MORPHOMETRY AND SEDIMENT DYNAMICS OF THE CHURIYA RIVER AREA, SIWALIK RANGE IN NEPAL

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ABSTRACT

The Siwalik Range of Central Nepal has weakly consolidated rocks with thin soil cover. Being one of the several north-flowing subsequent tributaries, the Churiya River originated from the southern uplifted range of the Siwalik Group. Morphometry and hydraulic parameters of the Churiya River Basin (CRB) were studied to know how capable is the river for carrying its sediment out of the basin. In many cases, hypsometric integral (HI) in 1st order watershed was lower (0.33–0.57) compared to that of 2nd and 3rd order watersheds (0.45–0.54) suggesting that it had been undergoing severe erosion. The surface flow in the Churiya River appeared only during intense middle monsoon rainfall (June–August) and disappeared most of the time probably due to highly permeable riverbed. Stream powers (Ps) calculated from morphometric analyses of the drainage basin, and stream powers per unit bed area (Ω_b) computed from hydraulic data showed that 2nd order watershed in both cases were 2.5 times higher than 3rd order watershed. This suggests that stream powers of 2nd order watersheds had high potentiality of transporting sediments into 3rd order segment, where stream powers diminished due to reduction in slope, boundary shear stress, and increase of infiltration rate. Although, stream powers reduced downstream (in 3rd order segment), they were quite high enough to flush out from the basin even the largest grain size (d_{max}) of the riverbeds during the period of high flows. Therefore, sediment erosion should be controlled in the Churiya River Basin to reduce its impact on downstream segments and infrastructures.

Key words: Siwalik Range, morphometry, riverbed, sediment, grain size, stream power

MORFOMETRIA Y DINAMICA DE LOS SEDIMENTOS EN EL AREA DEL RIO CHURIYA, SERRANIA DE SIWALIK EN NEPAL

RESUMEN

La Serrania de Siwalik en la región central de Nepal presenta rocas débilmente consolidadas con una delgada cubierta de suelos. Siendo uno de los tributarios del norte, el rio Churiya se originó del levantamiento en el Sureste del Grupo Siwalik. La morfometria y los parámetros hidráulicos de la cuenca del rio Churiya (CRB) fueron estudiados para conocer la capacidad del rio de transportar sedimentos fuera de la cuenca. En muchos casos la hipsometría integral (HI) de parte aguas de primer orden fue muy baja (0.33-0.57) comparada con las de segundo y tercer orden (0.45–0.54), sugiriendo que ha sufrido erosión severa. El flujo superficial del rio Churiya aparece solo durante las intensas lluvias monzonicas (junio-agosto) y desaparece la mayoría del tiempo probablemente debido a la alta permeabilidad del lecho del rio. El poder de sedimentos (Ps), calculado a partir de los análisis morfometricos del drenaje de la cuenca y el poder de sedimentos por unidad del área del lecho (Ω_b) calculado de los datos hidráulicos mostraron el parte aguas de segundo orden en ambos casos fue 2.5 veces más alto que el de tercer orden, sugiriendo que los de segundo orden tienen más potencial de transporte que los de tercera dado a que en estos últimos disminuye el poder debido a la reducción en la pendiente, limite de cizalla por stress e incremento en la tasa de infiltración. Aunque en el parte aguas de tercer orden hay bajo poder de sedimentación y transporte, esto aumenta en los periodos de lluvias, por consiguiente, la erosión por sedimentación debe ser controlada en la cuenca del rio Churiya para reducir el impacto en la infraestructura.

Palabras claves: Serranía de Siwalik, morfometria, lecho de rio, sedimento, poder de corriente

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INTRODUCTION

The Siwalik Range (Churiya Range) extends E–W with a width of 10–20 km and rises from the Ganges Plain to an altitude of about 1500 m amsl (above mean sea level). Steep slopes of the Siwalik Range and weakly consolidated rocks with thin soil cover generally tends to promote severe surface erosion in spite of the thick vegetation (Galay, 1987). Almost every monsoon, sediment related disasters in the region have been causing countless misery to the inhabitants and causing havoc in the national infrastructures. Shrestha et al. (2005) highlighted the sediment dynamics and suggested that

the apparent reason for the huge sedimentation within the Siwalik basins could be because of fluvial characteristics. The fluvial characteristics are in turn influenced by topography and climate (Grantham and Velbel, 1988), tectonics and weathering (Johnson, 1990), composition of source area and riverbed materials. Assuming that tectonics, topography and weathering conditions are being consistent within a small basin, mobility of riverbed material may depend on the available lithology of the source area, hydrology and morphometry of the basin. Therefore, understanding of sediment dynamics of the region is an important concern in order to mitigate and control in the future the sediment-related disasters.
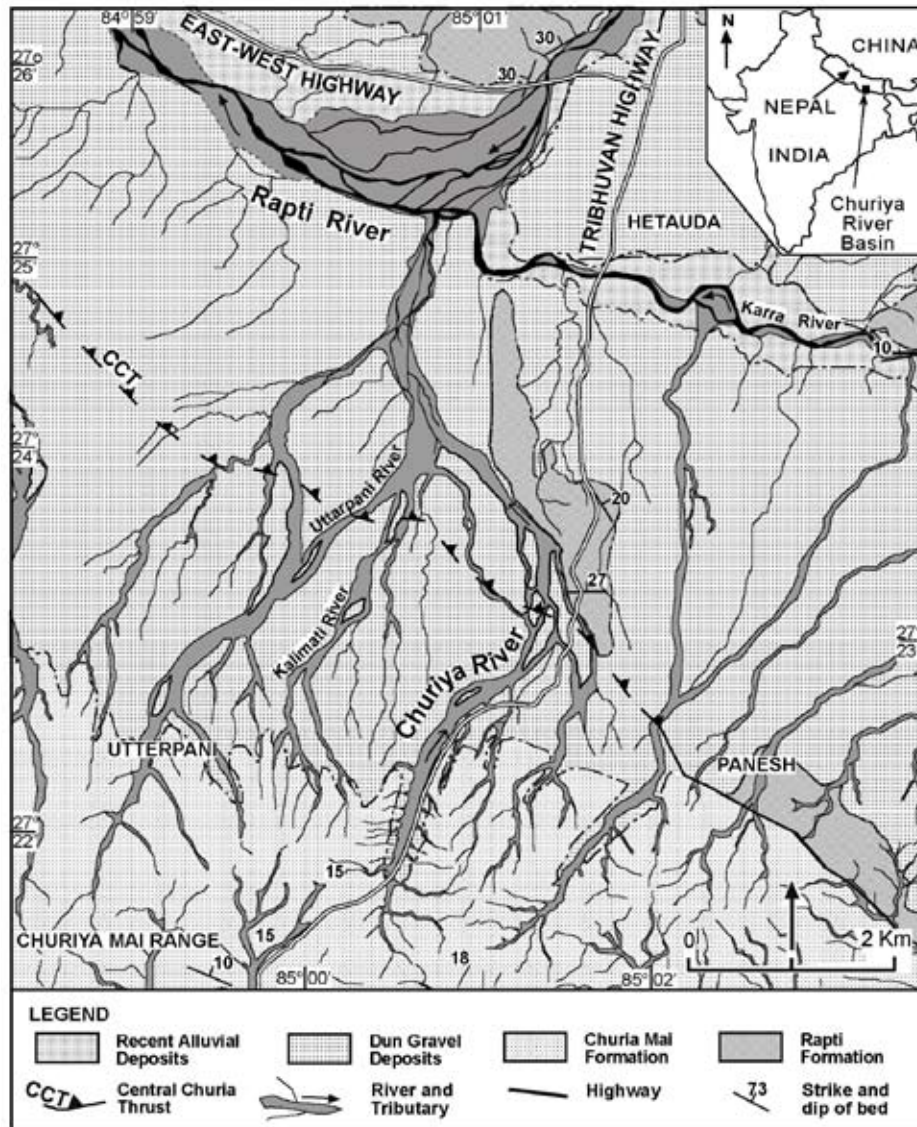

FIGURE 1. Location map and geology of the Churiya River Basin.

STUDY AREA

Geology

The CRB is located in the northern face of the Churia Mai Range having elevation of 800 m amsl, from which the Churiya River originates and contributes the Utterpani River a tributary of the Rapti River (FIGURE 1). The basin area and total stream length of the CRB is 7.6 km² and 18.2 km, respectively. The Churiya River has gravelly riverbed material.

The southern prominent ranges (Churiya Mai Range) came into existence in Late Pleistocene after southward thrusting of the Siwalik belts (Kimura, 1994). Since then, the northern slope of the Churia Main Range has been giving rise to northward flowing streams and their sediments to the inner belt in different levels of terraces, thus forming the extensive Dun Gravel Deposit (FIGURE 2).

Loosely consolidated matrix-supported conglomerate, sandstone and mudstone of the Siwalik Group, and the Dun Gravel Deposit crop out in the CRB. Clasts (size > 2 mm) of conglomerates are composed of limestone, marble, quartzite, sandstones, schist, phyllite, granite and gneiss. Roughly three levels of terraces occur in the north-facing slopes of the Churia Mai Range. Terrace deposits are composed of matrix-supported cobble and pebble with few sand layers. The sediments thus distributed in the CRB are loosely consolidated to unconsolidated and are susceptible to erosion.
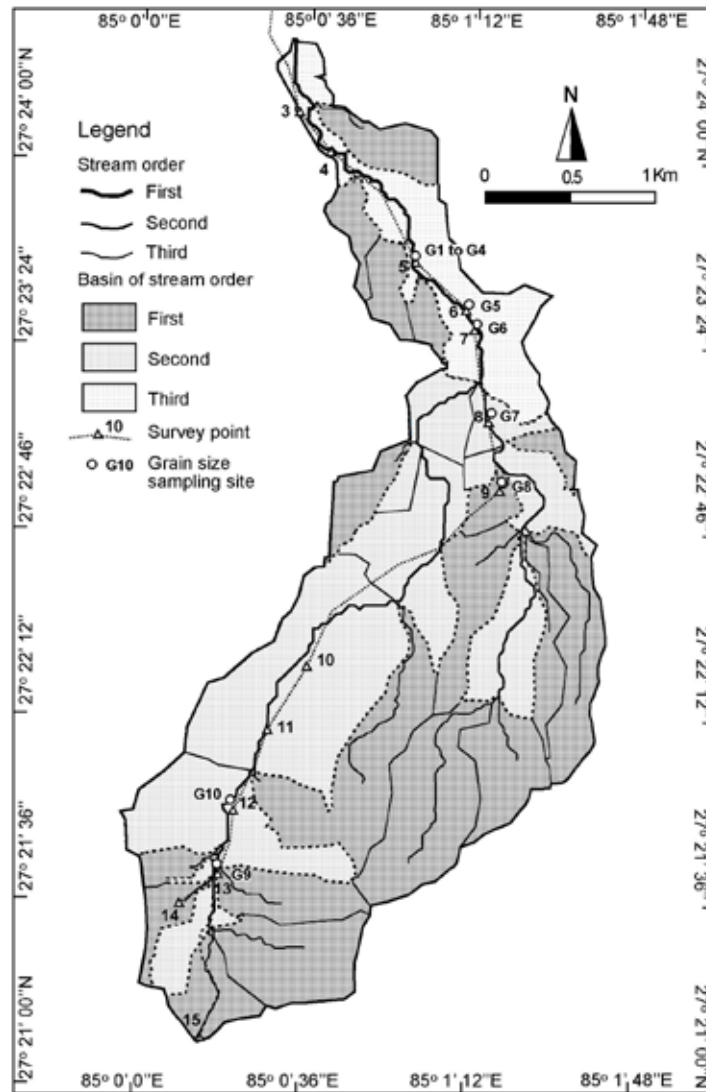

FIGURE 2. The Churia River Basin and its streams order. Numbers 1 to 15 represent survey points, Symbols G1 to G10 denote sampling point for grain size analysis.

Hydrometeorology

The mean annual rainfall (during 1987–2004 at Hetauda Meteorological Station (HMS) with elevation 470 m amsl) was 1847–3323 mm (FIGURE 3a). More than 80% of mean annual rainfall was observed during the monsoon period (June–September). The monthly maximum daily rainfall (1987-1994) ranged between 5 mm in November and 453 mm in August (FIGURE 3b). The total rainfall and rainy days recorded by Shrestha et al. (2001) at the headwater segment from 31 August 1997 to 5 May 1998 were 699.8 mm and 90 days, respectively.

Similarly, annual maximum, minimum and mean air temperatures recorded at the HMS from 1987 to 1994 were 29.3°C, 16.8°C and 23.1 °C, respectively. Annual mean relative humidity recorded at 8:45 Nepal Standard Time (NST) and 17:45 NST were 78% and 73%, respectively. The CRB lies in the subtropical zone.

LANDUSE AND COVER

For land use and cover changes within the CRB, USGS produced Landsat5-TM imagery acquired in October 18, 1988 was used. Geometric, radiance and reflectance corrections (Seker *et al.*, 2004) were conducted on the image before classifying land use/cover. Supervised classification method in the Erdas Imagine was followed. Ground truths were carried out by using sole black and white aerial photographs, 1/25,000 scale topo-map and field observations. Orthorectification was done for the aerial photos taken in 1987 and 1989 before using them as ground truths.

All the sub-watersheds have the largest coverage of dense forest followed by sparse forests, cultivated lands, river channels and grasslands in descending order (FIGURE 4). The protected Sal forest covers more than 70% of its neighboring area. Mixed forest of Chire pine (*Pinus roxburghii* Sargent), Khayer (*Acacia catechu* (L.f.) Willd) and Sisau (*Dalbergia Sissoo* Roxb.) show low forest coverage, 10 to 40%. Other species existing in the vicinity are: *Adina Cordifolia* (Wild. ex. Roxb.), *Hook* f., *Dalbergia latifolia* Roxb., Simal (*Bombax malabaricum* DC.), and Sajh (*Terminalia tomentosa* Wight et Arn.) (Shrestha *et al.*, 2001).

Cultivated lands at each order sub-watershed covers more than 30% of its corresponding total watershed area. River channel coverage at 2nd and 3rd order sub-watersheds is about two and three times, larger than that of 1st order sub-watershed, respectively. The cultivated lands that are prevalent and localized along/at main channel (FIGURE 4) are highly susceptible to the annual floods, and are prone to sediment sources (Shrestha, 2000; Shrestha et al., 2005; Shrestha and Miyazaki, 2005).
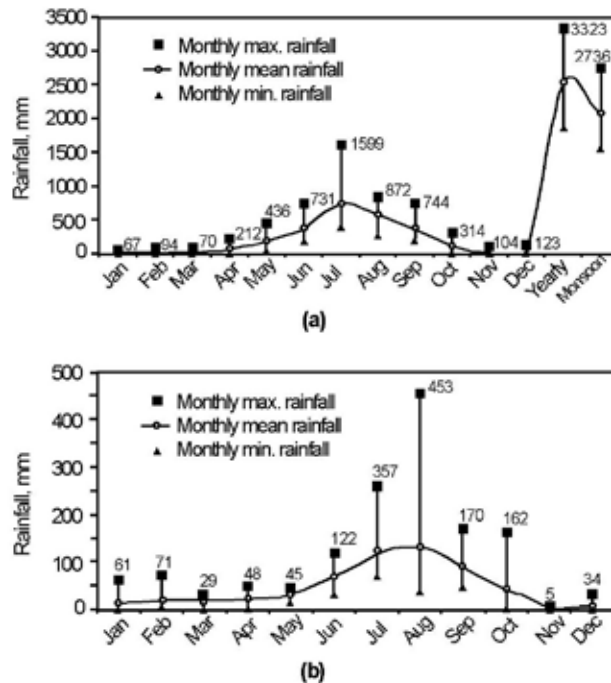

FIGURE 3. Rainfall recorded at HMS: (a) Monthly rainfall during 1987–2004, and (b) Maximum daily (24 hrs) during 1987–1994.
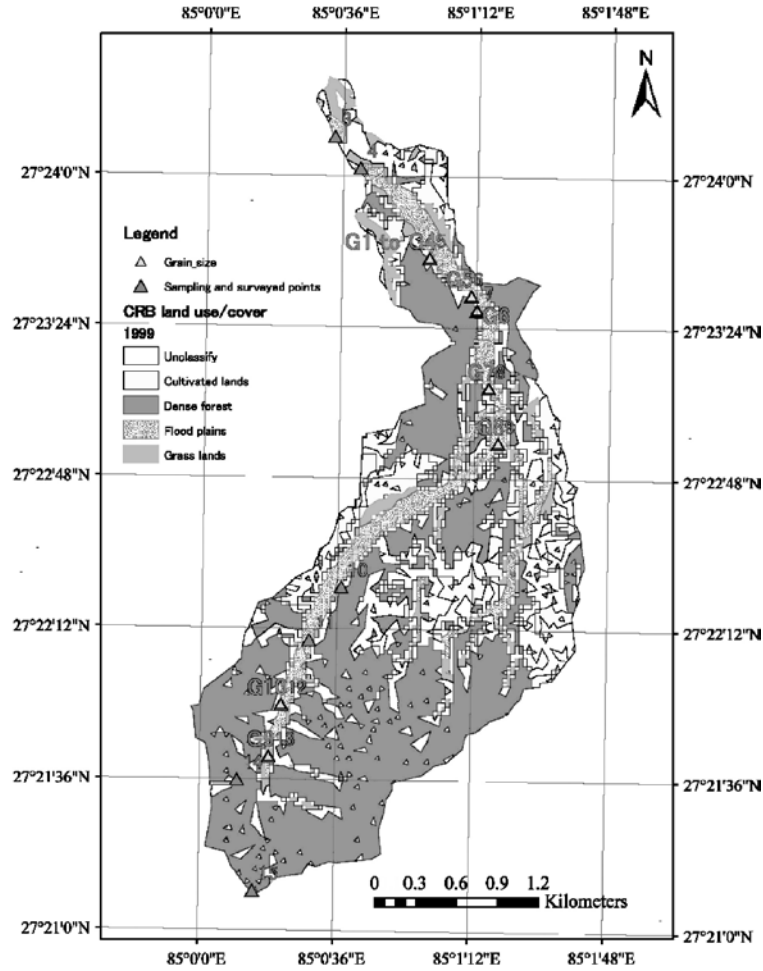
FIGURE 4. Land use and cover classification at each order reach catchment 1999.

BASIN MORPHOMETRY

Morphometric parameters

Terrain analysis was made to obtain the morphometry. Aster DEM (30 m) was used to extract channel networks and watersheds delineation, which were carried out in the ArcGIS 9.0 using TauDEM (Terrain Analysis Using Digital Elevation Models). In this model "DEM Curvature based" algorithm was used, and then the morphometric parameters were calculated (Tarboton et al., 1991 and 1992). In this study, for the stream drops and basin drops, elevation values were obtained from the 1/25,000 scale topo-map and contour-based data. The results are shown in TABLE 1.

The CRB is a 3rd order basin having 19 1st order and 2 2nd order sub-watersheds. First order sub-watershed has the maximum R_B of 9.50, whereas, 2nd order has 2.0 (TABLE 1). It suggests that inlet channels in the 2nd

order watershed are 9.50 times larger than the outlet channels. Similarly, R_A and R_L at 2nd order watershed suggest that total 2nd order drainage area is 15.90 times higher than total 1st order drainage area, and total stream length is 17.28 times longer than total 1st order streams.

In comparing to other Siwalik basins, the average R_B, R_A and R_L are significantly higher in the CRB (TABLE 1). In contrast to R_A and R_L, basin relief ratio (R_Z) is lower in the CRB. The second order sub-watershed of the CRB has characteristically different mean total drainage area and the mean total stream length compared with other Siwalik basins (FIGURE 5a and 5b). The basin and stream drops also differ (FIGURE 5c and 5d). Stream drops of the CRB are larger than other Siwalik basins. But, CRB's stream slopes are far less than that of other Siwalik basins (FIGURE 5e). Similarly, drainage density (D_D) is lower in the CRB (FIGURE 5f).

TABLE 1. Morphometric parameters of the Churiya River Basin and comparison with other basins

Basin	Stream order	Stream frequency, S_F	Bifurcation ratio, R_B	Area ratio, R_A	Length ratio, R_L	Basin relief ratio, R_Z	Slope ratio, R_S	Drainage density, D_D
Churiya River Basin	First	4.99	9.5			0.58	0.12	1.80
	Second	0.31	2	15.9	17.28	0.87	0.82	2.40
	Third	0.13		2.4	2.45			2.45
Average		1.81	5.75	9.15	9.86	0.58	0.47	2.22
*Siwalik Basin (GIS)			4.77	13.8	1.43	2.18		3.2
*Mahabharat Basin (GIS)			3.74	1.32	1.34	2.24		1.75
*Siwalik Basin (topo-map)			4.4	5.71	5.39	1.45		6.69
*Mahabharat Basin (topo-map)			4.24	5	4.84	1.55		6.53

* After Shrestha et. al. (2005) ; $S_F = N_w / A_w$; $D_D = L_w / A_w$; $R_B = N_w/N_{w+1}$; $R_B = N_w/N_{w+1}$; $R_L = L_{w+1}/L_w$; $R_A = A_{w+1}/A_w$; $R_z = Z_w/Z_{w+1}$; $R_S =S_w/S_{w+1}$, where, N_w, A_w, L_w, Z_w and S_w, are the number of streams, average drainage area, average stream length, average basin relief, average stream slope of the watershed of stream order w.
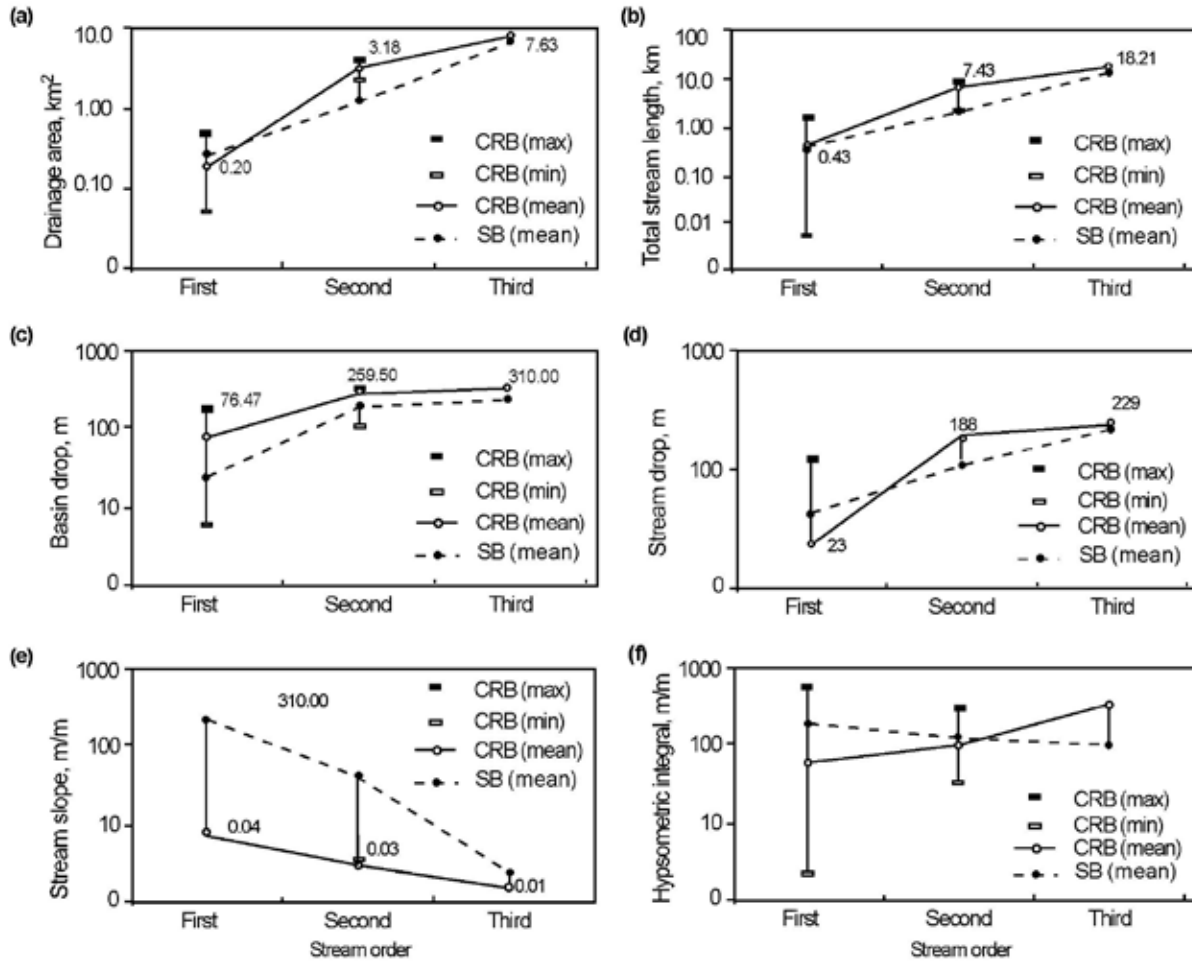

FIGURE 5. Results of terrain analysis of the Churiya River Basin. (a) Total drainage area, (b) Total stream length, (c) Basin drop, (d) Stream drop, (e) Stream slope, and (f) hypsometric integral.

Hypsometric Integrals (HI)

Hypsometric integral (Strahler, 1952) is sensitive to factors that control elevations within a watershed such as tectonics and erosion in landscape building; and are tractable through hypsometric analysis. *HI* was computed as:

$$HI = (Elv._{mean} - Elv._{min})/(Elv._{max} - Elv._{min}) \quad (1)$$

where, $Elv._{mean}$, $Elv._{max}$ and $Elv._{min}$ are the mean, maximum and minimum elevations within the watershed, respectively. The *HI* value ranges between 0 and 1, as a value closes to 0 suggests significant incision, slope movement, and erosion of soil mass since the formation of the watersheds (Bishop et al., 2002). The mean hypsometric integrals (*HI*) for the CRB is 0.48–0.55 suggesting the stage of maturity (Strahler, 1952), and shows homogeneity within the basin (FIGURE 5f). In comparison to other Siwalik basins (Shrestha and Miyazaki, 2005), excluding 3rd order sub-watershed, *HI* are less in the CRB, and it suggests significant incision and slope movement of topsoil and bedrock materials. Sub-watersheds of 2nd and 3rd order streams have similar D_D and *HI* values, which would probably suggest the similar erosional morphology. Low *HI* values and high variation of D_D at 1st order sub-watershed suggests that it has been undergoing severe erosion compared to its corresponding higher order sub-watersheds.

SEDIMENT CHARACTERISTICS

Grain size of riverbed material

As riverbed materials were heterogeneous, grain size analysis was made using digital images obtained from the riverbed surfaces at ten different locations (FIGURE 2). The Scion Image Analyzer was applied, and intermediate axes of about 400 grains per square meter were counted using a grid–by–number method, that is comparable to a volume-by-weight analysis (Kellerhals and Bray, 1971). These apparent sizes were corrected after Adam (1979), and were then counted for Udden–Wentworth Size-Grade Scale. The mean of 10 largest clasts (grain > 2 mm) in each sample was taken as D_{max}.

The surface sediments of the riverbed in each point represent chiefly pebble grade and subordinately cobble grade (TABLE 2). FIGURE 6a and b show downstream views of respectively the second and third order segments of the Churiya River showing its riverbed material. In most of the sampling points D_{max} is cobble but is pebbly sand and sandy muddy pebbles in some places. The average D_{max} of 2nd and 3rd order segments are 73 and 97 mm, respectively. The D_{50} lies on pebble grade (4–37 mm) and varies widely. The clast/matrix ratio is as high as 77.85 and as low as 0.21 (TABLE 2). The results show heterogeneity in grain size among the samples within a river segment.

TABLE 2. Grain size of the riverbed sediments of the Churiya River

Sample	D_{max}, mm	D_{50}, mm	Clast/matrix	Cobble:pebble:matrix	Sediment
1	109.29	14.42 (pebble)*	5.15	6.25:77.25:16.25	pebble
2	95.20	28.84 (pebble)	49.00	10.00:88.00:2.00	cobble pebble
3	106.8	13 (pebble)	39.00	7.00:90.50:2.50	pebble
4	32.94	1.46 (sand)	0.21	0.25:17.00:82.75	pebbly sand
5	78.5	32 (pebble)	27.57	6.75:89.75:3.50	pebble
6	16.56	4.26 (pebble)	1.80	0:64.29:35.71	sandy pebble
7	70.49	13.92 (pebble)	29.77	1.25:95.5:3.25	pebble
8	118.08	36.76 (pebble)	92.5	12.03:86.90:1.07	cobble pebble
9	93.87	9.19 (pebble)	25.67	3.50:92.75:3.75	pebble
10	103.69	34.3 (pebble)	77.85	13.01:85.72:1.27	cobble pebble

* Cobble (64–256 mm); pebble (2–64mm); sand (0.63–2mm); D_{max} = mean of 10 largest clasts

Permeability rate

Permeability tests at the headwater segment (both source area or hill slope) and riverbeds were made using an infiltrometer. The amount of water and time to percolate through the cylinder was measured, and the permeability rate was calculated in mm/hour. The result is shown in FIGURE 7. Mossy hill slope has the lowest permeability rate of 7 mm/h and subsurface gravelly riverbed (at 1 m depth) has the highest permeability rate of 1169 mm/h. The permeability rate increases with the increase of volume of gravelly clast present.

Sediment source

The riverbed materials have been derived from the valley walls formed of loosely consolidated conglomerates of the Siwalik Group, and of the gravelly terrace deposits (FIGURE 8). Besides, the Churiya River also erodes its banks. The matrix-supported gravelly outcrops are also susceptible to slope failure, because they are poorly stratified and unconsolidated (Tamrakar, 1999). High permeability rate in gravel deposit allows percolation of rainwater down the gravel deposit and increases fluid pressure, which when exceeds strength of the gravel deposit, the latter disperses due to buoyancy (Collinson and Thompson, 1989). The gravity and the fluid contribute in dispersing grains or erosion of the hill slopes. With mass wasting and associated physical disruption of clasts from matrix of gravel deposits, a huge volume of debris has been supplied from the headwaters and the riverbanks.

The cultivated lands (situated along the banks or terraces) and sparse forests (mainly of Sal) yielded enormous sediments because these lands were unable to resist erosion. Sal forest floors had been poorly vegetated and damaged due to grazing and litter collection that impair the resisting erosive forces exerted during intense rainfall (Shrestha, 2000). Additionally, Sal has intensive main root type (Shrestha et al., 2001), and possess stake-like main root which is very thick and strong enough to penetrate hardpans of red soils (lateritic soil) but, it has extremely few lateral hair roots, thus, has very low effects in protecting surface erosion.
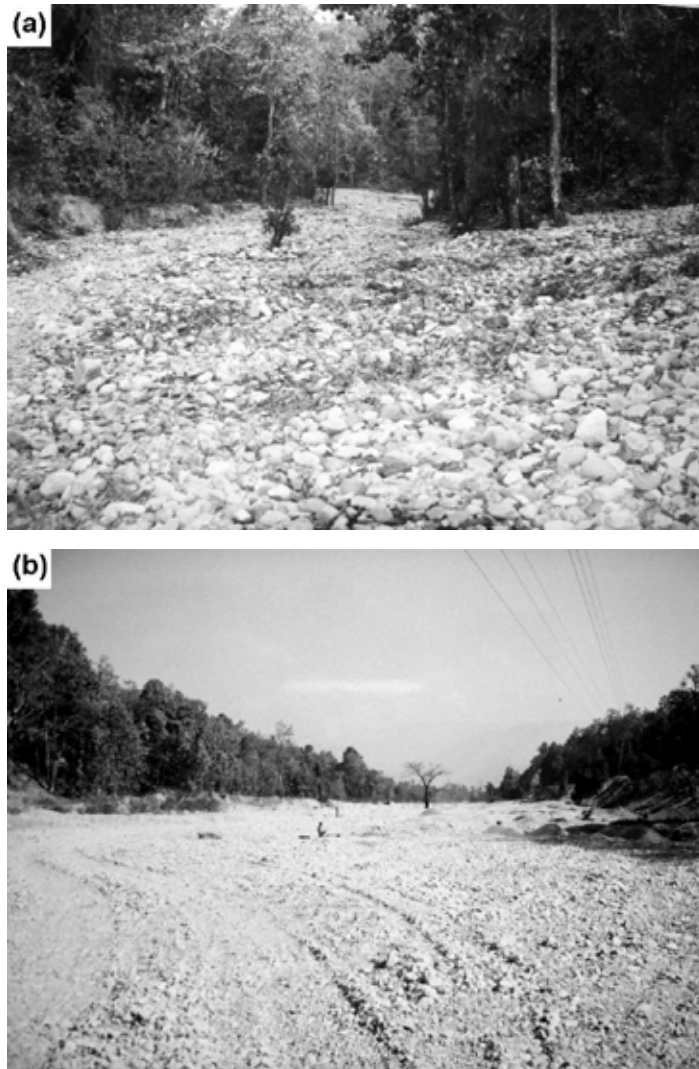

FIGURE 6. The Churiya River: (a) Downstream view of the second order segment at about 200 m upstream of the point 13 in FIGURE 2, (b) Downstream view of the third order segment between the points 4 and 5 in FIGURE 2.
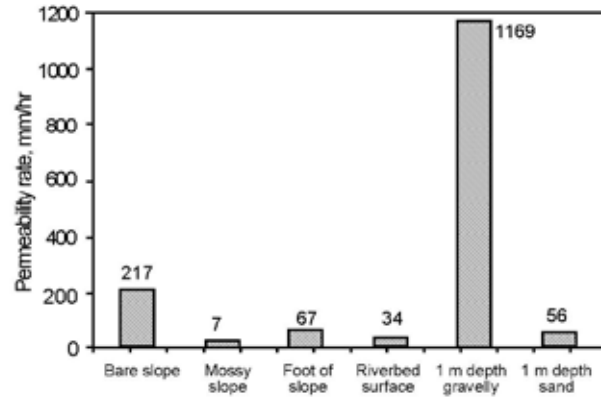
FIGURE 7. Results of permeability test.

FIGURE 8. Sources of sediment supply: (a) River terrace, (b) Slope and gully, and (c) River banks

HYDRAULIC PARAMETERS

The CRB lacks gauge station, therefore discharge (Q) and velocity (V) of the Churiya River were estimated using continuity equation and Manning's equation (Chow, 1959), respectively as:

$$Q = V A \qquad (2)$$

$$V = \left(R^{2/3} \, S^{1/2} \right) n \qquad (3)$$

where, A is cross-sectional area at bankfull stage, R is hydraulic radius, which is a ratio of A to sum of width and twice the bankfull depth, S is an average channel slope and n is Manning's roughness coefficient. River hydraulic parameters (stream length, drop in elevation and stream width) were obtained from terrain analysis. The average depth for the channel from field survey was 2 m. The segment considered for the channel width calculation was from the beginning of the second order mainstem (Churiya Bridge) to the end of the third order mainstem river (FIGURE 2).

The length and drop of the mainstem Churiya River are 8.73 km and 293 m, respectively. The channel gradients of 1st, 2nd and 3rd order streams are 0.050, 0.042 and 0.017 m/m, respectively (TABLE 3) As shown in FIGURE 9, the channel gradient is not uniform and is relatively steeper at the upstream segment and major slope break exists between each order mainstem.

The average widths of 2nd and 3rd order streams are 95.21 m and 140.49 m, respectively. The width/depth ratio (W/D ratio) nearly doubles in the 3rd order segment. The average bankfull discharges of 2nd and 3rd order streams are 1000 m³/s and 1421 m³/s, respectively. Similarly, the average bankfull velocities are 5.25 m/s and 5.06 m/s, respectively, and these do not differ largely. In the downstream segment the discharge increases due to increased stream cross-sectional area and the corresponding drainage area.

Comparing the boundary shear stress (τ) on the channel bed at bankfull discharge with the critical shear stress (τ_c) required to transport a specific bed material size, the competency of the river was evaluated. The boundary shear stress and critical shear stress for D_{50} was obtained using the following expressions (Shield, 1936):

$$\tau = \gamma R S \qquad (4)$$

$$\tau_c = \theta_c g \left(\rho_s - \rho \right) D_{50} \qquad (5)$$

where, γ = unit weight of water (9810 N/m³), R = hydraulic radius (m), S = slope of stream (m/m), θ_c = Shields parameter for critical dimensionless shear stress, g = gravitational constant (9.81 m/s²), ρ_s = density of sediment (2650 kg/m³), ρ = density of water (1000 kg/m³), and D_{50} = median diameter of particle (m). For coarse-bedded stream, where dimensionless viscosity may exceed tens of thousand, the θ_c approaches nearly a constant value of 0.045 from the Shields Curve, and therefore, this value was considered.

Boundary shear stresses of 2nd and 3rd order segments of the Churiya River are 791 N/m² and 324 N/m², respectively. These boundary shear stresses are large enough to entrain respectively the size grades of 543 mm and 222 mm. Considering the average D_{50} of 2nd (24 mm) and 3rd order streams (16 mm), the critical shear stresses required to entrain D_{50} (τ_{c50}) approach 18 and 12 N/m², respectively. Even the critical shear stresses required to move D_{max} (τ_{cmax}) of 2nd (53 N/m²) and third order streams (70 N/m²) are very small compared to the corresponding boundary shear stresses (TABLE 4). Therefore, boundary shear stresses exerted by 2nd and 3rd order segments at the bankfull flow are strong enough to transport riverbed material from the basin.
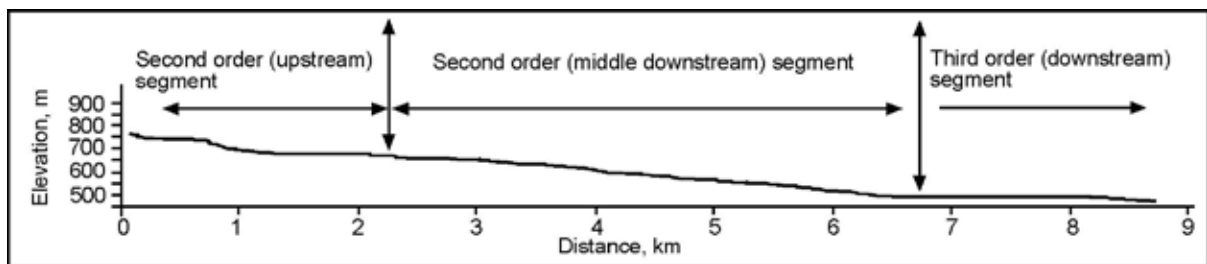

FIGURE 9. Longitudinal profile of the Churiya River. The vertical scale is exaggerated two times.

TABLE 3. Flow competence parameters of the Churiya River

Stream order	segment length	Elevation drop	Slope	Width, W	Area, A	Depth, D	W/D ratio	Hydraulic radius, R	Discharge, Q	Velocity, V
	(m)	(m)		(m)	(m^2)	(m)		(m)	(m^3/s)	(m/s)
Second	5956	248	0.042	95.21	190.42	2.00	47.61	1.92	1000	5.25
Third	2714	45	0.017	140.49	280.98	2.00	70.25	1.94	1421	5.06

TABLE 4. Hydraulic parameters of the Churiya River

Stream order	R	Q	V	τ	D_{50}	D_{max}	τ_{c50}	$\tau_{c\,max}$	64 - 256 mm (cobble grade)	Ω_b
	(m)	(m^3/s)	(m/s)	(N/m^2)	(mm)	(mm)	(N/m^2)	(N/m^2)	$\tau_{c\,cobble}$ (N/m^2)	(m-kN/s/m^2)
Second	1.92	1000	5.25	791	24	73	17	53	46.62 - 186.47	4.16
Third	1.94	1421	5.06	324	16	97	12	70	46.62 - 186.47	1.64

STREAM POWERS

The stream power per unit bed area as defined by Brookes (1990) was calculated as:

$$\Omega_b = V\tau \qquad (6)$$

where, Ω_b = stream power per unit bed area (m-kN/s/m^2), V = bankfull velocity from equation (3), and τ = boundary shear stress (kN/m^2) from equation (4).

The scouring rate is strongly influenced by the stream power (Ps). It was calculated as:

$$Ps = QS \qquad (7)$$

where, Q is the discharge and S is the stream slope. The rational equation was used to estimate discharge, allowing equation (7) to be rewritten as:

$$Ps = (1/3.6)f.r.A.S \qquad (8)$$

where, f is the runoff coefficient, r is the rainfall intensity, A is the drainage area, and S is the average stream slope. The values of f and r were considered to be equal within the same basin; thus, the ratio of average stream powers between the lower (w) order and higher (w_{+1}) order sub-watersheds were thus calculated from the measurements of their drainage area and average stream slope as:

$$Ps_{w+1} = (A_{w+1}.S_{w+1}.Ps_w)/(A_w.S_w) \qquad (9)$$

where Ps_w, A_w and S_w are stream power, average drainage area and average stream slope of the w order watershed. S_w is the ratio of stream drop to stream length of the w order watershed. Both stream power per unit bed area (Ω_b) and the ratio of stream power of higher to lower order watershed (Ps) were calculated for the CRB.

Stream powers per unit bed area (Ω_b) of 2nd and 3rd order segments were 4.16 and 1.64 m-kN/s/m^2, respectively. Because the bankfull velocities in both segments are nearly equal, Ω_b is mainly a function of τ. The rates of transport per unit bed area in 2nd and 3rd order segments are high enough to mobilize riverbed materials D_{50} as well as D_{max} during the bankfull flow. The stream of 2nd order segment is 4.26 times and that of 3rd order segment is 1.75 times strong enough to transport the largest cobble (256 mm). Undoubtedly, Ω and Ω_b of 3rd order stream diminish due to reduction in slope and τ. This reduction (of about 2.5 times) perhaps indicates that the 3rd order stream has been depositing significant volume of sediments on its channel bars each time during the subsidence of flood.

Mean stream power (Ps) of 1st order sub-watershed is 1.12 and 2.85 times higher than 2nd and 3rd order sub-watersheds, respectively (FIGURE 10a). Similarly, mean stream power of 2nd order sub-watershed is 2.54 times larger than 3rd order sub-watershed. It suggests that stream powers of 1st and 2nd order sub-watershed have high scouring power and potentiality in transporting sediments into the 3rd order sub-watersheds. Most of the 3rd order sub-watersheds, localized near the confluence with the Uttarpani River, at the outlet of the CRB, have longer reach length (FIGURE 10b) and smaller catchment area (FIGURE 10c) compared to its corresponding lower order sub-watersheds, therefore bear low stream power.

Other possibility for diminish of stream power of 3rd order stream is an abrupt reduction of stream slope from 2nd to 3rd order segment. On of the causes of this slope break is an extension of the Central Churia Thrust (FIGURE 2). Such a slope break is accompanied with riverbed gravels, which

are highly permeable. On these, surface flows appear only during intense rainfall that exceeds permeability rate, called 'wadji' rivers by Nelson et al. (1980) and Bruinjnzeel and Bremmer (1989).

During the survey in dry season (November to December), surface water was not observed up to the sampling point 3 to 4 (FIGURE 2). Surface flows at upper segments (2nd and 3rd order segments) were seen only during the intense rainfall of July and August when average daily and monthly rainfall exceeded 100 mm and 350 mm, respectively. During this time the surface water level could rise up to 2 m, and flows are capable of entraining and transporting all the size-grades present on the riverbed. However, the stream powers exerted by the river during flood stage tend to cease immediately after

decline of rainfall, and no surface flow appears to move riverbed material. Therefore, without surface flows, entrainment and transportation of riverbed sediments may not be expected during the dry season.

Furthermore, sediment concentrations are elevated soon after the first monsoon rains, when the soils are dry, the protective vegetative cover is minimal, and fine-grained unconsolidated material is available in adequate quantity (Kale and Hire, 2004). This means that irrespective of the flow magnitude, the sediment concentration is higher during the early monsoon season. Therefore, it is evident that fewer high-magnitude flows can remove a large proportion of suspended sediment from the 1st and 2nd order basin and deposit near/at the bifurcations of the streams.
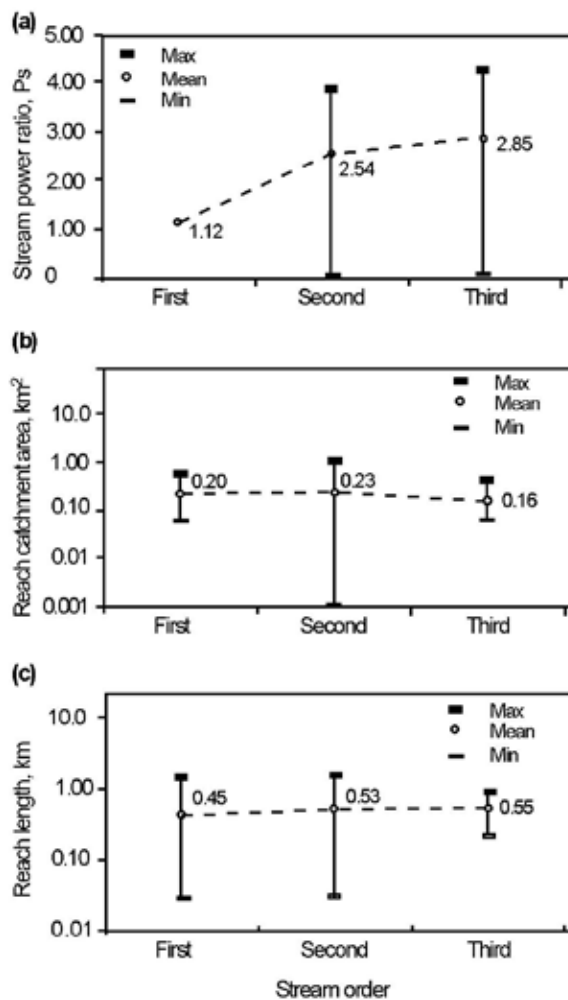

FIGURE 10. A schematic diagram of the reach catchment and reach length: (a) Stream power ratios, (b) Reach length and (c) Reach catchment area.

CONCLUSIONS

From the results, the sediment dynamics of the CRB could be expressed by carrying out morphometric analysis, land use and cover classification, grain size analysis of riverbed material and using river hydraulic parameters. The CRB has longer stream lengths and larger drainage areas than other Siwalik basins. From the nature of the loosely consolidated conglomerate or gravelly outcrop and riverbed material, it is observed that the river carries significant amount of sediments as available in the source. During high rainfall period, the river possesses large boundary shear stress, and has exceeding competency and capacity to flush out material from the outcrop, river banks and riverbed, and finally from the Churiya basin. Stream power diminishes from 2nd to 3rd order segments mainly because of great reduction of slope, boundary shear stress, catchment areas, and increased infiltration rate.

The scenario of the river dynamics changes when dry season prevails and sediment transport is ceased. Comparing the 2nd with 3rd order segments, during transitional period between high flow and subsiding flow, while 2nd order segment is still capable of transporting coarse riverbed material, 3rd order segment ceases its competency to move sediments out of the basin. Therefore, the sediments derived from 2nd order segment are mostly deposited in river bars of 3rd order segment. Hence, 3rd order segment possibly is the zone of deposition throughout the year, except during the intense rainfall period.

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