IV ROLE OF VEGETATION AND LAND USE

Now that the broad regional hydrological patterns have been discussed in Chapter III, we are in a position to examine the hydrological effects of changes in land cover more closely.

As pointed out by Hamilton (1987), the term "deforestation" is often used so ambiguously that it has become rather meaningless as a descriptor of land-use change. As such it should be replaced by a more specific description of the actual activity: e.g. commercial logging of natural forest followed by replanting with fast-growing trees, or forest clearing for permanent agricultural cropping, etc.

In the following sections the effects of forest conversion to other types of land use and vice versa (i.e. reforestation) will be discussed with respect to annual water yield (IV.1.1), dry-season flows (IV.1.2) and peakflows (IV.1.3), as well as on surface erosion (IV.2.1), mass movements (IV.2.2) and stream sediment loads (IV.2.3).

IV.1 HYDROLOGY

IV.1.1 **Annual water yield**

A common notion about the role of forests is that the complex of litter, roots and forest soils acts as a "sponge" soaking up water during rainy spells and releasing it evenly during dry periods (Eckholm, 1976).

Although there is no doubt that forest soils generally have higher infil-tration rates and storage capacities than soils having less organic matter or that have become compacted (Patnaik & Virdi, 1962; Gilmour et al., 1987; see also the next section), tall forests also exhibit greater evapotranspiration (ET) rates than most other types of vegetation or land-use.

Evapotranspiration from forested areas consists largely of two terms, viz. transpiration (i.e. uptake of soil water by the roots, ***Et***) and rainfall interception (i.e. evaporation of water intercepted by the canopy, ***Ei***). The third term, evaporation from the forest floor (***Es***), is rather small and can often be neglected (Pathak et al., 1985)

Both ***Et*** and ***Ei*** are usually larger in the case of tall forest than for any other type of vegetation. The former because of the generally better devel-oped root systems of trees, and the latter because of the greater aero-dynamic roughness associated with tall objects (Calder, 1982).

As such, total amounts of streamflow from forested basins may be expected to be smaller than from non-forested ones, other factors being equal (Bosch & Hewlett, 1982).

What happens if the original forest cover is removed in terms of total water yield ?

When confronted with this question, one immediately faces a methodological difficulty. Simply comparing streamflow figures for adjacent catchment areas with contrasting land-use types may lead to wrong conclusions, because of possible differences in basin leakage (Section III.2).

For example, Balla (1988a) reported streamflow totals for two small (50 ha) catchments in the lower Middle Hills of West Nepal, suggesting that water yield from the forested basin might be some 130 mm/yr less than that from the adjacent agricultural basin (corrected for 28 % of trees / scrubland in the latter).

Although this value seems quite reasonable at first sight, one cannot be sure to what extent the quoted difference reflects a real vegetation effect or also a difference in catchment leakage.

Likewise, a comparison of streamflow totals for the (pine)-forested Bemunda catchment in Tehri Garhwal (Puri et al., 1982) with runoff values for the nearby agricultural Fakot area, as produced by very similar rainfall totals (Anonymous, 1984), suggests the annual water use of the pines to be lower than that of the crops by more than 340 mm/yr. This unlikely result must reflect differences in non-recorded sub-surface flow between the two areas, since the Fakot basin is much smaller (370 ha) than the Bemunda catchment (1754 ha). Similar examples from the more humid tropics have been detailed by Bruijnzeel (1989b).

Another complicating factor in the evaluation of the hydrological effects of cover transformations is the year to year variability of weather. Also, areal precipitation estimates for larger catchments, especially forested ones where raingauge densities are usually low, are frequently unreliable due to the large spatial variability of rainfall (Section II.3.1).

Zollinger (1979) examined a time-sequence of streamflow data for the Sapt Kosi in eastern Nepal for the period 1948 to 1976 and suggested that deforestation had produced a recent increase in the discharge rates of the river.

However, annual streamflow totals showed a similar trend to the corresponding rainfall figures for Chainpur East (assumed to be more or less representative of trends for the area at large) over the period 1948 - 1985 (Figure 43a). Furthermore, a comparison of the relationship between rainfall and streamflow totals for the first and second halves of the period under observation did not show a statistically significant difference (Figure 43b,c).

One might conclude, therefore, that variations in rainfall override any "deforestation" effects in the case of the Kosi. Alternatively it could be argued that the time span for which data are available is far too short to evaluate such an effect, since presumably the bulk of "deforestation" took place well before 1948 (Section II.4.3).

Similarly, Dyhr-Nielsen (1986) was unable to detect any systematic changes in streamflow patterns in eastern Thailand, despite extensive forest clearance over the last 30 to 40 years. Qian (1983) arrived at the same conclusion after analyzing streamflow and rainfall records for the island of Hainan, southern China, over the 1960s and 1970s, during which period large-scale "deforestation" occurred.

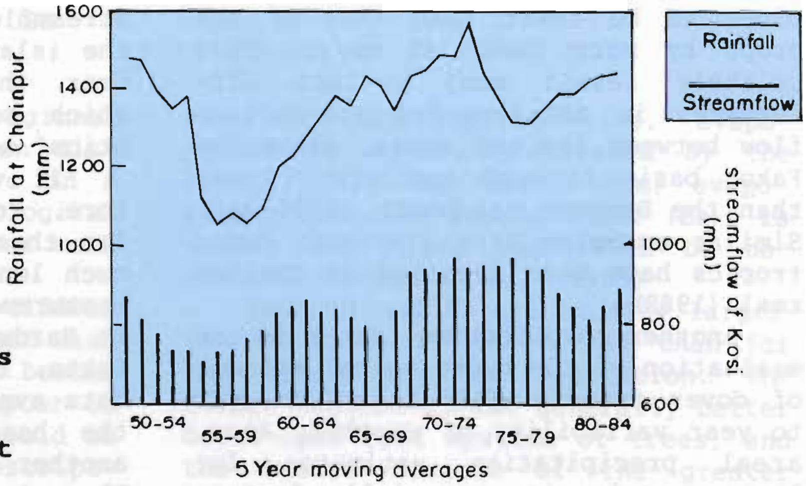
It would be interesting, therefore, to conduct a similar analysis for those Himalayan rivers for which much longer time series of streamflow measurements exist, such as the Ganges at Hardwar (gauged since 1901 (Seth & Datta, 1982), with long-term rainfall data available for 23 stations within the headwater area itself and for another 37 sites in the neighbourhood: Dhar et al., 1982b).

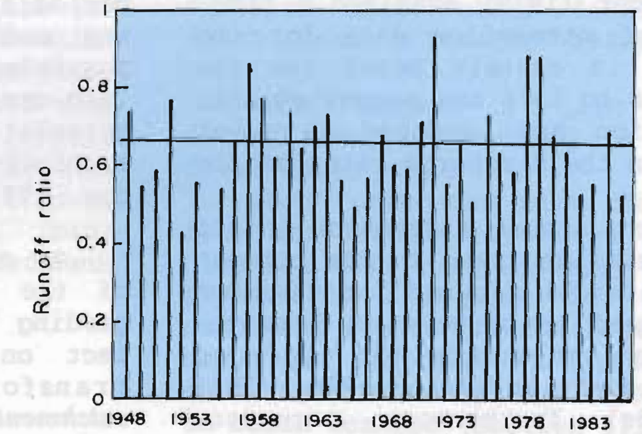
In fact, a rainfall-runoff analysis for the Ganges headwater basin has been conducted by the Uttar Pradesh Irrigation Research Institute for the period 1925-1956. However, no mention was made of any trends that could possibly be related to changes in land-use over time. In addition, the correlation between streamflow and rainfall was low (r = 0.44; Anonymous, 1981a).

An effective way to overcome most of the above-mentioned problems regarding the determination of the effect on streamflow of land-cover transformations is the "***paired catchment method***" (Hewlett & Fortson, 1983).

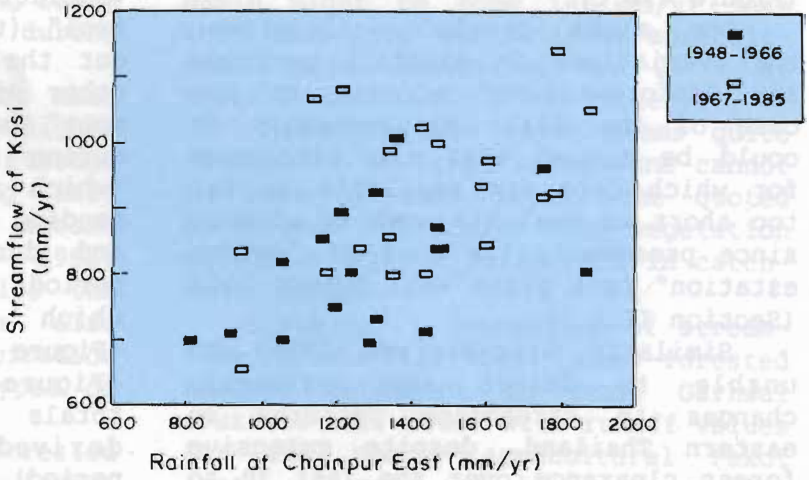
The technique basically involves a comparison of streamflow outputs from (at least) two basins of similar size (usually rather small), geology and vegetation. One is called the "control" (to be left unchanged throughout the observation period) and the other the "experimental" or "treatment" basin. The comparison is made during an initial calibration phase (which may take several years, depending on local rainfall variability) and during a subsequent treatment period (Figure 44). The degree to which linear regression equations (Figure 45a) or double mass curves (Figure 45b) relating streamflow totals from the two catchments (as derived during the calibration period), change after the treatment, is a measure of the effect of the latter. The total duration of such an

Figure 43
(a) Five-year moving averages of annual streamflow for the Kosi river at Bharakshetra and rainfall at Chainpur East (mm), 1948-1985.





(b) Annual ratio between streamflow at Bharakshetra and rainfall at Chainpur East, 1948-1985.



(c) Scatter plot of the variables from Figure 43b.

Sources of data:
streamflow 1948-1976: Zollinger, 1979;
streamflow 1977-1986: Uprety, 1988;
rainfall: Mr. Madan Basnyat, personal communication).

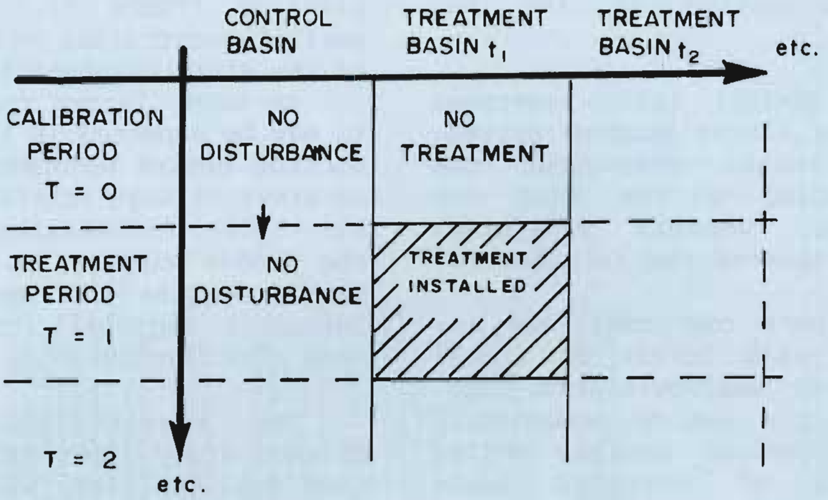


Figure 44. The paired catchment technique: general experimental design (after Hewlett & Fortson, 1983).

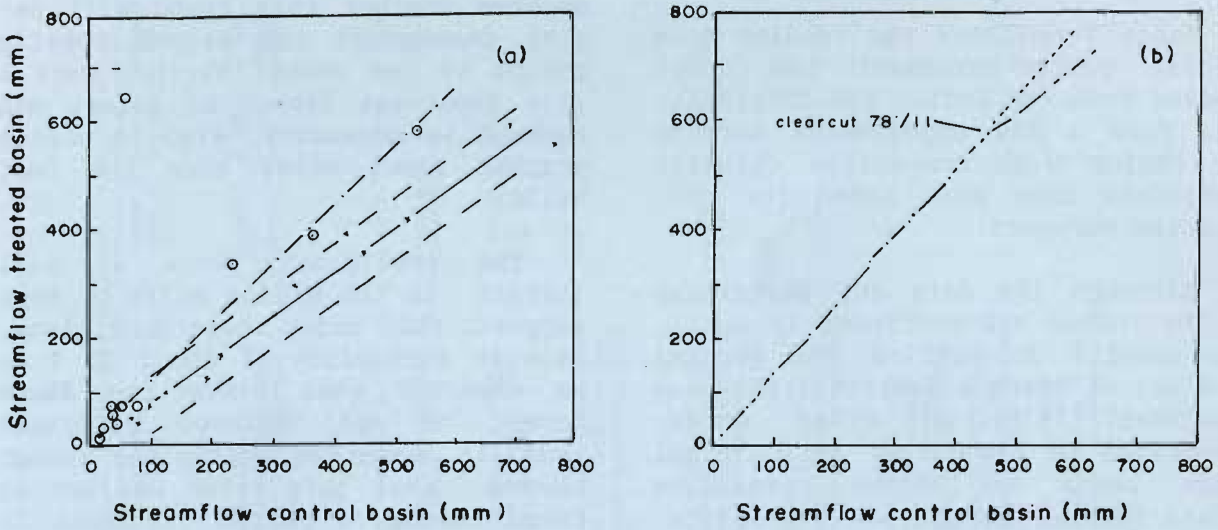


Figure 45 Evaluation of treatment effect on streamflow by statistical analysis, (a) linear regressions, (b) double mass-curves (after Hsia & Koh, 1983).

experiment may easily span a decade (calibration, clearing of forest, planting, maturation of the new vegetation).

Bosch & Hewlett (1982) reviewed the results of almost hundred paired-basin experiments throughout the world, including a few from the (sub)-tropics, whereas Bruijnzeel (1986, 1987) updated the data set for the tropics.

These authors concluded that replacement of tall forest by annual crops or other shallow-rooted vegetation invariably led to permanently increased streamflow totals, whilst reforestation of degraded lands produced a decline in total water yield.

The magnitude of the change depends not only on the type of conversion, but also on a region's climatic and geological setting as well as on rainfall patterns after the conversion (Bosch & Hewlett, 1982; Bruijnzeel, 1986). Regardless of the type of conversion, the highest increase in discharge is usually observed in the first year after forest removal, followed by a more or less regular (depending on rainfall) decline associated with the establishment of the new cover (Hibbert, 1967).

Table 7 collates the results from several paired-catchment and other studies from the Indian sub-continent. Data from a few experiments outside the region with comparable climatic conditions have been added for comparative purposes.

Although the data set pertaining to the Indian sub-continent is small, the results do confirm the general findings of Bosch & Hewlett (1982) and Bruijnzeel (1986). In other words, conversion of forest to agricultural crops leads to higher streamflow totals (Balla, 1988a), whilst replacement of grazing or cultivated land by fast-growing tree plantations produces a gradual reduction in water yield after about four years (Jaykumar et al., 1980; Samraj et al., 1988).

It should be noted, however, that the reduction in streamflow of about 20 % approximately five years after planting (Table 7), corresponds to partial conversions only (47 and 59 % of the study catchments respectively).

As such, larger reductions (35-45 %) may be expected in the case of converting entire watersheds, especially in areas of high rainfall (Jaykumar et al., 1980). Reforesting large areas in the Middle Himalaya with fast-growing exotic species will hence undoubtedly influence regional streamflow totals (see also Section IV.1.2).

The results obtained in the Selakui study (Doon Valley) have limited applicability, since the streams there are not perennial and unknown amounts of water will be leaving the catchments as sub-surface flow (see also Section III.4). They do show, however, that a well-developed understorey, once exposed to full sunlight after coppicing the main tree crop, plus the vigorous regrowth of the coppiced trees may well reduce flows considerably (Viswanatham et al., 1982). Samraj et al. (1984) also reported a 30 % reduction after coppiccing eucalypts in the Nilgiris. Since the magnitude of the reduction appears to decrease with time after coppicing (Table 7), it would be interesting to observe whether this trend will persist throughout the second rotation period of ten years. Further work on this important aspect of forest management is necessary, also in physiographic zones other than the foothills.

The preliminary work of Balla (1988a) in the Middle Hills of Nepal suggests that under these conditions a gain in streamflow of about 25 % may be expected when converting ***Shorea*** forest to well-terraced cultivated land. It cannot be emphasized enough, however, that this value was not derived through a paired catchment investigation covering several years. Again, further work of a more stringent nature is needed, if the effects of land cover transformations on water yield and timing in the Middle Himalaya are to be evaluated properly.

Table 7 Land cover transformations and changes in water yield: results from selected studies

Location and Physiographic Zone	Type of transformation	Catchment size (ha)	Elevation (m.a.s.l.)	Precipitation	Change in water yield (mm. yr) 1st year	2nd year	3rd year	nth yr	Remarks
Indian Sub-continent									
Selakui, Dun	5-yr old secondary scrubland replaced by Eucalyptus grandis and E. camaldulensis in 30 cm deep pits (2x2 m spacing)	control 0-87 treated 1.45	ca. 520	ca. 1430 (monsoon only)	-26% over first five years				Relatively flat topography; topsoil infiltration improved because of numerous pits dug for tree planting storey growth; flow not perennial; quoted figures correspond to summer monsoon season only and therefore mainly represent stormflow; vigorous growth of understorey and coppiced trees
ibidem[2]	Eucalypts coppiced after 10 years	as above	as above	as above	-68%	-47%	+2%		
Rajpur Siwaliks[3]	Dense Shorea forest subjected to 20% thinning	control 6.5 treated 5.2	895	2950	no detectable change		-	-	Typical Siwalik watersheds with sandy soils; flow starts after 350 mm of cumulative rain has fallen
Gorkha, Middle Hills[4]	Single catchments with Shorea forest and agricultural (72%) plus scrub land (28%)	forest 50 cultivated 49	675 775	1670				+130 (ca 26%)	Actual recorded difference of ca 90 mm/yr corrected for 28% trees/scrubland; rainfall input determined at Ghorka, 6 km away; catchments probably watertight
Parsons's Valley, Ootacamund, southern plateau[5]	Single catchment: natural grassland for 47% planted with Acacia melanoxylon, Eucalyptus globulus in 1960	1450	2150?	ca 2050				-290 (-22%)	Quoted value derived by inserting mean annual rainfall in pre- and post-planting regression equations (1930-1957 and 1965-1979 respectively) for single watershed
Wenlock Downs, Ootacamund, southern plateau[6]	Natural grassland plus scattered stunted evergreen montane forest planted with Eucalyptus globulus for 59% of catchment area	control 33 treated 32	2200	1535	average over 10 years: -87 mm/yr (-16%) ibidem after 4-10 years: -120 " (-21%)				Very deep soils, low rainfall intensities, no erosion or overland flow; eucalypts grown in 10-yr rotations
Elsewhere in the (sub-)tropics									
Lien-Hua-Chi, Taiwan[7]	Clearcutting of mixed evergreen hill forest; regeneration	5.9	2100	725-785	+448 (58%)	+204 (51%)			Results perhaps applicable to intermediate elevations in eastern parts of Brahmaputra basin
Kimakia, Kenya[8]	Montane rain forest/bamboo vs. plantation of Pinus patula of high stocking	36.4	2200	2440					
	I agricultural intercropping phase (3 yrs)					+127			
	II rapid growth phase until canopy closure (6 yrs)						+76		
	III continued growth; stabilised canopy (7 yrs)						+6		
Kericho, Kenya[9]	Montane rain forest/bamboo to tea plantation (54%)	702	2035	2300					
	I clearing & planting (3 yrs)								
	II plantation establishment (4 yrs)					+220			
	III plantation maturing (6 yrs)						(-100)		

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[1] Mathur et al. (1976); Mathur & Sajwan (1978); [2] Viswanatham et al. (1980, 1982); [3] Subba Rao et al. (1985); [4] Balla (1988a); [5] Jaykumar et al. (1980); [6] Samraj et al. (1988); [7] Hsia & Koh (1983); [8] Blackie (1979a); [9] Blackie (1979b)

Accepting the above-mentioned values of gains and reductions in streamflow following clearing, c.q. planting of forest at face value, it would seem that the replacement of the original ***Shorea*** forest (as opposed to degraded scrubland) by faster growing eucalypts could also lead to a moderate reduction in water yield (Table 7). Experimental work is necessary to test this assertion, however.

The non-Indian studies quoted in Table 7 are all characterized by slightly higher rainfall totals than usually experienced in the western Himalayas. In the absence of local studies, however, the results could be used to assess the hydrological effects of such important conversions as the establishment of tea or pine plantations on former montane forest land (Blackie, 1979a,b) or temporary clearing (Hsia & Koh, 1983), e.g. in the context of shifting cultivation in the eastern parts of the basin.

There may be one exception to the general rule of increased water yield following forest clearance: the intriguing vegetation type that is often called "cloud forest" or "mossy forest" (Stadtmüller, 1987; Plate 11). In such cases, the loss of additional inputs of moisture through "cloud stripping" (Zadroga, 1981) after logging may offset the gains associated with reduced evapotranspiration (Harr, 1980). Virtually no experimental work has been published in this regard for the tropics (Hamilton & King, 1983; Bruijnzeel, 1989a). It would be wise, therefore, not to undertake any conversion of mossy forest in the Himalaya to grazing land before more is known about the possible hydrological consequences.

Although large-scale reforestation would certainly influence streamflow totals within a physiographic zone (say, the Middle Mountains), the effect could be lost at the macro-level. For example, if all cultivated and grazing land of the Nepalese Middle Mountains (ca. 15 % of the country: Carson et al., 1986) were converted to eucalypt plantation forest (assuming an eventual reduction in local flow of 35 % : Samraj et al., 1988), the effect on the total flow of the Ganges would be in the order of 3 % (section III.1), and therefore undetectable.

IV.1.2 **Dry-season flow**

Under the highly seasonal conditions prevailing over much of the region, amounts of streamflow available for irrigation or reservoir storage during the dry season become extremely important, especially during the hot pre-monsoonal months (cf. Figure 14). In this context, any further reduction in streamflow as described in the preceding section, may result in unacceptable shortages of water with disproportionately large economic losses.

Reduced dry-season flows have also oftenbeen ascribed to "deforestation" (Eckholm, 1976; Sharma, 1977; Myers, 1986). At first sight this seems to contradict the evidence presented with respect to total water yield (Bosch & Hewlett, 1982). However, the conflict can be resolved by taking into account the net effect of changes in infiltration opportunities and evapotranspiration associated with the respective land-use types (Hamilton & King, 1983; Bruijnzeel, 1989b).

Thus, if infiltration opportunities after forest removal have decreased to the extent that the amounts of water leaving an area immediately as overland flow during rainstorms exceed the gain in baseflow associated with decreased ET, then diminished dry-season flow results.

Reduced infiltration may either be caused by an increase in the area occupied by impervious surfaces (roads, villages, etc.), the use of heavy machinery during forest harvesting or subsequent agriculture, overgrazing or other improper agricultural practices (Bruijnzeel, 1986). This situation is, of course, widespread and can generally be held responsible for the commonly observed deteriora-

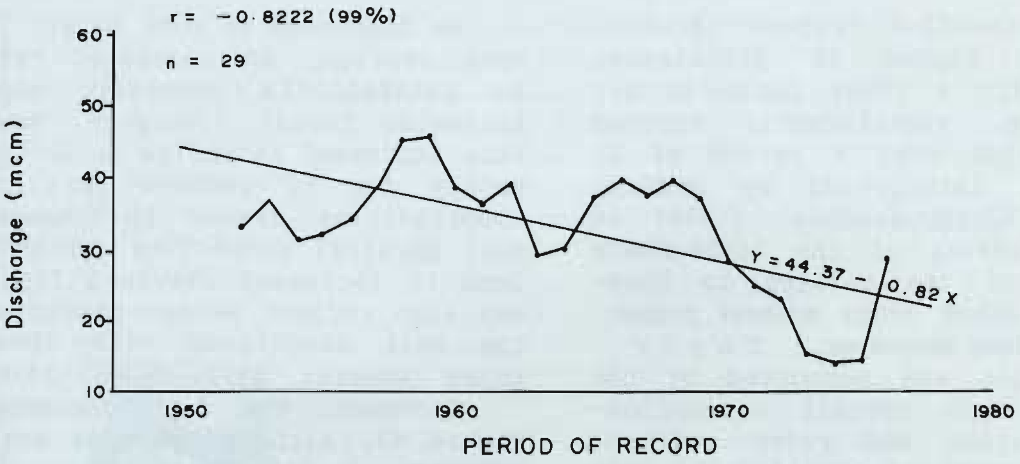

Figure 46. Decline in dry-season flow rates for the Mid-Mahaweli basin, Sri Lanka (after Madduma Bandara & Kuruppuarachchi, 1988).

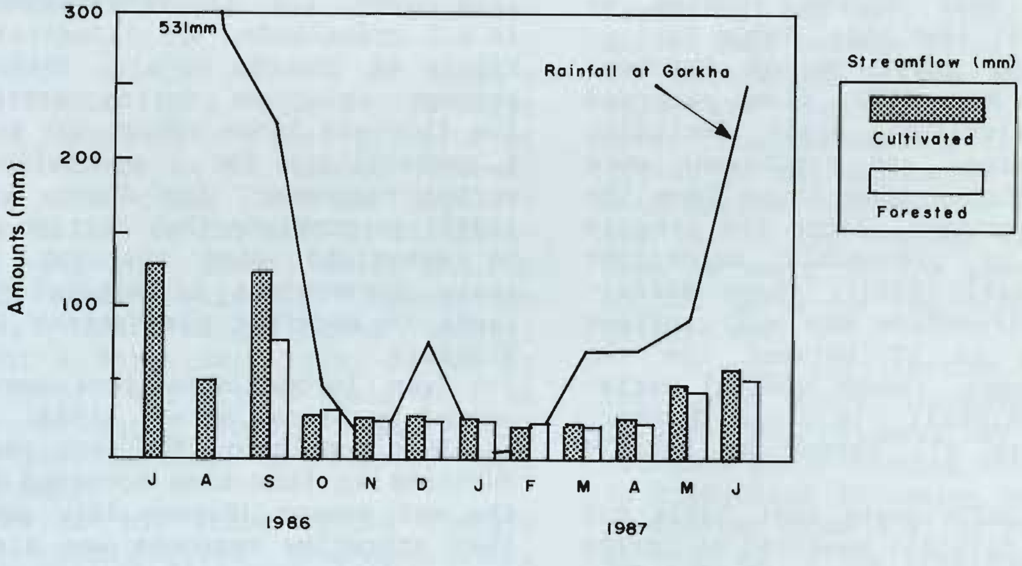

Figure 47. Monthly rainfall and streamflow for a forested and a cultivated catchment near Gorkha, Nepal (based on original data from Balla, 1988a).

tion of streamflow regimes (Bruijnzeel, 1989b). Figure 46 illustrates the point for a river basin in Sri Lanka. Here, significantly reduced low-flow rates over a period of 25 years were interpreted by Madduma Bandara & Kuruppuarachchi (1988) as being the result of the large-scale conversion of tea estates to homesteads and other crops ***without proper soil conservation measures***. Their interpretation was supported by the fact that both overall streamflow-rainfall ratios and river sediment loads had increased considerably over this period.

However, if surface infiltration characteristics can be maintained, then the effect of reduced ET after clearing will show up as increased baseflow. The effect becomes more prominent as the length of the dry season increases, reflecting differences in rooting depth between forests and cultivated crops (Eeles, 1979; Bruijnzeel, 1989b).

Figure 47 shows monthly streamflow values for the forested and cultivated catchments near Gorkha studied by Balla (1988a) (see also Table 7).

Over the (dry) period October, 1986, until May, 1987, flows recorded for the agricultural basin (including 28 % of tree- and scrubland) were generally higher than those from the forested catchment. Since the area is underlain by presumably watertight slates (Kizaki, 1987), these differences in streamflow may well reflect differences in ET between the two land-use types, though spatial variations in rainfall (e.g. in October, 1986: Figure 47) cannot be totally excluded.

It is unfortunate that Balla had to rely on rainfall measured at Gorkha town, which is not only situated 6 km from the study site, but also at a higher elevation (1100 m a.s.l. vs. 700 m). Differences in streamflow totals between the two catchments increased during wet months, though results were not very consistent (cf. September, 1986; June/July, 1987; Figure 47).

As discussed in more detail in the next section, an increased response to rainfall is generally observed following forest clearance. However, this increased stormflow is not necessarily due to reduced infiltration opportunities caused by changes in soil physical properties (which could lead to increased overland flow). It may also reflect wetter conditions in the soil associated with lower ET rates (Edwards, 1979; Eeles, 1979).

As such, the data presented in Figure 47, although perhaps not very accurate, do illustrate the point made earlier that dry-season flows from cultivated land will be higher than from forests, ***as long as infiltration capacities are maintained*** (Edwards, 1979; Bruijnzeel, 1989b).

It is unfortunate, therefore, that the Gorkha study had to be terminated in July, 1977, after only one year of observations, due to lack of funds (M.K. Balla, personal communication).

The effects on dry-season flows associated with the opposite change in land cover, i.e. the ***reforestation*** of (e.g.) grasslands, are illustrated in Figure 48 (Sharda et al., 1988). The average reduction during months of low flow was large enough (23 % at 50 % probablilty) for a partially converted catchment) for Sharda et al. (1988) to conclude that caution should be exercised when planning large-scale conversions of natural grasslands to eucalypt plantations in the Nilgiris.

Even larger reductions were observed by Samraj et al. (1984) after eucalypt coppicing. The fact that reductions in flow also occurred during the wet season (Figure 48), suggests that stormflow response was also reduced following afforestation (cf. Mathur et al., 1976). Since overland flow is a rare phenomenon in this area (regardless of land cover) due to the low rainfall intensities prevailing at this high altitude (Samraj et al., 1977; Jayakumar et al., 1978), the decreased response must reflect drier soil conditions. This was confirmed by weekly observations of soil moisture (Sharda et al., 1988).

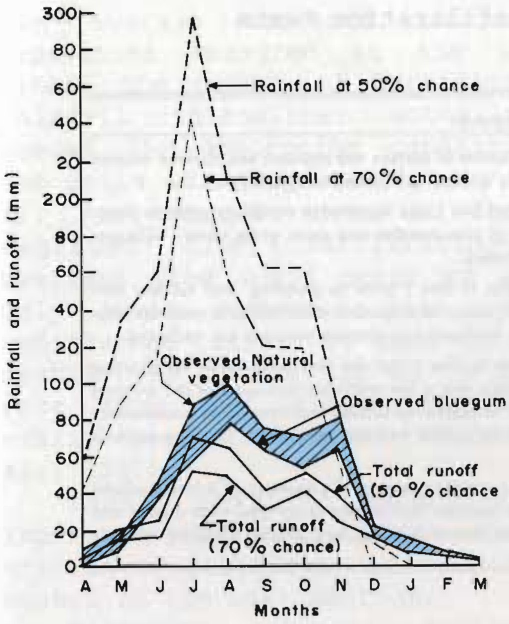

Figure 48. **Expected rainfall and, total flow at 50 and 70% probability levels and monthly reduction in total flow due to afforestation with bluegum (*Eucalyptus globulus*) at Ootacamund (after Sharda et al., 1988).**

The question could be asked, whether reforestation of severely degraded soils in the Himalayas would eventually lead to such improved infiltration conditions that the gain in amounts of infiltrated rainfall could offset losses due to increased ET.

Based on the results of Balla's study (Table 7), a value of 130 mm/yr may be taken as a first estimate of the difference in ET between (*Shorea*) forest and crops in the Nepalese Middle Hills. In the case of reforestation with chir pines, which exhibit (much) higher rainfall interception values than broad-leaved species (Dabral & Subba Rao, 1968; Pathak et al., 1985), the figure could well be twice as high, though experimental data are lacking to support this assertion.

How do the above values compare with infiltration characteristics associated with different soil- and land-use types in the Lesser and Middle Himalayas? Gilmour et al. (1987) determined the near-saturated permeabilities of top- and sub-soils under conditions ranging from heavily grazed and trampled grassland through five- and twelve-year old pine plantations to relatively undisturbed natural forest in the Middle Hill region of Nepal.

Table 8 gives a brief description of their study sites and the results of the measurements are summarized in Figures 49 and 50.

As shown in Figure 49, hydraulic conductivity values for the deepest layers of the soil profiles did not differ much between sites, since these are determined by the nature of the substrate rather than vegetative cover. The variability is seen to increase as one approaches the surface, with maximum differences occurring in the top 10 cm; average values ranged from 39 mm/hr at the overgrazed site to 524 mm/hr in the original forest (Figure 49).

Top-soil infiltration rates in the reforested sites increased with age (Figure 50). Gilmour et al. (1987) ascribed these changes to a reduction in compaction following the exclusion of grazing animals after reforestation as well as to the breakdown of litter by the soil fauna and microflora.

Before one can decide on the actual hydrological effect of such increased infiltration opportunities, one needs to take into account the prevailing rainfall intensities (cf. Figure 29). Gilmour et al. (1987) determined the average number of days on which certain rainfall intensities were recorded and compared these with

Table 8 Description of locations of infiltration tests carried out by Gilmour et al., (1987).

Site	Aspect	Slope (°)	Description
1	ENE	16	Probably deforested more than 100 years ago. Patches of surface soil exposed and surface erosion widespread. Grass cropped to soil level. Heavily grazed and trampled grassland.
2	ENE	17	Planted with *Pinus patula* five years ago. Adjacent to Site 1 and identical in condition prior to planting. Soil surface now covered with a thin layer of pine needles and short grass cover. Villagers cut grass by hand but grazing animals are excluded.
3	ESE	19	Planted with *Pinus roxburghii* 12 years ago. Similar to Site 1 prior to planting. Soil surface now covered with a layer of pine needles and patches of grass with a number of broadleaved trees developing as a minor understorey. Villagers cut grass by hand but grazing animals are excluded.
4	NE	24	Planted with *P. roxburghii* 12 years ago. Adjacent to Site 1 but the vegetation prior to planting consisted of low shrubs and herbs about 40 cm high plus a few scattered remnants of the original forest. Surface now covered with a dense layer of broadleaved shrubs and trees as an understorey beneath the pines. Leafy material cut by villagers for animal bedding and fodder. Grazing animals are excluded.
5	NE	24	Religious forest—probably a near-natural stand consisting largely of a mixture of *Schima wallichii* and *Rhododendron arboreum* with a few other minor species. Soil surface is covered with shrubs and moss but little grass. Some leafy material cut for animal bedding and fodder. Grazing animals are generally excluded.

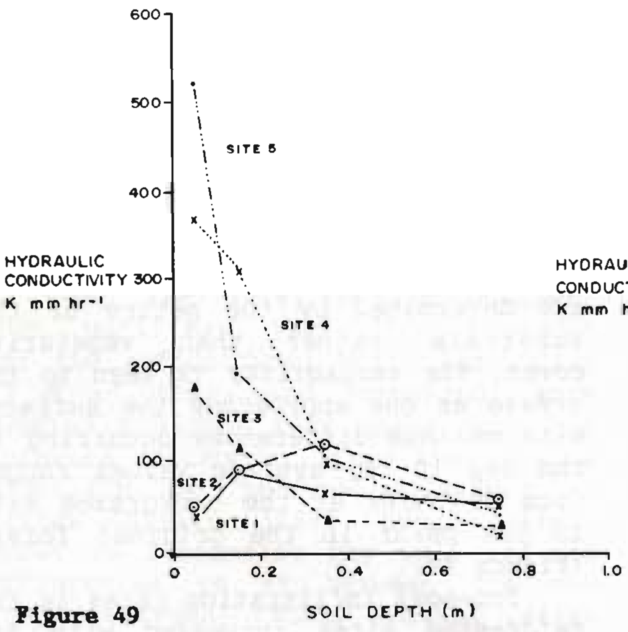

Figure 49

Field saturated hydraulic conductivity values (K) for each of the sample sites at various depths. (K values plotted against the mid-point of the sampled soil layer.)

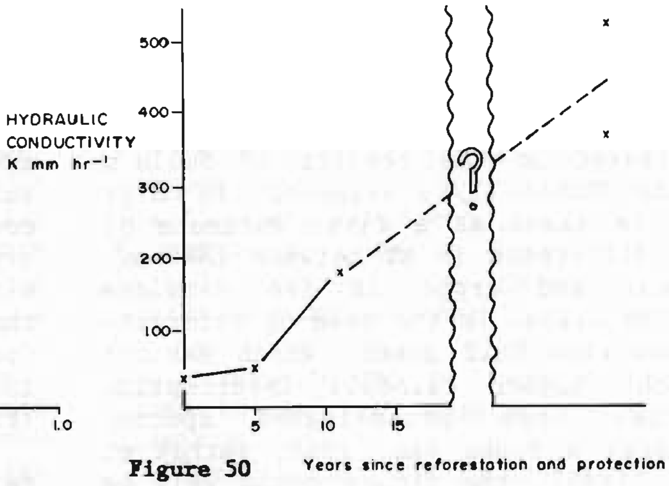

Figure 50

Likely trend of changes in field saturated hydraulic conductivity (K) of surface (0-0.1 m) soil following reforestation and protection of heavily grazed and trampled grassland.

Table 9

Annual number (and percentage) of rain-days during main monsoon season where 5-minute rainfall intensity exceeds the log-mean field saturated hydraulic conductivity for the impeding layers at each site

Depth interval (m)	Number of rain-days				
	Site 1	Site 2	Site 3	Site 4	Site 5
0 -0.1	6.7 (17%)	3.7 (9%)	tr	tr	tr
0.1-0.2	tr	tr	0.4 (1%)	tr	tr
0.2-0.5	tr	tr	6.7 (17%)	0.6 (1%)	0.6 (1%)
0.5-1.0	tr	tr	11.7 (29%)	4.4 (11%)	11.7 (29%)

the average top-soil infiltration capacities measured at the various sites. The number of occasions that rainfall intensities actually exceeded the absorption capacities of the soils was surprisingly low (Table 9). For example, even at the most degraded site, infiltration-excess overland flow would occur on average only seven times a year. At the undisturbed sites (4 and 5), permeabilities of the top 20 cm of soil were such that all rainfall could easily be accommodated (Gilmour et al., 1987).

These results naturally have important implications for the generation of peakflows, as will be discussed in the next section.

Although top-soil infiltration capacities had improved by more than 140 mm/hr, twelve years after reforesting degraded grassland (Figure 50), it is unlikely, on the basis of the relatively low rainfall intensities in the area, that the extra amounts of rain actually infiltrating the soil after reforestation will exceed the 130-250 mm/yr supposedly required for increased dry-season flow. Further experimental work is desirable.

One should be careful not to overgeneralize the findings of Gilmour et al. (1987), who themselves considered their work to be of a "preliminary nature". The interplay between rainfall and infiltration characteristics may well be different in other parts of the Himalaya. For example, Patnaik & Virdi (1962) reported much lower infiltration rates for various soils in the Siwalik-Dun zone in India (Figure 51).

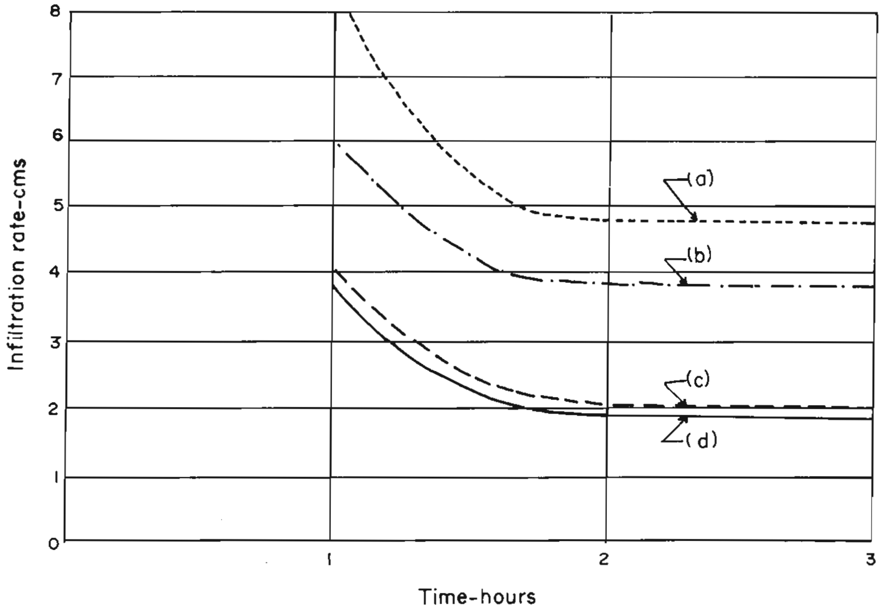

Figure 51. Hourly infiltration curves for 4 groups of sites in Doon valley: (a) cultivated Himalayan upland, (b) forested Himalayan upland, (c) forested Siwalik slope and (d) cultivated bottom land (after Patnaik & Virdi, 1962).

These investigators measured near-saturated rates for forest soils in the Doon valley of 21 mm/hr in the case of soil trampled by grazing cattle and of 58 mm/hr for "Sal forests with good leaflitter". Narayana & Sastry (1983) reported even lower values for an agricultural field in the same area.

According to various Annual Re-Reports of the Central Soil and Water Conservation Research and Training Institute, Dehradun, the number of rainstorms in the area with hourly totals of more than 30 mm range between six and eleven per year. Much higher intensities (over 100 mm/hr) occur frequently for shorter periods (Ram Babu et al., 1980).

As such, infiltration-excess overland flow is likely to occur much more frequently in the Siwaliks/ Duns than at higher elevations, especially given a situation of high grazing pressure (Pant, 1983; cf. Figure 29). Indeed, some of the most serious surface erosion in all of Nepal has been observed in the Dun zone (Nelson et al., 1980).

One can only speculate as to whether reforestation of degraded hillslopes in the Siwalik-Dun zone could restore base-flow levels. Pant (1983) maintained that prior to 1850 perennial streams rose in the hills near Chandigarh, supporting agriculture in the plains below, though he was not specific about the size of these streams.

Subba Rao et al. (1985), on the other hand, observed that streams draining densely forested small headwater catchments in the Indian Siwaliks would not start flowing until at least 350 mm of rain had fallen after the onset of the monsoon. Flow also dropped off rapidly at the end of the rainy season, possibly because of rapid infiltration into the coarse-textured riverbeds (Sharma, 1977; cf. Plates 7 and 15).

This observation was confirmed in several other small-catchment studies conducted in the area, which showed that although stormflow volumes were significantly reduced following reforestation, there was no such thing as increased baseflow (Gupta et al., 1974; 1975; Mathur & Sajwan, 1976). It must be concluded, therefore, that in this case evapotranspiration and geological effects override those associated with improved infiltration characteristics.

However, the evidence presented in this section that reforesting degraded lands will generally reduce rather than restore dry-season flows under Himalayan conditions, should not lead one to the conclusion that reforestation programmes should be discontinued. Rather, and this cannot be emphasized enough, reforestation has various on-site benefits such as reduction of surface erosion (see Section IV.2.1) and the maintenance of soil fertility, which are often more important than changes in streamflow patterns downstream (Chapter V).

IV.1.3 **Peakflows**

As indicated in Section III.5, there are a number of convincing reasons why regular and widespread flooding is likely to happen in the lowland areas of the Ganges-Brahmaputra river basin. It was also suggested that temporal and spatial variations in extreme rainfall constituted the chief determinant of flooding in the area (cf. Figures 32 and 33) at the meso- and macro-scales.

This section will review the evidence with respect to the influence of land management on the magnitude of peakflows and stormflow volumes at the micro-scale (up to 500 km2). In addition, we will examine the available evidence with respect to time trends.

Table 10 summarizes results obtained by several studies, mainly conducted by the Central Soil and Water Conservation Research and Training Institute, Dehra Dun, in the Indian Dun-Siwalik zone and the Nilgiris (southern plateau area).

Relatively little work seems to have been carried out in the Middle Mountain zone, which is thought to be more responsive to rainfall than any

TABLE 10. Effects of (changes in) land cover on stormflow volumes and peakflows: results from selected small-catchment studies.

Study site	Type of land use/ conversion	Effect on stormflow		Effect on peakflow	Remarks
Selakui, Dehra Dun[1,2]	-Secondary scrub vs. Eucalyptus sp.	-28% reduction in total flow during the first five years after reforestation		73% reduction during the first five years after reforestation	Paired catchment study in relatively flat terrain (cf. Table 7); 8 years of calibration prior to treatment; watersheds closed to grazing; streams only flow during the monsoon (June-September);
	-Copping of the eucalypts after 10 years	-68%, 47% and no reduction			
Ibidem[3,4]	-Soil conservation measures in cultivated catchment; forested basin used as control	76% reduction in total flow during the 14 years following treatment (62% in the first five years)		47% reduction for the first five years after treatment	Paired catchment study; 10 years of calibration prior to treatment in 55-ha basin; forested catchment (70 ha) heavily grazed; stormflow in forest partly from foot paths
Ibidem[4,5]	-Cultivation (no soil conservation) vs. grazed forest	Cultivated: 128 mm Forested: 166 mm		Cultivated: 3.5 m^3/sec/km^2 Forested: 6.4 m^3/sec/km^2	Long-term (1960-1983) comparison of monthly flows from single watersheds: cultivated (25 ha) and Sal forest (70 ha); quoted peakflow values correspond to a return period of two years;
Rajpur, Dehra Dun[6]	-Twenty percent thinning operation in grazed Shorea forest	Not detectable		9% increase in first year; effect disappeared after the second year	Paired catchment study in typical Siwalik environment (cf. Table 7); thinning produced an increase in crowndrip of 5%;
		1974	1975	(1974)	Multiple-paired catchment study (0.7-4.2 ha); 7 years of calibration prior to treatment in 1973; steep terrain on marls/sandstones; quoted figures computed from original data by Gupta et al.
Chandigarh[7,8]	Poorly vegetated scrubland subjected to:				
	- annual burning	+ 26%	+ 218%	+ 225%	
	- logging + overgrazing	+178%	+ 236%	+ 52%	
	- overgrazing	+ 31%	+ 552%	+ 47%	
	- reforestation + trenching	- 75%	- 29%	- 73%	
Chandigarh[9]	Poorly vegetated grass- and scrubland subjected to reforestation with eucalypts and Acacia, contour trenches and checkdams, no grazing	60% reduction during the first 6 years after treatment		61% reduction during the first 6 years after treatment	Paired catchment study in degraded Siwalik land; 20% slope; 9 years of calibration prior to treatment in 1969
Middle Himalaya					
Naini Tal[10]	- Oak forest (47% groundcover	0.44% of rain		-	Short-term observations of runoff from micro-headwater catchments on soil derived from limestones at an elevation of 2050 m; slopes 36-40°; stormflow values represent overland flow in a system dominated by sub-surface flow;
	- Semi-dense oak forest (41%)	0.49%			
	- Open forest (38%)	0.44%			
	- Open forest (19%)	0.45%			
	- Old landslide (31%)	0.45%			
	- Fresh landslide (18%)	0.60%			
	- Cropland (46%)	0.57%			
	- Soil deposition (12%)	0.60%			
Fakot area[11]	Cultivated part of basin (21%) bench-terraced	see Figure 52		-	Single watershed (370 ha), 36% poor woodland, 64% cultivated area plus wasteland
Lien-Hua-Chi, Central Taiwan[12]	Evergreen hardwood forest clearcut and replanted with China fir	No statistically significant effect		48% increase in median peak discharge value for three years after clearcutting	Paired catchment study in steepland conditions similar to the Middle Mountains of the Himalaya (cf. Table 7)

[1]Mathur et al., 1976; [2]Vishwanatham et al., 1982; [3]Ram Babu et al., 1974; [4]Sastry et al., 1983; [5]Ram Babu & Naranya, 1984; [6]Subba Rao et al., 1985; [7,8]Gupta et al., 1974, 1975; [9]Kausha et al., 1975; [10]Pandey et al., 1983/84; [11]Annual Reports of the Central Soil and Water Conservation Research and Training Institute, Dehadrun, 1981/1984; [12]Hsia, 1987.

other physiographic zone (Chyurlia, 1984; Section III.5).

The data collated in Table 10 clearly indicate the enormous local increases in stormflow volume and peaks that can be produced by such adverse land-use practices as burning and/or overgrazing of forest under-understorey vegetation (Gupta et al., 1974, 1975) or urbanisation/quarrying without any conservation measures (Haigh, 1982; Bandyopadhyay & Shiva, 1987) in the Himalaya.

The beneficial effects of reforesting, terracing and contour-trenching degraded soils at this scale are equally evident, as is the regenerative capacity of the ecosystem (Patnaik et al., 1974).

Although the stormflow response of a particular basin can undoubtably be modified considerably by manipulating its vegetation cover, this does not mean that peakflows from forested basins are necessarily smaller than from nearby cultivated basins.

Geological and topographical factors are also important, as is shown by a comparison of runoff values for several forested and cultivated catchments in the Doon valley (Table 10). For example, runoff from a 70-ha forested basin was consistently higher than for a nearby agricultural basin of 55 ha (168 vs. 132 mm respectively; Sastry et al., 1983).

Similarly, Pandey et al. (1983/4) found monsoonal runoff totals for very small catchments (30-240 m^2) with strongly contrasting land-use types in the Middle Mountains of the Kumaon Himal to vary very little (Table 10). Since these plots were underlain by limestones, their hillslope hydrological behaviour was dominated by sub-surface flow (Figure 28).

As such, it would be unsound to directly extrapolate the results obtained in the Doon valley catchments or the plots on limestones to the Himalaya at large, with its often much steeper topography and/or different geology.

Nevertheless, dramatic reductions in monsoon runoff following terracing were also reported by Narayana (1987) for the 370-ha Bhaintan watershed in the Middle Mountain zone of Tehri Garhwal. This area, which is drained by non-perennial streams, consists of two-thirds agricultural and wasteland with the remainder under poor woodland (Tejwani, 1985).

As shown in Figure 52, the lower runoff observed after terracing the fields must also be due to a reduced precipitation received in the last few years. Theoretically, the reduction over time in total streamflow for years of comparable rainfall (Figure 52) can only be explained by a concurrent decrease in overland flow from the treated fields. According to data presented in the Annual Reports of the Central Soil and Water Conservation Research and Training Institute from 1979 to 1981, overland flow from the improved terraces ranged between four and 12 % of incident rainfall, as compared to three and 34 % for unimproved terraces.

Since the corresponding runoff ratios for the catchment as a whole varied between 22 and 41 %, the flow recorded at the basin outlet must have included an unknown contribution from sub-surface stormflow (cf. Figure 31). Since terracing may be expected to increase sub-surface contributions at the cost of overland flow, it is difficult to explain the very low streamflow figures observed in some years (e.g. 1982/83; Figure 52).

A similar case of drastically reduced "runoff" following terracing 43 % of the 19.4 km^2 Coonoor watershed in the Nilgiris was presented by Jayakumar & Seshachalum (1984). Unfortunately, the results were again strongly influenced by (very) low rainfall totals following treatment.

Clearly, such uncertainties of interpretation can only be resolved by rigorous paired-catchment studies, supplemented with process-oriented hillslope hydrological work.

It is of interest to examine at what scale, land-use effects become "overshadowed" by effects associated with rainfall distribution.

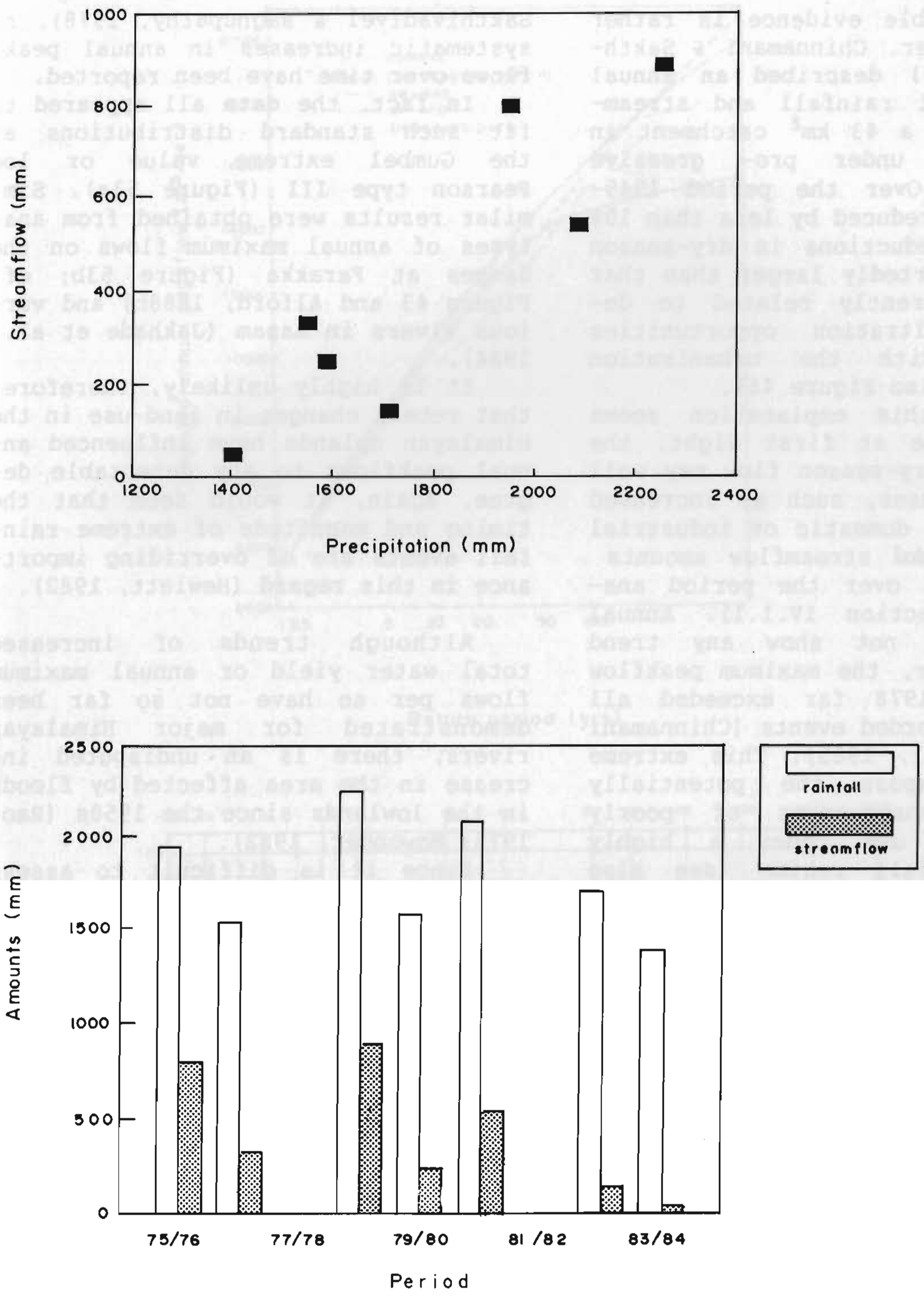

Figure 52. Annual rainfall and streamflow totals (mm) for the Bhaintan watershed, Teri Garhwal (based on data from Anonymous, 1981b/84).

The available evidence is rather limited, however. Chinnamani & Sakthivadivel (1985) described an annual time series of rainfall and streamflow data for a 43 km^2 catchment in the Nilgiris under progressive urbanisation. Over the period 1949-1979 rainfall reduced by less than 10% on average. Reductions in dry-season flow were reportedly larger than that and were apparently related to decreased infiltration opportunities associated with the urbanisation process (see also Figure 46).

Although this explanation seems quite plausible at first sight, the reduction in dry-season flow may well have other causes, such as increased extraction for domestic or industrial uses, since ***total*** streamflow amounts also decreased over the period analyzed (see Section IV.1.1). Annual peakflows did not show any trend either. However, the maximum peakflow observed in 1978 far exceeded all previously recorded events (Chinnamani & Sakthivadivel, 1985). This extreme event did expose the potentially disastrous consequences of poorly planned land use under a highly seasonal rainfall regime (see also Haigh, 1982).

Sharma (1977) has described several cases of highly disturbed flow regimes following deforestation in catchments with areas of several hundred km^2 in the Nepalese Siwaliks (cf. Figure 20d).

A similar study by Madduma Bandara & Kuruppuarachchi (1988) for a river basin of about 550 km^2 in Sri Lanka also revealed a clear change in river regime following the widespread conversion of tea estates to annual cropping without soil conservation measures (Figure 46).

Garczynski (1982) drew attention to several cases with detectable downstream discharge changes (mainly in North America) where areas of more than 2000 km^2 of forest had been destroyed by hurricanes or insects.

No such trend analyses seem to be available for Himalayan basins. Although long-term time series of annual peak flows have been studied for several rivers (Anonymous, 1981a; Sakthivadivel & Raghupathy, 1978), no systematic increases in annual peakflows over time have been reported.

In fact, the data all appeared to fit such standard distributions as the Gumbel extreme value or log Pearson type III (Figure 53a). Similar results were obtained from analyses of annual maximum flows on the Ganges at Farakka (Figure 53b; cf. Figure 43 and Alford, 1988b) and various rivers in Assam (Jakhade et al., 1984).

It is highly unlikely, therefore, that recent changes in land-use in the Himalayan uplands have influenced annual peakflows to any detectable degree. Again, it would seem that the timing and magnitude of extreme rainfall events are of overriding importance in this regard (Hewlett, 1982).

Although trends of increased total water yield or annual maximum flows per se have not so far been demonstrated for major Himalayan rivers, there is an undisputed increase in the area affected by floods in the lowlands since the 1950s (Rao, 1975; Bowonder, 1982).

Since it is difficult to assess the size of a flood unambiguously (stage, duration, amount of water involved?), the measure often used for policy making is the economic loss associated with a particular flood.

As pointed out by Rogers (1988), equating economic loss with severity of a flood produces a serious bias in that it gives the impression that floods are becoming more frequent and more damaging, whereas in reality increased losses mainly reflect economic growth and increased floodplain occupancy (Hamilton, 1987). As such, a flood may nowadays cause much more damage than a similar-sized one in the past (cf. Figure 18).

It is therefore understandable, however unfortunate, that many (e.g. Eckholm, 1976; Bowonder, 1982; Murty, 1985; Myers, 1986, etc.) have confused these two ways of expressing flooding severity.

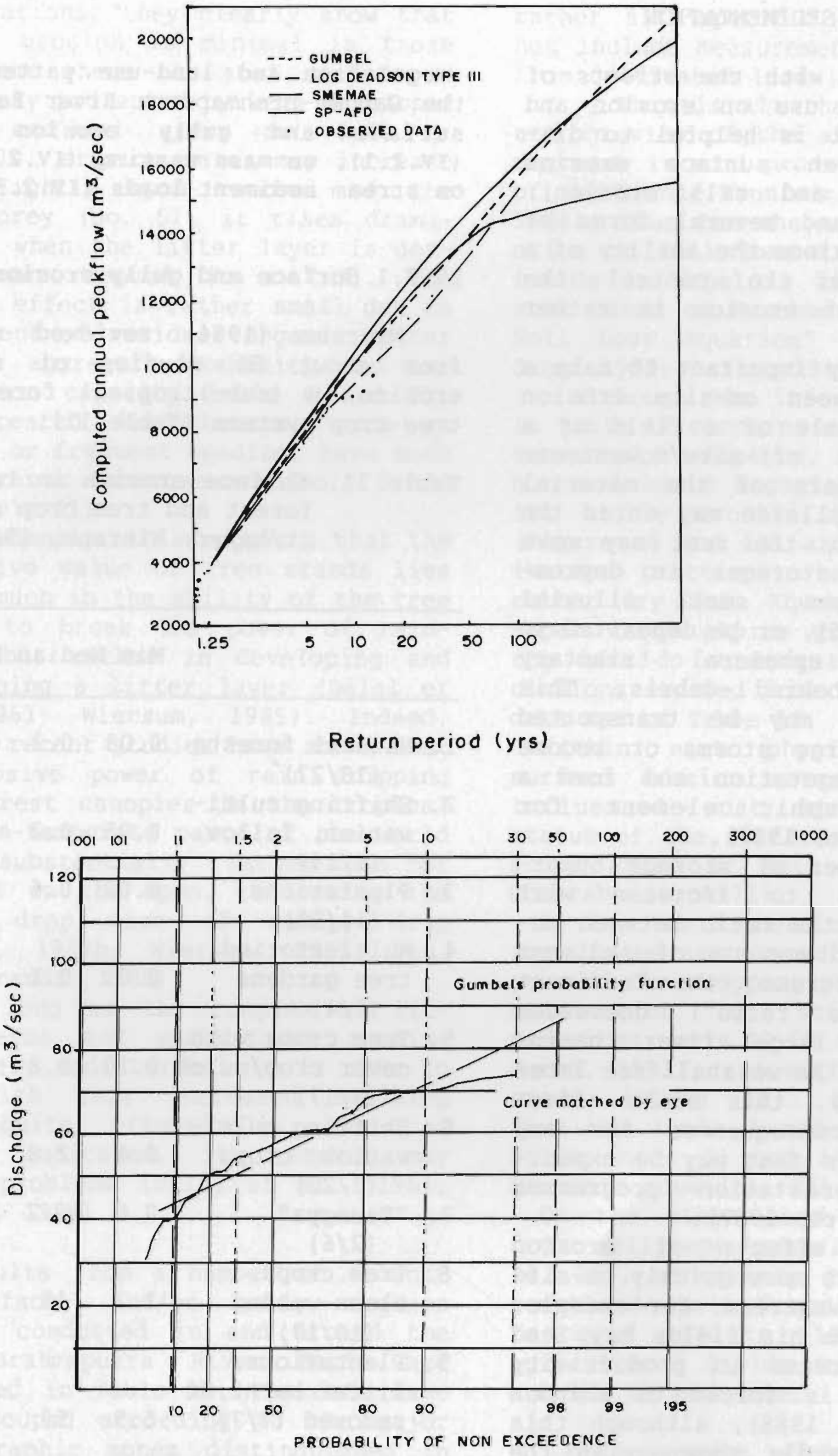

Figure 53. Annual peak discharges for different return periods for the river Ganges. (a) at Raiwala (after Sakthivadivel & Raghupathy, 1978). (b) at Farakka (based on UNESCO, 1976; Rodier & Roche, 1984).

IV.2 EROSION AND SEDIMENTATION

When dealing with the effects of changes in land use on erosion and sedimentation, it is helpful to distinguish between surface erosion (splash, sheet and rill erosion), gully erosion, and several forms of mass movements, since the ability of a vegetation cover to control the various forms of erosion is rather different.

It is equally important to make a distinction between on-site erosion (i.e. on the scale of a field or a hillslope) and off-site/downstream effects. Only part of the material eroded from a hillside may enter the drainage network, the rest may move into temporary storages in depressions, footslopes, small alluvial fans (cf. Plate 6), or be deposited in the beds of ephemeral tributary drainages or behind debris. This stored material may be transported again during large storms or become colonized by vegetation and form a stable topographic element for decades (Hamilton, 1987).

As the number of storage opportunities tends to increase with catchment size, the ratio between on-site erosion and amounts of sediment carried by a stream (the "sediment delivery ratio ratio") decreases markedly for large river basins (Walling, 1983). As we shall see later (Section IV.2.3), this scale effect has profound consequences for any off-site benefits that may be expected from reforestation programmes (Hamilton & Pearce, 1987).

Naturally, effects of erosion will be felt much more quickly on-site than further downstream. For example, soil losses from his fields may lead to such a decrease in productivity that a farmer is forced to abandon them (Shrestha, 1988), although this sediment may hardly show up in the streams of the area. Similarly, it may take decades before reduced surface erosion in upland areas is reflected in reduced sediment downstream (cf. IV.2.3).

In the following sections we will discuss the effects of changes in vegetation and land-use patterns in the Ganges-Brahmaputra River Basin on surface and gully erosion rates (IV.2.1), on mass wasting (IV.2.2) and on stream sediment loads (IV.2.3).

IV.2.1 Surface and gully erosion

Wiersum (1984) reviewed results from about 80 studies of surface erosion in (sub-)tropical forest and tree-crop systems (Table 11).

Table 11. Surface erosion in tropical forest and tree crop systems (t/ha/yr; Wiersum, 1984)

	Min	Median	Max
1. Natural forests (18/27)*	0.03	0.3	6.2
2. Shifting cultivation, fallow (6/14)	0.05	0.2	7.4
3. Plantations (14/20)	0.02	0.6	6.2
4. Multi-storied tree gardens (4/4)	0.01	0.1	0.15
5. Tree crops with cover crop/mulch (9/17)	0.10	0.8	5.6
6. Shifting cultivation, crops (7/22)	0.4	2.8	70
7. "Taungya" (2/6)	0.6	5.2	17.4
8. Tree crops, clean-weeded (10/17)	1.2	48	183
9. Plantations, litter burnt or removed (7/7)	5.9	53	105

* (a/b) a = number of locations
b = number of "treatments"

Although the data collated in Table 11 are of variable quality and reflect a variety of pedological situations, they clearly show that surface erosion is minimal in those ecosystems where the soil surface is adequately protected by well-developed litter- and herb layers (no's 1-4).

Whilst erosion rates may increase only slightly upon removal of the understorey (no. 5), it rises dramatically when the litter layer is destroyed or removed (no's 7-9). The initial effect is rather small due to the effect of residual organic matter on soil aggregate stability and infiltration capacity (no's 6 and 7), but repeated disturbances, such as burning or frequent weeding, have much more serious consequences (no's 8 and 9 in Table 11).

Incidently, this suggests that the protective value of tree stands lies not so much in the ability of the tree canopy to break the power of raindrops, but rather in developing and maintaining a litter layer (Dalal et al., 1961; Wiersum, 1985). Indeed, several recent studies have shown that the erosive power of rain dripping from forest canopies in the tropical and warm-temperate parts of the world may be substantially larger than for rainfall in the open, reflecting the larger drop size of canopy drip (Mosley, 1982b; Wiersum, 1985; Vis, 1986; Brandt, 1988).

As long as the complex of litter, herbs and understorey remains relatively undisturbed, it is able to deal with this increased striking force quite effectively, but, as already indicated, its removal may create problems (Dalal et al., 1961; Wiersum, 1984).

Results from a number of selected surface- and/or gully erosion studies conducted in and around the Ganges-Brahmaputra River Basin are presented in Table 12. The data have been grouped according to the major physiographic zones distinguished in Section II.2.

In contrast to most of the Indian studies quoted in Table 12, which often lasted for several years and may be considered to be relatively relialiable, the few data available for Nepal derive from short-term and rather site-specific studies, and do not include measurements of soil loss from cultivated land (Ramsay, 1986).

This is all the more unfortunate in view of the already indicated decrease in soil productivity in parts of the Middle Mountain zone (Shrestha, 1988). Thus far the available information on soil loss from agricultural fields in Nepal is limited to estimates based on Wischmeier's "Universal Soil Loss Equation" (e.g. Fetzer & Jung, 1979; Balla, 1988b).

Although the information collated in Table 12 concerns an array of environmental conditions, ranging from the hot and humid Meghalaya plateau with its highly erosive rainfall pattern (Figures 8 and 13) and shifting cultivation practices, to the cool and rather dry Solo Khumbu area in East Nepal where alpine grazing prevails, the data do confirm the general conclusions derived from the pan-tropical data set of Table 11.

Within each physiographic zone, surface erosion rates are generally influenced most strongly by the status of the surface, rather than by slope angle or soil type (see also Chakrabarti, 1971).

By far the highest rates of erosion seem to be associated with the second year of the cropping phase of shifting cultivation (no soil conservation practices; no's 19-22 in Table 12; cf. Hurni, 1982), and with heavily grazed areas (Plate 18), be it in the Siwaliks (no's 7 and 9), the Middle Hills (no's 13 and 14), or the High Mountain zone (no. 15).

On the other hand, erosion rates from well-kept grassland (no's 1-3, 14, 16), moderately grazed forest or scrubland (no's 6 and 14), and well-terraced (Plate 19) or mulched agricultural fields (no's 1-3, 8, 10) are low to moderate.

Gully erosion within the Ganges River Basin is especially widespread in the westernmost Siwaliks (Pant, 1983) and along the Yamuna (3900 km^2) and Chambal (ca. 5000 km^2) rivers,

Table 12. Effects of land cover on surface and/or gully erosion rates in the Ganges-Brahmaputra River Basin

Location	Type of land use or conversion	Runoff (% of rainfall)	Erosion (t/ha/yr)	Remarks
(a) **Himalaya**				
Dun valleys and adjacent slopes				
Dehradun ^{1,2}	- Cultivated fallow	69	185	Standard runoff plots (22.1x1.8 m); 8% slope; silt loam; maize cultivation; values are for 1978 monsoon season (1906 mm of rain); strip tillage: only along seed lines
	- Normal tillage	52	52	
	- Ibidem + mulch @ 4 t/ha	25	9	
	- Strip tillage	50	40	
	- Grass (type not specified)	2	0.4	
	- Maize, planted up and down the slope	43	22	Same plots as above; values are averages for 1982 and 1983; corresponding rainfall totals 836 and 1095 mm resp.; mulch consists of grass cuttings
	- Ibidem along centour	37	18	
	- Maize + mulch @ 2 t/ha	18	7	
	- Maize + mulch @ 4 t/ha	15	5	
Dehradun ^{3}	- Strawberry + weeds	28	9	Runoff plots 20x5 m; 11% slope; silt loam; values are for 1974 monsoon season (1180 mm); weeds removed by cultivation; results for clean-weeded strawberries biased due to high mortality of plants
	- Ibidem - weeds	29	26	
	- Pineapple + weeds	9	3	
	- Ibidem - weeds	11	11	
	- Pomegranate + weeds	12	3	
	- Pomegranate - weeds	31	19	
	- Perennial grass (*Cymbopagon citratus*)	20	4	
	- Cultivated fallow	25	33	
Dehradun ^{4,5}	- Cultivated (W3A)	9	2.1	Small catchments drained by stabilized gullies; W3A, B gauged since 1960; W3A (55 ha) bunded in 1970; post-bunding period 1970-1980; W3B (70 ha) intensively grazed; most sediment coming from trails and bank collapse; W2C (4.4 ha) gauged since 1972; checkdams erected in 1976; most sediment coming from unmetalled road; all sediment essentially bedload trapped behind weirs, suspended load unknown
	- Ibidem, bunded	6	0.1	
	- Grazed forest (W3B)	18	1.4	
	- Grazed forest (W2C)	17	4.3	
	- Ibidem, with checkdams	19	2.6	

<u>Siwaliks</u>				
Rajpur, Dehradun [6]	- *Shorea* coppice forest (20 years old)	42	0.2	Typical grazed Siwalik headwater catchment; 6,5 ha; sandy; 22-30° slopes; annual rainfall 2950 mm; values are averages for 1967-1970 monsoons (June-October); sediment is fraction trapped behind weir
Nurpur, H.P. [7]	- Heavily grazed forest	?	22	No further details given
Chandigarh [8]	- Terraced land, upto 50% maize cultivation	27 27	2.5 2.5	Small basin (4.6 ha); grassed waterways; values are averages for 1977-1984 monsoons (630 mm of rain)
Chatra, East Nepal [9a]	- Various, forest to grazing	-	8-37	Southerly aspect; sandstone; no further details
Surkhet, West Nepal [9b]	- Severely degraded, heavily grazed forest, on intensively gullied bedlands	-	200	Southerly aspect; sandstone; 60% slope; no further details
<u>Middle Hills</u>				
Fakot, U.P. [10]	- "Improved" terracing			
	1979 (1660 mm)	7	4.4	Plot of 240 m^2; terraces 2-5% lateral slope, 1-2% inward slope; plot heavily mulched in 1981
	1980 (1770 mm)	12	1.3	
	1981 (1160 mm)	4	0.2	
	- Poor terracing			
	1979 crops	23	2.8	Plot of 310 m^2; terraces 5-10% lateral slope, 5-20% outward slope; overall slope 55%; plots located in experimental watershed of Figure 52
	1980	34	4.9	
	1981; natural grasses	3	2.1	
Naini Tal [11]	- Oak forest (47% cover)	0.44	0.025	Micro-headwater catchment areas of 30-240 m^2; 36-40°; elevation 2050 m; annual rainfall 2820 mm; well-drained soils derived from Krol limestones; values are averages for monsoons of 1981 and 1982 (1438 and 1561 mm)
	- Open forest (38%)	0.44	0.040	
	- Open forest (19%)	0.45	0.026	
	- Old slide (31%)	0.45	0.042	
	- Fresh slide (18%)	0.60	0.062	
	- Cropland (46%)	0.57	0.064	
	- Soil deposition (12%)	0.60	0.081	

Mussoorie[12]	- "Forested" - "Deforested"	- -	0.75 4-5	Four micro-catchments (0.8-1.0 km^2) on south-facing slope (20-30°) underlain by shales and sandstones; elevation ca. 2200 m; values are for 1978 monsoon, which was of twice-normal intensity; sediment measured trapped by road crossed by the "experimental" streams; original volumes converted to weight by application of a density factor of 1.4 g/cm^3
Banpale, Pokhara, Central Nepal[13]	- Fenced pasture - Unfenced grazing land	- -	9 35	One 10x1 m plot on south-facing stage (25°); elevation 1500 m; clay loam on phyllitic schist; four measurements between 29 June and 5 July 1978
Ibidem[14]	- Tree seedlings in fenced pasture	6-15	1	Location as above; number of plots doubled; daily sampling between 11 June and 15 October 1979; corresponding rainfall 3850 mm
	- Overgrazed land	26-47	8-12	
Tamagi, Pokhara, Central Nepal[14]	- Dense forest	<1	0.4	One 10x1 m plot on north-east facing slope (70%); elevation 1800 m; clay loam on (quartzite) schist; 11 composite measurements between 1 July and 7 October 1979
<u>High Mountains</u>				
Namche Bazar Dingboche, East Nepal[15]	- Sub-alpine forest - Shrub-grassland - Heavily grazed alpine	- - -	0.5 g/week 0.9 g/week 23 g/week	Thirty-five unbounded plots with 0.5 m long collection troughs ("Gerlach" type); elevations 3390 to 4416 m; sandy loams; replicated and stratified sampling design; weekly measurements between 6 April and 1 November 1984; forest on northeast-facing and scrub on south-facing slopes
(b) Indo-Gangetic Depression				
Agra[16]	- Cultivated fallow - <u>Cenchrus ciliaris</u> grass - Millet, cowpea, etc.	50 15 30-38	16 2 4-6	Bounded runoff plots on 2% slope; values are averages for 1981-1983 summer monsoons; corresponding mean rainfall 490 mm

Jhargram, West Bengal 17	- Bushy <u>Shorea</u> coppice	2.5	0.31	Plots of 60x5 m laid out on 1.5% slope in <u>Shorea</u> plantation; daily measurements; plots protected from grazing since start of experiment in 1964/65; trenches 10 m apart; values are averages for 1965, 1967 and 1969; corresponding average rainfall 1463 mm; both runoff and erosion in the well-vegetated plots decreased as time progressed, whilst they increased in the burnt and bare plots
	- Ibidem, with trenches	2	0.26	
	- Tall <u>Shorea</u> coppice	2.2	0.38	
	- Ibidem, with trenches	1.5	0.22	
	- Tall coppice, burnt twice a year, no undergrowth	5	0.71	
	- Bare plot	13	4.0	

(c) Old Southern Plateau's

Hyderabad 18	- Broadbed-and-furrow cultivation (two crops)	14	1.6	Small catchment comparison in the black soil belt; 0.5-3.0% slopes; heavy clays; values are average seasonal (June-October) totals between 1973 and 1978
	- Traditional cultivation (rainy season fallow + weeding, one crop per yr)	25	5.6	
Shillong, Meghalaya 19	- Shifting cultivation	6	41	No details given, but presumably representing conditions very similar to 20, 21
	- Food crops, Puerto Rican type of terracing	15	28	
	- Ibidem, but with bottom third of slope bench-terraced	12	14	
	- Ibidem, fully bench-terraced	7	3	
	- Secondary (bamboo) forest	0.5	0.5	
	- Secondary forest plus habitation	11	19	
Ibidem 20	- Shifting cultivation first year	-	147	Unspecified number of unbounded plots sampled "periodically"; slopes 50-60%; soil lateritic; rainfall during study year 2220 mm; no information on age of vegetation in abandoned field, probably recent; measurements must be regarded as very crude and probably overestimates
	- Ibidem, 2nd year	-	170	
	- Abandoned field	-	30	
	- Bamboo forest (8-10 years)	-	8	

Ibidem [21]	- Freshly burnt fields under cropping:			One 10x1 m plot for each treatment; steep slope; (angle not specified) on lateritic soil; elevation <1000 m?; study year 1978 very dry (1420 vs. 2200 mm of normal rainfall);
	30-year cycle	21	22.5	
	10-year cycle	24	23	
	5-year cycle	26	30	
	- Fallows (regrowth)			
	5 years old	19	1.1	
	10 years old	13	0.8	
Ibidem [22]	- Cultivated fields			Four(?) 20x2 m plots for each treatment on 40° slope; elevation 1500 m; lateritic soil; values averages for two years 1977-1979; corresponding rainfall ca. 1785 mm/yr
	10-year cycle	30	50	
	5-year cycle	33	55	
	- Fallows (regrowth)			
	1 years old	25	7.5	
	5 years old	21	3.5	
	10 years old	13	2	

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[1] Khybri et al., 1978; [2] Khybri, 1983; [3] Ghosh, 1974; [4] Ram Babu et al., 1980; [5] Ram Babu et al., 1981; [6] Subba Rao et al., 1973; [7] Ghosh & Subba Rao, 1979; [8] Mittal et al., 1984; [9a] Chatra Research Centre, in Laban, 1978; [9b] K.M. Sakya, personal communication, in Laban, 1978; [10] Anonymous, 1981b, 1984; [11] Pandey et al., 1983/84; [12] Haigh, 1982; [13] Mulder, 1978; [14] Impat, 1981; [15] Byers, 1987; [16] Bhushan & Prakash, 1983; [17] Ray, 1971; [18] Kampen et al., 1981; [19] Singh & Singh (1981) in Das & Maharjan, 1988; [20] Singh & Singh, 1980; [21] Toky & Ramakrishnan, 1981; [22] Mishra & Ramakrishnan, 1983a

Plate 18 Prolonged overgrazing after forest removal produced this seriously eroding landscape on vulnerable red soils in the Kabhu Palanchok district, Central Nepal.

Plate 19 Excellent terracing of a hillslope in the Middle Mountain zone of the Kumaon Himalaya enables sustainable rice cultivation (photograph by J. Rupke).

most of it caused by mismanagement of these relatively dry and therefore ecologically sensitive areas (Haigh, 1984b).

Similarly, in the Himalaya, the clearance of vegetation and subsequent overgrazing in places where highly erodible soils (such as those found on sandstones, quartzites, deeply weathered gneisses or lacustrine deposits) occur, have lead to intense gullying (Nelson et al., 1980; Brunsden et al., 1981; see also Plate 18).

The influence of vegetation in case of actively eroding gullies is rather limited and rehabilitation schemes will often need to be supplemented with mechanical measures, such as check dams, retaining walls as well as protected waterways diverting the water from the eroding headwall (Narayana & Sastry, 1985).

Although the Central Soil and Water Conservation Research and Training Institute at Dehradun has achieved a fair deal of success in developing techniques to reclaim gullied lands in the western parts of the Ganges basin (Das, 1977; Haigh, 1984b), gully rehabilitation remains a complex and often costly affair (Hudson, 1971).

Whilst the data presented in Table 12 do indicate the very real possibility of minimizing on-site, and to a lesser extent also gully, erosion rates by proper conservation practices or reforestation, it should be realized that the amounts of sediment carried by Himalayan rivers (Tables 5 and 6; Section III.6) are much larger than most of the field erosion rates quoted in Table 12. This points again to the importance of riparian mass wasting as a source of sediment in these young mountains (Figure 41b; Meijerink, 1974; Carson, 1985).

Therefore, any discussion of the possible benefits that large-scale upland rehabilitation programmes may have for sedimentation in the lowlands, is bound to raise false expectations as long as it fails to take this aspect into account (Narayana, 1987; Section IV.2.3).

IV.2.2 **Mass movements**

The high incidence of landsliding in the Himalaya is immediately apparent on geomorphological maps of the area (Meijerink, 1974; Brunsden et al., 1981; Lakhera, 1982; Kienholz et al., 1983; Fort et al., 1984, etc.). Indeed, the importance of mass movement processes as contributors to the overall sediment loads of streams in the Himalaya is more or less generally accepted in the (scientific) literature on the subject (Laban, 1979; Narayan et al., 1983; Carson, 1985; Ramsay, 1986; Fleming, 1988; Euphrat, 1987).

However, in contrast to this wealth of information on spatial frequencies of mass movements, there is a paucity of data on temporal frequencies (Prasad, 1975) or the actual quantities of material moved (Starkel, 1972).

Ramsay (1986, 1987b) reviewed a number of studies on mass wasting in and around Nepal. Most authors quoted by him ascribed the high level of mass wasting prevailing in the Himalaya mainly to a combination of geological and climatic factors, and to a lesser extent to land-use factors.

Steep dip-slopes, unstable nature of rocks due to their structural disposition (e.g. degree of fracturing), depth and degree of weathering, high seismicity, and oversteepening of slopes through undercutting by rivers, ranked among the most important geological factors (Bansode & Pradhan, 1975; Suneja, 1979; Brunsden et al., 1981; Caine & Mool, 1982; Peters & Mool, 1983; Wagner, 1983; Narayan et al., 1983).

Figure 54 compares frequencies of various types of landslides for different lithologies in East Nepal (Brunsden et al., 1981). Debris slides (relatively shallow (1-3 m) and elongate (100-1000 m) masses of fine earth, frequently triggered by heavy storms) and rock slides occurred on all rock types, but were much less frequent on gneiss and quartzites than on schists, shales and phyllites.

The low frequency of mass movements on the gneisses was explained by the fact that neither the structure of these rocks nor their deep and irregular weathering did permit the development of planar slide surfaces and unstable weathering mantles. As indicated above, however, these gneisses were quite prone to gully erosion (Brunsden et al., 1981). In addition, mass movements in this area were highly concentrated in low level undercut situations, such as ravines and outer river bends (Plate 20).

Of particular interest is the study by Prasad (1975), who discussed ten years of observations of seismic activity, rainfall and landslide occurrence in part of the Kosi basin in eastern Nepal. In general, landslides were most frequent during times of both rainfall and earthquake activity (mainly in July and August). Since slides also occurred during times of low seismicity, Prasad (1975) concluded that intense precipitation and the associated saturation of soils were apparently more important than seismic shocks.

The latter contention is supported by many other observations in the region. For example, Carson (1985) related how in one area in the Middle Hills of Nepal, villagers indicated that the landslides still visible in the early 1980's had all occurred during two events of heavy rain, one in 1934 (!) and the other in 1971 (cf. Manandhar & Khanal, 1988). Similarly, Starkel (1972) found that during an extreme rainfall event of more than 700 mm in three days near Darjeeling, many new landslides were initiated and old ones reactivated. He estimated the associated erosion rate at about ten times the annual average.

Of particular importance seems to be the occurrence of preferential soil water flow paths in zones of structural discontinuity, such as faults (Brunsden et al., 1981; Ramsay, 1985; Nainwal et al., 1985-86). Where also deeply weathered and fractured, such zones often give rise to what Brunsden et al. (1981) have termed "mass wasting catchments": steep, rapidly eroding channels with active, expanding heads supplying material to the channels by a variety of mass movements.

Ramsay (1985) found such mass wasting catchments to be responsible for about 90 % of all the sediment produced by mass wasting processes in the Phewa Tal watershed in the Middle Hill zone of West-Central Nepal (see also Tang et al. (1981) and Du & Zhang (1981) for a classification of debris flow types in the Trans-Himalayan zone and information on their spatial distribution).

With such strong geological and climatic controls over mass movement processes, it is somewhat difficult to evaluate the influence of certain disturbances on land-slide frequency and magnitude in the Himalaya with any degree of certainty. Also, remaining areas of forest in the Middle Mountain zone tend to be on slopes too steep for terraced cultivation. This immediately introduces the methodological difficulty of finding comparable control sites (the forested slopes being steeper and therefore more susceptible to gravity).

For example, it was hoped that the detailed geomorphological mapping of the Kakani area north of Kathmandu would shed some light on the role of forest in preventing mass movements (Kienholz et al., 1983, 1984). Unfortunately, however, the forested areas were found on a different rock formation. As such, the lack of slides on the forested hillslopes could not be ascribed with certainty to the presence of a better vegetation cover.

Laban (1979) carried out a reconnaissance survey of slope failure intensities all over Nepal, counting the number of slides larger than 50 m^2 per linear km as seen from one side of a light aircraft flying at a constant speed of 100 miles per hour.

By necessity, the methodology was simplistic: landslides occurring on forested land (i.e with more than 50 % crown cover) were assumed to be "natural", whilst those seen on land

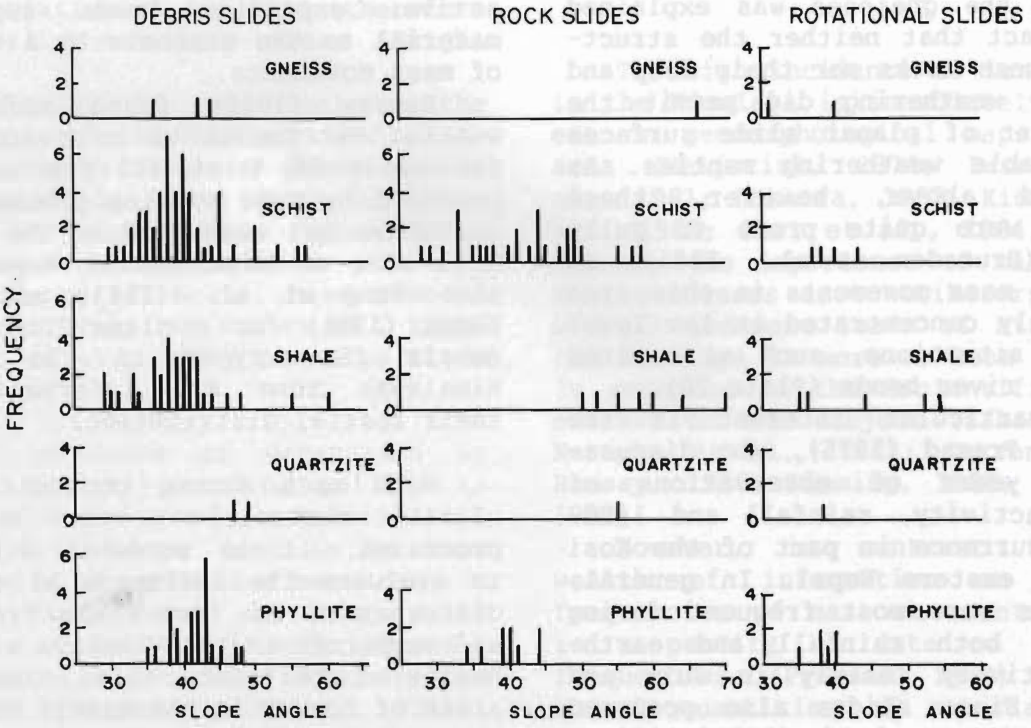

Figure 54. Frequency of mass movements as a function of slope angle and rock type in the Dhankuta and Leoti Khola areas, East Nepal (After Brunsden et al., 1981).

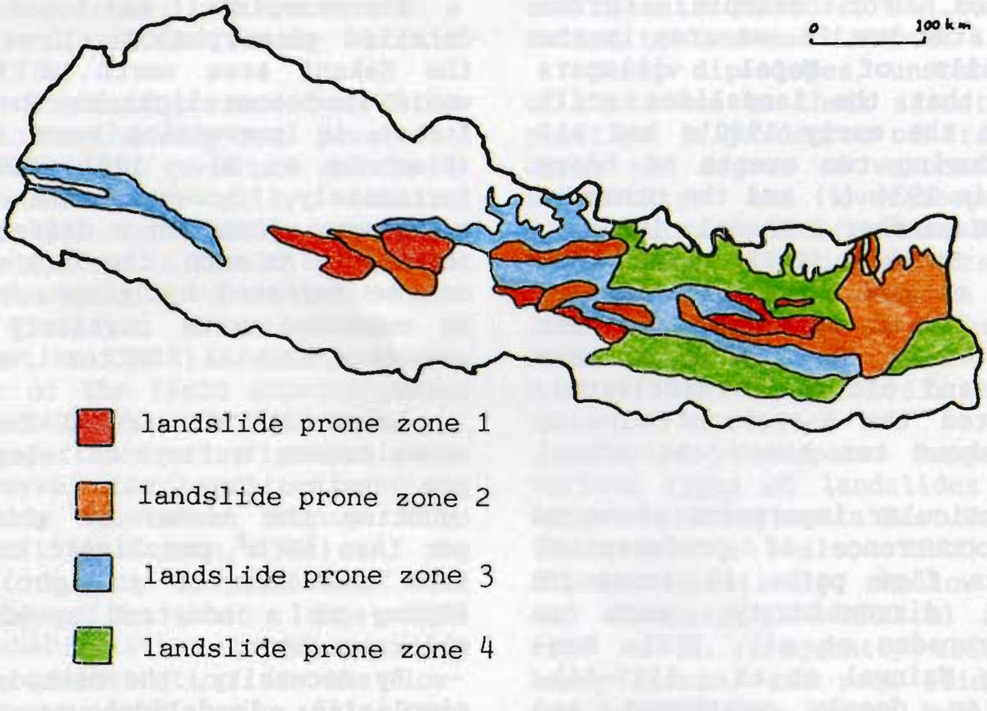

Figure 55. Preliminary distribution of landslide zones in Nepal (modified from Paudiyal & Mathur, 1985).

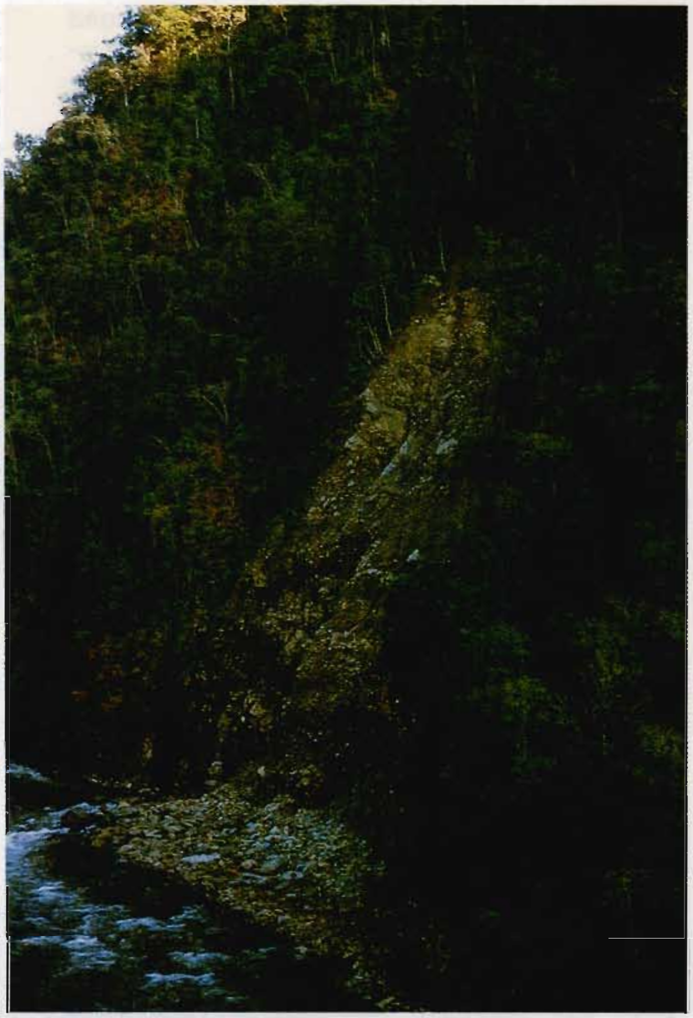

Plate 20

Undercutting of steep slopes in river bends constitutes a major sediment producing mechanism in the Himalaya. Note the fully forested condition of the slope.

with less than 50 % crown cover were by implication "man-caused". Failures associated with trails and roads ("man-caused") as well as undercutting by streams ("natural") were distinguished separately.

The results, expressed per ecological zone (Nelson et al., 1980; cf. Figure 4) and combined with an index of rock erodibility, were used later as a (very rough) indicator for regional patterns of landslide hazards in Nepal by Paudyal & Mathur, 1985) (Figure 55).

Laban (1979) himself did not consider his observations "sufficiently adequate to give insight into the different roles of man and nature in precipitating landslides", although "the acivities of man increased landslide density in many cases". All in all, Laban (1979) suggested that roughly 75 % of all slope failures in Nepal could be considered as "natural". No attempt was made to convert landslide frequencies into volumes of sediment so produced.

Euphrat (1987) conducted a survey of landslide volumes, distribution and approximate age in a 55-ha catchment (47 % cultivated; 43 % scrub and grassland) near Dhulikhel in the Middle Hills of Central Nepal. He concluded that about 80 % of the 474 slides that were recorded, could be classified as "occurring naturally". More than half of these "natural" slides were encountered in the riparian zone (cf. Plates 3 & 20).

Ramsay (1986) distinguished two categories of disturbances: changes in land use (principally the removal of forest cover, followed by grazing or cultivation, possibly with terracing and irrigation), and construction activities (mainly roads, irrigation canals and housing).

As for the influence of (tall) vegetation on slope stability, the net effect is generally considered positive, the major factor being mechanical reinforcement of the soil by the tree roots (Ziemer, 1981; O'Loughlin, 1984).

Although the removal of tall vegetation may lead to wetter conditions in the soil due to reduced evapotranspiration (cf. Section IV.2), which would tend to increase slide hazard, this is not thought to be very important in the case of the Himalaya. After all, most of the failures occur during the second half of the rainy season (Prasad, 1975; Carson, 1985; see also Figure 41b), when slopes have become thoroughly wetted by antecedent rains anyway. Under such conditions, the extra cohesion imparted by tree roots may be critical to slope stability.

It is important, however, to make the distinction between deep-seated and shallow (less than, say, 3 m) slides, as the former do not seem to be influenced appreciably by the presence or absence of a well-developed root network (Starkel, 1972; Carson, 1985). Similarly, Brunsden et al. (1981) reported how mass wasting in phyllitic terrain in eastern Nepal during a few heavy storms, that occurred in late July 1974, was much more intensive on steep forested slopes than in the more gently sloping cultivated areas. Failures were generally restricted to deep ravine headwater areas and along the lower valley sides and banks where undercutting occurred.

Starkel (1972) his contention, that the role of vegetation in preventing *shallow* slope failures (often triggered during heavy rain) is "most important", was demonstrated rather dramatically by the study of Manandhar & Khanal (1988) in the Lele catchment, an area underlain by limestones and phyllites, some 20 km south of Kathmandu. Examination of aerial photographs taken in 1972 and 1986 showed an increase in the number of landslide scars from 93 to 743. Most of these failures occurred on slopes steeper than 33 degrees and had been triggered during a single cloudburst in September 1981 (see photograph III in Carson, 1985).

Interestingly, local informants told the investigators that such heavy storms occurred about once every ten to twelve years (Manandhar & Khanal, 1988), thus confirming the suggestion made by Brunsden et al. (1981) for the return period for formative events for slope and valley landforms in (East) Nepal. Only a few landslides occurred in the thickly vegetated headwater area of the catchment, the majority being found on sparsely vegetated slopes and near limestone quarries (Manandhar & Khanal, 1988; see also Haigh, 1982,1984a).

Although numerous, these small and shallow failures found in mid or upper slope positions usually heal rather quickly (Ramsay, 1985; Euphrat, 1987). In addition, they are only modest contributors of sediment to the streams as they become rarely incorporated in the drainage network (Ramsay, 1987a; cf.section IV.2.3).

Terracing of hillslopes after vegetation removal is generally not considered a direct cause of mass wasting (Ramsay, 1986), although Marston (1988) noted that poor control of terrace drainage in the Langtang-Jugal Himal area of Nepal was important in this respect. As pointed out by Carson (1985), the length and intensity of human occupation in the Middle Mountains is such, that areas liable to slide due to addition of irrigation water would probably have done so a long time ago (cf. Plate 19).

Rather, existing irrigated terraces are stable and small slumps and collapsed terrace risers (Euphrat, 1987) quickly repaired. As described by Johnson et al. (1982), farmers are well aware of increased slide hazards associated with the accumulation of water on terraces.

This perception has sometimes lead them to shift from irrigated to rain-fed cropping. A consequence of this practice, however, is an in- crease in surface erosion (Table 12), as rain-fed terraces are outward-sloping. This is done deliberately in order to dispose of excess rainfall during the monsoon, which could damage the crops by waterlogging (Johnson et al., 1982).

According to Ramsay (1986), irrigation canals in upland areas are frequently associated with slope failures due to both the removal of toe support from slopes and to saturation of the weathering mantle by seepage and overflow.

This brings us to the effects of *construction activities* on mass movements and sediment production.

The construction of large dams with the subsequent inundation of a valley will have on-site and off-site consequences. Around the reservoir itself, the increased pore pressure associated with the saturation of the slopes may well trigger slides when the water level in the artificial lake is lowered for some reason (Carson, 1985; Galay, 1987). Below the dam, a new cycle of riparian mass wasting may be initiated as the river will tend to regain its lost (i.e. trapped by the dam) sediment load by increased incision (Rudra, 1979; Mahmood, 1987; Galay, 1987).

However, by far the most important construction impact on the stability of slopes in the Himalaya, is the ***building of roads*** (Misra & Agarwal, 1982; Haigh, 1984a).

Laban (1979) estimated that ca. 5 % of all landslides in Nepal were due to trails and roads, whilst Euphrat (1987) found a comparable figure of 7 % of total landslide volume to be associated with trails in his study area in the Middle Hills east of Kathmandu. Although perhaps (still) minor in terms of total sediment contribution, this implies an enormous amount of material being moved from a limited area, presenting equally enormous problems of road maintenance (Haigh, 1984a; Carson, 1985).

Similarly, a survey of the state of the hill-roads of the Tehri-Garhwal and Dehra Dun districts of northern India, conducted at the close of the monsoon of 1975, revealed on average ten slides of 500 m^3 per km of road-bed (Bansal & Mathur, 1976).

Although it can be shown, that proper road engineering can solve many of the problems (see Schaffner (1987) his account of the building of a "green" road in the Middle Mountain zone of Nepal), it should be realized that associated costs are extremely high. For example, Carson (1985) quotes the construction costs of the Dharan-Dhankuta road in East Nepal, according to him one of the best engineered roads in Nepal, as amounting to more than 1 million US dollars per km. He went on to say that "in spite of the care made in the assessment of the alignment and during construction, this road has been closed during part of the last two monsoons by serious landslide activity. In the 1984 monsoon over 5 million dollars of damage was done by slope failure".

Clearly, the Himalayan environment is "extremely hostile to road building" (Ramsay, 1986), although the reverse is probably even more true. Therefore, also in view of the present stage of economic development of the Himalaya, the construction of single lane roads with pullouts, suited to farm tractors with trailers (rather than heavy trucks), as suggested by Carson (1985), as feeder roads in the hills holds some promise.

IV.2.3 **River sediment loads**

As shown in the preceding sections the influence of the presence or absence of a good vegetation cover c.q. land management on surface erosion and shallow landslides is quite pronounced at the scale of a farmer's field or very small catchments (Table 12). In this final section on land-use influences we will investigate to what extent changes in on-site erosion induced by land management show up in the sediment loads of streams draining larger catchments in the Himalaya.

Himalayan streams carry high to very high amounts of sediment, especially those in the Middle Mountains (Tables 4-6). The question may be raised to what extent this high rate of sediment production in the Middle Himalaya is man-caused. After all, the forests in this part of the Himalaya have been under rather great pressure for quite some time (Section II.4.3).

The work of Meijerink (1974) in the Aglar catchment, a typical Mid-Himalayan catchment of 320 km^2 in the western Garhwal Himalaya, is particularly relevant in this respect. On the basis of a morphometric analysis of river terrace levels, using aerial photography and field checks, Meijerink calculated that the Aglar river had removed about 1990 m^3 of sediment from a riparian zone of ca. 34 km^2 since the formation of these terraces, some 10-15,000 years ago (cf. Plates 21 and 1).

This would correspond to a long-term natural erosion rate of 40 to 60 m^3/ha/yr, i.e. similar to the values quoted for this zone in Tables 4, 5 and 6. Meijerink (1974) considered most of this sediment to have been derived from slopes that became over-steepened by undercutting by the incising river (cf. Plates 3 & 20).

It could be argued that climatic changes since the Pleistocene have been such, that erosion rates must have varied considerably. Also, the Aglar area is rather dry as it is situated in the rainshadow of the "Mahabharat" (cf. Figure 10). On the other hand, the process of riparian mass wasting is far less sensitive to climatic conditions than, for example, surface erosion.

Similarly, Brunsden et al. (1981) reported stream incision in the Middle Himalaya of eastern Nepal to have been greater than ridge crest lowering during the Pleistocene, resulting in valley-side profiles of generally convex shapes. According to the same authors, the rapidly incising river network is transmitting the effects of tectonic and iso-static uplift to the hillslopes through undercutting and landsliding, thereby moving large amounts of debris directly into the streams (cf. Plates 3, 6 and 20).

Currently accepted rates of tectonic uplift are in the order of 1 mm/ yr (Zeitler et al., 1982; Iwata et al., 1984), although rates as high as 9 mm/yr have been reported for the westernmost part of the Himalaya (Zeitler et al., 1982) and even higher values for the Nanda Devi area (J. Rupke, personal communication).

On the basis of the above evidence we may conclude that river incision is generally keeping pace with uplift and that natural stream sediment loads in the Himalaya must always have been high to very high. The very thick alluvial deposits of the Bhabar zone (Figure 6) bear testimony to this as well (Weidmer, 1981).

Interestingly, and quite unlike most other big river systems in the world, the specific sediment load (i.e. per km^2) of the Ganges increases with basin area (Figure 56). Normally, only a few sub-basins within a given drainage basin exhibit (very) high rates of sediment production (Holeman, 1968; Milliman & Meade, 1983). Not so in the Himalaya, however, where most major streams carry large amounts of sediment (Figure 37), and where the main stream flows all along the mountain range, thus receiving a continuously high input of sediment along its course (Figure 1; Abbas & Subramanian, 1984).

It will be clear from the above, that opportunities to influence such huge transport rates of sediment will be limited. In addition, sediment delivery ratio's (SDR) tend to decrease with catchment size, thereby diminishing off-site effects of changes in on-site erosion (Mou, 1986; Bruijnzeel, 1986; Hamilton, 1987), as will be demonstrated by the following examples from the Indian and Nepalese Himalayas.

Plate 21 Repeated phases of uplift and river incision produced this fine series of river terraces in alluvial deposits in the Middle Mountain zone of the Kumaon Himalaya (photograph by J. Rupke).

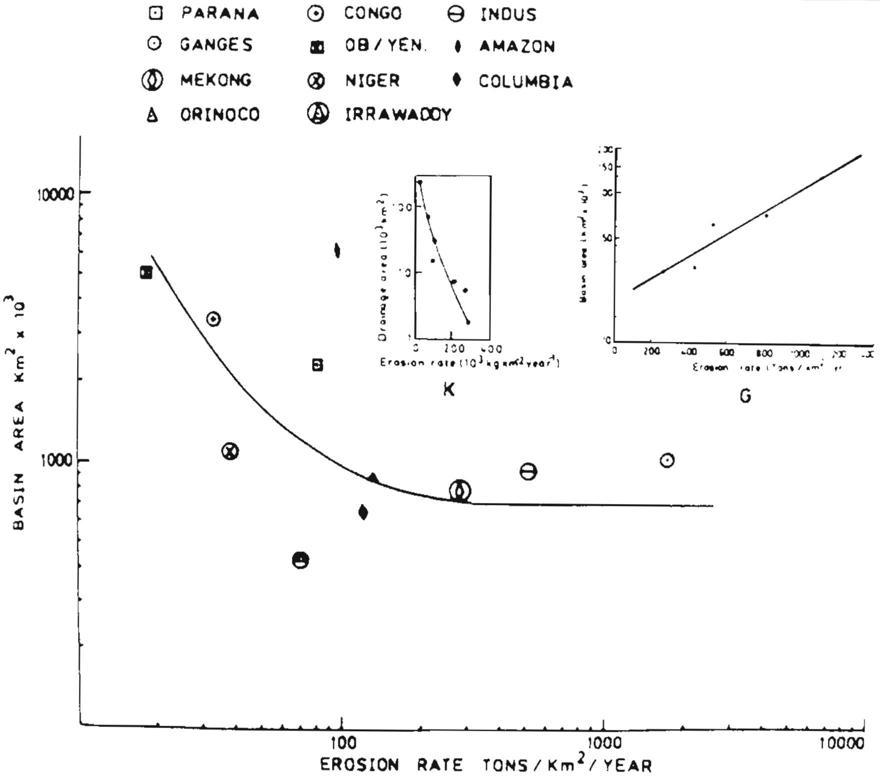

Figure 56. Sediment yield vs. basin area for major tropical river basins. Inset (G): Ganges; (K): Krishna, India (after Abbas & Subramanian, 1984).

Sukhna Lake, Chandigarh

The 229-ha Sukhna lake near Chandigarh is fed by two flashy streams of about equal size, the Kansal and the Sukhetri, which together drain an area of about 44 km^2, 80 % of which is located in the Upper Siwalik formation. This part of the basin consists of forest on steep slopes, with sandy to gravelly soils that are highly susceptible to erosion as well as rather unstable. The forest land is subjected to intense grazing and suffers from sheet erosion (cf. Table 12) and (riparian) sliding. The remaining 20 % of the basin is under cultivation on slopes varying from 0.2 to 5 % Annual rainfall is 1064 mm (Gupta, 1983).

Between 1958 and 1979 the lake lost 60 % of its capacity, despite two partial dredgings (Gupta, 1983). This would correspond with an average inflow of sediment of about 70 m^3/ha/yr. The two streams are connected by an artificial channel, which in itself is a major source of sediment. Concentrations of suspended sediment during the monsoon in the main channel of the Kansal were almost 40 times higher than in three thickly forested headwater catchments (Anonymous, 1977).

Narayana (1987) listed a combination of mechanical, agronomical and forestry measures that have been developed specifically for degraded lands in the Siwaliks by the Central Soil and Water Conservation Research and Training Institute, Dehradun. Application of these measures had a profound effect on the sediment inputs into the lake (S. Chatterji, personal communication).

In this particular case, much of the sediment derived from surface- and channel erosion (Gupta, 1983). As we have seen (Table 12), the former is relatively easy to remedy, whilst the construction of (numerous) spurs, checkdams and debris basins can be very effective in reducing amounts of sediment transported through stream channels (Ram Babu et al. (1980,1981; Narayana, 1987).

Such measures may be expected to be similarly successful in other areas where contributions from surface erosion dominate overall sediment production, such as at the southern plateau (Tejwani, 1985; Narayana, 1987).

Quite a different picture exists, however, for those areas in the Himalaya where riparian mass wasting is the dominant mechanism of sediment supply (Narayan et al., 1983).

Carson (1985) presented a rough calculation of overall (i.e. weighted by land use) surface erosion for the 63-ha Lohore catchment in the Middle Mountains of West Nepal, based on Laban (1979) and Impat (1981)'s comparative data (cf. Table 12). He then assumed an SDR of 50 % and compared the resulting amount of sediment entering the river with a "zonally representative" estimate for stream sediment load of 21 t/ha. Surface erosion in this semi-hypothetical example constituted only 17 % of the total sediment carried by the river (Carson, 1985).

One could argue that in this steep terrain an SDR of 70 % might perhaps have been more appropriate, which would have raised the contribution of surface erosion to 23 %. However, as shown in Table 5, river sediment loads in the Middle Himalayas may be closer to 45 rather than 20 t/ha/yr. Therefore, Carson's estimate of 17 % may well be too high. The inferred rate of sediment production in the riparian zone would amount to some 180 t/ha/yr (Carson, 1985), which is very high in any case.

Although semi-hypothetical, this example is nevertheless instructive, in that it clearly shows that under Himalayan conditions, better management of eroding fields may not necessarily show up as reduced stream sediment loads. If in the present case all surface erosion would have been reduced to that observed under forest, the corresponding reduction in stream sediment would amount to about 10 %.

This of course does not mean that restorative measures should not be applied. They definitely should, but rather in view of the already indicated losses of productivity of cultivated fields in certain parts of the

Himalaya (Shrestha, 1988).

It could be argued that few solid data have been brought forward to illustrate the case. After all, Carson's exercises were largely empirical, although based on considerable field experience. Fortunately, some quantitative data has become available recently, which can be used to test the above view.

Pipal Chaur watershed

The inventory of volumes, types and distribution of slope failures in a 55-ha catchment in the Middle Hills near Dhulikhel, underlain by phyllites and quartzites (Euphrat, 1987), has already been referred to.

Out of 474 landslides with a total volume of 2945 m^3, one major compound slide, located for 90 % in the riparian zone, made up 23 % of the total volume, whilst "naturally occurring" slides (largely in the streamside zone) constituted 80 % of the total volume. Combining volumetric measurements with rough estimates of slide age, Euphrat derived approximate rates of erosion associated with mass wasting per land-use type, which ranged from less than 4 m^3/ha/yr for cultivated land to almost 120 m^3/ha/yr in the riparian zone. Interestingly, the latter value is in the same order of magnitude as that "derived" by Carson (1985) for the Lohore catchment.

In an attempt to assess the importance of mass wasting with respect to contributions by surface erosion, Euphrat (1987) compared his estimates of landslide intensity per land-use category with the surface erosion rates reported by Mulder (1978), Laban (1979) and Impat (1981) for similar types of land use near Pokhara (see Table 12). In addition, as a first approximation of trail erosion, he used an estimate of erosion for a heavily used forest road in the USA as reported by Reid & Dunne (1984). The result of the exercise was that mass movements contributed one-third of the total sediment generated in the area, and various forms of surface erosion the remaining two-thirds.

However, in view of the fact that the area around Pokhara receives more than three (and possibly four) times the amount of precipitation recorded in Euphrat's study area, it is highly unlikely that surface erosion totals for the two areas would be similar.

Also, the erosion rate assumed for trails (1100 t/ha/yr) seems excessive. Schomaker (1988), for example, reported a soil loss from built-up areas (including compacted trails) in Java, Indonesia, under a more aggressive rainfall regime to be in the order of 150 t/ha/yr.

Finally, soil moved by slides in the riparian zone will certainly have more chance of reaching the stream than material eroded from a ridge-crest path. In other words, different weightings would have to be assigned to the various sediment sources in terms of their importance to basin sediment yield.

Therefore, Euphrat (1987)'s conclusion, that stream sediment loads in his area were dominated by surface erosion, is highly questionable. It would be just as easy to "prove", by 1) assigning an SDR of 60 % to all forms of surface erosion as well as to non-riparian slides, 2) by adopting the more modest estimate of trail erosion, and 3) by halving the erosion rates from Pokhara to correct for a much lower rainfall total, that surface erosion in the Pipal Chaur area contributed less than 40 % of the total amount of sediment carried by the stream.

The data on landslide volume and distribution presented by Euphrat are extremely valuable. What is needed to put them in the proper perspective, however, are measurements of surface erosion, that are more representative of regional conditions than the ones derived for the Pokhara area, which is one of the wettest pockets in all of Nepal (Figure 11).

Phewa Tal

A similar analysis can be conducted for the 117 km^2 Phewa Tal catchment in the Middle Mountains near Pokhara, arguably the most researched basin of that size in the entire Himalaya.

Available data include estimates of basin sediment yield based on bathymetric surveys of Phewa lake (Impat, 1981), rates of surface erosion associated with various types of land use (Impat, 1981; to a lesser extent also Mulder (1978) and Balla (1988b)), and observations on mass movement processes (Ramsay, 1985).

Before doing so, however, it must be realized that these data have their limitations. For instance, the results of the bathymetric surveys should be viewed with caution as the difference in storage between the two readings amounted to only 3 % of the total volume of the lake (Impat, 1981) and therefore well within the confidence limits of such an operation. The caveats associated with the erosion plots have been commented upon already in Section IV.2.1 (see also Roels (1985) for a general discussion of the spatial representativity of such installations), whilst Ramsay (1985) himself explicitly stated that his estimates for surface lowering by landsliding should never be used without the prefix "based on a small sample".

Bearing these limitations in mind, the combination of available information presents an interesting picture of sediment production and transport in the Middle Mountain zone of Nepal.

On the basis of the bathymetric surveys Impat (1981) estimated the total amount of sediment trapped in the lake over the period 1976-1979 at 26 m^3/ha/yr, i.e. about 33 t/ha/yr. Assuming a trap efficiency of 90 % this would correspond with an average inflow of sediment into the lake of about 37 t/ha/yr, which is quite comparable to the values quoted for other Mid-Himalayan catchments in Tables 5 and 6 (Section III.6).

Impat (1981) also computed rates of surface erosion for different types of land use by means of the Universal Soil Loss Equation, which were often surprisingly close to actually measured values. Adding up the respective contributions he arrived at a basin-wide estimate of on-site erosion of 89,000 t/yr. Applying an SDR of 0.3 (a reasonable value for a basin this size: Walling, 1983), this would imply that of the 430,000 tonnes (37 t/ha times basin area) of sediment entering the lake each year, about 27,000 tonnes (0.3 times 89,000 t) or 6 % is contributed by surface erosion.

Even if the higher estimate of total surface erosion in the area suggested by Balla (1988b), viz. 135,000 t/yr, is accepted, the contribution of surface erosion remains very modest at less than 10 % of the total sediment yield. The remainder must be supplied by (riparian) mass movements and gully erosion.

Interestingly, on the basis of independent observations of landslide volumes and frequencies in the Phewa valley, Ramsay (1985) arrived at an average estimate of surface lowering by landsliding of about 2.5 mm/yr. In other words, roughly 310,000 m^3 of material is annually transported downhill through various mass wasting processes.According to Ramsay (1985), about 90 % of this material (280,000 m^3) was supplied by a few large failures in groundwater discharge zones. As such, these large features will exhibit a very high transport efficiency and therefore must be responsible for a high proportion of overall sediment movement into the valley bottom river system (Ramsay, 1987a; cf. Brunsden et al., 1981).

Since the central reach of the main river in the area is energy-limited (see Ramsay, 1985 for details), one can only guess as to what fraction of the material thus arriving at the valley floor is transported more or less directly to the lake. Further work is necessary in this regard. Nevertheless, one cannot help noticing the similarity in volumes of sediment generated annually by these large slope failures and those deposited in the lake.

Therefore, the conclusion seems justified that the bulk of the sediment transported by streams in the Middle Himalaya is generated by (a few large) mass movements. Contributions by (accelerated) surface erosion are generally minor.

This finding, of course, has profound implications with respect to the benefits of any upland rehabilitation programmes that can be expected downstream (Hamilton, 1987; cf. III.6).

Fleming (1988) carried out a tentative computation to determine the effect on the siltation rate of the lake of reducing soil loss from overgrazed lands in the Phewa Tal area to a level associated with protected pastures (based on Impat's data). Not surprisingly in the light of the above considerations, the effect was negligible (about 1 % reduction in siltation).

When Carson et al. (1986) carried out a similar analysis for the Kali Gandaki river basin in West-Central Nepal (11,138 km ^{2}), they arrived at a reduction of 7 % in basin sediment yield following rehabilitation measures.

Apart from the magnitude of downstream effects of upland watershed management activities, there is also a time scale involved (Pearce, 1986). This is clearly illustrated by the fact that the sudden inputs of sediment mobilized during the 1950 earthquake in Assam (Poddar, 1952) remained detectable in the sediment load of the Brahmaputra for more than twenty years (Goswami, 1985; see also Section III.6).

As pointed out by Pearce (1986), there would be very little change for decades in the amounts of sediment carried by major rivers in their lower reaches, even if all man-induced erosion in the uplands could be eliminated at once. The reason for this lies in the fact that there is so much sediment (both from previous man-caused and natural erosion) stored in the system, that this effectively forms a long-term supply.

This idea is also supported by the results obtained from a major land- and stream rehabilitation programme in China, which indicated that under prevailing conditions, reductions in sediment yield upto 30 % could be expected for catchments upto 100,000 km^2 after about two decades (Mou, 1986).

Clearly, the frequently voiced claim that upland reforestation will solve most downstream problems does require some specification of the time scale involved as well.