The Effect of Surface Conditions on Soil Erosion and Stream Suspended Sediments

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1. INTRODUCTION

Much is said about the effects of upland erosion on those living downstream. For instance, in the Middle Mountains of Nepal, farming practices are often blamed for generating widespread flooding in the lowlands of Bangladesh (Eckholm, 1975). Many statements are made about the causes of basin sediment output from upland basins. In the Middle Mountains, the cutting of trees is often put forth as the reason for alleged elevated basin sediment output. However, little or no quantitative data exist which examine the actual sediment dynamics within these headwater basins, especially during the monsoon season. Hence, it is very difficult to evaluate the causes of upland erosion and basin sediment output.

In this paper, attention is focused on erosion and sediment dynamics within a highly-monitored headwater basin in the Middle Mountains. The goals of this paper are to describe patterns of sediment transport within this headwater basin in the Jhikhu Khola Watershed and to provide some explanations of observed sediment regimes.

2. MONITORING NETWORK

Hydrometric monitoring started in 1989 in the Jhikhu Khola Watershed with the establishment of five hydrometric stations (Shah et al., 1991). In 1992, detailed hydrometric monitoring was initiated. The complete network consisted of four automated hydrometric stations, four manual hydrometric stations, five erosion plots, five tipping-bucket rain gauges, and up to fifty 24-hour rain gauges. The majority of the hydrologic measurements are concentrated in the Andheri sub-watershed as shown in Figure 1. Intensive flow and sediment monitoring programs were carried out throughout the entire 1992, 1993, and 1994 monsoon seasons (June through September) with detailed monitoring of flow and suspended sediments occurring during most individual storm events. Over a typical monsoon season, up to 100 individual basin flood events were monitored. At the same time, runoff and soil-loss measurements were made at all five erosion plots. Samples were analyzed to determine total losses from the 70 - 100 m^2 plots for each event over the three-year monitoring period.

The basins discussed in this paper are the Andheri and Kukhuri basins, covering 540 ha and 72 ha respectively. The Kukhuri basin forms part of the headwaters of the Andheri sub-watershed. The streams of these basins are extremely steep with slopes of 5-15 degrees in the Kukhuri basin reducing to 2-5 degrees in the lower reaches of the Andheri basin.

3. STREAM SEDIMENT REGIME

The data for all measured stream flow and sediment samples were compiled into a comprehensive database. Figures 2 and 3 show the combined sediment rating curves for Andheri and Kukhuri basins over the three- year study period.

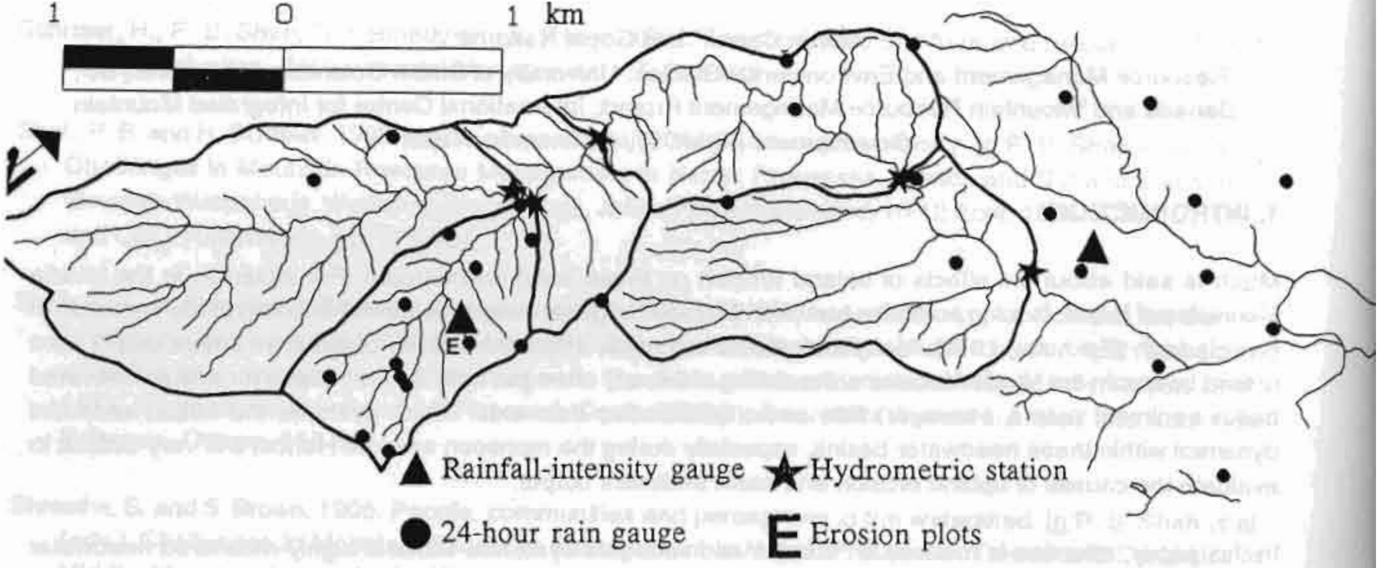

Figure 1. Hydrometric monitoring network in the Andheri Khola sub-watershed.

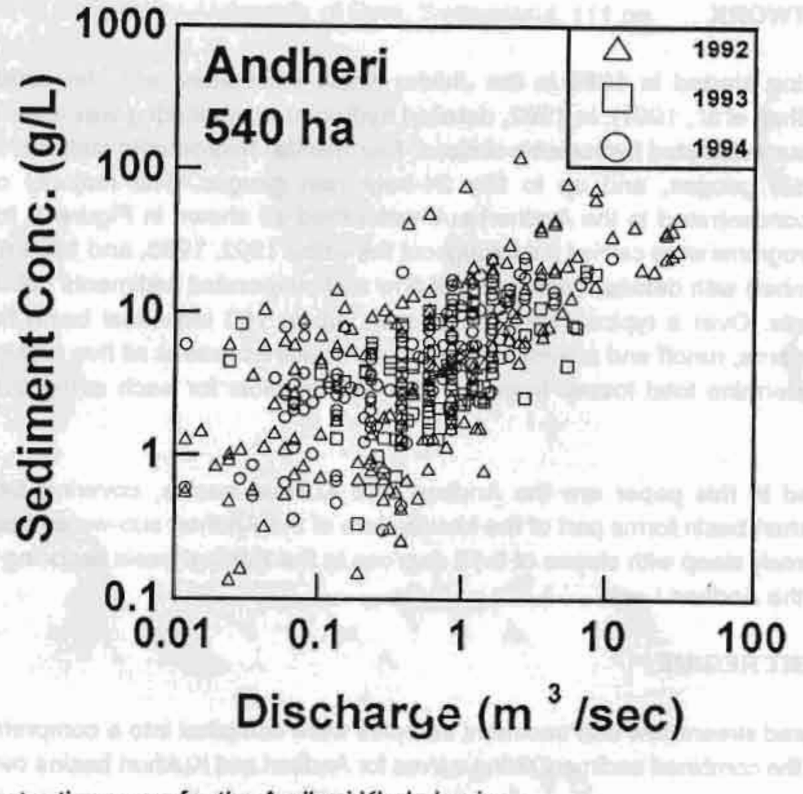

Figure 2. Sediment rating curve for the Andheri Khola basin.

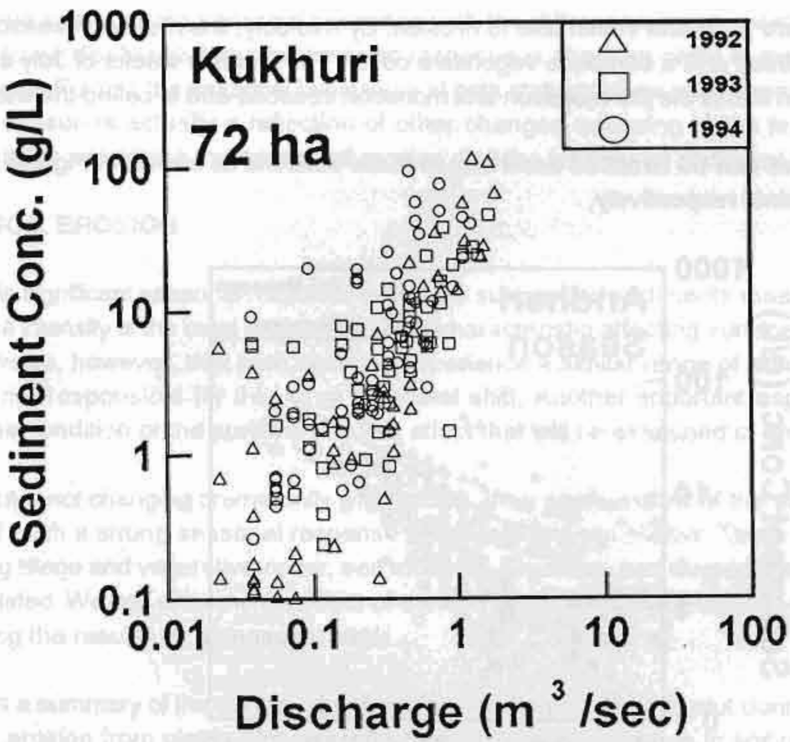

Figure 3. Sediment rating curve for the Kukhuri Khola basin.

A sediment rating curve relates the suspended-sediment concentrations at a stream hydrometric station to its corresponding flow rate or discharge. In both cases, stream sediment concentrations show a strong dependence on discharge. For most discharges, 1 to 2 orders of magnitude of scatter is evident.

To account for the wide scatter of points, it is essential to consider the factors that can influence the sediment-discharge relationship. These include:

- rainfall characteristics
- surface conditions
- sediment storage
- antecedent flood history
- hysteretic effects
- season

Unfortunately, most of these factors interact, making interpretations a challenge.

The surface vegetative cover and the extent of degradation of the land are two surface-condition factors which are important in the Andheri sub-watershed. These factors are examined in this paper in relation to sediment transport. To assess the way in which these two variables shape the basins' sediment regimes, we first consider the importance of the effect of season on erosion and sediment transport.

Perhaps the most common approach to evaluating sediment rating curves is to separate the data according to season. In the study area, there are distinct seasons as the climate changes from the dry to the wet seasons. When the rains arrive in the late spring (the pre-monsoon season), the land surface is extremely dry and the upland cultivated fields are bare and vulnerable to erosion. By mid-July, the monsoon season is well under way, bringing regular rainfall and a complete vegetative cover. The first few weeks of July show behaviour which intergrades between that of the pre-monsoon and monsoon seasons and is called the transition season.

The sediment rating curves can be stratified according to these seasons as shown in Figures 4 and 5 for the Andheri and Kukhuri basins, respectively.

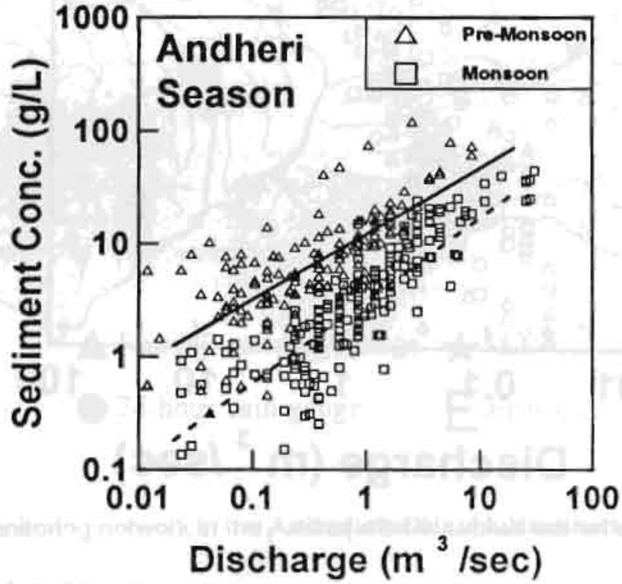

Figure 4. Seasonally-stratified sediment rating curve for the Andheri Khola basin.

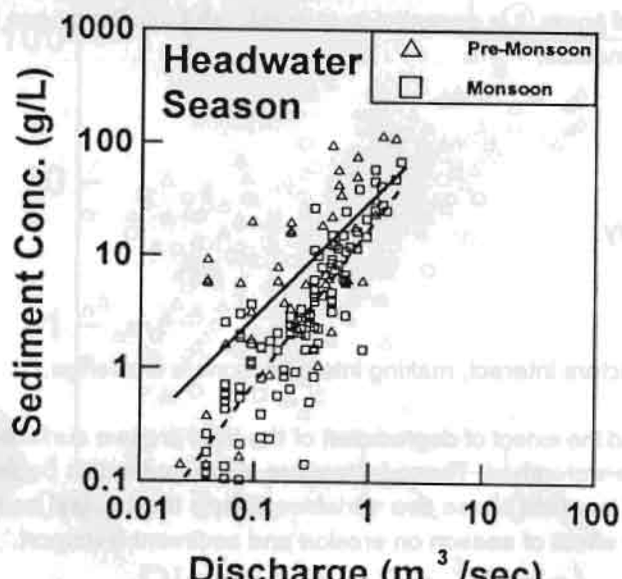

Figure 5. Seasonally-stratified sediment rating curve for the Kukhuri Khola basin.

In each case, we see a strong seasonal response with the difference being greater for the Andheri basin. Generally, for a given discharge, the pre-monsoon response is about an order of magnitude greater than the monsoon response. Further, the seasonal behaviours at both stations show a tendency to merge at the highest flows. Though season is actually a reflection of other changes occurring in the farming system, it forms a convenient basis for examining the causes of erosion and the sources of sediment to the streams.

4. SURFACE SOIL EROSION

What causes this significant seasonal response in stream suspended sediments measured at the hydrometric stations? Rainfall intensity is the most important rainfall characteristic affecting surface erosion. The three-year rainfall record shows, however, that both seasons experience a similar range of rainfall intensities, indicating that rainfall is not responsible for this large seasonal shift. Another important aspect which does change seasonally is the condition of the surface. It is this effect that will be examined in greater detail in this paper.

If the rainfall input is not changing dramatically with season, then some aspect of the surface must be changing in order to yield such a strong seasonal response at the hydrometric station. There are many aspects to the surface including tillage and vegetative cover, soil moisture, land use, and degradation. Further, these factors are often interrelated. We can examine the effect of surface cover on surface erosion by turning to the erosion plots, expressing the results on a seasonal basis.

Table 1 presents a summary of the annual rate of soil loss from each erosion plot during 1992-1994. The large variation in soil erosion from plot to plot is a reflection of the large variation in soil properties across the five plots. We can stratify these results by season to compare them to the stream sediment rating curves. This result is presented in Table 2 and shows that regardless of soil properties, most of the annual erosion occurs in the pre-monsoon season.

Table 1. Annual rate of soil loss (tonnes/ha) at all erosion plots, 1992-1994.

Plot No.	Annual Rate of Soil Loss (tonnes/ha)		
	1992	1993	1994
1	18	4.1	42
2	23	34	6.4
3	38	37	6.9
4	0.1	0.2	2.9
5	0.1	0.3	2.6

5. SURFACE VEGETATIVE COVER

The major seasonal change in surface condition which occurs at each plot is a change in surface cover as weed growth and the summer crop develop. The farmers also frequently intercrop providing a further protection of the soil from intense rainfall.

Changes in vegetative cover can also explain the large inter-annual variation in soil loss at a given plot. Surface cover does not develop immediately but requires rainfall to get started and then takes several weeks to be complete. If damaging rains occur when the surface cover is only partially complete - which is common - then significant losses are likely at the plot. And if this cover is inadequate when an intense rainfall occurs then the losses can be large. Table 3 shows the percentage of each plot's annual soil loss that occurred in the two most-damaging events. At all plots and in all years, about 50 - 90% of the annual total occurs in only two events. The timing of these events was particularly unfortunate in plots 2 and 3 in 1992 and 1993 as they occurred very early in the pre-monsoon period when vegetation cover was at a minimum. These events are reflected in the production of high annual soil erosion losses as shown in Table 1.

Table 2. Percentage of annual total soil loss occurring in the pre-monsoon and transition seasons for all erosion plots, 1992-1994.

Plot No.	Percentage of Annual Soil Loss Occurring in Pre-Monsoon Season (%)		
	1992	1993	1994
1	65	25	88
2	96	100	99
3	99	100	97
4	87	68	100
5	31	78	100

Table 3. Percentage of the total annual erosion at each plot which occurred in the two most-damaging events of each year, 1992-1994.

Plot No.	Total Annual Erosion (%)		
	1992	1993	1994
1	55	50	44
2	96	88	87
3	78	91	82
4	69	40	60
5	60	57	67

6. SURFACE -SOIL DEGRADATION

As vegetative cover is important in shaping erosion levels, so is the condition of the soil at the surface. The erosion plots discussed in the previous section are situated on land which is largely well managed. Farmers take great care to prevent soil loss in these upland cultivated fields. However, large tracts of land in the Middle Mountains are degraded as a result of over utilization and extreme surface erosion. These lands have deeply-exposed surface soil and subsoil, have extensive rills and gullies and often experience surface crusting. These surfaces are poorly vegetated and since they are not cultivated, do not experience the seasonal development of a strong surface cover. Not only do these lands have a poor surface cover year-round but they are also very susceptible to soil erosion.

To show the influence of degraded land, Carver (1995) compares the sediment regime of the degraded Dhap basin to that of the Andheri basin (presented above in Figure 4). The Dhap basin covers about the same area but is much flatter than the Andheri basin. On the basis of topography alone, one expects a higher response in sediment output from the Andheri basin than from the Dhap basin, yet exactly the opposite is measured. Though the surface-cover effect may be part of the explanation, probably a bigger part is related to the extent of degradation. Over 13.6% of the Dhap basin (by area) is gullied land in contrast to the Andheri basin which has only 5.4% of its area classified as degraded (based on 1990 1:20,000 mapping). These degraded lands have largely been abandoned to a non-productive condition due to an advanced state of surface erosion. Hence, though they are not particularly steep in comparison to many frequently-cultivated soils in the Middle Mountains, they contribute a proportionately larger amount of sediment to the overall basin output. In contrast, in the conventionally-managed land, the drop in erosion at the end of the pre-monsoon season is dramatic resulting in a more reasonable sediment regime during much of the monsoon season.

7. DISCUSSION

These results illustrate how land-use practices change soil surface conditions, thereby influencing the overall sediment regime of a sub-watershed. Under conventional hill-farming, sediment output due to surface erosion from cultivated fields can be high for short periods during the pre-monsoon season. These rates of surface erosion drop dramatically due to the development of an effective surface vegetative cover as the crop develops. The risk of large losses due to erosion resulting from pre-monsoon storms is high and though the timing of crop planting is critical, resulting soil loss is largely up to chance. In some years, the farmers are unlucky with the timing of the pre-monsoon rains and high levels of soil loss result. In other years, the vegetative cover is adequately advanced to protect the soil from heavy pre-monsoon rains and low levels of soil erosion result. It is worth stressing that these dynamics are associated with well-managed soils.

Where land has been lost from productivity altogether, a more serious problem results regarding the land's contribution to overall basin sediment output. On a year-round basis, these areas lose soils at an elevated rate, potentially in excess of the rate in the pre-monsoon season on conventionally-managed land. In such cases the seasonal effect is much reduced and the overall contribution during the monsoon season is much more substantial.

Individuals trying to mitigate erosion and improve basin sediment regimes should pay careful attention to the specific goals of their project. For instance, if one is concerned largely with downstream sedimentation perhaps for hydropower development, then it is probably more effective to concentrate one's effort on getting degraded soils back into production or under a vegetative cover. This approach is likely the most efficient way to reduce the amount of material leaving a basin. However, if one is more concerned with improving the productivity of the farming system, then supporting farmers in their conventional management is more effective. In particular, findings ways to reduce soil loss during the pre-monsoon season, by establishing a vegetated surface early in the season, will contribute greatly to improving the overall productivity of the farming system.

8. CONCLUSIONS

The principal conclusions of this paper are:

1. Stream sediment concentrations in the pre-monsoon season are almost an order of magnitude higher than during the monsoon season; the seasonal behaviours tend to merge at the highest flows.

2. Surface erosion is highly variable with potential annual rates of over 40 tonnes/ha; surface erosion is also strongly seasonal with 50-90% of annual surface soil loss typically occurring in only two pre-monsoon events.

3. There is little evidence of significant seasonal differences in rainfall intensities. The observed large changes in erosion and sediment transport cannot be attributed to this factor.

4. The development of a complete vegetative surface cover strongly inhibits surface erosion though unfortunate timing of rainfall in advance of adequate vegetation can yield high losses in the pre-monsoon season.

5. Land with a degraded soil surface contributes to basin sediment output at a potentially greater rate and through the entire rainy season than steeper, well-managed cultivated land.

This paper has tried to diagnose some causes of erosion in headwater basins. Though we now have a better understanding of the causes of sediment dynamics, we ultimately must know the relative influences of these and other factors. To do this we must construct sediment budgets over various spatial and temporal scales and this is the subject of the following paper (Carver and Schreier, 1995).

9. REFERENCES

Carver, M. 1995. How do indigenous management techniques affect soil and water movement? In P. B. Shah et al. (eds.) Challenges in Mountain Resource Management in Nepal: Processes, Trends and Dynamics in Middle Mountain Watersheds. Workshop Proceedings, Jhikhu Khola Watershed, 10-12 April, 1995. ICIMOD, IDRC and UBC. Kathmandu. pp. 193-202.

Carver, M. and H. Schreier 1995. Sediment and nutrient budgets over four spatial scales in the Jhikhu Khola watershed: Implications for land-use management. In P. B. Shah et al. (eds.) Challenges in Mountain Resource Management in Nepal: Processes, Trends and Dynamics in Middle Mountain Watersheds. Workshop Proceedings, Jhikhu Khola Watershed, 10-12 April, 1995. ICIMOD, IDRC and UBC. Kathmandu. pp. 163-170.

Eckholm, E. P. 1975. The deterioration of mountain environments. Science 189:764-770.

Shah, P. B., H. Schreier, S. Brown and K. W. Riley 1991 (eds.) Soil fertility and erosion issues in the Middle Mountains of Nepal, Workshop Proceedings, Jhikhu Khola Watershed, April 22-25, 1991, 285 pp.