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Scale influence on water and sediment output in a first-order mountain basin in Nepal

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Abstract In determining water and sediment fluxes and budgets in tropical and subtropical mountainous regions, the choice of measurement scale is often more important than in temperate regions where the surface hydrological response is better understood. In this study, a dense network of rainfall monitoring stations has enabled us to remove the effect of rainfall variability in examining basin flow-duration and suspended-sediment curves. Storms during the pre-monsoon season typically have higher sediment rates than during the monsoon season and differences in land use and management can have a large influence within the basin which is not seen at the outlet. In heterogeneous hydrological environments, monitoring must pay special attention to scale resolution especially in light of limited research resources.

INTRODUCTION

In studying and managing mountain watersheds, temporal and spatial scales frequently present problems for hydrological extrapolation. In well-understood environments such as many temperate regions, extrapolation can result in accurate approximations (Brooks *et al.*, 1991). Unfortunately, processes and their interactions in many tropical and subtropical environments are poorly understood and experience from temperate regions can be misleading. In this paper, we look at some key processes in a subtropical basin in the Middle Mountains of Nepal where the significance of temporal and spatial variabilities suggest a careful rethinking of some standard hydrological monitoring.

A small headwater basin in the Middle Mountains of Nepal is chosen as the setting to discuss the effect of scale. This physiographic region is one of the most humanly-manipulated landscapes in the world (Jodha *et al.*, 1992), providing an opportunity to study the effect of human influence on the hydrological regime. The specific aims of the paper are:

(a) to illustrate how differently typical storm events can influence the overall sediment rating curve;
(b) to examine the effects of rainfall distribution, season, land use, and human manipulation on basin hydrological response; and
(c) to discuss temporal and spatial scale influences on sediment and water budgets.

STUDY AREA

The Jhikhu Khola basin, located in the Middle Mountain physiographic region of Nepal, has been studied since 1989 (Schreier *et al.*, 1994). The basin is located 35 km east of Kathmandu, covers an area of 12 000 ha, and is unaffected by snow and ice. Its precipitation regime is monsoonal with heavy rainfall from June to September and a distinct dry season from January to May. The elevation varies from 800 to 2030 m with terraced agriculture practised throughout. The aims of the project are to examine resource and land-use dynamics and to determine the sustainability of current forestry and agricultural practices.

A general monitoring programme was initiated in 1990 (Schreier *et al.*, 1991) and a more detailed hydrological study started in 1991 on the 5.4 km^2 Andheri Khola basin, a tributary of the Jhikhu Khola (Fig. 1). The elevation of this basin varies from 850 to 1740 m and the headwaters are intensively used for dry land, terraced agriculture while the lowlands have large areas of degraded land, often gulleyed, with sparse vegetation cover.

METHODS

The complete monitoring network in the Andheri Khola basin is shown in Fig. 1. The 24-h rainfall measurements are made at 30 points in and around the basin throughout the wet season. These rainfall measurement points are concentrated in two areas corresponding to the high and low elevation parts of the basin. Automated rainfall intensity measurements are made at two locations, centrally located inside the upper and lower clusters of the 24-h raingauge network.

Measurement of surface runoff are made over several scales. A small headwater sub-basin of 0.75 km^2 is isolated for detailed study to help differentiate hydrological processes there from the lowland ones. In this paper, the automated hydrometric station on this upland stream is called the Headwater Station and the station on the Andheri Khola at the outlet of the basin is referred to as the Outlet Station. Water and flow measurements were made at these two stations on a storm-by-storm basis. Two erosion plots (70 m^2) situated in the headwaters were also monitored during each storm to provide an indication of the level of surface erosion at the field scale.

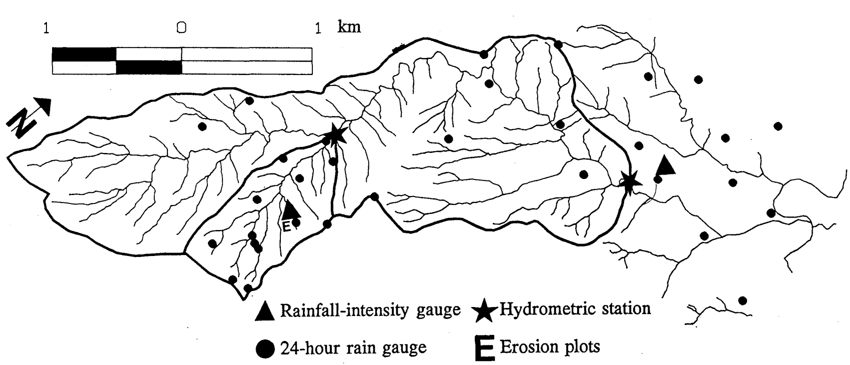

Fig. 1 Hydrological monitoring network in the Andheri Khola basin.

RESULTS

Overall surface-runoff behaviour

Annually, there were typically 15 measurable runoff events at both the Outlet and Headwater Stations. Most of the sediment transport occurred over a very short period of at most a few hours per flood. This fact stresses the need for measurements made on a storm basis: a daily sediment sampling programme does little to describe the changes of such a temporally-dynamic sediment transport system.

All 1992 and 1993 records of rainfall and runoff have been combined in a digital data base. This linked data base facilitates the assembly of summary basin relationships such as the sediment rating curves shown in Fig. 2. The Outlet Station shows a strong seasonal dependence whereas the Headwater Station exhibits only a minor dependence on season. Such integral representations can clearly be useful but, unfortunately, they can also mask many important dynamics resulting from scale-related variabilities within the basin. For example, the Outlet rating curve does not show the upland behaviour indicated in the Headwater rating curve. In turn, the Headwater rating curve does not always reflect the behaviour at the erosion plots, as discussed below. To illustrate the causes of these scale-related variabilities, key features of characteristic events will now be examined.

Rainfall variability

Storm rainfall in this region rarely occurs as even coverage over the basin. The total *annual* rainfall is somewhat uniform throughout the basin but there are marked temporal and spatial differences in its character. For instance, as Table 1 shows, the lowland experienced much lower intensity rainfall than the upland area. Further, the data base reveals a greater frequency of higher intensity storms in the pre-monsoon season than in the monsoon season.

These variabilities have important implications for the way in which the rainfall

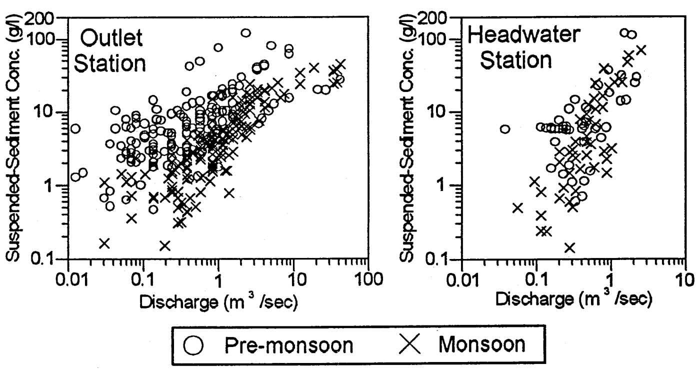

Fig. 2 Seasonally-stratified sediment rating curves for Outlet and Headwater Stations using 1992 and 1993 data.

Table 1 Selected rainfall variables from 1992-1993 rainfall intensity data.

Gauge location	Average annual (mm)	Maximum monthly (mm)	Maximum 24-h (mm)	Maximum intensity, 10 min ($mm\ h^{-1}$)	Maximum intensity, 60 min ($mm\ h^{-1}$)
Upland	1000	314	107	109	60
Lowland	915	355	75	76	42

input is estimated. For instance, to measure rainfall at one location and extrapolate to the entire basin will certainly lead to frequent grossly inaccurate estimates of rainfall intensity and total rainfall input even at this small scale of only a few square kilometres.

Event description

Flow-duration curves for four characteristic events from the 1992-1993 data base have been selected to illustrate basin hydrological processes (Fig. 3). The rainfall for these events occurred over known parts of the basin. Removing the effect of rainfall variability helps develop a clearer view of other effects resulting from season, land use, and management. Events A and C occurred in the pre-monsoon season, before the onset of consistent rainfall. This season is characterized by high-intensity rainfall over, at times, bare cultivated land. Events B and D took place during the monsoon season when saturated conditions and a more complete vegetative cover generally exist. Events A and B involve storms occurring dominantly over the well-managed, terraced headwaters of the basin. This area contrasts with the lower-elevation area which is dominated by degraded lands with exposed, and often gulleyed, soil (events C and D). Both land use types are frequently found in the Middle Mountains. And finally, some insights into the management effect can be seen through an examination of all four events.

Season

The events illustrated in Fig. 3 reflect the behaviour seen at the Outlet Station: sediment loads are highest in the pre-monsoon season. The levels for Event A are particularly high because of the nature and timing of its rainfall: the rainfall intensity was high and it fell on steep, recently-cultivated ground. The high concentrations recorded at the Outlet Station were reflected at the Headwater Station at over 120 $g\ l^{-1}$. Though the suspended sediment concentrations for Event C (over the lowland) are much lower, they are very high given the modest rainfall.

The chosen events suggest that during the pre-monsoon season, sediment movement is transport limited. Once the suspended sediment concentration has increased in a pre-monsoon flood, it remains elevated even down to low flow rates. This contrasts with its supply limited monsoon season behaviour, where levels drop off sharply with discharge. The rating curve for the Headwater Station (Fig. 2) showed no strong seasonal dependence. However, the erosion plots clearly indicate that there are enormous changes in

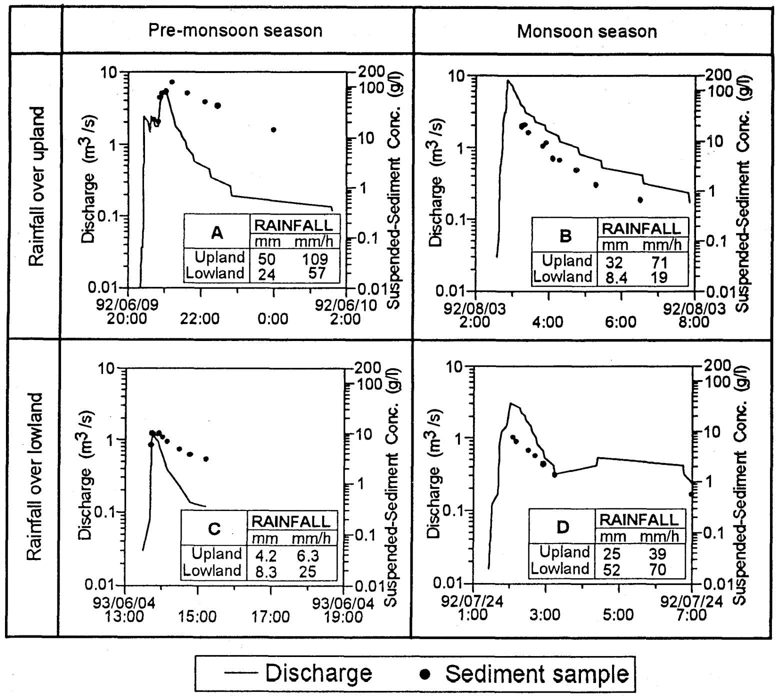

Fig. 3 Flow duration and suspended sediment curves for four floods at the Outlet Station.

surface erosion with season: a storm during the monsoon season typically causes about 1-10% of the surface erosion that the same storm can cause in the pre-monsoon season. One must conclude that there is a seasonal change in the source of stream suspended sediment inside the small Headwater basin yet the net effect at the Headwater Station is to show no change overall. This conclusion underlines the importance of spatial resolution here to within an area of less than 1 km^2.

Land use

The events in Fig. 3 also hint at a pattern evidenced throughout the 1992-1993 data set: for rainfall events of similar magnitude, there appears to be a greater propensity for surface erosion on the degraded lowland than on the well-managed upland. This occurs despite the fact that the uplands are very steep and the lowlands are of gentle slope. Although the overall highest measured suspended sediment levels come from pre-monsoon storms over the upland, this is probably because such high-intensity storms appear not to occur over the lowland where the land surface is generally more susceptible to erosion.

Examination of the entire data set has shown that storms over only the lowland occur frequently. These storms transport significant amounts of sediment to the main stem but because the storms are not large, much sediment can remain stored in the stream bed, unaccounted for by that flood at the Outlet Station. A subsequent heavy upland storm has the opportunity to re-entrain this material and carry it through the Outlet Station, misleading us into thinking that the material originated in the upland. Hence, once again, one must have sufficient scale resolution to be confident of the erosive origin of the sediment sampled at the hydrometric station.

Management

The manipulation of soil and water by the local farmers is extensive and one can look to the hydrological measurements for evidence of their impact. For instance, the hydrological response of this system is extremely fast. In the upland, the onset of heavy rainfall is often separated from the peak flow at the Headwater Station by only a few minutes. Throughout the myriad terraced agricultural fields, farmers maintain small runoff ditches to facilitate the rapid removal of storm runoff from their fields. These ditches form an anthropogenic extension of the fluvial system to the highest points in the basin.

A further manipulation is the ubiquitous diversion of water from the main channel for irrigation purposes. This practice is most profound during the pre-monsoon season when water is most needed. There is preliminary evidence in the hydrological record revealing the consequences of this diversion. For instance, Event A shows an unusually late peak flow, probably due to extensive diversion of the flood wave throughout its passage toward the Outlet Station. With this diverted water goes considerable sediment, which is never accounted for at the Outlet Station.

IMPLICATIONS FOR MONITORING

The data point to a potential need for greater monitoring resolution of the rainfall/runoff process. The surface of some landscapes, and in particular some extensively humanly-manipulated ones, is far too variable to be adequately understood with only a few point measurements. There is little doubt that knowledge of where the rain fell is extremely useful in diagnosing the origin of eroded material. A detailed plot study is also very useful but unfortunately, if there is a wide variability in soils, topography, and management, it is extremely expensive to attempt an adequate characterization of surface erosion at that scale. And, in fact, such a study would be of little use in identifying larger-scale dynamics such as, in this case, the diversion of flood runoff and the consequent storage of sediment in agricultural fields.

There is a need to give careful consideration at the outset to the environment under study. Research constraints insist that in these hydrologically-variable environments, we must be very judicious in our selection of measurements. They should cover a range of scales and work efficiently to diagnose based on clearly stated goals.

CONCLUSION

We have contrasted characteristic storms to illustrate how variable sediment transport can be throughout even a very small headwater basin. The results show that hydrological response changes dramatically from the plot scale to headwater and other larger basin scales. Sediment rating curves are strongly influenced by rainfall variability and by other differences involving the surface condition. Sediment rates were clearly observed to be higher in the pre-monsoon season than in the monsoon season. It was shown that the effects of land use and management can easily be masked if there is not sufficient monitoring resolution.

This study emphasizes the need to give careful consideration to scale-related variabilities especially when examining heterogeneous environments. Compared to temperate environments, rainfall is frequently more concentrated and the surface more variable. Indigenous farmers often have a long association with their landscape and have developed techniques which can influence soil and water dynamics surprisingly. As a result, more intensive sampling strategies are needed to understand some aspects of tropical surface hydrological processes.

Though research in subtropical mountain environments often requires a finer scale of resolution than is appropriate in temperate regions, this is not always feasible. Thus, greater uncertainty in the research conclusions can result. However, decisions might still be reached about land management based on the research. If development projects are planned with inappropriate extrapolation of point measurements, there could be far-reaching effects on the livelihood of struggling mountain farmers.

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