchment Ratio (ER) were taken as two important parameters to measure vertical stability of various segments of the Kodku River, while Meandering Width Ratio (MWR), W/D ratio, Bank Erosion Hazard Index (BEHI), and Near Bank Stress (NBS) (Rosgen, 1996 and 2001) were taken for evaluating lateral stability.

When the banks exceed BHR of 1.5, they were considered highly unstable (Rosgen, 2001). The Kodku River banks in all the segments reveal exceedingly highly unstable BHR. Despite of high bank height ratio, the segments show non-entrenchment (entrenched streams have ER less than 1.4 ± 0.2 according to Rosgen (1994)) and exhibit somewhat stable segments in terms of vertical stability. The Badikhel segment having ER = 1.7 (Table 14) is more entrenched segment when all the

Table 13: Result of Pfankuch stream reach condition assessment of the Kodku River

| | Condition category and rating | | | | | | |
|---|---|---|---|---|---|---|---|
| Segment | Stream type | Excellent | Good | Fair | Poor | Total Pfankuch score for reach | *Reach condition by stream type |
| Badikhel | B4c | | | | | | |
| BT1 | | 10 | 38 | 24 | 0 | 72 | Fair |
| BT3 | | 11 | 32 | 18 | 4 | 65 | Fair |
| BT4 | | 6 | 48 | 9 | 16 | 79 | Fair |
| BT6 | | 5 | 50 | 21 | 4 | 80 | Fair |
| Taukhel | C6c | | | | | | |
| TT3 | | 2 | 62 | 9 | 4 | 77 | Good |
| TT5 | | 5 | 40 | 36 | 4 | 85 | Good |
| TT7 | | 5 | 36 | 42 | 4 | 87 | Fair |
| TT8 | | 1 | 52 | 27 | 4 | 84 | Good |
| Arubot | C4c | | | | | | |
| AT1 | | 0 | 46 | 30 | 16 | 92 | Fair |
| AT3 | | 2 | 52 | 15 | 16 | 85 | Good |
| AT5 | | 2 | 38 | 33 | 24 | 97 | Fair |
| AT7 | | 6 | 32 | 42 | 4 | 84 | Good |
| Thaiba | C4c | | | | | | |
| TbT2 | | 5 | 42 | 9 | 32 | 88 | Good |
| TbT3 | | 2 | 44 | 33 | 12 | 91 | Fair |
| TbT4 | | 2 | 44 | 33 | 12 | 91 | Fair |
| TbT5 | | 13 | 22 | 33 | 12 | 80 | Good |
| Harisiddhi | C4c | | | | | | |
| HT1 | | 2 | 22 | 66 | 12 | 102 | Fair |
| HT3 | | 4 | 18 | 42 | 44 | 108 | Fair |
| HT5 | | 4 | 18 | 42 | 28 | 92 | Fair |
| HT8 | | 4 | 20 | 51 | 28 | 103 | Fair |

* Conversion of stability rating to reach condition by stream type (after Rosgen 2001)

| Stream type | A1 | A2 | A3 | A4 | A5 | A6 | B1 | B2 | B3 | B4 | B5 | B6 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Good | 38-43 | 38-43 | 54-90 | 60-95 | 60-95 | 50-80 | 38-45 | 38-45 | 40-60 | 40-64 | 48-68 | 40-60 |
| Fair | 44-47 | 44-47 | 91-129 | 96-132 | 96-132 | 81-110 | 46-58 | 46-58 | 61-78 | 65-84 | 69-88 | 61-78 |
| Poor | 48+ | 48+ | 130+ | 133+ | 133+ | 111+ | 59+ | 59+ | 79+ | 85+ | 89+ | 79+ |
| Stream type | C1 | C2 | C3 | C4 | C5 | C6 | D3 | D4 | D5 | D6 | | |
| Good | 38-50 | 38-50 | 60-85 | 70-90 | 70-90 | 60-85 | 85-107 | 85-107 | 85-107 | 67-98 | | |
| Fair | 51-61 | 51-61 | 86-105 | 91-110 | 91-110 | 86-105 | 108-132 | 108-132 | 108-132 | 99-125 | | |
| Poor | 62+ | 62+ | 106+ | 111+ | 111+ | 106+ | 133+ | 133+ | 133+ | 126+ | | |
| Stream type | DA3 | DA4 | DA5 | DA6 | E3 | E4 | E5 | E6 | | | | |
| Good | 40-63 | 40-63 | 40-63 | 40-63 | 40-63 | 50-75 | 50-75 | 40-63 | | | | |
| Fair | 64-86 | 64-86 | 64-86 | 64-86 | 64-86 | 76-96 | 76-96 | 64-86 | | | | |
| Poor | 87+ | 87+ | 87+ | 87+ | 87+ | 97+ | 97+ | 87+ | | | | |
| Stream type | F1 | F2 | F3 | F4 | F5 | F6 | G1 | G2 | G3 | G4 | G5 | G6 |
| Good | 60-85 | 60-85 | 85-110 | 85-110 | 90-115 | 80-95 | 40-60 | 40-60 | 85-107 | 85-107 | 90-112 | 85-107 |
| Fair | 86-105 | 86-105 | 111-125 | 111-125 | 116-130 | 96-110 | 61-78 | 61-78 | 108-120 | 108-120 | 113-125 | 108-120 |
| Poor | 106+ | 106+ | 126+ | 126+ | 131+ | 111+ | 79+ | 79+ | 121+ | 121+ | 126+ | 121+ |

segments are compared, and shows some degree of vertical instability and is also a potentially degrading stream.

MWR and W/D provide information on lateral stability of channel. High W/D ratio is associated with bank erosion and channel widening (Rosgen, 1996). High amount of MWR reflects greater degree of channel accretion compared to the low MWR. The Badikhel and the Harisiddhi Segments possess moderate MWR while other three segments exhibit high MWR showing their greater potential towards lateral instability. Similarly, W/D ratio of all the segments fall into the unstable stability rating category (after Rosgen, 2001), showing that these segments have undergone bank erosion and channel widening. When lateral widening and instability of the Harisiddhi Segment is compared with the other segments, W/D ratio is two times those of the other segments, and shows that

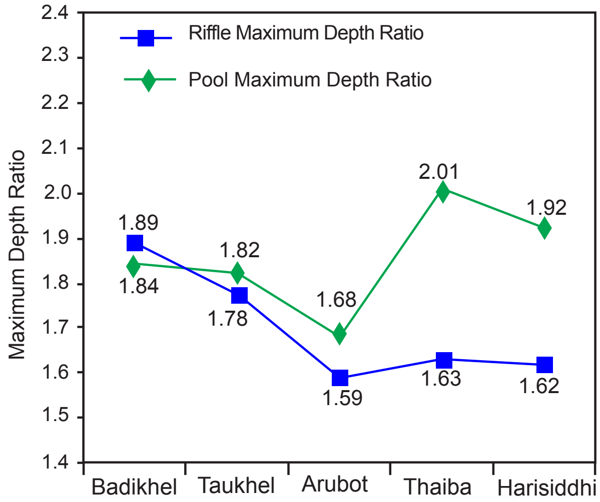



Fig. 20 Riffle maximum depth ratio and pool maximum depth ratio of different segments of the Kodku River.

though its meander width could not get expanded, its channel width is becoming wider due to bank erosion.

## Aggrading/Degrading Potential

Aggradation/degradation potential was evaluated using Schumm's (1963) relationship,

$$F = 255\ M^{-1.08} \qquad (5)$$

where, F and M are defined as:

$$F = W_{bkf}/D_{bkf} \qquad (6)$$

$$M = [(S_r\ .W_{bkf})+(S_b\ .\ 2D_{bkf})]/(W_{bkf}+2D_{bkf}) \qquad (7)$$

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.

$S_r$ was already derived from the Wolman pebble counting of the channel cross-section. $S_b$ was obtained from sieving of the bar material sampled. The results of the % silt and clay of the bar and the wetted perimeter of a riffle materials have been presented in Table 15 and Fig. 21. The median diameter of these sediments show coarse sand to pebble size grades. Both $S_r$ and $S_b$ were incorporated in equation (7).

When Schumm's (1963) F- versus M-factor plot has been constructed (Table 15; Fig. 22), it is seen that the Badikhel Segment plots in the degrading field, while the rest of the other segments plot on the aggrading field. The Badikhel Segment being plotted closer to the stability line shows that though it is degrading is not far from the stability. The Thaiba and the Harisiddhi Segments are plotted far from the stability line and show higher degrees of aggradation compared to the other segments. Recent activities of active faults in the Kathmandu Basin have been studied by Yagi et al. (2000) and Saijo et al. (1995). They estimated an average vertical displacement rate of 1 mm/yr on the Kathmandu South Fault which runs along the southern margin of the Kathmandu Basin (Yagi et al., 2000). Faulting can be the cause for upliftment of the southern hills and therefore, causes for the degrading condition of the incising segment of the Kodku River.

## Channel Dimension Relation

Regional and planform relationships have been formulated for large number of natural and artificial streams by Leopold and Wolman (1960) and Williams (1986). For instance, $L_m$ = 10.9W1.01 (Leopold and Wolman, 1960) and $W_{blt}$ =4.4W1.12 (Williams, 1986),

Table 14: Level III Stream channel stability evaluation

| Segment | Stream type | [1]Stream size/order | Vertical stability | | | | Lateral stability | | | | Aggrading/Degrading condition |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | [2]BHR | | [3]ER | | [4]MWR | | [5]W/D ratio | | |
| Badikhel | B4c | S-5, 3rd | 1.6 | HU | 1.7 | NE | 5.6 | M | 14.3 | U | Deggrading |
| Taukhel | C6c | S-4, -5, 4th | 2.2 | HU | 7.1 | NE | 12.4 | H | 10.5 | U | Aggrading |
| Arubot | C4c | S-4, -5, 5th | 1.8 | HU | 6.3 | NE | 11.9 | H | 15.2 | U | Aggrading |
| Thaiba | C4c | S-5, 5th | 2.0 | HU | 5.4 | NE | 12.4 | H | 15.3 | U | Aggrading |
| Harisiddhi | C4c | S-6, 5th | 2.4 | HU | 3.7 | NE | 6.1 | M | 29.5 | U | Aggrading |

[1]Stream size/order: S-4 = 4.6-9 m; S-5 9-15 m; S-6 15-22.8 m; 3 = third order; 4 = forth order; 5 = fifth order

[2]BHR (Bank Height Ratio): Stability rating: Stable, U (BHR = 1.0-1.05); Moderately unstable, MU (1.06-1.3); Unstable, U (1.3-1.5); Highly unstable, HU (>1.5)

[3]ER (Entrenchment Ratio): Entrenched, E (ER = 1.2-1.4); Moderately entrenched, ME (1.4-1.6), Non entrenched, ER = (>1.6)

[4]MWR (Meander Width Ratio): Low, L (MWR <5.0); Moderate (5.0-10.0); High (>10.0)

[5]W/D ratio: Unstable, U (W/D ratio >1.4); Moderately unstable, MU (1.21-1.4); Stable, S (1.0-1.2); Very stable (<1.0) (Rosgen, 2001)

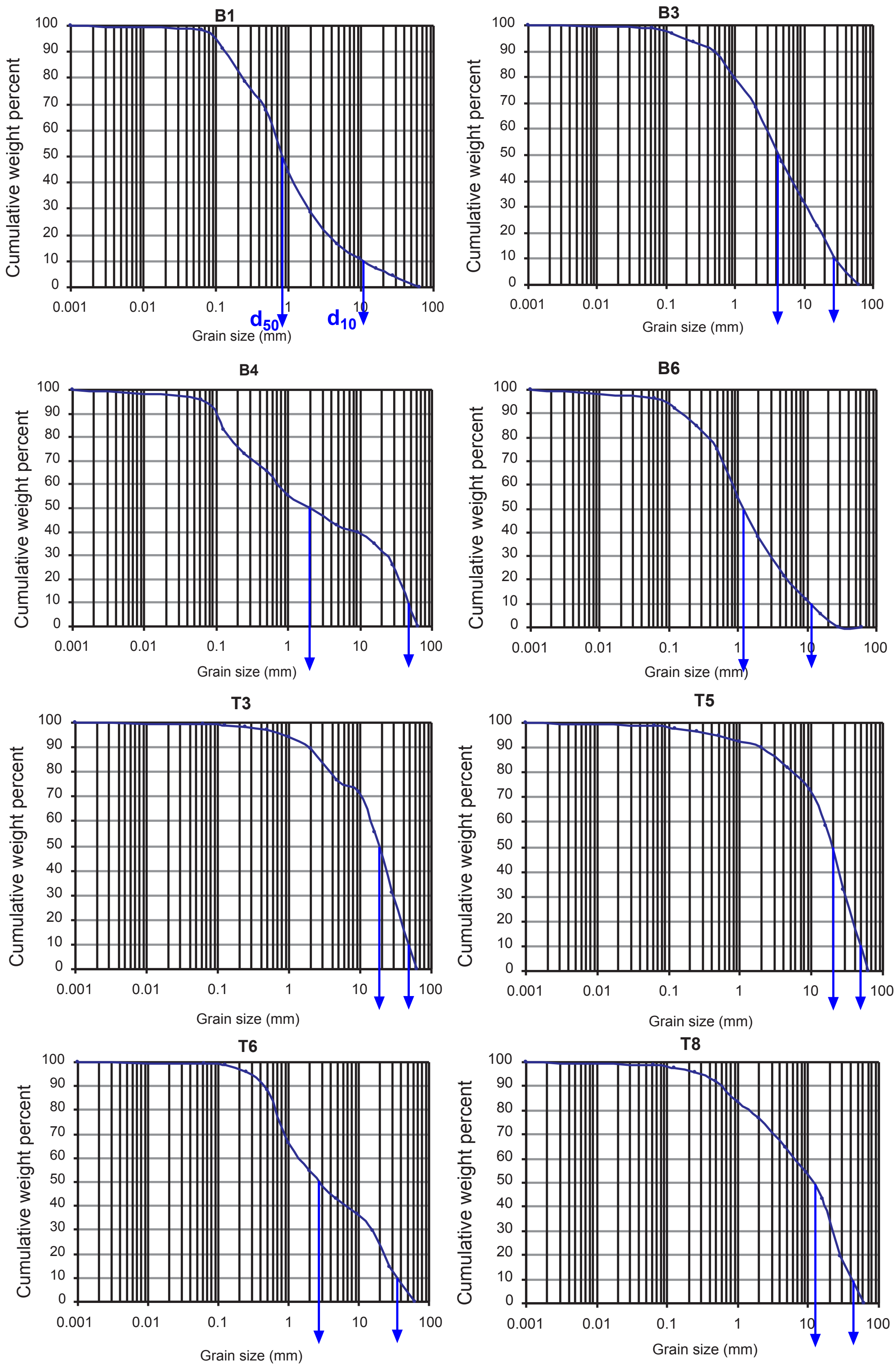



Fig. 21 Grain size distribution of the bar samples from the various segments of the Kodku River showing $d_{50}$ and $d_{10}$.

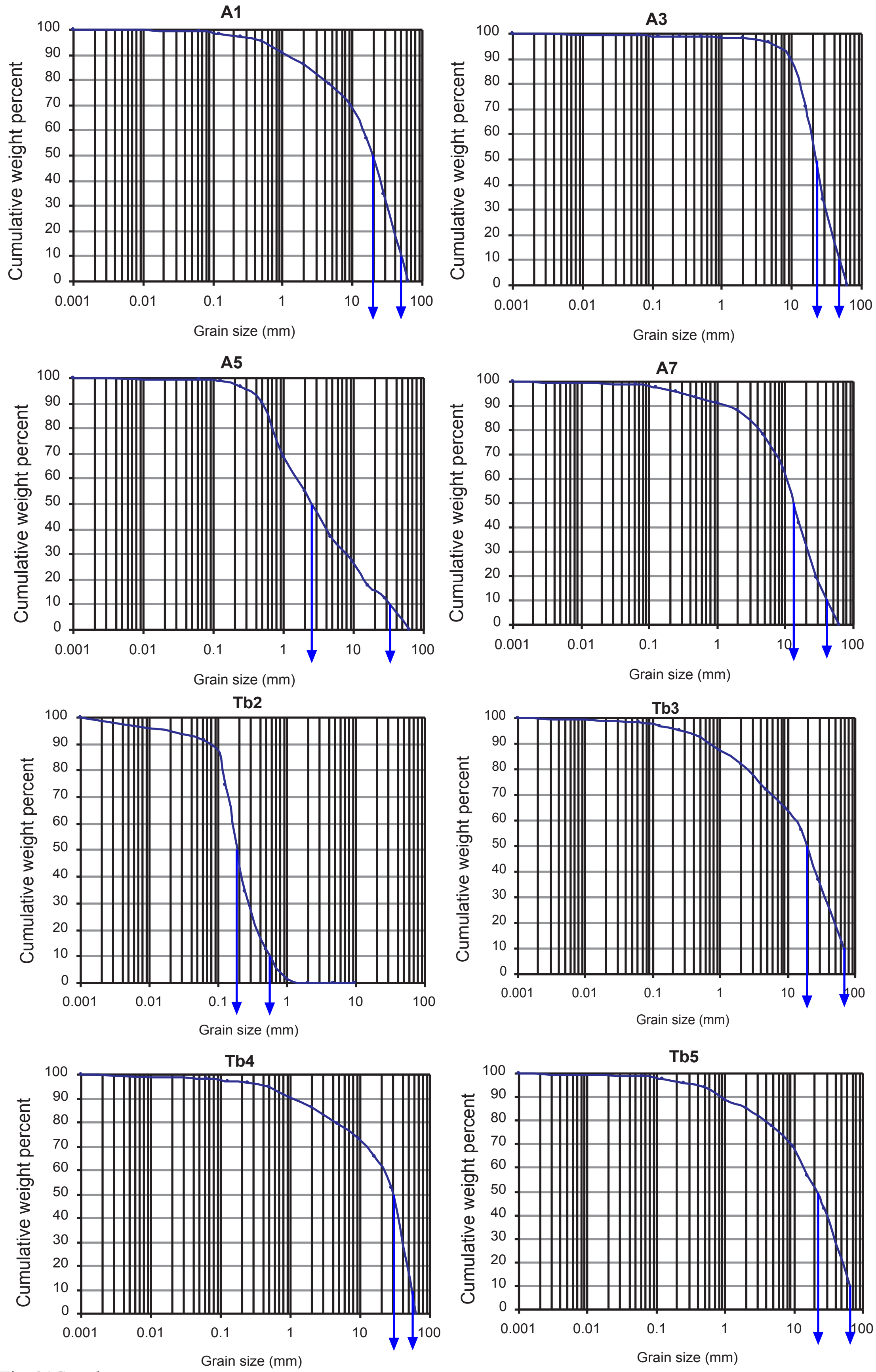

A1
A3
A5
A7
Tb2
Tb3
Tb4
Tb5
Cumulative weight percent
Grain size (mm)
0 10 20 30 40 50 60 70 80 90 100
0.001 0.01 0.1 1 10 100

Fig. 21Contd.

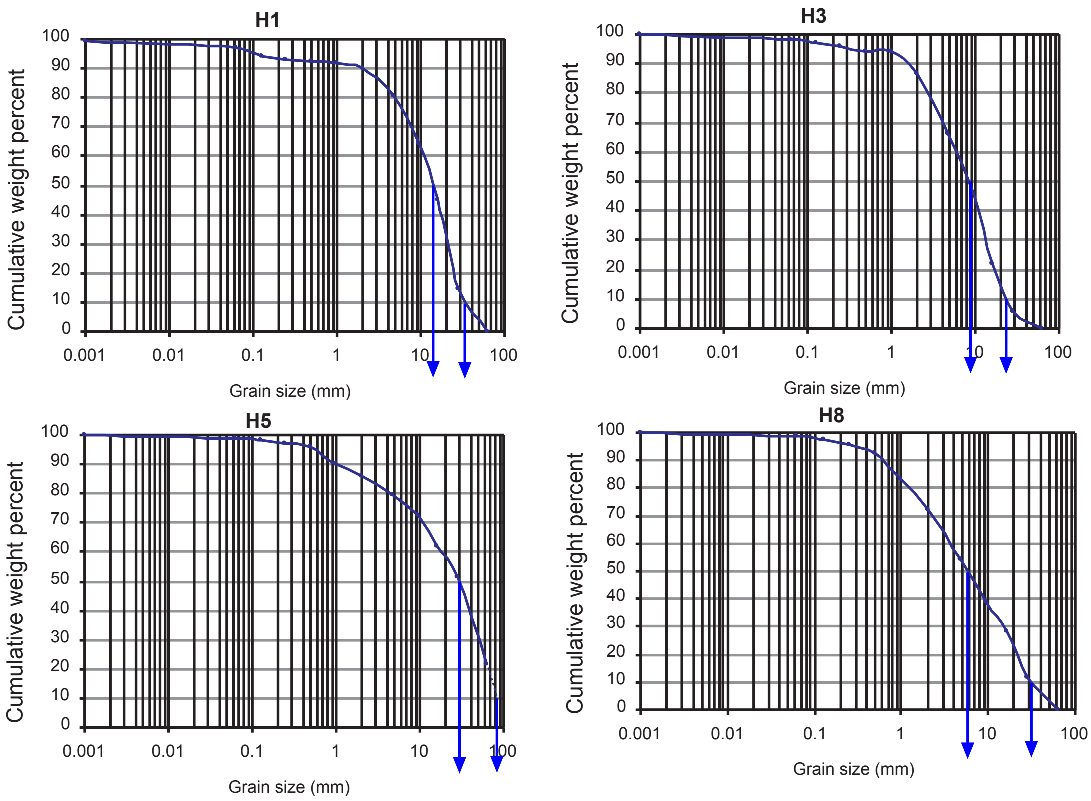



Fig. 21 Contd.

Table 15: Computation of F- and M-factors

| Segments | $W_{bkf}$, m | $D_{bkf}$, m | F-factor = W/D ratio | % Silt and clay: Riffle $S_r$ | % Silt and clay: Bar $S_b$ | *M-factor |
|---|---|---|---|---|---|---|
| Badikhel (B) | 10.3 | 0.8 | 14.3 | 11 | 3 | 9.87 |
| Taukhel (T) | 5.8 | 0.6 | 10.5 | 60 | 1 | 49.86 |
| Arubot (A) | 8.1 | 0.5 | 15.2 | 38 | 1 | 33.92 |
| Thaiba (Tb) | 8.0 | 0.5 | 15.3 | 55 | 3 | 49.24 |
| Harisiddhi (H) | 15.2 | 0.7 | 29.5 | 48 | 2 | 44.09 |

where $L_m$ is a meander length, W is a bankfull width, and $W_{blt}$ is a meander belt width. These relationships were used as references, in order to find out deviation of the existing river channel from stability.

Considering the plot of the meander length versus channel width, the segments show some degree of deviation from the stability curve (Fig. 23). In the plot of meander belt versus channel width except the Badikhel and the Harisiddhi Segments, other segments reveal deviation from the stability. Here, the adjustment between meander belt and the channel width is balanced in these two segments. However, the W/D ratio which varies from 10.5 to 29.5 for all these segments represents unstable channels (based on Rosgen's (2001) criterion).

## Stream Channel Scour/Deposition Potential

The morphology of the river itself reflects the dynamics of river. For instance, a passive river flowing of a gentle slope is sinuous, whereas rivers flowing on steep slope is much active as they can transport huge amount and large sized sediments, and thus produce several mid-channels bars and braiding pattern. There are other measures of dynamism, i.e., stability condition, competence of river, aggrading/degrading potential, etc. The boundary shear stress was obtained

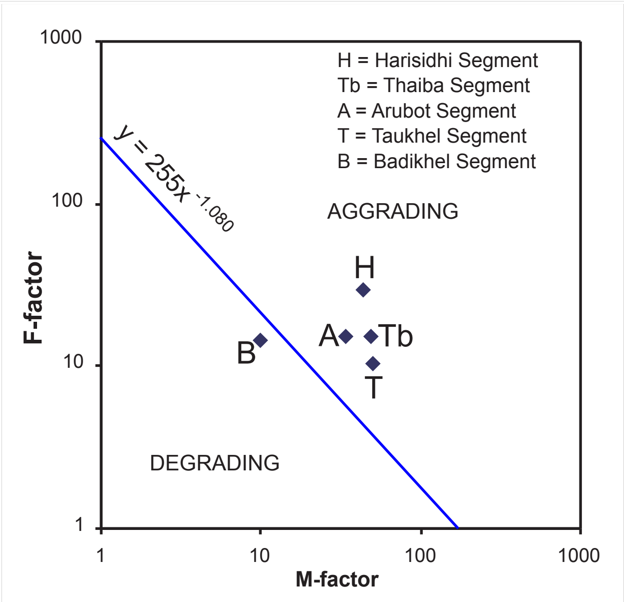



Fig. 22 F-versus M-factor showing aggrading/degrading potential of the segments of the Kodku River. The line shows boundary between aggrading and degrading fields after Schumm (1963).

using the expression of Shields (1936):

$$\tau = \gamma RS \qquad (8)$$

where, $\gamma$ is specific weight of water (9810 N/m3), $\tau$ is boundary shear stress ($N/m^2$), R is hydraulic radius (m), and S is channel slope (m/m). The boundary shear stresses of the Badikhel (31.8 $N/m^3$) and the Taukhel (11.8 $N/m^3$) Segments are very much greater than those of the Arubot (3.9 $N/m^3$), the Thaiba (4.4 $N/m^3$) and the Harisiddhi (1.2 $N/m^3$) Segments.

Shields (1936) showed that the hydraulic conditions required to entrain particles could be explained by the dimensionless shear stress (Shields constant), $\tau_{i*}$ as below:

$$\tau_{i*} = D_S/(S_s-1)d_i \qquad (9)$$

where, $d_i$ is the particle diameter which is coarser than ith % of the riverbed material, $S_s$ is specific gravity of the sediment (2.65), and D is the bankfull depth (m). Bradley and Mears (1980) used Shields constant between 0.45 and 0.06 for computation of bedload transport using Shields criteria. Because the dimensionless shear stress varies with bed material size distribution, for armored beds, Andrews (1983) derived the relationships as below:

$$\tau_{ci}* = 0.0834\ (d_i/d_{s50})^{-0.872} \qquad (10)$$

where, $\tau_{ci}*$ is a threshold dimensionless shear stress required to entrain di of the riverbed material and $d_{s50}$ is a median grain diameter of subsurface bed or bar material. In gravelly stream, the $\tau_{ci*}$ value may range from 0.02 to 0.25, and for the ratio $d_i$ /$d_{s50}$ greater than 4.2, $\tau_{ci*}$ becomes 0.02 but it may be as low as 0.01 for eroding stream (Andrew, 1983). In this instance, the $d_i$ of the equation (9) and (10) was replaced by the $d_{10}$ (Fig. 21) to get $\tau_{ci*}$ for the bed material of coarse percentile, and then parameters were calculated (Table 16). The $\tau_{ci*}$ varies from 0.012 to 0.018. The $\tau_{ci*}$ varies between 0.002 and 0.166 (Table 16). Only in the Badikhel Segment, the dimensionless shear stress

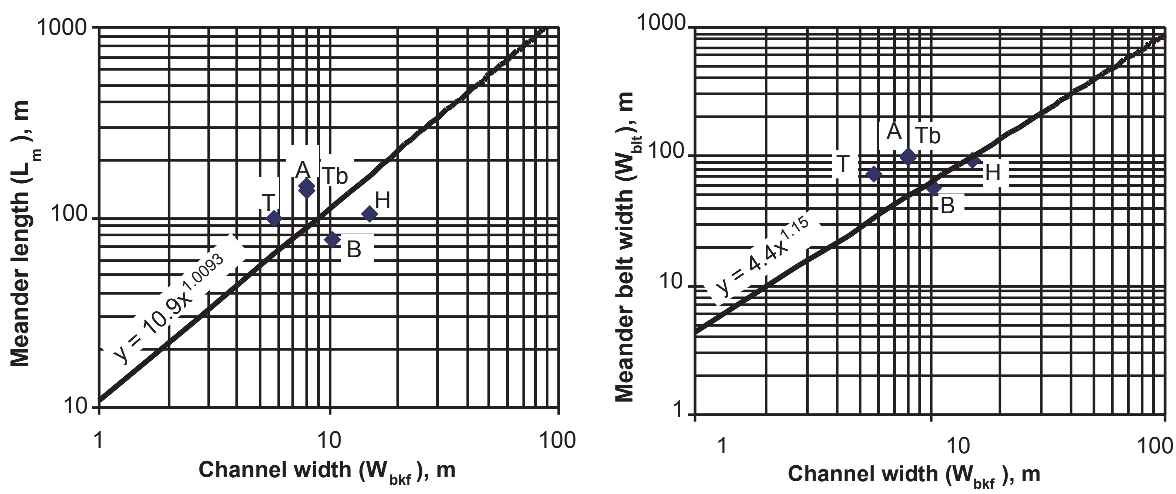



Fig. 23 Meander geometry relationships showing deviation of the Kodku River channels from stability. The curves denote established relationships for stable rivers (after Leopold and Wolman (1960); Williams (1986)).

Table 16: Showing results of competence evaluation

| Segment | R (m) | S (m/m) | $D_{bkf}$ (m) | $d_{s50}$ bar, (m) | $d_{10}=d_i$, riffle (m) | $d_{50}$, riffle(m) | $\tau$ ( $N/m^2$) | $\tau_i$* | $\tau_{ci}$* | $D_c$ (m) | $S_c$ (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Badikhel | 0.6 | 0.0054 | 0.7 | 0.002 | 0.1400 | 0.02000 | 31.78 | 0.016 | 0.002 | 0.09 | 0.001 |
| Taukhel | 0.5 | 0.0024 | 0.5 | 0.013 | 0.04 | 0.00003 | 11.77 | 0.018 | 0.031 | 0.86 | 0.004 |
| Arubot | 0.5 | 0.0008 | 0.5 | 0.0132 | 0.006 | 0.00105 | 3.92 | 0.040 | 0.166 | 2.05 | 0.003 |
| Thaiba | 0.5 | 0.0009 | 0.6 | 0.0176 | 0.008 | 0.00180 | 4.41 | 0.041 | 0.166 | 2.43 | 0.004 |
| Harisiddhi | 0.6 | 0.0002 | 0.8 | 0.0142 | 0.0078 | 0.00310 | 1.18 | 0.012 | 0.141 | 9.05 | 0.002 |

$\tau = \gamma RS$ ($N/m^2$) $\tau_i^* = DS/(S_s-1)d_i$ $D_c = (1.65\tau_{ci}^*\, d_i)/S$ $S_s = 2.65$ $\gamma = 9810\ N/m^3$ $\tau_{ci}^* = 0.0834\ (d_i/d_{s50})^{-0.872}$ $S_c = (1.65\tau_{ci}^*\, d_i)/D$

exceeds the critical dimensionless shear stress by the factor of 8, suggesting that there is a greater potential of scouring or entrainment of particles from the riverbed of the Kodku River as the bankfull flow is capable of mobilizing the riverbed material as large as the 10th percentile fraction flow in that segment. This result is in accordance with the degrading nature of the Badikhel Segment.

The critical depth, $D_c$ and critical slope, $S_c$ required to initiate movement of di are expressed as:

$$D_c = (1.65\tau_{ci}^*\, d_i)/S \qquad (11)$$

$$S_c = (1.65\tau_{ci}^*\, d_i)/D \qquad (12)$$

where, D is the existing depth at bankfull and S is the existing slope.

The existing depth (D) and slope (S) in the Badikhel Segment (third order) exceed the critical depth and slope of the same segment (Table 16) suggesting high scouring potential. In the rest of the segments, as the existing depth and slope are significantly lesser than the calculated critical depth, $D_c$ and slope, $S_c$ (Table 14), the channel bed materials in the Kodku River are less prone to erosion by bankfull flow.

## Manning's Roughness, Discharge and Velocity

The Manning's roughness coefficient base-value was based on median diameter of the streambed sediments (after Aldridge and Garrett, 1973). The n-adjustment parameters were derived from field investigation following the criteria of Aldridge and Garrett (1973) and are listed in Table 17. The Manning's roughness coefficients (n) of segments were calculated using the following equation of Cowan (1956):

$$n = (n_b + n_1 + n_2 + n_3 + n_4)\, m \qquad (13)$$

where, $n_b$ is the base value,

$n_1$ = a correction factor for the effect of surface irregularities on the channel

$n_2$ = a value for fariations in shape and size of the channel cross-section,

$n_3$ = a value for obstructions on the channel,

$n_4$ = a value for vegetation on the channel,

m = a correction factor for sinuosity of the channel.

The n-value is higher for the first and the last segment studied (0.100–0.119), compared to the segments of the intermediate locations (0.058–0.089) along the Kodku River. The higher values are mainly due to channel irregularities, high sinuosity, large riverbed sediment size and notable instream vegetation.

The bankfull discharge and velocity after Manning's equation and continuity equation, respectively, are defined as:

$$Q = (A\, R^{2/3}\, S^{1/2})/n \qquad (14)$$

$$V = Q/A \qquad (15)$$

where, A = bankfull cross-sectional area ($m^2$), R = hydraulic radius (m), n = Manning's roughness coefficient, V = velocity (m/s) and Q = discharge ($m^3/s$). The bankfull discharge ranges from 0.84 to 3.24 $m^3/s$, while the bankfull velocity from 0.08 to 0.53 m/s.

## Stream Power

The flow regime is governed by the size of the bed materials and the stream power that is a measure of energy transfer. Stream power per unit bed area was calculated using the expression of Brookes (1990):

$$\Omega = \gamma Q S_w \qquad (16)$$

Table 17: Manning's n value assigned for the various segments of the Kodku River

| | | Manning's roughness assignment | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Segment | Stream type | Basic value, nb | Degree of irregularity, n1 | Variation in channel cross-section, n2 | Effect of obstruction, n3 | Amount of vegetation, n4 | Degree of meandering, m | *Manning's n = (nb+n1+n2+ n3+n4) m | Average n |
| Badikhel | B4c | Cobble | | | | | **K = 1.2 | | 0.100 |
| BT1 | | 0.033 | 0.008 | 0.003 | 0.010 | 0.002 | 1.00 | 0.056 | |
| BT3 | | 0.033 | 0.101 | 0.001 | 0.010 | 0.002 | 1.00 | 0.147 | |
| BT4 | | 0.033 | 0.006 | 0.005 | 0.003 | 0.050 | 1.00 | 0.097 | |
| BT6 | | 0.033 | 0.008 | 0.005 | 0.003 | 0.050 | 1.00 | 0.099 | |
| Taukhel | C6c | Silty | | | | | K = 1.3 | | 0.058 |
| TT3 | | 0.024 | 0.005 | 0.001 | 0.004 | 0.010 | 1.15 | 0.051 | |
| TT5 | | 0.024 | 0.005 | 0.001 | 0.004 | 0.010 | 1.15 | 0.051 | |
| TT7 | | 0.024 | 0.007 | 0.001 | 0.004 | 0.020 | 1.15 | 0.064 | |
| TT8 | | 0.024 | 0.005 | 0.003 | 0.005 | 0.020 | 1.15 | 0.066 | |
| Arubot | C4c | Coarse sand | | | | | K = 1.7 | | 0.089 |
| AT1 | | 0.026 | 0.009 | 0.004 | 0.010 | 0.010 | 1.30 | 0.077 | |
| AT3 | | 0.026 | 0.010 | 0.005 | 0.010 | 0.010 | 1.30 | 0.079 | |
| AT5 | | 0.026 | 0.015 | 0.005 | 0.025 | 0.010 | 1.30 | 0.105 | |
| AT7 | | 0.026 | 0.008 | 0.004 | 0.025 | 0.010 | 1.30 | 0.095 | |
| Thaiba | C4c | Coarse sand | | | | | K = 1.2 | | 0.067 |
| TbT2 | | 0.028 | 0.006 | 0.005 | 0.015 | 0.010 | 1.15 | 0.074 | |
| TbT3 | | 0.028 | 0.010 | 0.003 | 0.005 | 0.010 | 1.15 | 0.064 | |
| TbT4 | | 0.028 | 0.008 | 0.001 | 0.005 | 0.015 | 1.15 | 0.066 | |
| TbT5 | | 0.028 | 0.001 | 0.001 | 0.010 | 0.015 | 1.15 | 0.063 | |
| Harisiddhi | C4c | Pebble | | | | | K = 1.2 | | 0.119 |
| HT1 | | 0.030 | 0.015 | 0.012 | 0.005 | 0.016 | 1.15 | 0.090 | |
| HT3 | | 0.030 | 0.160 | 0.015 | 0.005 | 0.010 | 1.15 | 0.253 | |
| HT5 | | 0.030 | 0.015 | 0.005 | 0.010 | 0.002 | 1.15 | 0.071 | |
| HT8 | | 0.030 | 0.015 | 0.004 | 0.004 | 0.002 | 1.15 | 0.063 | |

* n value relation after Cowan (1956) **K = sinuosity

Where,

Ω = Specific stream power (N/s),

γ = Specific weight of water (9810 N/m$^3$), and

$S_w$= Water surface slope (m/m).

The unit or total stream power (w) which is a stream power per unit bed area, is obtained as:

$$\omega = \gamma Q S_w / W \qquad (17)$$

Where,

ω = Stream power per unit bed area (N-m/s/m$^2$) and

W = Bankfull width of channel (m).

The results of unit stream power are from the upstream to the downstream segments are respectively 16.64 N-m/s/m$^2$ (Badikhel), 7.11 N-m/s/m$^2$ (Taukhel), 0.85 N-m/s/m$^2$ (Arubot), 1.30 N-m/s/m$^2$ (Thaiba) and 0.11 N-m/s/m2 (Harisiddhi) as given in Table 18. The unit stream power is the highest (16.64 N-m/s/m$^2$) in the Badikhel Segment, and is the lowest in the Harisiddhi Segment (0.11 N-m/s/m$^2$). The flow capacity of the Badikhel Segment is contrastingly higher compared to the other segments and bears potential towards streambed scouring. In other downstream segments where wide flood plains exist, the stream power is low showing low bed scouring potential. The unit stream power seems to be highly influenced by the slope of the channel.

## Channel Evolution Scenario

Channel Evolution Models (CEM) were developed by Schumm et al (1984). Simon (1989) later developed similar model to predict evolution scenario of the channels. Based on Simon's (1989) CEM, the segments of the Kodku River will have the tendency of change from the current channel types to the following types:

(a) Badikhel Segment: channel type B4c (CEM type III; degrading) evolving into G4c

Table 18: Results of discharge, velocity and stream power of the segments of the Kodku River

| Segment | $W_{bkf}$, (m) | $A_{bkf}(m^2)$ | R (m) | $S_w$ (m/m) | n | *Q ($m^3$/s) | **V (m/s) | ***Ω (N/s) | ****ω (N–m/s/$m^2$) |
|---|---|---|---|---|---|---|---|---|---|
| Badikhel | 10.3 | 6.2 | 0.6 | 0.0054 | 0.100 | 3.24 | 0.52 | 171.40 | 16.64 |
| Taukhel | 5.8 | 3.3 | 0.5 | 0.0024 | 0.058 | 1.75 | 0.53 | 41.25 | 7.11 |
| Arubot | 8.1 | 4.4 | 0.5 | 0.0008 | 0.089 | 0.88 | 0.20 | 6.90 | 0.85 |
| Thaiba | 8.0 | 4.2 | 0.5 | 0.0009 | 0.067 | 1.18 | 0.28 | 10.44 | 1.30 |
| Harisiddhi | 15.2 | 10 | 0.6 | 0.0002 | 0.119 | 0.84 | 0.08 | 1.66 | 0.11 |

*Bankfull discharge, $Q = (A R^{2/3} S^{1/2})/n$ ($m^3$/s) **$V = Q/A$ (m/s) ***$\Omega = \gamma Q S_w$ (N/s), $\gamma$ = specific weight = 9810 (N/$m^3$) and $S_w$ = water surface slope (m/m)
****$\omega = \gamma Q S_w / W_{bkf}$ (N-m/s/$m^2$), $W_{bkf}$ = Bankfull width (m)

(b) Taukhel Segment: channel type C6c (CEM type V; aggrading), evolving into E6c or F6c

(c) Arubot, Thaiba and Harisiddhi Segments: channel type C4c (CEM type V; aggrading and widening), evolving into F6c

## FLOODPRONE AREA DELINEATING AND BANK EROSION HAZARD MAPPING

### Floodprone Width along the Kodku River Corridor

Floodprone width ($W_{fpa}$) was measured with the help of an Ushikata Theodolite, a measuring tape and a staff. Initially, the $D_{max}$ was measured and the level at twice this depth was taken at the level for floodprone area delineation at the both right and the left banks. The distance was measured from the thalwage to the left/right bank where the twice of the $D_{max}$ at bankfull height intersects the river floodplain. The distances obtained from left and right bank was plotted in the 1:10,000 topo map. This process was applied in overall river corridor to prepare a floodprone map.

The $W_{fpa}$ is variable along this river (36–600 m), and it depends on the landforms from where it flows and also on the bankfull depth. It was very narrow (36–56 m) and close to the channel in the third order stream such as from Badikhel to upper reach of the Taukhel area. In these areas, the river flows with high gradient. $W_{fpa}$ increases form Taukhel to the upper reach of Jharuwarasi (93–230 m) but decreases in Jharuwarasi (56 m), where the gorge exist. At this location, the width was closed to the channel. Downstream from the gorge, $W_{fpa}$ increases and becomes very high between Harisidhi and downstream reach (Table 19 and Fig 24).

Table 19: Floodprone width of the Kodku River channel at various sample sites

| Sample Station | Segment | Bankfull depth, $D_{bkf}$ (m) | Floodprone width (m) |
|---|---|---|---|
| BE1 | | 0.9 | 44 |
| BE2 | | 0.9 | 55 |
| BE3 | BT1 | 0.8 | 50 |
| BE4 | BT3 | 1.0 | 56 |
| BE5 | BT4 | 0.6 | 44 |
| BE6 | BT6 | 0.7 | 43 |
| BE7 | | 0.7 | 36 |
| BE8 | | 0.8 | 42 |
| BE9 | TT3 | 0.8 | 93 |
| BE10 | TT5 | 0.5 | 123 |
| BE11 | TT7 | 0.6 | 135 |
| BE12 | TT8 | 0.7 | 130 |
| BE13 | AT1 | 0.5 | 124 |
| BE14 | AT3 | 0.6 | 126 |
| BE15 | AT5 | 0.5 | 178 |
| BE16 | AT7 | 0.4 | 230 |
| BE17 | | 0.5 | 125 |
| BE18 | | 0.5 | 56 |
| BE19 | TbT2 | 0.6 | 199 |
| BE20 | TbT3 | 0.5 | 276 |
| BE21 | TbT4 | 0.6 | 242 |
| BE22 | TbT5 | 0.5 | 268 |
| BE23 | | 0.6 | 275 |
| BE24 | | 0.6 | 162 |
| BE25 | | 0.6 | 220 |
| BE26 | | 0.6 | 188 |
| BE27 | HT1 | 0.3 | 187 |
| BE28 | HT3 | 0.5 | 209 |
| BE29 | HT5 | 1.0 | 240 |
| BE30 | HT8 | 0.9 | 86 |
| BE31 | | 0.9 | 73 |
| BE32 | | 0.8 | 269 |
| BE33 | | 0.9 | 262 |
| BE34 | | 1.0 | 204 |
| BE35 | | 1.1 | 432 |
| BE36 | | 1.2 | 600 |
| BE37 | | 1.0 | 341 |
| BE38 | | 1.3 | 322 |
| BE39 | | 1.2 | 476 |

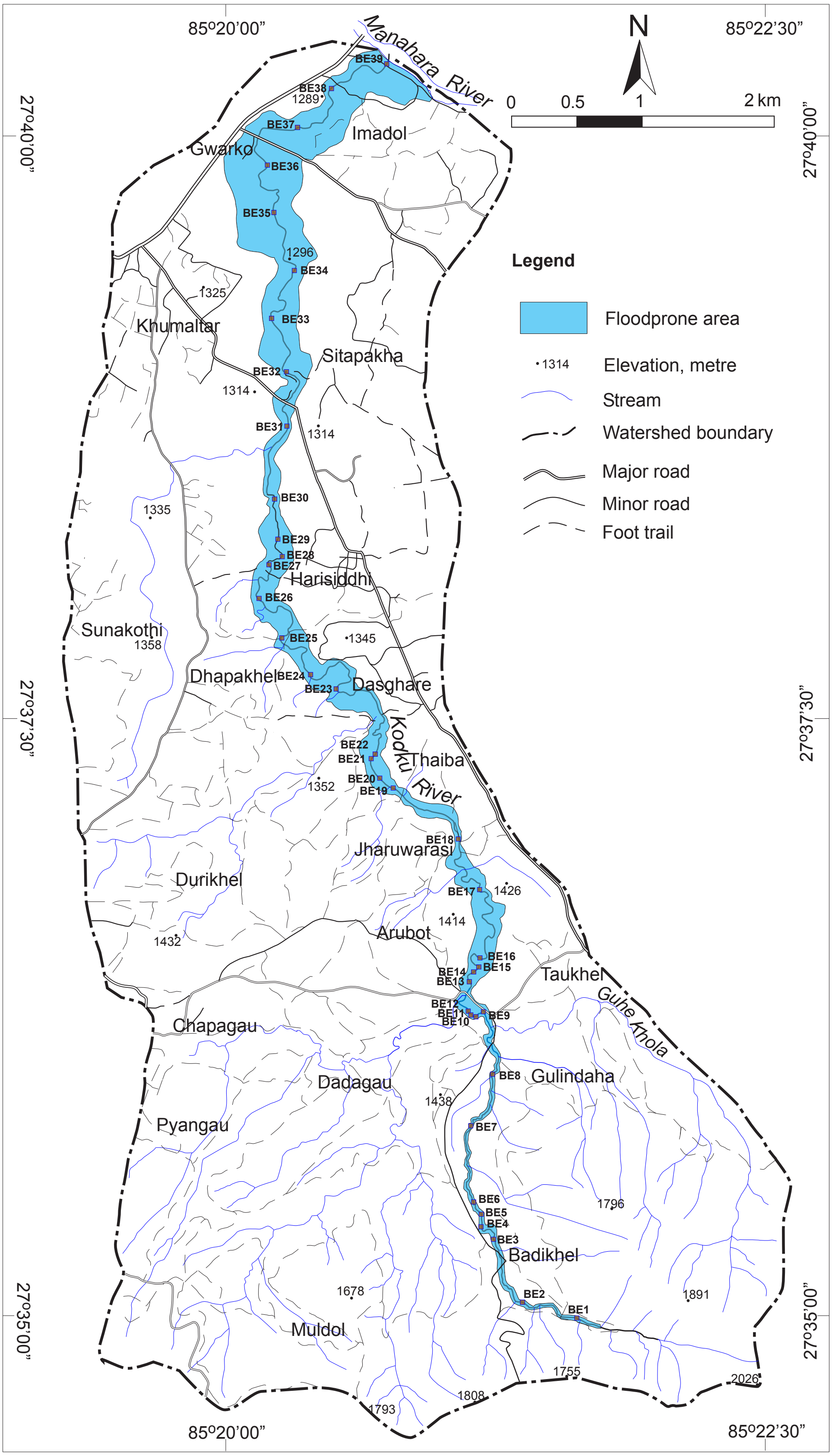



Fig. 24: Floodprone map of the Kodku River.

Depending on the width of the floodprone area, it can be suggested that the upsream third and the fourth order reaches of the river (Badikhel to Taukhel) are less affected by flood whereas the downstream reach such as Arubot, Thaiba and Harisidhi areas are highly affected as compared with the upper reaches. Huge agricultural land loss is to be faced during flooding time. But in the case of downstream of the Harisidhi Segment such as Sitapakh, Gwarko and Imadol, the width of the floodprone area is very high and covers most of newly constructed houses, apartments, roads and schools. Therefore, these areas are highly prone to flooding and can affect very huge areas and structures.

## Bank Erosion Hazard Mapping

Mapping was done using criteria of the BEHI of individual location and taking the floodprone width to limit the access of the flood water to the channel floodprone width. The bank erosion hazard index was calculated on 39 different locations along the river and then the hazard level was categorized as low (10–19.5), medium (20–29.5), high (30–39.5) and very high (40–45) condition after Rosgen (2001) (Table ). Based on these categories, bank erosion hazard mapping was prepare along the river corridor within the floodprone width (Fig. 25 and Table 20).

The upper reach of the third order river falls on low hazard category. This segment is covered by dense vegetation. The bank material contains bedrock or huge boulders which help to reduce BEHI value. The area between Badikhel to upper reach of the Taukhel Segment shows mix category from low to medium with high hazard at one of Badikhel location. High to medium hazard is dominant between Taukhel to Jharuwarasi but low to very high hazard zones are found in the Thaiba Segment. Mixed categories of medium and high hazard are observed between the Thaiba and the Harisidhi Segments, though Harisiddhi Segment itself lies in very high hazard zone. The downstream areas such as Sitapakha, Gwarko and Imadol show high hazard with wide floodprone widths.

Considering the Kodku River corridor as a whole, the fifth order river is at high hazard for bank erosion and flooding. The BEHI value and floodprone width are very high as compared with the upper third and forth order streams. Considering only the fifth order segments, some parts of the Thaiba and the overall Harisidhi Segment show very high hazard condition. These areas have very low surface protection and root density due to absence of vegetation along the river bank. The bank and channel materials contain cohesionless sand and silty clay which can easily be eroded during low velocity flow period also. Human activities such as encroachment of river bank, clearing of vegetation from the banks, and modification of channel are also severe in the downstream segments. Such activities directly or indirectly influence in the stability condition of the river.

The hazard level will increase, if no mitigation measure is applied. In recent time, the upstream reach shows low hazard level but it will be increased in future. The downstream reach already is in high hazard condition, therefore requiring the mitigation. The bank erosion is very high in meander loops as compared with the cross overs. Bank instability is created due to the scouring of the toe of the banks. Hence, mitigative measures can be applied using bio-engineering methods. Plantation is will be useful to recover a riparian zone. Human activities such as modification of channel and encroachment should be limited.

## CONCLUSIONS

(1) The Kodku River is a southern tributary of the Manahara River, located at southern part of the Kathmandu Valley. It extends for about 15.86 km with 35.67 sq. km area. The high relative relief and fine drainage texture is localized to southern mountainous area with bedrock and steep slopes, whereas low relative relief and coarse drainage texture is located towards the mid to northern part of watershed where gentle sloped terrace landforms have developed.

(2) All the stream segments are sinuous (K = 1.2) whereas the Arubot Segment is the highly meandering (1.7). Both meander wavelength ($L_m$) and belt width ($W_{blt}$) increase with increasing stream order. But the fifth segment shows the diminishing trend probably due to anthropogenic alteration of the river.

(3) Five types of valleys as I, II, IV, VI and VIII are identified in the watershed area. The individual stream

Table 20: Level III Stream channel stability evaluation

| | | Bank Angle | | Bank Height Ratio (BHR) | | | | Root Depth Ratio (RDR) | | | Root Density | | Surface Protection | | Adjust-ment | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample Station | Seg-ment | Value (deg.) | Score | BH (m) | BKFH (m) | *BHR | Score | RD (m) | **RDR | Score | Value (%) | Score | Value (%) | Score | | | BEHI |
| BE1 | | 30 | 3 | 5 | 1 | 5.00 | 10 | 0.7 | 0.14 | 8 | 95 | 1 | 95 | 1 | -10 | 13 | L |
| BE2 | | 85 | 7 | 2 | 1.3 | 1.54 | 6 | 1 | 0.50 | 4 | 80 | 2 | 50 | 4 | -10 | 13 | L |
| BE3 | BT1 | 110 | 9 | 1.6 | 1.2 | 1.33 | 6 | 0.5 | 0.31 | 6 | 20 | 8 | 50 | 4 | -10 | 21 | M |
| BE4 | BT3 | 120 | 10 | 2.1 | 1.5 | 1.40 | 6 | 0.7 | 0.33 | 6 | 22 | 7 | 20 | 8 | -10 | 17 | M |
| BE5 | BT4 | 90 | 8 | 1.7 | 1.4 | 1.21 | 6 | 0.5 | 0.29 | 6 | 70 | 3 | 75 | 3 | 5 | 31 | H |
| BE6 | BT6 | 85 | 7 | 2.5 | 1.5 | 1.67 | 6 | 0.4 | 0.16 | 7 | 70 | 3 | 40 | 5 | -10 | 18 | L |
| BE7 | | 75 | 6 | 3.0 | 1.0 | 3.00 | 10 | 0.8 | 0.27 | 6 | 85 | 2 | 60 | 4 | -10 | 18 | L |
| BE8 | | 80 | 6 | 2.7 | 1.4 | 1.929 | 7 | 0.5 | 0.19 | 7 | 45 | 4 | 60 | 4 | -5 | 23 | M |
| BE9 | TT3 | 95 | 8 | 1.7 | 1.7 | 1.00 | 1 | 1.5 | 0.88 | 2 | 50 | 4 | 80 | 2 | 5 | 21 | M |
| BE10 | TT5 | 70 | 5 | 3.2 | 1.2 | 2.67 | 9 | 1 | 0.31 | 6 | 40 | 5 | 70 | 3 | 5 | 33 | H |
| BE11 | TT7 | 85 | 7 | 1.1 | 1.1 | 1.00 | 1 | 0.6 | 0.55 | 4 | 20 | 7 | 25 | 7 | 5 | 31 | H |
| BE12 | TT8 | 110 | 9 | 1.5 | 1.2 | 1.25 | 4 | 0.7 | 0.47 | 4 | 15 | 8 | 25 | 7 | 5 | 37 | H |
| BE13 | AT1 | 110 | 9 | 0.9 | 0.9 | 1.00 | 1 | 0.5 | 0.56 | 4 | 30 | 6 | 70 | 3 | 0 | 23 | M |
| BE14 | AT3 | 85 | 7 | 1.2 | 1.0 | 1.20 | 4 | 0.9 | 0.75 | 3 | 30 | 6 | 55 | 4 | 0 | 24 | M |
| BE15 | AT5 | 110 | 9 | 1.2 | 1.2 | 1.00 | 1 | 0.6 | 0.50 | 4 | 20 | 8 | 10 | 9 | 5 | 36 | H |
| BE16 | AT7 | 83 | 7 | 1.4 | 1.3 | 1.08 | 2 | 1.1 | 0.79 | 2 | 25 | 7 | 60 | 4 | 2 | 24 | M |
| BE17 | | 105 | 9 | 1.5 | 1 | 1.5 | 6 | 0.25 | 0.17 | 7 | 60 | 4 | 50 | 4 | 0 | 30 | H |
| BE18 | | 78 | 7 | 12.0 | 1.5 | 8.00 | 10 | 0.3 | 0.03 | 10 | 45 | 5 | 60 | 4 | 0 | 36 | H |
| BE19 | TbT2 | 75 | 6 | 1.3 | 1.3 | 1.00 | 1 | 1.1 | 0.85 | 2 | 40 | 5 | 75 | 3 | -5 | 12 | L |
| BE20 | TbT3 | 110 | 9 | 1.0 | 0.8 | 1.25 | 4 | 0.4 | 0.40 | 5 | 20 | 8 | 10 | 9 | 10 | 45 | VH |
| BE21 | TbT4 | 105 | 8 | 1.2 | 1.2 | 1.00 | 1 | 0.5 | 0.42 | 5 | 20 | 8 | 10 | 9 | -2 | 30 | H |
| BE22 | TbT5 | 105 | 8 | 1.0 | 1.0 | 1.00 | 1 | 0.3 | 0.30 | 6 | 60 | 4 | 75 | 3 | -2 | 20 | M |
| BE23 | | 105 | 8 | 2.1 | 1.5 | 1.40 | 4 | 0.72 | 0.34 | 6 | 35 | 5 | 40 | 5 | 5 | 33 | H |
| BE24 | | 100 | 8 | 2.3 | 1.6 | 1.438 | 4 | 0.75 | 0.33 | 6 | 50 | 4 | 55 | 4 | -5 | 21 | M |
| BE25 | | 95 | 8 | 2.5 | 1.3 | 1.923 | 8 | 0.5 | 0.20 | 7 | 65 | 3 | 45 | 4 | 5 | 35 | H |
| BE26 | | 85 | 7 | 2 | 1.3 | 1.538 | 6 | 0.7 | 0.35 | 6 | 68 | 3 | 90 | 2 | 0 | 24 | M |
| BE27 | HT1 | 105 | 8 | 1.3 | 1.3 | 1.00 | 1 | 0.5 | 0.38 | 5 | 20 | 8 | 10 | 9 | 5 | 36 | H |
| BE28 | HT3 | 87 | 8 | 1.5 | 1.3 | 1.15 | 2 | 0.2 | 0.13 | 8 | 10 | 9 | 10 | 9 | 5 | 41 | VH |
| BE29 | HT5 | 95 | 8 | 2.0 | 1.3 | 1.54 | 6 | 0.2 | 0.10 | 8 | 10 | 9 | 20 | 8 | 5 | 44 | VH |
| BE30 | HT8 | 105 | 9 | 1.0 | 1.0 | 1.00 | 1 | 0.1 | 0.10 | 8 | 10 | 9 | 5 | 10 | 5 | 42 | VH |
| BE31 | | 85 | 7 | 2.3 | 1.7 | 1.353 | 4 | 0.4 | 0.17 | 7 | 80 | 2 | 85 | 5 | 5 | 30 | H |
| BE32 | | 85 | 7 | 3.6 | 1.9 | 1.895 | 7 | 0.5 | 0.14 | 8 | 75 | 2 | 80 | 5 | 5 | 34 | H |
| BE33 | | 95 | 8 | 1.8 | 1.4 | 1.286 | 4 | 0.57 | 0.32 | 6 | 25 | 6 | 8 | 9 | 5 | 38 | H |
| BE34 | | 65 | 5 | 2.3 | 1.3 | 1.769 | 6 | 0.35 | 0.15 | 8 | 78 | 2 | 86 | 2 | 5 | 28 | M |
| BE35 | | 88 | 7 | 4 | 1.5 | 2.667 | 9 | 0.55 | 0.14 | 8 | 65 | 3 | 70 | 3 | 5 | 35 | H |
| BE36 | | 90 | 8 | 4.5 | 1.8 | 2.5 | 9 | 0.4 | 0.09 | 8 | 40 | 5 | 55 | 4 | 5 | 39 | H |
| BE37 | | 90 | 8 | 2.5 | 1.3 | 1.923 | 8 | 0.3 | 0.12 | 8 | 40 | 5 | 55 | 4 | 5 | 38 | H |
| BE38 | | 80 | 6 | 4.5 | 2 | 2.25 | 8 | 0.4 | 0.09 | 8 | 45 | 5 | 55 | 4 | 5 | 36 | H |
| BE39 | | 90 | 8 | 3 | 1.2 | 2.50 | 9 | 0.4 | 0.13 | 8 | 40 | 5 | 60 | 4 | 0 | 34 | H |

*BHR = Bank height ratio = Bank height (BH)/Bankfull height (BKFH)    **RDR = Root depth (RD)/Bank height (BH)

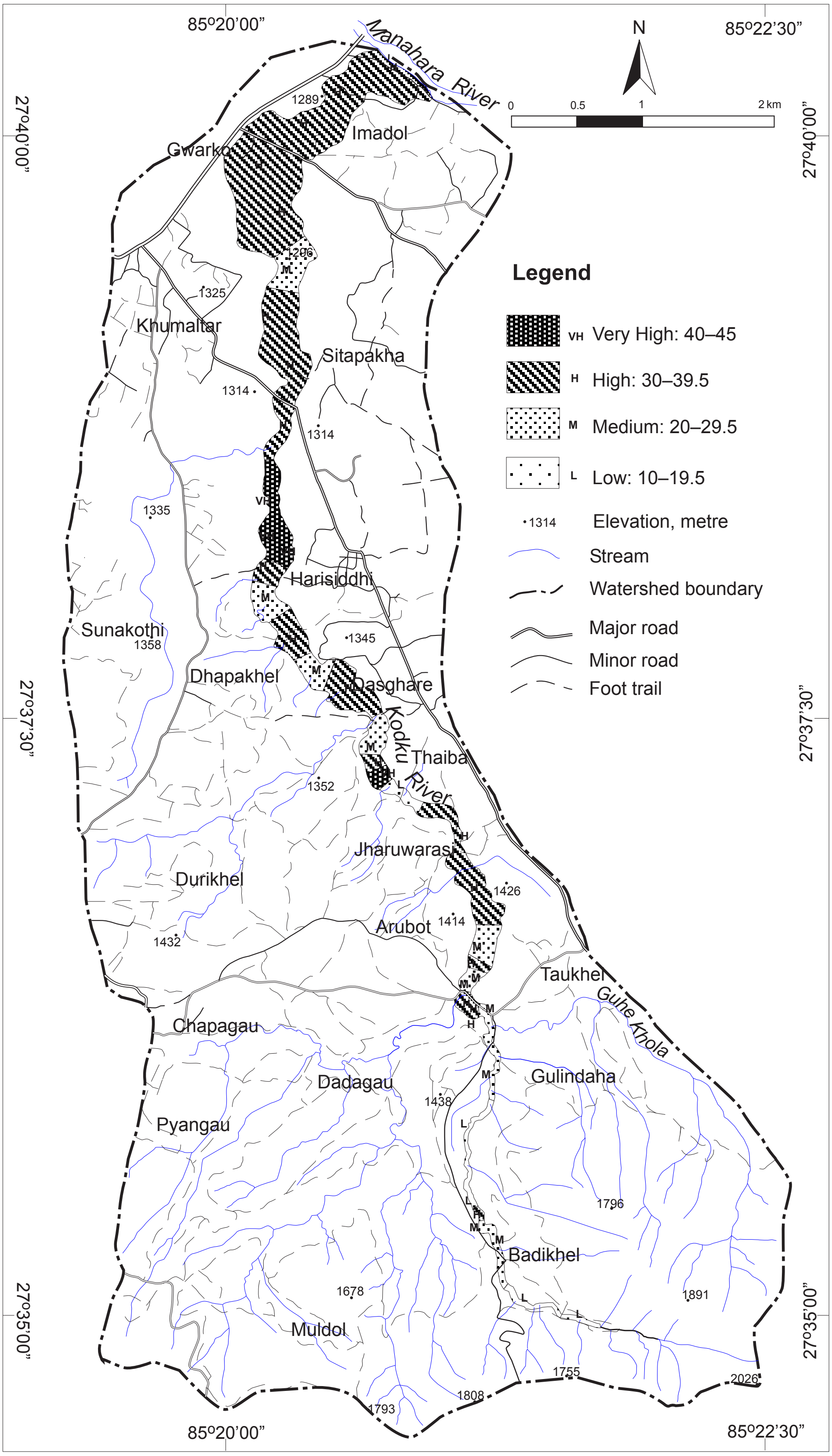



Fig. 25: Bank erosion hazard map of the Kodku River.

segments of the river are classified (Level I broad classification) as 'B', 'C' and 'Aa+' type streams. The 'B' type streams are all located in the third order segment. Expect the Aa+' type stream at the gorge near Jharuwarasi, all four and fifth order stream segments belongs to 'C' type stream.

(4) The median sizes of sediments of the Badikhel Segment are coarse pebble, where as those for Taukhel Segment are silt/clay mixture. Sizes of the Arubot and the Thaiba Segments belong to very coarse sand and the Harisidhi segment possesses very fine pebbles. Thus, the Kodku River is a gravelly mixed-load meandering river. Level II classification distinguishes the Badikhel Segment as a 'B4c' type stream, the Taukhel Segment as a 'C6c' type, and the fifth order segments such as the Arubot, Thaiba and Harisidhi Segments as 'C4c' type streams. The 'B4c' type stream is entrenched and somewhat laterally confined by steep valley slopes and terrace landforms. It has tendency of vertical and lateral accretion. The 'C6c' type stream is a meandering stream with shallow channel and wide valley. The 'C4c' type streams have shallow and wide meandering channels with well developed flood plains and lateral bars and have tendency of lateral instabilities.

(5) The Bank Erosion Hazard Index (BEHI) is low to high in the Badikhel and the Thaiba Segments, moderate to high in the Taukhel and the Arubot Segments, and high to very high in the Harisidhi Segment. BEHI decreases in steep slope with dense vegetation and where huge boulders as bank and channel material exist. Near Bank Stress (NBS) derived from the Method 5 is moderate to high in the Badikhel Segment, high to very high in the Taukhel Segment, moderate to extreme in the Arubot Segment, high to extreme in the Thaiba Segment and low to extreme in the Harisidhi Segment. These extreme near bank stresses impliy that there is a great potential of bank erosion in almost all the segments of the Kodku River as the near bank shear stresses there are more than 1.6 times the boundary shear stress.

(6) Pfankuch stream stability is fair in the Badikhel and the Harisidhi Segments, whereas it is good to fair in the Taukhel, the Arubot and the Thaiba Segments. The overall segments of the river are vertically unstable as the bank height ratio (BHR) varies between 1.6 (Badikhel Segment) and 2.4 (Harisiddhi Segment), and exceeds 1.5. The entrenchment ratio ranges from 1.7 to 7.1 and the Badikhel Segment is relatively more entrenched (1.7) while the Taukhel Segment is the least entrenched (7.1) among them. Since ER exceeds 1.6, the stream segments of the Kodku River are considered to have moderate to low entrenchment.

(7) Width/Depth ratio varying between 10.5 and 29.5 indicates laterally unstable channel segments. Meander width ratio (MWR) is moderate in Badikhel and Harisidhi segments and high in remaining segmnets indicating greater potential for lateral instabilities.

(8) Schumn's F versus M facror plot indicates that dynamic equilibrium of the Badikhel Segment is in degrading condition while the rest of the other segments are in the aggrading condition. The existing depth and slope in the Badikhel Segment exceeds the calculated critical depth and slope suggesting high scouring potential. In the remaining segments, the existing depth and slope are lesser than the critical depth, thus the channel bed material in the Kodku River is less prone to erosion by bankfull flow. The unit stream power is the highest (16.64 N-m/s/$m^2$) in the Badikhel Segment, and is the lowest in the Harisiddhi Segment (0.11 N-m/s/$m^2$). The flow capacity of the Badikhel Segment is contrastingly higher compared to the other segments and bears potential towards streambed scouring.

(9) The floodprone width is very narrow in the upper third order stream whereas very wide in the downstream stretches such as at Gwarko and Imadol. Wide floodprone widths in downstream stretches indicate high potential of inundation and damage of settlements during flooding. The bank erosion hazard map within the floodprone area indicates that the upper third order stretch and some areas of the downstream stretches from the gorge near Jharuwarasi lie in low hazard zone, but the overall areas of the Harisidhi Segment, Gwarko, Imadol and some of other areas lie in high to very high hazard zone.

(10) The major causes for very high streambank erosion potential and lateral instabilities in the river are thought to be devegetation, modification of channels and other anthropogenic activities besides the nature of the bank materials. Bank erosion and lateral instabilities can be mitigated by implementing bio-engineering measures, especially armoring and retaining structures

and plantation of deep root vegetation, and also by reducing anthropogenic activities.

## ACKNOWLEDGEMENTS

Authors are thankful to University Grant Commission (UGC) for providing a partial support to carry out work. Authors also thank Central Department of Geology for providing necessary facilities.

## REFERENCES

Adhikari, B. R., and Tamrakar, N. K., 2005. Bank instability and erosion problems in Bishnumati River, Kathmandu, Nepal, Jour. of Nepal Geol. Soc., v. 23, pp. 37.

Aldridge, B.N. and Garrett, J.M., 1973. Roughness coefficients for stream channels in Arizona, U.S. Geol. Survey Open-File Report, U. S. Geological Survey.

Andrews, E.D., 1983. Entrainment of gravel from naturally sorted riverbed material. Geol. Soc. America Bull. V. 94, pp. 1225–1231. http://dx.doi.org/10.1130/001-7606(1983)94<1225:EOGFNS>2.0.CO;2

Andrews, E.D., 1984. Bed material entrainment and hydraulic geometry of gravel-bed rivers in Colorado. Geol. Soc. America Bull., v. 97, pp. 11012–1023. http://dx.doi.org/10.1130/0016-7606(1986)97<1012:DEOFGR>2.0.CO;2

Andrews, E.D. and Nankervis, J. M. (1995). “Effective Discharge and the Design of Channel Maintenance Flows for Gravel-Bed Rivers,” Natural and Anthropogenic Influences in Fluvial Geomorphology, Geophysical Monograph 89. American Geophysical Union. pp. 151–164. http://dx.doi.org/10.1029/GM089p0151

Bajracharya, R. and Tamrakar, N.K., 2007. Environmental status of Manahara River, Kathmandu, Nepal. Bull. of Department of Geol., Tribhuvan University, Kathmandu, Nepal, v. 10, pp. 21–32. http://dx.doi.org/10.3126/bdg.v10i0.1417

Bradley, W.C. and Mears, A.I., 1980. Calculations of flows needed to transport coarse fraction of Boulder Creek alluvium at Boulder, Colorado. Geological Society of America Bulletin, Part II, 91, pp. 1057–1090. http://dx.doi.org/10.1130/GSAB-P2-91-1057

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.

Cowan, J., 1959. 'Pre-fab' wire mesh cone gives doves better nest than they can build themselves. Outdoor California, v. 20, pp. 10–11.

DMG, 1998. Engineering and Environmental Geological Map of Kathmandu Valley, Dept. Mines and Geol., Lainchaur, Kathmandu.

Horton, R.E., 1945. Erosional development of streams and the streams and their drainage basins: Hydrological approach to quantitative geomorphology. Bull. Geol. Soc. Am., Vol. 56, pp. 275–370. http://dx.doi.org/10.1130/0016-7606(1945)56[275:EDOSAT]2.0.CO;2

Lane, E.W., 1955, The importance of fl uvial morphology in hydraulic engineering: American Society of Civil Engineering Proceedings, v. 81, 745, pp. 1–17.

Leopold, L. B. and Wolman, G. M., 1960. River meanders. Geol. Soc. America Bull., v. 71, pp. 769–794. http://dx.doi.org/10.1130/0016-7606(1960)71[769:RM]2.0.CO;2

Leopold, L.B., Wolman, M.G. and Miller, J.P., 1964. Fluvial processes in geomorphology. W. H. Freeman & Co., San Fransisco, U.S.A., 522p.

Mackin, J.H., 1948. Concept of the graded river. Geol. Soc. America Bull., v. 59, pp. 463–512. http://dx.doi.org/10.1130/0016-7606(1948)59[463:COTGR]2.0.CO;2

Maharjan, L. and Dangol, V., 2007. Engineering hydrology of Kodku Khola Basin, Lalitpur, Nepal. Bull, Dept. Geol., Tribhuvan University, Kathmandu, Nepal, Vol. 10, pp. 107–116. http://dx.doi.org/10.3126/bdg.v10i0.1426

Maharjan, V. and Tamrakar, N.K., 2010. Morpho-hydraulic parameters and existing stability condition of Nakhu River, southern Kathmandu, Central Nepal. Bull. Dept. Geol., Tribhuvan University, v. 13, pp. 1–12. http://dx.doi.org/10.3126/bdg.v13i0.3961

Pfankuch, D. J. 1975. Stream Reach Inventory and Channel Stability Evaluation. USDA Forest Service, R1-75-002. Govt. Printing Office, 696-260/200, Wash. D.C. 26 p.

Rosgen, D.L., 1994. A classification of natural rivers, Cantenna, V. 22, pp. 169–199. http://dx.doi.org/10.1016/0341-8162(94)90001-9

Rosgen, D. L. 1996. Applied River Morphology. Wildland Hydrology Books, Pagosa Springs, Colorado.

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

Saijo, K., Kimura, K., Dangol, G., Komatsabara, T., and Yagi, H., 1995. Active faults in southern Kathmandu basin, Central Nepal, Journal of Nepal Geological Society (Special issue), v. 11, pp. 217–224.

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

Schumm, S.A., 1981. Evolution and Response of the Fluvial System, Sedimentologic Implications. Society of Economic Paleontologists and Mineralogists Special Publication 31:19-29. http://dx.doi.org/10.2110/pec.81.31.0019

Schumm, S.A., M.D. Harvey, and C.C. Watson, 1984. Incised Channels: Morphology, Dynamics, and Control. Water Res. Publications, Littleton, Colorado, 200 pp.

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

Shrestha, P. and Tamrakar, N.K., 2007. Streambank erodibility and lateral instability hazard in the Manahara River, Kathmandu basin, Nepal, Jour. Nepal Geol. Soc., v. 35, pp. 55-66.

Shrestha M. B., Tamrakar, N.K., and Miyazaki, T., 2008. Morphometry and sediment dynamics of the Churiya River area, Siwalik Range in Neoal. Boletin de geologia, v. 30, no. 2, pp. 35–48.

Simon, A., 1989. A Model of Channel Response in Disturb Alluvial Channels. Earth Surface Processes and Landforms: 14, 11–26. http://dx.doi.org/10.1002/esp.3290140103

Strahler, A.N., 1957. Quantitative analysis of watershed geometry. Trans-American Geophysical Union, v. 38, pp. 913–920. http://dx.doi.org/10.1029/TR038i006p00913

Strahler, A. N., 1964, Quantitative geomorphology of drainage basins and channel networks, In: VT Chow (ed), Handbook of Applied Hydrology. McGrew Hill Book Company, New York, Section, pp. 4–11.

Stöcklin, J., 1981. Geology of Nepal and its regional Frame. Journal of the Geological Society of London, 137p. 1–34. http://dx.doi.org/10.1144/gsjgs.137.1.0001

Stöcklin, J., Bhattarai, K.D., 1977. Geology of the Kathmandu area and central Mahabharat range, Nepal Himalaya. Report of Department of Mines and Geology/ UNDP (unpublished), 86p. http://dx.doi.org/10.1144/gsjgs.137.1.0001

Tamrakar, N.K., 2004a. River degradation problems along the Bishnumati River corridor in the Kathmandu Basin, 37p. http//www.human-g.com

Tamrakar, N.K., 2004b. Disturbances and Instabilities in the Bishnumati River Corridor, Kathmandu Basin. The JUSAN, v. 9, issue 16, pp. 7–18.

Tamrakar N.K and Bajracharya R., 2009, Fluvial Environment and Existing Stability Condition of the Manahara River, Central Nepal, Journal of Nepal Geological Society, v. 39, pp. 45–58.

Tamrakar, N.K., Bajracharya, R., and Shrestha, P., 2011. River dynamics and existing stability condition of the Manahara River, Kathmandu basin, Central Nepal Himalaya. Bull. Dept. Geol., Tribhuvan University, Kathmandu, Nepal, Vol. 14, pp. 1–8. http://dx.doi.org/10.3126/bdg.v14i0.5430

Tamrakar, N.K., Prajapati, A., and Manandhar, S., 2007. Sedimentology, dynamics and debris flow potential of Champadevi River, southwest Kathmandu, Nepal Bull. Dept. Geol., Tribhuvan University, Kathmandu, Nepal, Vol. 10, pp. 9–20. http://dx.doi.org/10.3126/bdg.v10i0.1416

Williams, G.W., 1986. River meanders and channel size. Jour. Hydrology, v. 88, pp. 147–164. http://dx.doi.org/10.1016/0022-1694(86)90202-7

Wolman, M.G., 1954, A method of sampling coarse river-bed material. Trans. Am. Geophys. Union, v. 35, pp. 951–956. http://dx.doi.org/10.1029/TR035i006p00951

Yagi, H., Maemoku, H., Ohtsuki, Y., Saijo, K., and Nakata, T., 2000. Recent activities faults distributed in and around Kathmandu Valley, Lower Himalayan Zone. In: Okumura, K., et al. (eds), Active faults Research for the New Millenium. Proceeding of the Hokudan Internalational Symposium and School on Active Faulting, pp. 557–560.