Discharge and sediment loads of two streams in the mid-hills of central Nepal

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Stream flow, nutrient loading, and sediment yield closely reflect land use and management practices in relation to growing seasons in mid-hill watersheds of the central Himalaya. A preliminary study was conducted to determine approximate total water discharge and sediment yields from the Galaundi and Pokhare catchments. Mean discharge and sediment loads during the 2002 rainy season were 2.1 $m^3 \cdot s^{-1}$ and 0.9 $kg \cdot s^{-1}$ for Galaundi Khola and 0.45 $m^3 \cdot s^{-1}$ and 0.28 $kg \cdot s^{-1}$ for Pokhare Khola. Estimates of total annual discharge of water and sediment were, respectively, 27.8 million m^3 and 11,400 t (Galaundi) and 6.4 million m^3 and 3,500 t (Pokhare). These corresponded to about 71.6% and 60.4% of total rain volumes and soil loss rates of 5.18 $t \cdot ha^{-1}$ and 5.83 $t \cdot ha^{-1}$ for Galaundi and Pokhare sub-watersheds, respectively. Good correlations were observed for stream discharge vs. sediment concentration (R^2 = 0.83 and 0.94 respectively) and rainfall amount vs. discharge (R^2 = 0.94 and 0.96 respectively) for both streams.

Key words: stream flow, sediment concentration, land use, pre-monsoon, sub-watershed

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The mid-hill watersheds of central Nepal are characterized by a myriad of ephemeral and perennial streams, many with steep gradients from source areas to confluence junctions with major rivers. The seasonal nature of rainfall, being concentrated mostly within the five-month period May to September and steep terrain govern the hydrologic characteristics of these streams. Thus, many streams that run dry or dwindle to a mere trickle for much of the year are transformed into raging, torrential streams up to 2 m deep in some areas. Moreover, land use practices, seasonal paddy cropping, and diversion for irrigation all substantially influence flows and sediment concentration in the streams.

Studies in the watersheds of the Jhikhu Khola (Kavre district) and Yarsha Khola (Dolakha distric) in the mid-hills of Nepal have shown that, while major storm events are responsible for generation of the highest flows and channel scouring in the steep mountain streams, the medium-sized events are more likely to be influenced by land cover and land use (Merz et al. 2000). Furthermore, Nakarmi et al. (2000) reported that while water storage within those same watersheds was more effective on agricultural than on grazing (grass/shrub) land, erosion was higher at cultivated sites during small to medium rain events. However, in the case of high rainfall events, degraded areas were the main sources of sediment; the likely mechanism is soil compaction, which causes reduced water infiltration and storage capacity, resulting in high runoff velocities, which lead to gully erosion.

Many studies indicate that soil erosion, nutrient losses and sediment transport in mountain streams is greatest on the occasion of those few major storms that typically occur during the pre-monsoon and early growing season (Carver and Nakarmi 1995, Nakarmi et al. 2000, Atreya et al. 2002). The main reasons for this are that during this critical period soil cover is at a minimum and farming operations (tillage, planting, weeding, etc.) are in progress.

The Himalayan region in general, and the mid-hills of Nepal specifically, are faced with the conflicting needs of a growing human population on the one hand, and, on the other, natural ecosystems urgently in need of protection. This has resulted in escalating environmental degradation due to unsustainable timber, fodder, and fuel wood extraction; subsistence agriculture on marginal lands; and infrastructure development. These activities impact the hydrology of mountain watersheds, particularly with regard to flow characteristics and sediment loads, due to soil erosion and changes in water storage and runoff patterns. See Ives and Messerli (1989) as well as the Ives (2004, forthcoming) for a comprehensive assessment of these trends.

Land use changes due to forest clearing; intensification of agriculture (off-season cash crops) and diversion of stream waters for irrigation all impact stream flow, sediment content and nutrient dynamics (Carver and Schreier 1995, Schreier and Shah 2000, Sharma et al. 2002). Therefore, such land use dynamics and farming intensification will require careful balancing of water and nutrient budgets for sustainable production and environmental protection (Schreier et al. 1994).

Methods

The streams were sampled periodically (randomly) from January to September 2002, so as to obtain representative data for a range of conditions, from dry season minimum flows to rainy season high flows. Samplings were also performed in conjunction with critical events such as pre-monsoon storms, planting, and harvest, when streams carry unusually high sediment loads.

Data gathering was constrained, however, by the unfeasibility of sampling during peak flow periods, when river velocities and depths were prohibitively high. Also, it was difficult to time sampling so as to capture specific rainstorm events of high intensity, especially since these often occurred at night.

Stream velocity was determined using the floatation technique. Cross-sectional areas of each stream were determined by measuring the depth of water at 0.1 m intervals across relatively narrow and uniform segments of the streams. Sediment concentration was determined by taking one-liter grab samples from the middle depth of the stream. Water samples were allowed to settle and the residue was then oven-dried to obtain sediment weight per liter of water.

Stream discharge (Q, $m^3 \cdot s^{-1}$) and sediment delivery rate (SDR, $kg \cdot s^{-1}$) were calculated according to the following formulas:

$$Q = A * V \qquad \text{[Eq. 1]}$$

where,
A = cross-sectional area of stream, m^2
V = flow velocity, $m \cdot s^{-1}$

$$SDR = Q * C \qquad \text{[Eq. 2]}$$

where,
C = sediment concentration, $g \cdot l^{-1}$

Results and discussion

Stream flow measurements indicated that flow volumes in both streams are generally low (<1 $m^3 \cdot s^{-1}$ for Galaundi and <0.1 $m^3 \cdot s^{-1}$ for Pokhare). Flow increases dramatically (>4 $m^3 \cdot s^{-1}$ for Galaundi and >1 $m^3 \cdot s^{-1}$ for Pokhare) shortly after the onset of a major rainstorm, but diminishes rapidly upon cessation of the rainfall. Such quick responses and rapid fluctuations are likely due to the small size of the sub-watersheds and steep stream gradients, as observed by Merz et al. (2000).

Casual examination of the data gathered from random samplings during the rainy season of 2002 (**Table 1**) indicated high variability of both stream flow volumes (discharge) and sediment loads. Simple arithmetic means of the discharge and sediment yield rates during the rainy season were calculated to be about 2.1 $m^3 \cdot s^{-1}$ and 0.9 $kg \cdot s^{-1}$ for Galaundi, and 0.45 $m^3 \cdot s^{-1}$ and 0.28 $kg \cdot s^{-1}$, for Pokhare, respectively. These values are comparable to data from other similar sized sub-watersheds reported in the available literature (Merz et al. 2000). Taking the sub-watershed areas to be 22 km^2 and 6 km^2, we derived crude estimates of mean total water discharge and sediment yield during the rainy season of 25 million m^3 and 11,400 t for Galaundi and 5.7 million m^3 of water and 3,500 t of sediment for Pokhare, respectively (**Table 2**).

It was, however, established from both direct observation and inquiry with local residents that for about 7 months during the dry (October to April) period**,** stream flows are at a minimum and that sediment load is essentially zero. It was also noted that maximum flows and sediment loads occurred for only a few events, typically in the pre-monsoon and early rainy seasons (May-July) (**Table 1)**. At other times during the rainy season, flows and sediment concentrations were generally low to medium.

Thus, assuming that minimum flows correspond to about 0.16 $m^3 \cdot s^{-1}$ for Galaundi and 0.04 $m^3 \cdot s^{-1}$ for Pokhare, the total discharge volumes for these streams during the remaining (7 months) of the year were calculated to be 2.8 million m^3 and 0.7 million m^3, respectively. Since sediment loads during the rest of the year are negligible, total sediment yields may be taken to be those calculated for the rainy season alone. Summing the total water discharge and sediment yield values for rainy and dry seasons for each stream, estimates for the annual mean totals are shown in **Table 2**. Using the ten-year mean monthly rainfall data of Dhunbesi, Dhading, the total annual flow volumes represented 71.6% and 60.4% of the total rainfall volumes for Galaundi and Pokhare sub-watersheds, respectively (**Table 3**). The remaining water presumably percolates into the groundwater or is lost through evaporation and transpiration.

Total annual soil removal from the catchments areas, determined by dividing annual sediment yield by the total land area of each sub-watershed (approximately 600 ha for Pokhare and 2200 ha for Galaundi), was 5.83 $t \cdot ha^{-1} \cdot y^{-1}$ and 5.18 $t \cdot ha^{-1} \cdot y^{-1}$ for Pokhare and Galaundi sub-watersheds, respectively. These values fall in the lower range of observed soil loss rates reported in the literature (Chalise and Khanal 1997, Nakarmi et al. 2000, UNEP 2001) and reflect the well-managed upland terrace and forested areas over much of the two sub-watersheds. In general, soil erosion appears not to be a major problem in the study sub-watersheds. Thus, adequate management and conservation of agricultural and forest lands could lead to low overall soil erosion rates (at the catchment scale) and correspondingly low sediment loads in the streams.

TABLE 1. Stream flows, sediment yields and sediment concentration for Galundi Khola and Pokhare Khola

Sampling Date	Galundi Khola			Pokhare Khola		
	Discharge ($m^3 \cdot s^{-1}$)	Sed. yield ($kg \cdot s^{-1}$)	Sed. conc. ($g \cdot L^{-1}$)	Discharge ($m^3 \cdot s^{-1}$)	Sed. yield ($kg \cdot s^{-1}$)	Sed. conc. ($g \cdot L^{-1}$)
20/1/02	0.17	0.00	0.00	0.03	0.00	0.00
26/05/02†	0.57	0.75	1.30	0.27	0.03	0.12
04/06/02	0.16	0.01	0.04	0.04	0.01	0.02
02/07/02	4.60	1.41	0.54	1.16	1.08	0.93
02/07/02	4.80	1.27	0.50	1.04	0.73	0.70
02/07/02	4.24	2.48	0.30	0.83	0.50	0.60
02/07/02	3.92	2.39	0.36	0.69	0.29	0.42
13/07/02	0.30	0.03	0.10	0.08	0.06	0.07
02/08/02	0.90	0.32	0.35	0.14	0.04	0.30
30/08/02	1.00	0.19	0.19	0.11	0.02	0.14
09/08/02	0.72	0.14	0.20	0.12	0.03	0.10
Average*	**2.12**	**0.90**	**0.39**	**0.45**	**0.28**	**0.34**

† Outlier – excluded from regression analysis
* Average is for rainy season, i.e., May to September, sample size = 10

TABLE 2. Mean stream water discharge and sediment yield estimates for Galaundi Khola and Pokhare Khola (sample size = 10)

Stream	Rainy season		Dry season		Total Annual	
	Discharge volume (m^3)	Sediment yield (t)	Discharge volume (m^3)	Sediment yield (t)	Discharge volume (m^3)	Sediment yield (t)
Galaundi	25 million	11,400	2.8 million	~0	27.8 million	11,400
Pokhare	5.7 million	3,500	0.7 million	~0	6.4 million	3,500

TABLE 3. Mean monthly rainfall, mean total rain volumes and total annual rain volumes and discharge for the two sub-watersheds

Month	Mean rainfall (mm)	Total Rain Volume (X 10^3 m^3)	
		Pokhare	Galaundi
January	18.7	112.2	411.4
February	14.2	85.2	312.4
March	31.3	187.8	688.6
April	39.7	238.2	873.4
May	134.9	809.4	2967.8
June	309.2	1855.2	6802.4
July	418.1	2508.6	9198.2
August	492.2	2953.2	10828.4
September	228.9	1373.4	5035.8
October	48.4	290.4	1064.8
November	13.9	83.4	305.8
December	16.6	99.6	365.2
Total Annual Rain	1766.1	10596.6	38854.2
Total Discharge Volume ($m^3 \cdot s^{-1}$)		6400	27800
Percent of discharge to rainfall		60.40	71.55

Regression analyses

Regression plots of sediment concentration versus discharge (Q) for the streams indicated that there were good correlations between these parameters for both streams over the range of values obtained during the monitoring period. This was reflected in high R^2 values obtained for the logarithmic and linear regression functions for Galaundi ($R^2 = 0.83$) and Pokhare ($R^2 = 0.94$), respectively (**Figure 1** and **2**).

In the case of Galaundi, one outlier eliminated in the analysis. The relationships for each stream are given by the following equations:

For Galaundi

$$\text{Sediment Concentration} = 0.123 \ln(Q) + 0.25;\ R^2 = 0.83 \qquad \text{[Eq. 3]}$$

For Pokhare

$$\text{Sediment Concentration} = 0.696(Q) + 0.026;\ R^2 = 0.94 \qquad \text{[Eq. 4]}$$

Nearly 90% of the rainfall occurs during the months of May through September (**Figure 3**) which corresponds to the period of greatest stream flow, although the sediment concentration in stream water fluctuates greatly, being highest during the early season (May-July) and at sporadic critical periods throughout the rainy season, such as paddy planting time (**Table 1**) and during particularly intense storms, a pattern noted by other researchers (Carver and Nakarmi 1995, Nakarmi et al. 2000, Atreya et al. 2002).

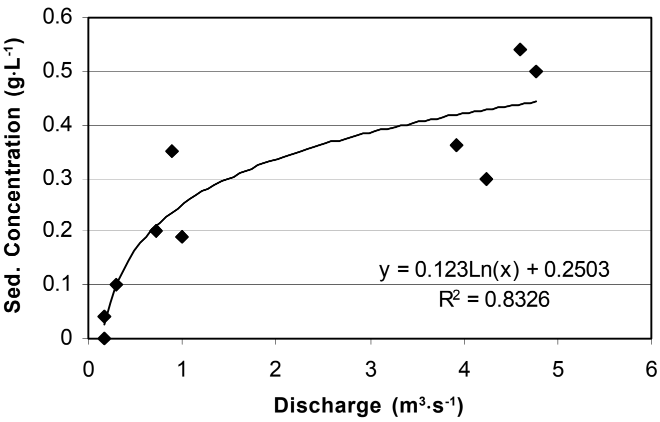

FIGURE 1. Regression plot of flow rate vs. sediment delivery for Galaundi Khola

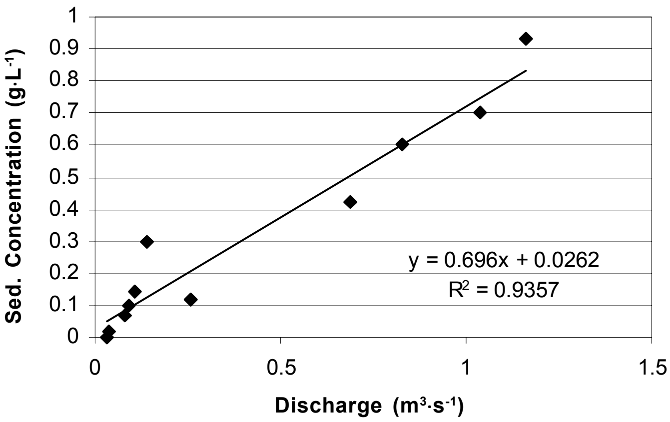

FIGURE 2. Regression plot of flow rate vs. sediment delivery for Pokhare Khola

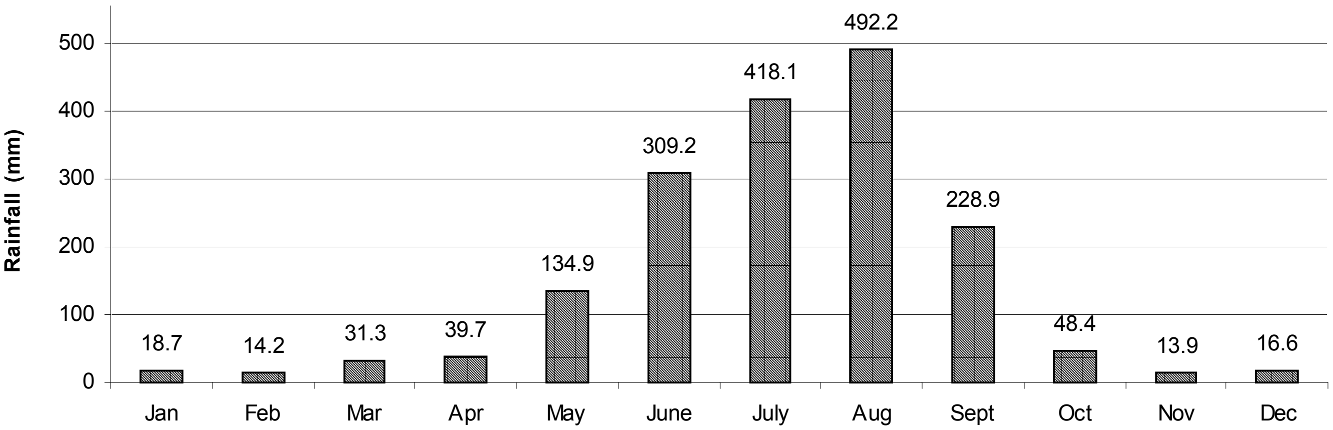

FIGURE 3. Mean monthly precipitation recorded for the study district over a ten-year period from 1991 to 2000 at Dhunbesi Station, Dhading (Source: Department of Hydrology & Meteorolgy, HMGN 1995, 1997, 1999; Climatological Records from 1987 to 1996)

Crude calculations of the total volume of precipitation falling over each sub-watershed, based upon the 10-year mean monthly rainfall and total annual stream flow volume as a percent of annual rainfall indicated that about two-thirds of the total rainfall flows out of the catchments as stream discharge (**Table 3**), the rest going to groundwater or evapo-transpiration. Moreover, stream discharge was significantly correlated with rainfall amount for the days monitored (24 h period during which sampling was done) as seen from the regression plots (**Figure 4**).

For the limited number of observations made, good correlations were seen between 24-hour rainfall totals and same-day discharge rates for both streams (**Figure 4**). This indicated that stream flow responds rapidly to rainfall due to the small size and steep gradients for both Pokhare and Galaundi sub-watersheds. Because of this fact, however, timing of stream discharge measurement is critical and pinpointing peak discharge is difficult.

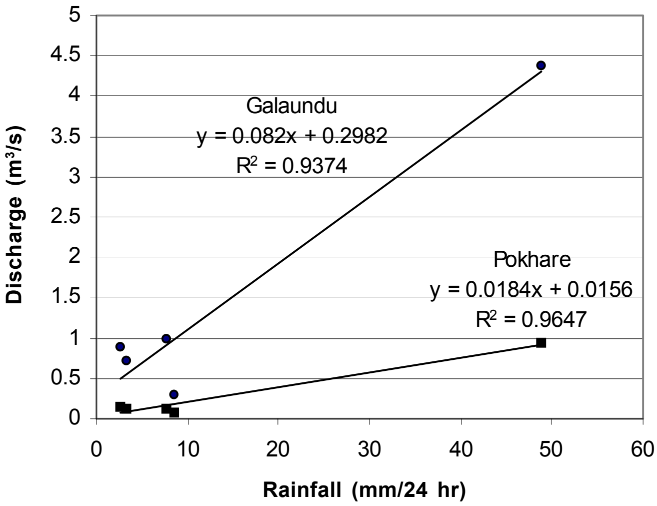

FIGURE 4. Regression plots of 24 h rainfall amount and stream discharge (flow rate, measured during the 24 h period)

Conclusions

Climatic and stream flow data revealed that most of the rainfall occurs from May to September and that during much of this period discharge from both streams is low. High flows tend to occur a few hours after heavy storms due to the steep gradients and small catchment areas of the streams. High sediment concentrations were confined to critical periods such as the pre-monsoon intense rains and during tillage/planting times when the soil is least protected and most disturbed. Soil erosion did not appear to be a major problem in the study watersheds, presumably due to adequate management and conservation practices on agricultural and forestlands. Despite limited observations, good correlations were obtained for discharge vs. sediment load and rainfall amount vs. discharge for both streams. Land use and farming practices clearly influence the nature of stream flow, as well as sediment loading in streams with steep gradients in the mid-hills. Further work is, however, needed to establish the causal relationships among land use, agricultural intensification, stream discharge, and soil and nutrient losses, in order to formulate ecologically and economically sound recommendations for sustainable land management. ■

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