Sediment and Nutrient Budgets over Four Spatial Scales in the Jhikhu Khola Watershed: Implications for Land Use Management

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1. INTRODUCTION

There are many factors which determine the type and amount of erosion in mountain watersheds in Nepal (Carver and Nakarmi, 1995). The diagnostic approach is an essential first step in evaluating the status of erosion in a watershed. To identify which factors contribute most to the overall basin sediment output, it is necessary to construct sediment budgets over different spatial and temporal scales. In this paper, we examine the effects of three major rainfall events on sediment and nutrient budgets: a heavy event in each of the pre-monsoon and monsoon seasons and an extreme event during the transition period between these seasons. The effects of these storms on erosion and sediment movement are evaluated by calculating the sediment and phosphorus budgets for each event for four different areas: an upland terrace (70 m^2), a mini-watershed (72 ha), a sub-watershed (540 ha), and the overall Jhikhu Khola watershed (11,141 ha).

Which process dominates depends on the spatial scale under consideration. We cannot look at one spatial scale, for example the agricultural field, deduce the cause and then assume that this cause is dominant over larger spatial scales. The same is true temporally. In this paper, we describe which processes dominate over different spatial and temporal scales because an understanding of highland-lowland interactions is essential in evaluating the future health of the farming system as a whole.

2. SOURCES AND PATHWAYS

A sediment budget is a quantitative expression of the movement and storage of sediment within a basin. The first step in constructing a sediment budget is to identify sediment sources and pathways, as illustrated in Figure 1. The causes of erosion and sediment transport should be understood to assure confidence in extrapolating the data. If nutrient dynamics are also understood, then nutrient budgets can also be constructed.

3. METHODS

Routine hydrometric monitoring was started in 1989 in the Jhikhu Khola Watershed at five hydrometric stations (Shah et al., 1991). In 1992, detailed hydrometric monitoring was initiated using a network 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 has been concentrated in the Andheri sub-watershed. 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. At the erosion plots, all run-off and soil loss have been determined for each event of the three-year monitoring period.

The three events described in this paper have been chosen to reflect a variety of important conditions within the annual farming cycle. The pre-monsoon and monsoon events typify sediment dynamics during these two major agricultural seasons. These two events are of similar magnitude with the pre-monsoon event being of higher rainfall intensity. The third event was the heaviest of the monitoring period and occurred in the period of transition between the pre-monsoon and monsoon seasons. It will be referred to as "the extreme event".

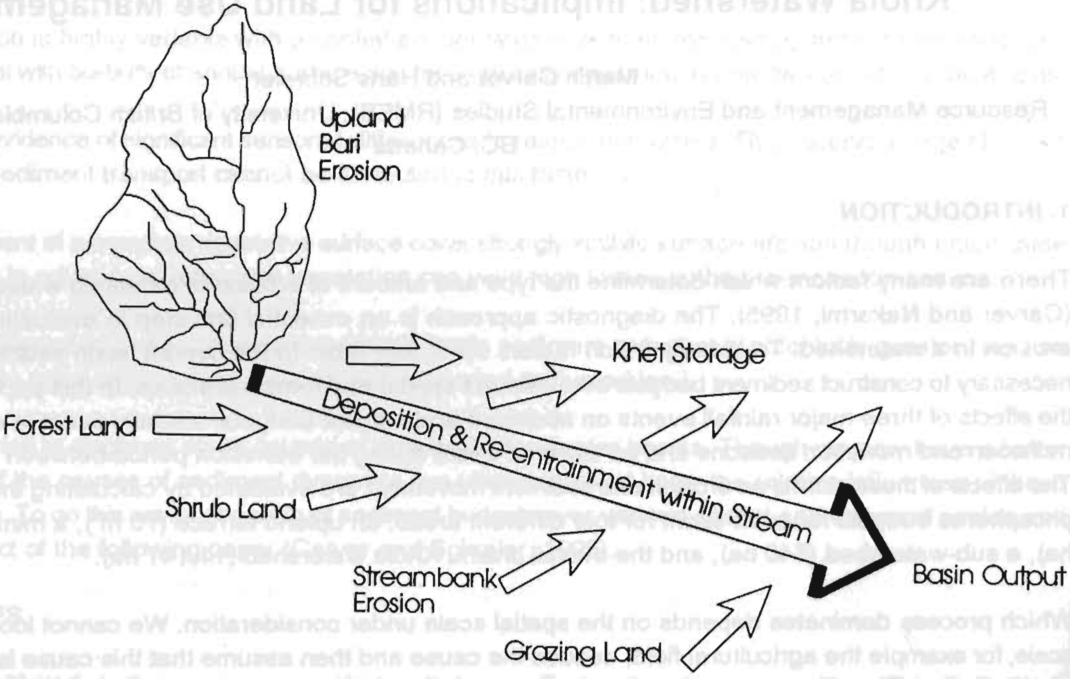

Figure 1. Sediment sources and pathways in the Andheri Khola basin.

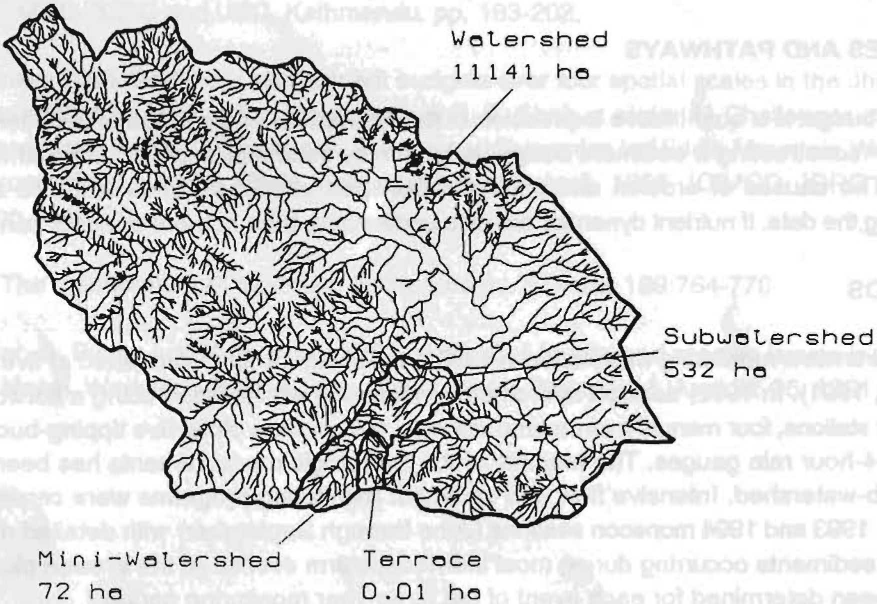

Figure 2. Spatial scales of the sediment and nutrient budgets within the Jhikhu Khola watershed.

The budgets were calculated by first defining the temporal and spatial scales of interest and then quantitative measurements from the long-term monitoring study were used to fill in the gaps between sample points. The temporal scale of interest here is fixed at the single event; budget calculations over entire seasons and years are still in preparation. Using data from the erosion plots and from three different stream hydrometric stations, budgets over catchments of 70 m^2, 72 ha, 540 ha, and 11,141 ha are calculated. The spatial scales are illustrated in Figure 2. In each case, the numerical results are integrated values representing the net result of all sediment and nutrient transfers and movements upstream of the monitoring location for the three specific events. Dissolved nutrients are not included.

The calculation of the budgets at the erosion plot was possible because monitoring was carried out on an event basis and because all eroded material was captured and measured after each storm event. For the budgets over the three larger spatial scales, sediment rating curves (Carver and Nakarmi, 1995) from stream hydrometric stations were used to develop seasonal relationships between stream discharge and sediment transport. These general seasonal curves were calibrated for individual events using actual flow and sediment measurements taken during the events themselves. Laboratory analyses were carried out to determine the phosphorus content in sediment collected from the erosion plot and at the stream monitoring stations. The sediment budgets were converted into phosphorus budgets by using representative phosphorus values derived from these laboratory analyses.

The results are rounded to one significant figure to reflect the level of uncertainty associated with these calculations. It is not the actual numbers but the relative magnitude between scales and events that is of greatest interest. As more data become available, the empirical relationships used in these calculations will no doubt change.

4. EVENT DESCRIPTIONS

From earlier analysis (Carver and Nakarmi, 1995), it is evident that soil erosion and sediment transport are strongly influenced by the seasonal effects associated with the pre-monsoon and monsoon seasons. Pre-monsoon sediment regimes are almost an order of magnitude greater than those of the monsoon season.

The rainfall characteristics for the three individual events evaluated in this paper are summarized in Table 1.

Table 1. Rainfall characteristics of three storm events measured at the upland recording gauge.

Rainfall Type	Season	Date	Peak Rainfall Intensity (mm/hr)	Rainfall Duration (hr)	Total Storm Rainfall (mm)
Upland	Pre-monsoon	June 9, 1992	109	6.4	49.5
Upland	Monsoon	July 17, 1993	63	2.5	35.8
Extreme	Transition	July 10, 1992	103	8.8	90.6

These event descriptions include rainfall intensity and total rainfall as derived from the recording rain gauge in the upland part of the Andheri basin. Using results from the dense network of 24-hour rain gauges within this basin, the spatial characteristics of each event have been determined and are displayed in Figure 3. These 3-dimensional images are not topographic maps but rather are representations of the spatial variation of rainfall amounts over the Andheri basin for each storm event. The event on June 9, 1992 was a heavy pre-monsoon storm centred over the upland portion of the basin. The event on July 17, 1993 was of similar magnitude but occurred in the beginning of the monsoon season. And the event on July 10, 1992 occurred in the middle of the transition season. This event was the heaviest storm rainfall recorded during the 3-year study period.

5. TERRACE SCALE (70 m²)

The rates of soil loss from the erosion plots for each of the three example events are given in Table 2 for both sediments and nutrients. Pre-monsoon losses are orders of magnitude above those of the monsoon season. In the pre-monsoon, the cultivated land is bare and susceptible to surface erosion as shown in Carver and Nakarmi (1995). As the monsoon season develops, so does a comprehensive vegetative surface cover, essentially halting surface erosion as illustrated by the 0.02 tonnes/ha result for the upland monsoon event. The losses in nutrients are proportionately higher in the pre-monsoon season because of the high nutrient status of the soils during that time.

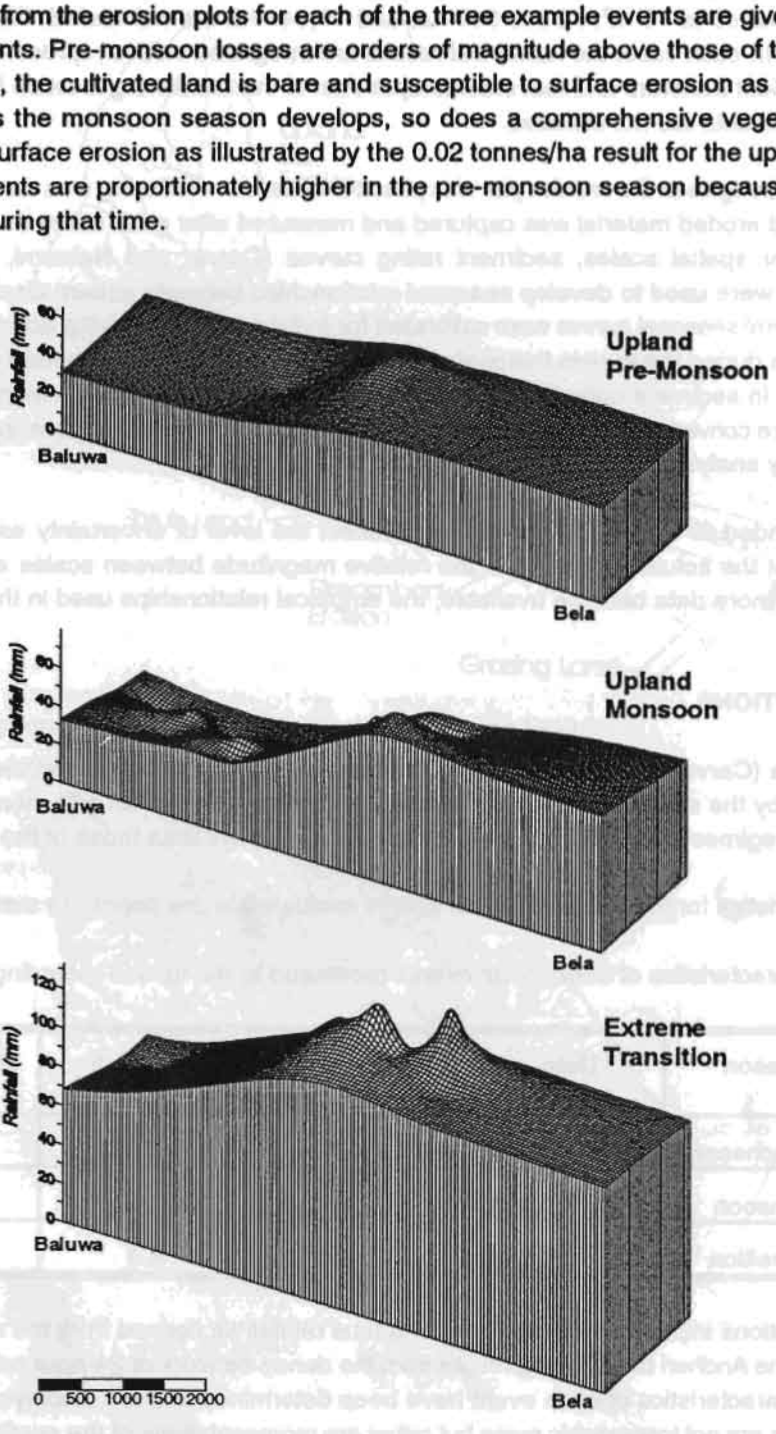

Figure 3. Three-dimensional representations of the rainfall spatial distribution for the three events over the Andheri sub-watershed.

Table 2. Sediment and nutrient budgets at the terrace scale (70 m^2) for the three events.

Rainfall Type	Season	Sediment (tonnes/ha)	Phosphorus (g/ha)
Upland	Pre-monsoon	20	300
Upland	Monsoon	0.02	0.1
Extreme	Transition	10	10

The extreme event, which was a particularly heavy rainfall event, was only half as damaging at the erosion plot as the pre-monsoon event of lower magnitude. This apparent anomaly is easily explained by considering the development of a surface cover. The extreme event occurred in the transition season between the pre-monsoon and monsoon seasons when the vegetative cover is developing but not yet entirely adequate to restrict the rain's ability to erode the soil surface. During this event, a partial vegetative cover existed enabling the loss to be half that of a lighter pre-monsoon event.

6. MINI-WATERSHED SCALE (72 ha)

Table 3 shows the sediment and phosphorus budgets calculated for the three events at the Kukhuri Khola hydrometric station, the 72-ha mini-watershed. The gap between the pre-monsoon and the monsoon events has narrowed. At this scale, other material such as that from terrace slumping serves to increase the loss during the monsoon season. In the pre-monsoon season, losses due to surface erosion are generally far higher than due to slumping and thus the rate decreases at this scale.

Table 3. Sediment and nutrient budgets at the mini-watershed scale (72 ha) for the three events.

Rainfall Type	Season	Sediment (tonnes/ha)	Phosphorus (g/ha)
Upland	Pre-monsoon	5	200
Upland	Monsoon	0.8	20
Extreme	Transition	7	200

At this scale, the extreme event contributes as much to the net basin output as the pre-monsoon event. This is reasonable because of the high degree of terrace slumping from the heavy rainfall. At the terrace scale, the pre-monsoon event produced twice as much sediment as during the extreme event but both were 2 to 3 orders of magnitude higher than the monsoon event. This pattern changes at the mini-watershed scale: the difference between the pre-monsoon and extreme events is gone but the budgets for these events both remain an order of magnitude greater than those of the monsoon event.

7. SUB-WATERSHED SCALE (540 ha)

Table 4 shows the sediment and phosphorus budgets calculated for the three events at the Andheri Khola hydrometric station, the 540-ha sub-watershed. At this scale, the relative difference between the pre-monsoon and monsoon events is similar to that at the mini-watershed scale. The values for both are declining, suggesting either a downstream reduction in sediment production and delivery to the stream or a recapture of material entrained upstream, perhaps through the irrigation system.

Table 4. Sediment and nutrient budgets at the sub-watershed scale (540 ha) for the three events.

Rainfall Type	Season	Sediment (tonnes/ha)	Phosphorus (g/ha)
Upland	Pre-monsoon	2	40
Upland	Monsoon	0.4	4
Extreme	Transition	40	1000

At this scale, the major change is in the large difference between the pre-monsoon and extreme events. The extreme event is now dwarfing the other two in magnitude. It is dominated by erosion associated with the stream which is now enormous. A stream survey following this event showed that the bed in particular was ripped apart by the swollen stream.

Each year, many rainfall events are spatially confined and, even if large areas of the basin experience no rain, a significant flood still occurs at the outlet. It is at the sub-watershed scale that nearly all events are noticed. However as we have seen above, the areal averages may not well represent the actual erosion condition because of the bias toward a small part of the catchment.

8. WATERSHED SCALE (11,141 ha)

Table 5 gives the average rates of soil and phosphorus loss measured at the 11,141-ha Jhikhu Khola hydrometric station for the three sample events. The gap between the pre-monsoon and monsoon events has gone. Either the monsoon event was much more damaging or the pre-monsoon event was much less damaging in other parts of the Jhikhu Khola Watershed than it was in the Andheri Khola sub-watershed. And, though the third event was extreme at the sub-watershed scale, it rates only as an annual event at the watershed. Its high rainfall was evidently not widespread beyond the sub-watershed and so the bigger Jhikhu Khola channel could easily carry the higher volume of run-off without suffering extensive damage to its bed and banks. In general, the signature of sub-watershed variability cannot be discerned: differences in the rainfall input or land-surface response over spatial scales within the sub-watershed are virtually invisible at this watershed scale.

Table 5. Sediment and nutrient budgets at the watershed scale (11,141 ha) for the three events.

Event Type	Season	Sediment (tonnes/ha)	Phosphorus (g/ha)
Upland	Pre-monsoon	0.1	1
Upland	Monsoon	0.1	0.8
Extreme	Transition	2	60

9. DISCUSSION

Table 6 summarises the sediment and phosphorus budgets across all spatial scales and suggests that scale and season are essential considerations when interpreting erosion data. The location of the sediment sources for each event is reflected in these results. In the pre-monsoon event, the source is dominantly the upland terraces: the erosion there is high and it declines steadily downstream due to deposition and recapture through water diversion. This contrasts with the monsoon event in which sediment and phosphorus losses increase up to the mini-watershed scale and then begin to decline, suggesting that sediment sources were due to slumping and streambank erosion resulting from the channelized run-off. The extreme event shows a pronounced increase at the sub-watershed scale: this event was heavy over the entire sub-watershed and the stream grew enormously causing extensive bed scouring and streambank erosion in the lowest reaches of the Andheri basin. At the watershed scale, this swollen stream easily left the basin with little new erosion because there was little addition from other parts of the watershed.

These trends in the sediment budgets across spatial scales are also applicable for the phosphorus budgets. However, the seasonal differences for phosphorus (and other nutrients) are accentuated due to the enriched nutrient content of the soils in the pre-monsoon season.

Table 6. Sediment and nutrient budgets across all scales for the three events.

Budget scale	Sediment (tonnes/ha)			Phosphorus (g/ha)		
	U/P	U/M	Ext/T	U/P	U/M	Ext/T
Terrace	20	0.02	10	300	0.1	10
Mini-Watershed	5	0.8	7	200	20	200
Sub-Watershed	2	0.4	40	40	4	1000
Watershed	0.1	0.1	2	1	0.8	60

10. CONCLUSIONS AND IMPLICATIONS

This paper has examined sediment and nutrient dynamics resulting from three characteristic storm events over four spatial scales in the Jhikhu Khola watershed. Specifically, the results are presented as sediment and phosphorus budgets for each event over 70 m^2, 72 ha, 540 ha, and 11000 ha. Comparing these budgets leads to the following conclusions regarding erosion, sediment sources, and the effects of season and scale in this Middle Mountain farming system:

1) The type of sediment source which dominates in the sediment budget changes seasonally from surface erosion in the pre-monsoon season to terrace slumping and streambank erosion during the monsoon season.

2) Erosion during the pre-monsoon season is most significant at the terrace (70 m^2) and mini-watershed scales (72 ha).

3) Erosion during the monsoon season is often minor except for heavy rainfalls which can be damaging at the mini-watershed and sub-watershed scale (540 ha).

4) Unusually-heavy rainfall creates an additional sediment source from downstream streambank erosion and streambed scouring.

5) Phosphorus budgets correspond closely to sediment budgets and the enriched soil fertility of the pre-monsoon season accentuates the seasonal difference.

6) At the watershed scale (11,141 ha), the signature of variability at all spatial scales within the sub-watershed is lost.

These conclusions suggest the following management implications:

1) Present management techniques are effective at avoiding sediment loss during the monsoon season.

2) The pre-monsoon season is a period of vulnerability when high soil and, particularly, nutrient losses are possible due to the lack of a vegetative cover (see Carver and Nakarmi 1995). This is of great concern for on-farm productivity and does not appear to have a major effect downstream.

3) High basin sediment output is caused by extremely-heavy (and widespread) rainfall. This is of greatest concern for downstream development such as hydropower.

4) A sediment monitoring program should clearly identify whether it is directed at those within or those downstream of these headwater areas: the location, timing, and frequency of sampling will be different for each program.

11. 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 G. Nakarmi 1995. The effect of surface conditions on surface erosion and stream suspended sediments. 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. 155-162.

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