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Mountain Environments

Trans Himalayan River Expedition

Report to Mount Everest Foundation

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1 Background to the expedition

Deteriorating environmental conditions in the Himalayas are causing widespread changes throughout this once pristine environment and threatening the livelihood of millions of people. Himalayan degradation is however much mis-understood mainly because of the lack of sound scientific facts. Some changes are undisputed such as the rapid rates of glacial retreat and population growth while others are poorly understood such as deforestation, the pollution of water-courses and the siltation of rivers. Considering the scale of the problem and the number of people involved it is surprising that so few comprehensive environmental surveys have been undertaken.

Degradation of the Himalayan environment is a complex issue affecting the region in different ways. Background climate change in the Himalayas is most clearly seen in the retreat of the glaciers. Most reliable reports of the positions of glacial snouts show substantial changes during the 20th century although the rates of change appear to be different throughout the region. The melt could be an indication of either increased temperatures, decreased precipitation or a combination of both. Rapidly melting glaciers should increase river flows but the volumes of water stored in the Himalayan cryosphere has now been so depleted that the volumes of melt water are reducing, seriously impacting river flows. Changes to the long term seasonal weather patterns are however difficult to determine because of the lack of reliable and long-term meteorological data.

Probably the most dramatic recent anthropogenic change in the Himalayas has been an increase in the human population, primarily attributed to better health care in many regions. The precise rate of increase is unknown because of difficulties in completing accurate population censuses but there is undoubtedly an increased pressure on the supply of food and water. Increased food production has been met by an expansion of agriculture into marginal hill regions, increasing the demand for water and the use of chemical fertilisers. This has however resulted in the decline of land available for animal grazing increased erosion and landslides and has had serious impacts on local and downstream water resources.

Deforestation is closely associated with the population growth and expansion of agriculture. Large areas of forests were removed to provide timber for building materials, fuel, fodder and agricultural land. There is no doubt that deforestation caused environmental degradation in numerous Himalayan regions but the lack of understanding of how different regions have been affected results in a continued belief that deforestation causes massive flooding in the Ganges and Indus plains. Recent controls on timber use and re-forestation programmes warrant better publicity.

There is an urgent need to improve the understanding of the current conditions throughout the Himalayas to reverse the degradation processes. Monitoring the changing environmental conditions in the region is difficult because of the remoteness of many areas. The problem of Himalayan degradation also needs to be addressed on both an extensive and intensive basis with strong links between both approaches. Extensive studies produce regional records of environmental conditions while intensive studies produce an understanding of how certain parameters are inter-linked.

The Trans Himalayan River Expedition aimed to carry out an extensive survey of the Arun river basin to add to the information database of the Himalayan region. The parameters chosen to be monitored were intended to provide information on key indicators of environmental change. By collecting this information conditions in the watershed could be compared with previously surveyed watersheds in the Himalayas and identify which parameters could be monitored there in the future. The expedition did not achieve all of its objectives because of finance and the weather. This report is a summary of the expedition and includes details of the logistics behind the expedition, the survey methodologies, results from the analysis and a more detailed summary of Himalayan river sediments and streamwater chemistry.

2 Aims of the expedition

The Trans Himalayan River Expedition aimed to undertake an environmental survey across the Himalayas to complement previous surveys and provide a benchmark for sustainable development in the next millennium. The expedition originally aimed to follow the Arun river from the Tibetan plateau through the high mountains to the edge of the Ganges plain. The Arun river basin was selected as it is one of the major Himalayan rivers with a history of previous exploration and conservation.

The Arun rises in Tibet as a pro-glacial river sustained in its upper reaches by snow and ice melt. As it passes through the mountains it becomes deeply incised forming a deep gorge. South of the high mountains the Arun is joined by several large tributaries, most notably the Barun Khola, Sabhaya Khola and Pikhuwa Khola fed by snow and glacial melt and heavy rains which exceed 3000 mm in some parts.

The original route of the expedition was to use the road from Kathmandu up the Sun Kosi to Kodari, follow the Arun from one of its tributary sources at the Rongbuck Glacier, across the Tibetan Plateau and through the high mountains to the Nepalese Middle Hills and the Terai. If this could have been done it would have effectively circumnavigated the Everest Massif providing a unique opportunity to carry out an environmental survey. Unfortunately a border crossing to the east of Everest was closed and the additional time and cost involved in retracing the Sun Kosi route to reach the Arun was not possible on this expedition. The final route therefore followed the course of the Arun and Barun rivers from the lowlands to the high mountains and Makalu Base Camp. It is still considered that the full expedition would be extremely valuable in the future and hopefully the results from this shortened expedition will show the potential for that.

The fieldwork programme was planned to undertake rapid surveys of key environmental indicators as the expedition passed through the region. Those indicators which were considered to most useful were socio-economics, streamflow, weather, streamwater chemistry, fluvial sediments and the locations of landslides and glaciers. Poor weather conditions during the first half of the expedition restricted the data collection as sampling in the high river flows could have given un-representative readings. Details of the survey methodologies used on the expedition and the results are given later in this report.

3 Logistics of the expedition

The five man expedition departed the UK for Kathmandu on October 12th 1998 and returned to the UK on November 15th 1998. Preparation for the expedition mainly involved trying to raise sufficient finances, fitness training and equipment checking. The fund raising experience was demoralising as almost every letter brought rejection. Certainly the past dependence on sponsorship can not be relied on in years of economic difficulty and expeditions such as this have to rely on private fund raising schemes over many months. Insurance for each team member was arranged through Adventure Travel who offer specialist policies for this type of travel.

In Kathmandu the logistical support team was organised including the guides, cooks and porters. This was mostly achieved by contracting one of the major trekking agencies in Kathmandu. Initial difficulties were encountered in explaining that the expedition did not necessary want to go the scenic route and we would stop in some non-routine places to take samples. The Arun is a remote location where few foreign visitors go, hence there is a lack of places to camp and buy food. Our expedition had no choice but to take a full team of cooks and porters, once over the Shipton Pass we were entirely dependent on them. No specialist climbing equipment was required on the expedition but portable scientific was taken. Each member carried a camera so a comprehensive photographic record of the expedition was created. Standard first aid packs were supplied to each team member, no major medical incidents occurred although in hindsight an emergency satellite telephone system should have been taken because of the remoteness of the region.

Permission for foreign nationals to travel to Makalu Base Camp is in the form of a trekking permit, obtained from the local Department of Immigration in Kathmandu and a National Park entry fee paid on the trek. No problems were encountered either in Kathmandu or along the route where there are occasional police check points.

The journey from Kathmandu to the Arun was undertaken in a light aircraft the alternative being an overnight bus journey to Dhankuta. The route of the expedition was to follow the Arun river north to Tumlingtar, Num, up the Kasuwa Khola to the Shipton Pass and along the Barun Khola to Makalu Base Camp. By following this route a large altitude range would be sampled from 350 m to 5000 m including land uses of intensive agriculture, mixed agriculture/forest, sub-nival vegetation and glaciated catchments. The route north was along the main footpath where most developments were taking place but on the return journey the low path on the west side of the Arun was followed through more remote farming communities. The main paths are well marked and presented no problems to the expedition but care had to be taken on the return route not to get lost in the maze of paths.

4 Scientific results

4.1 Meteorology and hydrology

Meteorological and hydrological data for the Arun region are limited in the number of stations and duration of the records. The Department of Hydrology and Meteorology in Kathmandu supplied a small number of rainfall records for the region, Table 4.1. The data from the four stations show considerable differences between years and between sites. The inter year variations at Num are particularly noticeable with the lowest rainfall in the 14 year period being 2621 mm in 1972 while the highest rainfall was 5809 mm recorded in 1979. The records from Dhankuta and Tumlingtar have many missing years making a comparison between the stations difficult. However the mean rainfall for the years with data indicate the lowest rainfall occurs in the mid-valley section of Dhankuta and Tumlingtar while the northern section around Num has the highest rainfall. Indications from other major river basins in Nepal suggest the rainfall in the high altitudes is low and it was estimated that rainfall in the ungauged northern Barun was in the range 1000 - 1500 mm.

Table 4.1 Rainfall records from the Arun valley

Year	Dharan	Dhankuta	Tumlingtar	Num
1971	3316	674	*	2786
1972	2178	604	*	2621
1973	2973	961	*	3627
1974	2744	1020	*	5249
1975	2737	*	*	4430
1976	2806	*	*	4596
1977	2220	*	*	5356
1978	1609	*	1531	4248
1979	2236	*	1601	5809
1980	1432	*	1083	4914
1981	2335	*	1338	3666
1982	1835	*	813	2902
1983	2646	962	1444	3070
1984	2347	1201	1407	3208
Mean	2387	904	1317	4034

* missing data

River flows in the Arun have been recorded just north of Tumlingtar since 1975 however the data could not be obtained. During the expedition selected tributaries of the Arun were gauged to give spot values of the flows. The methodology used was a gulp dilution gauging technique using salt as a tracer and recording streamwater conductivity as the dissolved salt passed downstream. The measurements were greatly restricted in number because of the poor weather, primarily the heavy rainfall in the first part of the expedition. Results, shown in Table 4.2, give little information about environmental change but if these gaugings can be repeated and added to over a long period then any hydrological changes in different parts of the river basin should be detected.

Table 4.2 Tributary flows in the Arun

Site	Altitude, m	Area, km^2	Latitude/Longitude (Deg,min,sec)	Flow, $m^3\ s^{-1}$
1	1790	0.6	27 36 05/87 16 07	0.02
2	1990	2.2	27 30 48/87 16 25	0.10
3	2005	2.0	27 37 38/87 14 10	0.09
4	2540	1.8	27 38 21/87 13 19	0.11
5	3185	2.8	27 43 34/87 12 38	0.16
6	3515	2.6	27 43 04/87 12 45	0.15
7	4410	1.2	27 48 16/87 06 30	0.02
8	4450	2.6	27 48 15/87 06 29	0.05

4.2 Social surveys

Surveys of the social conditions throughout the Arun valley were limited by the time available for the expedition and for individual surveys. It was considered that the two major anthropogenic impacts which could affect the local communities in the Arun were developments in trekking and hydro power generation. Trekking in the Arun is currently very small compared to the most popular routes but there are demands for more routes to be developed to ease other areas such as Everest and Annapurna. Information on the numbers of visitors to the Makalu-Barun National Park passing through Sedua was obtained from the Park Office. Annual numbers average 282 (Table 4.3), about 15% of the total number of people entering the Park. No significant change has occurred in these numbers over the past five years but in comparison with the 17 000 people each year visiting the Everest region, the Makalu trek is currently much less popular. The Makalu-Barun National Park currently have regulations in place where camping is permitted (7 places within the whole area) and the prohibition of using wood for fuel. There are also limitations on the building of houses although porters' shelters are being erected.

No evidence of the proposed Arun 3 hydro-power scheme was found in the area and very few locals were aware of the scheme.

Table 4.3 Numbers of visitors to the Makalu-Barun National Park

Year	Trekkers	Expedition members	Total
1993	248	52	300
1994	286	19	305
1995	329	42	371
1996	286	45	331
1997	263	46	309
Mean	282	41	303

The survey during the expedition was designed to provide background information on the influence of trekkers and hydro-power developments on local communities. Information was gathered on the types of buildings and businesses in the villages, any modern developments such as electrical supplies or any new infrastructures such as roads. This information proved to be very sparse as the area is still totally pedestrian, only a few villages have electricity, water supplies are only to a common tap in each village and there is only a small involvement in the tourist trade. Although the results of the survey will look sparse it could prove an invaluable baseline data set if trekking and hydro power develop in the future.

4.3 Fluvial sediments

Fluvial sediments are a key indicator of the erosion processes, dynamic nature of the river system and of recent catastrophic events within the catchment. Sediments are usually divided into two groups: suspended and bedload. The suspended sediment regime of a river gives the characteristics of the erosion sources but requires a long programme of sampling during flood events. On rapid surveys, during low flow conditions, the bedload sediments are relatively accessible for sampling to indicate the state of the river. The dynamic rivers of the Himalayas transport large amounts of coarse sediment, breaking it down and sorting it as it moves downstream. Samples of bedload sediments from small tributary catchments indicate the sediment supply processes within the catchment while samples taken from main rivers mostly indicate the sediment transport processes.

Sampling on the 1998 expedition was planned to include tributaries of the rivers Arun and Barun as well as both main rivers. In the field the access to the main rivers was found to very limited and hazardous so the programme was confined to the tributaries. A range of tributaries was sampled over the full altitude range so that different land uses were represented as well as catchment geology and rainfall. Standard sampling techniques have been developed over several seasons in Himalayan watersheds so that an adequate number of representative particles are measured. For these small tributaries 30 particles were sampled selected from near the waters edge and including only those particles which are regularly moved. This last requirement is sometimes difficult to judge but generally if there is no algal growth on any surface then it is likely to be moved regularly. The sizes of the three axes are measured as well as the diameter of the sharpest corner.

Data analysis was carried out to generate standard statistics describing each sample. The derived statistics include size of b axis, sorting, skewness, sphericity, roundness and flatness. Table 4.4 shows the results for the Arun tributaries.

Table 4.4 Tributary sediment size, shape and distribution

	Mean	Tumlingtar	Num
Mean b	49	78	34
Sorting	-0.78	-0.93	-0.62
Skewness	0.03	-0.01	0.30
Sphericity	0.64	0.67	0.62
Roundness	0.14	0.13	0.19
Flatness	2.50	2.10	2.90

Results showed that particles in the Arun tributaries are small in size, flat but angular in shape and poorly sorted. Results from other river basins in the Himalayas have shown the size and roundness increasing as rainfall increases to around 1800 mm but then both statistics decreasing in higher rainfall regions. Rainfall in the Arun was previously shown to range from 1317 mm at Tumlingtar to 4034 mm at Num. The mean sediment sizes and shapes of the tributaries in these two areas show the difference in sediment characteristics between the locations with very different rainfall regimes (Table 4.4).

The value of these results are both in the understanding of the controls of particle size and shape and in the ability to monitor environmental changes through a key parameter such as fluvial sediments. The major results from the Arun survey have been in the sampling from areas with contrasting rainfall regimes and in a watershed with so few landslides. Repeat sampling in these tributaries will show if any changes occur in the sediment size and shape which can now be related to physical changes in the watersheds.

4.4 Landform survey

The landform survey in the upper Barun near Makalu base camp was intended to develop a historical picture of glaciation in this area. A detailed survey would have taken many weeks to complete but this first survey mapped the positions of the major features, details of which can be added in future expeditions.

The area has been heavily glaciated in the past with the Barun Glacier feeding in from the north west below Makalu II and the Lower Barun Glacier from Baruntse and Chonku Chuli to the west. Smaller glaciers joined the main mass of ice from the south face of Makalu and the east face of Peak 4. The extensive moraines and fluvial features related to these glaciers have preserved evidence of past advances of the ice and the more recent actions of the rivers in modifying the system.

Positions of the moraines, the river channel and the type of sediment were surveyed. The current positions of the glacial snouts were substantially different to those marked on trekking maps and maps obtained from the 1954 French expedition to Makalu (Fig.4.1). The major moraines in the area show the extent and sequence of historical advances of the glaciers. The Barun valley contains extensive glacial deposits above some 4000 metres with, in general, deposits from the minor glaciers post-dating the main Barun Glacier. Lateral moraines and debris cones were found along the length of the upper Barun showing that the maximum depth of ice was around 50 metres above the present valley floor. A series of large moraines has developed at the foot of the south face of Makalu marking the maximum extent of the most recent advance of the Barun Glacier and the smaller Makalu Glaciers. The moraine now partially dams the glacial melt river forming a small lake some 100 m long. An extensive fluvial outwash plain has developed below the moraines which the river continues to rework.

The small glacier from Peak 4 has retreated up the valley side but has left evidence of a substantial advance into the main valley. Moraines show the glacier swept into the valley almost damming the river and leaving a massive cone of debris across the valley floor. A melt water river still flows from the glacier and a small glacial lake has developed in the moraine debris. At the junction of the Barun with the Lower Barun the melt water rivers are separated from each other by a large moraine from the Lower Barun Glacier. This moraine has been a major influence on the landforms in this area creating an extensive deposition zone for sediment transported from the Barun Glacier. A breach is forming in the moraine which, when fully formed, will cause major changes in the river flow and sedimentation patterns.

4.5 Location of landslides

Landslides are a major environmental problem in the Himalayas causing extensive and sometimes catastrophic damage to hillslopes and rivers. The triggering mechanisms are combinations of heavy rains, increased soil water content, tectonic movements and removal of protective vegetation cover. It is debatable how significant past deforestation has been in landslide activity but there is no doubt that large landslides have occurred in the Himalayas for centuries and their control is impossible. Developments within river basins need to consider landslide activity, whether the material will affect the site and if so when and with what type of material. Monitoring the extent, frequency and characteristics of landslides is important in river basin management.

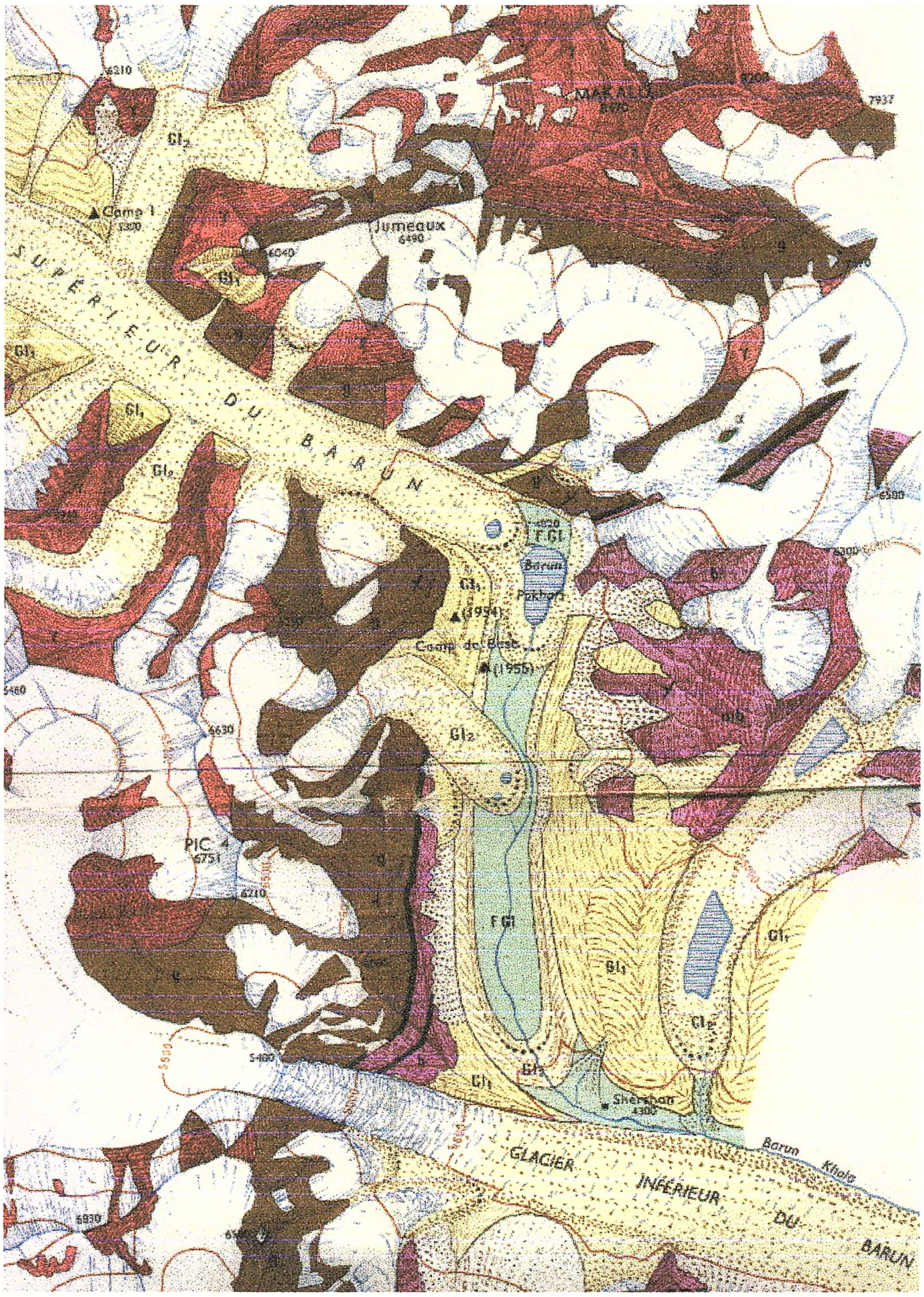

Fig.4.1 Map of the Makalu base camp area
(Copied from the report of the French Himalayan Expedition 1954-1955)

The Arun valley was expected to contain large numbers of landslides because of the very heavy rainfall in the region. The expedition planned to survey the location and characteristics of all recent and major landslides but only one tributary valley was found with substantial activity. This tributary was on the north side of the Kasuwa Khola opposite Tashi Gaon, and unfortunately inaccessible. The lack of landslides contrasted with other river basins surveyed in previous years. The reason is likely to be a combination of the relative lack of tectonic activity and preservation of substantial areas of forest compared to other regions. Certainly with the heavy rainfall in the area there is an enormous potential for extensive landslide activity.

4.6 Streamwater chemistry

Streamwater chemistry samples were taken from 43 sites ranging from low altitude terraced catchments to high altitude glacial melt streams. Baseflow sampling in other river basins has shown the value of this type of survey in identifying the background chemical conditions of the water. During the dry season the chemistry is dominated by the bedrock and glacial melt but in the wet season the chemistry can show major changes depending on the source of the airmass. Atmospheric pollution threatens the pristine high altitude streams and the most reliable method of monitoring the long term impacts of this pollution is to monitor the baseflows.

In the field, measurements were made of pH, conductivity and temperature and two 100 ml filtered samples taken for full chemical analysis in the UK. Notes were also kept of the GPS location, altitude of the sample point and an assessment made of the land use in the catchment. Additional catchment characteristics were obtained from a central data base of catchment area, dominant bedrock geology, topography and land use.

The field measurements showed a large range of altitudes and land uses sampled with a range of pH values from 5.57 to 7.85. In general the pH values in the altitude range 3000 to 4000 metres were much lower than at other altitudes probably due to the dominance of gneiss bedrock. Conductivity ranged from 001 to 080 μS with a cluster of low values in the altitude range 2500 to 3500 metres. The acidic lakes on the Shipton La contained no biological life, possibly a result of anthropogenic pollution.

5 Himalayan fluvial sediments: a summary

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. Himalayan rivers are important for supplying water, hydropower generation and irrigation in the densely populated mountains and lowlands but the high sediment loads result in problems such as the siltation of reservoirs, damage to turbines, reductions in the quality of water supplies, transport of chemical pollutants and degradation of biological habitats (Singhal and Singhal, 1981; Pandey *et al*, 1983; Das *et al*, 1994; Department of Soil Conservation, 1994; Carver and Schreier, 1995). There is now an urgent need to improve the qualitative and quantitative understanding of sediment supply and transport to enable the sustainable, long term management of these important rivers.

The qualitative and quantitative understanding of the sediment regimes of the rivers depends on a detailed knowledge 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. Quantifying the sediment supply and transport in the Himalayan river systems is probably the region's most challenging task facing geomorphologists. Before this can be addressed however, the controls on the characteristics of the material in the rivers must first be understood. Sediments are commonly sub-divided into the coarse particles (bedload) and fine particles (suspended load) and, although there is a considerable overlap, the coarse particles accumulate close to the source areas and have massive local impacts while the fine particles are transported much further down-river and so have more of a regional impact.

First order tributaries in a river basin provide a crucial link between the source areas and the river system. Material is released through hillslope erosion and weathering processes such as raindrop impact, overland flow, landslides and freeze-thaw action. A large proportion of this material remains in storage on the hillslopes as colluvial deposits but some falls into the many small stream channels where fluvial action takes over. Small mountain streams are often fast flowing and turbulent which initiates the downstream transport, sorting and abrasion of the sediment particles towards the main river. First order tributaries therefore act as gathering branches for the river system and a knowledge of the sediment particles in these streams is therefore an essential requirement for the improved understanding of the river basin sediment loads.

5.1 Surveys of coarse sediments

A series of watershed surveys have been undertaken in the Himalayas since 1992 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 exclusively concentrated on fine sediments transported in suspension and has identified that landslides, glaciers and agricultural hillslopes are the major sources of sediment. Landslides are controlled by the climate, tectonic activity and land use changes (Valdiya and Bartarya, 1989; Froehlich and Starkel, 1993; Haigh *et al*, 1995); glacial sediments are derived from sources of meltwater and from the exposure of deposits due to glacial retreat (Hasnain and Chauhan, 1993; Hasnain, 1996). Significant amounts of sediment are also released from deforested (Pandey *et al*, 1983; Rawat and Rawat, 1994) and intensively farmed (Carver and Nakarmi, 1995; Gardner and Jenkins, 1995) catchments. Although these results are few in number and only refer to fine sediments they indicate the range of sources of sediment which need to be included in surveys of whole river basins so that load quantification and sediment transport models can be improved (Rawat, 1987).

Surveys of sediments in the Himalayan region need to consider the main sediment sources, the dominant bedrock geology and climate; the limited amount of information is a fundamental problem in this type of work. The logistics of undertaking surveys in remote regions can be difficult, some locations are accessible due to tourism and trekking developments but others are much less accessible and require an expeditionary approach. The lack of basic information such as topographical and geological maps, is also a problem so route finding and catchment characterisation can be difficult.

The geology of the Himalayas is young in age, very active and is essentially comprised of a series of west to east structures caused by the tectonic plate of the Indian sub-continent passing underneath the Eurasian plate, elevating the Tibetan plateau and creating the Himalayan mountain range on the forward edge of the Indian plate. The Tibetan Marginal Range in the north consists of sedimentary rocks such as limestones and shales which have been little affected by metamorphism, while the High Himalayas consists predominantly of highly metamorphic rocks most commonly gneiss, quartzite and schist. The main central thrust separates the High Himalayas from the Middle Mountains which consist of moderately metamorphosed rocks (schist and phyllite) with some igneous intrusions (granite) and sedimentary beds (limestone). The southernmost structure is the Siwaliks composed of unconsolidated and highly erodible sedimentary rocks (greywacke and sandstone). The major structural contrasts are therefore in a north-south direction with the west-east direction being comparatively homogeneous.

The topography of the Himalayas forms a major physical barrier which controls the climate and creates well defined regional patterns of precipitation. Due to the wind flow patterns in the summer monsoon season, rainfall is greater and the duration of the monsoon season longer in the north east however the proportion of annual precipitation falling as snow in the mountains is greater in the north west. Orographic enhancement of the rainfall creates a south to north trend but also complicates the east to west gradient as centres of high rainfall exist on the windward sides of the major mountain massifs. Rainfall increases northwards through the Siwaliks and Middle Mountains but then decreases towards the high mountains resulting in a rain shadow effect, and an abrupt decrease in rainfall in the northern Tibetan plateau.

Eight river basins were surveyed in the period 1992-1998. From west to east these were: Pindar, Simikot, Dunai, Manaslu, Langtang, Likhu Khola, Makalu and Kanchengunja. The selection of these river basins took account of the regional gradients in geology and rainfall and the major sediment sources (glaciers, landslides and terraced hillslopes) and land covers (rock, scrub, forests, barren land and terraced areas). Sample sites on each survey were first order tributary streams, chosen systematically so that over the 100-200 km length of the survey, the sampled streams were regularly spaced and included the full range of major environmental controls. At each tributary stream site, up to 100 sediment particles down to 10 mm in size, were randomly selected and measurements made of the particles' three axes and the diameter of the sharpest corner. In addition, the catchment location, altitude, land cover and geology were determined. The land cover was assessed by on-site observations and analysis of remotely sensed images, and categorised 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 geo-chemical classification of the streamwater sampled on the surveys as either silicate, carbonate, dolomite or fluoride.

5.2 Statistical analysis

The data on coarse sediment dimensions were analysed to generate information on the mean size and shape of the particles in each site. Four measurements were made in the field on each particle: the major axis (a axis), intermediate axis (b axis) and minor axis (c axis) and the diameter of the sharpest corner (d) in the plane of the a and b axes. From these measurements, standard formulae, listed in Richards (1982), enable the calculation of the following parameters:

1. Mean a, b and c - means of the three axes (mm) of 100 measured pebbles;
2. Sphericity - 3 dimensional shape of particles - where 1 = spherical particle and 0 = flat particle;
3. Roundness - degree of smoothing by attrition - where 0.1 = highly angular particle and 1.0 = perfectly rounded particle;
4. Flatness - 2 dimensional shape of particles - where 1 = an equi-dimensional particle increasing as the particle becomes more disc-like.

Also using the distribution of the b axis measurements the following can be calculated:

1. Sorting - variability in the frequency distribution of the particle size - where a value greater than -0.5 indicates a well sorted set of particles and less than -1.0 indicates poorly sorted particles;
2. Skewness - asymmetry of the distribution of the particle size - where a value of 0 indicates a symmetrical distribution, positive values represent a coarse tail and negative values a fine tail in the distribution.

Observations in the field indicated that the sediments in landslide impacted tributaries were different to sediments in other tributaries appearing to be more angular with a greater range in the size of particles. Because of these visual observations it was decided to test whether there were statistical differences between the landslide and non-landslide tributaries. The analysis, shown below, of the 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. This was interpreted as a state of total chaos in the landslide tributaries contrasting with the non-landslide tributaries; all subsequent analysis was carried out on the two sub-groups, landslide and non-landslide.

The mean size and shape of the sediment particles in the non-landslide tributaries (Table 5.1) indicates that the particles are generally large, angular and poorly sorted with a mean b axis of 51-110 mm, a roundness of 0.11-0.24 and a sorting index of -0.77 to -1.19. This would indicate that, in general, these tributary streams are highly impacted with mobile sediment deposits. The landslide impacted tributaries show similar mean sizes but with more angular, flatter particles which are very poorly sorted.

Table 5.1 Summary statistics of the size (mm) and shape of non-landslide sites' sediment particles in the basins and the landslide impacted catchments

	Pindar	Simikot	Dunai	Manaslu	Langtang	Makalu	K'junga	Landslide
Mean a	99	73	103	136	162	72	120	115
Mean b	66	51	64	91	110	49	83	70
Mean c	36	31	34	51	67	33	51	37
Sphericity	0.62	0.67	0.59	0.66	0.69	0.64	0.67	0.60
Roundness	0.11	-	-	0.16	0.13	0.14	0.24	0.10
Flatness	2.68	2.24	2.98	2.59	2.11	2.50	2.20	3.27
Sorting	-1.01	-1.19	-1.19	-1.07	-0.89	-0.78	-0.77	-1.20
Skewness	-0.06	-0.15	-0.09	0.04	-0.05	0.03	-0.01	-0.10

Using a Box and Whisker analysis the data for the non-landslide impacted tributaries suggest regional trends. The distribution of mean b (Fig.5.1) indicates that the size increased from the western areas to Langtang then decreased again to the eastern areas. The mean size of the Langtang sediments was more than double that of the Simikot and Makalu sediments. A regional trend in roundness (Fig.5.2) was also found with increasing roundness of particles from west to east. The sorting of the sediments was poorest in Simikot and Dunai increasing to the west and east of that location. Flatness generally decreased to the east of Dunai and the Simikot particles were much less flat than those in either Dunai or Pindar.

The survey results suggest differences between basins in the size and shape of the sediments in the tributary streams. To identify the major groups of variables, a principal component analysis was first carried out on the data set including sediment size and shape and catchment land use, from the non-landslide impacted sites. The first principal component indicated a strong correlation between the mean sizes of the three axes (mean a, b and c) while the second and third principal components indicated the main land use controls to be percentage barren and percentage forest cover. Land cover was considered to be a useful catchment indicator as it is likely to represent the integral of a number of other catchment characteristics such as soil type, climate and topography. These characteristics are difficult to assess without major surveys hence the benefits of using land use as an index of broader catchment characteristics.

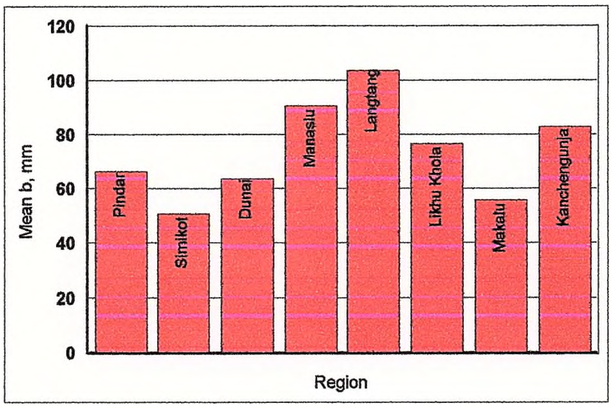

Fig.5.1 Mean size of the b axis for different regions

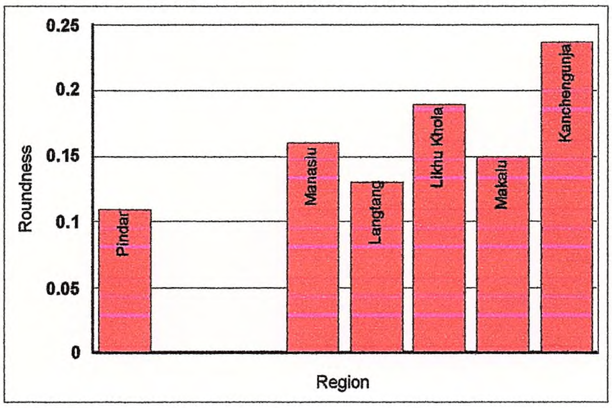

Fig.5.2 Mean value of the roundness index for different regions

The differences in the observed size and shape of the sediment particles in each of the six basins were found, using the Kruskal-Wallis Test, to be highly significant (>99%) for all variables (Table 5.2). However, significant differences between the size and shape parameters were not always found when the tributaries were grouped according to either the percentage barren land in the catchment or the dominant geology of the catchment. When grouped by percentage barren land highly significant (>99%) differences were found in the size of the a axis and the roundness of the particles and a less significant difference (>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.

To investigate whether certain basins could be grouped and how the basin, land use and geological controls combined, a general linear modelling procedure was used on the data from both non-landslide and landslide impacted catchments. Using the Waller-Duncan K-ratio T test the data hints that clustering can be found on all size and shape parameters for the non-landslide catchments. The two most frequent clusters being the Pindar-Simikot-Dunai basins and the Langtang-Makalu-Kanchengunja basins i.e. a distinction between the western basins and the eastern basins.

Table 5.2 Statistical difference between the sample size and shapes when the sites are grouped by region, percentage barren land and geology

	Basin	% Barren land	Geology
Mean a	***	***	
Mean b	***	*	
Mean c	***		**
Sphericity	***		**
Roundness	***	***	***
Flatness	***		***
Sorting	***		
Skewness	***		

Statistical significance of the difference between the means is represented by *** greater than 99%, ** greater than 95% and * greater than 90%.

A multi-variate ANOVA procedure was used to test the significance of differences in particle size and shape according to the basin, geology and land use of the catchment. The combination of the controls for the non-landslide catchments (Table 5.3a) indicated that basin was a significant (99%) control on mean a, b and c, roundness and flatness, the percentage of barren land had a significant (98%) control on mean a and b while the geology had a significant (99%) control on flatness. For the landslide catchments (Table 5.3b) basin was a significant (99%) control for roundness; there were no significant controls on the remaining size and shape parameters identified by the basin, geology or land use.

Table 5.3 Significance of controls on the sediment size and shape by the basin, land use and geology

a. Non-landslide catchments

	Basin	% Barren land	Geology
Mean a	0	0	0.45
Mean b	0	0.01	0.58
Mean c	0	0.04	0.11
Roundness	0	0.44	0.32
Flatness	0	0.04	0
Skewness	0.67	0.36	0.06

b. Landslide catchments

	Basin	% Barren land	Geology
Mean a	0.26	0.89	0.74
Mean b	0.13	0.87	0.69
Mean c	0.09	0.88	0.44
Roundness	0.02	0.25	0.36
Flatness	0.14	0.88	0.41
Skewness	0.31	0.19	0.89

5.3 Interpretation of results

The results of the analysis of coarse sediments in tributary streams of the Himalayas showed that there is a dominant difference in the size and shape of particles according to basins with lesser differences according to the geology and land-use of the catchments. The main contrast between the basins where the sampling was carried out, was the climate, in particular the rainfall regime. Table 5.4 shows the mean annual rainfall totals, based on the gauges located along the survey routes. The data show that the Manaslu, Langtang, Makalu (Num) and Kanchengunja surveys are in the wetter rainfall regions with the Pindar, Simikot, Dunai and Makalu (Tumlingtar) surveys in drier regimes.

A comparison of the summary data in Tables 5.1 and 5.4 indicates that sediment size and shape could be related to rainfall. 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 basins (Manaslu and Makalu (Num). 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. Although roundness was not measured in the two low rainfall basins a peak in roundness is again seen at 1700 mm. 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.

Table 5.3 Mean basin rainfall data from the gauges located along the survey routes

Basin	Number of gauges	Annual rainfall, mm
Pindar	0	1200
Simikot	2	778
Dunai	2	653
Manaslu	5	2137
Langtang	1	1893
Makalu (Tumlingtar)	1	1317
Makalu (Num)	1	4034
Kanchengunja	3	1680

The analysis of rainfall and sediment size and shape indicates that the differences in sediment characteristics between the various basins are likely to be due to the rainfall characteristic of the basin. An increasing rainfall up to a value of 1700 - 2000 mm appears to result in increasing size, sorting and roundness due to the greater movement of the sediments. Beyond 1700 - 2000 mm rainfall the size, sorting and roundness all decrease probably due to the higher flows causing greater erosion and transport rates but also a break-down of sediment particles in the channel by increased physical impacts. The change in skewness is explained by the higher flows increasing the winnowing action and removing the finer sediments.

The main geological structures were earlier shown to be in the north-south direction rather than in the west-east direction but the six surveys still included a large range of different bedrock types. The statistical analysis showed that geology was only a significant control of the size of the c axis, hence the flatness of the particles. Even though a range of bedrock types were sampled the phyllites, schists, gneiss and shales all have well formed cleavage lines and strong cleavage textures encourage breakdown by weathering processes forming flatter more platy-shaped particles. This suggests that it is not the geological type which is important to the size and shape of the sediment particles but the geological texture i.e. the cleavage of the particles.

The barren land catchments are likely to have different hydrological regimes compared to catchments with other land uses explaining the reason for this type of land use having most control on the sediments. Barren land was essentially classed as land too steep to cultivate or where the forest cover had been removed. This lack of vegetation cover is likely to produce more rapid runoff compared to forested or terraced hillslopes. As such, the erosion potential will therefore be greater, the rivers more competent to transport larger particles and hence, as the proportion of barren land increases, the sediment particles transported by the streams would be larger.

The differences in the coarse sediments of non-landslide tributaries between the basins therefore appear to be mainly due to the regional rainfall pattern but the geology and land use can also have significant impacts on the sediment characteristics. These results clearly indicate regional contrasts in the size and shape of coarse sediments with more movement of this coarse sediment in the wetter eastern basins creating more mobile deposits in the river channels. The landslide-impacted streams were shown to be significantly different to the non-landslide tributaries and the sediment deposits in these are described as chaotic. Any landslide impacted tributaries in the wetter regions will be highly unstable and mobile as the rivers recover from the impact but in the drier regions the rivers will take much longer to recover because of the lack of streamflow.

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 characterised by large, rounded and well sorted particles. In regions with rainfall less than 1700 mm the particles would be less mobile, hence smaller, less rounded and more poorly sorted because of the reduced rates of transport. In regions with rainfall greater than 2000 mm the high energy flood flows produce extreme mobility resulting in transport en masse with a smaller overall mean particle size, less well rounded, more poorly sorted and with a positive skewness. The smaller and less well rounded characteristics are probably a result of the frequent impacts between particles which cause physical damage. The positive skewness is probably due to the greater winnowing of finer material during medium flow events. Three levels of sediment mobility are therefore suggested:

i. low mobility - the drier regions (annual rainfall <1700 mm) where streamflow is less and the fluvial working of the sediments is low;
ii. high mobility - the wetter regions (annual rainfall 1700 - 2000 mm) where streamflow is higher and the sediments are frequently transported and sorted by the rivers;
iii. extreme mobility - where particles are transported en masse, are physically damaged by the high energy flows and have greater degree of winnowing.

5.4 Conclusions

1. Few qualitative or quantitative sediment data are available from Himalayan river. This lack of knowledge is a fundamental gap in the management of river basins and the long term sustainability of water supplies to the densely populated mountain and lowland regions;
2. The first order streams in the region form a crucial link between the sediment source areas and the main rivers and the characteristics of the sediments in these streams indicate the processes of supply and transport into the river systems. Sediment characteristics are related to the geology, climate and hydrology of the catchments as well as to the nature of the source areas. Through systematic sampling of the sediments in tributary streams, the major controls on the sediments can therefore be understood, an essential foundation for the quantification of sediment loads on a river basin scale;

3. The size and shape of the coarse sediments were found to be significantly different between the basins where the surveys were carried out. The main regional contrasts were considered to be the rainfall regimes with the higher rainfall generating more river flow which increase the competence of the rivers to transport sediment. This explained the larger particles with greater sorting and roundness in the Langtang and Kanchengunja basins due to the more frequent movement. The basins with very high rainfall totals indicated that the sediment particles were being broken down by the high energy river flows. Landslides were found to produce chaotic sediment deposits in the tributary channels compared to the sediment in the non-landslide tributaries.
4. The importance of these results are that, for the first time, regional patterns have been identified in the characteristics of the coarse sediments which are significant for understanding the stability of the channels and quantifying sediment loads. The results also showed the importance of rainfall on the sediment characteristics and the relatively low significance of any anthropogenic influences. The chaos in landslide catchments is a clear comment on the major disruption caused by these events; the river channels are totally changed by the landslides with the impacts likely to last for long periods, especially in the drier regions where the river flows are less. The breakdown of sediment particles by abrasion and splitting along cleavage lines is due to a combination of the geological texture of the particles and the frequency of movement by the rivers.

6 Himalayan streamwater chemistry: a summary

The high mountains of the Himalayas represent one of the most remote regions of the world. As a consequence, they are probably one of the least chemically disturbed environments that is their remoteness presumably precludes anthropogenic influences from local human activity. On the other hand the emissions of acidic oxides of S and N from fossil fuel burning is a phenomenon which has led to widespread pollution of Western Europe and North America. The long range trans-boundary nature of this pollution means that no region no matter how remote is immune from impacts. The emissions of S and N oxides is already high in SE Asia and is predicted to increase dramatically as economies develop over the next two decades. The risk to the pristine environments of the Himalayas and the ecosystems they support is unknown. The risk requires quantification if the widespread damage observed in Western Europe is to be avoided.

6.1 Sampling and analytical methods

Over 800 samples were collected for chemical analysis over the course of the surveys from 1992 to 1998. The data analysis included 743 locations in the Annapurna, Dunai, Everest, Kanchengunja, Langtang, Manaslu, Makalu and Simikot areas of Nepal and Pindar and Roopkund areas of NW India. The Langtang was sampled in three separate years to determine the consistency of the results, data from the first Langtang survey is used in this regional analysis.

At each location stream water was collected in a 100 ml syringe and filtered immediately through a 0.45 mm cellulose-ester membrane into two 60 ml HDPE bottles. One of these bottles was acidified immediately to 1% using high purity concentrated HNO_3. Samples were transported to the UK and analysed 4-6 weeks after collection. Electrical conductivity temperature and pH were measured in the field using portable meters.

In the laboratory the acidified sample was analysed for Ca, Mg, Na, K, Si, Sr, Ba, Fe, Mn, SO_4 and Al using Inductively Coupled Plasma Optical Emission Spectrometry (ICPOES). The un-acidified sample was analysed for NO_3, F, Cl and PO_4 using colorimetric procedures. Bicarbonate was calculated as the total anion charge deficit or Acid Neutralising Capacity (ANC) sine the other contributions to ANC are organic ions and aluminium. In this respect organic concentrations are assumed to be low and Al concentrations are known to be low. Excess pCO_2 (the ratio of the computed pCO_2 for the water and air equilibrated value of $10^{-3.5}$) was estimated based on an equilibrium value corresponding to:

$$[H^+].[HCO_3^-] = 5.13$$

where the concentrations are expressed in meq l^{-1}. Excess pCO^2 ranges from 1 to 30 times atmospheric and 95% of samples are below 10 times atmospheric. This is consistent with reported ranges for natural surface waters in other areas. Samples with excess pCO_2

greater than 10 indicate a groundwater or spring source which has not yet equilibrated with atmospheric CO_2. This may explain some of the low pH levels observed.

In comparing water chemistry from different regions sampled in different years, it is assumed that water chemistry exhibits similar characteristics from year to year. Clearly this could not be expected in the monsoon season when storm characteristics and rainfall composition may import a significant fingerprint on stream chemistry characteristics. In the dry season, however, it is assumed that catchment physical and chemical characteristics such as bedrock geology and land use, impart the dominant controls on stream chemistry and these can be assumed constant in the short term (3-5 years). To test this assumption streams in one region, the Langtang, were repeat sampled in 1992, 1994 and 1995. Comparison of the mean streamwater chemistry for each of the three years data showed very similar values supporting the synoptic survey strategy adapted and this implies that the regional surveys are comparable despite being carried out during different years.

6.2 Chemical characteristics of Himalayan streams

The general picture of stream chemistry that emerges for the Himalayan region is typical of an environment dominated by mineral weathering, with acidity controlled by the dissolved CO_2 and which has received little anthropogenic influence. The resulting high concentrations of bi-carbonate and near neutral pH represent conditions which are presumably close to the chemistry of natural waters in other regions of the world before anthropogenic pollution occurred.

Frequency distributions of all ions, except Si, are negatively skewed and those describing the major base cations (Ca, Mg, K, Na) and anions (SO_4) exhibit long tails indicating that extremely high concentrations are not uncommon. Silica concentrations and pH approximate normal distributions. All mean ion concentrations have large standard deviations indicating a high degree of variability across the region.

Metal concentrations are generally extremely low and in the majority of samples, iron, manganese and aluminium are below detection limits. Nevertheless, the maximum concentrations observed are significant in relation to irrigation and drinking water standards. For example, WHO maximum levels for drinking water are generally exceeded by the maximum observed values: Fe = 0.3 mg l^{-1}, Mn = 0.5 mg l^{-1} and Al 0.2 mg l^{-1}. Strontium and Ba are routinely found in low concentrations. Fluoride is also commonly found in low concentrations but with maximum values (2.04 mg l^{-1}) in excess of the WHO level for drinking water (1.5 mg l^{-1}). Nutrient concentrations are mainly below detection limits and when detected are very low relative to concentrations reported in the bigger rivers of Asia.

6.3 Geological controls on stream chemistry

The chemical composition of streamwater in unpolluted regions depends on the bedrock geology in that the mineralogy of the rock determines the weathering products. The dominant anion in over 90% of Himalayan stream waters is HCO_3, its major source being carbonate rocks. A few samples exhibit a high proportion of SO_4 probably associated with local occurrences of gypsum and sulphide rocks. In all but some 1% of the samples Cl is unimportant and generally contributes less than 10% of the anion charge and this reflects the lack of a marine influence.

In terms of hydrochemical classification this pattern of elemental composition indicates that streams of the Himalayan region:

- Are dominated by weak acids ($HCO_3 + CO_3$);
- Are dominated by carbonate hardness (Ca + Mg);
- Are rarely characterised by very soft water;
- Exhibit no characteristics of marine influence;
- Are rarely influenced by strong acids (and when they are, this is most probably associated with small scale SO_4 mineral veining.

With respect to per cent composition of cations the waters fall into three main categories:

i.	Calcium waters:	>60% Ca	<30% Mg	<30% Na+K
ii.	Magnesium-Calcium waters	<60% Ca	>30% Mg	<30% Na+K
iii.	Sodium-Potassium waters	<60% Ca	<30% Mg	>30% Na+K

Each category also has a broadly defined HCO_3 – pH relationship. These three hydrochemical classes identified are broadly related to geological facies. Electrical conductivity provides a consistent measure of the weathering characteristics and bedrock mineralogy:

i. Calcium waters

These are mainly found at higher altitudes, often contain high concentrations of SO4 and are mainly associated with the Tethyan Sediments. These comprise Palaeozoic limestones, sandstones and shales. Mean EC is 110 mS.

ii. Magnesium-Calcium waters

These waters are associated with the Kuncha and Nuwakot Groups which comprise Pre-Cambrian to Palaezoic sandstones, metasandstnes and stromatolitic limestones. Mean EC is 240 mS indicating high weathering rates.

iii. Sodium-Potassium waters

These are characterized by very low electrical conductivity with a mean of 30 ms, indicating a low rate of weathering. They drain from areas within the Kuncha and Nuwakot Groups which are characterized by phyllite and schist. They also drain areas underlain by the Higher Himalayan Crystallines which comprise gneisses, quartzites and marbles as well as Tertiar granites to the NW of Manaslu.

The geochemical classification can be mapped back onto the detailed survey areas to further illustrate the geological control on stream chemistry. In the Roopkund and Pindar areas the geological boundaries closely correspond to the three classes and the differences in electrical conductivity and highlighted. In other areas, for example Annapurna, Kanchengunja and Manaslu, the hydrochemistry classes show only a broad agreement with the mapped lithology. The mis-matches may result from: i) the catchments upstream of the sampling point draining areas of different geology; ii) local mineral veining and micro-scale geological structures; or iii) incorrectly mapped geological boundaries due largely to the scale of the map and the difficulties of geological mapping in these mountainous areas.

Table 6.1 Mean chemistry characteristics of the 830 Himalayan streams

Variable	Mean	Minimum	Maximum
Mg	3.79	0.05	44.8
Ca	12.57	0.02	98.0
SO_4-S	6.49	0.10	132.0
Si	4.35	0.05	33.5
Na	2.71	0.05	318.0
K	1.63	0.37	69.5
F	0.13	0.01	2.04
Cl	1.57	0.10	570.0
NO_3-N	0.21	0.01	8.88
Sr	0.032	0.0005	2.8
Ba	0.011	0.0025	0.54
Fe	0.095	0.0075	55.0
Mn	0.005	0.0015	0.85
Al	0.106	0.10	4.84
PH	7.66	4.54	8.9
EC	106.4	6.0	2270.0
PO_4-P	0.04	0.02	2.76

Units: mg l^{-1} for major ions; mg l^{-1} for metals and mS for electrical conductivity (EC)

6.4 Anthropogenic influences

Anthropogenic influences on these remote headwater streams in the Himalayas is most likely from two sources: deposition of acidic oxides from the atmosphere as a result of long-range trans-boundary air pollution and runoff from areas under agricultural land use subject to inputs of agrochemicals, especially nutrients. The impact of agricultural influences is likely to be limited to streams at lower altitudes since steep slopes, remoteness, hostile climate and lack of local population preclude agriculture from higher altitudes. The impact of acidic deposition is potentially likely at all altitudes.

The stream chemistry data provide no clear evidence of any impact from deposition of acidic oxides resulting from long-range trans-boundary air pollution. Some waters are however influenced by strong acids. High S concentrations are most likely derived from local mineral sources of SO_4. High NO_3 concentrations are found at high altitudes in two of the regions, Pindar and Makalu. These may reflect high deposition of N species which is not utilized by terrestrial biota but soil and vegetation characteristics of these two regions is not significantly different from the other regions and so no consistent explanation can be found. Nevertheless, detailed chemical analysis f the major ion chemistry and pH relationships across the region clearly demonstrate a potential future problem of, and indicate those areas which are most susceptible to, future surface water acidification.

The calcium and magnesium-calcium hydrochemical classes are dominated by high concentrations of Ca and Mg and exhibit high pH. Sodium-potassium waters are uniformly low in Ca and Mg and generally exhibit lower pH. Sodium is apparently not important in controlling acidity and demonstrates no relationship with pH. This indicates that the silicate waters are the most susceptible to acidification.

The relationship between EC and Ca, Mg and pH is also clear and the three hydrochemical classes demonstrate clear characteristics. In this respect EC is apparently a good indicator of susceptibility to acidification; low EC indicates low pH, low weathering sources of Ca and Mg and consequently a high sensitivity to acidic deposition. From a practical viewpoint this is an important finding since EC is a quick, easy, inexpensive and reliable parameter to measure in the field and could be used as the basis for future survey work.

The impact of agricultural land use on surface water chemistry cannot be determined from this data set. Within each hydrochemical water class catchments dominated by agriculture are few and so statistical testing is not possible. Agricultural catchments are also mainly located at lower altitudes and bedrock geology is related to altitude.

6.5 Conclusions

1. The chemistry of headwater streams in the Himalayas is dominated by dissolved CO_2 and base cations derived from mineral weathering. This promotes generally near neutral pH and metal concentrations are correspondingly low;
2. The waters are generally soft and no marine or anthropogenic influence was found; strong acids were present in some samples but were believed to result from local S bearing minerals. No explanation can be found for the high concentration of NO_3 observed in the Pindar and Makalu regions but the streams were not influenced by agriculture and so the origin of the high NO_3 may well be atmospheric deposition;
3. Bedrock geology determines the base cation characteristics of the waters; three hydrochemical classes were identified on the basis of cation percentages and can be used to define the broad hydrochemical characteristics of the Himalayas;
4. Waters dominated by sodium-potassium tend to contain low concentrations of base cations and have low calculated critical loads; these waters are potentially susceptible to acidification in the future. Waters dominated by calcium and magnesium-calcium have high base cation contents and are unlikely to be susceptible to increased acidic deposition;
5. Waters dominated by sodium-potassium generally originate from the Higher Himalayan crystalline geological group and from the schist and phyllite facies of the Nuwakot and Kuncha Groups; geological maps therefore provide a good first estimate of the areal extent of sensitivity to acid deposition. These geological units make up some 30% of the Himalayas, according to mapped geology.
6. In comparison with the geological maps, the hydrochemical classification indicates some local scale anomalies which may relate to inaccuracies in the geological map;
7. Electrical conductivity of the stream waters has been found to provide an excellent indicator of the chemical characteristics of the water and has potentially utility in future field assessments of sensitivity to acidic deposition.

7 Expedition budget

The budget (£) for the expedition is shown below:

Expenses	
Airfares	3850
Kathmandu	220
Logistical support	4770
Maps	35
Scientific equipment	250
GPS	145
Photography	80
Personal equipment	1000
Insurance	450
Total	10800

Income	
RGS Grant	1000
MEF Grant	500
Mountain Environments	2500
Brasher Boots	150
Caledonian Countrywear	50
Personal contributions	6600
Total	10800

No major sponsor was found for the expedition but grants were obtained from the Royal Geographical Society: expeditions and field research overseas and the Mount Everest Foundation. In addition the expedition leader's environmental consultancy, Mountain Environments, contributed funds and some equipment was supplied by the Brasher Boots Company and Caledonian Countrywear, Callander.

8 Conclusions

The 1998 Trans Himalayan River Expedition undertook a significant environmental survey of the Arun valley in Nepal. The original objectives of the expedition had to be reduced substantially because of the lack of a major sponsor. Problems were encountered in the field related to poor weather which made sampling some of the variables difficult and un-representative. The environmental survey included:

Meteorology and hydrology
Social surveys
Fluvial sediments
Landform survey
Location of landslides
Streamwater chemistry

The results from the expedition are still being analysed but will eventually form part of a more extensive Himalayan river basin data base. The Arun has a very high rainfall with the rivers fed by the rainfall runoff and snow and ice melt. Surveys of the glacial features showed the history of glaciation in the upper Barun and indicated the potential problems with further glacial retreat and erosion of the moraines by rivers. Very few landslides were noted in stark contrast to other areas. Fluvial sediments were however indicative of the high rainfall being small in size, angular in shape and poorly sorted. At mid altitudes the chemistry of the stream waters indicated acidic conditions especially in two small lakes where biological life was non-existent. The region is very under-developed in comparison to other trekking routes in the Himalayas. The National Park controls the upper areas but there is a significant potential for future change as trekking increases and the hydro-power developments on the Arun are expanded.

By comparing the different river basins a better understanding of the spatial variations in environmental conditions throughout the Himalayas has been found and by repeating these surveys on future expeditions the changes over time will be determined.

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Caledonian Countrywear

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