The mountain-lowland debate: Deforestation and sediment transport in the upper Ganga catchment

R.J. Wasson^{a,*}, N. Juyal^b, M. Jaiswal^b, M. McCulloch^d, M.M. Sarin^b,
V Jain^c, P. Srivastava^c, A.K. Singhvi^b

^aCharles Darwin University, Darwin, NT 0909, Australia

^bPhysical Research Laboratory, Ahmedabad 380 000, India

^cWadia Institute of Himalayan Geology, Dehra Dun 248001, India

^dResearch School of Earth Sciences, Australian National University, ACT 0200, Australia

^eSchool of Earth Sciences, Macquarie University, Sydney, NSW 2109 Australia

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Abstract

The Himalaya-Gangetic Plain region is the iconic example of the debate about the impact on lowlands of upland land-use change. Some of the scientific aspects of this debate are revisited by using new techniques to examine the role of deforestation in erosion and river sediment transport. The approach is whole-of-catchment, combining a history of deforestation with a history of sediment sources from well before deforestation. It is shown that deforestation had some effect on one very large erosional event in 1970, in the Alaknanda subcatchment of the Upper Ganga catchment, but that both deforestation and its effects on erosion and sediment transport are far from uniform in the Himalaya. Large magnitude erosional events occur for purely natural reasons. The impact on the Gangetic Plain of erosion caused by natural events and land cover change remains uncertain.

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1. Introduction

In a short paper, following other claims (see [Ives and Messerli, 1989](#), for discussion), [Eckholm \(1975\)](#) posited an environmental crisis in the Himalaya. Among other claims, deforestation of the mountains was blamed for increasing flooding of the Gangetic Plain in India and Bangladesh. Detailed criticism of the postulated crisis, which became known as the theory of Himalayan degradation (THED), followed (e.g. [Ives and Messerli, 1989](#); [Ives, 2004](#)). THED became embedded in public policy in Nepal, India and China, so that the early highly speculative papers had a disproportionately large impact ([Blaikie and Muldavin, 2004](#)).

THED has also become an iconic example of an environmental myth. [Thompson et al. \(2006\)](#) argued that

the scale of scientific uncertainty was so large that nothing sensible could be gleaned for public policy from existing research. They argued further, in a post-modern flourish, that nothing of value could ever be known about the complex of interacting natural and human forces in the Himalaya. [Stott and Sullivan \(2000\)](#) saw the work of [Thompson et al. \(2006\)](#) as an example of a crucial aspect of political ecology, namely the re-framing of ‘accepted environmental narratives, particularly those directed via international environment and development discourses to resource users in the South’.

This quote makes evident the political underpinnings of grand environmental narratives, at least in the view of these and other political ecologists. The need to make these underpinnings clear makes the research landscape very complex. [Stott and Sullivan \(2000\)](#) saw creative research to deal with this complexity as transcending the divide between natural and social sciences; engaging with a range of methods; using complementary sources of data to build

*Corresponding author. Tel.: +61 2 8946 6868.

E-mail address: robert.wasson@cdu.edu.au (R.J. Wasson).

a rich picture of land-use and environmental ideas, including local narratives; using theoretical frameworks to constrain environmental narratives; understanding the cultural basis of the separation of people and nature; understanding that temporal and spatial scales of observation influence findings; and recognising the importance of history and contingency in the construction of narratives and in the way that environments and technology are managed.

The analysis by Stott and Sullivan (2000) pays insufficient attention to the application of new and evolving techniques from the natural sciences. We contend that much of the scientific input to THED was weak, largely because it failed to take adequate account of temporal and spatial scale. This view was earlier expressed by Ives and Messerli (1989).

In this paper, we examine one part of what became known as THED. We use techniques that were not available to scientists whose work was included in THED. We include many aspects of the research agenda of Stott and Sullivan, including temporal and spatial scale, history and contingency, complementary data sources, theoretical frameworks, and local narratives. However, THED in our view is not a hypothesis worthy of further debate. It is ill-posed and, in many important ways, impossible to test. Even though what follows was considered part of THED, we do not intend by our study to re-enliven the entire hypothesis. However, our study fits into the ongoing upland–lowland debate, a topic considered next.

2. The debate and the present study

Debate about the impact on the Gangetic Plain of land cover and land-use changes in the Himalayan mountains has produced two positions (Ives and Messerli, 1989; Ives, 2004; Hofer and Messerli, 2006): (i) deforestation increases

runoff and erosion thereby increasing river channel sedimentation leading to flooding in the lowlands caused by both increased river discharge and reduced river channel capacity; and (ii) deforestation has a trivial effect on erosion, and forests minimally affect runoff, therefore flooding is unaltered.

The link between deforestation, erosion and river sedimentation in the Upper Ganga catchment of the Central Himalaya (Fig. 1) is the focus of our study. River sedimentation and the putative link to flooding on the Gangetic Plain (e.g. CIFOR and FAO, 2005) is not examined. We also only examine the Alaknanda River catchment of 13,993 km², one of two major tributaries of the Ganga in the Himalaya upstream of Haridwar. This was the site of the infamous 1970 Alaknanda flood and sediment transport event, which the local people blamed on deforestation. The flood was also one of the triggers for the internationally acclaimed Chipko movement (Bahuguna, 1987).

The spatial framework for the study is based on geologic/geomorphic zones in the catchment. From north to south, the Alaknanda/Ganga traverses the Tethyan Sedimentary Series (TSS) on the margin of the Tibetan Plateau, the higher crystalline Himalaya (HCH) where several peaks almost reaching 8000 m are separated by deep valleys, the Lesser Himalaya (LH), where lower peaks occur, and the Siwaliks (LS) which consist of low hills at the boundary between the LH and the Gangetic Plain (Ahmad et al., 2000). TSS is mostly above the tree-line, HCH is at or below the tree-line, and LH and LS are below the tree-line.

Using this spatial framework, the study has the following components:

- Evaluation of the existing records of deforestation.
- Determination of the most significant sources of river sediment over the last 6000 years (6 ka hereafter) using

Fig. 1. Location map. H—Haridwar, R—Rishikesh, D—Devprayag, S—Srinagar, Go—Ghona Tal, B—Badrinath, M—Malari, C—Chamoli.

geochemical tracers and optically stimulated luminescence (OSL) dating.

- Estimation of the volume of the 1970 deposit in a storage zone by comparison with earlier deposits from different sources.
- Examination of the links between deforestation and erosion sources through time.
- Exploration of the vulnerability to erosion of the main source of the 1970 deposit.

3. Deforestation

The first written record of the forests of this catchment is from 1624 AD, suggesting vast forest cover in the LH and LS (Wessles, 1924). By the 1920s ‘immense tracts’ of forest still existed in the LH (Dudgeon and Kenoyer, 1925), but the descriptions also suggest less forest than in 1624. While the qualitative trend of deforestation is clear (Negi et al., 1997), quantification using the same definitions and methods for exactly the same areas is difficult. In 1922, about 25% of British Garhwal was forested (Singh et al., 1984), and in 2001 about 45% of the original area of forest of the state of Uttaranchal (which includes the former British Garhwal) was forested (Forest Survey of India, 2001). Official records of the District of Chamoli (mostly HCH and some LH) indicate 57% forest cover in 1970 and 32% in 2001 (Zurick and Karan, 1999). The District of Garhwal (all LH) had 84% forest cover in 1970 and 59% in 2001 (Zurick and Karan, 1999; Forest Survey of India, 2001). Importantly, in 1990 the cropped area was 8% in Chamoli District and 28% in Garhwal District (Zurick and Karan, 1999). These values were 9% and 32% in 1970, respectively, showing that agriculture was not the cause of deforestation.

Between 1803 and 1815 AD, large numbers of trees were cut during Gorkha rule in the Central Himalaya, but it was mainly during the nineteenth century that *Deodar* and *Chir* pines were commercially exploited (Tucker, 1982). Road construction in the catchment after 1962 facilitated commercial logging (Tucker, 1982) that reduced forest cover in Chamoli and Garhwal Districts (Zurick and Karan, 1999). Thus, accelerated forest loss occurred from 1803 onwards, particularly since 1962. For discussion of the politics and further explanation of land cover change, see, for example, Rangan (1995) and Saberwal (1999).

The accuracy of the quantitative forest cover data is debateable. Definitions of forest, classification of satellite images, protocols for estimating forest cover from aerial photos are all open to question. Fortunately, these issues are not highly important in this study, as accurate data do exist for the area of particular importance, as will be shown.

4. Sources of sediment

Being places of high relief, glaciation and landslides, HCH and TSS are likely major sources of sediments in the Alaknanda River. TSS and HCH are mostly above the tree

line and if they do supply most sediment then deforestation can be discounted as a factor in rates of erosion in the catchment. To test this proposition, the proportion of river sediment derived from HCH and TSS was estimated.

The geologic/geomorphic zones have different values of the rare earth tracer $\epsilon\text{Nd}(0)$ (Ahmad et al., 2000; McCulloch and Wasserburg, 1978; Robinson et al., 2001). $\epsilon\text{Nd}(0)$ tracer values are the result of a physical mixture of grains from different sources. No chemical partitioning or chemical fractionation occurs. Previously measured values of $\epsilon\text{Nd}(0)$ in modern river samples (Vance et al., 2003) were combined with the data for the present study, determined by methods reported previously (Wasson et al., 2002).

The geologic/geomorphic zones now need a little more elaboration. Within the LH is an area of HCH rocks known as the Chandpur Formation (Ahmad et al., 2000). The LH upstream of this Formation is called here Inner Lesser Himalaya (ILH), the Chandpur Formation is OLH(C), and the LH downstream of the Formation is OLH(K), where K refers to the Krol Formation.

The input to modern river sediments from each geologic/geomorphic source zone (TSS, HCH, LH, LS) was calculated as follows. A linear two-end-member mixing model was used when either only two end members (TSS and HCH) exist or can be reasonably assumed (ILH and HCH because the TSS signal completely disappears in the HCH zone). Further downstream where for example a sample is a mixture of HCH, ILH and OLH (C), the ratio HCH/ILH immediately upstream of OLH (C) was taken as one end member and the $\epsilon\text{Nd}(0)$ value for OLH (C) was the other end member. This procedure assumes that the ratio HCH/ILH in the sediments that are receiving input from OLH (C) is maintained, but the percentages of HCH and ILH in the sample are reduced by the amount of OLH (C) input. The assumption of a constant ratio is plausible because the wide range of lithologies in each sample indicates that the bulk density of the sediments does not vary along the river and so differential transport of sediment of the same particle size from different sources does not occur.

The data show that sediment derived from TSS is rapidly overwhelmed by HCH material downstream of Malari (Fig. 2). As the river enters the ILH, $\epsilon\text{Nd}(0)$ values decline to a minimum within about 30 km showing that, near the Main Central Thrust (the MCT, which separates the ILH and HCH), the ILH contributes substantial quantities of sediment. The OLH(C) also contributes sediment to the river, as shown by less negative values. There is a small change in $\epsilon\text{Nd}(0)$ in the OLH (K) zone, but none is detectable in the upstream part of LS.

The results (Table 1) show that at Rishikesh, at the downstream end of the catchment, about 54% of the modern river sediment comes from the HCH and the remainder from the ILH. The OLH (K) and LS contribute negligibly. It is noteworthy that the average $\epsilon\text{Nd}(0)$ at Rishikesh is -17.3 ± 0.22 , which is consistent with 100% derivation from the HCH. Similar results from the Ganga in the lowlands have been used to conclude that about 80% of the river

Fig. 2. $\epsilon\text{Nd}(0)$ variation along the Alaknanda River through the geologic/geomorphic zones. The mean $\epsilon\text{Nd}(0)$ value for each zone is shown. M—Malari, J—Joshimath, B—Birehi Ganga/Alaknanda junction, R—Rudraprayag, S—Srinagar, Ba—Bagwan, D—Devprayag, R—Rishikesh, H—Haridwar.

Table 1
 $\epsilon\text{Nd}(0)$ results and source estimates from Malari to Rishikesh

Location	Distance from Malari (km)	$\epsilon\text{Nd}(\text{O})$	Percentage from					
			TSS	HCH	ILH	OLH (C)	OLH (K)	LS
Malari	7	-12.7^+	100					
	13	-16.0^+	9	91				
Joshimath	50	-15.5^+		100				
Helang	55	-16.1^+		100				
	57	-16.3^+		100				
Birehi	75	-19.2		63	37			
Rudraprayag	136	-20.1^+		52	48			
	136	-19.8^+		56	44			
Srinagar	156	-19.2		63	36	1		
Bagwan	176	-18.2^+		60	34	6		
Devprayag	195	$18.7 \pm 1.0^{*+}$		59	33	8		
Lower Alaknanda	212	-17.7^+		54	30	16	ND	ND
	220	-17.6^+		54	30	16	ND	ND
Rishikesh	255	-17.5		54	30	16	ND	ND
	255	-17.0		54	30	16	ND	ND

* $x \pm 1\sigma$; $n = 5$. Uncertainties for single $\epsilon\text{Nd}(\text{O})$ values are $<1.5\%$. $^+$ Data from Vance et al. (2003). ND—not detectable.

sediment is derived from the HCH (France-Lanord et al., 2000). The pattern of variation of $\epsilon\text{Nd}(0)$ along the Alaknanda (Fig. 2, Table 1), however, does not support such an interpretation.

The discussion of sediment sources has thus far focussed on spatial sources. The alarmist paper by Eckholm (1975) stressed loss of topsoil, presumably by sheet and rill erosion. This loss was seen as a disaster for both the agricultural society of the mountains and the plains people who had to endure flooding supposedly caused in part by river channel shallowing as a result of topsoil deposition.

The topsoil tracer ^{210}Pb (excess) (Wasson et al., 1987) in samples from the Ganga River at Rishikesh and the Birehi Ganga was measured to obtain at least a qualitative

indication of the amount of topsoil in the rivers. Low activities of $31 \pm 6 \text{ mBq/g}$ at Rishikesh and $47 \pm 7 \text{ mBq/g}$ in the Birehi Ganga suggest that, while some topsoil reaches the main rivers, it is minimal compared to the erosional processes that move subsoil; namely, landsliding, gully, and channel erosion. Quantification of the topsoil component of river sediments in this catchment must await further work.

5. History of erosion and sediment sources

$\epsilon\text{Nd}(0)$ of modern sediment may represent only a few years of transport from its source(s). Erosion rates based on ^{10}Be and ^{26}Al provide an average value over 200–1000 years,

as follows: TSS 1.2 ± 0.1 mm/a; HCH 2.7 ± 0.3 mm/a; and LH 0.8 ± 0.3 mm/a (Vance et al., 2003). Modern suspended sediment loads for the Alaknanda below Helang (at the MCT) were derived by regressing measured loads (data tabulated by Kale and Gupta, 2001) on catchment area at each station, and then loads from each source terrain were calculated using the regression equation. The ratio of loads from the HCH and LH is 2.1 for the long term and 1.8 for the modern suspended load. The ratios are 1.5 and 1.1 for the ILH and OLH, respectively. Even though the loads for the long-term are higher than the modern rates, because bedload is included in the former, the change of ratios between the long term and today suggests that the LH and OLH are now a more significant source.

For a time-specific history of sediment sources, and their relationship to two centuries of deforestation, a stratigraphic sequence from the alluvial deposits of the Alaknanda River at Srinagar was examined (Figs. 1 and 3). This wide part of the valley is immediately upstream from a narrow gorge, and acts as a sediment trap. The sampling site is close to the downstream margin of the ILH. It was assumed that TSS was an unimportant source at Srinagar, being swamped by HCH (Table 1). Therefore, only HCH and LH sources were considered. Each deposit was optically dated using blue–green stimulated luminescence of 90–150 μ m quartz grain separates. The single aliquot regeneration method and the minimum 10% palaeodose were used to calculate the ages (Aitken, 1998). Dose rate was estimated using thick source ZnS (Ag) alpha counting and NaI(Tl) gamma spectrometry.

The oldest sediment at 6.3 ± 0.7 ka is from a braid deposit on the left bank (Table 2). Between 2.7 ± 0.7 and 0.8 ± 0.1 ka a lateral accretion deposit accumulated, topped by boulders forming part of a building. A silty clay overbank deposit accumulated at 400 ± 40 a on top of the boulders, the surface

of which is occupied by the Keshav Rai temple built in 1624/25 AD (Negi, 1988). Covering this layer is ~ 3 m of sediment unambiguously assigned by the local people to the 1970 flood. On the right bank, basal deposits in a large lateral bar were deposited in flood couplets at about 230 ± 60 a, and are overlain by the 1970 deposit.

The ϵ Nd(0) results from these deposits (Table 2) show that the sediments at 6.3 and 2.7 ka were mainly derived from the HCH, probably as a result of enhanced monsoon rainfall that penetrated further north than at present (Bookhagen et al., 2005). The 0.8 ka sediment was approximately equally derived from the ILH and HCH. The 400 a and 230 a flood deposits were mostly from the HCH. The 1970 deposit had the highest contribution from the ILH, and modern sediment is mostly from the HCH.

It appears that only a small proportion of modern sediment in the Ganga and Birehi Ganga comes from topsoil, but we currently have no technique for estimating this proportion for sediments older than about 100 years.

Table 2
OSL dates and source estimates for alluvial deposits at Srinagar

Age of deposit	Sediment type	HCH (%)	ILH (%)
Modern	River channel	64	36
1970 AD	Overbank	45	55
230 ± 60 a	Flood couplets	67	33
400 ± 40 a	Overbank	86	14
800 ± 100 a	Laterally accreted fluvial sand	52	48
2700 ± 700 a		86	14
6300 ± 800 a	Braid bar	78	22

Fig. 3. Stratigraphic columns for alluvial deposits of Srinagar. OSL dates and ϵ Nd(0) values are shown.

6. The 1970 event

These results show that, at this site, during the last 6.3 ka, the highest proportion of ILH sediment in any of the deposits is in the sediments of the 1970 flood; although there is little difference between the 0.8 ka and 1970 deposits. Major deforestation occurred just before 1970, in the ILH source area of this deposit, and the 1970 deposit in this part of the valley constitutes ~30% of the total accumulation during the last 6.3 ka. The 0.8 ka deposit is of uncertain volume because it is the top of a deposit only dated by two analyses, but it certainly seems to be of much smaller volume than that of 1970.

Field survey of the 1970 deposit makes it clear that most of it originated in the Birehi Ganga catchment, where the flood sediment is up to 14 m thick. The deposit begins near the upstream end of Ghona Tal (lake) (Fig. 1) where the right bank tributary Pui Gadhera reaches the valley floor (Kimothi and Juyal, 1996). At this point, the deposit comprises 100% LH (Table 3) showing that the intense rain at the time had minimal effect on the HCH upstream of Ghona Tal in the Birehi Ganga Valley. Deposits 15 km downstream in the Birehi Ganga are also 100% LH. At Srinagar the deposit comprises between 36% and 54% HCH, and at Bagwan, 100 km downstream from the Birehi Ganga on the Alaknanda River, the deposit comprises 50 and 73% HCH. At Bagwan, on the right bank, three benches of 1970 deposit were probably formed by surges of sediment of decreasing magnitude. The lowest (youngest) surge includes 73% HCH material, while the middle surge has only 50% HCH content. These results show that, although the calcareous rocks of the LH near the MCT were a major source, HCH material was also entrained both from areas upstream of the MCT (probably from landslides near Tapovan) and reworking of pre-1970 flood sediment along the Alaknanda valley.

The 1970 flood and sediment transport event in the Birehi Ganga valley were preconditioned by a huge landslide near the village of Ghona in 1893. Ghona Tal, the lake formed by the landslide, had a volume of about $408 \times 10^6 \text{ m}^3$ and the landslide debris was between 150 and $200 \times 10^6 \text{ m}^3$ in volume (Nand and Prasad, 1972; Weidinger, 1998; Glass, 1896). The dam breached in 1894 sending sediment as far downstream as Haridwar. The bed of the

Birehi Ganga just downstream of Ghona was raised ~70m by deposition, and at Chamoli the Alaknanda river bed was raised by ~15m. The landslide debris, and the alluvium derived from the breach of 1894, provided a readily erodible source of sediment for future floods.

In 1924, a landslide upstream of Ghona Tal displaced water from the lake which then eroded more of the landslide debris and downstream alluvium (Gupta, 1974). The runoff of 1970 breached the landslide dam again and emptied the lake. Part of the dam was mobilised along with the downstream alluvium deposited in 1894 and probably 1924. Landslides in the Patal Ganga and Garud Ganga catchments also formed lakes that burst within hours of their formation, adding sediment to that from the Birehi Ganga to be transported down the Alaknanda River (Nand and Prasad, 1972). Sediment once again reached Haridwar where the Upper Ganga Canal was filled over a stretch of 11 km.

Without the natural landslide of 1893, there would have been less water and sediment available in 1970. The role of history and contingency in the analysis of the event is therefore crucial.

We now examine the role of deforestation in the landslides of 1970. In the Birehi Ganga, Patal Ganga and Garud Ganga catchments, Forest Department records enabled identification of compartments that were clear-felled between 1959 and 1969. These were identified on 1972 Landsat images and landslide scars were mapped (Kimothi and Juyal, 1996). About 70% of the deforested compartments were sites of landslides in 1970, and the remainder of the landslides occurred in forest and alpine pasture. The main area of landslides in the Patal Ganga catchment occurred where hillslopes with an average angle of 25° had been deforested. Although the volumes of the landslides were not measured after the 1970 event, they were almost all shallow (see Barnard et al., 2001). Therefore, an estimate of the area of landslides that occurred in deforested compartments is probably a reasonable approximation to the volume affected by deforestation.

The event of 1970, and also that of 1894, deposited sediment on the Gangetic Plain near Haridwar, and caused local flooding (Nand and Prasad, 1972). The sedimentary structures in the 1970 deposits show that the valley floor was braided over extensive reaches. Once the mainly landslide debris was exhausted, and the flood was over, the deposits were incised by subsequent smaller flows. Sediment from this event can be seen in the floodplain a little downstream of Haridwar. Whether or not this sediment shallowed the Ganga channel, or contributed only to floodplain deposits, is not known.

7. Vulnerability to erosion of the source area of the 1970 event

Most of the sediment carried downstream in 1970 came from within 30 km of the MCT (Kimothi and Juyal, 1996), an area already identified as producing a large amount of

Table 3
εNd(0) data and source estimates for the 1970 deposit

	εNd (O)	LH (%)	HCH (%)
Ghona Tal	−22.12±0.22	100	
	−21.65±0.12	100	
Birehi Ganga	−21.52±0.16	100	
	−21.07±0.13	100	
Srinagar	−19.98±0.16	46	54
	−21.26±0.24	64	36
Bagwan	−20.18±0.20	50	50
	−18.56±0.13	27	73

Fig. 4. Longitudinal profiles of the Alaknanda between Devprayag and Mana Pass, and of the Dhauliganga between Vishnuprayag and Niti Pass. Also shown is the envelope of greatest altitude (dashed line) and the geologic/geomorphic zones. D—Devprayag, S—Srinagar, C—Chamoli, H—Helang, V—Vishnuprayag, Mal—Malari, B—Badrinath, M—Mana, MP—Mana Pass, NP—Niti Pass, TT—Tons Thrust, MT—Munsiari Thrust, VT—Vaikrita Thrust, STDS—South Tibetan Detachment system.

the modern river sediment (Fig. 2). This area is particularly sensitive to disturbance. Fig. 4 shows a longitudinal profile of the Alaknanda River based on both a 1:150,000 map by the Schweizerischen Stiftung für Alpine Forschungen (2002) and Pal (1986). Upstream of Vishnuprayag, longitudinal profiles of both the Alaknanda and Dhauliganga are provided along with the envelope of maximum elevations. The longitudinal profiles are steep above the MCT zone, which in this region is defined by the Munsiari and Vaikrita Thrusts. Also of note is the convexity of the Dhauliganga between Malari (at the southern Tibetan Detachment System, that separates the TSS from the HCH) and Vishnuprayag. A less prominent convexity is also evident in the Alaknanda longitudinal profile.

The convexity is explained as the result of uplift (possibly by extrusion) of the HCH at a rate faster than fluvial downcutting (Beaumont et al., 2001). In this zone of fastest uplift in the Central Himalaya (Jackson and Bilham, 1994), modelling and estimates of rates of erosion given by fission track cooling ages in rocks of the HCH (Sorkhabi et al., 1996) indicate an erosion rate of ~ 2 mm/year averaged over the past 2.4 million years. This implies that fluvial incision is < 2 mm/year in the convex zone. Erosion is also focussed in this part of the Himalaya (the Southern Himalayan Front, SHF) by high orographic rainfall (Hodges et al., 2004), and stream power is at a maximum, particularly in the Alaknanda Valley (Finlayson et al., 2002).

High stream gradients and stream power imply both rapid stream incision and rapid evacuation of sediments, and creation of steep hillslopes, adjacent to rivers, that

erode quickly. Mean hillslope angle, mean relief and erosion rate are all highly correlated in the Himalaya (Montgomery and Brandon, 2002; Gabet et al., 2004). The greatest relief in the Alaknanda Valley is 5.5–6.0 km between Helang and Chamoli (Fig. 4) where average hillslope angles adjacent to the river are about 30° . Further downstream average hillslope angles range between 20° and 13° , where maximum relief falls to between 1500 and 2000 m (Pal, 1986).

8. Discussion

Deforestation increased during the last 200 years and, particularly since 1962 in the LH. Sediment currently being transported by the Ganga River at the mountain front is derived in approximately equal amounts from the HCH and LH. It is therefore clear that the high relief HCH does not dominate modern sediment sources. Also, nearly 70% of the LH sediment comes from within 30 km of the MCT. A small but as yet unquantified proportion of modern river sediments is derived by erosion of topsoil.

In the last 6.3 ka, the largest contribution from the LH to sediment deposited at Srinagar occurred in 1970, and this deposit constitutes $\sim 30\%$ of the total sediment deposited in this section of the valley during the past 6.3 ka. Almost the same proportion of LH material occurred in the 0.8 ka deposit, well before deforestation. The cause of this erosion of the LH was natural, related to rainfall and/or an earthquake. Most of the sediment transported during the 1970 Alaknanda Flood came from the same area as the modern sediment, that is, the SHF both a little upstream of the MCT and within 30 km downstream of the MCT. The SHF is the area of highest total and mean relief, steepest hill slopes, fractured and sheared rocks, fastest uplift, and high rainfall. Hill slope gradients are maintained at or near the threshold for shallow landsliding (and sometimes deep landsliding) by rapid fluvial downcutting. During the prolonged and at times intense rainfall of 1970, about 70% of the landslides occurred on deforested hillslopes, adding substantially to deposition downstream. Some of the sediment also came from the breach of Ghona Tal.

The role of land cover in landslide location and magnitude identified in the Alaknanda Valley is consistent with some quantitative studies elsewhere in the Himalaya (Starkel and Basu, 2000; Valdiya and Bartarya, 1989). By contrast, erosion and sediment transport that dramatically reduced the capacity of a reservoir and thereby Nepal's main source of hydro-electricity in the Kulekhani catchment was caused by landslides that occurred in grassland and forest areas (Dhital et al., 1993). Also, Gardner (2002) showed that in the Kullu District of Himachal Pradesh, little deforestation has occurred but landslides and debris flows are a common occurrence. Road construction has, however, caused landslides.

Deforestation does have an effect, but it occurs in concert with undercutting of slopes by road construction, zones of sheared rock, and saturating rainfall that can

trigger landslides even in well-forested land on steep slopes and that precondition the landscape to produce even more sediment transport during later periods.

The central Himalaya is a very complex landscape, prone to very high rates of erosion and sediment transport often produced under extreme conditions. The role of land-use, particularly deforestation, in this landscape is difficult to discern. Only the 1970 event can be partly explained by deforestation, with a significant role played by pre-existing (or contingent) events; namely, the creation and breach of Ghona Tal.

The extreme vulnerability of the SHF indicates that erosion here will always be high whatever the land-use. But under some circumstances deforestation will cause increased erosion. It follows that reforestation will help to moderate the effects of some extreme rainfall events, but cannot be expected to stop erosion and destructive sediment transport. The effects on local people of reforestation of course need careful consideration (Sinha, 2001).

The impact of human-induced erosion in the Himalaya on channel sedimentation in the Gangetic Plain has not been investigated in our study. Construction of histories of both channel and floodplain sedimentation will be necessary, and estimates made of the travel times of sediment in the main rivers (cf. Schreier and Wymann von Dach, 1996) so that correlations between land cover changes and erosion in the mountains with sedimentation on the plains are meaningful.

Finally, if current ideas about paying upland land users for environmental services provided to lowlanders (Wunder, 2005) are put into practice, the role of land cover will need to be quantified. Otherwise, payments will be stalled in uncertainty, argument and possibly litigation.

9. Conclusion

Identifying the role of human agency in the erosion and sediment transport system of the Himalaya is difficult. Nonetheless, by using geochemical sediment source tracers and a historical approach set within a whole-of-catchment framework, it has been possible to show that deforestation had some impact on at least one very large erosion and sediment transport event. The temporal and spatial framework adopted is different from that previously used, and historical contingency has been explicitly analysed. We have drawn upon many data sources including local narratives. By a careful step-by-step approach, the upland–lowland debate in the Himalaya–Gangetic Plain can be sensibly re-examined, and public policy appropriately informed.

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