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Bank instability and erosion problems in Bishnumati River, Kathmandu, Nepal

***Basanta Raj Adhikari and Naresh Kazi Tamrakar**
Central Department of Geology, Tribhuvan University
Kirtipur, Kathmandu, Nepal
*(*Email: limestone20@hotmail.com)*

ABSTRACT

The Bishnumati River, a major tributary of the Bagmati River in the Kathmandu basin, suffers from bank erosion, river instability, and environmental degradation. These processes are responsible for the loss of sediments, modification of river morphology, loss of vegetative buffer zone, and deterioration of stream environment. Bank erosion hazard in the Bishnumati River was assessed at ten different reaches using bank height ratio, ratio of riparian vegetation rooting depth to bank height, rooting density percentage, bank slope, and bank surface protection. Vertical and lateral stability of the river was assessed at four reference segments, namely at Bishnumatigaun, Okhaltar, Mahadevtar, and Tamsipakha, respectively from upstream to downstream.

The riverbanks in the Bishnumatigaun segment show fluctuating trends of bank erosion potential from upstream to downstream. All the four segments of the Bishnumati River are vertically unstable and all the segments except the Okhaltar are entrenched. The Tamsipakha and Okhaltar segments have a high risk of lateral shifting, as they possess high values of bank erosion hazard index, meandering width ratio, and width–depth ratio. The Bishnumati river is in a degrading condition and capable of eroding sediments. The main causes of river instability are the excavation of river sediments, encroachment on riverbanks, clearing of riparian vegetation, and canalisation.

INTRODUCTION

The Bishnumati River, a major tributary of the Bagmati River, is located in the northwest part of the Kathmandu valley (Fig. 1). It is one of the severely disturbed rivers in the Kathmandu basin (Tamrakar 2004). The population of the Kathmandu valley is growing haphazardly and the people are disposing of the municipal waste to the river (Shrestha et al. 2002). They are mining construction materials and encroaching upon the river channel. Consequently, the river is facing bank instability and erosion problems.

The perennial Bishnumati River is fed by springs and storm flows, and its watershed occupies about 102.09 sq km. The river originates in the Shivapuri hills near the Shivapuri National Park and confluences with the Bagmati River at Teku covering a length of 18.4 km. It is a sixth-order stream based on Strahler's (1957) classification. Its main tributaries are the Ludi Khola, Sangla Khola, Mahadev Khola, Bhauchakhusi Khola, Samakhusi Khola, and the Manamati Kholsi. The Bishnumati watershed is occupied by cultivated land (63.92%), forest (18.87%), barren land (10.11%), built-up area (6.23%), bushes (0.23%), industrial area (0.12%), and others (0.52%).

The maximum and minimum monthly rainfall recorded in the Shivapuri range during 1987–2003 (DHM 2004) were respectively 559 mm (July) and 8.65 mm (November). Usually June, July, and August are the wet period whereas November, December, and January are relatively dry. The yearly extreme maximum discharge varies between 1.04 and 3.4 m^3/s whereas the annual extreme minimum discharge is as low as 0.02 m^3/s. The monthly mean discharge was the highest in August during 1965–1985.

GEOLOGICAL SETTING

The Lukundol Formation, Gokarna Formation, Tokha Formation, and Kalimati Formation constitute the valley sediments (Fig. 2). The basement of valley sediments comprises mostly the Palaeozoic rocks of the Phulchauki Group and partly the Bhimphedi Group of the Kathmandu Complex constituting a synclinorium (Stöcklin and Bhattarai 1977). The Chandragiri Formation, Sopyang Formation, Tistung Formation, and Sheopuri gneisses are distributed around the study area. The rocks essentially trend WNW–ESE and are intensely folded and faulted (Fig. 2). The axial trace of the Mahabharat Synclinorium passes through the peaks of Phulchauki (2765 m) and Chandragiri (2550 m). Many longitudinal faults run parallel to it, and the northern and southern margins of the basin are bounded by the Kalphu Fault and the Chandragiri Fault respectively (Sakai 2001). Both are active faults cutting the late Pleistocene sediments. The lower-order streams of the Bishnumati River flow through the gneissic and metasedimentary rocks whereas

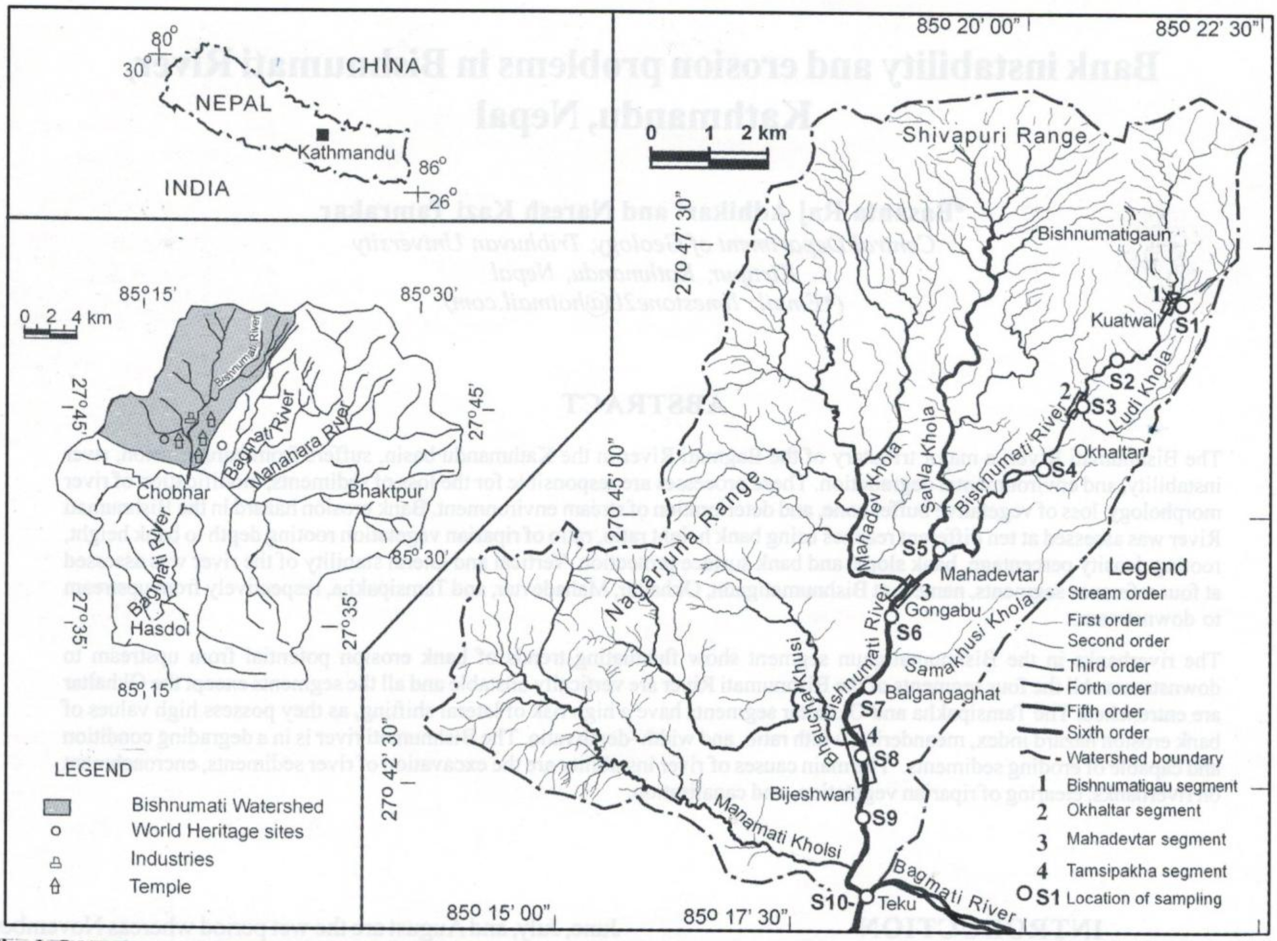

Fig. 1: Location and drainage map of Bishnumati watershed showing its four segments and sites of bank erosion hazard assessment

the higher-order (5–6th order) ones flow on the substrate of fluvio-lacustrine deposits of the Tokha and Kalimati Formation (Fig. 1).

METHODOLOGY

Bank erosion hazard in the Bishnumati River was assessed at ten different reaches from the head to the mouth of the main stream (Fig. 1). Accelerated stream bank erosion is a major cause of non-point source pollution associated with an increased sediment supply. For calculating the stream bank erosion potential, the bank erosion hazard index (BEHI) indicating the probability of occurrence of erosion (Rosgen 1996) was used (Table 1).

Table 1: Stream bank characteristics used to develop BEHI (Rosgen 1996) consist of the following variables: 1. Bank height ratio (Stream bank height/maximum bankfull depth), 2. Root density, 3. Root depth ratio (rooting depth/bank height), 4. Per cent surface area protection, 5. Bank angle, and 6. Bank material and degree of stratification.

The vertical and lateral stabilities of the river were assessed at four reference segments, namely at Bishnumatigaun (3rd order), Okhaltar (4th order), Mahadevtar (5th order), and Tamsipakha (6th order) from upstream to downstream respectively (Fig. 1). Various hydraulic parameters were measured for describing the condition of the Bishnumati River.

The critical dimensional shear stress (τ_{ci}) was estimated using the following relationship (Andrew 1983).

$$\tau_{ci} = 0.0834\ (d_i/ds_{50})^{-0.887}$$

where d_i = largest particle from the marginal bar sample and ds_{50} = median diameter of the bar sample.

At critical dimensionless shear stress conditions, the minimum bankfull mean depth and the bankfull water surface slope were calculated using the following Shield criteria:

$$D_r = (1.65 .\ \tau_{ci} .\ d_i)/S_e$$

$$S_r = (1.65 .\ \tau_{ci} .\ d_i)/D_e$$

where D_r = bankfull mean depth required, 1.65 = submerged specific weight of sediments, S_e = existing bankfull water surface slope, S_r = bankfull water surface slope required, D_e = existing or design mean bankfull depth and other symbols

Table 1: Stream bank characteristic used to develop Bank Erosion Hazard Index (Rosgen 1996)

Category		Bank ht. ratio (ft/ft)	Root depth ratio (%)	Root Density (%)	Bank angle (°)	Surface protection (%)	Total Index*
Very low	Value	1.0–1.1	100–80	100–80	0–20	100–90	
	Index	1–2	1–2	1–2	1–2	1–2	<10
Low	Value	1.1–1.2	80–55	80–55	20–60	90–50	
	Index	2–4	2–4	2–4	2–4	2–4	10–20
Moderate	Value	1.2–1.5	55–30	55–30	60–80	50–30	
	Index	4–6	4–6	4–6	4–6	4–6	20–30
High	Value	1.5–2	30–15	30–15	80–90	30–15	
	Index	6–8	6–8	6–8	6–8	6–8	30–40
Very high	Value	2–2.8	15–5	15–5	90–120	15–5	
	Index	8–9	8–9	8–9	8–9	8–9	40–45
Extreme	Value	>2.8	<5	<5	>120	<5	
	Index	10	10	10	10	10	>45

*Total Index adjusted for specific nature of bank materials and stratification. Bank material: bedrock (very low), boulder (low), and 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 layer.

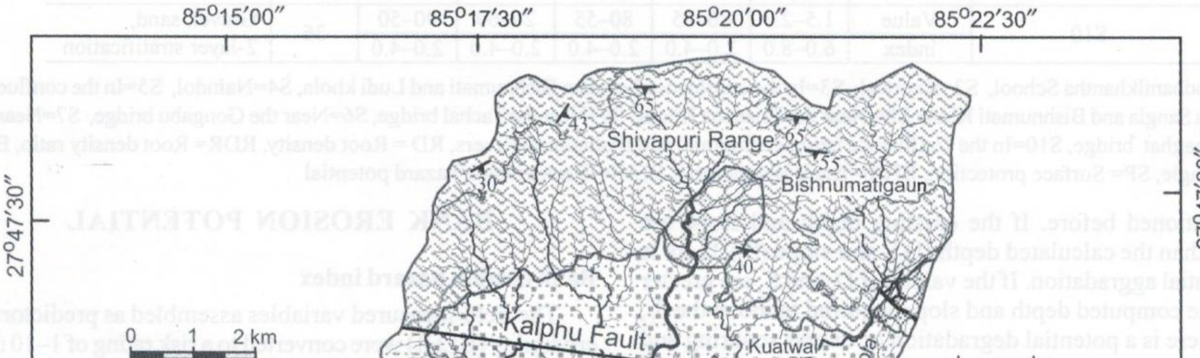

Fig. 2: Geological map of Bishnumati watershed (compiled form Stöcklin and Bhattarai 1977, DMG 1998, Kalphu fault after Arita et al. 1973)

Table 2: Result of different parameters and BEHI rating

Locality*/Category*	Attribute	BHR	RDR	RD	BA	SP	BEHI	Remarks
S1	Value	2.0–2.8	30–15	55–30	20–60	90–50	25	Boulder, cobbles
	Index	8.0–9.0	6.0–8.0	4.0–6.0	2.0–4.0	2.0–4.0		
S2	Value	1.0–1.1	30–15	55–30	60–80	100–90	35	Gravel, sand, 2-layer stratification
	index	1.0–2.0	6.0–8.0	4.0–6.0	4.0–6.0	1.0–2.0		
S3	Value	1.5–2.0	<5	15–5	80–90	90–50	42	Gravel, sand, 4-layer stratification
	index	6.0–8.0	10	8.0–9.0	6.0–8.0	2.0–4.0		
S4	Value	1.0–1.1	55–30	80–55	60–80	90–50	37	Gravel, sand
	index	1.0–2.0	4.0–6.0	2.0–4.0	4.0–6.0	2.0–4.0		
S5	Value	1.0–1.1	55–30	30–15	60–80	50–30	38	Gravel, sand
	index	1.0–2.0	4.0–6.0	6.0–8.0	4.0–6.0	4.0–6.0		
S6	Value	1.2–1.5	80–55	80–55	60–80	30–15	33	Sand, gravel
	index	4.0–6.0	2.0–4.0	2.0–4.0	4.0–6.0	6.0–8.0		
S7	Value	1.0–1.1	80–55	80–55	80–90	90–50	28	Sand
	index	1.0–2.0	2.0–4.0	2.0–4.0	6.0–8.0	2.0–4.0		
S8	Value	>2.8	30–15	80–55	20–60	50–30	39	Gravel, sand, 2-layer stratification
	index	10	6.0–8.0	2.0–4.0	2.0–4.0	4.0–6.0		
S9	Value	>2.8	80–55	100–80	80–55	90–50	37	Gravel, sand
	index	10	2.0–4.0	1.0–2.0	2.0–4.0	2.0–4.0		
S10	Value	1.5–2.0	80–55	80–55	20–60	90–50	36	Gravel, sand, 2-layer stratification
	index	6.0–8.0	2.0–4.0	2.0–4.0	2.0–4.0	2.0–4.0		

*S1=Budhanilkhantha School, S2=Kautwal, S3=In the confluence between Bishnumati and Ludi khola, S4=Naindol, S5=In the confluence between Sangla and Bishnumati Khola, S8= Near the Bhaucha Khola, S9=Near the Tachal bridge, S6=Near the Gongabu bridge, S7=Near the Balgangaghat bridge, S10=In the confluence between Bagmati and Bishnumati Rivers, RD = Root density, RDR= Root density ratio, BA= Bank Angle, SP= Surface protection, BHR= Bank Height ratio, BEHI= Bank erosion hazard potential

as mentioned before. If the existing depth and slope are lower than the calculated depth (D_r), and slope (S_r), there is a potential aggradation. If the values of D_e and S_e are greater than the computed depth and slope required to move the d_i, then there is a potential degradation or excess scouring and incision leading to a potential instability.

Schumm's factors F and M were calculated by the following relationships (Schumm 1963).

$$F = W_{bkf} / D_{bkf}$$

where W_{bkf} = width at bankfull stage and D_{bkf} = depth at bankfull stage.

$$M = (S_c \cdot W_{bkf}) + (S_b \cdot 2D_{bkf}) / (W_{bkf} + 2D_{bkf})$$

where S_c = percentage of silt and clay in bed material, S_b = percentage of silt and clay in bank material.

Stream instability was assessed using field variables such as stream morphology, vegetation cover, entrenchment ratio (ER), bank height ratio (BHR), meandering width ratio (MWR), BEHI and width–depth (W/D) ratio. ER is computed as the ratio of width of flood-prone area to width at bankfull stage whereas BHR is the ratio of top of bank to maximum depth at bankfull stage. MWR is the ratio of the distance between two successive crests or two successive troughs of the curved channel to the width at bankfull stage. W/D ratio is the ratio of bankfull width to mean depth at bankfull level.

River instability was evaluated by calculating all the parameters and by comparing these values with the modified Pfankuch's (1957) system of channel stability rating chart.

BANK EROSION POTENTIAL

Bank erosion hazard index

The field-measured variables assembled as predictors of erodibility (BEHI) were converted to a risk rating of 1–10 (10: the highest level of risk). The risk rating form 1 to 10 indicates the corresponding adjective value of risk of very low, low, moderate, high, very high, and extreme potential erodibility. The total points obtained as converted from the measured bank variables to risk rating are shown in Table 2.

Bank height ratio (BHR)

BHR is high in S8 and S9, and it is low in S2, S4, S5, and S7. At S8, S9, and S10 an increase in BHR is noted owing to waste and gravel fill during road construction. BHR exceeds 1.5 in S1, S3, S8, S9, and S10, and therefore the banks show a high degree of incision and a high risk of degradation.

Vegetation characteristics

The vegetation cover on the lower banks is poor except in some reaches. Root depth ratio (RDR) was calculated in percentage by inspecting the plant roots in the banks. Root density is high in S9 and low in S3. RDR is very low in S3. Surface protection (both by vegetation and river training structures) was calculated in percentage, and is good in S2 whereas very poor in S6. Canopy is good in the upstream areas of the river up to the 3rd order segments and it decreases towards the downstream.

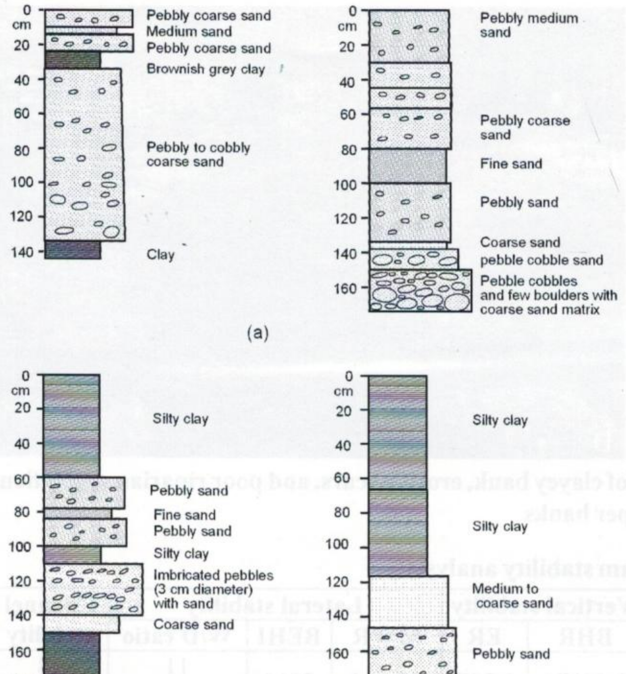

Fig. 3: Lithologs of bank material from upstream to downstream: (a) Upper part, (b) Middle part, and (c) Lower part

Bank angle

Bank angle is one of the main factors determining BEHI. It is high (80–90°) in S3 and S7 (near the Balgangaghat Bridge) and low (20–60°) in the rest of the segments. The lowermost portion of most of the riverbanks is vertical and the portion between the bankfull elevation and the lower top of the bank is around 30°. Most of the reaches of the 4th order streams also exhibit scoured banks.

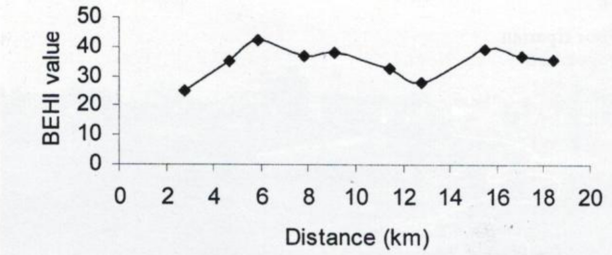

Fig. 4: Plot of BEHI against bank distance

Bank material and sequence

The riverbank materials vary in composition and texture from upstream to downstream reaches. In the upstream (around S1), the gravel is very thick-bedded and contains thin clay layers (Fig. 3). The grain size in the gravel reaches 65 mm. In the middle segment of the river (S5), bank material is composed mainly of medium to coarse sand. The proportion of clay beds found here is higher than that of gravel beds. Towards the downstream segments of the river (i.e. towards S10) sand and gravel beds predominate over the clay beds, and the grain size of gravel and sand decreases considerably (Fig. 3). Throughout the riverbank, stratification is moderately developed.

BEHI varies from upstream to downstream reaches of the Bishnumati River (Fig. 4). The Bishnumatigaun segment exhibits low bank erosion potential probably due to the presence of mega gravel in banks. Downstream of the Bishnumatigaun segment, the bank erosion potential increases almost up to the confluence with the Ludi Khola. The banks of the Bishnumati River near the confluence with the Ludi Khola exhibit a high potential of bank erosion hazard due to a high BHR, low RDR, and low rooting density. Near the Balgangaghat Bridge, the bank erosion potential is low, probably due to the presence of well rooting density, low BHR and good surface protection. But the bank erosion potential increases between Bijeswori and Teku (Figs. 5 a, b).

CHANNEL INSTABILITY

The alluvial channel, because it is formed in erodible sediments and because the stress exerted by the flowing water often exceeds the strength of the sediments forming the bed and banks of the channel, will change naturally with time (Chorley et al. 1985). Stream morphology, riparian vegetation, vertical stability, and lateral stability were assessed to determine the channel stability and the results are shown in Table 3.

Stream morphology

The morphological variables can change even in a short distance along a river channel due to the influence of geology and tributaries (Rosgen 1994). Therefore, the morphological description incorporates the field measurements of the stream channel type, size and order, flow regime, and depositional pattern from the selected reaches (Table 4). Accordingly,

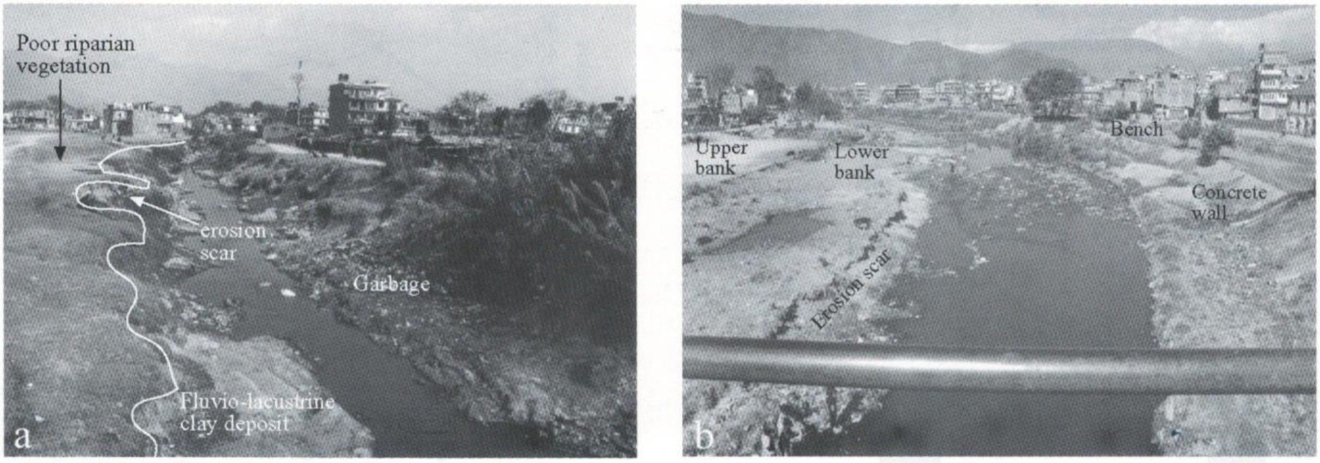

Fig. 5: a. Upstream view from Mahadevtar depicting exposure of clayey bank, erosion scars, and poor riparian vegetation, b. Upstream view from Bijeswori Bridge showing lower and upper banks

Table 3: Results of stream stability analysis

Stream Segment	Stream morphology	Riparian vegetation	Vertical stability		Lateral stability			Channel stability
			BHR	ER	MWR	BEHI	W/D ratio	
Bishnu-matigaun	A4 stream, 4.5–9 m wide, 3rd order with point bars and side bars	Good	2.53HU	1.28E	29.6M	29M	11 U	28 Fair
Okhaltar	C4stream, 4.5–9 m wide, 4th order with point bars and side bars	Good	1.79HU	4.78	70.4L	32H	12 U	39 Fair
Mahadev-tar	F5 stream, 9–15 m wide, 5th order with point bars, point bars with few mid-channels bars and side bars.	Poor	2.44HU	1.37E	11.6H	37H	26 U	35 Poor
Tamsi-pakha	F4 stream, 9–15 m wide, 6th order with point bars, point bars with few mid-channels bars and side bars.	Fair	3.11HU	1.30E	73.7L	38H	21 U	36 Poor

HU=highly unstable; U=unstable; E=entrenched (<1.4); M=moderate; H=high; L=low

Bishnumatigaun, Okhartar, Mahadentar, and Tamsipakha segments can be classified as Au, C4, F5, and F4 streams respectively (Tamrakar 2004).

Riparian vegetation

Since the river passes through an urban area the vegetation is poor. However, some trees and shrubs are present on the riverbanks and floodplains. A number of plants growing on the banks are primarily of exotic species.

The Bishnumatigaun segment has a better canopy than the rest of segments (Fig. 6 a). Some bamboos line up on the banks in addition to other plants. Downstream of S1, Banmara (*Eupatorium adenophorum*) is abundant and in some other places Utis (*Alnus nepalensis*) is found. The Okhaltar segment also possesses good riparian vegetation (Fig. 6 b). Discontinuous riparian vegetation with sparse trees forming a weak canopy is observed in the Mahadevtar segment. The shrubs, trees, and grasses in the Tamsipakha segment occur in patches. Some parts of this segment have been re-vegetated by the Kathmandu Municipality. However, in some reaches of this segment trees are sporadic and therefore the canopy is almost absent. In other words, the riparian vegetation is poor in the Mahadevtar segment, is fair in the Tamsipakha segment, and it is relatively good in the Okhaltar and Bishnumatigaun segments. Vegetation destruction is pronounced in the Mahadevtar and Tamsipakha segments due to human encroachment.

Vertical stability

From the field measurements of BHR and ER, and documented excessive erosion, it is inferred that there is an accelerated channel incision in the Bishnumati River. The obtained values of ER are compared with the stability rating chart of Rosgen (2001).

BHR of all the segments exceeds 1.5 and therefore all the segments show a high degree of incision and a high risk of degradation. The Okhaltar, Mahadevtar, Bishnumatigaun, and Tamsipakha segments exhibit respectively the risk of degradation in an increasing order. The Mahadevtar, Bishnumatigaun, and Tamsipakha segments are more entrenched than the Okhaltar segment.

Having high BHR and ER, the Bishnumatigaun segment shows a high risk of degradation. Although the degree of incision in the Okhaltar segment is high, it shows a wide flood-prone area due to active lateral shifting. Owing to a

Fig. 6: a. Upstream view from Bishnumatigaun segment showing stream bank sediments and vegetation, b. Riparian vegetation in Okhaltar segment

Table 4: Hydraulic parameters and sediment characteristics required for calculation of F-factor and M-factor

Attribute	Bushnumati-gaun	Okhaltar	Mahadev-tar	Tamsi-pakha
Mean depth at bankfull, D_{bkf}	0.580	0.640	0.540	0.510
Width at bankfull, W_{bkf} (m)	6.100	7.670	13.800	10.850
Slope, S_e (m/m)	0.133	0.008	0.004	0.005
$*d_{i\,(m)}$	0.089	0.090	0.083	0.069
d_{s50} (m)	0.024	0.046	0.049	0.024
d_i/d_{50}	5.235	6.923	3.320	3.833
τ_{ci}	0.009	0.007	0.013	0.012
D_r (m)	0.009	0.112	0.410	0.247
S_r	0.001	0.001	0.002	0.002
S_c	2.920	5.830	8.130	12.560
S_b	0.100	0.000	0.170	0.170
F- factor	10.520	11.98	25.550	21.270
M- factor	2.470	5.000	7.550	11.50

$*d_i$ = largest particle from bar sample, d_{50} = median diameter of riffle sample, d_{s50} = median diameter of bar sample, τ_{ci} = critical dimensional shear stress, D_r = bankfull mean depth required, S_r = bankfull water surface slope required, Sc = percentage silt-clay in bed material, S_b = percentage silt-clay in bank material

slope break between the 3rd and 4th order streams, the Okhaltar segment receives gravel and sand. But these sediments have been frequently excavated for gravel and sand. Thus the riverbed is deepening and consequently BHR is increasing. In the Mahadevtar and Tamsipakha segments, the river has incised into the fluvio-lacustrine deposits and clay is exposed in the mid channel at Mahadevtar, in the Gongabu Bus Park area, and at Balgangaghat.

Lateral instability

Meander width ratio (degree of confinement), BEHI, and W/D ratio were used to find out lateral stability. These parameters are often linked with stream bank erosion, excessive sediment deposition, stream flow changes, and channel widening from one stream to another and direct alteration of channel shape from canalisation. The W/D ratio is compared with the stability rating chart of Rosgen (2001).

The values of MWR for the Okhaltar (70.4) and Tamsipakha segments (73.7) are much higher than those for the Bishnumatigaun (29.6) and Mahadevtar (11.6) segments. This fact shows that lateral channel shifting is potential in Okhaltar and Tamsipakha segments. The Mahadevtar segment indicates lateral confinement, probably due to the presence of clayey banks with overlying stratified gravel and sand (Tamrakar 2004). Owing to the artificial confinements in the Mahadevtar and Tamsipakha segments the Bishnumati River tends to incise rather than accrete.

Channel aggradation–degradation potential

The aggrading or degrading conditions in the Bhishnumati River were determined from its hydraulic parameters as well as from the grain size of channel sediments (Table 4). The obtained critical dimensionless shear stresses are 0.003, 0.007, 0.013, and 0.012 in the Bishnumatigaun, Okhaltar, Mahadevtar, and Tamsipakha segments respectively. The calculated depth (D_r) and slope (S_r) required to move the largest particle in all the stream segments are less than the existing depths (D_e) and slopes (S_e) indicating that the Bishnumati River is potentially degrading.

Schumm's (1963) F versus M plots (Fig. 7) also indicate that the Bishnumati River is in a degrading condition. The sixth-, fifth-, fourth-, and third-order stream segments of the Bishnumati River are in an increasing order of degradation respectively. However the sixth-order segment is in a critical condition. The other three segments have low F and M values due to their higher bankfull depth than the bankfull width and the presence of coarser sediments.

The results of river channel instability analysis are presented in Table 3. The Modified Pfankuch's (1975) channel stability rating was used to categorise stream segments with respect to channel stability, such as excellent (score <11), good (11–22), fair (22–33), or poor (33–44) conditions. The Bishnumatigaun and Okhaltar segments are

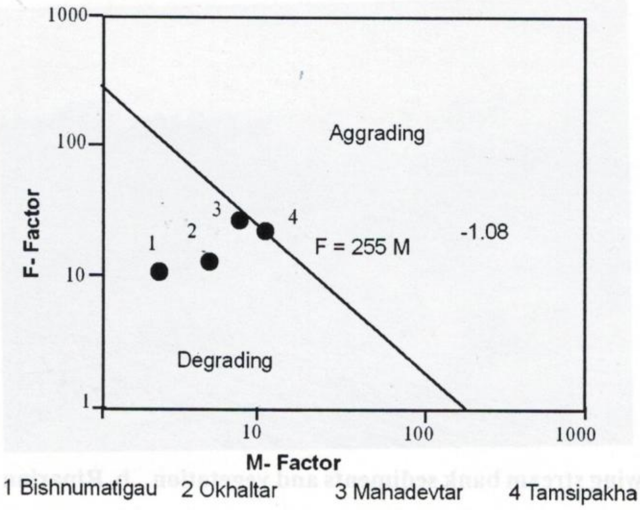

Fig. 7: F versus M diagram indicating dynamic equilibrium in Bishnumati River segments; boundary between aggrading and degrading fields: after Schumm (1963).

in a fair stability condition, which is supported by a low W/D ratio, a low BEHI, and good vegetation whereas the Mahadevtar and Tamsipakha segments are in a poor stability condition due to a high W/D ratio, a high BEHI, and poor to fair vegetation cover.

CAUSES OF RIVER INSTABILITY

The presence of longitudinal faults and base-level changes are the natural factors whereas the excavation of sediments, encroachment of banks, vegetation clearing, and canalisation are the anthropogenic factors responsible for the channel instability. Excessive sand mining results in the lowering of the riverbed and triggers bank failures (as observed in the Sangla Khola). Human encroachment (e.g. buildings and roads) is the commonest phenomenon and most pronounced in the Mahadevtar segment as well as in the vicinity of Gongabu Bus Park, Balgangaghat, and Tamsipakha. Check dams are located in the downstream portion of the bridges in the Mahadevtar and Balgangaghat segments. They have created a slope break leading to headward erosion. Intense vegetation clearing is observed in the Okhaltar and Tamsipakha segments.

CONCLUSIONS

The banks of the Bishnumati River near the confluence with the Ludhi Khola, and between Bijeswori and Teku have a high erosion potential, whereas those around Bishnumatigaun and Balgangaghat have a low potential. The Bishnumatigaun and Okhaltar segments are in a fair stability condition, whereas the Mahadevtar and Tamsipakha segments are in a poor stability condition. All the four segments are vertically unstable and, except the Okhaltar segment, have a high risk of lateral shifting. The Bishnumati River is in a degrading condition based on the Schumm's F–M relationship. Since the depth and slope of the Bishnumati River are much greater than the required depth and slope for moving the largest bar particles, the river is potentially degrading. The overall channel stability of the Bishnumati River is rated at fair to poor.

The main causes of bank instability and erosion are the excavation of river sediments, encroachment upon riverbanks, clearing of riparian vegetation, and canalisation.

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