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GEOMORPHIC AND FOREST COVER CONTROLS ON MONSOON FLOODING, CENTRAL NEPAL HIMALAYA

RICHARD MARSTON[1], JACK KLEINMAN[2], AND MAYNARD MILLER[3]

ABSTRACT Devastating monsoon season floods in the central Nepal Himalaya have been difficult to predict with any precision, reliability, or accuracy. Deforestation is often blamed as the principal cause of flooding. This paper uses field data at 22 stream crossings, together with drainage basin morphometric data and forest cover data, to determine the dominant controls on bank-full discharge from monsoon storms. Results demonstrate that 82 percent of the variation in bank-full discharge can be explained as a function of drainage area alone; forest cover did not add explanatory power. Findings from this study can be used to guide planning for future projects that will be affected by flood hazards in the central Nepal Himalaya, including irrigation, hydropower, and footbridge construction.

RÉSUMÉ *Régulation des inondations de mousson par la géomorphologie et la couverture forestière de l'Himalaya du Népal central.* Les inondations dévastatrices de mousson dans l'Himalaya du Népal central sont difficiles à prédire avec précision, fiabilité et exactitude. La cause principale des inondations est souvent attribuée à la déforestation. Cet article utilise les données collectées à 22 passages de cours d'eau, ainsi que les données morphométriques du bassin hydrographique et les données de couverture forestière, pour déterminer les facteurs dominants de régulation du débit proche du débordement produit par les tempêtes de mousson. Les résultats démontrent que 82 pour cent de la variation du débit proche du débordement peuvent s'expliquer uniquement en fonction du bassin hydrographique, la couverture forestière ne fournissant aucun éclaircissement supplémentaire. Ces résultats peuvent être utilisés pour aider à la planification de projets futurs exposés aux dangers d'inondation dans l'Himalaya du Népal central, y compris l'irrigation, l'énergie électrique et la construction de passerelles à piétons.

ZUSAMMENFASSUNG *Geomorphische und Waldflächen-bezogene Einflüsse auf Überschwemmungen während des Monsun im Himalaya von Zentralnepal.* Vorhersagen von verheerenden Überschwemmungen während des Monsun im Himalaya von Zentralnepal sind weder zuverlässig noch genau. Oft wird Entwaldung als Hauptgrund für Überschwemmungen verantwortlich gemacht. Diese Arbeit benutzt Feldmessungen an 22 Flußkreuzungen zusammen mit morphometrischen Daten aus den Einzugsgebieten und über deren Bewaldung, um die Hauptparameter zu bestimmen, die die Ablaufvorgänge bei Hochwasser während der Monsunregenfälle beschreiben. Ergebnisse zeigen, daß 82% der Unterschiede in den Abflußraten bei Hochwasserstand nur als Funktion der Struktur des Abflußgebietes allein erklärt werden können; Bewaldung, dagegen, beeinflußt die Vorhersage nicht. Die Ergebnisse dieser Studie können Richtlinien für zukünftige Projekte liefern, die im Himalaya von Zentralnepal durch Überschwemmungen gefährdet werden könnten. Solche Projekte betreffen z.B. den Bau von Bewässerungsanlagen, Wasserkraftwerken und Fußgängerbrücken.

INTRODUCTION

Devastating floods occur in the central Himalaya of Nepal during the monsoon months of June through September. Monsoon floods differ from glacial lake outburst floods (GLOFs) and floods from breaching of landslide dams in that monsoon floods are of longer duration and less sudden in onset. Nevertheless, attempts to estimate the magnitude of specific flood events using approaches such as the rationale formula have largely failed (Bruijnzeel and Bremmer, 1989). The understanding and predicting of monsoon-related floods have been hampered by the lack of adequate hydrologic data on rivers needed to perform regional flood frequency analyses or empirical, synoptic modeling with any precision, accuracy, or reliability (Kattelmann, 1987; Bruijnzeel and Bremmer, 1989; Hofer, 1993).

The magnitude of floods is exacerbated in the Himalaya of Nepal by the tremendous relief (Kalvoda, 1992; Shroder, 1993). The world's highest mountains and deepest gorges provide the setting for some of the world's most erosive rivers (Figure 1). The damage from floods takes several forms (HMG/WECS, 1987). First, floods destroy foot bridges that often provide the only link between remote mountain villages (Bishop, 1990). Second, irrigation diversions are demolished on a regular basis. Third, peak flows trigger mass wasting by undercutting steep, stream-adjacent slopes. Channel aggradation due to

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[1] Foundation for Glacier and Environmental Research and University of Alaska Southeast, Juneau, AK 99801, and Department of Geography and Recreation, University of Wyoming, Laramie, WY 82071-3371, U.S.A.

[2] Deceased; formerly U.S. Geological Survey Cascades Volcano Observatory, Vancouver, WA 98661, U.S.A.

[3] Glaciological and Arctic Sciences Institute, University of Idaho, and Foundation for Glacier and Environmental Research, Moscow, ID 83843, U.S.A.

stream-adjacent mass wasting accelerates the undercutting of hillslopes by subsequent floods, creating a positive feedback that feasible engineering structures cannot arrest (Froehlich and Starkel, 1993). Fourth, floodplain agricultural land is damaged by erosion and sedimentation associated with flood events. International conflict has resulted between Nepal on the one hand and India and Bangladesh on the other hand from devastating floods and related sediment discharge and channel instability in the Ganges River plain (Bandyopadhyay and Gyawali, 1994). Mountain subsistence farmers in the headwater regions of the Ganges drainage have been blamed by politicians and lowland farmers in India and Bangladesh for accelerating the problems because of deforestation and other poor land management practices (Ives, 1987).

Deforestation is suspected as a major control on flooding in the central Nepal Himalaya and downstream. This belief is reinforced by two factors. First, severe deforestation has been documented for some regions of the Nepal Himalaya (e.g., Tucker, 1987; Bishop 1990; Stevens, 1993) and assumed by others to exist on a widespread and irreversible basis elsewhere (World Bank, 1984; Ives and Messerli, 1989). Second, scientific studies in temperate climates have demonstrated that deforestation leads to an increase in peak flows (Troendle and Leaf, 1980; Reid, 1993) and the temptation exists to translate these results to the data-poor Himalaya. The link between deforestation in the Nepal Himalaya and monsoon season flooding in the downstream lowlands has been explored by a number of researchers, notably Goswami (1983), Ives (1987), Ives and Messerli (1989), and Hofer (1993). These studies generally conclude that heavy rainfall and river control works in the lowland regions, rather than upstream deforestation, are responsible for the majority of flood problems during the monsoon season. No studies have been forthcoming on the effects of deforestation on monsoon flooding locally within the Nepal Himalaya, although Wohl (1995) has reconstructed flood peaks for streams subject to GLOFs.

The objectives of this field investigation were to determine: 1) if the potential for monsoon-related floods could be estimated from a combination of terrain analysis techniques; and 2) to what degree forest cover explains the geographic variation in peak flows in the central Nepal Himalaya. It is anticipated that these findings will provide some decision criteria for land management and outside intervention targeted for flood control.

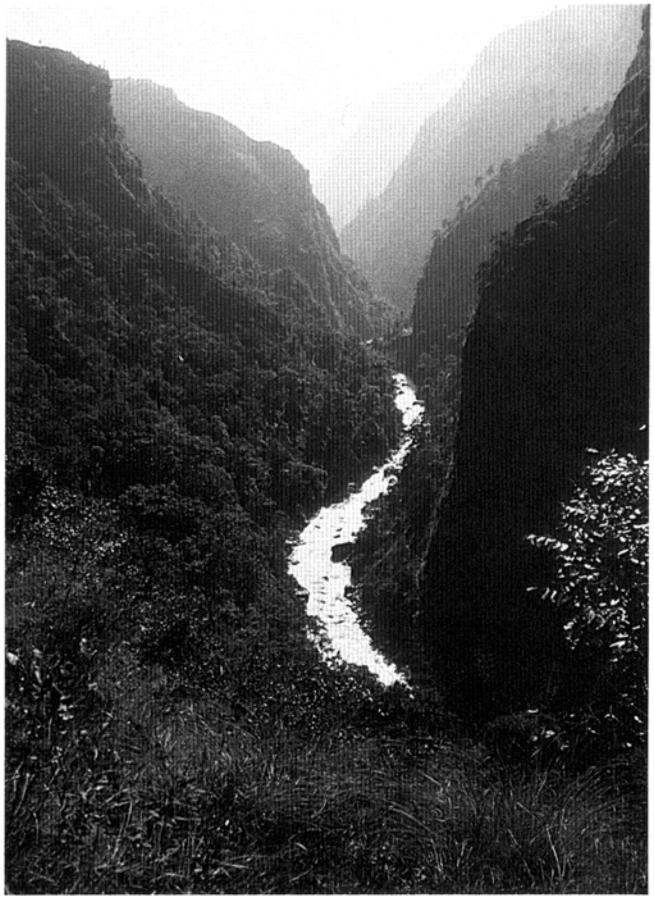
FIGURE 1. Buri Gandaki Gorge and River looking downvalley near Kholabenesi. Local relief on the hillslopes in this view is approximately 1,500 meters.

RESEARCH DESIGN

The study concentrated on the high mountain physiographic region of central Nepal. The bedrock is structurally competent, composed of gneiss and schist, weathering to coarse textured soils. The higher valleys were glaciated and have experienced significant postglacial downcutting. The study sites are situated within the Marsyandi and Buri Gandaki drainages, tributaries to the Trisuli and part of the Ganges River system (Figure 2). Data were collected at 22 stream crossings along a 240-km long transect on remote mountain trails where access allowed channel measurements. The mean elevation for the study basins above the 22 sites ranged from 1,190 to 4,330 meters. Channels affected by glacial lake outbursts which occurred in the last several decades were avoided in this study (Lochan Devkoka and Suresh Chalise, Tribhuvan University, pers. comm).

Bankfull discharge is a useful indicator of the overall potential for monsoon-related floods in Himalayan rivers not subject to GLOFs. In the case of Chepa Khola (site 3), which began gauging records in 1966, bankfull discharge occurs at a recurrence interval of 2.00 years. The stage where water fills the channel to the top of its banks marks the condition of incipient flooding. This is recognized by the topographic break between the channel and floodplain alluvium (Figures 3 and 4). In a gorge, bankfull discharge is recognized by a scour line or break in vegeta-

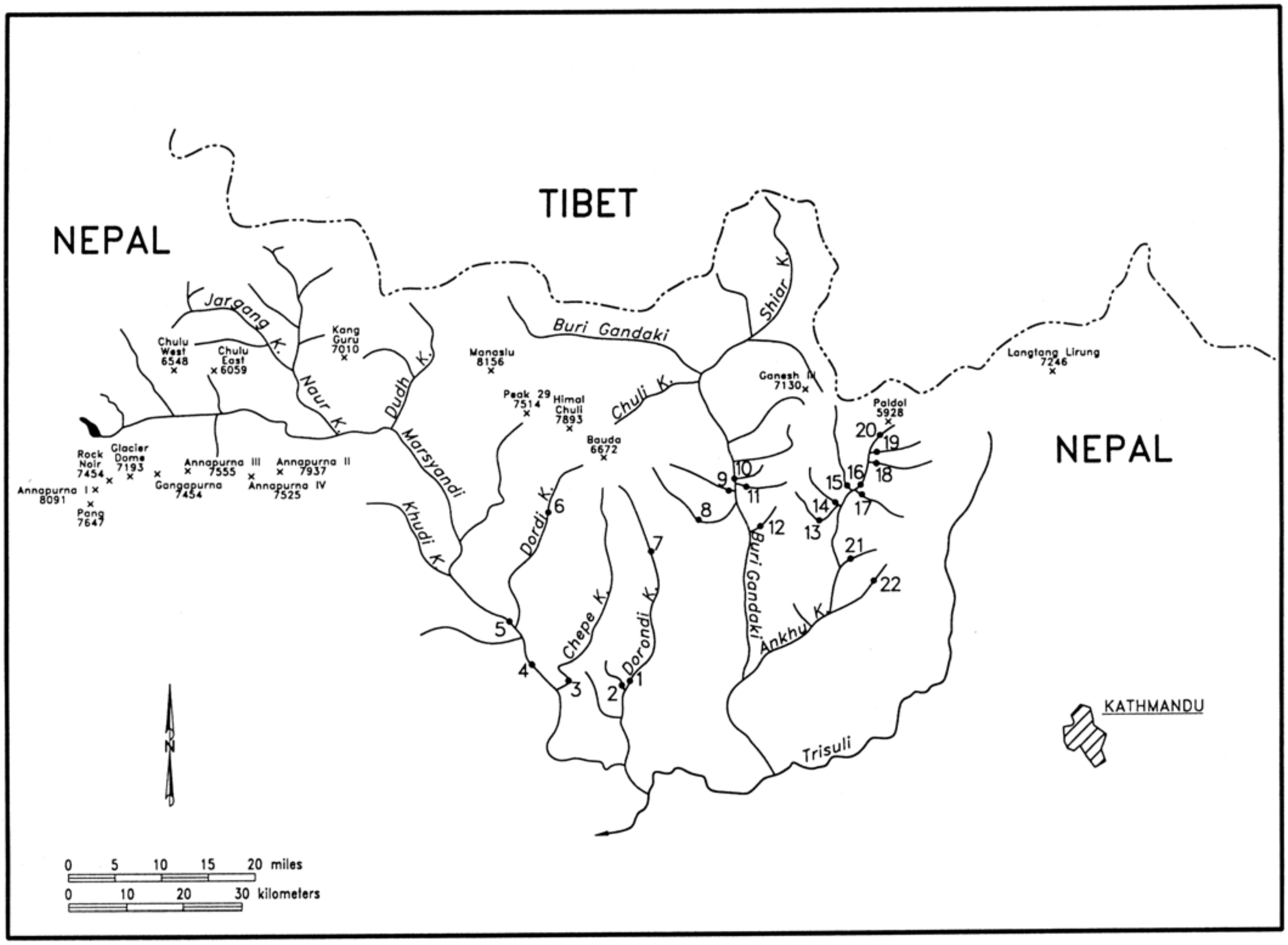

FIGURE 2. Location of the 22 study sites in the Marsyandi and Buri Gandaki drainages of central Nepal.

tion (Figure 5). Williams (1978) and Wohl (1995) have reviewed the various definitions of bankfull discharge and the methods used to measure it. Although Wohl used bankfull discharge to estimate rare GLOF peak flows, streams in the Manaslu-Ganesh Himal used in this study are not subject to GLOFs; they are either unglaciated or have no identified water stored behind ice dams or moraines. Following the strategy of Dalrymple and Benson (1967), the Manning equation was used to estimate bankfull discharge:

$$Q_{bf} = \frac{A(R^{0.667})(S^{0.5})}{n} \tag{1}$$

where Q_{bf} is bankfull discharge in cubic meters per second; R is hydraulic radius at bankfull stage in meters equal to A/P; S is an approximation of the energy gradient at bankfull stage expressed as a decimal fraction; and n is Manning's roughness coefficient at bankfull stage. A is channel cross-section area in square meters equal to the channel width (W) times the channel depth (D); and P is the wetted perimeter in meters equal to 2D + W. Direct measurements were acquired of channel width, depth, and gradient at the bankfull stage. Manning's n was estimated with Jarrett's (1984) regime equation for high gradient streams:

$$n = (0.39)(S^{0.38})(R^{-0.16}) \tag{2}$$

where S and R are as above. This equation has been validated for the range of S and R encountered in the present study (Jarrett, 1985, 1990).

Indian topographic survey maps at a scale of 1:63,360 were used to measure characteristics of the drainage basin upstream of each study site. Morphometric variables were chosen that have been demonstrated in the literature to affect peak flows, particularly in mountain regions (Gregory and Walling, 1973; Marston, 1978). Measurements were made of basin area (A), basin perimeter (BP), and basin elongation (BE) as defined by Schumm (1956). To calculate basin elongation, basin length (BL) had to be measured; the method of Potter (1961) was utilized. A high value of BE would indicate a more circular shaped drainage basin which would be expected to generate higher peak flows than an elongated basin. Measurements were also made of basin relief along the axis used to measure basin length (BL); relief ratio (RR) which equals basin relief (BR) measured along BL divided by the distance BL; and maximum basin relief (XBR) which

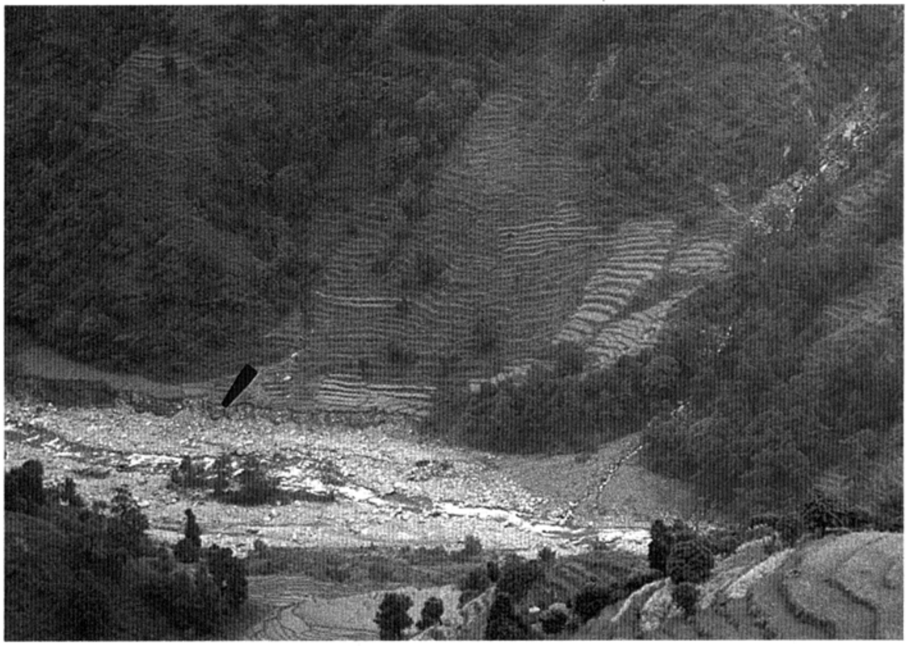

FIGURE 3. Bankfull discharge is identified by a distinct topographic break between the channel and floodplain alluvium, where a floodplain exists. This is a view of the Dorandi Khola, looking east from the village of Ghoachok. Arrow marks location of Figure 4.

equals the difference between the maximum and minimum elevation in the basin. No morphometric measurements were made of the drainage network because of the vagaries of delineating the network in the Himalaya by either remotely sensed imagery or contour crenulations.

Land-cover measurements were made from multispectral images acquired by the SPOT satellite in October and December 1986. These dates were selected to provide optimum conditions for using soil moisture contrast to enhance vegetation patterns since the soil would be wet but not saturated. In addition, snow cover was minimal at this time. Color positive transparencies of the images were purchased at a scale of 1: 400,000 and then photoenlarged to 1: 150,000 to improve mapping capabilities. The images are multispectral composites of three bands: green (0.50 to 0.59 microns), red (0.61 to 0.68 microns), and near-infrared (0.79 to 0.89 microns). A ground resolution of 20 meters has been claimed by the distributors of color composite SPOT imagery. The percent forest cover in each drainage basin (FOR) was measured using a dot grid from the imagery and was found to compare well with ground truth data from the field expedition and maps published by Nelson *et al.* (1980). From the 22 study sites, 11 were selected randomly for regression analyses. The regression equation was tested by correlating values of Q_{bf} predicted with the equation with field estimates of Q_{bf} for the 11 basins that had not been selected to develop the regression.

FIGURE 4. The difference between bankfull stage (at arrow) and low flow (below feet of person) at the site shown in Figure 3. Poorly sorted and imbricated colluvial deposits overlie stratified alluvium.

FIGURE 5. Flood-produced vegetation scour line in the gorge of a tributary to Ankhu Khola. Note, for scale, one of the co-authors located midway on the suspension bridge and another on the left edge of the bridge.

TABLE 1

Characteristics of drainage basins upstream of the 11 stream sites (refer to text for meaning of symbols in column headings)

Basin #/Name	Area (km²)	BP (km)	BL (km)	BE (df)	BR (km)	RR	XBR (m)	FOR %	BFW (m)	BFD (m)	S	n	Qbf (cms)
1. Dorandi Khola	377	122	30.7	.714	2.50	.0814	5547	50	32.1	1.62	.02	.094	219
*2. Unnamed	30.3	24.1	5.86	1.06	.731	.125	1280	65	20.1	.914	.01	.053	30.9
3. Chepa Khola	312	84.0	25.7	.775	2.29	.0891	4206	20	34.7	1.39	.02	.092	214
*4. Marsyandi @ Tark.	3240	298	79.4	.809	5.21	.0656	7498	40	50.3	5.49	.02	.057	1860
5. Marsyandi @ Phal.	2770	264	80.6	.747	4.74	.0588	7330	50	45.3	4.00	.02	.107	1105
6. Dordi Khola	150	57.5	17.1	.808	5.46	.319	6492	45	24.7	1.63	.05	.132	546
*7. Upper Dordi Khola	118	59.4	15.9	.771	3.72	.234	4938	20	41.1	1.83	.04	.087	243
8. Machha Khola	52.2	46.4	13.9	.587	3.17	.228	4267	25	14.9	1.66	.04	.121	98.9
*9. Namyung Khola	54.5	33.3	13.3	.626	3.54	.266	3536	15	24.4	2.13	.07	.106	194
*10. Buri Gandaki	3930	235	74.3	.952	4.51	.0607	7071	35	36.6	5.49	.05	.082	1430
11. Unnamed	29.7	20.6	6.97	.882	1.95	.280	2255	20	29.1	.808	.05	.120	98.7
12. Unnamed	34.3	23.8	7.61	.868	2.19	.288	2804	25	22.9	1.48	.05	.130	117
*13. Ghattya Khola	16.8	15.9	4.44	1.04	1.49	.336	2255	10	13.1	2.13	.08	.115	93.9
*14. Gandhkhani Khola	30.9	22.2	7.29	.860	1.68	.230	2591	20	13.1	2.44	.08	.112	119
*15. Unnamed	131	50.7	18.1	.714	5.64	.312	5639	50	21.3	2.44	.08	.110	212
*16. Manjor Khola	144	49.1	13.3	1.02	4.11	.309	4420	60	25.9	3.66	.05	.087	491
*17. Durgun Khola	35.4	23.8	8.56	.784	1.68	.196	2042	40	7.32	3.05	.03	.078	69.3
18. Linju Khola	18.8	15.1	5.07	.965	1.62	.320	2103	55	23.8	.962	.05	.123	79.3
19. Unnamed	16.4	16.5	6.02	.759	2.38	.395	2377	35	25.3	1.02	.04	.114	75.9
*20. Upper Manju Khola	15.9	15.8	4.44	1.01	1.40	.315	2774	30	13.7	1.83	.04	.089	72.2
21. Dungsei Khola	30.8	22.2	6.97	.898	2.44	.350	2651	30	19.8	1.69	.04	.122	129
22. Unnamed	21.0	17.4	6.34	.816	1.46	.230	2073	20	16.7	1.98	.03	.111	22.5

*Signifies watersheds used in developing equation 3.

BFW = bankfull width; BFD = bankfull depth; other symbols defined in text.

RESULTS

Field data collected for calculations of bankfull discharge are listed in Table 1. Estimates of bankfull discharge ranged from 31 to 1,860 m^3/sec. Values of Manning's roughness coefficient are high but not atypical of steep mountain rivers with severe turbulence (Trieste and Jarrett, 1987; Marcus *et al.*, 1992). Drainage basin characteristics upstream of the 22 stream sites are also presented in Table 1. The area of drainage basins above these 22 sites ranged over three orders of magnitude, from 15.9 to 3,930 km^2. A range in basin shape from elongated (low BE) to circular (high BE) is revealed. The percent coniferous forest cover ranged from 10 to 65 percent.

An equation was developed using stepwise regression procedures with data from the 11 basins marked with an asterisk in Table 1. Bankfull discharge was estimated as a function of basin area:

$$Q_{bf} = 11.5(A)^{.618} \qquad (3)$$

with an adjusted $r^2 = 0.84$, significant at $p < 0.001$, and a standard error of estimate = 0.219. Several morphometric variables could not be used in a multiple regression because of spurious correlations with basin area (e.g., relief ratio, basin perimeter, mean basin slope). No statistically significant differences could be found in the peak flow-basin area relationship among streams drainages contrasting geologic units. No statistically significant relations were revealed between bankfull discharge and forest cover or other watershed variables at the $p = 0.10$ level of significance. The partial correlation in a power relation between percent forest cover and bankfull discharge, controlling for basin area, was –0.41 using all 22 cases, not statistically significant at the $p = 0.10$ level (Figure 6). Caine and Mool (1981) also found a statistically significant relation between peak flows and drainage area using 43 channel cross-sections along two streams in the Middle Hills of Nepal. The exponent of 0.805 in the Caine and Mool equation was described by the authors as higher than reported elsewhere, but not unreasonable for small, steep drainages. Thus, the exponent of 0.618 in equation 3 is lower than that of Caine and Mool as well as exponents reported for other regions (e.g., Dunne and Leopold, 1978). We feel that our smaller exponent can be attributed to the fact that monsoon storm rainfall intensity is greater over smaller basins than over larger basins.

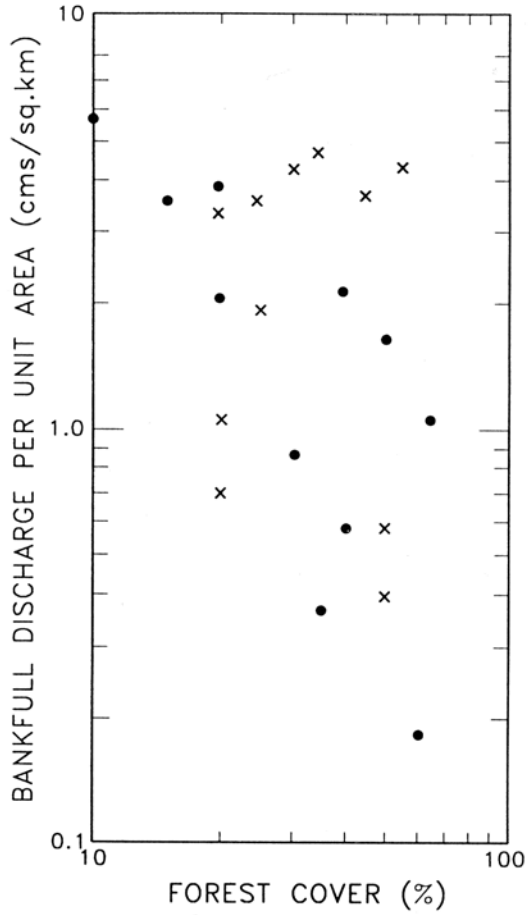

FIGURE 6. Scatterplot of percent forest area and bankfull discharge per unit area. Data points used to develop equation 3 are designated with dots. Crosses designate the 11 study sites used to test equation 3.

Equation 3 was used to predict values of Q_{bf} for the 11 basins that had not been used to develop the equation (Table 1). A coefficient of determination, r, of 0.70 was revealed between the predicted values from equation 3 and the field estimates of Q_{bf} (Figure 7). This correlation was significant at the $p < 0.001$ level, with a standard error of estimate = 0.24, indicating an acceptable degree of predictability with equation 3.

CONCLUSIONS

This project has demonstrated that it is possible to use geomorphic measurements of bankfull discharge to estimate the hazard of flooding at ungauged sites from monsoon rainstorm events. Moreover, it has been shown that bankfull discharge in the Central Nepal Himalaya can be accurately estimated using basin area alone as a predictor. Wohl (1995) did not find this relation to exist in her study streams in Nepal because they are affected by GLOFs and channel dimensions do not typically reflect an adjustment to rare, catastrophic events. Our finding that percent forest cover did not exert a significant control on bankfull discharge may lead one to conclude that deforestation is not contributing to the flood hazard, a conclusion reached by Ives and Messerli (1989), Hofer (1993), and others. This conclusion must be tempered by recalling that measurements of the variable of percent

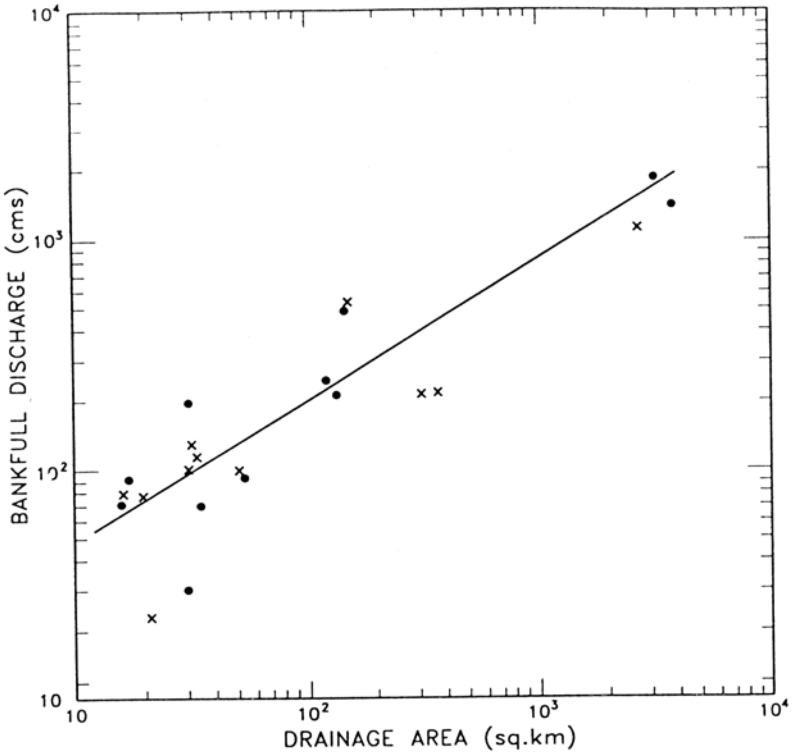

FIGURE 7. Relation between drainage area and bankfull discharge. The regression line was derived using the 11 study sites designated with dots. Crosses designate the 11 study sites used to test equation 3.

forest cover in this study are from 1986 imagery alone; the change in forest cover over time is not taken into account. Nevertheless, our findings indicate that geomorphic variables, not forest cover, exert the dominant control on peak flows. The work by Goswami (1983) reproduced in Ives and Messerli (1989) provides evidence using a different approach that deforestation *over time,* where it does exist, does not cause higher peak flows. Findings from this study can be used to guide planning for future projects that will be affected by flood hazards in the central Nepal Himalaya, including irrigation, hydropower, and footbridge construction.

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