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Initial design of a model for Himalayan river sediments

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Abstract The main sources of sediment in Himalayan rivers are glacial deposits, landslides and intensively cultivated hillslopes, these sources produce immense volumes of material and river sedimentation is probably the major water quality problem of the region. To combat the further degradation of the water resource by the river sediments, a detailed knowledge is needed of the rate of supply, the characteristic size and shape of the sediment particles, hillslope and channel storage and the downstream transport and attrition of particles. Sediment surveys have been carried out in six Himalayan river basins which demonstrate the regional controls in the coarse sediments. The size and shape of the coarse sediments were found to be significantly different between the basins but the main control in each basin was rainfall. A GIS framework is being developed for two basins incorporating the sediment data and catchment characteristics. Empirical relationships between rainfall and sediment loss have been applied to the Langtang enabling the quantification of hillslope sediment loss for different land uses.

BACKGROUND

Himalayan rivers are a vital resource for the densely populated mountains and lowlands of the region supplying domestic and industrial water, irrigating fields and generating power. High sediment loads in the rivers however, result in major problems such as the siltation of reservoirs, damage to turbines, reductions in the quality of water supplies and transport of chemical pollutants (Singhal & Singhal, 1981; Pandey *et al.*, 1983; Das *et al.*, 1994; Department of Soil Conservation, 1994; Carver & Schreier, 1995). The main sources of sediment in Himalayan rivers are glacial deposits, landslides and intensively cultivated hillslopes, these sources produce immense volumes of material and river sedimentation is probably the major water quality problem of the region.

To combat further degradation of the water resource by the river sediments a detailed knowledge is needed of the rate of supply, the characteristic size and shape of the sediment particles, hillslope and channel storage and the downstream transport and attrition of particles. In a remote region such as the Himalaya this type of information is rarely available for each river basin. It is therefore important to understand the processes of erosion and transport of the sediment so that techniques can be developed to apply the results throughout the whole region.

A programme of research undertaken by the UK Institute of Hydrology has so far included erosion plot studies under different land uses, surveys of coarse sediments on the river basin scale and the monitoring of landslide impacts on river systems. Six basins have been surveyed during the period 1994–1997 from the Pindar in northwest India to the Tamur in eastern Nepal. The results form a unique

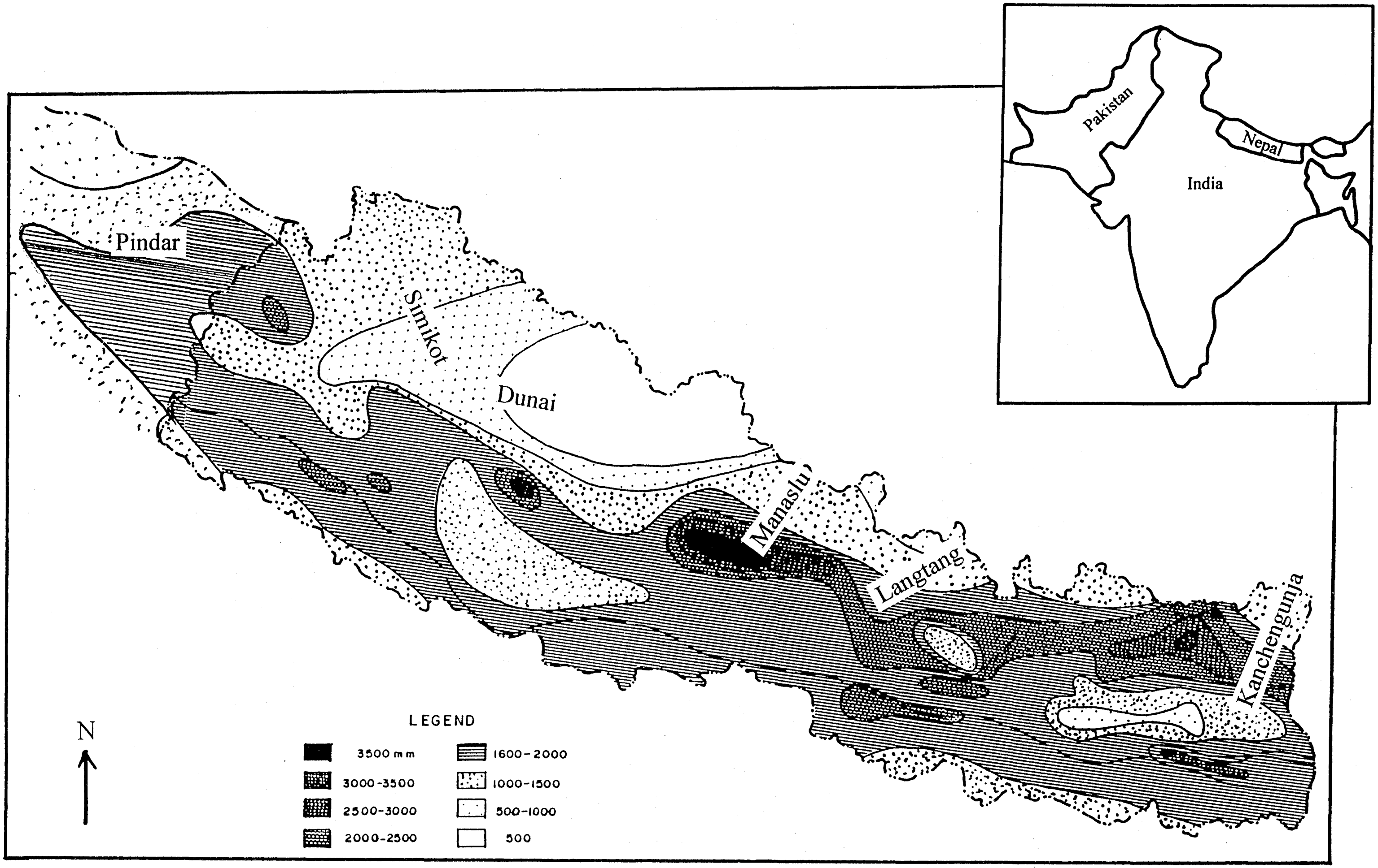

Fig. 1 Regional rainfall pattern of Nepal and northwest India and locations of the survey basins.

database in the region which is being used to determine anthropogenic influences on the sediment regimes and to develop management techniques to combat further degradation of the rivers. This paper uses the results of the sediment surveys to show that regional controls can be determined and demonstrates the potential use of the results in a management model.

SEDIMENT SURVEYS

The aim of undertaking surveys of coarse sediments in the Himalaya was to investigate the major controls on the type of sediment in the river channels, in particular to establish whether anthropogenic influences had a significant impact. Previous work on Himalayan sediments has identified that landslides, glaciers and agricultural hillslopes are the major sources of sediment (Valdiya & Bartarya, 1989; Hasnain, 1996; Rawat & Rawat, 1994; Gardner & Jenkins, 1995). Although these results are few in number they indicate the range of sediment sources which need to be included in surveys of whole river basins so that load quantification and sediment transport models can be improved.

Six river basins were selected for sediment surveys (Fig. 1) to take account of the regional gradients in geology and rainfall, the major sediment sources and land covers. The surveys resulted in a total of 151 sites being sampled. At each site, up to 100 sediment particles were selected and measurements made of the particles' three axes (a, b and c) and the diameter of the sharpest corner. The land cover was assessed by on-site observations and analysis of remotely sensed images, and categorized as the percentage cover of terraces, grazing, barren land, forest and rock and the presence of glaciers or landslides noted. The dominant geology of the catchment was determined from the sediment particles found in the stream and the geochemical classification of the streamwater sampled on the surveys.

Analysis of the data from landslide impacted tributaries revealed little statistical relationship between the catchment characteristics and the shape or size of the particles, while the statistical analyses on the non-landslide impacted catchments indicated significant relationships between all of the catchment characteristics and the sediment particles. The mean size and shape of the sediment particles in the non-landslide tributaries (Table 1) indicates that the particles are generally large, angular

Table 1 Summary statistics of the size (mm) and shape of non-landslide sediment particles in the six basins and the landslide impacted catchments and the mean annual rainfall in the basins.

	Pindar	Simikot	Dunai	Manaslu	Langtang	Kanchengunja
Mean a	99	73	103	136	162	120
Mean b	66	51	64	91	110	83
Mean c	36	31	34	51	67	51
Sphericity	0.62	0.67	0.59	0.66	0.69	0.67
Roundness	0.11	-	-	0.16	0.13	0.24
Flatness	2.68	2.24	2.98	2.59	2.11	2.20
Sorting	−1.01	−1.19	−1.19	−1.07	−0.89	−0.77
Skewness	−0.06	−0.15	−0.09	0.04	−0.05	−0.01
Rainfall	1200	778	653	2137	1893	1680

and poorly sorted with a mean *b* axis of 51–110 mm, a roundness index of 0.11–0.24 (higher numbers indicating rounder particles) and a sorting index of from -0.77 to -1.19 (higher numbers indicating better sorting). The landslide impacted tributaries showed similar mean sizes but with more angular particles which were very poorly sorted and highly skewed. This result indicated a state of chaos in the landslide tributaries contrasting with the more organized state of the non-landslide tributaries.

The data for the non-landslide impacted tributaries suggest regional trends (Fig. 2); differences between each of the six basins, using the Kruskal-Wallis test, were found to be highly significant (>99%) for all variables. However, significant differences between the size and shape parameters were not always found when the tributaries were grouped according to either the land use or the dominant geology of the catchment. When grouped by percentage area of degraded land, highly significant (>99%) differences were found in the size of the *a* axis and the roundness of the particles but less significant differences (>90%) in the size of the *b* axis. When comparing the sites grouped according to their dominant geology it was found that roundness and flatness showed highly significant differences (>99%) but the size of the mean *c* axis and sphericity were less significantly different (>95%). A characteristic of each basin other than land use or geology, therefore appears to have a major control on the size and shape of the particles.

INTERPRETATION OF RESULTS

The results of the analysis of coarse sediments in tributary streams of the Himalaya showed that there is a dominant control on the size and shape of the particles which is not geology or land-use of the catchments. The main contrast between the six

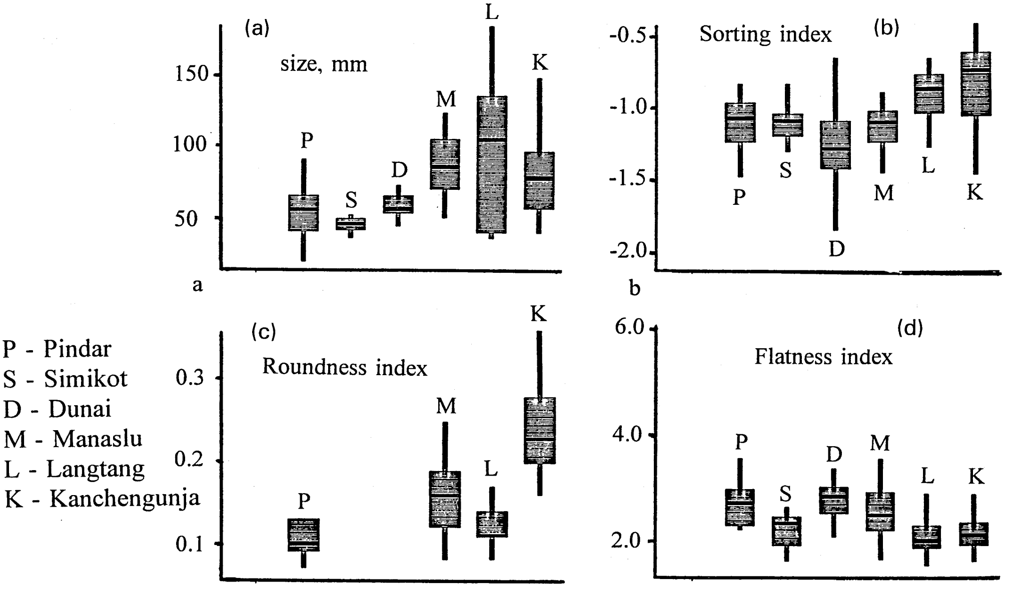

Fig. 2 Mean size and shape analyses of coarse sediment particles in the six survey basins.

basins was the climate, in particular the rainfall regime. Defining the rainfall regime of each basin is difficult because of the paucity of raingauges in these mountain regions. Figure 1 showed a generalized distribution of annual rainfall totals for the whole region and Table 1 showed the mean values of the annual rainfall from the gauges located along the survey routes. The data show that the Manaslu, Langtang and Kanchengunja surveys were in the wetter rainfall regions with the Pindar, Simikot and Dunai surveys in drier regimes.

A comparison of the summary data in Table 1 indicates that sediment size and shape are closely related to rainfall (Fig. 3). The low rainfall basins (Simikot and Dunai) have the smallest sizes of sediment particles, poorly sorted and a skewed size distribution with a fine tail. The size of particles increases as the rainfall increases to around 2000 mm (Langtang) but then decreases in the higher rainfall basin (Manaslu) (Fig. 3(a)). The sorting shows a similar pattern, increasing from the low rainfall basins to a peak at 1700 mm (Kanchengunja) then decreasing in the higher rainfall basins (Fig. 3(b)). Although roundness was not measured in the two low rainfall basins, a peak in roundness is again seen at 1700 mm (Fig. 3(c)). For skewness an increase in rainfall is matched by an increase in skewness index to a value of 0, indicating a normal distribution, at around 2000 mm becoming positively skewed at higher rainfall values (Fig. 3(d)).

These results can be interpreted in terms of the mobility of the sediments in the river channels. Those rivers in regions with annual rainfall totals of 1700–2000 mm would be expected to have mobile sediment deposits with large sized, rounded and well sorted particles. In regions with rainfall less than 1700 mm the particles would be less mobile, becoming smaller, less rounded and more poorly sorted because of

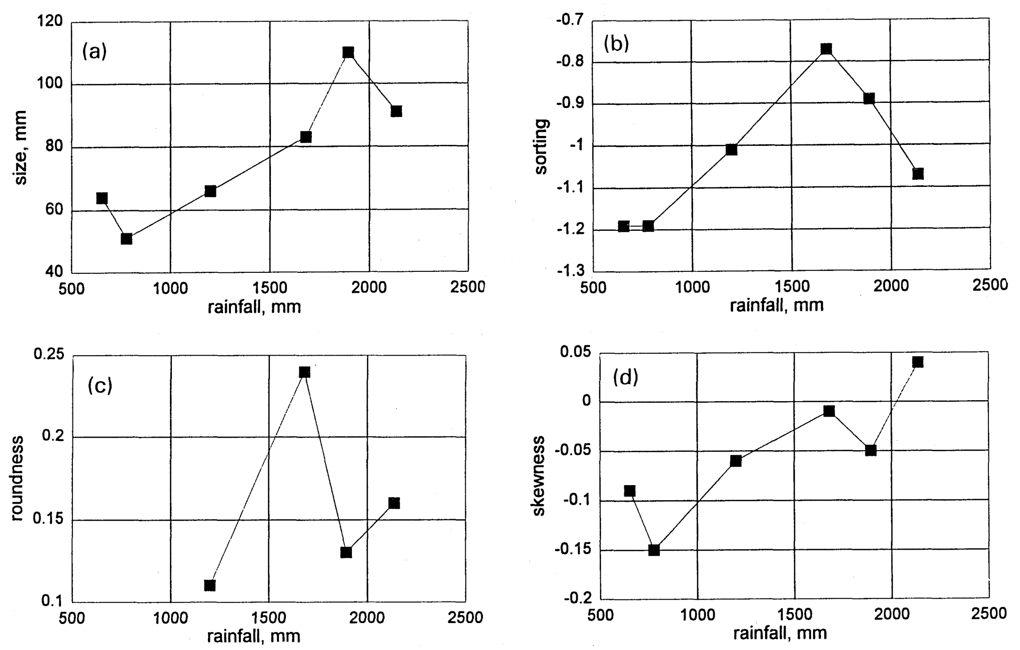

Fig. 3 Variation of mean sediment size and shape with mean annual rainfall in the six survey basins.

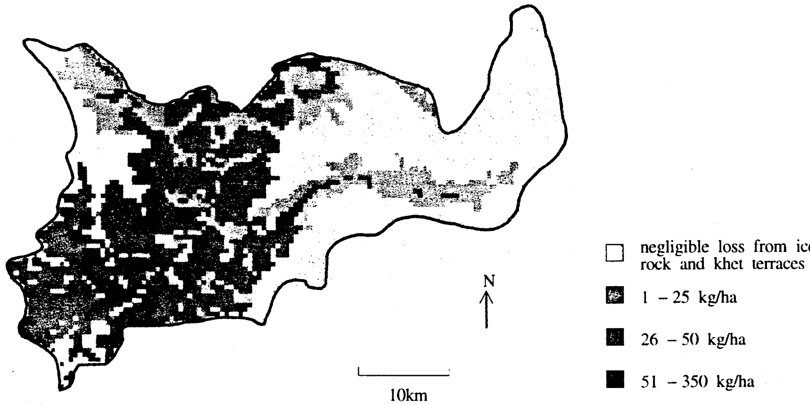

Fig. 4 Example of hillslope sediment loss from the Langtang river basin, Nepal.

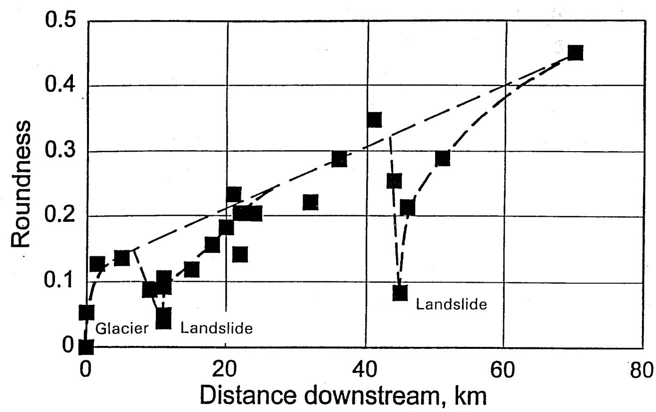

Fig. 5 Downstream gradient of particle roundness in the Pindar River basin, northwest India.

the reduced river flows. In regions with rainfall greater than 2000 mm the high energy river flows would produce extreme mobility which would result in smaller sized material, less well rounded and more poorly sorted because of the frequent impacts between particles and the resulting physical damage.

OUTLINE OF THE RIVER BASIN MODEL

A GIS framework utilizing Arc/Info is being developed for two of the river basins, Pindar and Langtang. Comprehensive sets of attribute data, including land use, topography, geology, river network and sediment characteristics have been digitized to enable analysis of the sediment in a spatially distributed manner on a river basin scale. The establishment of this framework will be fundamental in the quantification of both sediment supply from the major sources, the transportable load within the river channel and the downstream impacts of major events such as landslides.

Previous erosion plot studies in the Nepal middle hills (Gardner & Jenkins, 1995) established empirical relationships between rainfall characteristics and runoff and sediment loss. Rainfall characteristics were described by the EI_{15} index, which incorporates both the kinetic energy of rainfall and the maximum 15-min intensity. The relationships were derived through a wide range of storm events and for a number of differing land-use types: khet and barri terraces, forest of varying density, shrub, grass and degraded land. These relationships have been applied to the Langtang catchment by incorporation into the GIS source code. This enables the quantification of hillslope sediment loss and runoff for a given storm event for each 500 m^2 land-use grid cell (Fig. 4). Barri terraces located on steep slopes and areas of degraded forest are the land-use types most susceptible to sediment loss.

In September 1994 two major landslides occurred in the upper Pindar devastating the river channel. Surveys of the sediment characteristics and the channel form are producing information on the scale of the downstream impact and the recovery of the river in subsequent years. As an example, the survey results of particle roundness (Fig. 5) showed that the landslide material moved some 30 km downstream in the eight months following the event. Repeat surveys show that the coarse landslide material did not move very far downstream in the two following monsoon seasons, however observations have shown that the downstream impact of the fine material transported in suspension, was much greater.

In the design of the sediment model, equations incorporating runoff volume and velocity, slope angle and a land cover roughness coefficient will be used to model the movement of sediment to the nearest river channel. Once in the channel, modelling of downstream sediment movement may be achieved by a number of potentially appropriate transport equations applicable to both bed load and suspended material however the validity of using these equations in rivers with excessive loads, may be questionable.

CONCLUSIONS

High sediment loads in Himalayan rivers create major water resources management problems such as the siltation of reservoirs, damage to turbines, reductions in the quality of water supplies and transport of chemical pollutants. The main sources of sediment in Himalayan rivers are glacial deposits, landslides and intensively cultivated hillslopes. However little qualitative or quantitative information is available on the sediments released from these sources. To combat further degradation of the water resource by the river sediments a detailed knowledge is needed of the rate of supply, the characteristic size and shape of the sediment particles, hillslope and channel storage and the downstream transport and attrition of particles. This paper has demonstrated the initial development of a river basin sediment model utilizing information from detailed sediment surveys, spatial data sets and rainfall records.

A model of sediment transport must be applicable to the entire region therefore regional controls on erosion and sediment characteristics must be understood and incorporated into the model. Surveys of coarse sediments in six Himalayan river basins have generated a unique database which showed that significant differences exist in the size and shape of the particles between basins but the dominant control in all basins was rainfall. Erosion plot studies undertaken in central Nepal showed that soil loss under different land uses was varied, the major control being 15-min rainfall intensity. Therefore, in these basins, rainfall is probably the most important parameter for a sediment model.

Further work is planned to determine the suspended sediment regimes of contrasting catchments and to develop a better understanding of the localized impact of coarse sediments and the regional impacts of fine sediments. This sediments model will be of value to water resources planners both in designing an infrastructure to cope with the existing sediment loads and in assessing the potential benefits of erosion control in agricultural areas.

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