Aquatic Biodiversity in the Himalaya

Final Scientific Report to the Darwin Initiative

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Executive Summary

The Darwin Initiative for Aquatic Biodiversity in the Himalaya aimed to study the spatial patterns of aquatic biodiversity and to assess the use of biota as indicators of environmental change. Specific objectives were:

1. To determine, using synoptic survey, the ecological, chemical and sediment characteristics of streams in the Himalaya.

2. To assess the potential of these features as indicators of status and change.

3. To assess the impact of land-use and acidic deposition on Himalayan stream ecosystems.

4. To undertake information exchange through meetings, field visits with local scientists and workshop discussions.

Seven regions of the Hind-Kush Himalaya (HKH) were surveyed from Kumaun Himalaya in the west to Kanchenjunga in the east. These represent the major types of altitude, geology, climate and land-use in the region. In all, data were collected from 743 locations for chemistry and with biological data collected at subsets of sites (108 to 182).

The chemistry of the streams was dominated by dissolved $C0_2$ and by base cations derived from bedrock weathering promoting near neutral pH and low metal concentrations. No anthropogenic influence from land-use or acidic deposition could be identified but a high degree of susceptibility to acidification was found.

The biological data reveal expectable and major effects by altitude on stream biota. However, there was also evidence of important additional effects by habitat structure (on all groups), stream chemistry (on bryophytes and diatoms) and land use (on bryophytes and diatoms) that further reveal the potential of stream organisms in indicating river and catchment quality in the Himalaya. Contrasting response between groups to different features show how different kinds of environmental change pervade food webs to different levels, and show how different groups of organisms provide complimentary information on stream quality.

Together these data on stream chemistry, sediment and biota provide the most comprehensive inventory of river biodiversity ever collected in the Himalaya. We recommend that the data now be exploited as a key baseline from which to assess future change in this globally important and sensitive region. Its use as a tool in future research and monitoring should not be underestimated.

Scientific Conclusions

1. The chemistry of headwater streams in the Himalaya 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. The waters are generally soft and no marine or anthropogenic influence was found.

2. 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 Himalaya.

3. Electrical conductivity of the stream waters has been found to provide an excellent indicator of the chemical characteristics of the water and has potential utility in future field assessments of sensitivity to acidic deposition.

4. The size and shape of the coarse sediments were found to be significantly different between the regions. Rainfall was considered to be the major control in particle size, sorting and roundness.

5. Landslides had a profound effect on sediment characteristics. In the wetter regions the impacted tributaries are highly unstable and mobile as the rivers recover but in the drier regions the rivers take much longer to recover because of lower streamflow.

6. The River Habitat Survey, developed by the Environment Agency in Britain, with minor modifications, was effective in describing habitat structure in Himalayan streams despite their complexity. It illustrated major habitat trends with altitude, detected major effects by catchment land use, and provided meaningful correlates with biological pattern in all the groups examined.

7. Among the habitat effects, there were highly significant differences in character between streams from terraced catchments and others; agricultural streams were typified by wider channels with mid- or side-bars; riffles over finer substrata rather than cascades over boulders; and banks with small slopes, fewer tree-related features and simplified vegetation structure. Terraced sites had several types of modification in the channel and banks, including diversions for irrigation. In view of the importance of habitat effects on organisms, these land use effects illustrate potential for influences by catchment land use on river biota.

8. Change in diatom community composition between sites is a major aspect of diversity in Himalayan streams; it has great potential to indicate natural and anthropogenic changes in the river ecosystems and their catchments.

9. A range of probable effects from altitude, water chemistry and habitat character on diatom communities were detected, among which chemistry and to a lesser extent habitat have been detected elsewhere. However, this study covering an altitudinal range of c. 4000 m showed that altitudinal effects have by far the strongest influence on diatom communities; the role of climate and temperature requires further study.

sampling to polluted streams, and if effects, for example, by acidification in the Himalaya, become stronger.

18. The richness of river birds in the Himalaya is the greatest in the world. Partly because most of the species studied are altitudinal migrants, most river birds showed distinct altitudinal distribution. River Lapwing, Large Cormorant, Common Sandpiper, Slaty-backed Forktail, while Little Forktail and Spotted Forktail characterised mid-altitudes.

19. After accounting for altitude, highly significant effects by stream habitat structure were apparent in most river birds. Of all the groups that contribute to river biodiversity, birds are ideally suited to studies linking diversity with habitat characteristics because their territories are comparable in size with the geographical scale of habitat measurements. River birds have potential value in indicating habitat alterations caused, for example, by catchment management but relationships between river bird occurrence and chemistry, invertebrate distribution and stability were weak.

20. This unique database has provided for a first assessment of large spatial pattern in stream quality and biological character in the HKH. It has revealed marked natural influence on pattern with evidence of strong effects by land-use on river habitat structure, diatoms and bryophytes and weaker effects on invertebrates, birds and stream chemistry.

21. Further comparative studies should focus on more heavily degraded catchments. The integrated perspective contained within the existing data provides impetus for the development of quality indices for Himalayan streams with great utility in water resource assessment and management and for identification and quantification of environmental change in these sensitive ecosystems.

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Contents

1 Background to the Project

The Himalaya are a 3500 km long mountain range which is geologically young and tectonically active. The climatic gradients are extreme and the altitudinal range is the greatest on Earth. The natural environment of the Himalaya and the biodiversity they support are unique because of the great variety of environmental conditions.

For over two decades, there has been speculation about effects by human activity on the Himalayan mountains (Ives and Messerli, 1989; Messerli and Ives, 1997). An initial postulate was that population pressures across the Himalaya - currently with 120 million people and growth of over 2.5% per year - would lead to widespread replacement of semi-natural lands by agriculture; change in hillslope stability, soil erosion, runoff quantity and fluvial character would then exacerbate natural effects from an intense monsoonal climate (Eckholm, 1975). Although more recent perspectives emphasise chemical effects by local agricultural intensification (Jenkins *et al*, 1995; Gardner and Jenkins, 1995; Collins and Jenkins, 1996), or regional air pollution from rapid economic growth (Bhatti *et al*, 1992), catchment-scale effects on rivers remain central to the debate about Himalayan change. However, quantitative investigations of hydrochemical and biological effects are still remarkably scarce.

While environmental change in the Himalaya affects human environments (Rhoades, 1997), natural ecosystems are also at risk (Hunter and Yonzon, 1993). In view of pronounced endemism, physico-chemical heterogeneity, and location at the borders of the Oriental and Palaearctic biological realms, the biodiversity of the Himalayan mountains is globally significant (Myers, 1988; 1990). This biological importance extends into river systems because they support endangered species of freshwater reptiles, cetaceans or fishes (Shrestha, 1990; Smith, 1993), supports the world's greatest richness of river birds (Buckton and Ormerod, unpubl.) and contain high alpha and beta richness of benthic organisms (Brewin *et al*, 1995; Ormerod *et al*, 1994; 1997; Rothfritz *et al*, 1997). There is already evidence, published from data collected during this programme, that stream biota respond to agricultural intensification by altered community composition or increased abundance among some groups, for example reflecting enrichment by fertilisers and suspended organic material (Ormerod *et al*, 1994; Jüttner *et al*, 1996(b)). However, quantitative studies are still rare at the large geographical scales necessary to add to those in individual basins that might not faithfully represent wider patterns.

This project, funded under the Darwin Initiative, is focused on the 'Aquatic Biodiversity in the Himalaya' and aimed to study the spatial patterns of aquatic biodiversity and to use biodiversity as an indicator of environmental change from natural and anthropogenic sources. The work was undertaken through established links between two British research organisations and institutions in Nepal and India.

2 Regional Surveys

Seven regions were selected for survey taking account of gradients in geology, rainfall and land cover. Selection was informed by four previous surveys. All surveys covered a range of land use from terraced agricultural land at lower altitude to glaciers at high altitude. The location of survey regions is shown in Figure 2.1 and the dates of the surveys listed below:

India:	Pindar	1995
	Roopkund	1995
Nepal:	Simikot	1994
	Dunai	1994
	Manaslu	1996
	Annapurna	1992[1]
	Langtang	1992[1]/1994[2]/1995[2]
	Likhu Khola	1993[2]
	Everest	1992[1]
	Makalu	1994
	Kanchenjunga	1996

1 Funded by the US Environmental Protection Agency
2 Funded by the Overseas Development Administration

The remoteness of some regions resulted in a lack of basic information such as topographical and geological maps so determining the characteristics of some catchments was difficult.

Surveys were undertaken during low flow conditions in October or November each year. The monsoon months were avoided since storm characteristics influence the biological, chemical and sedimentological properties.

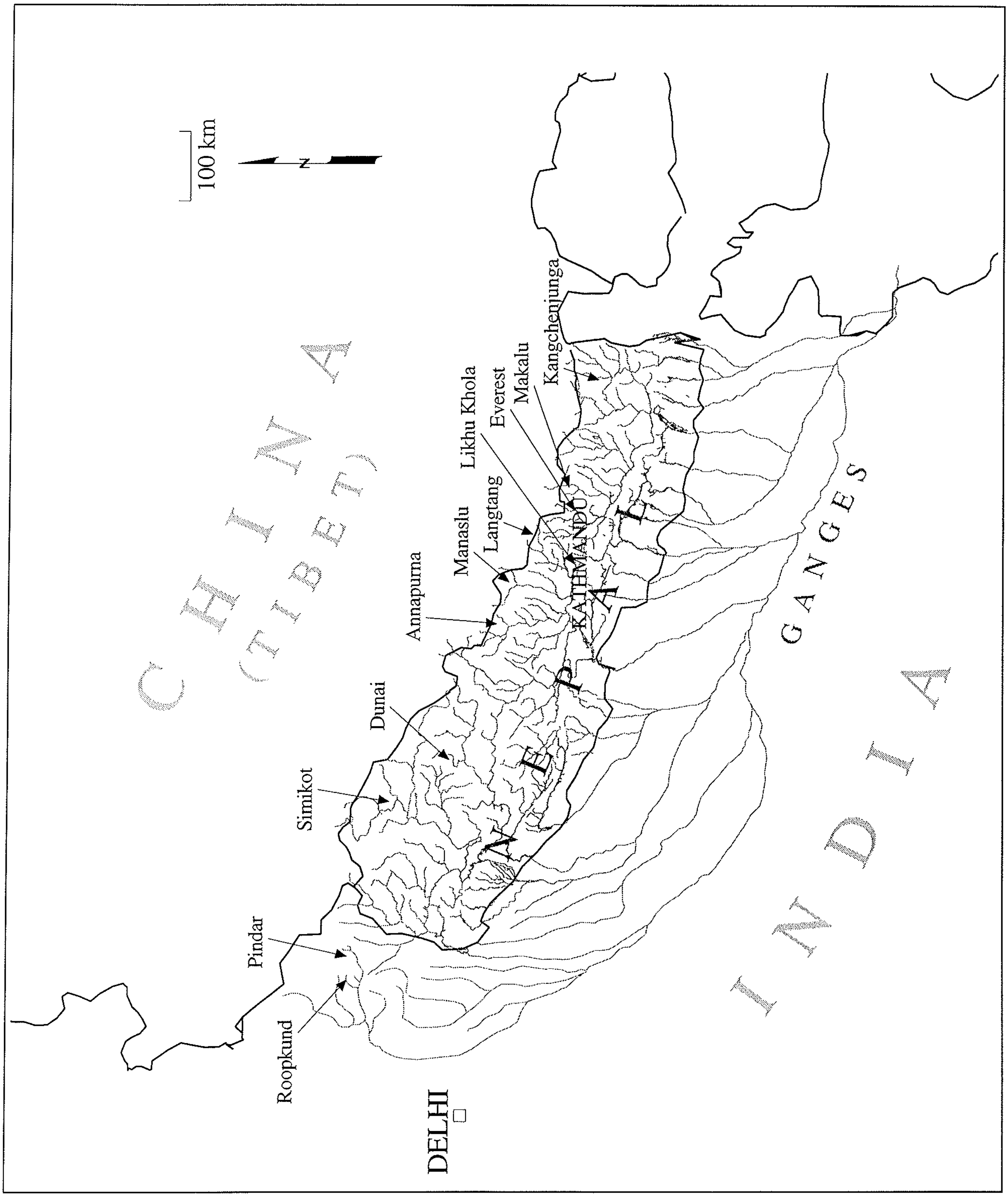


Figure 2.1 *Location of the regions surveyed*

3 Catchment Data

Geology, topography, river and land-use information were obtained in digital format from the International Centre for Integrated Mountain Development (ICIMOD) in Kathmandu while map data for NW India were obtained from the Royal Geographical Society in London. The spatial data were transferred to GIS and the relevant catchment data for each sample site extracted. A final composite database was produced incorporating field observations, spatial and cartographic data.

3.1 GEOLOGY

The Himalaya is essentially comprised of a series of west to east orientated structures caused by the Indian tectonic plate subducting beneath the Eurasian plate (Fig. 3.1). The mountain range can be divided into four main structures. 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 Himalaya consists predominantly of highly metamorphic rocks most commonly gneiss, quartzite and schist. The main central thrust separates the High Himalaya 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 (graywacke and sandstone).

The surveys were undertaken from the Middle Mountains to the High Himalaya and so crossed a range of different geologies. Sample points were located within five main lithological groups:

- **Limestones, sandstones and shales**
  These rocks are comprised of Late Cambrian to Cretaceous sedimentary rocks divided into an upper and a lower zone. The lower section contains impure limestone/marble with layers of phyllites, sandstone/quartzite, black shales, limestone and sandy dolomite. The upper section consists of limestone with alternating layers of shales, slates, and sandstones. Mesozoic rocks are indicated by the presence of calcsandstone, black shale and limestone in succession. Jurassic rocks are composed of sandy limestone and dolomite, bedded shales, sandstone, ferruginous black shale and sandstones.

- **Granite**
  Tertiary leucocratic granite with tourmaline.

- **Gneisses, quartzites and marbles**
  These are collectively termed the Higher Himalayan Crystallines and were formed during the continental collision of the Indian and Eurasian plates. The resulting rock structures are consequently highly distorted and metamorphosed. The crystalline layers can be roughly divided into an upper sequence consisting of kyanite-sillimanite gneiss and quartzite; a middle sequence comprising calcareous gneiss with marble; and a lower layer of augen gneisses, granitic gneisses and migmatites

- **Dolomites, marbles and phyllites**
  This assembly falls within the geotectonic division of the Lesser Himalaya and can be split into two further categories. Firstly the Kuncha group dominated by phyllite, semi-schist, metagreywacke, phyllitic quartzite, and characterised by phyllite with detrital bluish quartz, feldspar and muscovite. Secondly the Nuwakot group consisting of argillaceous/quartzitic grey phyllites and dark slates with secondary bands of limestone/dolomite and calc-phyllite. White to pink quartzite, vari-coloured phyllites and pink dolomites can also be present.

- **Phyllites, schists and gneisses**
  These form the Kuncha group, see above, and are only present in Eastern Nepal

3.2 CLIMATE

The climate of the Himalayan region is highly influenced by the mountains which form a major physical barrier and create well defined regional patterns of precipitation (Fig. 3.2). 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.

3.3 LAND-USE

Spatial land-use data for Nepal were digitised from 1:50,000 land utilisation maps compiled by HMG Survey Department, 1985. The maps provided were derived from remotely sensed satellite and photogrammetric data. Forest and agricultural land-uses are specified as a crown density describing the percentage area covered by tree crowns and intensity of cultivation respectively. The percentage area not assigned to forestry or agriculture was assumed to be scrub. The percentage land-use attributable to each sub-catchment was estimated using the following set of information:

- The digitised land-use map.
- Elevation contours and stream networks, superimposed upon the land-use map.
- Sample points plotted on the maps.
- Original maps of sample locations to assist in determination of sub-catchment extent.
- Field note-books for information about the nature of the stream, i.e. main stream, spring etc.

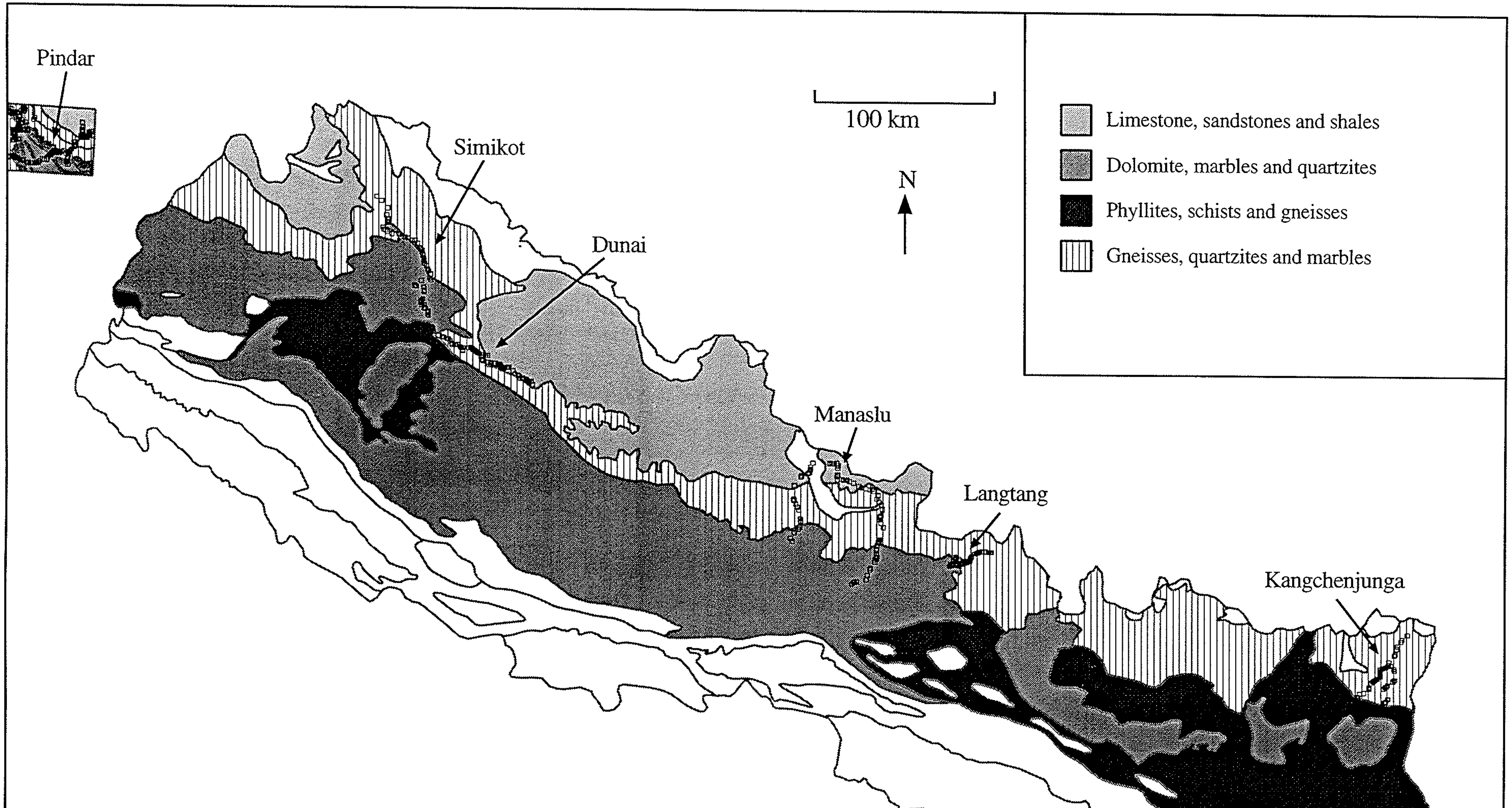


Figure 3.1

Nepal geology map showing the regional survey sites.

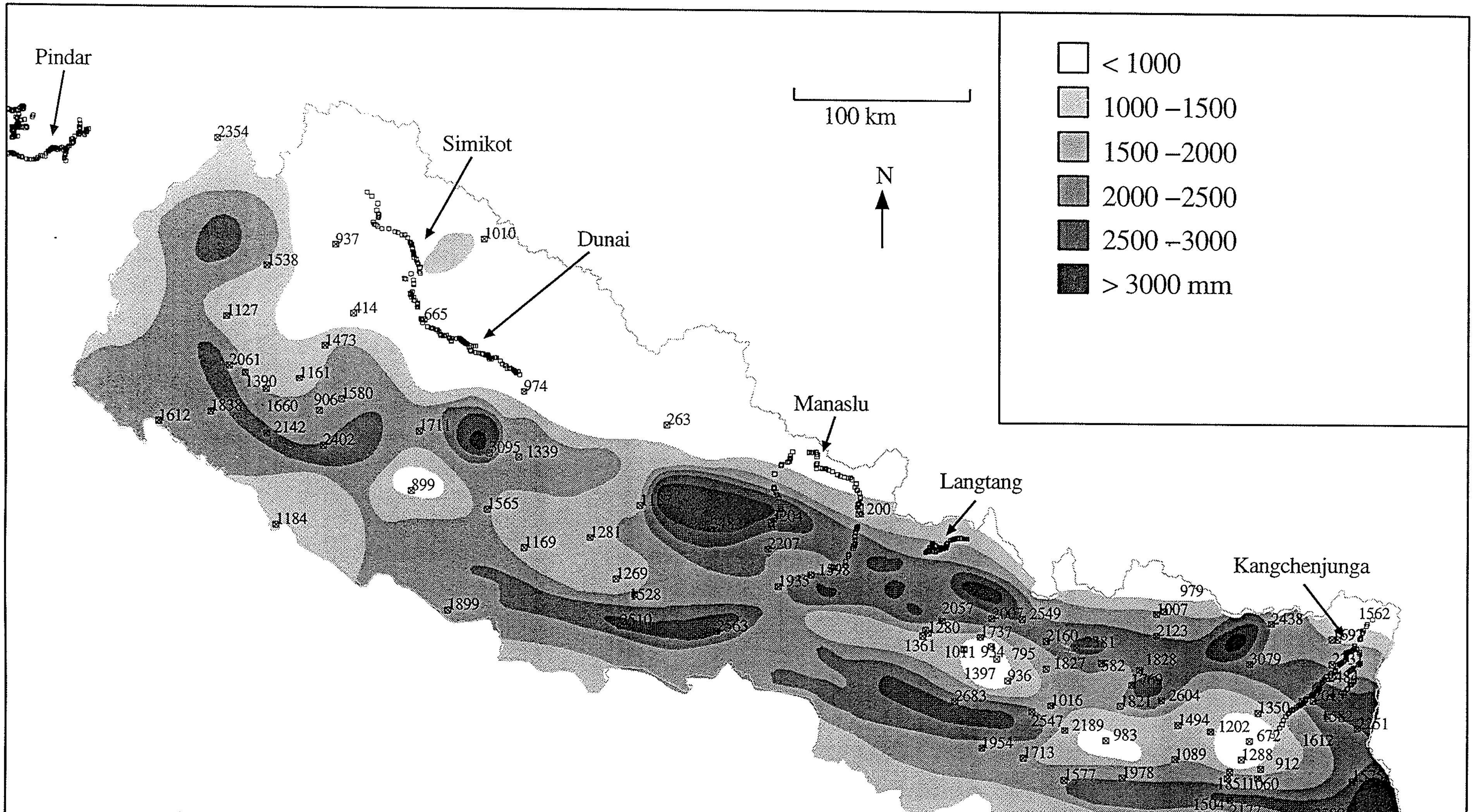


Figure 3.2
Contours of mean annual rainfall 1961–1970 (HMG Data) with additional point rainfall data for 1976 and 1977 (after Alford, 1992).

4 Stream Chemistry

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

4.1 SAMPLING AND ANALYTICAL METHODS

Over 800 samples have been collected for chemical analysis over the course of the surveys. The data analysis includes 743 locations in the Annapurna, Dunai, Everest, Kanchenjunga, 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 (L1) is used in the 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) since 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 (see later). Excess pCO_2 (the ratio of the computed pCO_2 for the water and the 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} (Avila and Roda, 1991). Excess pCO_2 ranges from 1 to 30 times atmospheric (Figure 4.1) 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 (Figure 4.1).

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 stream chemistry for each of the three years data (Table 4.1) shows only three significant differences in the entire suite of chemicals analysed. Of these, the higher Na and pH for the 1992 survey may reflect the different season of sampling to the later surveys. The 1992 survey was conducted in March (pre-monsoon) and the later surveys were conducted in October (post-monsoon). In general, these results support the synoptic survey strategy adapted and this implies that the regional surveys are comparable despite being carried out during different years.

4.2 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 dissolved CO_2 and which has received little anthropogenic influence (Table 4.2). 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 (Figure 4.2) 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 (Table 4.1) 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 greatly 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} (WHO, 1993). Strontium and Ba are routinely found in low concentrations. Fluoride is also commonly found in low concentrations but with maximum value (2.04 mg l^{-1}) in excess of the WHO level for drinking water (1.5 mg l^{-1}). The ecological significance of these ions is unknown. Nutrient concentrations, namely PO_4-P and NO_3-N, are mainly below detection limit and when detected are very low relative to concentrations reported in the bigger rivers of Asia (for example, Degens *et al,* 1990).

4.3 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 (Figure 4.3). 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 sulfide rocks. In all but *c.*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.

Table 4.1 *Mean chemistry characteristics of the Langtang region surveyed in 1992 (L1), 1994 (L2) and 1995 (L3). Number of streams sampled = n, standard deviation = SD. Units are mg* l^{-1} *for major anions and cations, mg* l^{-1} *for metals and mS* cm^{-1} *for Electrical Conductivity (Cond). Significant differences in true means (ANOVA) are identified in the footnote.*

	L1 (n = 55)		L2 (n = 25)		L3 (n = 34)	
	Mean	SD	Mean	SD	Mean	SD
Cl	0.31	0.46	0.17	0.17	0.36	0.36
NO_3-N	0.09	0.13	0.1	0.06	0.19[c]	0.17
SO_4	7.2	6.0	6.08	4.21	5.83	3.98
Na	2.25[a]	1.21	1.69	0.79	1.74	0.77
K	1.52	1.18	1.2	1.25	1.62	1.68
Mg	1.57	2.11	1.85	3.43	2.55	3.89
Ca	7.47	6.17	6.55	6.17	8.5	8.53
Si	4.27	1.9	3.55	1.43	3.75	1.35
Sr	22	17	16	8	23	18
Ba	5	6	5	7	7	10
Fe	15	19	29	41	24	39
F	65	68	64	54	74	54
pH	7.35[b]	0.45	7.95	0.45	7.74	0.59
Cond	90	58	58	53	69	64

Notes

[a] L1 mean Na is significantly higher (ANOVA, sig = 95%)

[b] L1 mean pH is significantly lower (ANOVA, sig = 99.9%)

[c] L3 mean NO_3 - N is significantly higher (ANOVA, sig = 99%)

In terms of hydrochemical classification (Figure 4.3), 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

Table 4.2 *Mean chemistry characteristics of the 830 headwater streams sampled in the Himalaya. Units are mg l^{-1} for major cations and anions, mg l^{-1} for metals and mS cm^{-1} for Electrical Conductivity (COND).*

Variable	Mean	Minimum	Maximum	Standard Deviation
Mg	3.79	0.05	44.8	6.88
Ca	12.57	0.02	98.0	13.85
SO_4-S	6.49	0.1	132.0	9.83
Si	4.35	0.05	33.5	2.53
Na	2.71	0.05	318.0	11.32
K	1.63	0.37	69.5	3.11
F	0.13	0.01	2.04	0.21
Cl	1.57	0.1	570.0	20.16
NO_3-N	0.21	0.01	8.88	0.63
Sr	0.032	0.0005	2.8	0.10
Ba	0.011	0.0025	0.54	0.02
Fe	0.095	0.0075	55.0	1.90
Mn	0.005	0.0015	0.85	0.042
Al	0.106	0.1	4.84	0.164
pH	7.66	4.54	8.9	0.58
COND	106.4	6.0	2270.0	129.4
PO_4-P	0.04	0.02	2.76	0.14

Each category also has a broadly defined HCO_3-pH relationship (Figure 4.4). 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 in at higher altitude, often contain high concentrations of SO_4 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 and Pre-Cambrian to Palaeozoic sandstones, metasandstones and stromatolitic limestones. Mean EC is 240 mS indicating high weathering rate.

(iii) Sodium-Potassium waters

These are characterised 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 characterised by phyllite and schist. They also drain areas underlain by the Higher Himalayan Crystallines which comprise gneisses, quartzites and marbles as well as the Tertiary 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 (Figure 4.5) the geological boundaries closely correspond to the three classes and the differences in electrical conductivity are highlighted. In other areas, for example Annapurna, Kanchenjunga and Manaslu (Figures 4.6-4.8), 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.

4.4 ANTHROPOGENIC INFLUENCE

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

4.4.1 Acidic Deposition

The stream chemistry data provide no clear evidence of any impact from deposition of acidic oxides resulting from long-range transboundary air pollution. Some waters are, however, influenced by strong acids (Figure 4.3). 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, the Pindar and Makalu. These may reflect high deposition of N species which is not utilised by terrestrial biota but the 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 of 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 (Figure 4.9). 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 susceptibility to acidification; low EC indicates lower pH, low weathering source 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.

Critical loads for S have been calculated for all surface water samples using the empirical level 1 approach as documented in the UNECE Manual on Methodologies and Criteria for Mapping Critical Levels/Loads (Werner and Spranger, 1996). Critical loads are generally high (Figure 4.10) with only c.10% of samples <2 Keq ha^{-1}. The mean critical loads for the three hydrochemical classes are 14, 41 and 6 Keq ha^{-1} yr^{-1} for calcium, magnesium-calcium and sodium-potassium waters, respectively. Minimum critical loads are 1.7, 0.9, and 0.9 Keq ha^{-1} yr^{-1} for calcium, magnesium-calcium and sodium-potassium waters, respectively. Waters with critical load < 2 Keq ha^{-1} are predominantly in the sodium-potassium class (Figure 4.10). Calcium waters are of intermediate acid sensitivity and Magnesium-calcium waters are not sensitive to acidification with very high critical loads (Figure 4.10). This emphasises the sensitivity of waters draining the phyllite and schist facies of the Kuncha and Nuwakot Groups and the Higher Himalayan Crystallines. On this basis, existing geological maps of the HKH may be used to identify areas susceptible to surface water acidification. No detailed information is available describing S deposition fluxes to the HKH region and so exceedance of critical load cannot currently be calculated.

4.4.2 Agriculture

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.

4.5 CONCLUSIONS

1. The chemistry of headwater streams in the Himalaya 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 is 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 Himalaya.

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 Himalaya, 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 potential utility in future field assessments of sensitivity to acidic deposition.

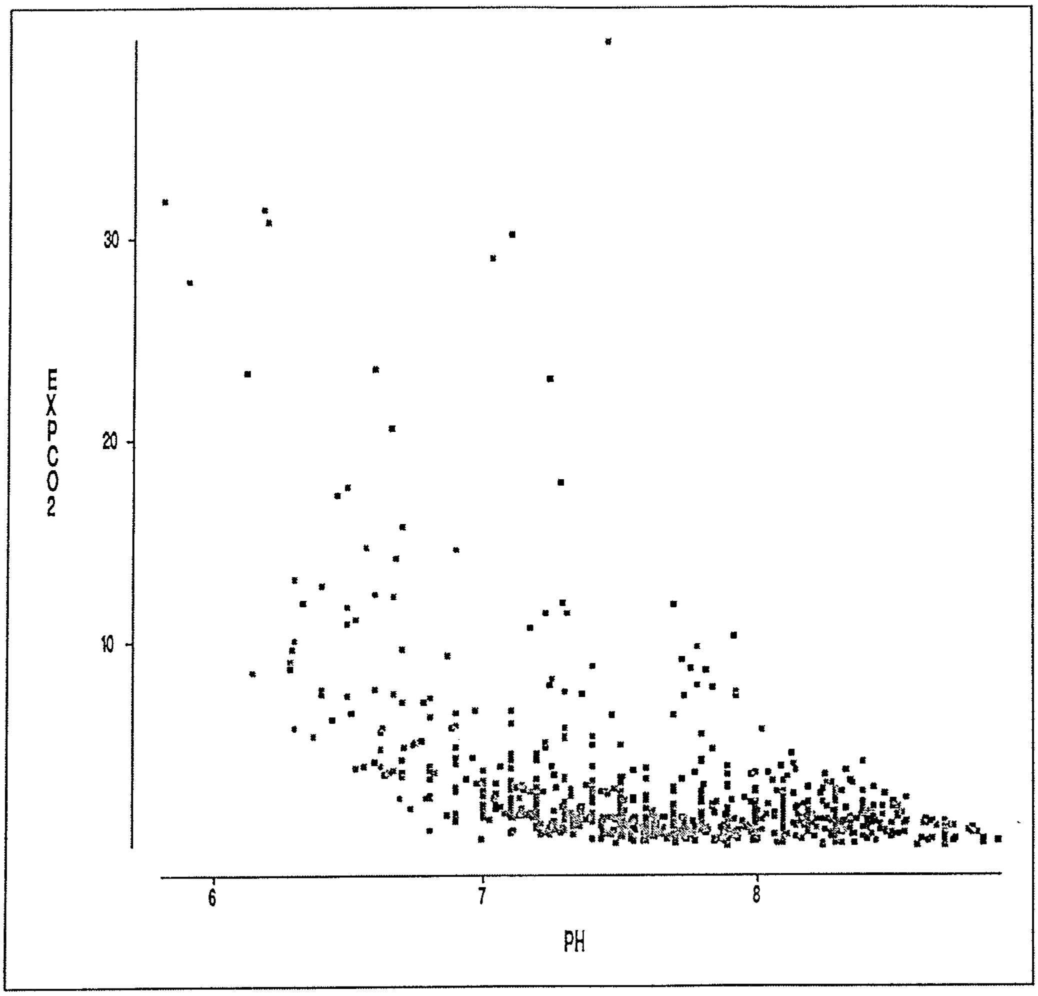


Figure 4.1 *Calculated excess pCO_2 and pH for all samples. Excess pCO_2 greater than 10 indicates a water which has not yet equilibrated with atmospheric CO_2.*

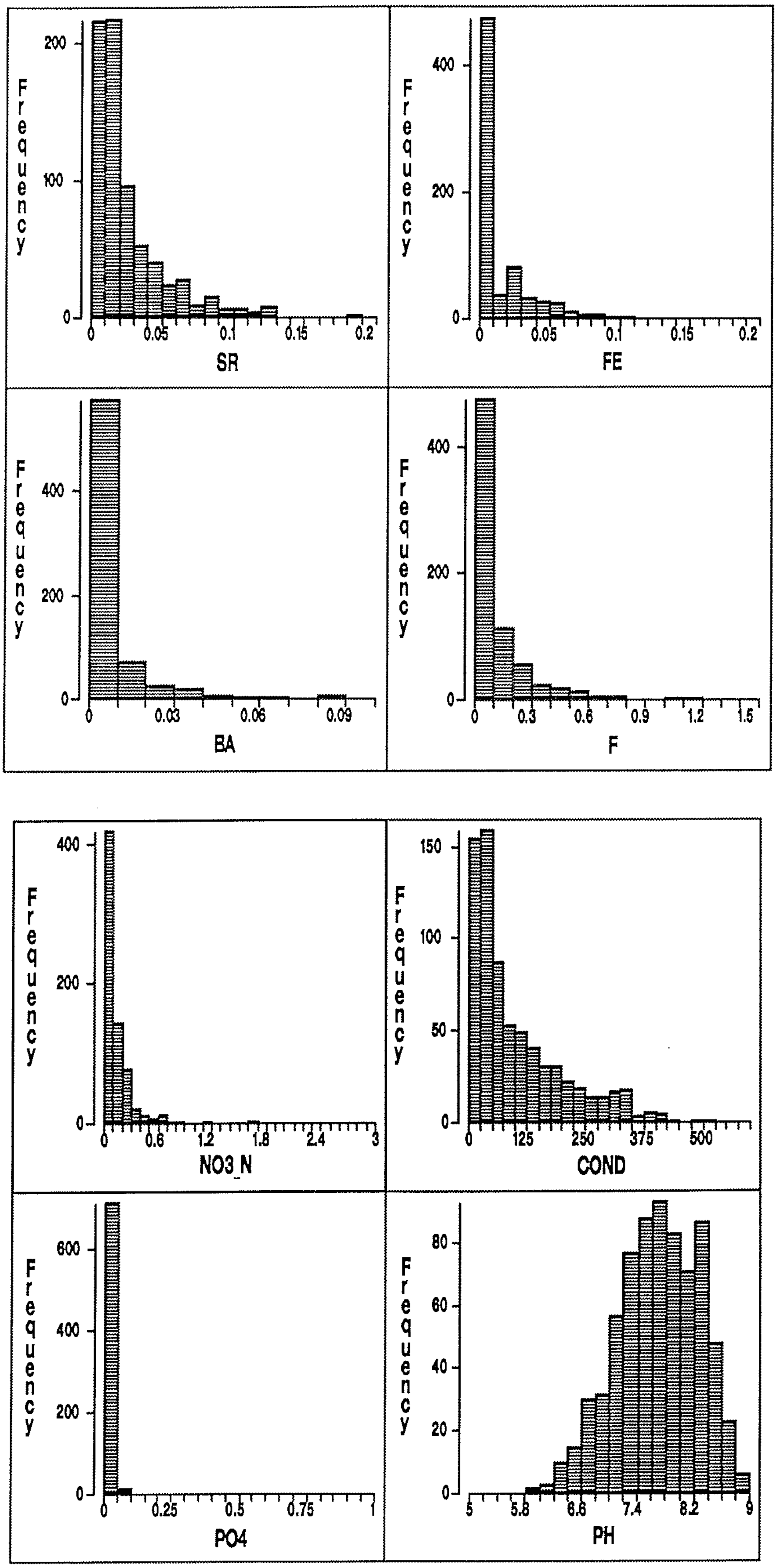


Figure 4.2 *Frequency distribution of all chemistry data.*

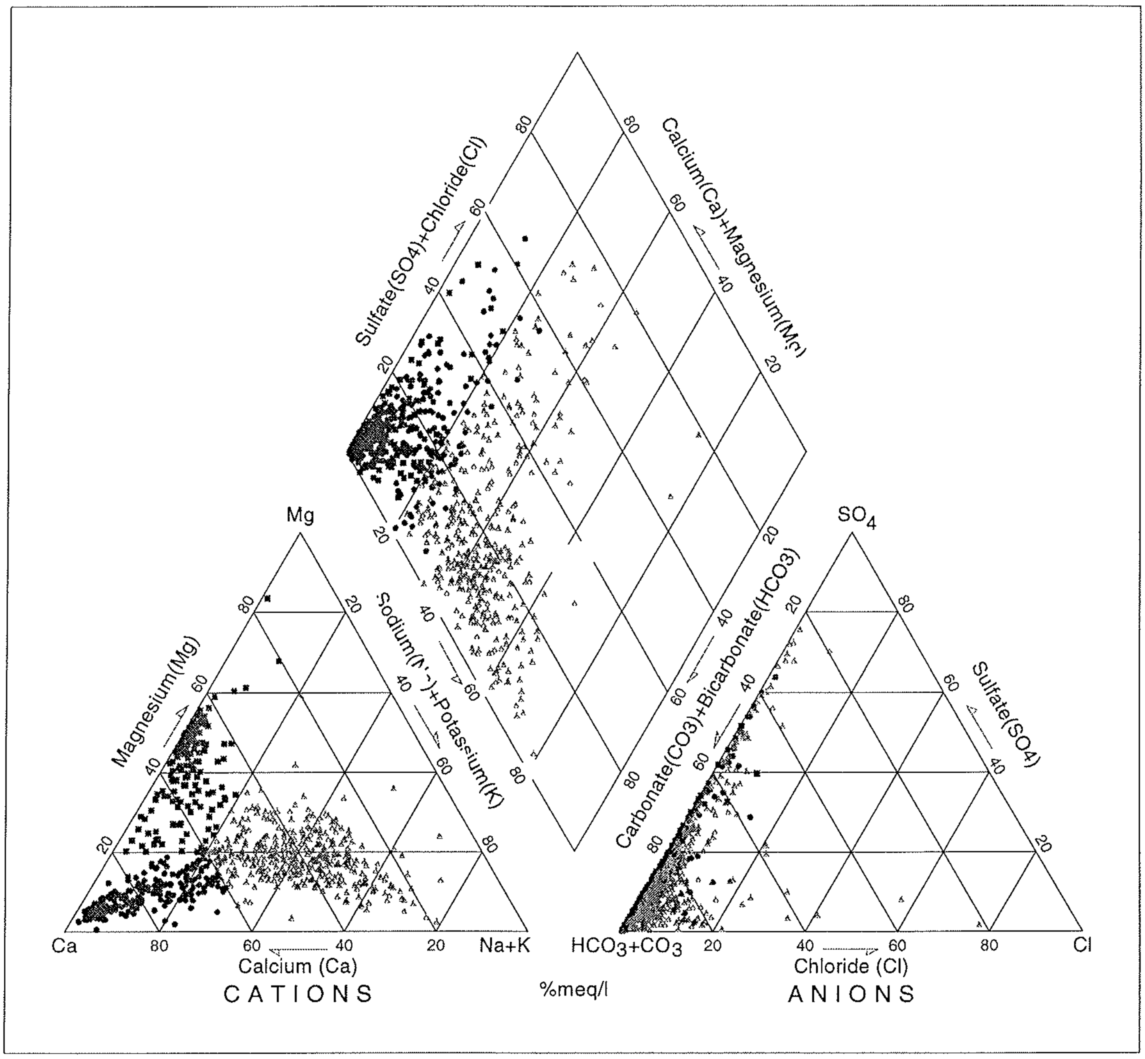


Figure 4.3 *The chemical composition of streams plotted as a function of major cations and anions which in turn reflect bedrock geology. Triangles represent Na-K waters; circles represent Ca waters; and, squares represent Mg-Ca waters.*

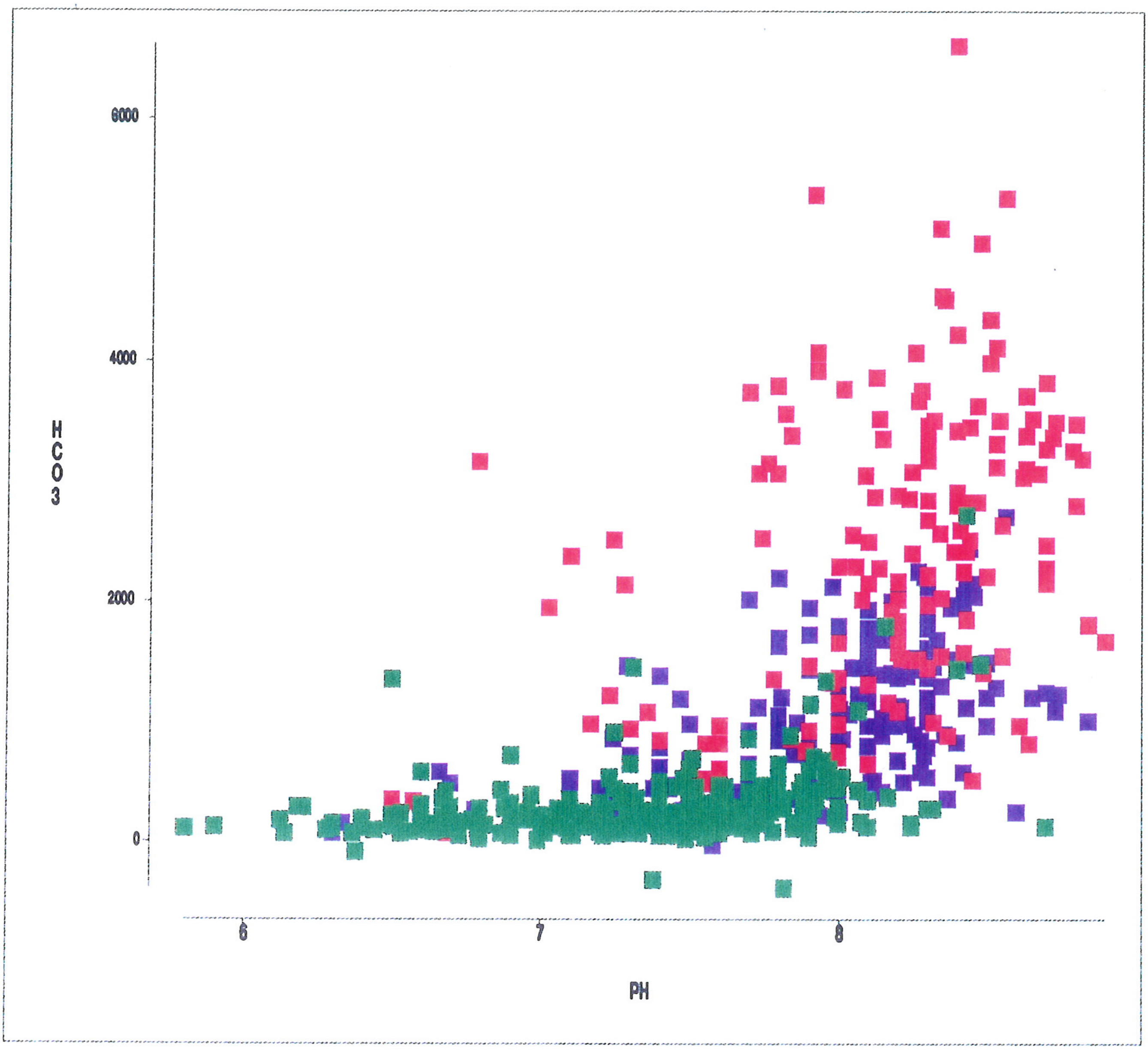


Figure 4.4 *Bicarbonate and pH characteristics of the three water types; red = Ca waters; blue = Ca-Mg waters; and, green = Na-K waters.*

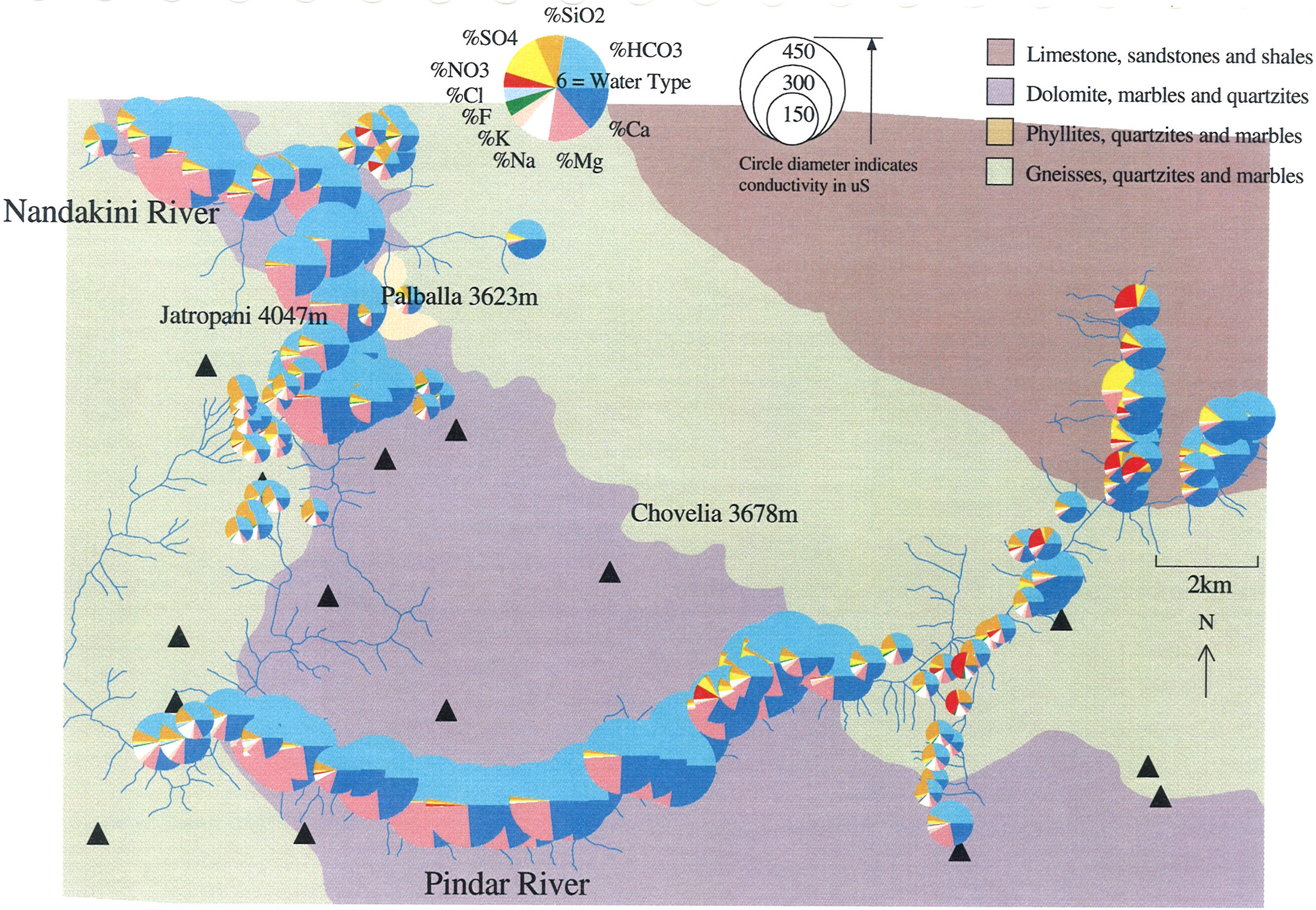


Figure 4.5 *The geochemical classification mapped back onto the geology of the Roopkund and Pindar survey areas. Each sample is represented by a pie depicting percentage concentrations of major ions. The pie is scaled to conductivity. The number 1 to 3 indicates the geochemical classification: 1 = Ca –Mg waters, 2 = Ca waters, 3 = Na –K waters*

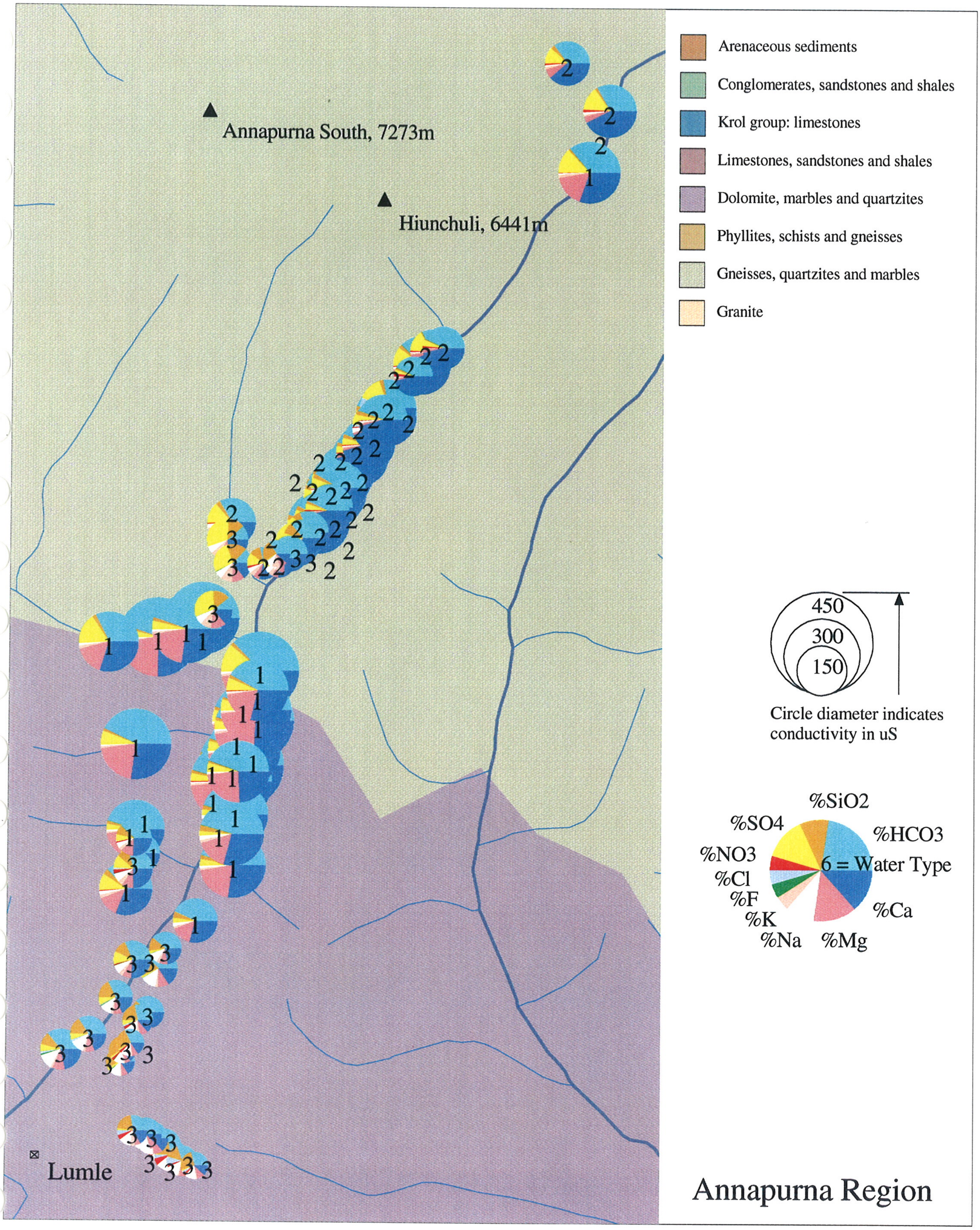


Figure 4.6 *The geochemical classification mapped back onto the geology of the Annapurna survey region*

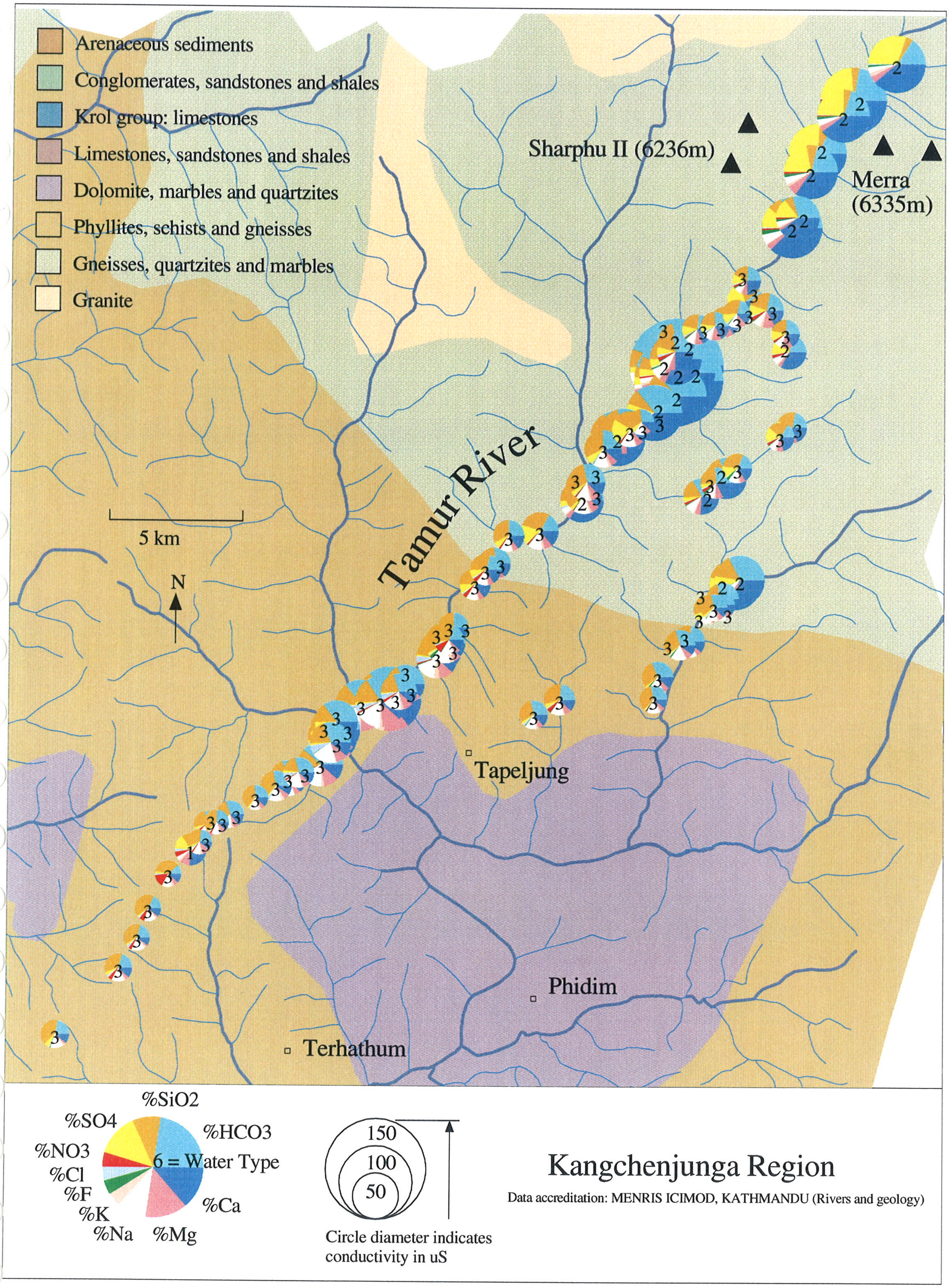


Figure 4.7 *The geochemical classification mapped back onto the geology of the Kangchenjunga survey region*

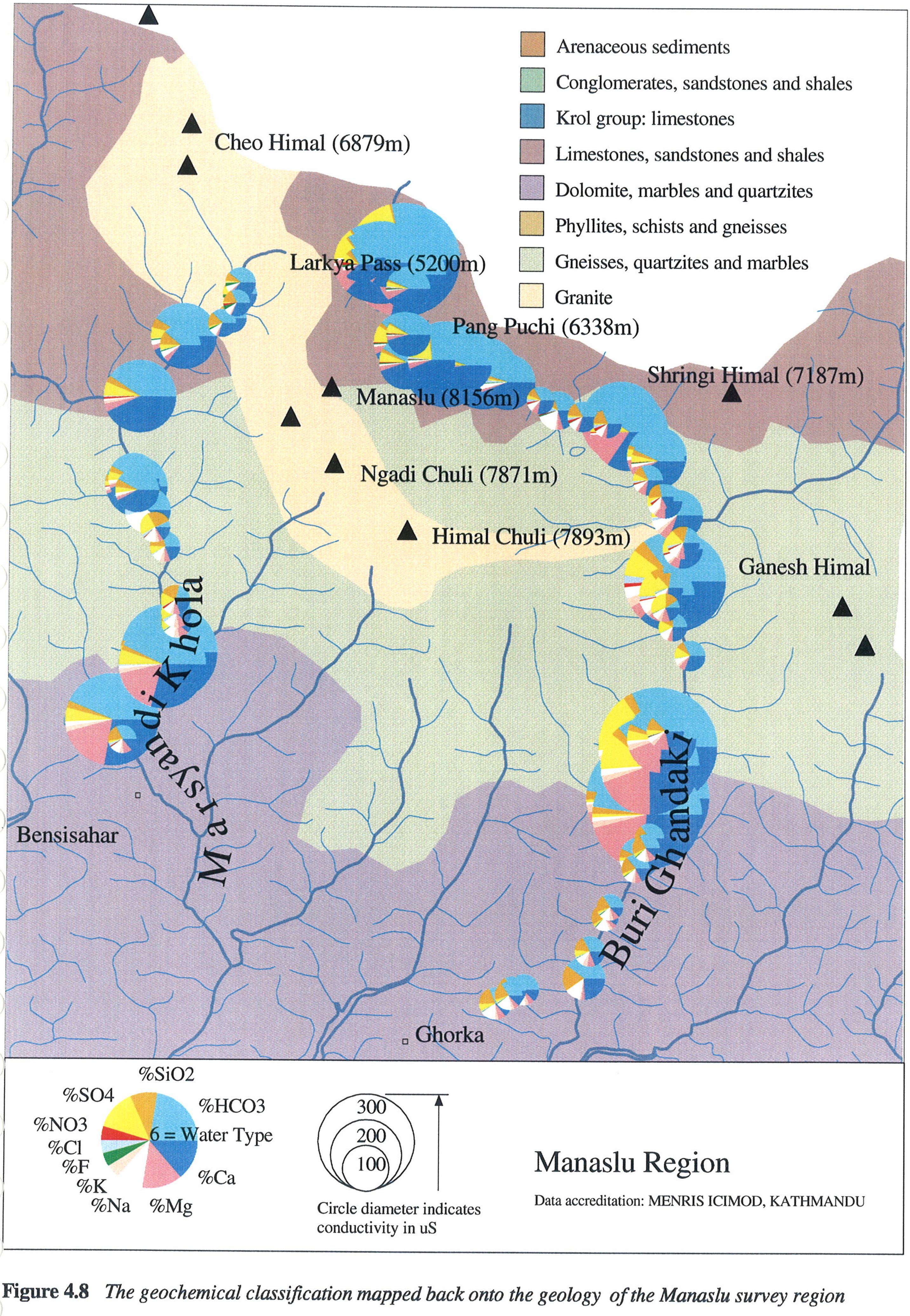


Figure 4.8 *The geochemical classification mapped back onto the geology of the Manaslu survey region*

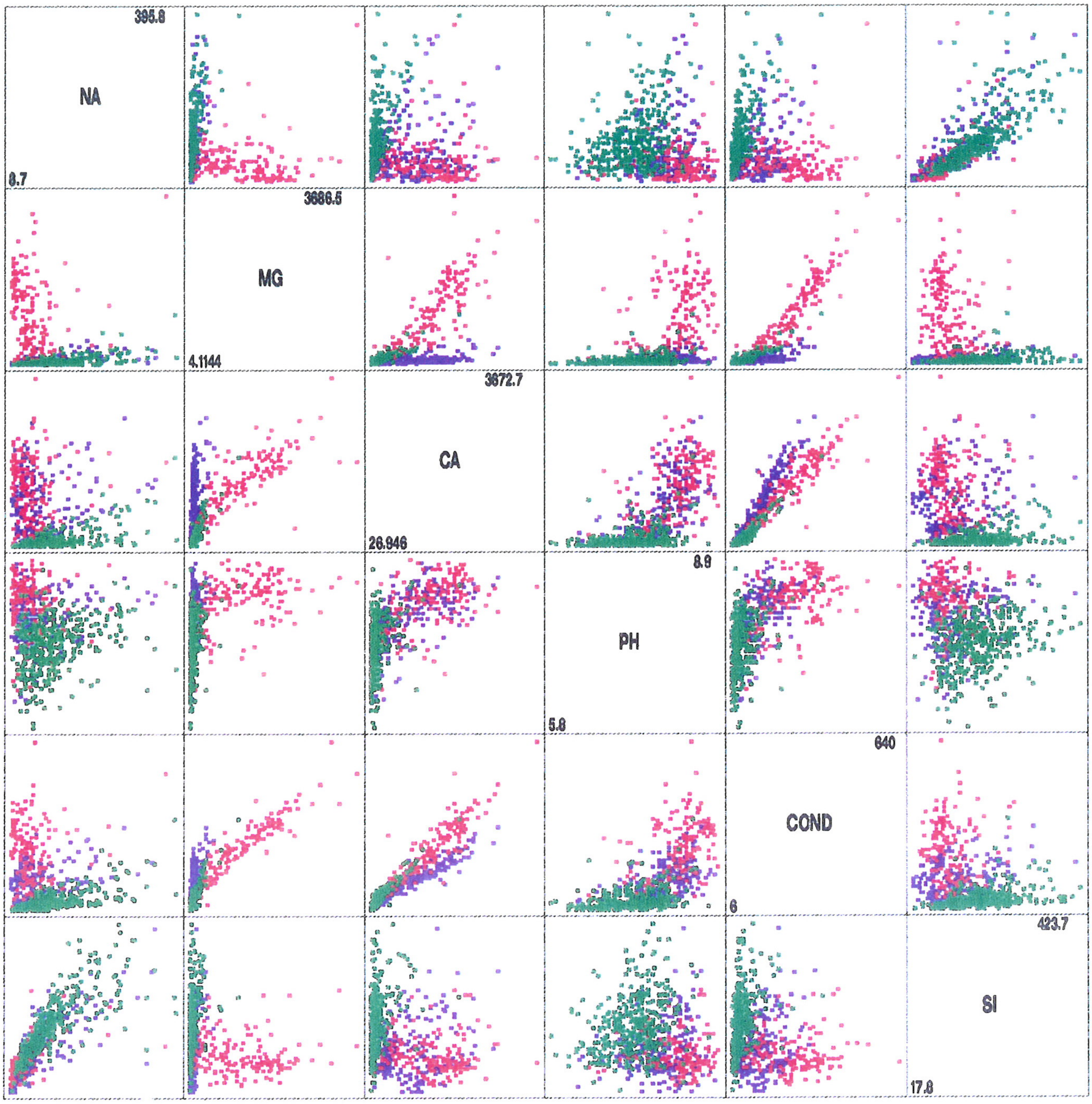


Figure 4.9 *Major ion relationships of the three geochemical water classes: red = Ca-Mg waters; blue = Ca waters and green = Na-K waters. Concentrations are: μeq l^{-1} for Na, Mg and Ca; log_{10} for pH; μg l^{-1} for Si and μS cm^{-1} for conductivity.*

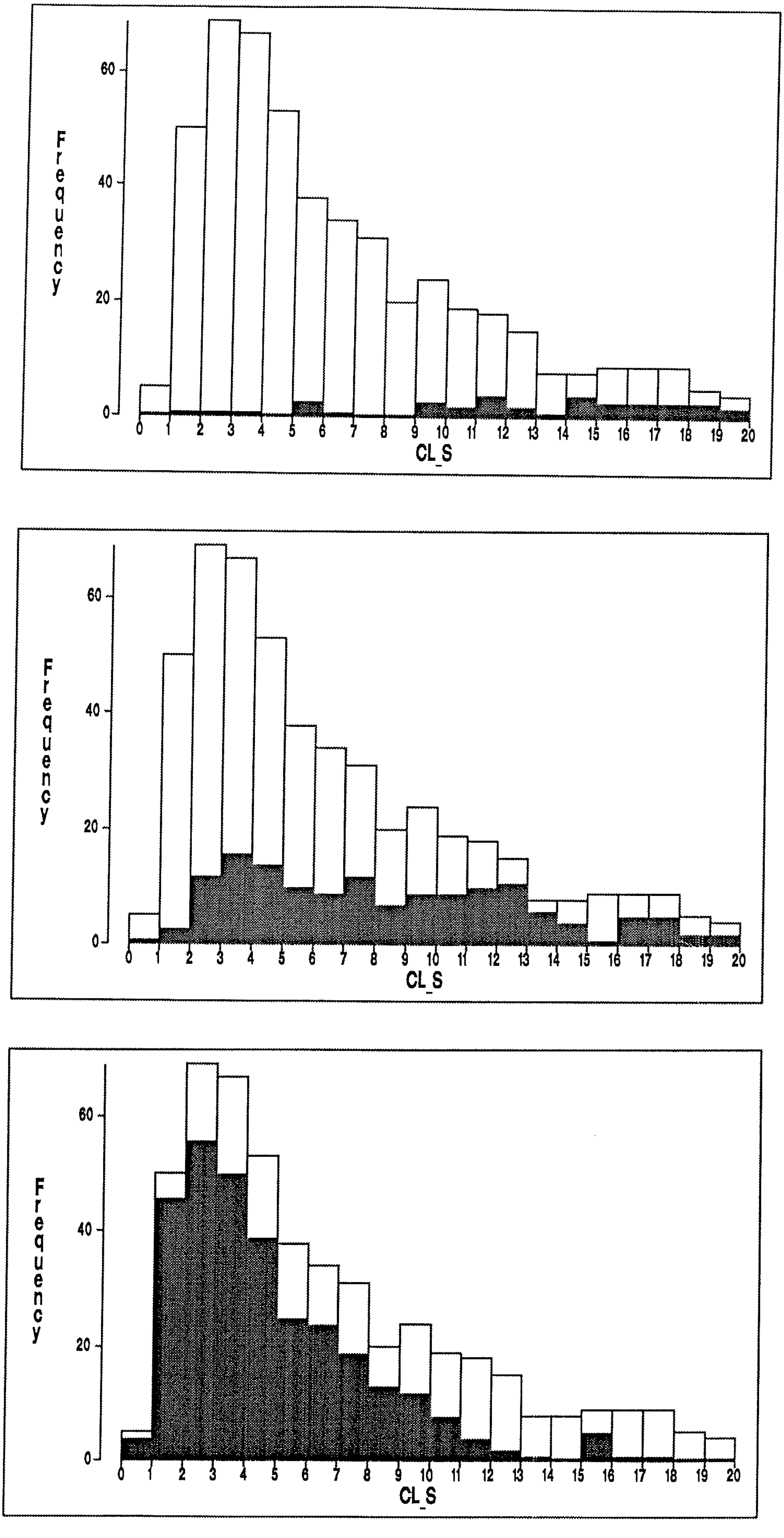


Figure 4.10 *Frequency distributions of calculated critical loads for all stream samples (open bars). Superimposed on this is the frequency distribution of critical loads for the Ca-Mg waters (top), Ca waters (middle) and Na-K waters (bottom). Critical loads greater than 20 keq ha^{-1} yr^{-1} are not included.*

5 River Sediments

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. 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 rivers.

The 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 most challenging task facing geomorphologists in the region. 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 flowing and turbulent which initiates the downstream transport, sorting and abrasion of the sediment particles. First order tributaries 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 river basin sediment loads.

5.1 SAMPLING METHODS

The aim of the coarse sediment surveys 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 have 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 climate, tectonic activity and land use change (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 studies of sediments in the Himalaya 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).

In addition to the main sources, surveys of sediment in the Himalayan region also need to consider the dominant bedrock geology and climate. The limited amount of information on this is a fundamental problem. Six basins were selected to cover the range of geological and climatic conditions found in the Himalaya. In order to characterise the sediment itself, a total of 151 streams were sampled. At each stream site, up to 100 sediment particles, >10 mm in size, were randomly selected and measurements made of the particles' three axes and the diameter of the sharpest corner. This provides an indication of both the size and slope characteristics and roundness, a measure of attrition, of the sediment.

5.2 ANALYTICAL METHODS

The data from the 151 tributary streams in six basins were analysed to provide 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 - three-dimensional shape of particles - where 1 represents a spherical particle and 0 represents a flat particle;

3. Roundness - degree of smoothing by attrition - where 0.1 denotes a highly angular particle and 1.0 denotes a perfectly rounded particle;

4. Flatness - two-dimensional shape of particles - where 1 represents an equi-dimensional particle, the value increasing as the particle becomes more disc-like.

Also using the distribution of the b axis measurement 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 a coarse tail and negative values a fine tail in the distribution.

5.3 SEDIMENT CHARACTERISTICS OF HEADWATER STREAMS

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 of the landslide-impacted tributaries revealed little statistical relationship between the catchment characteristics (land cover, geology, rainfall) 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 contain highly with mobile sediment deposits. The landslide impacted tributaries show similar mean sizes but with more angular, flatter particles which are very poorly sorted.

The data for the non-landslide impacted tributaries in each region (Figure 5.1) illustrate the difference between the locations and suggests regional trends. The distribution of mean b (Figure 5.1a) indicates that from west to east the size decreases to Simikot then increased to Langtang but decreased again to Kanchenjunga; the mean size of the Langtang sediments was more than double that of the Simikot sediments. A regional trend in roundness (Figure 5.1b) is not so clear although there is a large increase in the roundness of particles in the eastern location. The sorting of the sediments is poorest in Simikot and Dunai increasing to the west and east of that location (Figure 5.1c). Flatness generally decreases to the east of Dunai (Figure 5.1d) and the Simikot particles are much less flat than those in either Dunai or Pindar.

Table 5.1 *Summary statistics of the size (mm) and shape of non-landslide sediment particles in the six survey areas (basins) and the landslide impacted catchments.*

	Pindar	Simikot	Dunai	Manaslu	Langtang	Kanchenjunga	Landslide
Mean a	99	073	103	136	162	120	115
Mean b	66	51	64	91	110	83	70
Mean c	36	31	34	51	67	51	37
Sphericity	0.62	0.67	0.59	0.66	0.69	0.67	0.60
Roundness	0.11	-	-	0.16	0.13	0.24	0.10
Flatness	2.68	2.24	2.98	2.59	2.11	2.20	3.27
Sorting	-1.01	-1.19	-1.19	-1.07	-0.89	-0.77	-1.20
Skewness	-0.06	-0.15	-0.09	-0.04	-0.05	-0.01	-0.10

The preceding observations suggest differences in the size of the sediment in the tributary streams between basins. To identify the major groups of variables, a principal component analysis was carried out on the data set including sediment size and shape and catchment land use, from the non-landslide impacted sites. Land cover is 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. The first principal component indicates 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.

The differences in the observed size and shape of the sediment particles in each of the six basins were examined, using the Kruskall-Wallis Test, one found to be highly significant (>99%) for all variables (Table 5.2). However, significant differences between the size and shape parameters are not always found when the tributaries are 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 dominant geology, roundness and flatness show highly significant differences (>99%). 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.

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 for differences in particle size and shape according to geology and land use of the catchment. For the non-landslide catchments (Table 5.3a) basin is a significant (99%) control on mean a, b and c, roundness and flatness, the percentage of barren land has a significant (98%) control on mean a and b while the geology has a significant (99%) control on flatness. For the landslide catchments (Table 5.3b) basin is a significant (99%) control for roundness; there are no significant controls on the remaining size and shape parameters identified by the basin, geology or land use.

To investigate whether certain basins can be grouped and how the basin, land use and geological controls are related, 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 hint 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-Kanchenjunga basins i.e. a distinction between the western basins and the eastern basins.

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

	Basin	% Barren land	Geology
a. Non-landslide catchments			
Mean a	.0001	.0012	.4477
Mean b	.0001	.0122	.5817
Mean c	.0001	.0406	.1133
Roundness	.0001	.4364	.3151
Flatness	.0001	.0489	.0012
Skewness	.6739	.3581	.0632
b. Landslide catchments			
Mean a	.2601	.8913	.7376
Mean b	.1280	.8651	.6950
Mean c	.0912	.8798	.4375
Roundness	.0198	.2540	.3566
Flatness	.1380	.8818	.4057
Skewness	.3066	.1934	.8910

5.4 HYDROLOGICAL CONTROLS ON SEDIMENT CHARACTERISTICS

The results show that there is a dominant difference in the size and shape of particles between basins with lesser differences related to geology and land-use. The main contrast between the six basins is climate, in particular the rainfall regime. Defining the rainfall regime of each basin is difficult because of the paucity of raingauges in the mountain regions. Figure 3.2 shows a generalised distribution of annual rainfall totals for the whole region and Table 5.4 shows the mean annual rainfall totals and numbers of days each year with rainfall greater than 25 mm and greater than 50 mm, based on the gauges located along the survey routes. The data show that the Manaslu, Langtang and Kanchenjunga surveys are in the wetter rainfall regions with the Pindar, Simikot and Dunai 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 and Manaslu) (Figure 5.2a). The sorting, roundness and skewness show a similar pattern.

Table 5.4 *Mean basin rainfall data from the gauges located along the survey routes*

	Pindar	Simikot	Dunai	Manaslu	Langtang	Kanchenjunga
Number of gauges	*	2	2	5	1	3
Annual rainfall, mm	1200*	778	653	2317	1893	1680
Days with rainfall > 25 mm	-	7	5	21	27	17
Days with rainfall > 50 mm	-	1	1	6	2	3

* No raingauge data available - rainfall estimated from the rainfall distribution map (Figure 3.2)

The analysis of rainfall and sediment size and shape indicates that the difference in sediment characteristics between the basins is likely to be due to the rainfall characteristics of the basin. Increasing rainfall up to a value of 1700 - 2000 mm results in increasing size, sorting and roundness due to the greater movement of the sediments. Beyond 1700 - 2000 mm rainfall the size, sorting and roundness apparently 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.

5.5 GEOLOGICAL CONTROLS ON SEDIMENT CHARACTERISTICS

Statistical analysis shows that geology is only a significant control on the size of the c axis, hence the flatness of the particles. Even though a range of bedrock types were sampled, the phyllites, schists 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.

5.6 ANTHROPOGENIC CONTROLS ON SEDIMENT CHARACTERISTICS

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 a major control on sediment characteristics. Barren land is land too steep to cultivate or where the forest cover has 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 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 will be larger.

5.7 CONCLUSIONS

1. The size and shape of the coarse sediments are significantly different between the basins where the surveys were carried out.

2. The main regional contrasts are the rainfall regime with the higher rainfall generating more river flow which increases the competence of the rivers to transport sediment. This explains the larger particles with greater sorting and roundness in the Langtang and Kanchenjunga basins due to the more frequent movement and winnowing of finer material. The basins with very high rainfall totals indicate that the sediment particles are being broken down by high energy river flows.

3. 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 the reduced rates of transport. In regions with rainfall greater than 2000 mm the high energy flood 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.

4. The results do not provide evidence of a strong link between sediment characteristics and land cover or geology. This link is more likely to be established from detailed measurements through time in a single basin. Rainfall, and therefore streamflow, is found to be a significant factor determining the differences in sediment characteristics between the basins.

5. The landslide impacted streams are significantly different to the non-landslide tributaries and the sediment deposits are described as chaotic. Any landslide-impacted tributaries in the wetter regions are highly unstable and mobile as the rivers recover from the impact but in the drier regions the rivers take much longer to recover because of the lower streamflow.

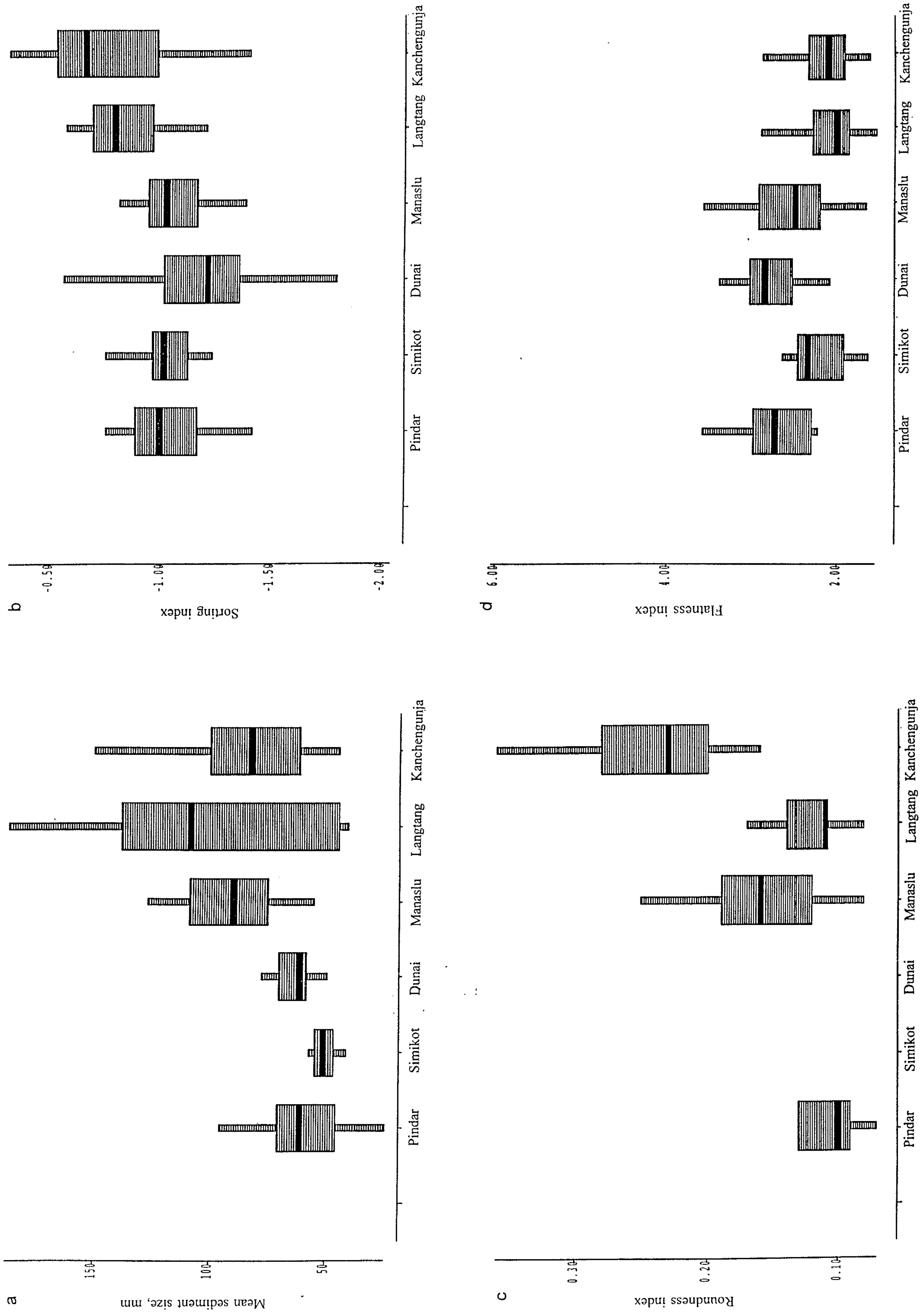


Figure 5.1 *Sediment characteristics of non-landslide impacted tributaries in each region.*

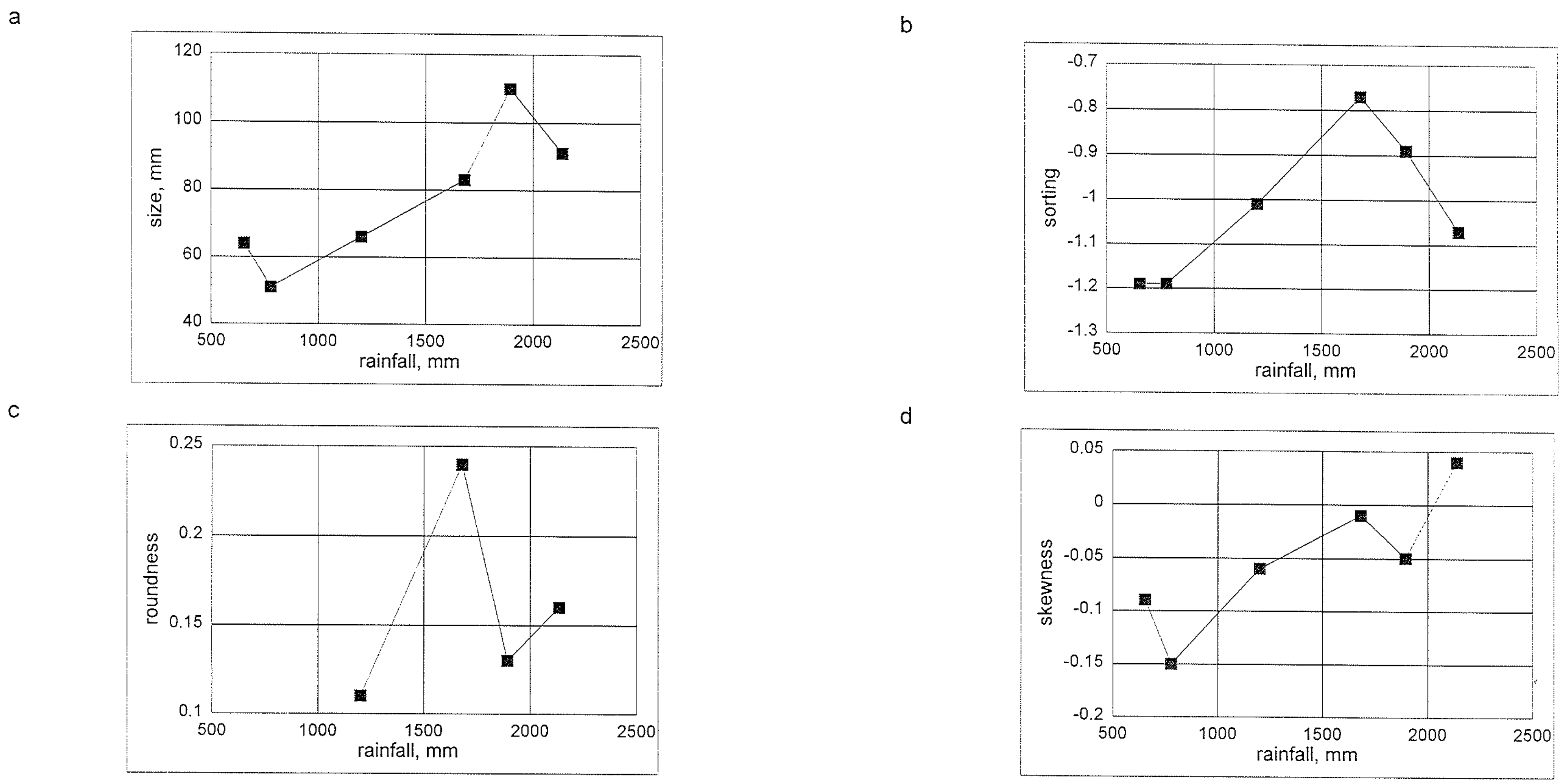


Figure 5.2 *Regional sediment characteristics and regional rainfall totals.*

6 Biology

6.1 OBJECTIVES

The aims of the biological studies were to:

i. Assess biological pattern in a range of groups (as richness, species presence or absence, and community composition);
ii. Relate biological pattern to environmental data;
iii. Assess whether measures from biota and habitat structure might provide indicators of change and status;
iv. Provide a set of baseline data against which future change might be judged.

Together, these elements were seen as central to improving our understanding of influences by natural and anthropogenic features on Himalayan stream ecosystems. The biology focused on four key groups:

i. diatoms	(= siliceous algae; Section 6.4);
ii. bryophytes	(= mosses and liverworts; Section 6.5);
iii. macroinverterbrates	(Section 6.6);
iv. river birds	(Section 6.7)

Research elsewhere has revealed how these groups are sensitive to chemical, physical or biological change in river systems which is liable, not only to reveal effects on biodiversity (Lawton, 1996), but reveal also their value as biological indicators. In addition, because habitat structure is recognised as an important influence on biological pattern, and an important component of biodiversity defined in Rio, detailed measurements of habitat physiography were also made (Section 6.3).

6.2 STUDY SITES

Although the basic study area for this section was identical to that in other parts of this report, biological work was confined for logistical considerations to a sub-set of 180 sites. Thus, all analyses of chemical pattern and habitat structure were confined to this set; the range of values for all physico-chemical measurements across this set is in Table 6.1.

Of the features relevant to biology, semi-natural vegetation includes forests of Sal *Shorea robusta* Gaertn, *Alnus nepalensis* D. Don, Chir *Pinus roxburghii* Sarg and Blue Pines *Pinus wallichiana* A. B. Jacks, Deodar *Cedrus deodara* (D. Don), *Rhododenderon* spp. and *Quercus* spp. At higher altitudes, these are replaced by *Picea smithiana* (Wall.) Boiss and *Abies pindrow* (Lamb), giving way to extensive *Juniperus* and *Berberis* spp. scrub, and eventually alpine scrub, tundra and boulder fields. Local land uses include rough seasonal pasture or subsistence crops of maize, barley, wheat, millet, sugarcane and potatoes grown in mostly rain-fed terraces known locally as *bhari*. Irrigated terracing for rice production, known locally as *khet*, is common at lower altitudes (< c. 2000m); in Nepal alone it covers 1.4 million hectares of land (c. 53% of all agriculture; Donner 1994), representing a major change in catchment character. Types of terracing were not distinguished in our survey since both often co-occur; they often involve applications of dung, urea and other nitrogenous fertilisers, some river diversions, and alterations in vegetation structure. Effects on stream chemistry can include increased solute content (Na, Cl, Si, K, Ca, Mg) due to increased weathering, and increased nutrients due to fertiliser additions (Jenkins *et al*, 1995; Collins and Jenkins, 1996).

Of the sites in this study, 6% had some urban land in their catchments; 33% had terraced agriculture present, 25% having extensive terrace cover; 69% had scrub or rough pasture; 70% had broadleaf or mixed forest; 16% had conifer; 10% had alpine character, and 6% had Sal forest (note that land uses within catchments are not mutually exclusive). These values varied moderately between regions, reflecting for example urban land in the Pindar region; more terracing near Makalu, small amounts of woodland in Manasalu and large amounts of conifer near Simikot (Fig. 6.1).

Tourism, trekking and its associated infrastructure is at much lower volumes in the regions surveyed than in the Annapurna, Everest and Langtang regions of Nepal, which currently receive 89% of visits by trekkers (Donner, 1994).

Further description of the biota of the study areas can be found in other papers (Ormerod *et al*, 1994; 1997; Jüttner *et al*, 1996(b); Rothfritz *et al*, 1997).

Table 6.1 *The range of site attributes recorded during surveys of 180 streams involved in biological work in NW India and Nepal in 1994-96.*

Variable	Minimum	Maximum	Median
Altitude (m)	350	4695	2117
Slope (deg)	1	35	10.0
Channel width (m)	0.4	60	7.0
Water width (m)	0.15	32	3.0
Water depth (m)	0.02	2.2	0.15
Bankfull height (m)	0.02	30	1.5
NO_3 mg/l	0.01	8.8	0.09
PO_4 mg/l	0.02	0.15	0.02
Cl mg/l	0.1	2.8	0.3
Na mg/l	0.2	9.0	1.3
K mg/l	0.04	17.9	1.0
Ca mg/l	0.02	54.0	8.5
Mg mg/l	0.1	26.0	0.9
Si mg/l	0.5	11.5	3.3
pH	6.3	8.7	7.7
Conductivity µS/cm	9	413	62.4

6.3 PHYSICO-CHEMISTRY

Specific methodological descriptions for each group are given in sections 6.5-6.8, but there are important methodological features that apply to the physico-chemical data and underpin all subsequent biological analysis. The most important consideration was to assess whether land use and altitude, both potentially major sources of variation, had any bearing on habitat structure.

We assessed possible effects by terraced agriculture (coded as scarce or absent versus extensive) on habitat and chemical principal components (= variates) at the biological sites using analysis of covariance; altitude was treated as a covariate using general linear modelling procedures in the *MINITAB* statistical package (Minitab, 1995). For chemistry, regional effects were possible in view of east-west geological variation across the Himalaya; to take them into account we coded the 7 regions separately as categories in a crossed analysis with land use, including also altitude as a covariable. In all cases, significant effects were tested against F. Requirements for homogeneity of variance, normality of error distributions and pattern among residuals were checked using protocols recommended by Fry (1993), although the use of principal components as explanatory variables ensured that analytical criteria were always met.

6.3.4 Results: habitat character and effects by land use

The biological sites ranged in altitude from 350 to 4695 m above sea level, with slopes from 1-30°, and channel widths from less than 1 m to 60 m. Water widths on average were only 43% of bank widths, reflecting the braided nature of Himalayan river channels; discharge at the time of sampling occupied only a proportion of the channel typically filled during monsoonal floods (Table 6.1). As expected, terraced catchments (1445 m ± 1030 SD) were at significantly lower altitudes than other catchment types (2436m ± 679 SD).

Orthogonal variates resolved from PCA on 'sweep up' RHS data included, most strongly, a trend from large braided streams with laminar or torrential flow to streams with tree related features and pool-riffle sequences (Sweep PC1); a trend from wide streams with boulders, bedrock, waterfalls and some trees on steep banks to those with gently sloping banks and pebble or gravel substrata (Sweep PC2); a trend from torrential streams with pebbles, riffles, bankside conifers and roots to those with sand, silt, boulders and vegetated side bars (Sweep PC3); a trend from streams with many anthropogenic features (e.g. outfalls, irrigation, diversion, bank modifications, weirs), fine substrata and pools to streams with boulders (Sweep PC4); and a trend from small streams with side or mid-channel bars, riffles, boulders and cobbles to wider streams with silt and undercut banks, often in Sal forest (Sweep PC5; Table 6.2a).

Additional information about habitat structure was provided by the spot-check data, although there was some inter-correlation between Sweep PC1 and Spot PC1 ($r = -0.72$, $P < 0.001$), and between Sweep PC2 and Spot PC2 ($r = -0.54$, $P < 0.001$). Spot PC1 described a trend from streams with various types of channel vegetation (notably bryophytes), leaf litter, complex bank vegetation and fine substrates among boulders to streams with more exposed rocks, boulder and cobble substrate, torrential flow and side or mid bars. Spot PC2 reflected a trend from streams with riffles, finer substrata and earth banks to streams in largely unmodified cascading channels with coarser substrate, channel bryophytes and complex vegetation on the banks, riparian zone and land-use zone. Spot PC3 mostly reflected bank and channel features, along a trend from reinforced section to streams with stable or eroding earth cliffs. Spot PC4 described trends from unmodified channels with glides between bedrock or clay banks to streams with exposed channel boulders, cobbles and earth cliffs. Finally, Spot PC5 reflected variation between cascading streams in bedrock channels to gliding streams with silt and clay banks, often bordered by complex vegetation (Table 6.2b).

Among these habitat variates, Sweep PC 2 (r = 0.50) increased with altitude, with positively scoring sites typically in alpine meadows or boulder fields. Spot PC2 (r = -0.25) and PC3 (r = 0.39) also varied weakly but significantly with altitude, indicating that higher sites had less complex riparian vegetation, riffles rather than cascades, banks of gravel and pebbles rather than boulders or bedrock, and few modifications (Table 6.2a); this combination of features occurred often in braided channels influenced by glaciers.

After accounting for altitudinal effects, there were highly significant differences in habitat character between streams from terraced catchments and others (Table 6.3a). Reduced scores on Sweep PC1, Sweep PC4, and Spot PC2, but increased scores on Sweep PC2, together suggested that agricultural streams were typified by wider channels with mid- or side-bars; riffles over finer substrata rather than cascades over boulders; and banks with small slopes, fewer tree-related features and simplified vegetation structure. Terraced sites had several types of modification in the channel and banks, including diversions for irrigation.

Some of these patterns have been resolved more fully in the sections for each specific organism group by splitting the habitat data into 'catchment', 'bank' and 'channel' features (see below).

6.3.5 Results: chemistry and land use at the biological sites

Reflecting the geological complexity of the Himalaya, stream chemistry varied across a wide range for most determinands: two exceptions were that nitrate concentrations were often low, and phosphate was mostly below detection limits. Base cation concentrations varied widely, often to very low concentrations, but were nowhere associated with low pH or apparent acidification (Table 1).

Strong variates detected by PCA included variations in base cations (PC1) and other major solutes (e.g. Na, Cl, K, Si, SO_4; PC2). Both altitudinal and regional variations were apparent, reflecting for example generally declining base-cation cations from west-to-east across the Himalaya. Once such effects were taken into account, no effects by terracing on chemistry were apparent (Table 6.3b).

Table 6.2 *Major trends in habitat structure from principal components analysis of RHS data from 180 streams in NW India and Nepal in 1994-96. Only variables correlating with each PC at P < 0.001 are displayed, and the percentage of variance explained by each PC is shown in parentheses.*

a) 'Sweep-up' data

PC1(12.1%)	PC2 (9.6%)	PC3 (7.2%)	PC4 (5.4%)
Shade +	Gently sloping banks +	Composite banks +	Boulder substrata +
Fallen trees +	Pebble substrata (%) +	Sand substrata (%) +	
Woody debris +	Gravel substrate (%) +	Vegetated side bars +	Bridges -
Overhanging boughs +		Outfalls +	Pools -
Exposed roots +	Pools -	Boulder substrata (%) +	Gravel substrata (%) -
Bankside trees +	Overhanging boughs -	Silt substrata (%) +	Vegetated point bars -
Underwater roots +	Water depth -		Sand substrata (%) -
Pools +	Torrential flow -	Irrigation/diversion -	Reinforced banks -
Riffles	Exposed bedrock -	Vertical and toe banks -	Culverts -
Exposed bedrock +	Bankside trees -	Cobble substrata (%) -	Unvegetated point bars -
Steep banks +	Vertical banks -	Reinforced banks -	Weirs/dams -
	Water width -	Underwater roots -	Reinforced bank-tops -
Boulder fields -	Exposed boulders -	Riffles -	Resectioned banks -
Water depth -	Waterfalls -	Bank height -	Silt substrata (%) -
Torrential flow -	Margin width -	Torrential flow -	Irrigation/diversion -
Laminar flow -	Channel width -	Pebble substrata (%) -	Outfalls -
Water width -	Boulder substrata (%) -	Unvegetated point bars -	
Margin width -	Bank height -		
Unveg mid-channel bars -			
Unvegetated side bars -			
Channel width -			

b) 'Spot-check' data

PC1(12.1%)	PC2 (9.1%)	PC3 (6.4%)	PC4 (4.8%)
Exposed channel rocks +	Complex riparian veg +	Stable cliffs +	Stable earth cliffs +
Boulder/cob substrata +	Complex catch veg +	Floating vegetation +	Diatoms +
Boulder/cobble banks +	Cascading flows +	Earth banks +	Boulder/cobsubstrata +
Side bars +	Bryophytes +	Eroding banks +	Expd channel rocks +
Torrential flow +	Bedrock banks +	Submerged vegetation +	
Unveg mid-channelbars+	Complex bank veg +		Silty substrata -
Eroding banks +	Bedrock substrata +	Reinforced channel -	Clay banks -
	Boulder/cobble banks	Reinforced banks -	Bedrock banks -
Bedrock substrata -	Vegetated side bars +	Bedrock banks -	Glide flow -
Silt substrata -		Complex catchment veg -	
Complex riparian veg -	Stable earth cliffs -	Dammed channel -	
Floating vegetation -	Culverts -	Pebble/gravel substrata -	
Pebble/gravel substrata -	Resectioned channels -	Resectioned channels -	
Filamentous algae -	Gravel/pebble banks -	Culverts -	
Static flow -	Pebble/gravel substrata -	Resectioned banks -	
Diatoms -	Resectioned banks -		
Emergent reeds - Riffles -			
Amphibious vegetation -	Earth banks -		
Submerged vegetation -			
Emergent herbs -			
Leaf litter -			
Stable earth cliffs -			
Complex bank veg -			
Gravel/sand substrata -			
Bryophytes -			
Riffle flow -			
Earth banks -			

Table 6.3 *Analysis of covariance assessing effects by terraced agriculture on river habitat structure and stream chemistry after accounting for altitude and regional effects using the general linear model.*

a) river habitat structure

Habitat variate	Altitude effects ($F_{1,176}$)	Agriculture effects ($F_{1,176}$)	Least squares mean PC score (with SD)	
			Extensive terrace (n=46)	Other land uses (n=134)
Sweep PC1	0.01^{NS}	5.84*	-0.72 (0.36)	0.40 (0.24)
Sweep PC2	67.4***	6.46*	0.63 (0.28)	-0.28 (0.19)
Sweep PC3	2.41^{NS}	0.37^{NS}	0.18 (0.28)	-0.04 (0.19)
Sweep PC4	10.14	32.84***	-0.99 (0.21)	0.50 (0.14)
Sweep PC5	1.26^{NS}	0.02^{NS}	-0.01 (0.21)	0.02 (0.14)
Spot PC1	0.73^{NS}	0.14^{NS}	0.11 (0.42)	-0.07 (0.23)
Spot PC2	21.6 ***	11.41***	-0.92 (0.32)	0.40 (0.18)
Spot PC3	28.12**	0.36^{NS}	0.20 (0.21)	0.05 (0.11)
Spot PC4	$3.35^{0.1}$	0.01^{NS}	-0.05 (0.26)	-0.02 (0.14)
Spot PC5	9.67*	$2.30^{0.1}$	0.35 (0.25)	-0.10 (0.14)

b) stream chemistry

Chemical variate	Altitude effects ($F_{1,169}$)	Regional effects ($F_{1,169}$)	Agriculture effects ($F_{1,169}$)
PC 1	12.99***	9.95***	0.30^{NS}
PC 2	31.02***	7.77***	1.55^{NS}
PC 3	0.79^{NS}	0.61^{NS}	0.00^{NS}
PC 4	28.52***	9.35***	0.88^{NS}

6.4 DIATOMS

6.4.1 Introduction

Diatoms are the most important microalgae in running waters, whose primary production forms a major energy source in mountain streams. This key trophic position in combination with logistical appeal has made them one of the most powerful indicator group for natural and anthropogenic change in freshwaters. Diatoms occur in all habitats from source to mouth in river ecosystems. They can easily be sampled, permanently preserved and identified up to a detailed taxonomic level due to the extensive taxonomic literature and cosmopolitan distribution. So far they have been used most often as indicators of water chemistry. However, as shown by this study they also provide great potential for the detection of changes in habitat structure and temperature, both major environmental factors contributing to global change in the Himalayan mountains. Prior to this study, however, there had been no comprehensive assessment of widescale pattern in diatom communities in the Himalaya.

6.4.2 Methods

Sampling and identification

Using established methods, epilithic diatoms were brushed from at least 5 stones in unshaded riffles at each site, and preserved in 5% formaldehyde. This habitat is least confounded by siltation and accumulation of dead cells, it occurs in all Himalayan rivers, and it represents communities also present in other stream habitats (Rothfritz *et al,* 1997). In the laboratory the samples were oxidised in H_2O_2 for one week and processed using standard methods involving counts of 400-500 valvae (Jüttner *et al,* 1996a). Diatoms were identified to species following Krammer and Lange-Bertalot (1986-1991), Krammer (1992), Lange-Bertalot and Krammer (1989) and Lange-Bertalot (1993), whose nomenclature we use here. Previous studies in Nepal have shown that identification of many of the taxa is possible using these sources (Jüttner *et al,* 1996b, Rothfritz *et al,* 1997). However, 15% of the taxa could only be attributed as "affinities" to described species, and a further 13% were not described in the literature used. There were also species which could not be consistently separated: the counts for *Diatoma mesodon* and *Diatoma hyemalis* had to be combined as *Diatoma hyemalis* sensu Hustedt, the counts for *Cymbella minuta* and *Cymbella silesiaca* as *Cymbella minuta* sensu Patrick and Reimer.

Data analysis

Chemical and physical habitat variables (including RHS data) were reduced to key variates using separate Principal Component Analysis (PCA) following log-transformation of all except altitude and pH.

Percentage abundances for each diatom species at each site were derived, and species richness, Shannon-Weaver diversity H', and evenness E calculated. For all further analysis species relative abundances were log transformed.

In addition to being one of the few microscopic groups in which patterns of biodiversity can be assessed, diatoms also have recognised value as bioindicators. The British (TDI) and French (IDG) trophic diatom indices were calculated according to Kelly (1996) and Rumeau and Coste (1988). The former is based on species groups, the latter on genera, to monitor trophic status (putatively as filterable reactive P $\approx$ orthophosphate) and organic pollution respectively. The British TDI also lists species which are known to be pollution tolerant.

Spatial patterns in diatom community composition were assessed using Canonical Correspondence Analysis (CCA, CANOCO 3.12; ter Braak, 1988). Environmental variables significantly correlated with species communities were chosen by forward selection. The relationship between diatom diversity, altitude, water chemistry and channel character, between TDI, percentage of pollution tolerant species and water chemistry, and between the TDI and IDG was demonstrated using correlation and regression, respectively. Differences between TDI scores at sites with different impact from terraced agriculture, and between the percentage of pollution tolerant species in the presence of terraced agriculture plus urban development, were assessed by one-way ANOVA (SPSS 6.0.1). One site (S30) with extreme chemistry had a highly atypical diatom assemblage and was excluded from all subsequent analysis, leaving 179 streams in total.

6.4.3 Results

Across all 179 streams 126 diatom taxa were identified. They included species representative of clean hill streams throughout the world from *Achnanthes*, *Cymbella*, *Fragilaria* and *Diatoma*. In addition there were many species from *Cocconeis*, *Gomphonema*, *Navicula* and *Nitzschia*, some of which are characteristic of enriched or even polluted conditions (Table 6.4).

All the diatom figures are colour coded relative to the map of the study area (Figure 6.2). There were marked variations between sites in assemblage composition which reflected apparently orthogonal variations in altitude, water chemistry and habitat character (Fig. 6.3); Whereas some regions had distinct physico-chemical character, on the whole diatom assemblages varied more across region than between regions (Fig. 6.4).

Increasing altitude was accompanied by increased relative abundance of *Gomphonema parvulum* v.1, *Fragilaria pinnata*, *Cymbella laevis*, *Amphora pediculus* and *Gomphonema rosenstockianum*. Chemical variations appeared to reflect distinct but separate effects by acid-base status (water chemistry PC1) and other solutes such as Na, Si, Cl and K (water chemistry PC2); decreasing base status was associated with increasing abundances of *Achnanthes siamlinearis*, *Navicula heimansioides*, *Achnanthes subhudsonis*, aff. *Gomphonema clevei*, and a hitherto undescribed *Navicula* species, that was widespread in streams of this type (Fig. 6.5). Increase in water chemistry PC2 was accompanied by increasing abundances of *Achnanthes exigua*, *Navicula pupula*, *Nitzschia palea*, *Navicula seminulum*, *Navicula decussis*, *Navicula minima* and *Navicula atomus*.

Changes in channel character, reflecting a trend from larger streams with coarse substrata to smaller streams with a pool-riffle sequence and finer substrata, provided the second most important correlate with assemblage composition. This trend was accompanied by increases in *Achnanthes lanceolata ssp. frequentissima*, *Navicula lundii*, *Fragilaria pinnata* and *Nitzschia linearis*.

Whereas the forgoing patterns illustrated how site to site change in assemblage composition contribute to biological diversity across the Himalayan mountains, spatial variations in richness or diversity were less marked. Across all regions diversity was not strongly correlated with altitude or stream chemistry; however in two regions diversity increased moderately but significantly with decreasing base status (Fig. 6.6a,b). By far the strongest correlate with diversity was channel character, due to higher values in small streams with pool-riffle sequence and finer substrata (Fig. 6.7a). These were particularly common in the Dunai region (coded 4 on Fig. 6.2 and 6.7b).

Important results arose from the calculation of trophic diatom indices (TDI and IDG) and assessments of the number of pollution tolerant species at each site. Both trophic diatom indices varied significantly with water chemistry PC2 (increase in Na, Si, Cl, K), although the relationship was stronger in the British TDI (Fig. 6.8). Probably this reflects the use of species groups in the latter defined on the basis of water quality features other than organic enrichment. In turn both water chemistry PC2 and the trophic diatom index varied significantly between sites grouped according to whether they had no, intermediate or extensive terraced agriculture on their catchment (Fig. 6.9). Increased Na, Si, Cl and K have been previously detected in agricultural catchments in Nepal due to mineral weathering or salinisation (Jenkins *et al*, 1995). By contrast, increased P or N concentrations have not so far been detected. Nor were there increased P or N at sites with increased TDI values. In Nepal, therefore, higher TDI in agricultural catchments might reflect increased nutrient load rather than increased aqueous nutrient concentrations; this contrasts with findings in Britain (Kelly and Whitton, 1995) and illustrates the real value of biological indicators in detecting effects not measurable by chemical analysis.

The percentage contribution by diatom species tolerant of organic pollution varied less clearly than TDI with water chemistry or agriculture. However, their percentage contribution did vary highly significantly between land use categories defined as terraced agriculture plus urban development (Fig. 6.8, 6.9). Almost certainly such patterns reflect inputs of organic material from animal dung or human sewage. Together, changes in TDI values and contributions by species tolerant of organic enrichment near to urban or agricultural land at around 30% of the sites show how anthropogenic activity in the Himalaya has probably altered the quality of primary producers in river food webs.

Table 6.4 *Diatom species from 179 Himalayan streams*

Achnanthes biasolettiana Grunow
Achnanthes bioretii Germain
Achnanthes chlidanos Hohn & Hellermann
Achnanthes clevei v. clevei Grunow
Achnanthes conspicua Mayer
Achnanthes exigua Grunow
Achnanthes imperfecta Schimanski
aff. *Achnanthes joursacense*
Achnanthes laevis Østrup
Achnanthes lanc. ssp. frequentissima Lange-Bertalot
Achnanthes lanc. ssp. lanc. var. lanceolata (Brébisson) Grunow
Achnanthes lanc. var. rostrata + ssp. biporoma (Østrup) Hustedt + (Hohn & Hellermann) Lange-Bertalot
Achnanthes lanc. ssp. rostrata v.1
Achnanthes minutissima Kützing
Achnanthes montana v. montana Krasske
Achnanthes oblongella Østrup
Achnanthes rupestoides Hohn
Achnanthes siamlinearis Lange-Bertalot
Achnanthes subatomoides (Hustedt) Lange-Bertalot & Archibald
Achnanthes subhudsonis Hustedt
Achnanthes undata Meister
Achnanthes spec.1
Achnanthes spec.2
Amphora inariensis Krammer
Amphora montana Krasske
Amphora pediculus (Kützing) Grunow
Anomoeoneis vitrea (Grunow) Ross
aff. *Caloneis bacillum*
Cocconeis placentula Ehrenberg
aff. *Cocconeis pseudothumensis*
Cymbella affinis Kützing
Cymbella laevis Naegeli
Cymbella microcephala Grunow
Cymbella minuta sensu Patrick & Reimer
Cymbella spec.1
Cymbella obscura Krasske
aff. *Cymbella reichardtii*
Cymbella sinuata Gregory
Cymbella tumida (Brébisson) Van Heurck
Cymbella turgidula Grunow
Denticula kuetzingii Grunow
Diatoma hyemalis sensu Hustedt
Didymosphaenia gemirata (Lyngbye) M. Schmidt
Epithemia spec.1
Eunotia minor (Kützing) Grunow
Eunotia muscicola v. tridentula Nörpel + Lange-Bertalot
Fragilaria arcus (Ehrenberg) Cleve
Fragilaria bidens Heiberg
Fragilaria brevistriata Grunow
aff. *Fragilaria brevistriata*
Fragilaria capucina Desmazières
Fragilaria construens v. construens Ehrenberg (Grunow)
aff. *Fragilaria construens*
Fragilaria delicatissima (W. Smith) Lange-Bertalot
Fragilaria leptostauron (Ehrenberg) Hustedt
Fragilaria pinnata Ehrenberg
Fragilaria ulna (Nitzsch) Lange-Bertalot
Fragilaria spec.1
Fragilaria spec.2
Fragilaria spec.3
Gomphonema angustatum (Kützing) Rabenhorst
aff. *Gomphonema clevei*
Gomphonema minutum (Agardh) Agardh
aff. *Gomphonema olivaceum v. minutissimum*
Gomphonema parvulum (Kützing) Kützing
Gomphonema parvulum v.1
Gomphonema rosenstockianum Lange-Bertalot & Reichardt
Gomphonema spec.1&2
Gyrosigma scalproides (Rabenhorst) Cleve
Navicula absoluta Hustedt
Navicula atomus (Kützing) Grunow
aff. *Navicula bryophila*
Navicula confervacea Kützing
Navicula contenta Grunow
Navicula cryptocephala Kützing
aff. *Nav. cryptotenella*
Navicula decussis Østrup
Navicula heimansioides Lange-Bertalot
Navicula ignota v. acceptata (Hustedt) Lange-Bertalot
Navicula lundii Reichardt
Navicula microcari Lange-Bertalot
Navicula minima Grunow
Navicula minuscula Grunow
aff. *Nav. minuscula*
Navicula mutica v. mutica Kützing
Navicula notha Wallace
aff. *Navicula parabilis*
Navicula pupula Kützing
aff. *Navicula reichardtiana*
Navicula schroeterii Meister
Navicula seminulum Grunow
Navicula soehrensis Krasske
Navicula subminuscula Manguin
Navicula subrotundata Hustedt
Navicula vandamii Schoeman & Archibald
aff. *Navicula venerabilis*
Navicula viridula (Kützing) Ehrenberg
Navicula spec.1
Navicula spec.2
Navicula spec.3
Navicula spec.4
Navicula spec.5
Navicula spec.6
aff. *Nitzschia agnita*
Nitzschia amphibia f. amphibia Grunow
Nitzschia angustiforaminata Lange-Bertalot
Nitzschia dissipata (Kützing) Grunow
Nitzschia fonticola Grunow
Nitzschia frustulum (Kützing) Grunow
Nitzschia gracilis Hantzsch
Nitzschia hantzschiana Rabenhorst
Nitzschia hantzschiana v.1
aff. *Nitzschia inconspicua*
Nitzschia linearis (Agardh) W. Smith
Nitzschia palea (Kützing) W. Smith
aff. *Nitzschia paleacea*
Nitzschia perminuta (Grunow) M Peragallo
Nitzschia sigma Sippe falsche
aff. *Nitzschia sigma*
Nitzschia sinuata v. delognei (Grunow) Lange-Bertalot
aff. *Nitzschia sublinearis*
Pinnularia mesolepta (Ehrenberg) W. Smith
Stauroneis anceps Ehrenberg
Surirella angusta Kützing
Surirella spec.1

Only species which appeared with ≥ 1% relative abundance in at least one sample are listed.

6.5 BRYOPHYTES

All analysis of the bryophyte material, and analysis of the bryophyte data, was carried out in partnership with the New Zealand Institute of Water and Atmosphere. The full description of the results is being published separately in the journal *Freshwater Biology,* of which a pre-printed copy is enclosed (Appendix 2).

The bryophyte study was based on a sub-set of 108 streams, and a total of 44 bryophyte taxa. Among these, mosses were dominant (38 taxa), with only 6 liverworts collected. The most diverse genera were *Fissidens* and *Rhynchostegium* (5 species each), and *Philonotis* (4 species).

Principal conclusions from the bryophyte study were as follows:

i) Community composition and cover in bryophytes varied highly significantly with altitude, streambed stability and base-richness; there were also effects by riparian land use. Cover was greatest in streams at low to middle altitude with steep slopes (> 15 deg), high stability and low conductivity (< 60 $\mu S\ cm^{-1}$); at such sites communities were dominated by two *Isopterygium* spp, two *Philonotis* spp., *Mnium punctatum* and Lejeunaceae.

ii) Richness (as numbers of taxa), by contrast, increased significantly but weakly at high altitude and moderate stability, where streams were dominated by *Eurynchium praelongum*, *Rhynchostegium* spp., *Fissidens grandifrons* and *Hygroamblystegium* spp.

iii) Both richness and cover were lowest in unstable streams at low altitude, often where terracing was a major land use.

iv) Together, these data illustrate that patterns in bryophyte community composition between sites of different character are an important contributor to biodiversity in Himalayan streams. Reductions in both richness and cover at unstable and possibly disturbed sites illustrates the potential to use bryophytes as indicators of catchment conditions; relationships between community composition and acid-base status also show how they might indicate chemical change.

6.6 INVERTEBRATES

Macroinvertebrates are a key feature of studies of stream ecosystems, for example providing an indication of quality, ecosystem status, and providing a major food source for important vertebrates. There have been few assessments of their communities in Himalayan streams except those stemming from our previous investigations (Rundle *et al,* 1993; Ormerod *et al,* 1994; Brewin and Ormerod, 1994; Brewin *et al,* 1995).

6.6.1 Methods

Macroinvertebrate samples were collected at a point directly adjacent to the water chemistry sample site at all 180 streams sampled for biology between October and November in 1994-1996. At each site, one standardised kick sample of 2 minute duration was collected from a riffle area (net aperture = 0.23 x 0.25 m; mesh size = 0.9 mm). To reduce the overall sample size for transportation back to the UK, the animal and organic material was elutriated from the heavier mineral sediments by repeated floatation and separation. The mineral matter was then sorted before being discarded to ensure that all animals had been removed and the remaining organic and animal material was placed in labelled HDPE bottles and preserved on site in 70% alcohol solution. In the laboratory, each sample was sorted in a white tray until all animals had been removed, which were then identified and counted. With the exception of Anisoptera, Zygoptera and a few non-insect taxa, invertebrates were identified to family level (Table 6.5). Further taxonomic penetration was prevented by the unavailability of more detailed generic or species specific taxonomic information for immature stages of invertebrates from this region of the world. However, invertebrates could be reliably identified to family level using a range of keys and literature from other regions, primarily from North American (e.g. Merritt and Cummins, 1984).

Data analysis

As with the physico-chemical data, the invertebrate data were complex, reflecting the abundance, or presence/absence of a range of different taxa at each site. Therefore, in order to describe spatial patterns in invertebrate communities and reduce the data into units which could be related to environmental variables, simple indices of taxon richness of all aquatic invertebrates and the taxon richness within the principle insect orders were derived for each site. These indices were used in correlations to indicate relationships with environmental variables, including site altitude, water chemistry PCs and habitat PCs, and in analysis of variance (ANOVA) to investigate significant differences between regions and land use types.

Relationships between invertebrate data and environmental variables were further assessed by partial correlation. This allowed the often strong influence of site altitude to be factored out of relationships between other variables and involved the correlation of the residuals from linear regression analysis between site altitude and the other variables. These partial correlations indicated significant relationships between invertebrates and environmental variables when altitude was held constant. Similarly, differences in the measures of invertebrate communities between land use types were assessed independently of site altitude by using a mixed general linear model (GLM) which included altitude as a covariate.

Multivariate analysis was also used to reduce the complexity or variation in invertebrate communities in to units that could be related to site attributes. These techniques have been widely used to assess the effects of environmental variables on macroinvertebrates (e.g. Wade *et al*, 1989; Rutt *et al*, 1990).

Classification

The classification of sites according to species composition was carried out by two way indicator species analysis (TWINSPAN; Hill, 1979). Classification by TWINSPAN arranged sites into hierarchical groups on the basis of their taxonomic composition, so that sites which have similar macroinvertebrate fauna were assigned to the same group. TWINSPAN classification was weighted using the 'psuedospecies' option according to three logarithmic abundance categories (1, 10, 100 & 1000). Differences in water chemistry, the measures of catchment character and stream habitat between the TWINSPAN site groups were assessed by analysis of variance (ANOVA).

Ordination

The ordination of invertebrate data involved both detrended correspondence analysis (DCA; CANOCO version 3.12) and Canonical Correspondence Analysis (CCA; CANOCO version 3.12; ter Braak 1990a). These techniques were used to arrange sites into an objective order along orthogonal axes, so that sites with a similar taxonomic composition occur most closely together. In all ordination analysis species data were $\log_{(x+1)}$ transformed, and rare species were downweighted to minimise their influence (ter Braak, 1990a).

For DCA, the major gradients in invertebrate data were identified independently of environmental data. Site scores along the DCA axes were used in correlations to assess relationships between invertebrates and environmental variables, including the chemical and RHS principle components. In this analysis detrending was by segments (ter Braak, 1990b).

CCA, in contrast, is a direct gradient ordination technique which identifies axes in species data that are constrained by linear combinations of environmental variables (ter Braak, 1990a). Therefore, the resulting direction and length of the environmental gradients in relation to the species axes can indicate the relative strength and direction of influence of individual environmental variables in the structuring of invertebrate communities. The environmental variables to be included in CCA were first identified by the forward selection procedure. This produced a subset of variables which explained the largest proportion of the variance in invertebrate data. The amount of variance explained by individual variables and the resulting individual CCA axes were tested for statistical significance with the Monte Carlo permutation tests (ter Braak, 1990a).

6.6.2 Results

Faunal composition

A total of 97 macroinvertebrate taxa were identified from the 180 streams surveyed for biology between October and November in 1994-1996 (Table 6.5). Invertebrate communities from all regions were dominated by larval aquatic insects, principally Ephemeroptera (36% of individuals), with Trichoptera, Diptera, Plecoptera and Coleoptera each comprised between 10 and 23% of the invertebrates at all sites (Fig. 6.10). Of these, the Trichoptera, Diptera and Coleoptera orders were represented by the greatest numbers of families (Fig. 6.11). The most widespread and abundant family was the Baetidae (Ephemeroptera) which occurred at 98% of all sites (Table 6.5 and 6.6). Other widespread and abundant invertebrate taxa which occurred at over 75% of sites and contributed greater than 5% to the total number of individuals included; Heptageniidae, Nemouridae, Hydropsychidae, Elminthidae and Chironomidae. Other common taxa which were occurred at more than 50% of the sites, included; Ephemerellidae, Perlidae, Lepidostomatidae, Rhyacophilidae, Philopotamidae, Anisoptera, Simuliidae and Tipulidae (Tables 6.5 and 6.6).

Table 6.5 *Frequency of occurrence of macroinvertebrate taxa at 180 sites in the Himalaya.*

Taxa	Frequency	Taxa	Frequency
Ephemeroptera		Odonata	
Baetidae	176	Anisoptera	92
Ephemerellidae	100	Zygoptera	40
Heptageniidae	163		
Ephemeridae	11	Coleoptera	
Siphlonuridae	8	Psephenidae	29
Caenidae	44	Elminthidae	134
Prosopistomatidae	1	Dytiscidae	22
Leptophlebiidae	25	Hydrophilidae	73
		Gyrinidae	12
Plecoptera		Hydraenidae	22
Perlidae	106	Noteridae	2
Nemouridae	139	Scirtidae	24
Chloroperlidae	22	Ptilodactylidae	4
Peltoperlidae	27		
Leuctridae	12	Diptera	
Perlodidae	53	Simuliidae	129
Capniidae	18	Chironomidae	150
Taeniopterygidae	32	Tipulidae	162
		Tabanidae	33
Trichoptera		Blephariceridae	14
Hydropsychidae	145	Athericidae	58
Rhyacophilidae	143	Psychodidae	34
Stenopsychidae	68	Dixidae	24
Philopotamidae	106	Ceratopogonidae	15
Psychomyiidae	12	Deuterophlebiidae	5
Polycentropodidae	26	Stratiomyidae	13
Glossosomatidae	81	Empididae	29
Odontoceridae	4	Ephydridae	1
Leptoceridae	28	Rhagionidae	7
Limnephilidae	84	Syrphidae	2
Uenoidae	27	Nymphomyiidae	1
Brachycentridae	52	Muscidae	4
Hydroptilidae	19	Thaumalidae	1
Lepidostomatidae	108	Dolichopodidae	6
Goeridae	9		
Hydrobiosidae	34	Miscellaneous	
Sericostomatidae	4	Osmylidae	13
Ecnomidae	1	Corydalidae	44
Helicopsychidae	8	Oligochaeta	71
Phryganeidae	6	Planariidae	61
Calamoceratidae	6	Collembola	5
Beraeidae	1	Ostracoda	4
Unidentified trichopteran	4	Potamonidae	15
		Hydracarina	13

Table 6.5 *(continued)*

Taxa	Frequency	Taxa	Frequency
Hemiptera		Hirudinea	2
Corixidae	2	Sphaeriidae	5
Naucoridae	21	Lymnaeidae	1
Gerridae	4	Hydrobiidae	7
Veliidae	18	Planorbidae	1
		Nematomorpha	3
		Pyralidae	8

Table 6.6 *Relative abundances of macroinvertebrate taxa recorded at sites from 7 regions of the Himalayas between 1994-1996, as a percentage of the total fauna of each region. Only taxon comprising greater than 0.01% of the fauna from all sites are shown.*

Region	**All**	**R**	**P**	**S**	**D**	**Man**	**Mak**	**K**
No. sites	**180**	**19**	**24**	**23**	**20**	**30**	**32**	**32**
Ephemeroptera								
Baetidae	xxxxx	xxxxxx	xxxxx	xxxx	xxxx	xxxxxx	xxxxx	xxxxx
Ephemerellidae	xxx	xxx	xxx	xxxx	xx	xxx	xxx	xxx
Heptageniidae	xxxx	xxxx	xxxx	xxxx	xxx	xxxx	xxxx	xxxx
Ephemeridae	o	o		o	o		o	o
Siphlonuridae	x			x			xx	o
Caenidae	x	xx	x	x	x	xx	o	xx
Leptophlebiidae	xx		o			o	xxx	x
Plecoptera								
Perlidae	xxx	xxx	xxx	xxx	xx	xxx	xxxx	xxx
Nemouridae	xxxx	xxx	xxx	xxxx	xxxx	xxx	xxx	xxxx
Chloroperlidae	o	x	x	x	x			o
Peltoperlidae	xx	xxx	x	o	xxx		x	o
Leuctridae	o	o		o	o		o	o
Perlodidae	xxx	xx	xxx	xxx	xxx	xx		xxx
Capniidae	x			o	o	o	o	xx
Taeniopterygidae xxx	xxx	xxx	o	o	xxx	o	xxxx	
Trichoptera								
Hydropsychidae	xxxx	xxxx	xxxx	xxxx	xxx	xxxx	xxxxx	xxxx
Rhyacophilidae	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
Stenopsychidae	xx	xx	x	x	xx	x	xxx	xx
Philopotamidae	xxx	xxx	xx	xxx	xxxx	x	xxx	xx
Psychomyiidae	o		o	x		o	o	o
Polycentropodidae	x	o	o	x	x		x	o
Glossosomatidae	xx	xx	x	xx	xx	x	xx	x
Odontoceridae	o		xx				o	
Leptoceridae	x	o	x	x	o	o	x	xx
Limnephilidae	xxx	x	xx	xxx	xxx	xxx	x	xx
Uenoidae	xx	o	x	xxx	xxx	o	o	x
Brachycentridae	xxx	xxx	o	xxxx	xxx	x	o	x
Hydroptilidae	o	o		o	x	x	x	o
Lepidostomatidae	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
Goeridae	o	o		o			o	o

Table 6.6 *(continued)*

Region No. sites	All 180	R 19	P 24	S 23	D 20	Man 30	Mak 32	K 32
Hydrobiosidae	x	x	x	o	o	o	x	x
Helicopsychidae	o						x	o
Phryganeidae	o	o	o	o	x			
Calamoceratidae	o		o	x			x	o
Odonata								
Anisoptera	xx	xx	xxx	xx	xxx	o	xxx	x
Zygoptera	x	x	xx		o	o	xxx	x

Continued below

Abundance categories: o = <0.1%; x = 0.1-0.5%; xx = 0.5-1%; xxx = 1-5%; xxxx = 5-15%; xxxxx = 15-30%; xxxxxx = >30%.

Table 6.6 continued

Region No. sites	All 180	R 19	P 24	S 23	D 20	Man 30	Mak 32	K 32
Coleoptera								
Psephenidae	xx					x	xxx	x
Elminthidae	xxxx	xxxx	xxx	xxxx	xxxxx	xxx	xxxx	xxx
Dytiscidae	o	o	o	o	o		x	o
Hydrophilidae	xx	xxx	x	x	x	x	xxx	xx
Gyrinidae	o	o					x	o
Hydraenidae	xx	o	xxx		o	o	x	xxx
Scirtidae	o	o	o	o	x	o	o	o
Hemiptera								
Naucoridae	x		o		o	o	xxx	x
Veliidae	x	o	o			o	xx	o
Diptera								
Simuliidae	xxx	xxx	xxx	xxx	xxx	xxx	xx	xxx
Chironomidae	xxxx	xxxx	xxxx	xxx	xxxx	xxxx	xxx	xxxx
Tipulidae	xxx	xxx	xxx	xxx	xxxx	xxx	xxx	xxx
Tabanidae	x	x	x	x	o	x	o	o
Blephariceridae	o	o	o	xx	o		o	o
Athericidae	xx	x	xxx	x	xx	x	xx	xx
Psychodidae	x	o	x	o	xxx	xx	o	x
Dixidae	o	o	o	o	x	o	o	o
Ceratopogonidae	o	o		o	o		o	o
Stratiomyidae	o	o		x	x		o	
Empididae	x	x	o	o		x	o	x
Rhagionidae	o		o		o		o	o
Muscidae	o						o	x
Thaumalidae	o							x
Dolichopodidae	o	o	o			o		o

Table 6.6 *(continued)*

Region No. sites	All 180	R 19	P 24	S 23	D 20	Man 30	Mak 32	K 32
Miscellaneous								
Osmylidae	o	o	o	o	x	o		o
Corydalidae	x	o	o		o	x	xx	x
Oligochaeta	xx	xxx	xxx	x	xx	xx	o	x
Planariidae	xxx	xxx	o	xxx	xx	xxxx	x	xxx
Ostracoda	o			o	x			
Potamonidae	o		o			o	o	o
Hydracarina	o	o		o		o	o	o
Sphaeriidae	o	x			x		o	o
Hydrobiidae	o	o				x	o	o
Pyralidae	o	o		o			o	o

Abundance categories: o = <0.1%; x = 0.1-0.5%; xx = 0.5-1%; xxx = 1-5%; xxxx = 5-15%; xxxxx = 15-30%; xxxxxx = >30%.

Region: R = Roopkund; P = Pindar; S = Simikot; D = Dunai; Man = Manaslu; Mak = Makalu; K = Kanchenjunga.

Taxon richness: Regional patterns

The total numbers of invertebrate taxa recorded in each region ranged from 52 in Manaslu and 55 in Pindar to 74 in Makalu and 78 in Kanchenjunga. Similar patterns were also apparent in regional differences in the mean taxon richness at each site which was significantly lower in the Manaslu and Pindar regions and ranged between 12 taxa per site in Manaslu to 22 taxa per sites in Kanchenjunga (Table 6.7). These differences were mainly due to relatively lower numbers of trichopteran and dipteran taxa recorded from sites in Manaslu and Pindar (Table 6.7; Fig. 6.12). Sites from Manaslu and Pindar also tended to have lower invertebrate abundances than were recorded at sites from the other regions (Table 6.7).

Relationships between richness and environmental variables

The number of macroinvertebrate taxa recorded at each of the 180 sites ranged between 3 to 36, with the greatest numbers occurring at sites between 1000-2500 m in altitude (Fig 6.13). Overall, taxon richness declined with increasing altitude and the lowest numbers were recorded from sites at the highest altitudes. However, there was also a tendency for taxon richness to decline at sites from the lowest altitudes. This pattern of maximum taxon richness at sites from intermediate altitudes was most apparent for taxa from the Trichoptera and Coleoptera orders, but generally absent for taxa from the other principle invertebrate orders. For the Ephemeroptera and Hemiptera, maximum taxon richness occurred at sites from the lowest altitudes and declined strongly with increasing altitude. Hemiptera in particular were only ever recorded from sites at lower altitudes. By contrast, Plecoptera were the only invertebrate order to show an increase in taxon richness with increasing altitude (Table 6.8; Figs 6.13). These relationships between taxon richness and altitude generally confirm established patterns from other regions of Nepal (Rundle *et al*, 1993; Ormerod *et al*, 1994; Brewin *et al*, 1995).

Correlation also indicated other significant relationships between invertebrate taxon richness and the environmental variables relating to measures of water chemistry and physical character (Tables 6.8 and 6.9; Figs 6.14 and 6.15). For the water chemistry variables these included an increase in the number of invertebrate taxa with increasing Chemistry PC1 scores (i.e. declining pH, conductivity and sulphate concentrations) and increasing concentrations of silicate (Table 6.8). These relationships were strongest for the total numbers of invertebrate taxa and were only marginally less significant in partial correlations when altitude was factored out (Table 6.9). For variables measuring the physical character of sites, correlation indicated significant relationships between the taxon richness of invertebrates and site habitat character (RHS habitat PC scores), channel gradient and stability (Table 6.8). The relationships with the RHS variables were strongest for HA PC1 and HA PC2 and indicated a significant increase in invertebrate taxon richness, particularly the numbers of Trichoptera and Coleoptera taxa, with increasing HA PC1 and decreasing HA PC2 scores (Fig. 6.15). These patterns represented a general increase in taxon richness at sites which tended to be smaller, steeper gradient streams with pools, riffles, cascades and water falls features, which had exposed boulders, and channel vegetation including bryophytes, and were in broadleaf woodland catchments with tree lined banks, tree features and a complex vegetation structure. The taxon richness of the other invertebrate orders also showed a relationship with stream habitat character, but with only part of this habitat complex (Table 6.8). In the case of Ephemeroptera, Plecoptera and Hemiptera the relationship was with Habitat PC 2 (increasing richness in steep wooded catchments), and for Diptera with Habitat PC 1 (increasing richness in smaller streams with bryophytes, riffles, pools and tree lined banks). All of the relationships between invertebrate taxon richness and the first two principle habitat PCs remained relatively unchanged in partial correlations when altitude was held constant. In contrast, site scores on Habitat PC 3 were related to the numbers of Ephemeroptera and Plecoptera taxa, but only before the effects of altitude were factored out of the relationships.

The total channel stability at a site was significantly related to the total numbers of invertebrate taxa, independently of the effects by altitude, which indicated that as channel stability increased so the number of invertebrate taxa at a site tended to decline (Tables 6.8 and 6.9; Fig 6.15).

A mixed General Linear Model (GLM) was used to assess differences in invertebrate taxon richness between sites in catchments with contrasting land use types independently of influence of altitude. The type of land use at each site was determined within a 100 m wide zone adjacent to the RHS sample reach and its extent was classified as being either absent, intermediate (present on either bank) or extensive (>33% of the catchment on both banks). Altitude was included in the model as a covariate to compensate for both the strong relationship between altitude and taxon richness and the influence of the restricted altitudinal distribution of the land use types. Thus, comparisons could be made between differences in altitude adjusted mean taxon richness between sites with contrasting levels of cover by particular land use types. From this analysis, significant differences in mean taxon richness were only evident between sites with contrasting amounts of cover by either mixed broadleaf forest or alpine land use types. For sites in catchments with extensive mixed broadleaf forest the numbers of invertebrate taxa was significantly higher than for those sites with only intermediate or no forest cover (Fig. 6.16). This pattern was apparent for the numbers of Plecoptera, Coleoptera, Trichoptera, Diptera and other aquatic taxa not included in the principle insect orders. By contrast, the taxon richness of these invertebrate groups and total invertebrate richness were significantly lower at sites with catchments containing intermediate or extensive alpine land use type (Fig. 6.17). There were no significant differences in the measures of invertebrate taxon richness between sites with differing levels of catchment cover by any of the other land use types including; terraced agriculture, grassland/pasture or coniferous forest.

Classification by TWINSPAN

Invertebrate assemblages were classified into groups by two-way indicator species analysis (TWINSPAN). This technique grouped sites based on the co-occurrence of taxa, which had been weighted to account for variations in abundance by invoking the 'pseudospecies' option. Analysis of the environmental character of site groups was used to indicate variables of potential importance to the taxonomic composition of invertebrate communities.

The classification of invertebrate assemblages from the 180 sites by TWINSPAN produced 9 site groups and five taxon groups at four levels of division (Figs 6.18 and 6.19). The numbers of sites per group ranged between 9 and 34, with site classification strongly reflecting differences between groups in site altitude and other environmental variables (Table 6.10). The first level of division identified 38 high altitude sites (groups 7-9; altitude > 2750 m; Fig. 6.20), which were indicated by the presence of the high altitude taxon Taeniopterygidae or by the absence of the low altitude taxa Perlidae, Hydropsychidae and Elminthidae (Fig. 6.18). Sites classified in groups 7-9 were characterised by high altitude taxa from taxon group five and a generally lower taxon richness, which included no hemipteran and only few coleopteran families (Table 6.11; Figs 6.19 and 6.21). In addition to altitude groups 7-9 had generally lower chemistry PC 2 score and therefore lower ionic strength than sites in the other TWINSPAN groups (Fig. 6.22). These high altitude sites were next divided into a group of 10 relatively lower altitude sites (group 7; altitude 2750-4000 m) which were indicated by the presence of two or more of the following families; Perlodidae, Philopotamidae or Lepidostomatidae. Sites in this group were characterised by greater numbers of plecopteran and trichopteran families and included more taxa from taxon groups 2 and 3 than sites classified in groups 8 and 9.

In addition to the differences in altitude, sites in group 7 had lower concentration of Sulphate and catchments with more broad leaf mixed wood land than sites in groups 8 and 9 (Fig. 6.23). The final division of high altitude invertebrate assemblages separated sites into groups 8 and 9 with Psychodidae, Tipulidae, Rhyacophilidae, Simuliidae and Hydracarina as negative indicators of group 8 and Taeniopterygidae as a positive indicator for group 9. Sites in group 8 (3295-4235 m) supported significantly greater invertebrate abundances and higher numbers of dipteran taxa than sites in group 9 (3030-4695 m), which tended to larger boulder strewn rivers with torrential flow, as measured by HA PC1, than sites in group 8.

For sites in groups 1-6, level two of TWINSPAN identified invertebrate communities at low altitude (groups 1-3) indicated by Perlidae, Zygoptera and Corydalidae and characterised by taxa for taxon group 1 including Hemiptera, from those at intermediate altitudes (groups 4-6) indicated by Perlodidae, Brachycentridae and Nemouridae. At the next division of the low altitude sites, invertebrate communities in group 3 (750-2140 m) were indicated by the presence of two or more of the following taxa; Tipulidae, Lepidostomatidae, Hydrophilidae or Nemouridae. Sites in this group had the highest mean invertebrate taxon richness, particularly that of coleopterans, of any TWINSPAN group. These sites had smaller streams with generally more gravel substrata, slower flowing water with riffle and pool features, channel vegetation including bryophytes and earth banks with more trees and tree related features, as indicated by HA PC1, than the other low altitude sites in groups 1 and 2. As nearly all the sites in group 3 were located in Eastern Nepal (Table 6.12), this group also had the highest Chemistry PC1 score, which corresponded to low acid base status.

The invertebrate assemblages from sites at intermediate altitudes (groups 4-6) were further separated by TWINSPAN into sites which were characterised by higher numbers of ephemeropteran taxa (group 4; 1500-3040 m), and sites with higher numbers of coleopteran and trichopteran taxa (group 6; 1800-3650 m) than those in group 5 (850-3500 m).

Table 6.7 *Mean (±SD) measures of invertebrates from sites in each region and the results of one-way analysis of variance (significance levels; *P=0.05, ** P=0.01, *** P<0.001).*

Region	Roopkund	Pindar	Simikot	Dunai	Manaslu	Makalu	Kanchenjunga	
No.sites	19	24	23	20	30	32	32	
	Mean(SD)	Mean(SD)	Mean(SD)	Mean(SD)	Mean(SD)	Mean(SD)	Mean(SD)	F
Taxon richness	20.0(6.0)	15.0(6.3)	20.0(3.6)	19.9(4.0)	12.2(4.6)	21.6(5.5)	22.0(7.5)	11.86***
Tot.abundance (log)	2.64(0.35)	2.26(0.51)	2.67(0.19)	2.55(0.25)	2.33(0.41)	2.61(0.29)	2.83(0.34)	9.05***
No.Ephemeroptera	2.95(1.03)	2.38(0.92)	3.04(0.83)	2.20(1.11)	2.47(0.94)	3.66(1.10)	3.31(1.18)	7.32***
No.Plecoptera	2.58(1.22)	1.79(1.50)	2.48(1.28)	2.60(1.31)	1.67(0.92)	1.78(0.9)	2.78(0.94)	4.70***
No.Trichoptera	5.90(2.21)	3.17(2.28)	7.35(2.12)	6.50(1.73)	3.03(1.97)	6.06(2.56)	5.66(2.93)	12.75***
No.Coleoptera	2.05(1.13)	1.13(1.30)	1.44(0.59)	1.80(0.83)	0.83(1.12)	2.84(1.63)	2.22(1.68)	8.37***
No.Hemiptera	0.05(0.23)	0.04(0.20)	0.04(0.21)	0.10(0.31)	0.10(0.31)	0.84(0.92)	0.25(0.44)	11.03***
No.Diptera	3.47(1.54)	2.46(1.56)	4.26(1.05)	4.80(1.15)	2.50(1.25)	3.72(1.33)	4.94(1.68)	13.85***
No.Other	2.95(1.31)	1.13(1.04)	1.39(0.99)	1.85(1.42)	1.53(1.11)	2.66(1.13)	2.84(1.71)	8.88***
DCA axis 1	112.5(46.4)	124.7(65.9)	112.7(22.6)	135.1(28.9)	137.2(75.1)	56.9(46.1)	126.9(71.3)	7.17***
DCA axis 2	76.1(24.1)	94.3(28.3)	46.8(25.0)	40.4(18.9)	97.3(33.6)	84.4(16.1)	93.2(29.9)	18.81***
DCA axis 3	80.2(21.9)	85.3(33.6)	88.3(20.7)	59.4(24.2)	90.9(29.2)	73.7(35.3)	75.1(31.4)	3.16**

Table 6.8 *Product moment correlation coefficients for relationships between invertebrate taxon richness, invertebrate abundance and environmental variables at 180 sites in the Himalaya (Significance levels: * P < 0.05; *** P < 0.001).*

	Taxon richness							
	Total	Ephemeroptera	Plecoptera	Trichoptera	Coleoptera	Hemiptera	Diptera	Log Abundance
Altitude	-0.30***	-0.58***	0.31***	-0.19*	-0.43***	-0.43***	0.06	0.01
Chemistry PC1	0.39***	0.36***	0.01	0.22*	0.35***	0.38***	0.15*	0.28***
Chemistry PC2	-0.01	0.12	-0.30***	-0.04	0.03	0.05	0.18*	0.00
Chemistry PC3	0.17*	0.08	0.08	0.18*	0.09	0.02	0.14	0.16*
pH	-0.26***	-0.24*	-0.09	-0.19*	-0.25***	-0.20	-0.11	-0.12
Si (log)	0.34***	0.34***	-0.20*	0.21*	0.34***	0.30***	0.26***	0.15*
SO4(log)	-0.36***	-0.33***	-0.3	-0.17*	-0.38***	-0.35***	-0.01	-0.17*
NO3 (log)	-0.04	-0.04	-0.05	-0.10	-0.16*	-0.08	-0.18	0.00
PO4 (log)	-0.05	-0.11	0.00	-0.03	0.05	-0.05	-0.03	-0.16*
Conductivity (log)	-0.34***	-0.24*	-0.08	-0.16*	-0.26***	-0.32***	-0.04	-0.20*
Ca (log)	-0.37***	-0.32***	-0.02	-0.20*	-0.34***	-0.37***	-0.09	-0.19*
Mg (log)	-0.19*	-0.13	-0.16*	-0.12	-0.11	-0.19	-0.09	-0.18*
HA PC1	0.29***	-0.14	0.09	0.28***	0.23*	0.03	0.39***	0.19*
HA PC2	-0.56***	-0.37***	-0.19*	-0.44***	-0.45***	-0.28***	-0.12	-0.25***
HA PC3	0.06	0.29***	-0.16*	0.05	0.12	0.16	-0.03	0.11
Gradient	0.32***	0.06	0.18*	0.19*	0.25***	0.00	0.26***	0.09
Total stability	-0.29***	-0.16*	-0.17*	-0.19	-0.16*	-0.05	-0.13	-0.17*
Channel width (log)	-0.10	0.27***	0.06	-0.09	-0.09	0.12	-0.28***	-0.07

Table 6.9 *Partial correlation coefficients (with altitude held constant) for relationships between invertebrate taxon richness and environmental variables at 180 sites in the Himalaya. Correlations between the residuals from regression analysis between each variable and altitude. (Significance levels: * P < 0.05; *** P < 0.001).*

	Taxon richness							
	All	Ephemeroptera	Plecoptera	Trichoptera	Coleoptera	Hemiptera	Diptera	Log Abundance
Chemistry PC1	0.31***	0.16*	0.16*	0.16*	0.21*	0.24*	0.19*	0.31***
Chemistry PC2	-0.10	-0.05	-0.23*	-0.10	-0.11	-0.09	0.21*	0.00
Chemistry PC3	0.16*	0.06	0.11	0.18*	0.07	-0.01	0.15*	0.16*
pH	-0.19*	-0.10	-0.19*	-0.15*	-0.15	-0.10	-0.12	-0.12
Si (log)	0.23*	0.06	-0.05	0.14	0.16*	0.11	0.34***	0.18*
SO4(log)	-0.26***	-0.10	-0.14	-0.10	-0.23*	-0.19*	-0.04	-0.19*
NO3 (log)	-0.04	-0.04	-0.06	-0.10	0.17*	-0.08	-0.18*	0.00
PO4 (log)	-0.05	-0.13	-0.01	-0.03	0.06	-0.05	-0.03	-0.16*
Conductivity (log)	-0.29***	-0.13	-0.16*	-0.12	-0.18*	-0.25***	-0.05	-0.21*
Ca (log)	-0.29***	-0.15*	-0.15*	-0.15*	-0.22*	-0.25***	-0.12	-0.21*
Mg (log)	-0.20*	-0.15*	-0.18*	-0.12	-0.11	-0.20*	-0.09	-0.18*
HA PC1	0.37***	-0.04	0.04	0.32***	0.35***	0.12	0.39***	0.19*
HA PC2	-0.51***	-0.23*	-0.33***	-0.41***	-0.36***	-0.16*	-0.15*	-0.27***
HA PC3	-0.10	0.02	-0.02	-0.05	-0.10	-0.05	0.00	0.14
Gradient	0.37***	0.16*	0.15*	0.22*	0.34***	0.06	0.26***	0.09
Total stability	-0.33***	-0.24*	-0.16	-0.20*	-0.21*	-0.09	-0.13	-0.17*
Channel width (log)	-0.22*	0.12	0.04	-0.15*	-0.26*	-0.02	-0.28***	-0.07

Table 6.10 *Mean (±SD) values for measures of invertebrate community composition for each TWINSPAN group and the results of one-way analysis of variance (significance levels; *P=0.05, ** P=0.01, *** P<0.001)*

	TWINSPAN GROUP									
	1	2	3	4	5	6	7	8	9	
Sites	16	30	22	34	16	24	10	9	19	F
R	15.1(4.3)	19.3(5.1)	24.7(5.6)	22.2(4.6)	17.4(5.4)	21.2(4.1)	18.2(5.7)	14(3.5)	8.1(2.8)	22.5***
T	2.29(0.3)	2.52(0.38)	2.7(0.24)	2.68(0.3)	2.39(0.36)	2.77(0.19)	2.56(0.36)	2.78(0.47)	2.23(0.6)	6.1***
E	3.81(0.98)	3.4(0.89)	3.46(0.91)	3.44(1.02)	2.13(0.72)	2.58(0.65)	2.5(1.43)	1.78(0.67)	1.63(0.6)	14.7***
P	1(0.73)	1.7(0.75)	2.05(0.72)	2.32(1.01)	2(1.16)	3.46(1.32)	3.7(1.06)	2.11(1.27)	1.84(0.9)	12.3***
T	2.69(1.7)	5.67(2.07)	6.73(2.8)	7.06(2.03)	4.5(2.45)	7.33(1.58)	5.3(1.25)	2.67(0.71)	1.42(0.69)	24.0***
C	1.94(1.34)	1.9(0.96)	3.64(1.56)	2.12(1.09)	2.13(1.26)	1.63(0.92)	0.5(0.71)	0.44(0.73)	0(0)	19.1***
H	0.63(0.81)	0.4(0.56)	0.73(0.94)	0.12(0.33)	0(0)	0.04(0.2)	0(0)	0(0)	0(0)	6.6***
D	2.19(1.05)	3.5(1.59)	4.55(1.41)	4.47(1.62)	3.38(1.96)	3.92(1.1)	4.5(1.84)	4.78(1.09)	2.26(1.1)	7.8***
O	2.06(1)	2.03(1.33)	3.55(1.57)	1.97(1.34)	1.75(1.13)	2.21(1.53)	1.7(1.25)	2.22(1.09)	0.9(0.94)	5.8***

R Taxon richness
A Total Abundance
E Number of Ephemeroptera
P Number of Plecoptera
T Number of Trichoptera
C Number of Coleoptera
H Number of Hemiptera
D Number of Diptera
O Number of other taxa

Table 6.11 *Mean (±SD) altitude, water chemistry and stream habitat variables for each TWINSPAN group and the results of one-way analysis of variance (significance levels; *P=0.05, ** P=0.01, *** P<0.001).*

	TWINSPAN GROUP									
	1	2	3	4	5	6	7	8	9	
No.Sites	16	30	22	34	16	24	10	9	19	F
Altitude (m)	762(390)	1217(460)	1395(440)	2205(466)	2276(622)	2750(421)	3246(413)	3604(313)	3781(446)	96.2***
Chemistry PC1	0.9(1.9)	0(1.8)	2(0.6)	-0.2(1.2)	-0.7(2. 1)	-0.5(1.7)	0.5(1.1)	-0.4(1.3)	-1.7(2)	8.6***
Chemistry PC2	0.6(1.2)	0.4(1.5)	0.1(1.7)	0.4(1.9)	0.4(2)	-0.3(1.2)	-1.3(0.7)	-1.1(1.1)	-0.8	(1)3.0***
Chemistry PC3	0.2(0.5)	-0.1(2.4)	0(0.4)	0.2(0.7)	0(1.2)	0.3(0.9)	0(0.5)	0.2(0.5)	-0.7(2.3)	0.8***
pH	7.6(0.7)	7.8(0.5)	7.3(0.5)	7.8(0.6)	7.9(0.6)	7.9(0.6)	7.8(0.4)	7.9(0.4)	8.1(0.3)	3.1***
Cond (log)	1.78(0.38)	1.88(0.41)	1.43(0.28)	1.89(0.38)	1.95(0.48)	1.94(0.37)	1.69(0.3)	1.9(0.4)	1.99(0.3)	4.5***
Si (log)	0.76(0.13)	0.68(0.14)	0.77(0.13)	0.68(0.12)	0.62(0.22)	0.61(0.14)	0.57(0.11)	0.51(0.1)	0.43(0.11)	11.8***
Ca (log)	0.84(0.43)	0.98(0.39)	0.5(0.24)	1.04(0.35)	1.07(0.51)	1.11(0.37)	0.92(0.35)	1.13(0.42)	1.24(0.3)	6.9***
Mg (log)	0.47(0.41)	0.56(0.45)	0.23(0.15)	0.49(0.33)	0.62(0.45)	0.52(0.41)	0.2(0.07)	0.35(0.34)	0.45(0.38)	2.7***
NO_3 (log)	0.05(0.16)	0.06(0.1)	0.06(0.09)	0.08(0.17)	0.03(0.03)	0.06(0.06)	0.12(0.2)	0.06(0.03)	0.07(0.1)	0.6***
SO_4 (log)	0.5(0.31)	0.67(0.35)	0.31(0.21)	0.77(0.32)	0.83(0.41)	0.79(0.29)	0.54(0.25)	0.89(0.37)	1.11(0.44)	9.3***
HA PC 1	-0.93(1.98)	-1.81(1.26)	1.11(1.65)	1.14(3.26)	0.69(4.05)	1.19(3.08)	0.86(2.4)	1.4(2.55)	-2.62(2.06)	7.0***
HA PC 2	0.03(2.45)	-0.47(2.05)	-1.68(2.65)	0.2(2.83)	-0.29(2.52)	-0.95(1.9)	0.2(2.25)	1.67(2.24)	2.76(1.63)	6.0***
HA PC 3	1.63(2.04)	0.58(1.73)	0(1.58)	0.69(2.81)	-0.22(2.09)	-0.39(1.23)	-1.73(1)	-0.79(1.61)	-1.67(1.22)	5.6***
Ch width (log)	0.8(0.3)	0.9(0.3)	0.5(0.2)	0.5(0.2)	0.4(0.2)	0.6(0.3)	0.5(0.2)	0.5(0.2)	0.7(0.2)	8.2***
Gradient	8.3(5.8)	8.7(6.4)	14.7(6.3)	13.8(8.9)	14.3(10.1)	10.5(4.8)	14(4)	8.6(7.2)	8.5(3. 8)	3.3***
Total stability	39.2(9.43)	41.17(10.38)	35.14(9.16)	38.29(10.23)	42.69(10)	36.57(6.58)	34.78(7.43)	35.89(8.61)	42.35(12.36)	1.7***

Table 6.12 *Number of sites from seven regions of the Himalayas classified on the basis of the invertebrate community by TWINSPAN.*

	Region						
TWINSPAN Group	R	P	S	D	Man	Mak	K
1	-	2	-	-	6	-	8
2	4	7	1	-	5	9	4
3	1	-	-	-	-	11	10
4	5	1	12	7	2	2	5
5	3	4	1	3	3	-	2
6	4	1	8	8	2	-	1
7	1	3	-	2	1	1	2
8	-	1	1	-	2	1	4
9	2	4	-	-	9	-	4

R Roopkund
P Pindar
S Simikot
D Dunai
Man Manaslu
Mak Makalu
K Kanchenjunga

Ordination by detrended correspondence analysis (DCA)

The principle patterns in invertebrate community structure were analysed using DCA, which produced sites scores reflecting change in species composition that can be related to environmental data. The ordination of invertebrate data by DCA explained 24% of the variation in macroinvertebrate assemblages in the first three axes. This value is typical for DCA by CANOCO, which generally identifies coherent ecological patterns on the first few axes and confines random variation and noise to later axes. The proportion of the variance explained is usually less important than the significance of the ordination axes and ecological patterns revealed (ter Braak, 1988).

The first DCA axis explained 14.9% of the variation in invertebrate assemblages and provided further evidence of the strong relationship between site altitude and aquatic invertebrate (Table 6.13). Site scores on DCA axis 1 were highly correlated with altitude and corresponded to a community gradient from taxa which occurred only at low altitude sites to ones found predominantly at high altitude sites (Fig. 6.24). This relationship between axis 1 and altitude remained strong between sites from each region (Fig. 6.25). DCA axis 1 also represented a gradient from relatively taxon rich communities with high numbers of ephemeropteran, trichopteran, coleopteran and hemipteran taxa to communities with greater numbers of plecopteran taxa.

In addition to the strong relationships with altitude, DCA axis 1 was also related to habitat character as measured by HA PC2 and PC3 and water chemistry as measured by Chemistry PC 1 (Table 6.13; Figs 6.25 and 6.26). However, only the relationship with HA PC2 remained significant in partial correlations when altitude was held constant (Table 6.14). Partial correlations also indicated a relationship between DCA axis 1 with HA PC1 and channel gradient (Table 6.14). Therefore, sites which had generally lower DCA axis 1 scores for their given altitude tended to be smaller, steeper gradient streams with pools, riffles, cascades and water falls features, which had exposed boulders, and channel vegetation including bryophytes, and were in broadleaf woodland catchments with tree lined banks, tree features and a complex vegetation structure. These relationships between invertebrate community composition and the habitat character of sites were similar to those indicated by the measures of invertebrate taxon richness. Similarly, in analysis of variance by GLM with altitude included as a covariate, the altitude adjusted DCA axis 1 scores were significantly lower at sites in catchments with extensive cover by broadleaf forests ($p = 0.05$), and higher at sites with extensive alpine catchments ($p = 0.001$), than at sites without these land use types.

The second DCA axis explained 4.9% of the variation in invertebrate data and represented a community gradient which was related to decreasing numbers of Trichoptera and Diptera taxa and lower invertebrate abundance as site scores on axis 2 increased. DCA axis 2 was related the habitat structure of sites as measured by RHS PC1, but not to site altitude (Table 6.13; Fig. 6.26). Therefore, DCA axis 2 represented, in part, a species gradient from taxa found more commonly in larger deeper rivers, with boulder, cobble substrata with torrential water flow and more rock features including mid-channel and side bars to smaller streams with more gravel substrata, slower water flow with riffle and pool features, channel vegetation including bryophytes and earth banks with more trees and tree related features (Table 6.13).

DCA axis 3 explained 4.2% of the variation in invertebrate data and represented a community gradient, which was related to decreasing taxon richness and in particular the richness of Coleoptera and Diptera taxa. DCA axis 3 was related to the acid base status of streams as measured by Chemistry PC1, with generally higher axis 3 scores at sites with lower pH (Table 6.13). Further evidence that DCA axis 3 was related to the acidity of sites included significantly higher DCA axis 3 scores at sites with high contributions of Sulphur to the concentration of the major anions (greater than 30% of; Cl, F, HCO_3, SO_4 as Sulphur μeq/l; $p = 0.004$). These sites were might considered on the basis of Sulphur contributions as being potentially sensitive to acidification. Although these sites with high contributions of Sulphur predominately occurred at higher altitudes, these differences in DCA axis 3 scores remained significant in analysis of variance by GLM with altitude included as a covariate. DCA axis 3 also showed a strong relationship with HA PC1, which given the strong relationship between DCA axis 3 with channel width and gradient is likely to represent a function of stream size.

The fourth DCA Axis explained 3.4% of the variation in invertebrate data and represented a community gradient, which was related to increasing Plecoptera and Trichoptera taxon richness with increasing sites scores on this axis. Site scores on axis 4 were again related to water chemistry (PC2 & PC3) and habitat PC2 (Table 6.13). Differences were also evident in axis 4 scores between sites with different land use types; they were significantly lower at sites in catchments with intermediate or extensive levels of agricultural when compared to sites in catchments without agriculture ($p = 0.01$).

Canonical correspondence analysis (CCA)

CCA was used to directly explore the relationships between invertebrate assemblages and environmental variables. A subset of six environmental variables which independently explained significant proportions of the variance in the invertebrate data were identified by forward selection for inclusion in this analysis (Table 6.15). Of these variables, altitude alone represented 49% of the total explained variance in invertebrate data, indicating its importance as an explanatory variable. The other variables each explained between 7 and 12% of the variances in invertebrates (Table 6.15).

The CCA analysis showed one dominant axis of variation, which explained 12.2% of the invertebrate data, and a second smaller axis explaining 3.1% of the variation (Table 6.16). The first axis was dominated by a highly significant relationship with site altitude and represented a gradient from samples associated with sites at low altitudes to samples from high altitude sites (Fig. 6.27). This corresponded to a taxon gradient from low altitude taxa including; Potamonidae, Zygoptera; the trichopterans, Helicopsychidae, Hydropsychidae and Stenopsychidae; the hemipterans, Gerridae, Naucoridae and Veliidae; the coleopterans, Psephenidae and Gyrinidae; and the ephemeropterans, Leptophlebiidae and Ephemeridae to taxa which occurred predominantly at higher altitudes including; Taeniopterygidae, Capniidae, Psychodidae, Hydracarina, Empididae, Planariidae and Limnephilidae (Fig. 6.26). CCA axis 1 was also related chemistry PC1, which increased in the direction of the base poor low altitude sites from the Makalu region, and Habitat PC3 which also increased in the direction of the low altitude sites, and in part, represented the higher levels of site modification and management at low altitudes (Table 6.16). However, these environmental variables explained considerably less of the faunistic variation of CCA axis 1 than altitude alone.

Table 6.13 *Product moment correlation coefficients for relationships between the first four invertebrate community DCA axes and environmental variables at 180 sites in the Himalayas. Significance levels; * P < 0.05, *** P < 0.001).*

	DCA axis 1	DCA axis 2	DCA axis 3	DCA axis 4
Eigen Value	0.249***	0.081***	0.071***	0.057***
Percentage variance	14.9	4.9	4.2	3.4
Altitude	0.894***	-0.120	-0.074	0.045
Chemistry PC1	-0.383***	0.020	-0.218*	0.008
Chemistry PC2	-0.245*	-0.045	0.005	-0.219*
Chemistry PC3	-0.110	-0.191*	-0.110	0.229*
pH	0.294***	-0.077	0.092	-0.086
Si (log)	-0.530***	-0.168	-0.216*	-0.064
SO_4 (log)	0.425***	-0.082	0.247***	-0.078
NO_3 (log)	-0.010	-0.075	0.104	0.063
PO_4 (log)	0.034	0.066	-0.047	0.124
Conductivity (log)	0.219*	-0.090	0.166*	-0.016
Ca (log)	0.345***	-0.113	0.186*	-0.008
Mg (log)	-0.038	-0.005	0.107	0.084
HA PC 1	0.009	-0.448***	-0.570***	0.048
HA PC 2	0.404***	0.114	0.165*	-0.394***
HA PC 3	-0.400***	-0.027	0.170*	-0.082
Gradient	-0.012	-0.060	-0.311***	0.274***
Total stability	0.016	0.179*	0.244*	-0.291***
Channel Width (log)	-0.203*	0.145	0.545***	-0.003

Table 6.14 *Partial correlation coefficients (with altitude held constant) for relationships between the first four invertebrate community DCA axes and environmental variables at 180 sites in the Himalayas. Correlations between the residuals from separate regression analysis between altitude and each variable. Significance levels; * $P < 0.05$, *** $P < 0.001$).*

	DCA axis 1	DCA axis 2	DCA axis 3	DCA axis 4
Chemistry PC1	-0.027	-0.035	-0.278***	0.029
Chemistry PC2	0.020	-0.084	-0.019	-0.215*
Chemistry PC3	-0.115	-0.201*	-0.116	0.232*
pH	0.119	-0.047	0.115	-0.101
Si (logn+1)	-0.192*	-0.268***	-0.296***	-0.047
SO4 (logn+1)	0.044	-0.029	0.320***	-0.110
NO3 (logn+1)	-0.044	-0.075	0.105	0.062
PO4 (logn+1)	0.053	0.068	-0.047	0.124
Conductivity (log)	0.012	-0.063	0.189*	-0.026
Ca (logn+1)	0.052	-0.075	0.228*	-0.026
Mg (logn+1)	-0.120	-0.003	0.109	0.084
HA PC 1	-0.332***	-0.437***	-0.567***	0.041
HA PC 2	0.247*	0.165*	0.202*	-0.435***
HA PC 3	0.052	-0.095	0.154	-0.069
Gradient	-0.265***	-0.046	-0.306***	0.271***
Total stability	0.159*	0.172*	0.239*	-0.288***
Channel Width (log)	0.163*	0.114	0.550***	0.011

The second CCA axis was related to habitat PC 1 site scores and stream gradient. Samples with low axis 2 scores tended to be larger lower gradient rivers with less bankside vegetation cover. At lower altitudes taxa associated with these sites included; Siphlonuridae, Stenopsychidae, Blephariceridae, Naucoridae and Corydalidae, whereas at higher altitudes, such taxa included; Taeniopterygidae, Empididae and Capniidae. The samples with high axis 2 scores tended to be smaller higher gradient streams which had more bank side vegetation and the taxa associated with these sites included as Phryganeidae, Psychodidae, Stratiomyidae, Helicopsychidae, Polycentropodidae and Scirtidae.

Although the third and fourth CCA axes were less important, only explaining 1.7 and 1.5% of variation in invertebrates respectively, they were both statistically significant on the basis of Monte Carlo permutation tests. The third axis was most strongly related to the acid-base status of sites as measured by chemistry PC 1, and the fourth axis was strongly related to both site gradient and habitat PC 2 (Table 6.16).

1989), not only because of their diversity, but also because streams are such important features of the local topography.

Using data from 180 sites the following questions were addressed:

1. What physical, chemical and biological features might be important in influencing distribution of Himalayan river birds in the winter?

2. Were there any trends in the distribution and/or abundance of river birds across different regions of the Himalaya?

6.7.2 Method

Surveys for birds were carried out once at 182 streams, over the same 200 m reach as the River Habitat Survey. The presence of all river bird species was recorded. Only measures of presence or absence were used in quantitative data analysis, since the numbers of registrations from single visits might be sensitive to activities such as incubation or brooding, or to periodic absences for other reasons. This technique is appropriate for such species which hold linear territories.

As surveys were carried out in autumn/winter, the breeding distribution of only one river bird species, the Brown Dipper, could be assessed. Brown Dippers breed considerably earlier than other river bird species (Inskipp and Inskipp, 1985), and pre-breeding behaviour (e.g. nest-site searching, copulation and nuptial feeding) was recorded during the surveys. All other species, however, breed in the spring (April - June) so that for these species only assessments of non-breeding distribution could be made.

Data analysis

Principal Components Analysis (PCA)

Habitat variables from RHS were reduced by principal components analysis (PCA) on the correlation matrix (MINITAB 10.5).

Analysis of Variance (ANOVA)

Variations in habitat characteristics between sites with and without each river bird species were assessed by ANOVA. Relationships between invertebrate abundances, water chemistry, and stream bed stability were also investigated in relation to species presence-absence using ANOVA. In assessing relationships between bird and invertebrate distribution, totals for each order were used, as trends were most likely to be detected at this taxonomic level (Ormerod *et al.* 1986). ANOVAs were also used to assess regional differences in bird distribution and habitat characteristics, and here Tukey-Kramer range tests (MINITAB 10.5) were used to identify significant differences between regions.

Canonical Correspondence Analysis (CCA) and TWINSPAN

Spatial trends in the composition of bird communities were assessed by Canonical Correspondence Analysis (CCA; CANOCO version 3.12; ter Braak, 1988). This direct gradient ordination technique detects the patterns in species occurrence data that can be best explained by linear combinations of the given environmental variables. Environmental variables used here were RHS PC scores, water chemistry PC scores, and altitude.

Sites were classified on the basis of bird communities using Two-way Indicator Species Analysis (TWINSPAN) (Hill, 1979). The lack of repeated surveys meant that only a crude measure of abundance could be used, so pseudospecies cut levels were set at 1 and 2 individuals per sample. Classification by TWINSPAN arranges site groups into a hierarchy on the basis of their taxonomic composition. Species are classified simultaneously based on their occurrence in site groups (Ormerod and Edwards, 1987).

6.7.3 Results

General patterns in bird distribution

River birds were recorded at 119 sites, involving fourteen species (Table 6.17). Of these, Little Forktail, Spotted Forktail, Slaty-backed Forktail, Brown Dipper, Plumbeous Redstart, River Chat, Blue Whistling-thrush, Grey Wagtail and Crested Kingfisher were recorded frequently enough for statistical analysis. Plumbeous Redstart was recorded most frequently, while Brown Dipper, River Chat, Little Forktail and Grey Wagtail were all recorded at over 20% of sites. Some other species (Large Cormorant, Common Sandpiper, Pied Wagtail and Large Pied Wagtail) were only found at a handful of sites and were not always confined to rivers. They were included in the CCA but not in the ANOVAs using PC scores.

Although altitudinal ranges varied between species, and river birds were recorded both at the highest and lowest altitude sites surveyed, overall river bird species richness and river bird abundance declined significantly with increasing altitude (Fig. 6.29). Distribution of most species showed strong trends with altitude (Fig. 6.30). Therefore, the altitudinal range of each species was calculated from all the sites surveyed and only those falling within this range for each species were used in subsequent statistical assessments within-species. The large number of sites sampled meant that excluding sites outside the altitude range of each species still allowed statistical analyses to be carried out (Table 6.18). This approach enabled a much more robust analysis of the relationship between habitat and river bird distribution, by excluding those sites where birds may be absent due to reasons other than physical habitat structure. As the altitudinal range of Brown Dipper covered all but one of the sites, PC scores from all sites were used in the analysis for this species. All sites were included in the initial PCAs however, to allow a comparison of habitat preferences between species as well as between sites.

Regional trends

Reflecting its generally lower altitude, streams in the Makalu region had greater mean species richness and mean river bird abundance than all other regions; differences were statistically significant from all other regions except Roopkund and Manaslu (Table 6.19; Fig. 6.31).

Of the nine frequently recorded species, Crested Kingfisher, Plumbeous Redstart, River Chat, Blue Whistling-Thrush, and Little and Slaty-backed Forktails were recorded most frequently in the Makalu region, occurring at between 12.5 and 71.9% of sites. Grey Wagtail was most often recorded in Manaslu (23.3%), and Brown Dipper (42.1%) and Spotted Forktail (10.5%) most frequently found at Roopkund sites (Table 6.19).

Table 6.17 *Bird species recorded during surveys of 182 stream reaches in NW India and Nepal, 1994-1996.*

Species	No. (%) of all sites
Large Cormorant *Phalacorax carbo*	3 (1.6)
Ibisbill *Ibidorhyncha struthseri*	2 (1.0)
River Lapwing *Vanellus duvaucelii*	1 (0.5)
Common Sandpiper *Actitis hypoleucos*	3 (1.6)
Common Kingfisher *Alcedo atthis*	5 (2.7)
Crested Kingfisher *Ceryle lugubris*	7 (3.8)
Grey Wagtail *Motacilla cinerea*	22 (12.1)
Pied Wagtail *M. alba*	6 (3.3)
Large Pied Wagtail *M. maderaspatensis*	4 (2.2)
Brown Dipper *Cinclus pallasii*	54 (29.6)
Plumbeous Redstart *Rhyacornis fuliginosus*	65 (35.7)
River Chat *Chaimarrornis leucocephalus*	59 (32.4)
Blue Whistling-thrush *Myiophoneus caeruleus*	37 (20.3)
Little Forktail *Enicurus scouleri*	44 (24.2)
Black-backed Forktail *E. immaculatus*	1 (0.5)
Slaty-backed Forktail *E. schistaceus*	9 (4.9)
Spotted Forktail *E. maculatus*	9 (4.9)
Any species	120 (65.9)

Table 6.18 *Altitudinal range of nine river bird species recorded during surveys of 182 stream reaches in NW India and Nepal, 1994-1996.*

Species	Altitude range	Sites in altitude range	No. (%) of occupied sites in altitude range
Crested Kingfisher	360-1630	58	7(12.1)
Grey Wagtail	530-2400	99	22(22.2)
Brown Dipper	360-4695	181	54(29.8)
Plumbeous Redstart	350-3120	143	65(45.5)
River Chat	350-3540	161	59(36.6)
Blue Whistling-thrush	360-2660	124	37(29.8)
Little Forktail	450-3050	136	44(32.4)
Slaty-backed Forktail	360-1460	49	9(18.4)
Spotted Forktail	900-3050	118	9(7.6)

Table 6.19 *Percentage of streams (±SD) occupied by individual river bird species, and mean species richness and abundance, in each of 7 regions in the Indian and Nepalese Himalaya, 1994-1996. R = Roopkund, P = Pindari, S = Simikhot, D = Dunai, MS = Manaslu, M = Makalu, K = Kanchenjunga.*

Region	R	P	S	D	Man	Mak	K
Number streams	19	24	24	20	30	32	33
Large Cormorant	0	0	0	0	0	3 (9.4)	0
Ibisbill	0	0	0	0	1 (3.3)	1 (3.1)	0
River Lapwing	0	0	0	0	0	1 (3.1)	0
Common Sandpiper	0	0	0	0	1 (3.3)	2 (6.3)	0
Common Kingfisher	0	0	0	0	1 (3.3)	4 (12.5)	0
Crested Kingfisher	0	2 (8.3)	1 (4.2)	0	0	4 (12.5)	0
Grey Wagtail	1 (5.3)	1 (4.2)	2 (8.3)	1 (5.0)	7 (23.3)	4 (12.5)	6 (18.2)
Pied Wagtail	1 (5.3)	0	0	0	3 (10.0)	2 (6.3)	0
Large Pied Wagtail	0	0	0	0	2 (6.7)	1 (3.1)	1 (3.0)
Brown Dipper	8 (42.1)	7 (29.2)	10 (41.7)	4 (20.0)	8 (26.7)	8 (25.0)	9 (27.3)
Plumbeous Redstart	10 (52.6)	7 (29.2)	6 (25.0)	2 (10.0)	10 (33.3)	20 (62.5)	10 (30.3)
River Chat	7 (36.8)	4 (16.7)	7 (29.2)	2 (10.0)	11 (36.7)	23 (71.9)	5 (15.2)
Blue Whistling-thrush	3 (15.8)	8 (33.3)	4 (16.7)	3 (15.0)	2 (6.7)	13 (40.6)	4 (12.1)
Little Forktail	0	9 (37.5)	4 (16.7)	3 (15.0)	6 (20.0)	12 (37.5)	10 (30.3)
Black-backed Forktail	0	0	0	0	1 (3.3)	0	0
Slaty-backed Forktail	0	0	0	0	0	7 (21.9)	2 (6.1)
Spotted Forktail	2 (10.5)	2 (8.3)	2 (8.3)	2 (10.0)	0	1 (3.1) 0	
Mean species richness	1.63 (1.12)	1.67 (1.71)	1.5 (1.89)	0.9 (1.52)	1.73 (1.60)	3.28 (2.28)	1.46 (1.99)
Mean abundance	2.32 (1.67)	2.17 (2.37)	1.96 (2.55)	1.2 (2.31)	2.8 (3.08)	5.3 (4.75)	2.0 (2.86)

CCA was carried out using data from the 120 sites where river birds were recorded. After the first analysis, Ibisbill, which occurred at two sites, was omitted as its presence at two contrasting sites (possibly stop-over sites as the birds were migrating to lower altitudes) had a substantial impact on the results. One of these sites had no other species recorded, so 119 sites were used in the final analysis.

The first two axes of the ordination explained 52.5% of the variance in the combined species-environment data (Table 6.20; Figs. 6.32a and b). Axis 1 declined significantly with increasing altitude, Sweep-up PCs 1 and 4 and Spot-check PCs 2 and 4. This axis also reflected significant increases in the first two chemistry PCs. Axis 2 increased significantly with site altitude, Sweep-up PC2 and Spot-check PC1 and declined significantly with Sweep-up PC3 and Spot-check PC2. Axis 3 increased significantly with altitude, Sweep-up PC4 and Chemistry PC4, and declined with Spot-check PC4 and Chemistry PC1 (Table 6.20).

Table 6.20 *Summary of Canonical Correspondence Analysis on streams and bird species from 119 sites in the Indian and Nepalese Himalaya (i.e. this analysis was confined to sites where birds occurred).*

Axis	1	2	3	4
Eigenvalue	0.247	0.183	0.137	0.092
Species-environment correlation	0.793	0.677	0.653	0.553
Species variance explained (%)	7.0	12.2	16.1	18.7
Species-environment variance explained (%):	30.1	52.5	69.1	80.3
Linear correlation with:				
Altitude	***-0.512	***0.295	***0.362	0.025
Sweep-up PC1	***-0.402	-0.098	-0.019	*0.224
Sweep-up PC2	0.110	***0.490	0.076	**0.269
Sweep-up PC3	0.001	***-0.401	-0.175	0.128
Sweep-up PC4	*-0.231	-0.046	**0.258	-0.070
Spot-check PC1	-0.156	**0.284	-0.154	***-0.363
Spot-check PC2	*-0.206	***-0.461	-0.033	-0.054
Spot-check PC3	0.034	0.031	0.085	-0.029
Spot-check PC4	***-0.540	0.146	**-0.293	-0.080
Chemistry PC1	**0.258	-0.113	**-0.234	-0.056
Chemistry PC2	*0.194	0.009	-0.158	0.043
Chemistry PC3	-0.071	0.118	0.015	0.046
Chemistry PC4	0.074	-0.055	**0.244	*-0.214

Eight site groups were produced at TWINSPAN level 3 which were strongly related to the axis scores produced in CCA; groups were related to site altitude, stream gradient, and trends in habitat features identified in PCA (Fig. 6.33). Groups 1 and 2 (with Grey Wagtail, Pied Wagtail and Black-backed Forktail) were characterised by low altitude and shallow gradients while group 5 sites (with Brown Dipper) were high altitude streams with moderate gradients. Groups 3, 4, 7 and 8 were moderate altitude streams with moderate gradients, and group 6 streams were of moderate altitude but with steep gradients. Groups 3 sites had the lowest mean Axis 1 score, and groups 1 and 2 the highest.

Four species groups were produced at TWINSPAN level 3. These groupings were strongly related to Axis 2 CCA species scores (Fig. 6.34). Species groupings were compared with site groupings (Fig. 6.35). The group 1 site held three species, including Black-backed Forktail which was only recorded here. Group 2 sites all held Grey Wagtail, and only one held another species, Large Pied Wagtail. Blue Whistling-Thrush was the only species recorded at group 3 sites, while group 4 sites all had Grey Wagtails and Blue Whistling-Thrush, with one site also holding River Chat. Brown Dippers were characteristic of group 5, being found at all but one site, with River Chat, Plumbeous Redstart, Spotted and Little Forktails also being found at some sites. Group 6 was characterised by Plumbeous Redstart, Little Forktail and Brown Dipper, while most group 7 sites held River Chat and Plumbeous Redstart. All other species except Black-backed Forktail were recorded at some group 7 sites. Group 8 sites were characterised by River Chat, Plumbeous Redstart, Slaty-backed Forktail and Blue Whistling-Thrush.

Bird distribution and habitat structure

For all the frequently recorded bird species (i.e. found at > 20% of sites) except Spotted Forktail and Crested Kingfisher, there were significant difference in habitat structure (as RHS PC scores) between occupied and unoccupied sites within the range of altitudes where the species was recorded (Table 6.21, Fig. 6.36a and b). For example, sites where Little Forktail, Brown Dipper, Plumbeous Redstart, River Chat and Grey Wagtail were present had significantly lower sweep-up PC1 scores, indicating a preference for wider, deeper streams with laminar or torrential flows, unvegetated side and mid-channel bars, wider margins and fewer tree-related features, often through alpine environments. On PC2, sites Brown Dipper, Plumbeous Redstart and River Chat had significantly higher scores, indicating a preference on this axis for larger tree-lined streams in broad-leaved/mixed forest, with boulder substrates, waterfalls, exposed boulders and bedrock, vertical banks and torrential flows. Sites occupied by Grey Wagtails on the same axis had pebble/gravel substrates and gently sloping banks, through alpine or semi-improved grassland. On PC3, Little and Slaty-backed Forktails showed a preference for streams with composite banks, vegetated side bars and a combination of sand/silt and boulder substrates, often where outfalls from irrigation systems were found. The obvious altitudinal component to PC4 was reflected in the preference for streams flowing through agricultural or urban land, with reinforced or resectioned banks (often as a result of terracing), finer substrates, vegetated and unvegetated point bars, and more man-made features (weirs, dams, culverts, bridges and outfalls) by River Chat, Blue Whistling-Thrush and Grey Wagtail (Fig. 6.36).

From the Spot-check PCA, sites occupied by Brown Dipper, Plumbeous Redstart and River Chat all had significantly greater PC1 scores, indicating a preference for streams with boulder/cobble banks and substrates, side and mid-channel bars, torrential flow and exposed channel rocks. On the same PC, Slaty-backed Forktail showed a preference for streams with stable earth banks, finer substrates, static flows and riffles, greater bankside and riparian vegetation complexity and more channel vegetation. On PC2, Grey Wagtails showed a preference for streams with gravel/pebble or earth banks, gravel/pebble substrates, more riffles, and often with resectioned banks and channels. On PC3, sites occupied by River Chat had significantly lower scores, indicating a preference for streams with bedrock banks and some modifications, such as resectioning or reinforcement, pebble/gravel substrates, and greater vegetation complexity in the land use zone. Blue Whistling-thrush showed a preference for streams with stable cliff banks, boulder/cobble substrates and exposed channel rocks on PC4, and clay or reinforced banks, silty substrates, laminar flows and greater bank vegetation complexity on PC5 (Table 6.21; Fig. 6.36c-e).

Bird distribution and invertebrates

Invertebrate taxon richness and Trichoptera and Hemiptera abundance were significantly higher at sites with Little Forktails, while sites with Spotted Forktails had higher Odonata abundance. Slaty-backed Forktails, were found at sites with more Odonata and Hemiptera, while sites with Brown Dippers had fewer Diptera. Plumbeous Redstarts occurred at sites with more Ephemeroptera and Hemiptera, and fewer Plecoptera and Diptera. Sites with River Chats also had more Ephemeroptera and Hemiptera, and fewer Diptera. Blue Whistling-Thrush were found at sites with more Ephemeroptera and Odonata, and Grey Wagtail at sites with more Ephemeroptera and fewer Plecoptera. Sites with Crested Kingfishers had more Odonata and Hemiptera. In all these cases, spurious effects with altitude are possible; no species showed significant trends with total riffle invertebrate abundance or Coleoptera abundance (Table 6.22; Fig. 6.37).

Bird distribution and chemistry

Sites where Slaty-backed Forktail, Plumbeous Redstart, River Chat, and Grey Wagtail were recorded all had significantly greater chemistry PC1 scores, reflecting greater base-richness at sites where these species were absent; this results probably reflects a spurious effect by altitude. Sites with Grey Wagtails had greater PC2 scores, reflecting greater ionic loading at the lower altitude sites where this species was most common (Table 6.23; Fig. 6.38).

Bird distribution and stability

Interestingly, possibly reflecting also effects by habitat structure, sites where Brown Dippers and River Chat were present had significantly lower stability (Table 6.24; Fig. 6.39). No other species showed any significant trend with stream-bed stability.

Table 6..21 *One-way ANOVAs on PCA scores from 'sweep-up' and 'spot-check' data from RHS of 182 streams in the Indian and Nepalese Himalaya. Only those sites in the altitudinal range of each species are included. Only significant results are shown. See Figure 6.36.*

Species	df	F	*P*
Little Forktail and:			
Sweep-up PC1	1, 134	7.39	0.007
Sweep-up PC3	1, 134	7.60	0.007
Slaty-backed Forktail and:			
Sweep-up PC3	1, 47	6.28	0.016
Spot-check PC1	1, 471	3.73	0.001
Brown Dipper and:			
Sweep-up PC1	1, 180	8.41	0.004
Sweep-up PC2	1, 180	7.92	0.005
Spot-check PC1	1, 1801	5.83	0.000
Plumbeous Redstart and:			
Sweep-up PC1	1, 1412	2.24	0.000
Sweep-up PC2	1, 1412	4.02	0.000
Spot-check PC1	1, 1411	3.46	0.000
River Chat and:			
Sweep-up PC1	1, 1591	8.35	0.000
Sweep-up PC2	1, 1591	4.56	0.000
Sweep-up PC4	1, 159	4.31	0.039
Spot-check PC1	1, 159	4.64	0.033
Spot-check PC3	1, 159	4.14	0.044
Blue Whistling-Thrush and:			
Sweep-up PC4	1, 122	5.55	0.020
Spot-check PC4	1, 122	6.60	0.011
Spot-check PC5	1, 122	5.45	0.021
Grey Wagtail and:			
Sweep-up PC1	1, 97	9.70	0.002
Sweep-up PC2	1, 97	4.18	0.044
Sweep-up PC4	1, 97	5.08	0.026
Spot-check PC2	1, 971	9.00	0.000

Table 6.22. *Results of One-way ANOVAs on invertebrate order abundances between 182 sites in the Indian and Nepalese Himalaya, grouped according to the presence or absence of each of 9 river bird species. Only results significant at P<0.05 are shown. Sites were sampled in 1994-1996. See Figure 6.37.*

	df	F	P
Little Forktail			
Taxon richness (riffles)	1, 180	9.29	0.003
Trichoptera abundance	1, 180	4.84	0.029
Hemiptera abundance	1, 180	10.29	0.002
Spotted Forktail			
Odonata abundance	1, 180	4.34	0.039
Slaty-backed Forktail			
Odonata abundance	1, 180	12.47	0.001
Hemiptera abundance	1, 180	17.60	0.000
Brown Dipper			
Diptera abundance	1, 180	9.44	0.002
Plumbeous Redstart			
Ephemeroptera abundance	1, 180	17.87	0.000
Plecoptera abundance	1, 180	7.70	0.006
Hemiptera abundance	1, 180	24.00	0.000
Diptera abundance	1, 180	10.19	0.002
River Chat			
Ephemeroptera abundance	1, 180	11.20	0.001
Hemiptera abundance	1, 180	13.19	0.000
Diptera abundance	1, 180	6.41	0.012
Blue Whistling-Thrush			
Ephemeroptera abundance	1, 180	4.37	0.038
Odonata abundance	1, 180	4.35	0.039
Grey Wagtail			
Ephemeroptera abundance	1, 180	8.85	0.003
Plecoptera abundance	1, 180	12.06	0.001
Crested Kingfisher			
Odonata abundance	1, 180	6.30	0.013
Hemiptera abundance	1, 180	4.41	0.037

Table 6..23 *One-way ANOVAs on scores from PCA on water chemistry data from 182 streams in the Indian and Nepalese Himalaya, sampled in 1994-1996.*

Species	df	F	*P*
Slaty-backed Forktail and PC1	1, 178	14.43	0.000
Plumbeous Redstart and PC1	1, 178	11.37	0.001
River Chat and PC1	1, 178	12.20	0.001
Grey Wagtail and PC1	1, 178	11.45	0.001
Grey Wagtail and PC2	1, 178	4.98	0.027

Table 6..24 *Results of one-way ANOVAs on Pfankuch Index between sites grouped according the presence of river bird species (see Figure 6.39).*

Species	df	F	P
Brown Dipper	1, 173	5.91	0.016
River Chat	1, 173	5.60	0.019

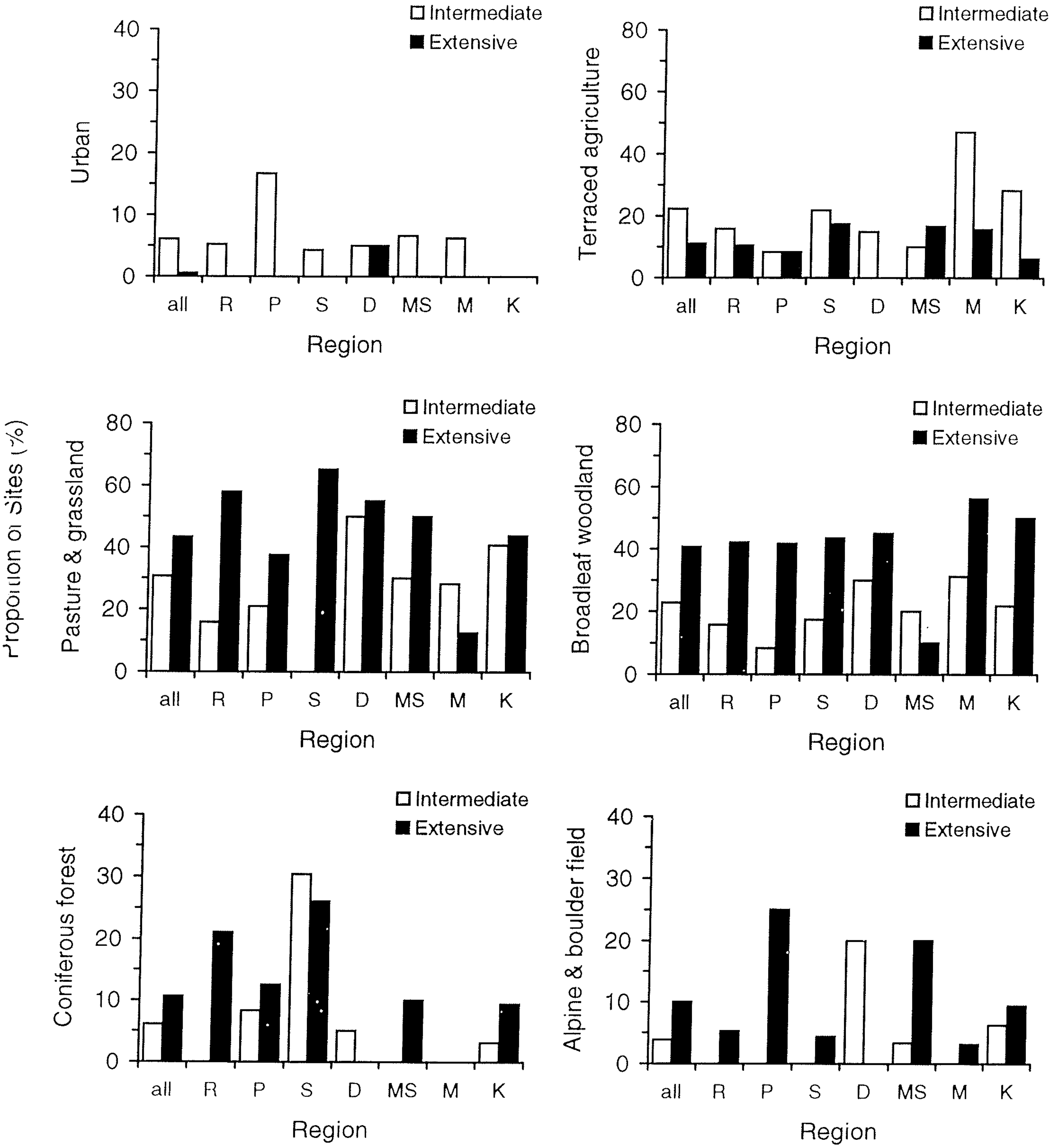


Figure 6.1 *The proportion of biological sites within each region with catchments containing either intermediate or extensive cover by different land use types.*

D1

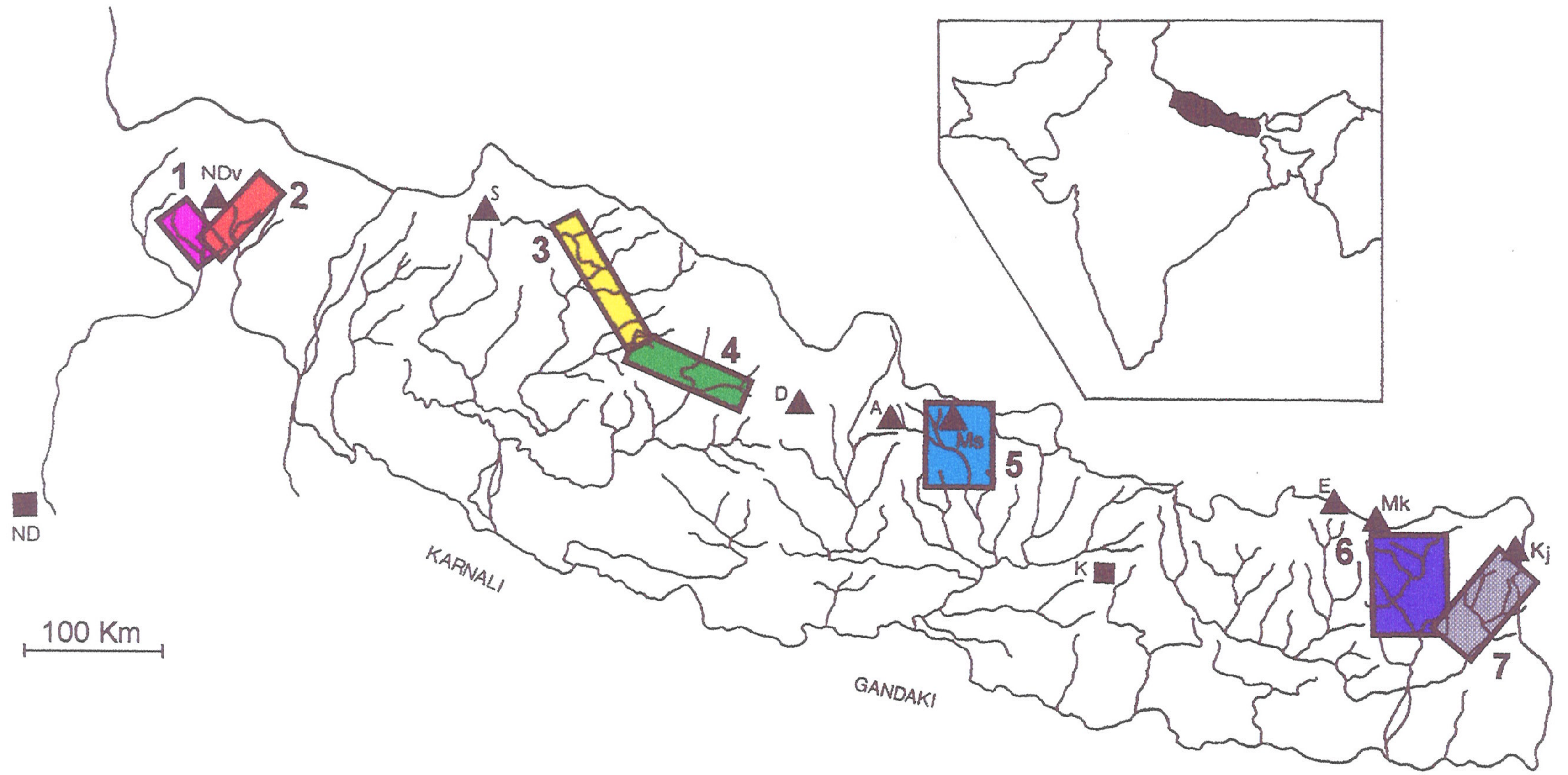
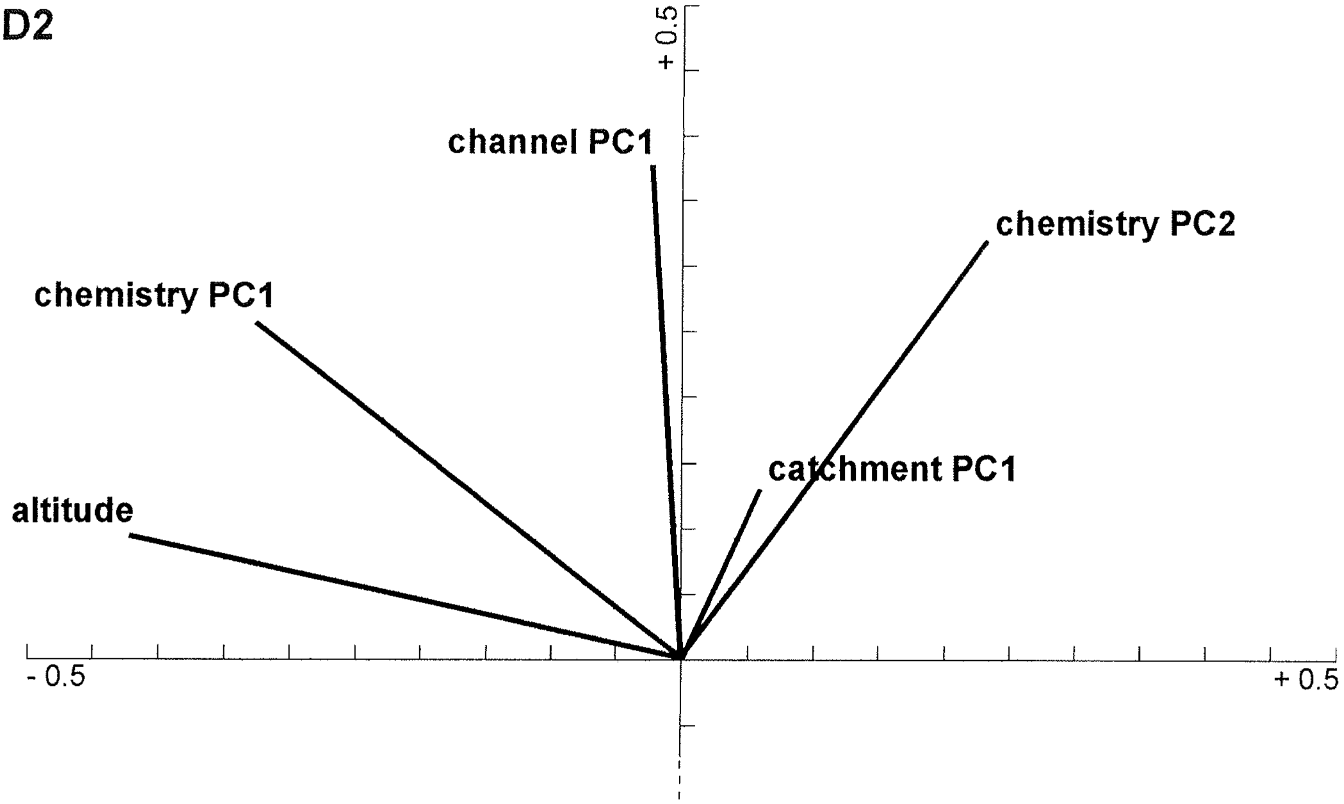


Figure 6.2

1: Roop Kund (R); 2: Pindari (P); 3: Simikot (S); 4: Dunai (D); 5: Manaslu (MS); 6: Makalu (M); 7: Kanchenjunga (K).

D2



Axis	*1*	*2*	*3*	*4*
Eigenvalue	0.293	0.145	0.104	0.052
Species-environment correlation	0.889	0.780	0.771	0.624
Species variance explained (%)	10.1	5.0	3.6	1.7
Species-environment variance explained (%)	47.3	23.3	16.7	8.4
Linear correlation with:				
altitude	- 0.75***	0.15	- 0.37***	0.09
water chemistry PC1	- 0.58***	0.40***	0.43***	- 0.04
water chemistry PC2	0.41***	0.50***	- 0.01	0.10
channel PC1	- 0.04	0.59***	- 0.37***	- 0.06
catchment PC1	0.10	0.20*	- 0.21*	- 0.55***

Summary of canonical community ordination of diatom species from 179 Himalayan streams. Significant environmental variables selected by a stepwise procedure (* $p < 0.05$, *** $p < 0.001$).

Water chemistry PC1	*Water chemistry PC2*	*Channel PC1*	*Catchment PC1*
Conductivity +	Sodium +	Bank width -	Shading +
Calcium +	Silica +	Water width -	Trees +
Magnesium +	Chloride +	Margin width -	Fallen trees +
Strontium +	Potassium +	Riffle +	O'hang. boughs +
Sulphate +		Torrential flow -	Bankside roots +
pH +		Unveg. side bars -	Mixed woods +
Barium +		% Gravel +	Underwater roots +
		Unveg. mid bars -	Alpine -
		% Boulders -	Boulder fields -
		Depth -	
		Exposed boulders -	
		% Pebbles +	
		Pool +	

Figure 6.3

Principal components, and variables with highest loading values, describing chemistry and habitat character of 179 Himalayan streams.

D3

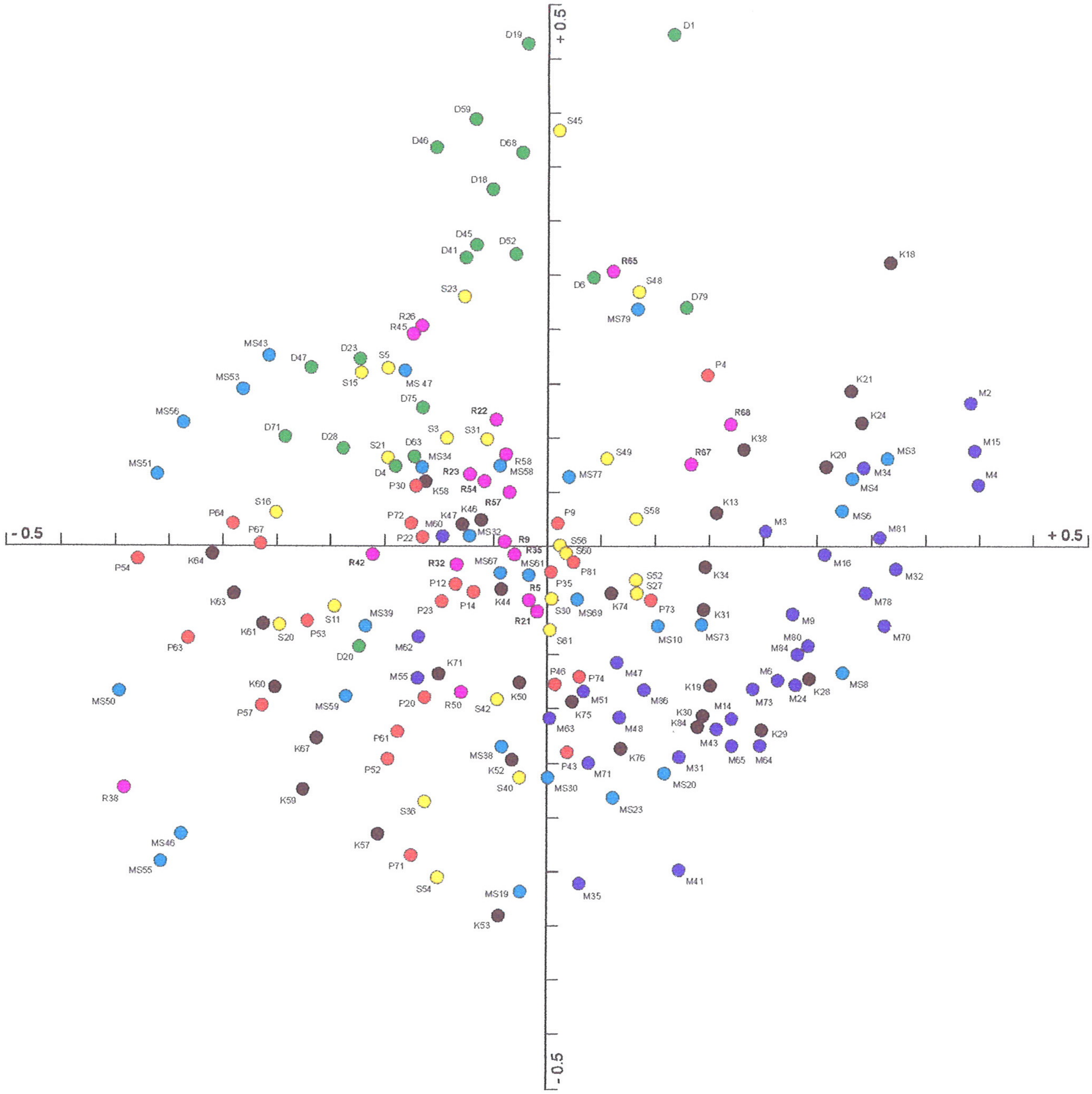


Figure 6.4

Ordination diagram based on canonical correspondance analysis (CCA) of relative abundances of diatoms from 179 Himalayan streams.
Sites lie at the centroid of the points of species that occur in them (see species plot). Species points close to site points therefore indicate high abundance (see map for colour code).

D4

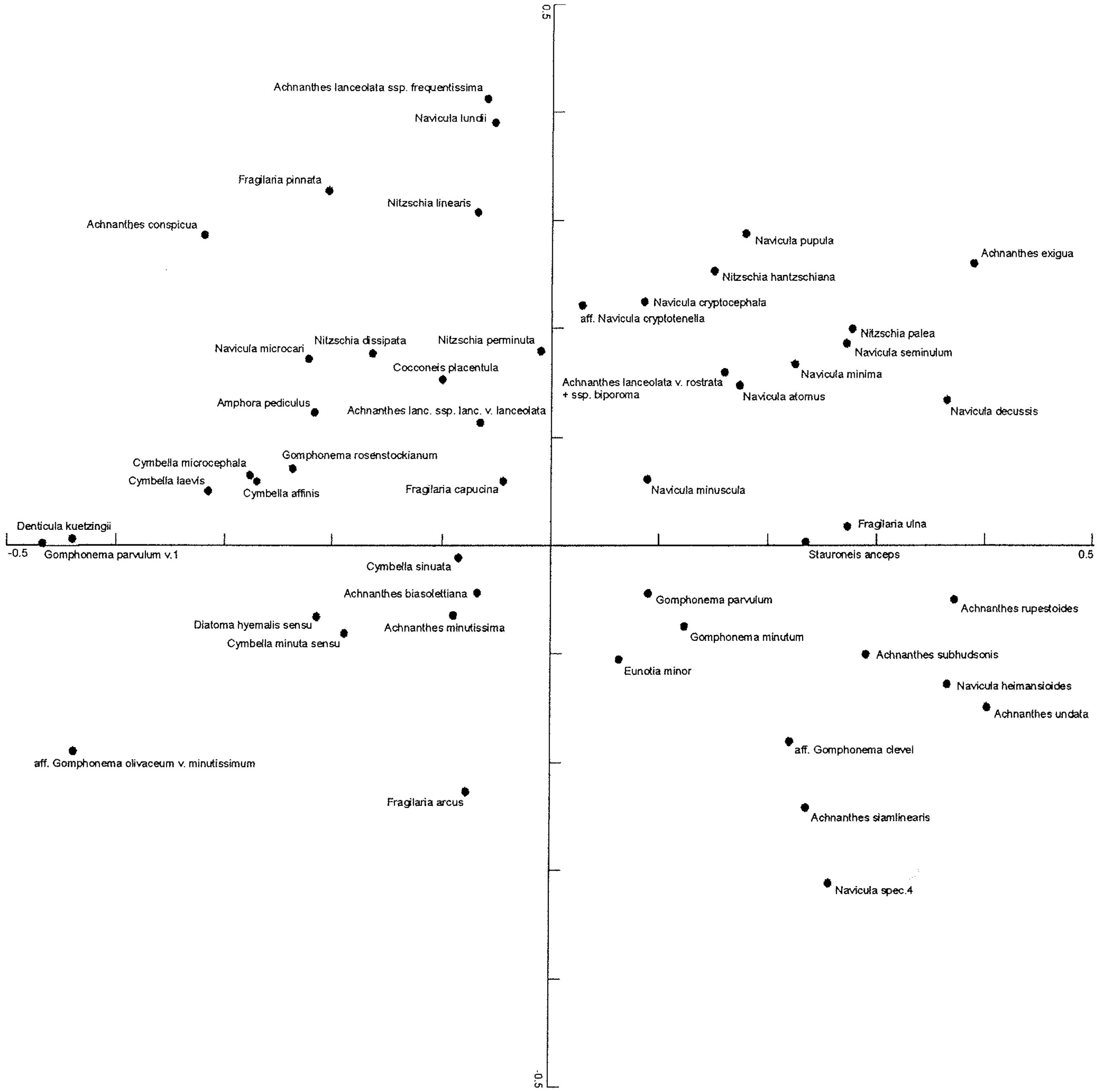


Figure 6.5

Ordination diagram based on canonical correspondance analysis (CCA) of relative abundances of diatoms from 179 Himalayan streams.
Points approximate weighted averages of each of the species with respect to each environmental variable.

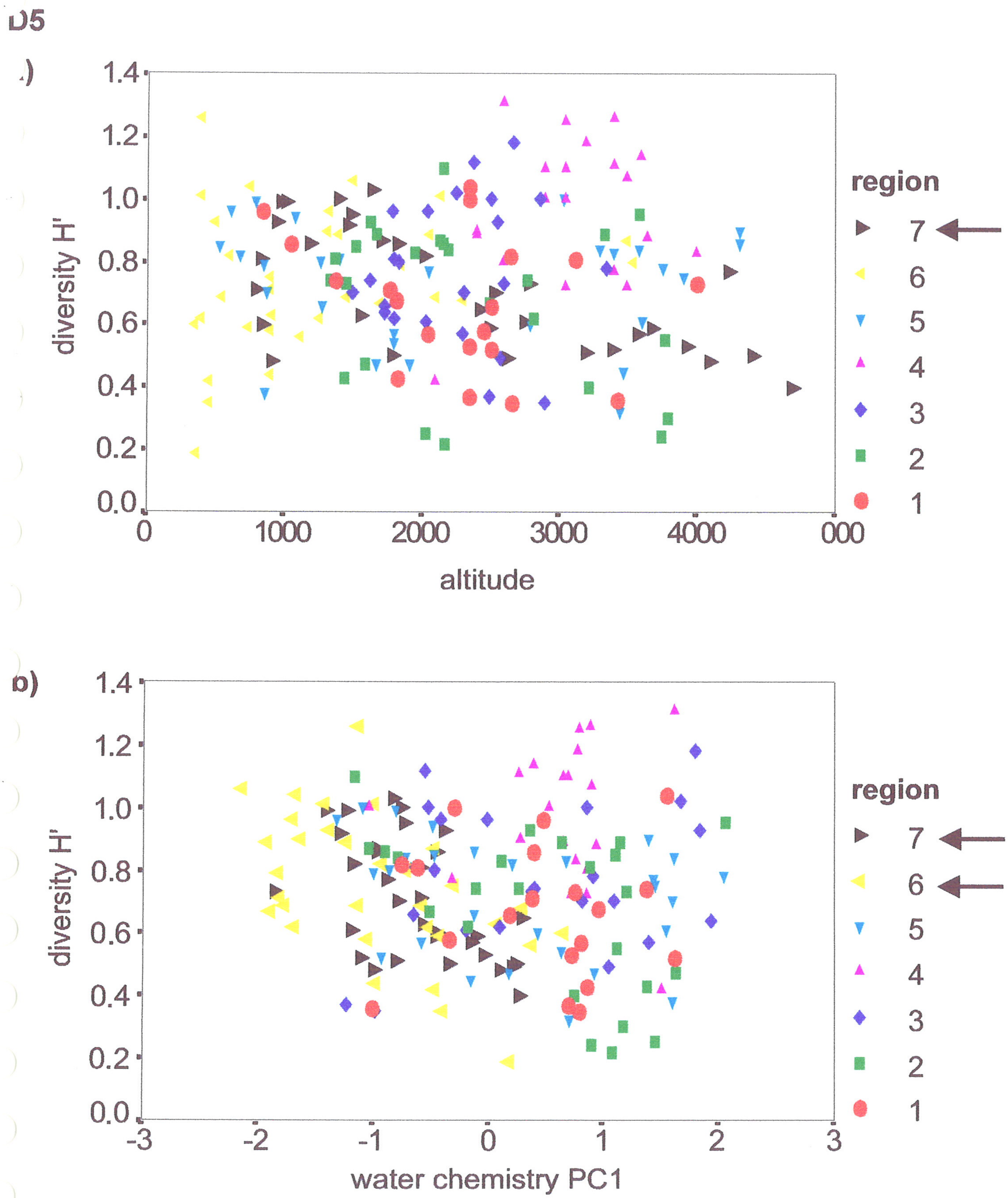


Figure 6.6

Relationship between diatom diversity, altitude (Fig. a) and water chemistry (Fig. b) in 179 Himalayan streams. The arrows indicate regions where diversity H' was significantly correlated with altitude and water chemistry PC1.

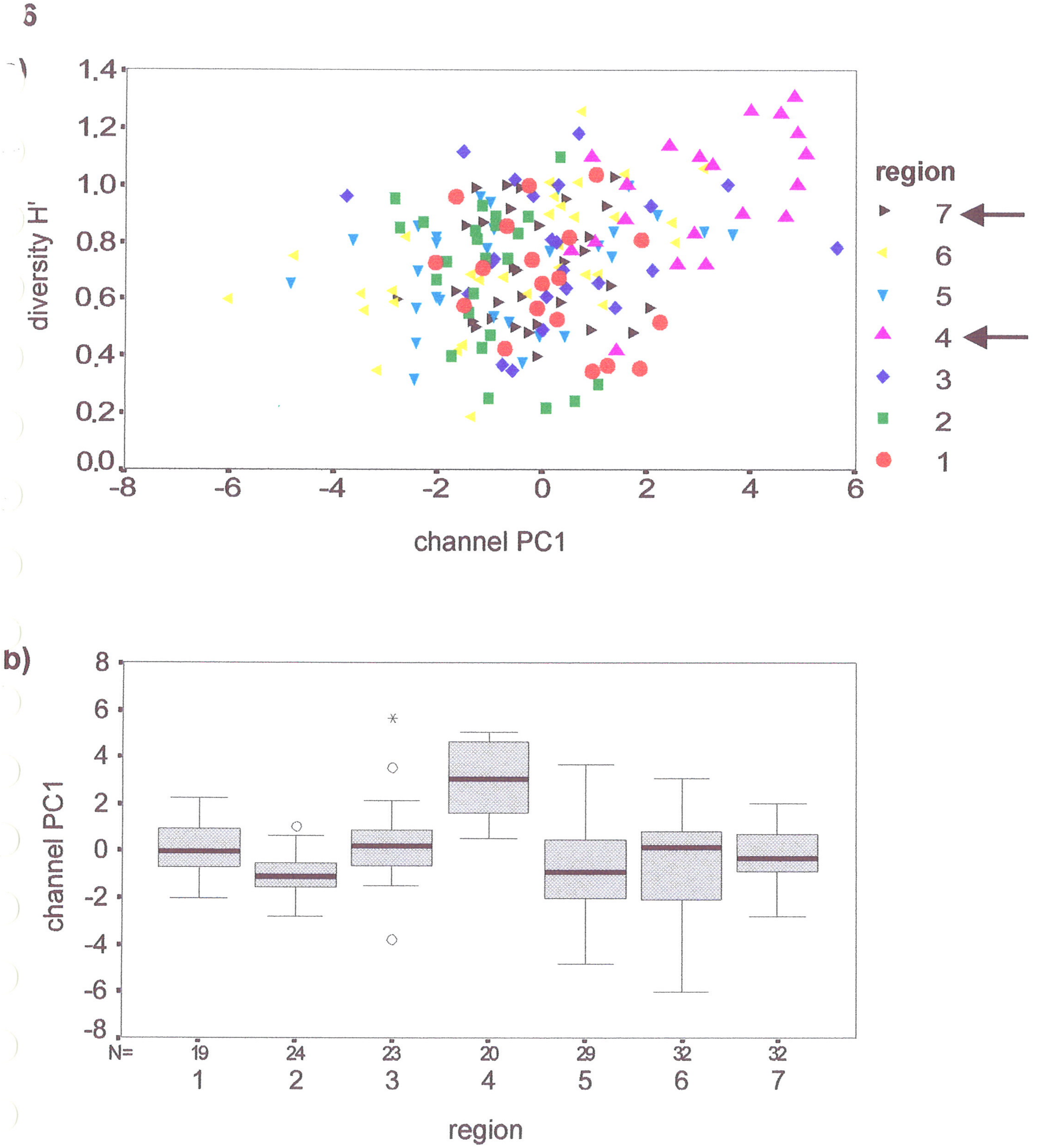
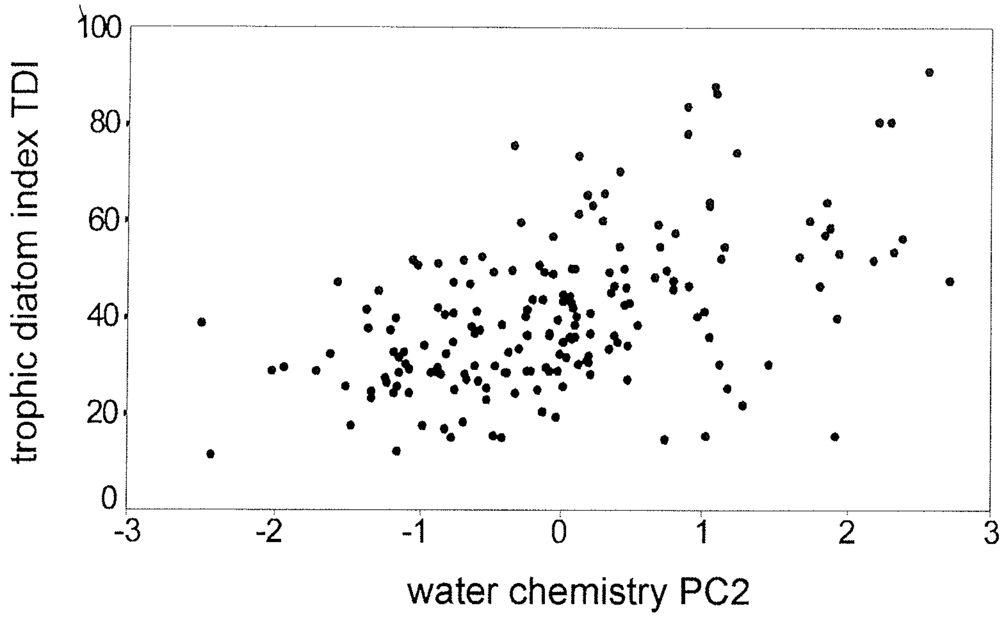


Figure 6.7

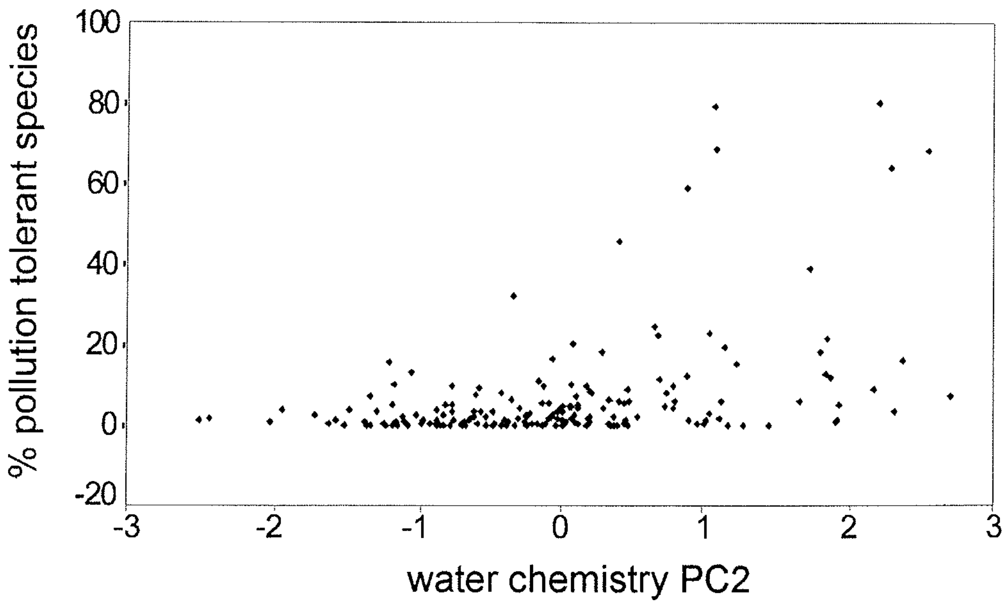
Relationship between diatom diversity and channel PC1 in 179 Himalayan streams. Channel PC1 represents a gradient from larger streams with coarse substrata to smaller streams with a pool-riffle sequence and fine substrata (Fig. a). Channel character, shown by PC1, in 7 Himalayan regions (Fig. b).

D7

a)



b)



Relationship between the trophic diatom index (Fig. a), % pollution tolerant species (Fig. b) and water chemistry PC2 from 179 Himalayan streams. Water chemistry PC2 represents an increase in Na, Si, Cl and K.

	a (± *SE*)	*b* (± *SE*)	*F*	r^2	*P*
TDI	40.86 (1.03)	8.08 (1.03)	61.27	25.7	< 0.001
IDG	18.44 (0.86)	4.95 (0.87)	32.47	15.5	< 0.001

Regression of the British (TDI) and the French (IDG) trophic diatom index on water chemistry PC2.

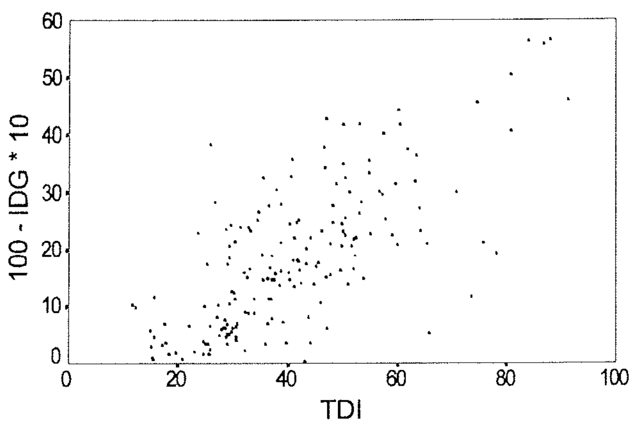
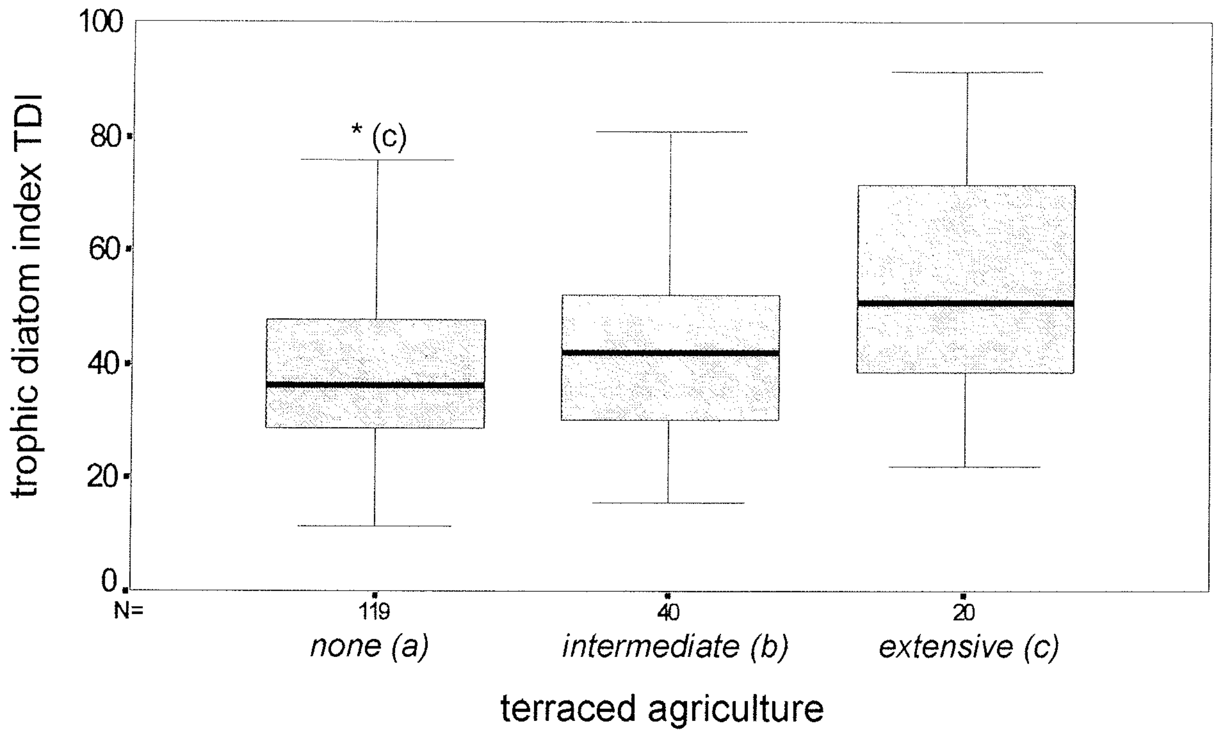


Figure 6.8

a)



b)

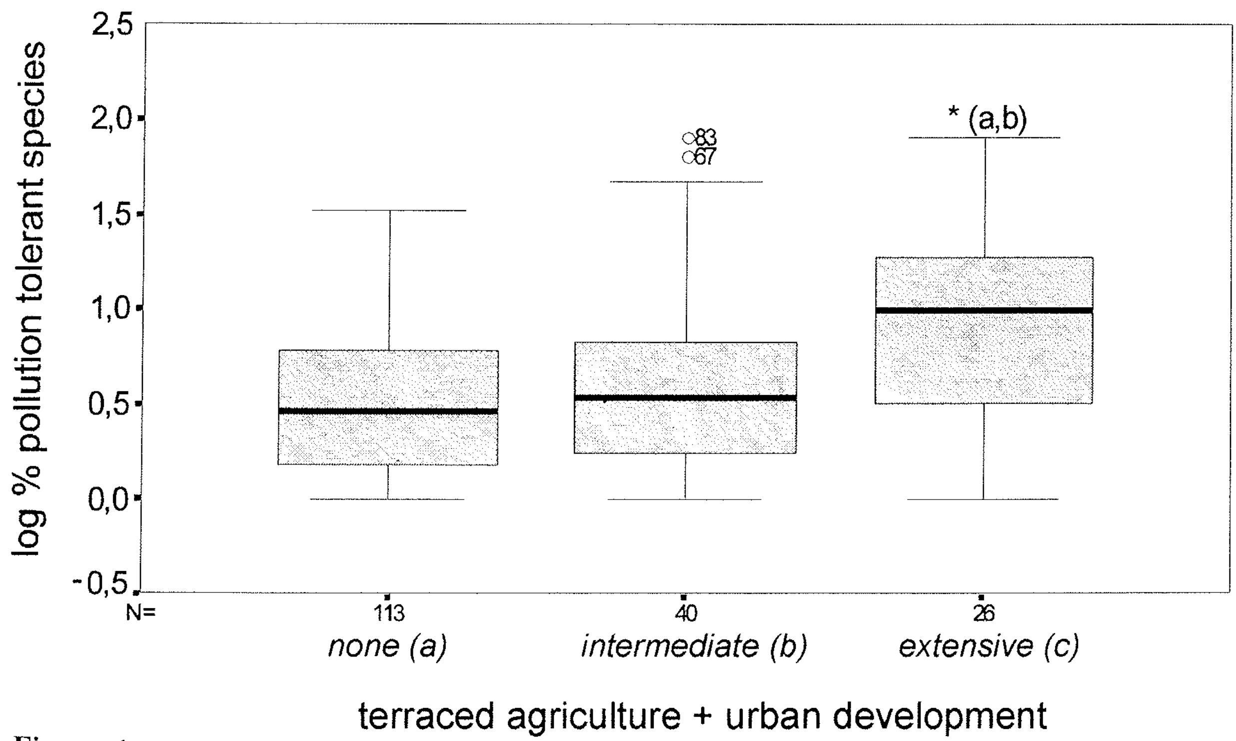


Figure 6.9

Differences in TDI scores (Fig. a) and percentage of pollution tolerant species (Fig. b) between land use categories in 179 Himalayan streams. ANOVAs on log transformed data: TDI: $F_{2,176}$ 9.13, $p < 0.001$, % pollution tolerant species: $F_{2,176}$ 9.04, $p < 0.001$; Significant pairwise differences according to Tukey Kramer range tests are indicated by letter coding. Boxplots give range, 50 percentile and mean.

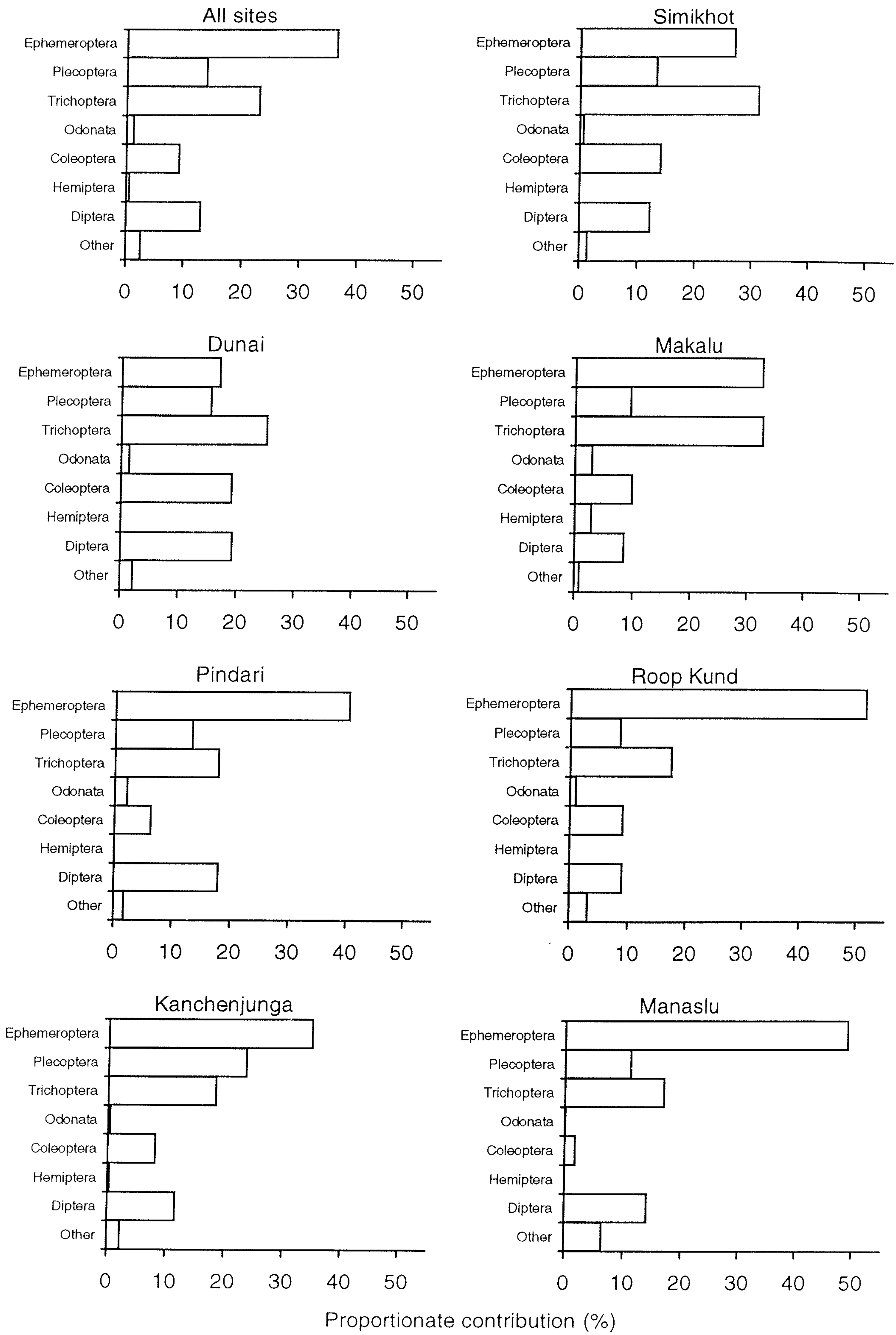


Figure 6.10 *Proportionate contribution by the major invertebrate orders to the aquatic invertebrate fauna of streams in seven regions of the Himalaya.*

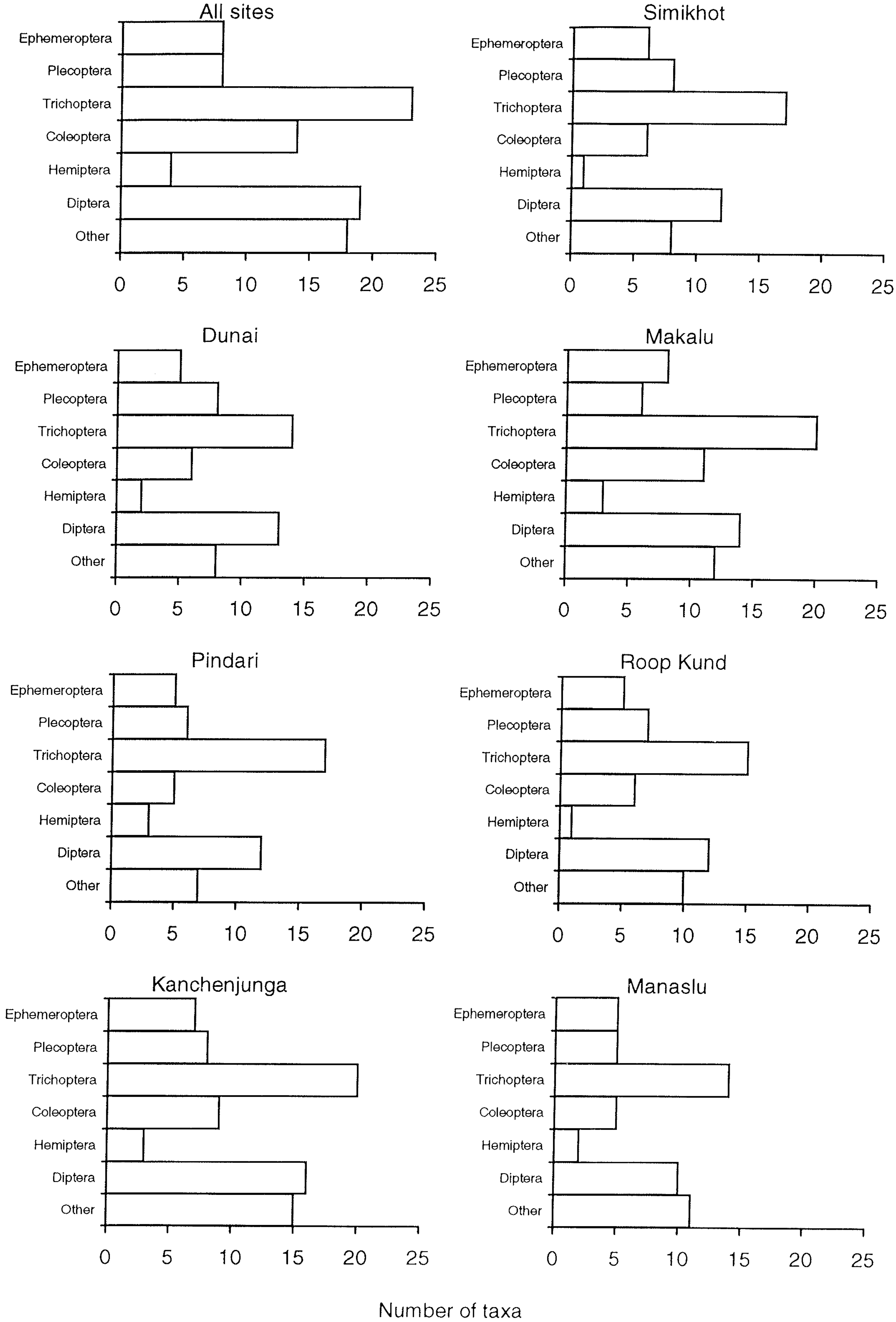


Figure 6.11 *Number of taxa from the major invertebrate orders recorded from streams in seven regions of the Himalaya.*

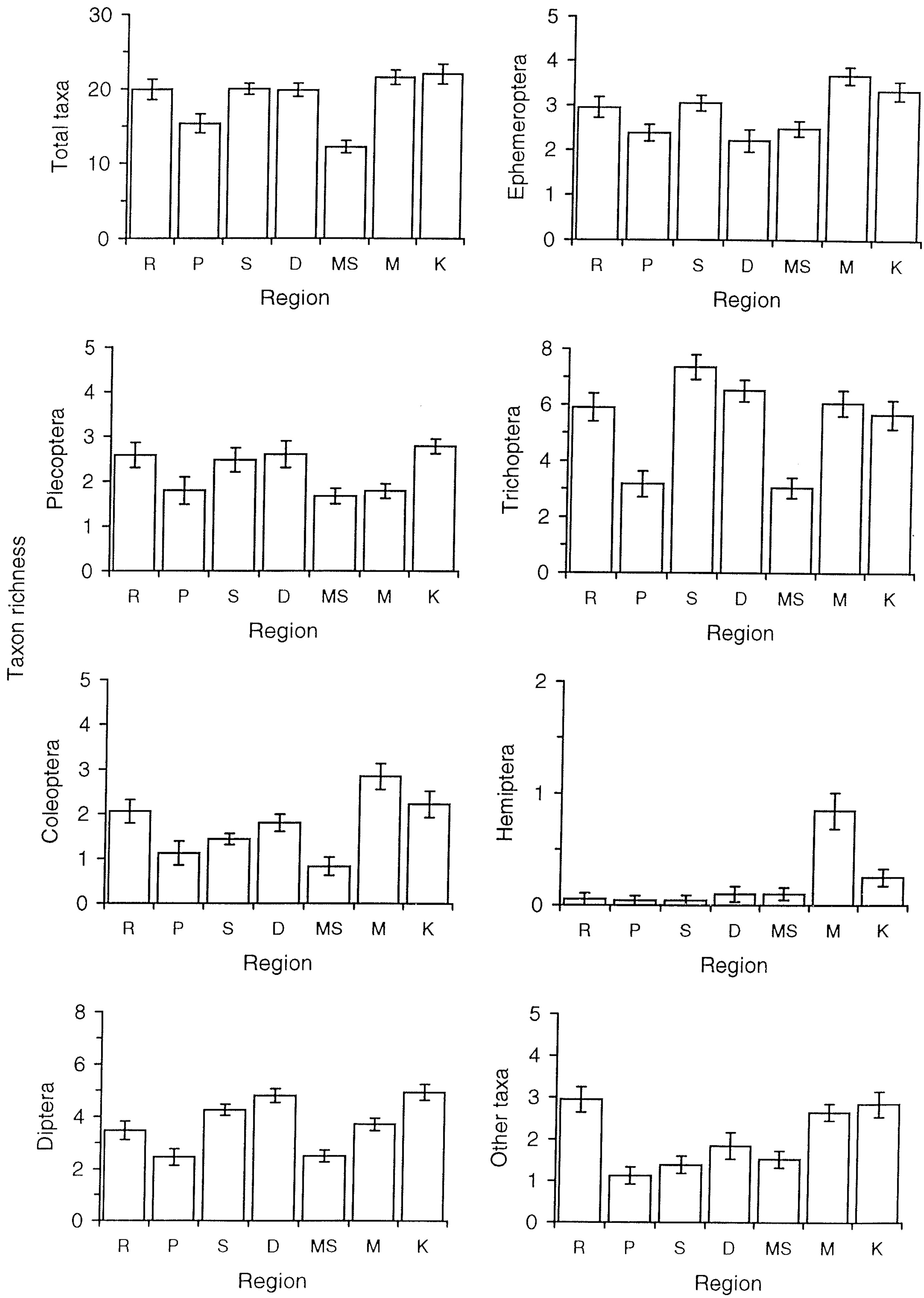


Figure 6.12 *Mean (± 1 SE) taxon richness and number of invertebrate taxa from each major order recorded at streams sites in seven regions of Himalayas.*

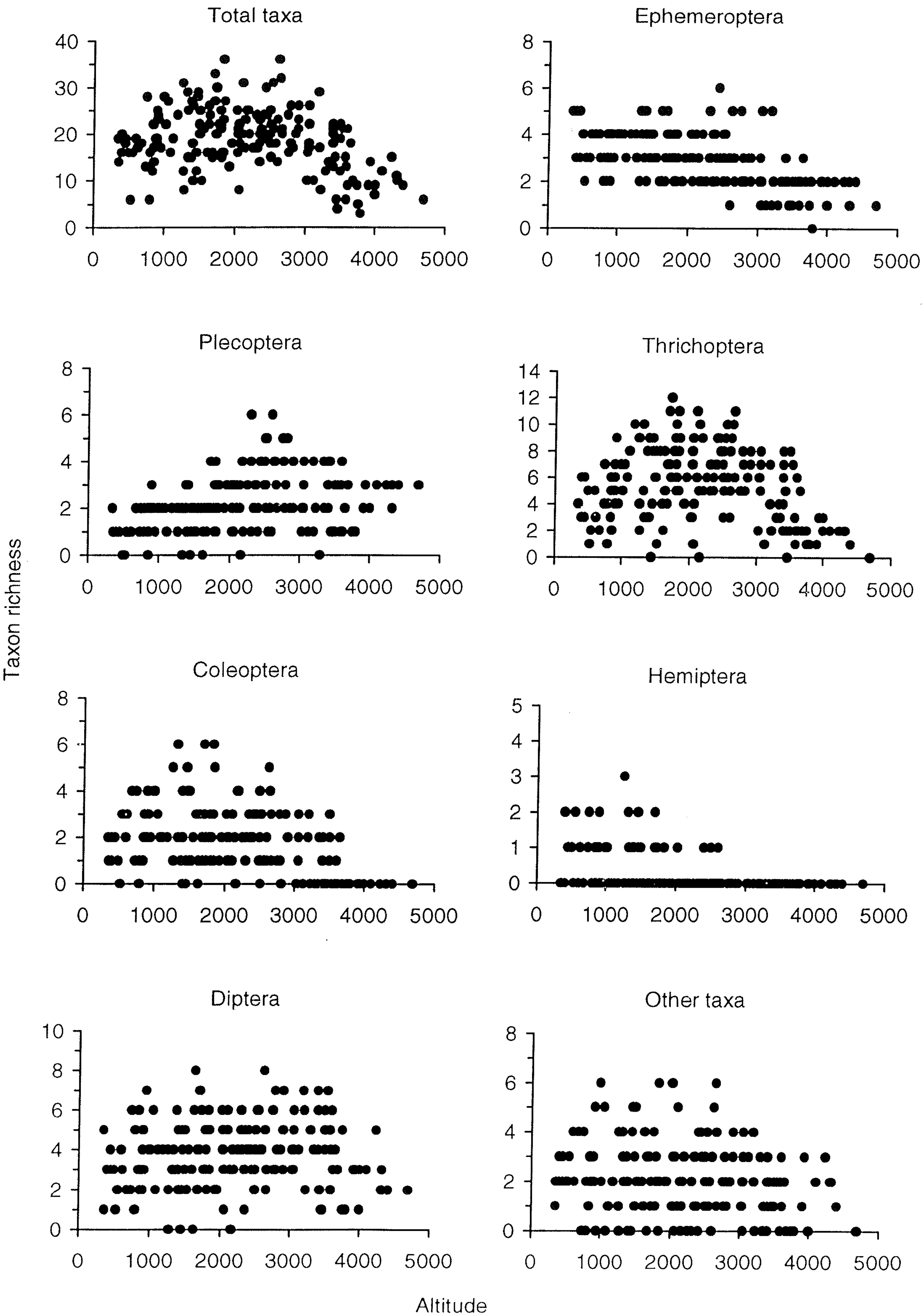


Figure 6.13 *Relationships between altitude and the number taxa in invertebrate orders at 180 streams of the Himalaya.*

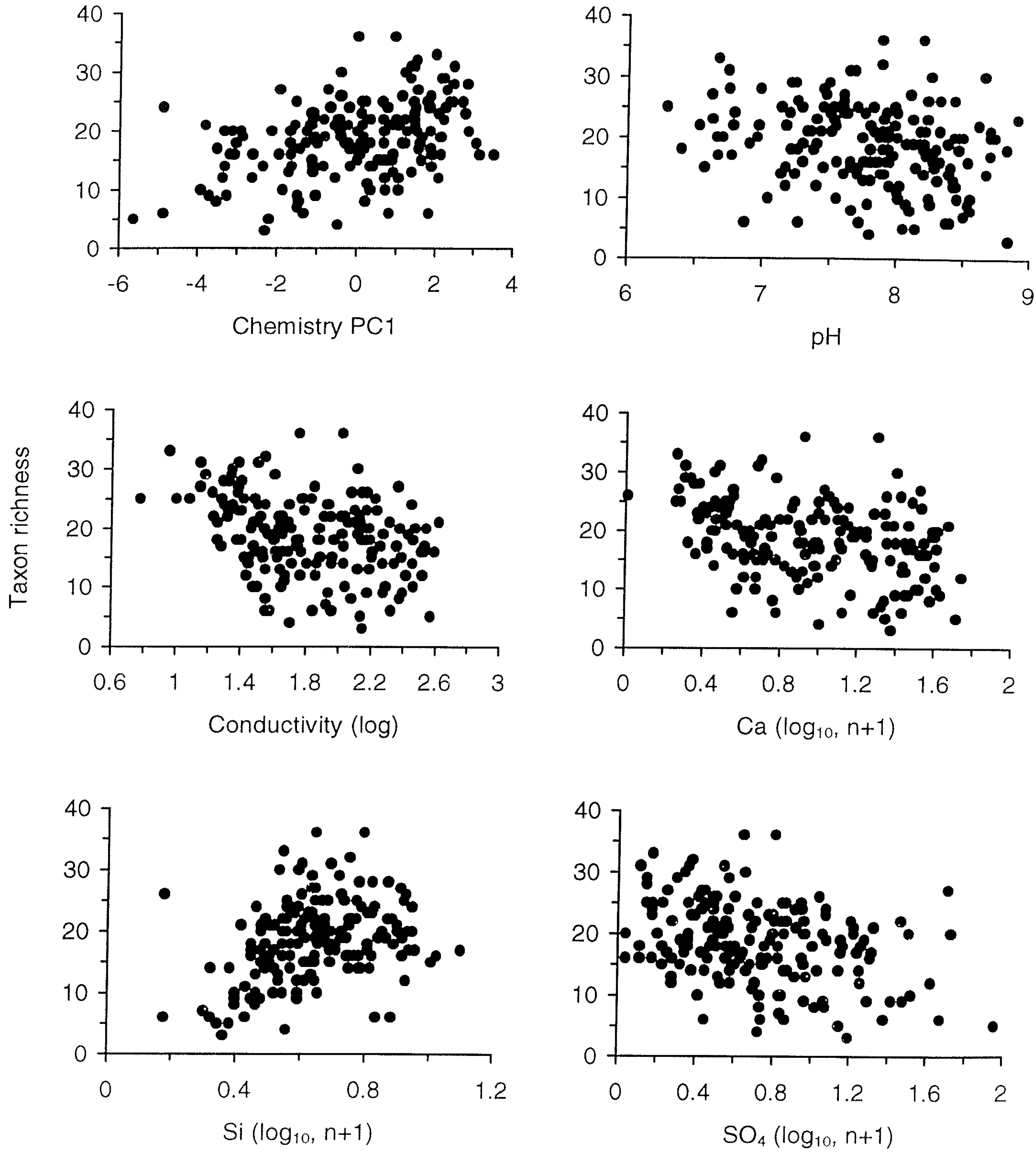


Figure 6.14 *Relationships between water chemistry variables and invertebrate taxon richness at 180 streams in the Himalayas.*

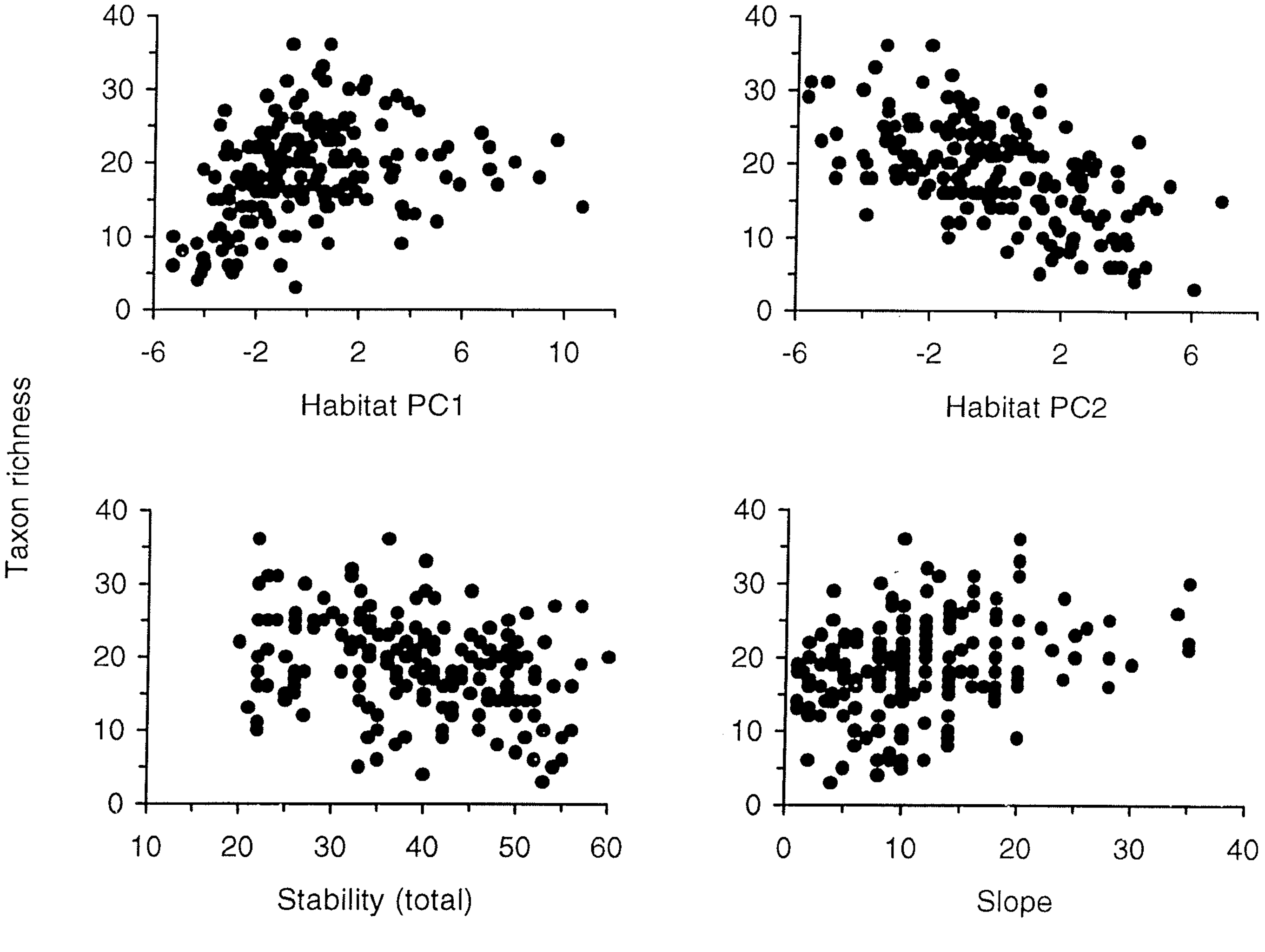


Figure 6.15 *Relationships between physical habitat variables and invertebrate taxon richness at 180 streams of the Himalaya.*

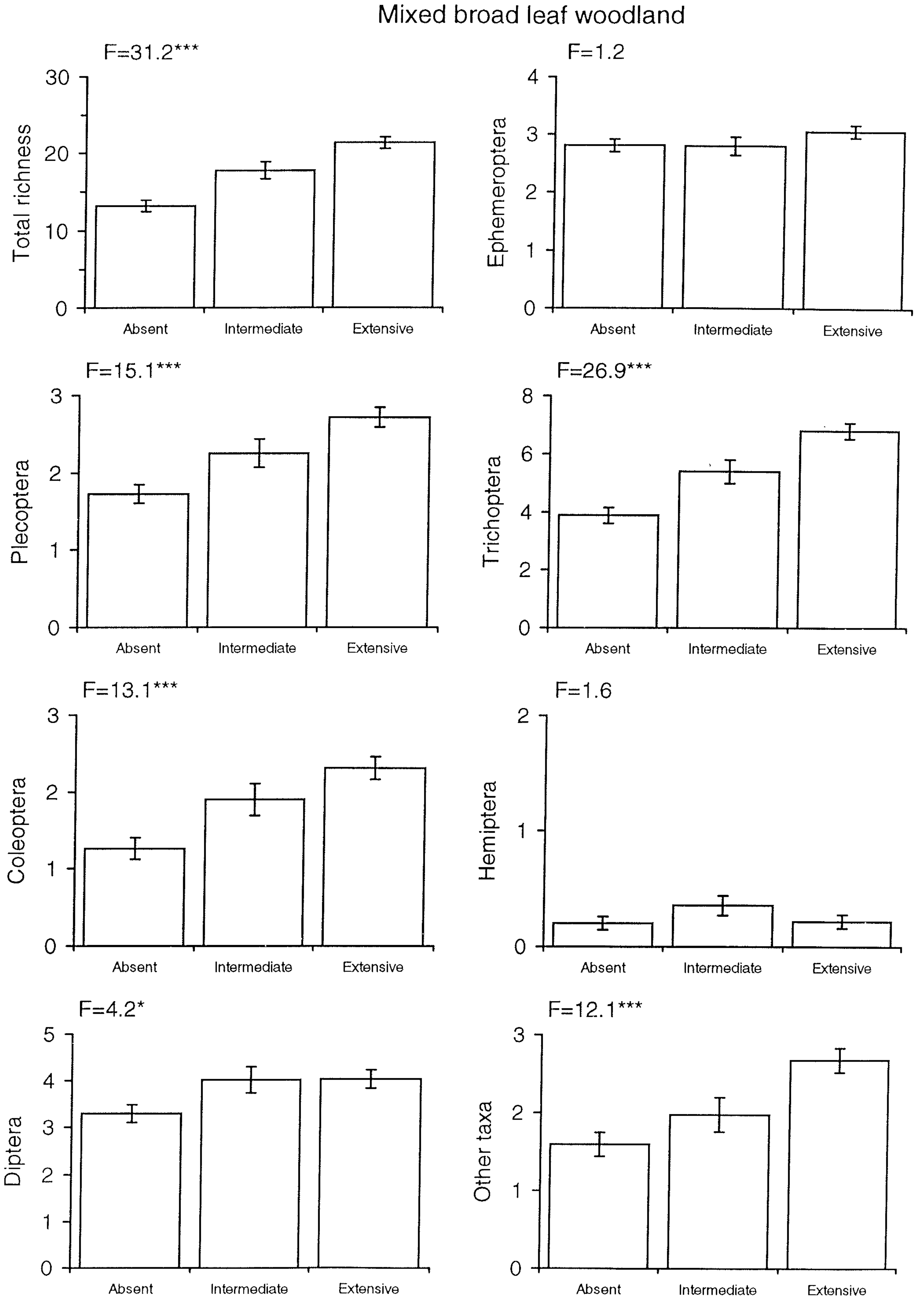


Figure 6.16 *Altitude adjusted mean (± 1 SD) number of invertebrate taxa in riffle habitats from sites with catchments containing contrasting levels of broad leaf mixed woodland. Results of ANOVA (GLM) with altitude held constant by inclusion as a covariable. Significance levels;* $*p = 0.05$, $***p < 0.001$.

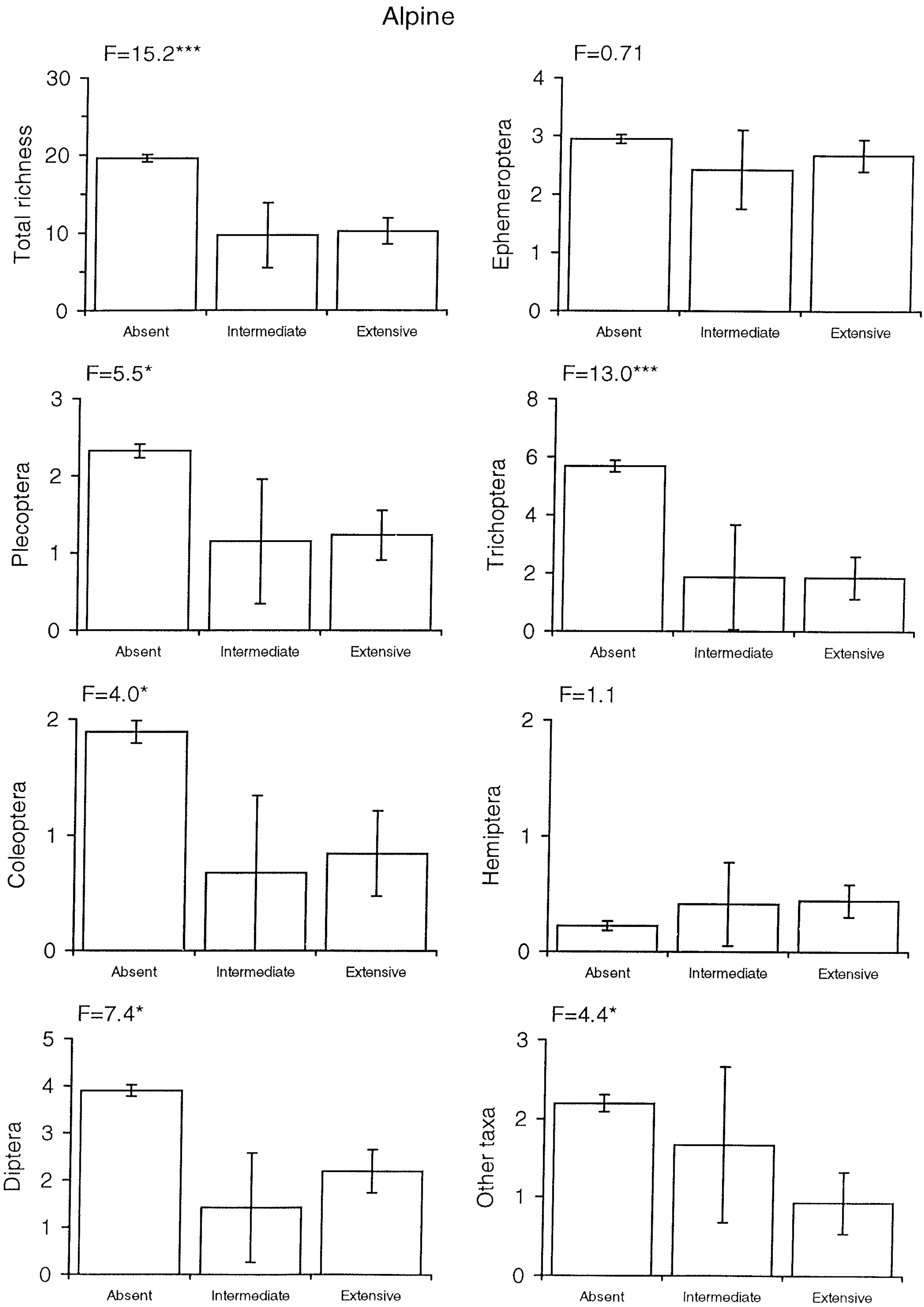


Figure 6.17 *Altitude adjusted mean (± 1 SD) number of invertebrate taxa in riffle habitats from sites with catchments containing contrasting levels of alpine land use.*
Results of ANOVA (GLM) with altitude held constant by inclusion as a covariable.
*Significance levels; *p = 0.05, ***p < 0.001.*

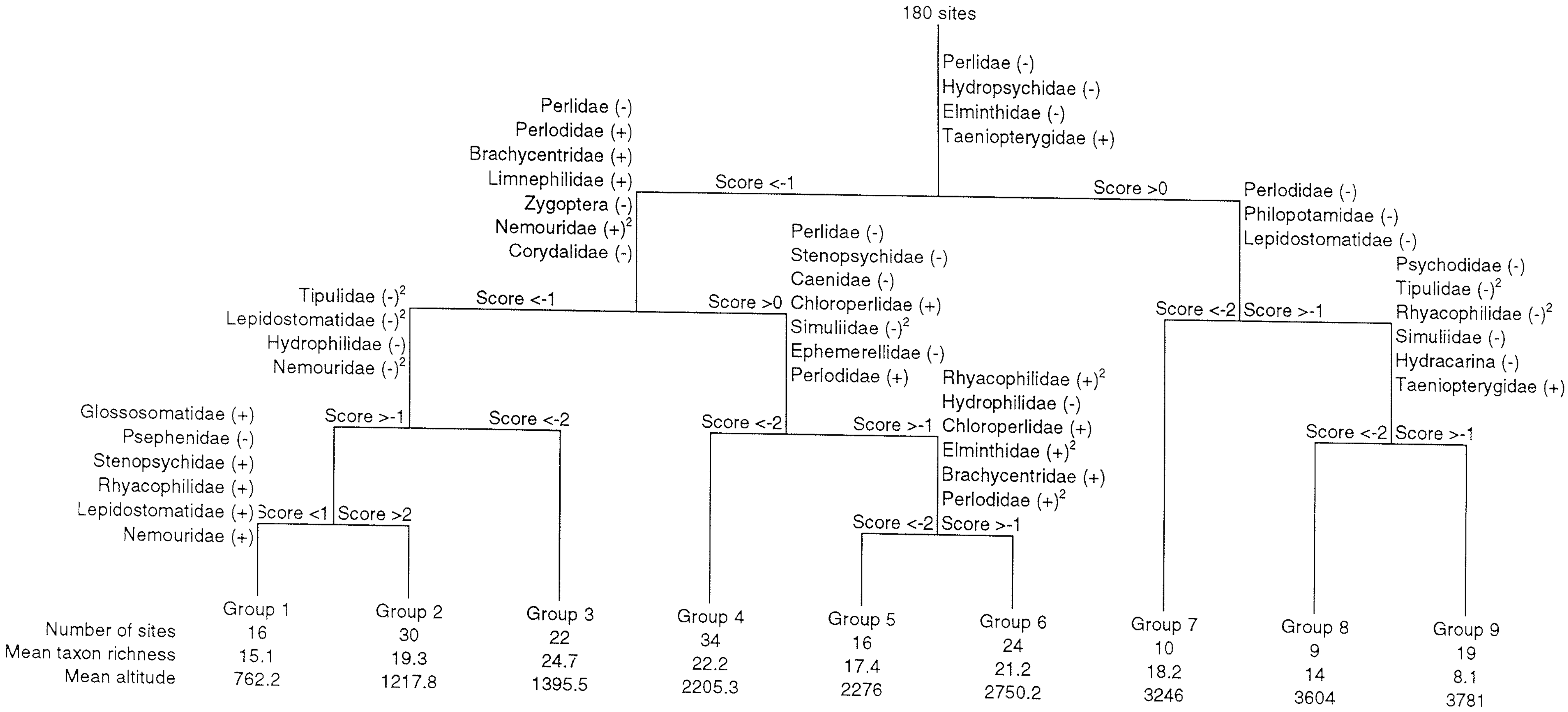


Figure 6.18 *Macroinvertebrate indicator taxa of TWINSPAN classification of 180 sites into 9 groups classified on the basis of their invertebrate communities.*
Indicator scores (+) = +1, (-) = - 1; a 2 raised above the line = > 10 individuals.

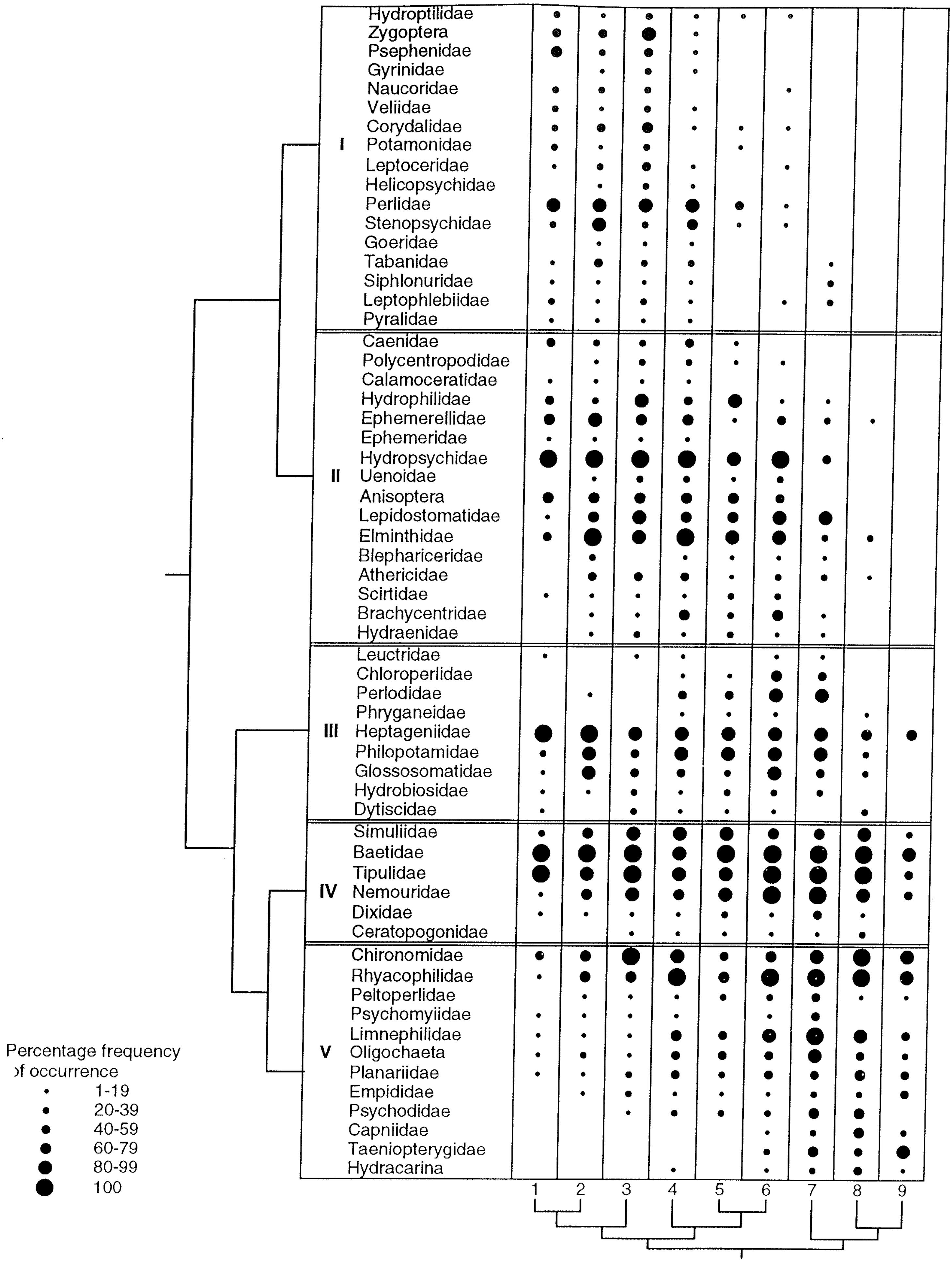


Figure 6.19 *Classification of species and sites by TWINSPAN. The circles show percentage frequency of occurrence of taxa at sites in each group (only the sixty most widely occurring taxa are shown).*

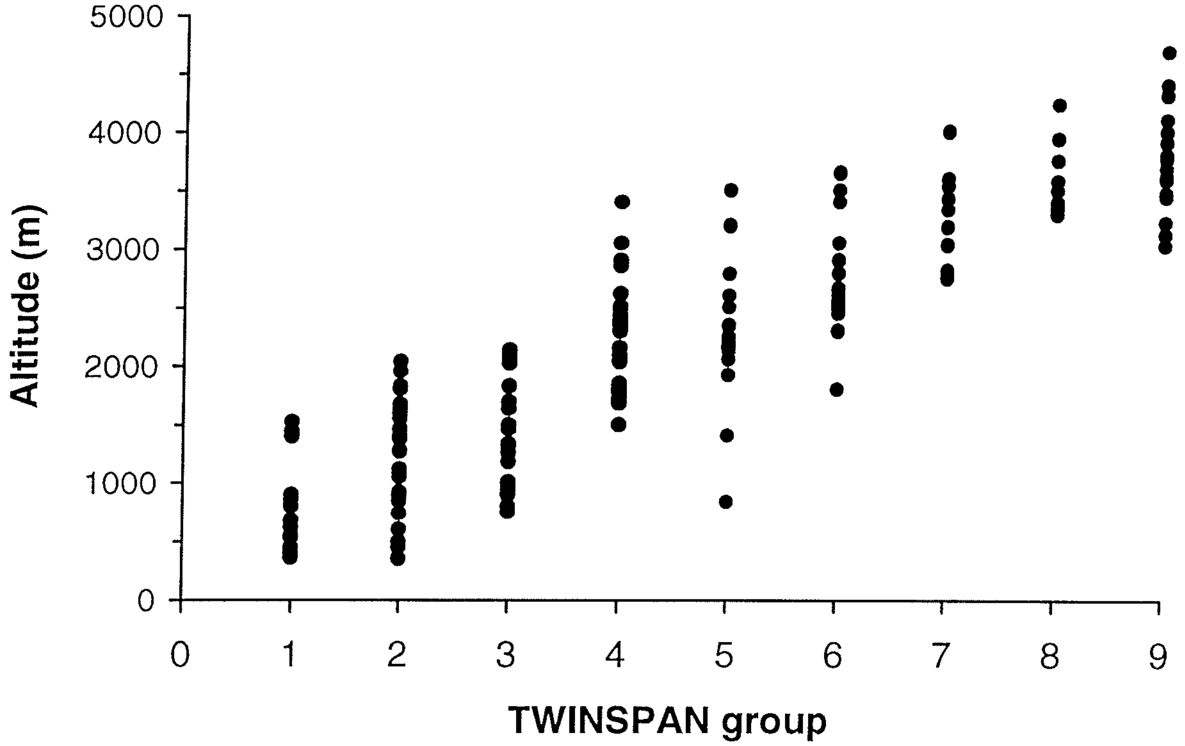


Figure 6.20 *The altitudinal distribution of sites in each TWINSPAN group classified on the basis on invertebrate communities sampled from 180 sites in the Himalaya.*

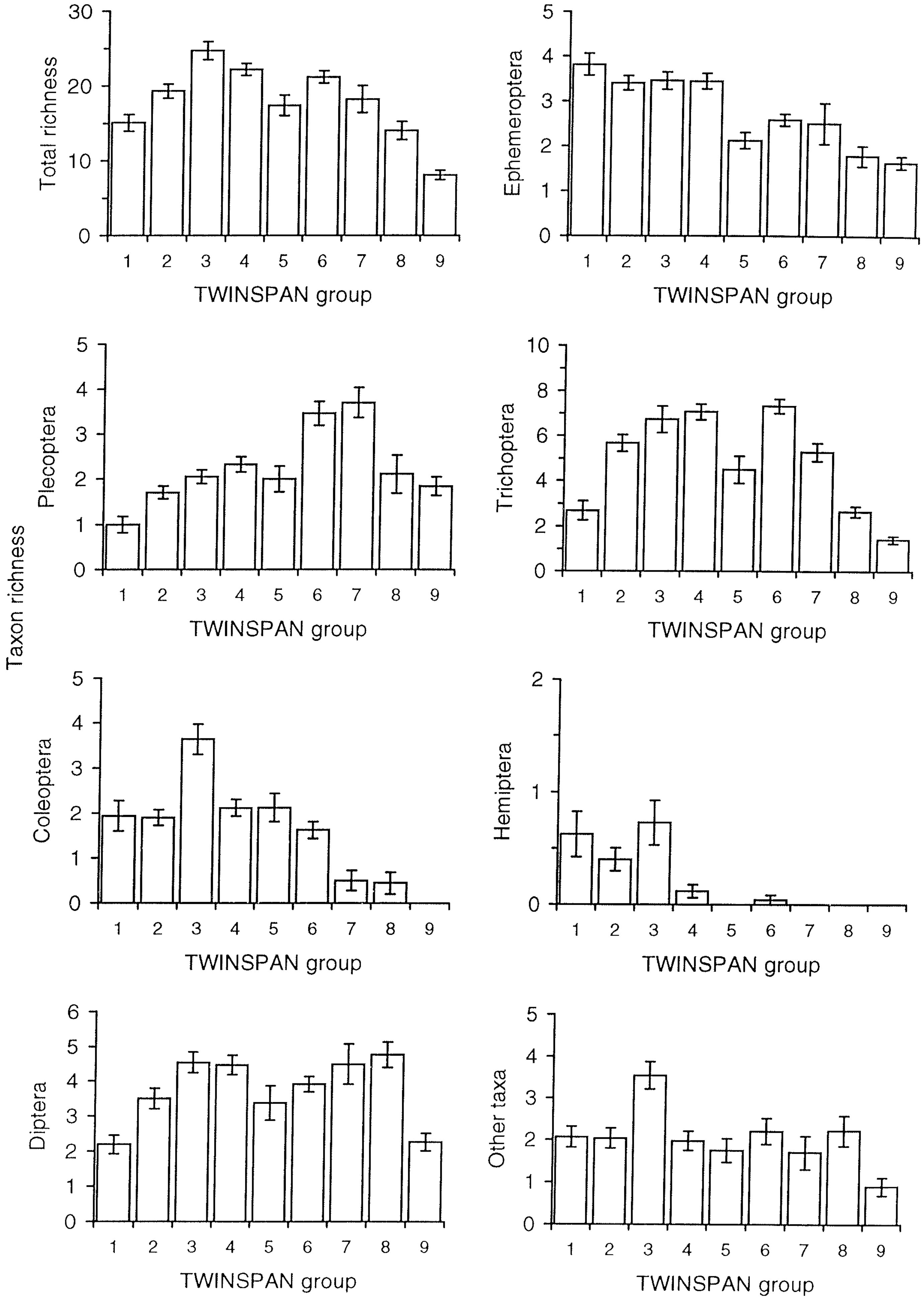


Figure 6.21 *Mean (± 1 SE) number of taxa from major macroinvertebrate orders and the mean overall taxon richness of sites in each TWINSPAN group.*

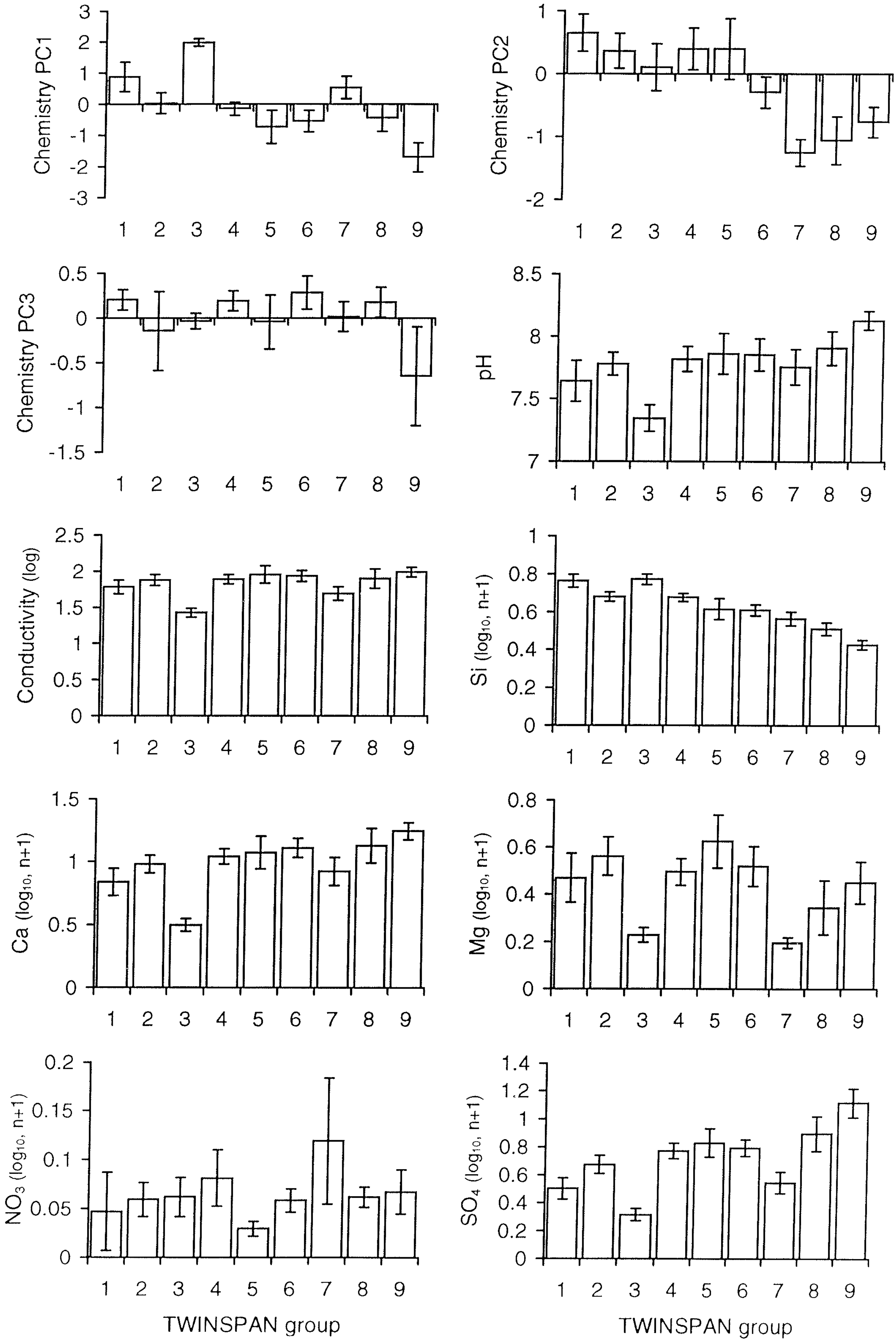


Figure 6.22 *Mean (± 1 SE) water chemistry variables at sites in each TWINSPAN group.*

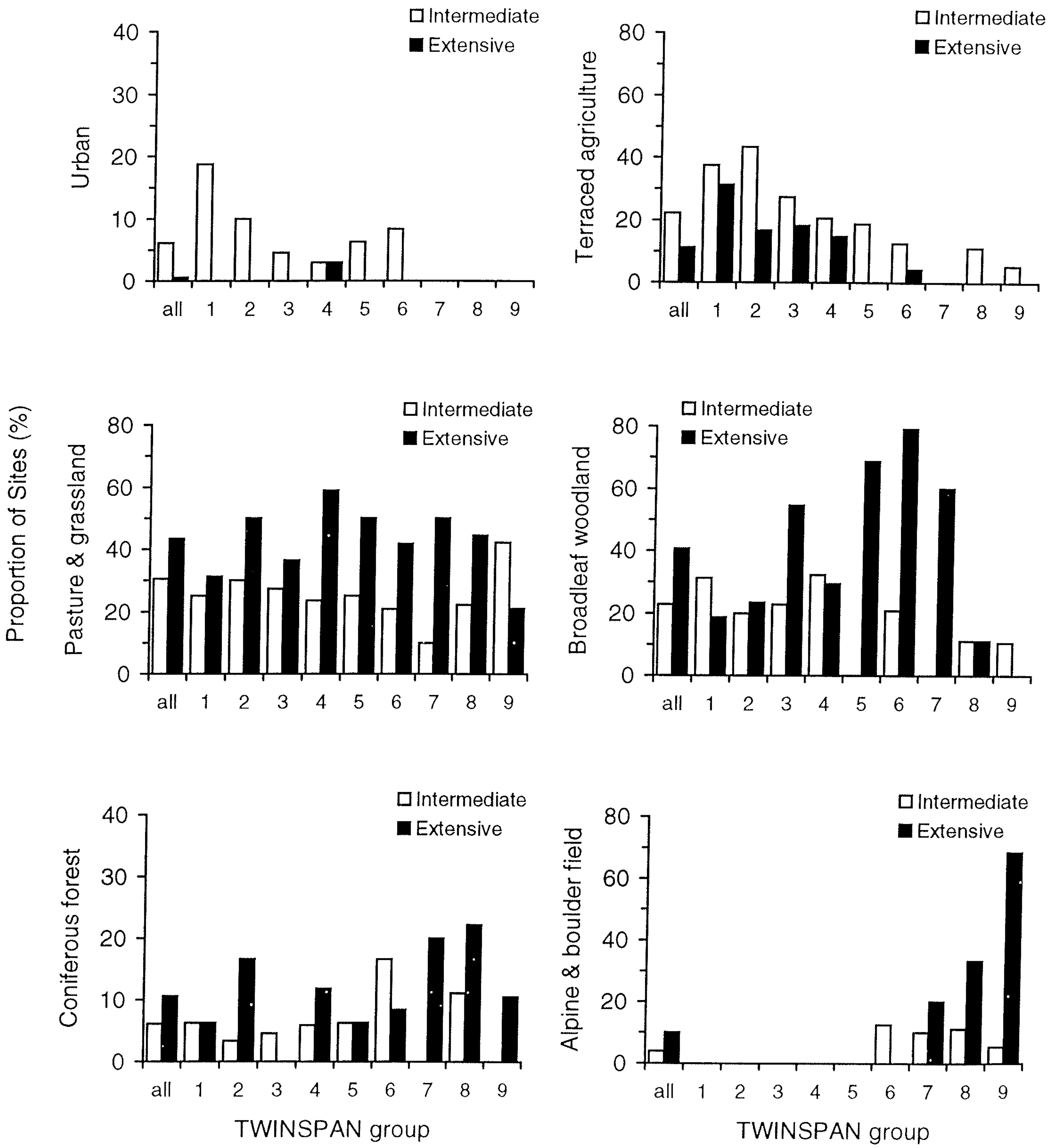


Figure 6.23 *The proportion of biological sites within each region with catchments containing either intermediate or extensive cover by different land use types.*

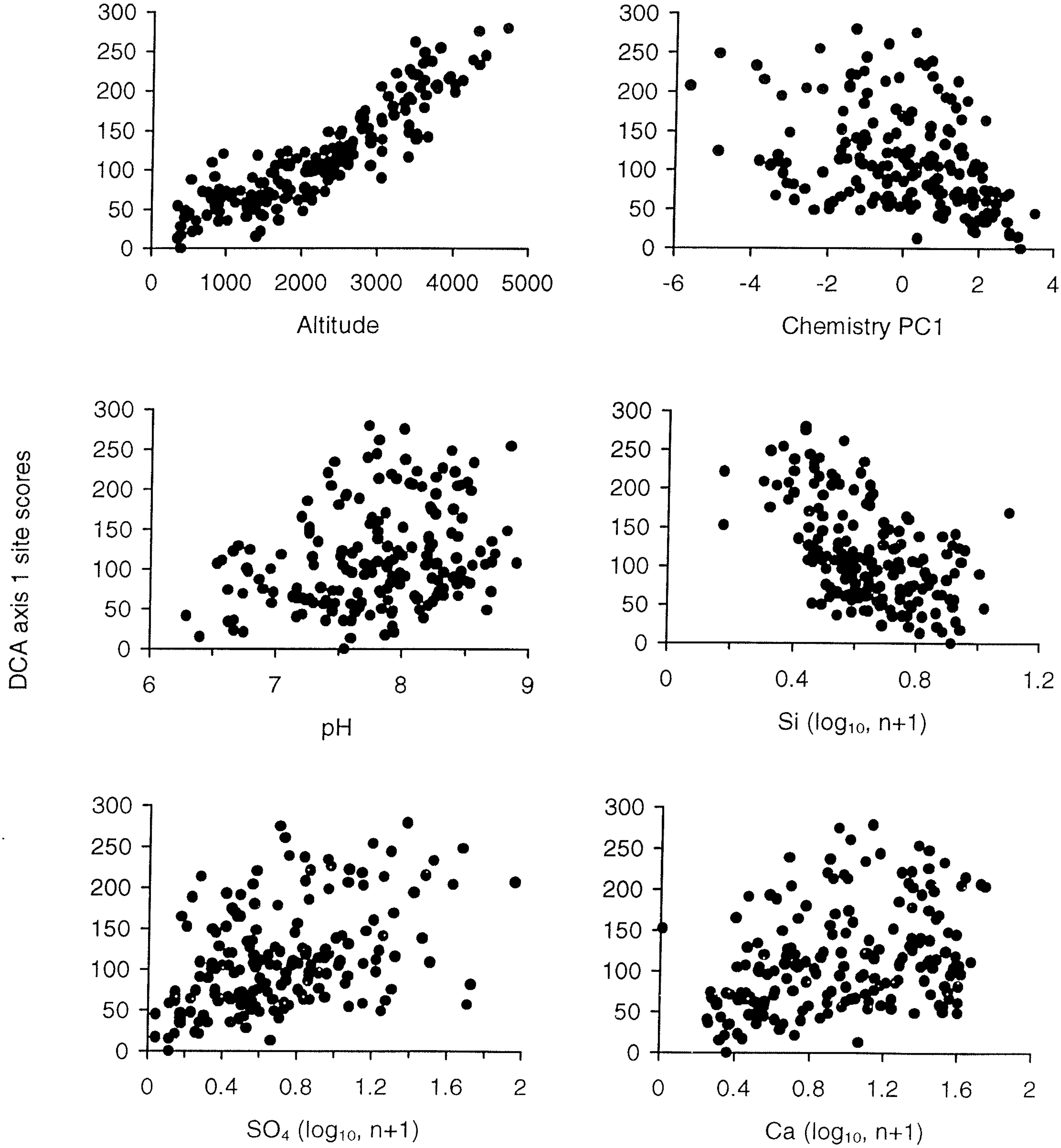


Figure 6.24 *Relationships between altitude, water chemistry variables and DCA axis 1 site scores for aquatic invertebrate communities at 180 sites in Himalaya.*

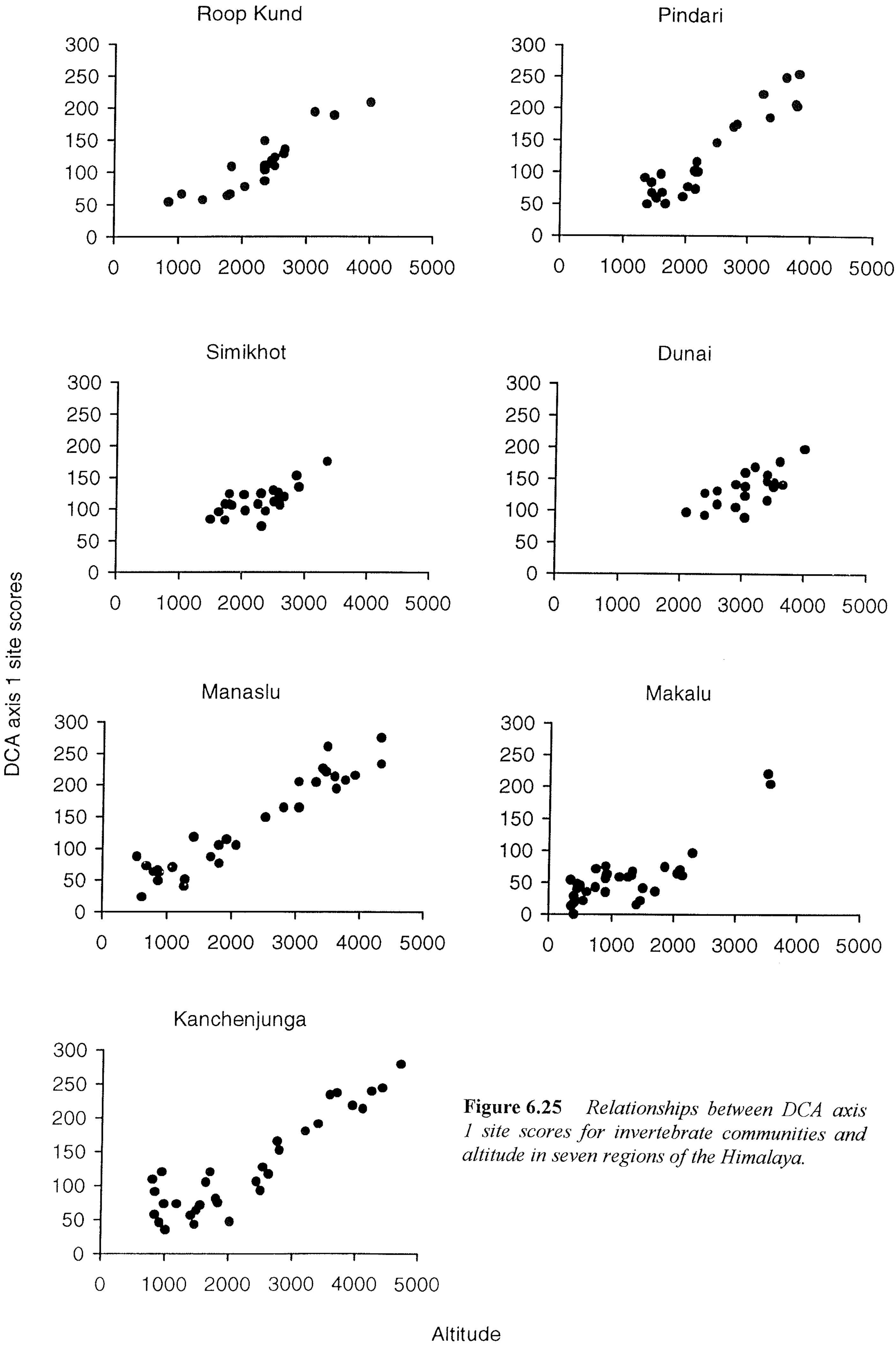


Figure 6.25 *Relationships between DCA axis 1 site scores for invertebrate communities and altitude in seven regions of the Himalaya.*

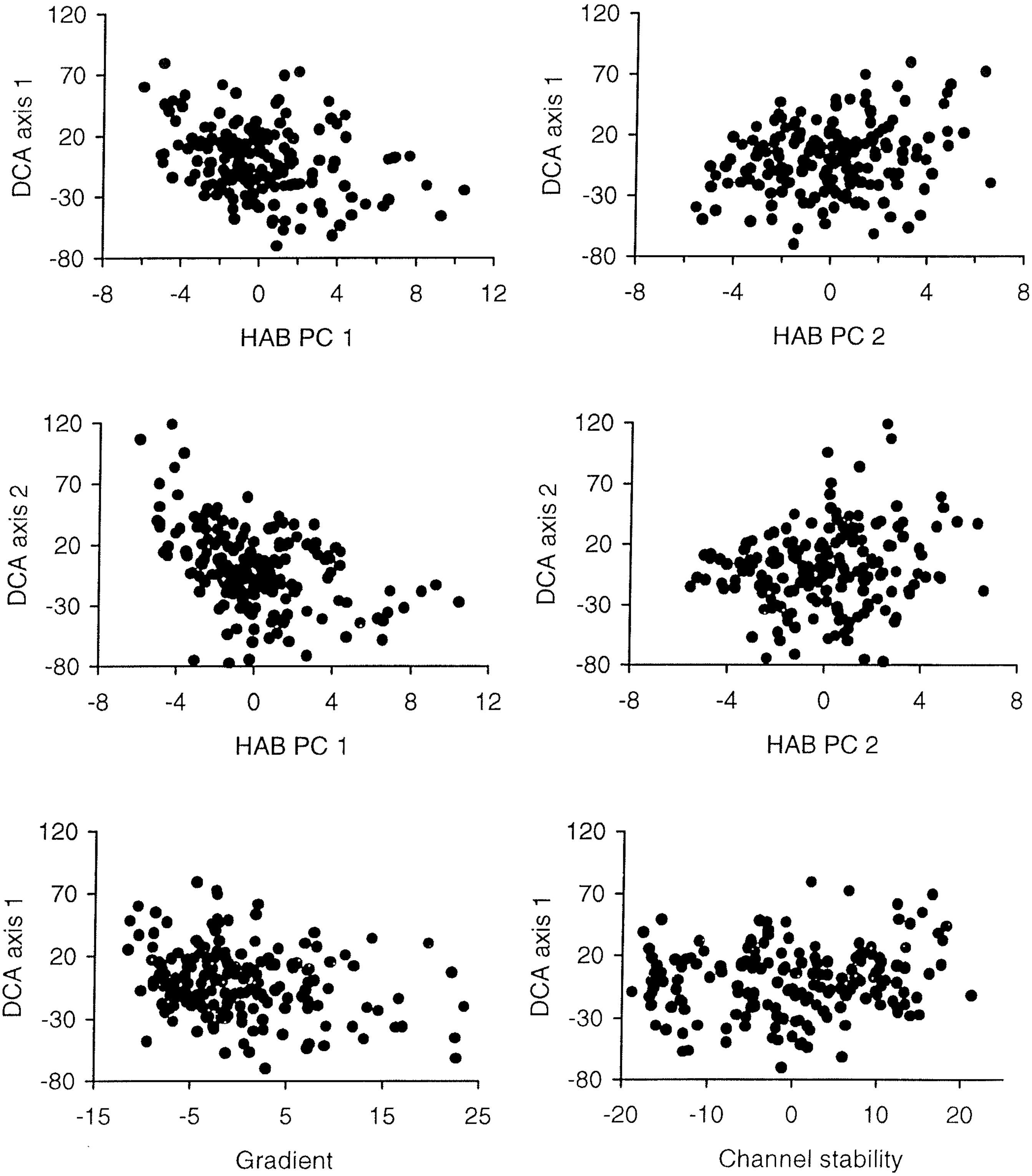


Figure 6.26 *Relationships after partial correlations between physical habitat variables and DCA axis 1 and 2 site scores for invertebrate communities at 180 streams of the Himalaya.*

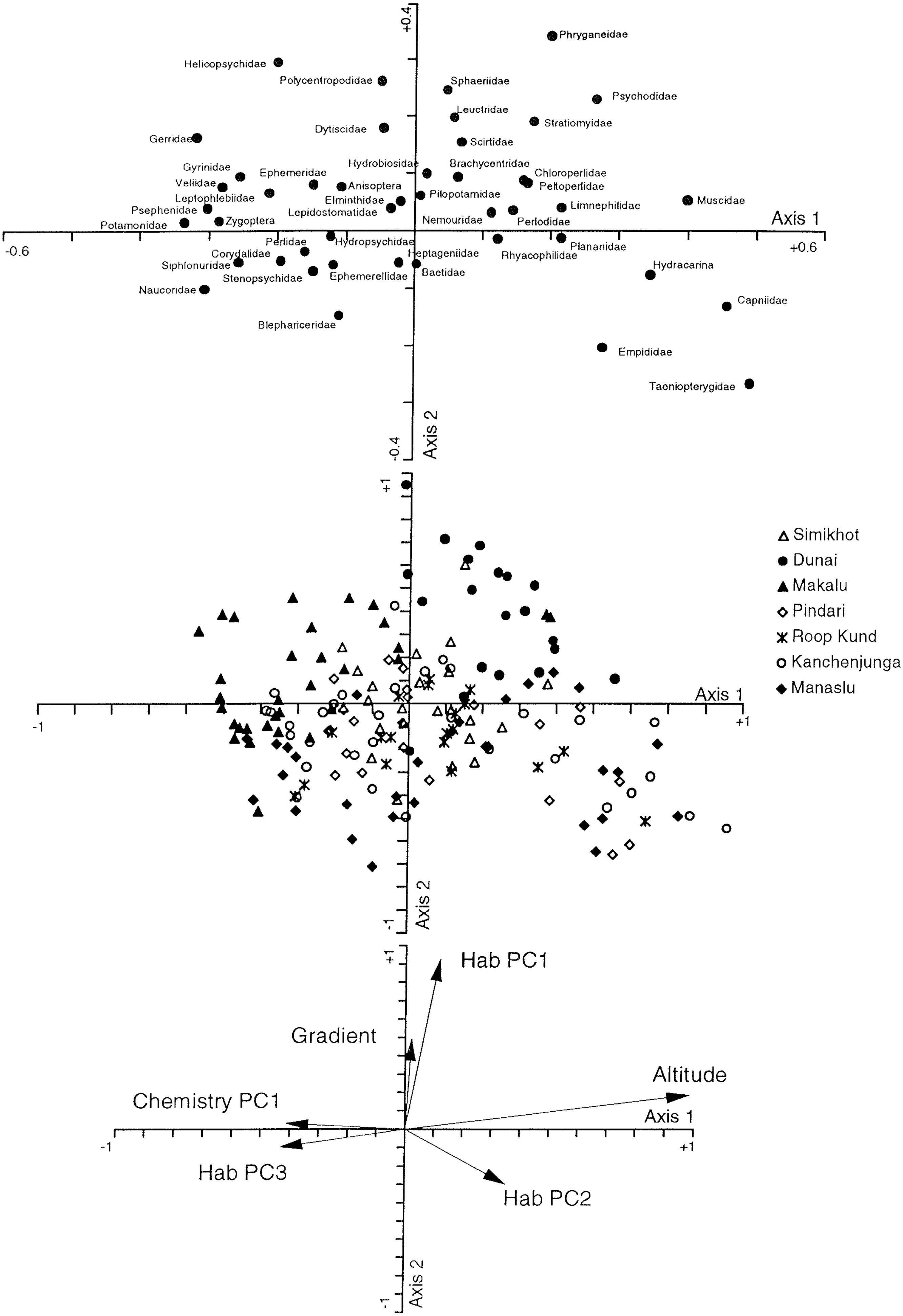


Figure 6.27 *CCA species, site and environmental variable plots for invertebrate communities at 179 sites in the Himalaya.*

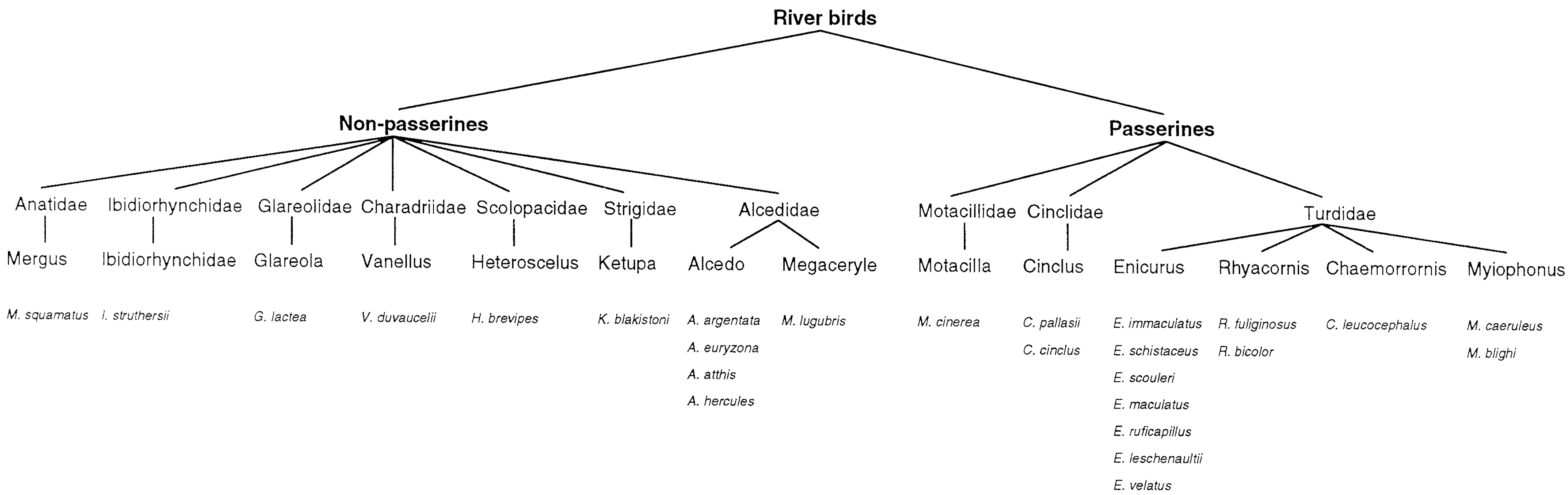
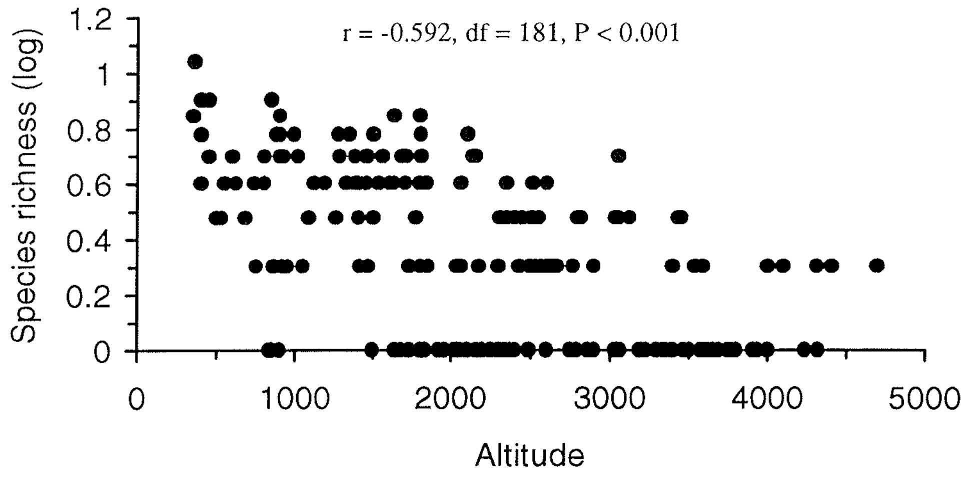


Figure 6.28 *Major sources of adaptive ratiation in Himalayan and Asian river birds.*



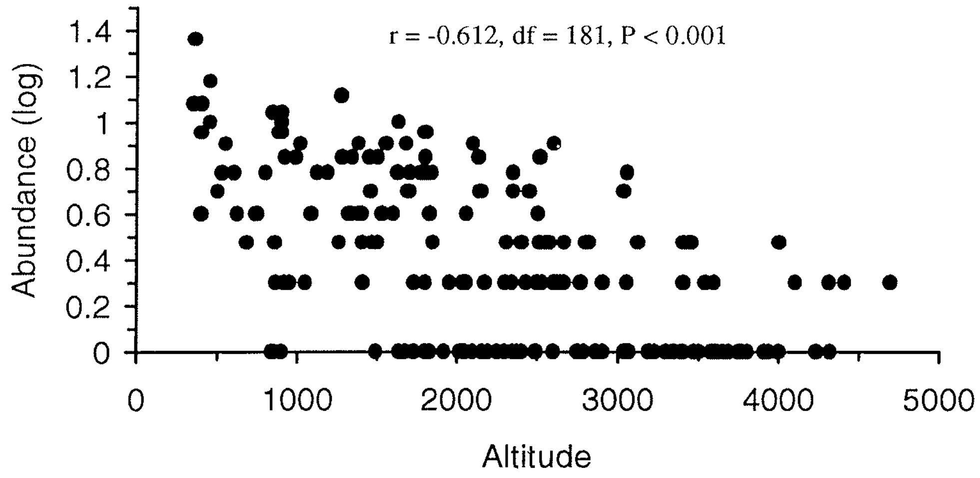


Figure 6.29 *Relationships between river bird abundance and species richness (log_{10} n+1) with altitude at 182 sites in the Indian and Nepalese Himalaya.*

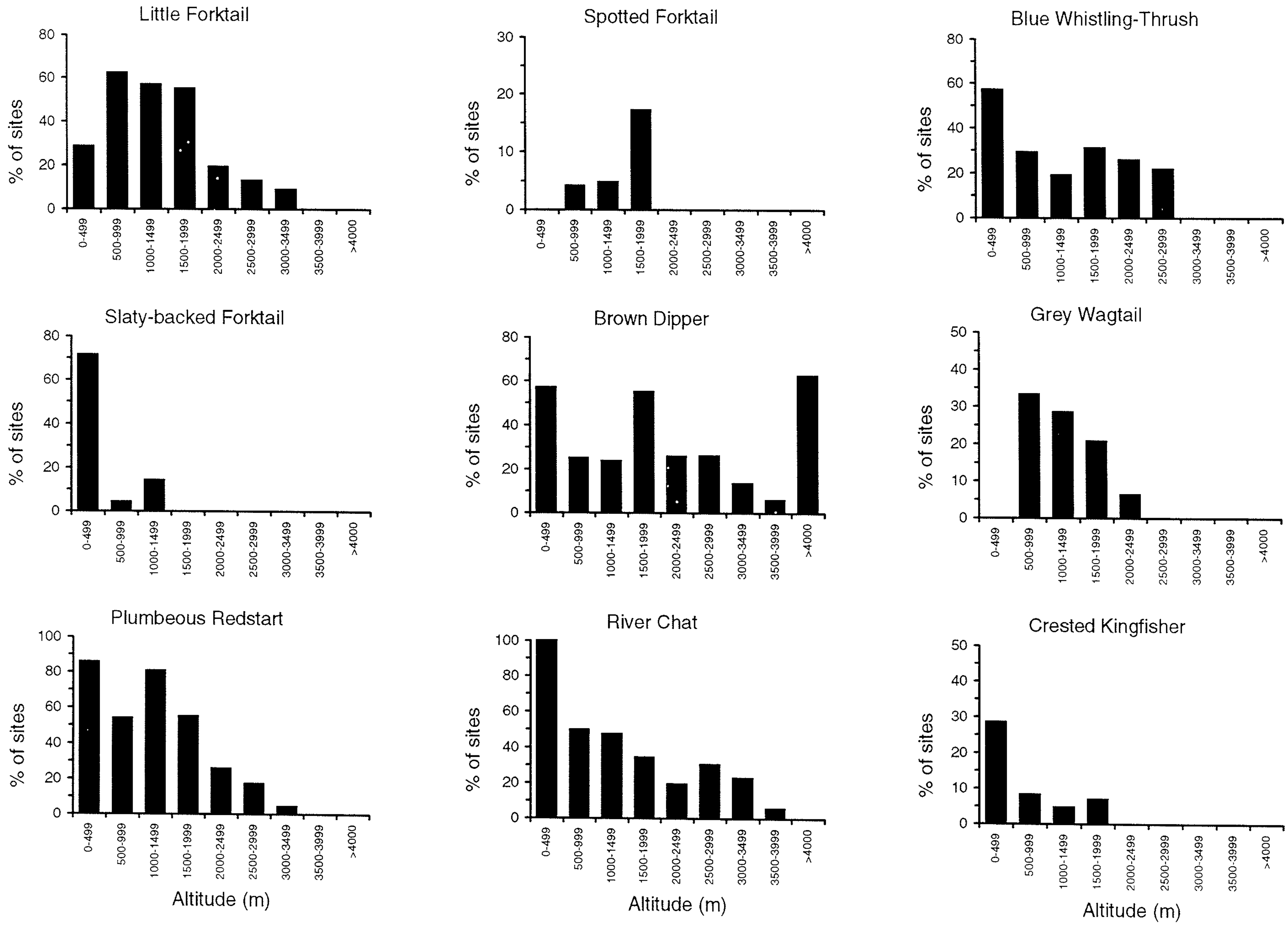


Figure 6.30 *Percentage of 182 sites in each of nine altitude bands occupied by river bird species in the Indian and Nepalese Himalaya.*

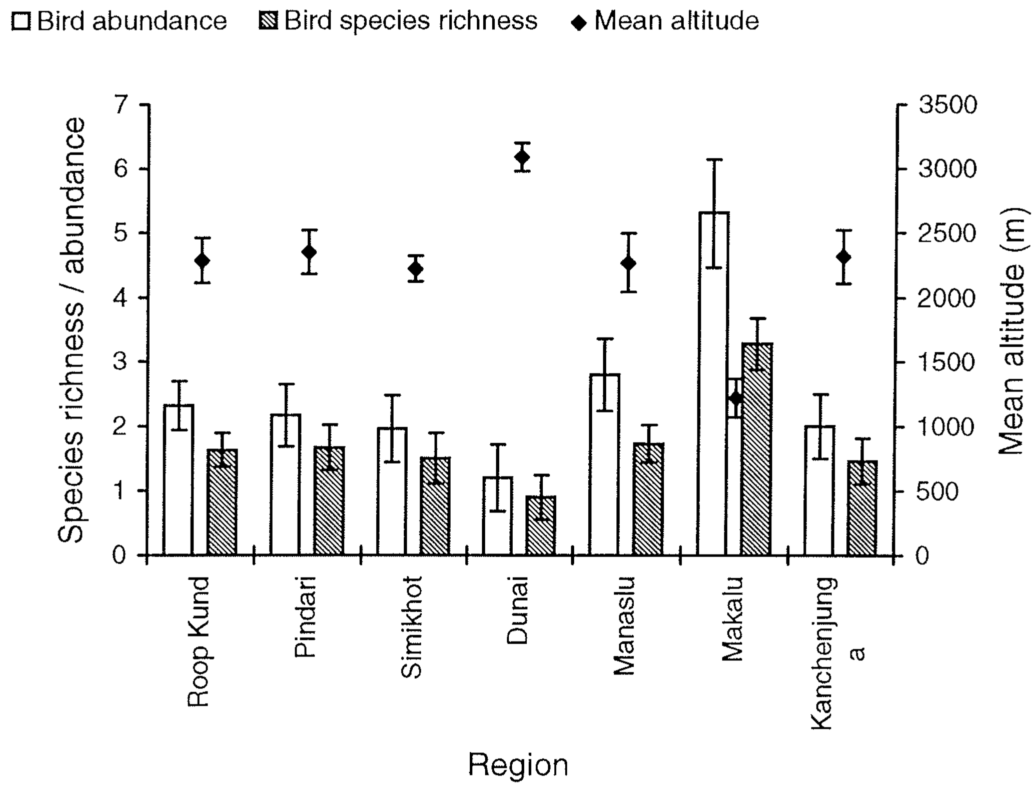


Figure 6.31 *Mean river bird species richness, abundance (both (log_{10} (n+1) transformed) and mean site altitude at 182 sites in seven regions of the Indian and Nepalese Himalaya. Error bars indicate ± 1 S.E.*

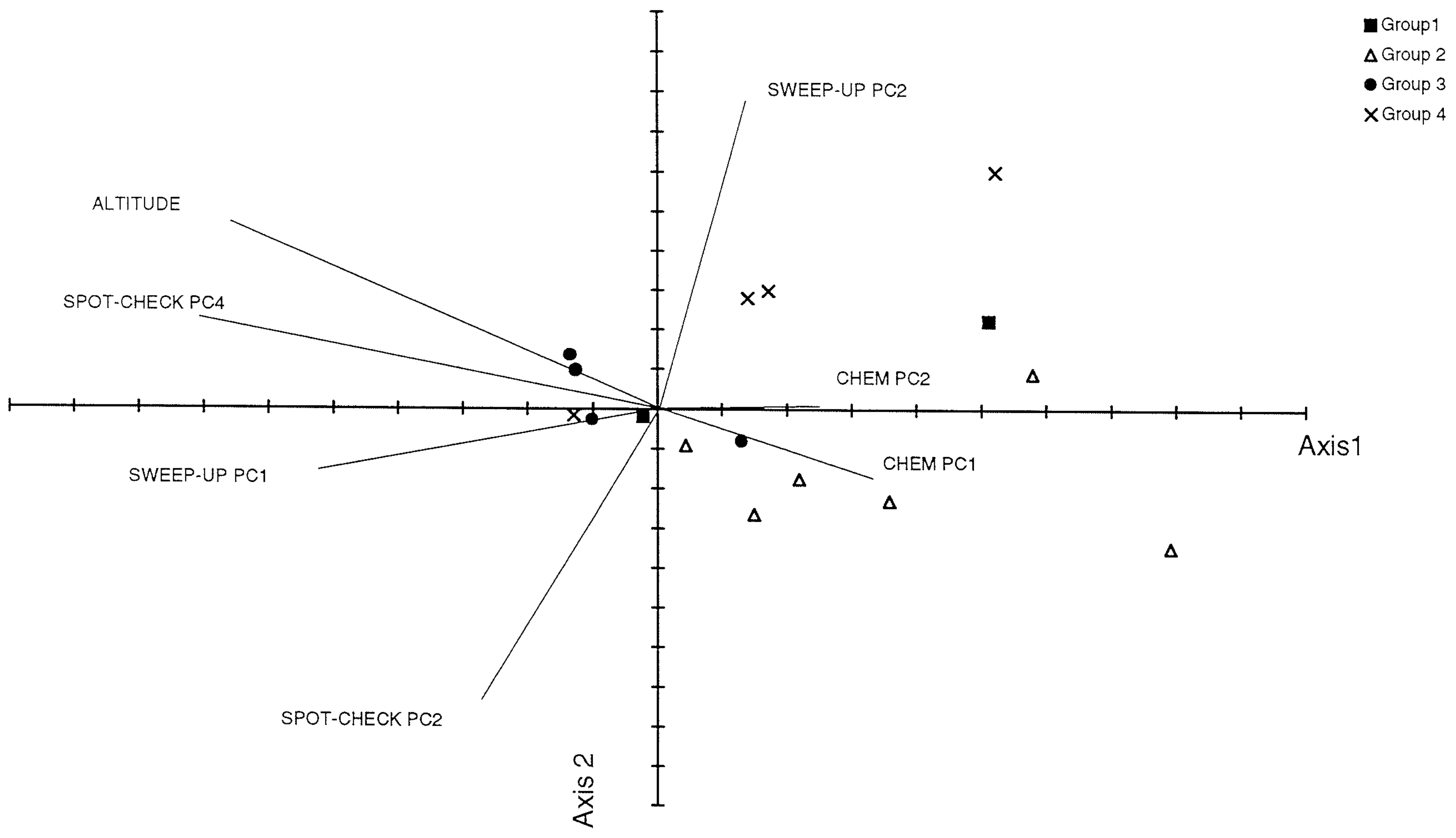


Figure 6.32(a) *Species scores from Canonical Correspondence Analysis of bird distribution at 119 streams in the Indian and Nepalese Himalaya, 1994-1996. Environmental correlates identified by CCA are also shown, as straight lines.*

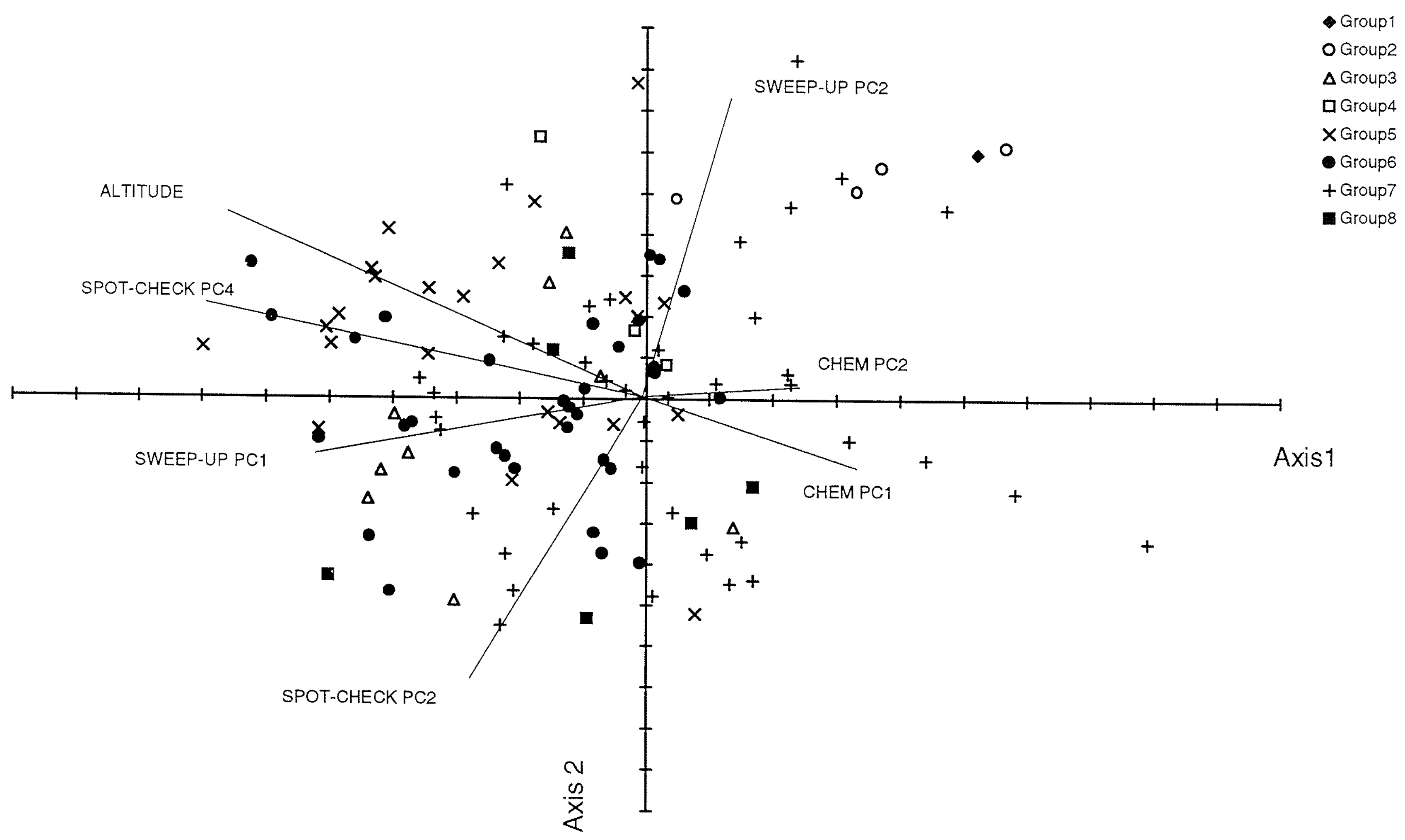


Figure 6.32(b) *Site scores from Canonical Correspondence Analysis of bird distribution at 119 streams in the Indian and Nepalese Himalaya, 1994-1996. Environmental correlates identified by CCA are also shown, as straight lines. Symbols indicate TWINSPAN groupings.*

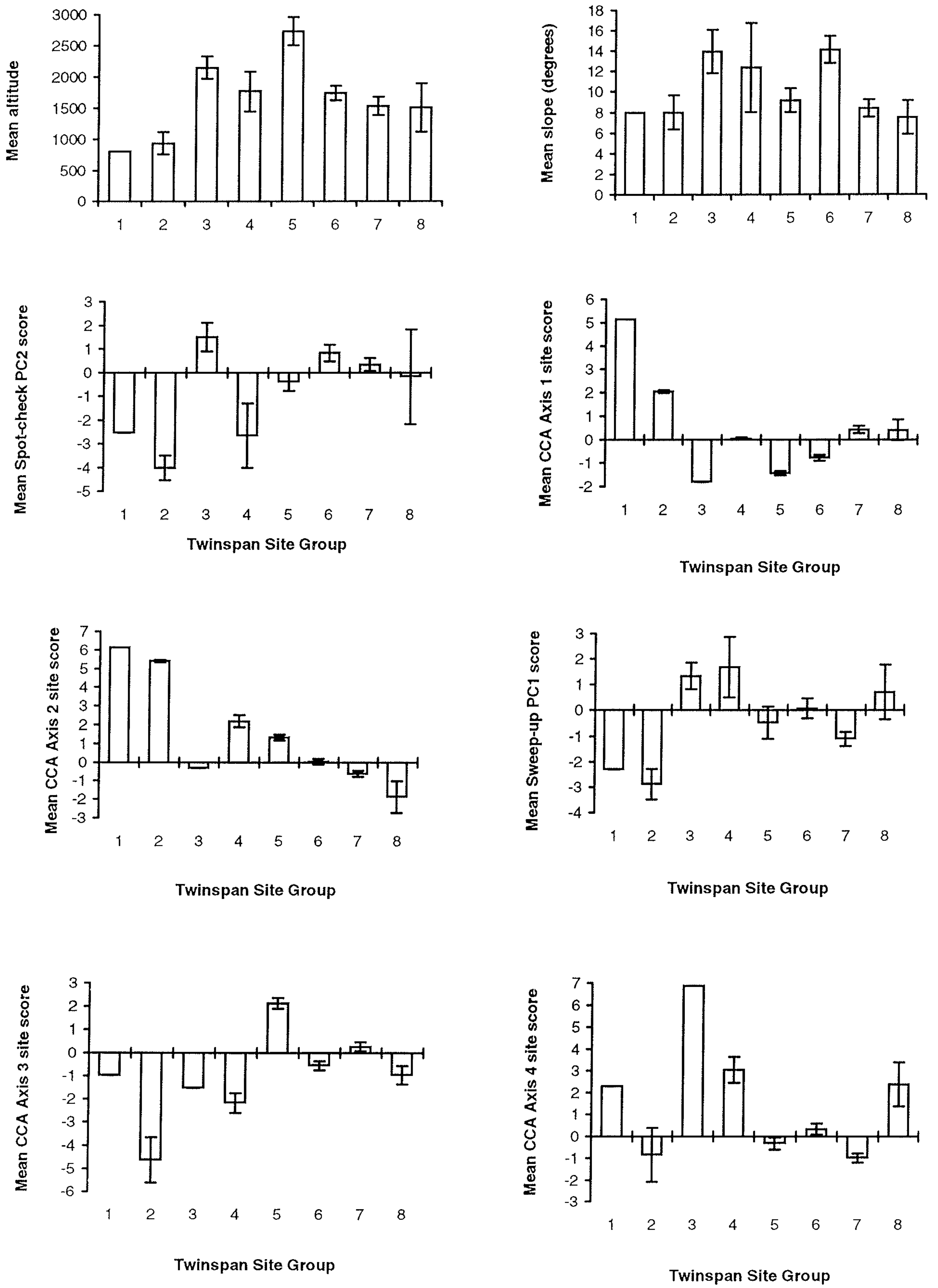


Figure 6.33 *Results of ANOVAs on site attributes between TWINSPAN site groups. Error bars indicate ± 1 S.E.*

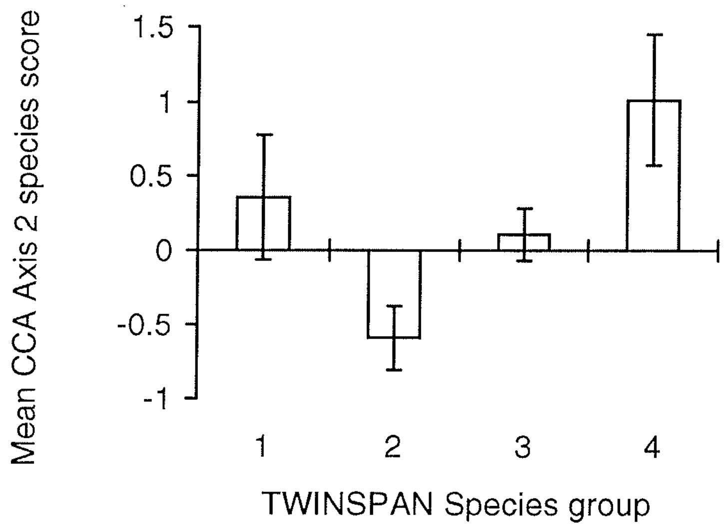


Figure 6.34 *Results of ANOVAs on CCA species Axis 2 scores between TWINSPAN site groups. Error bars indicate ± 1 S.E.*

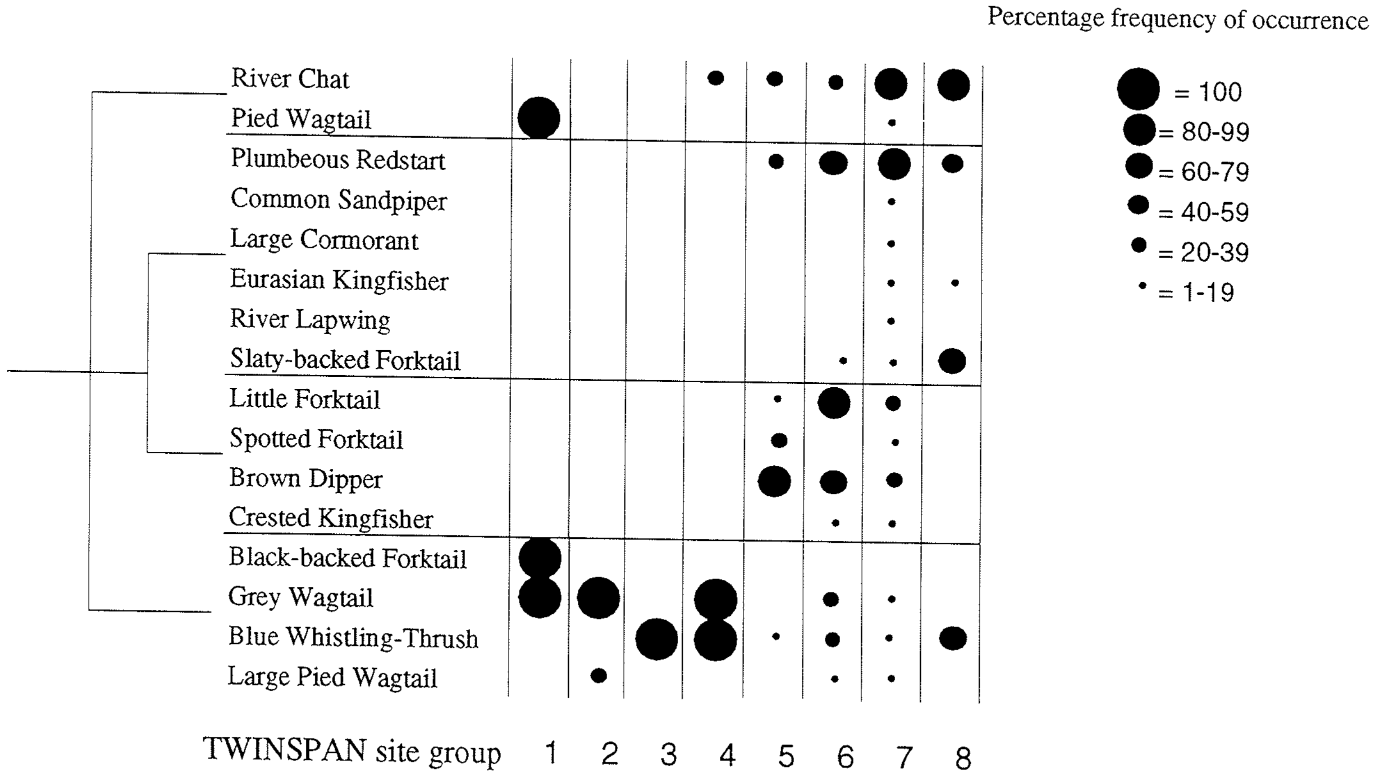


Figure 6.35 *Classification of species and site groups by TWINSPAN. Circles show percentage frequency of occurrence of each taxa between the sites in each group.*

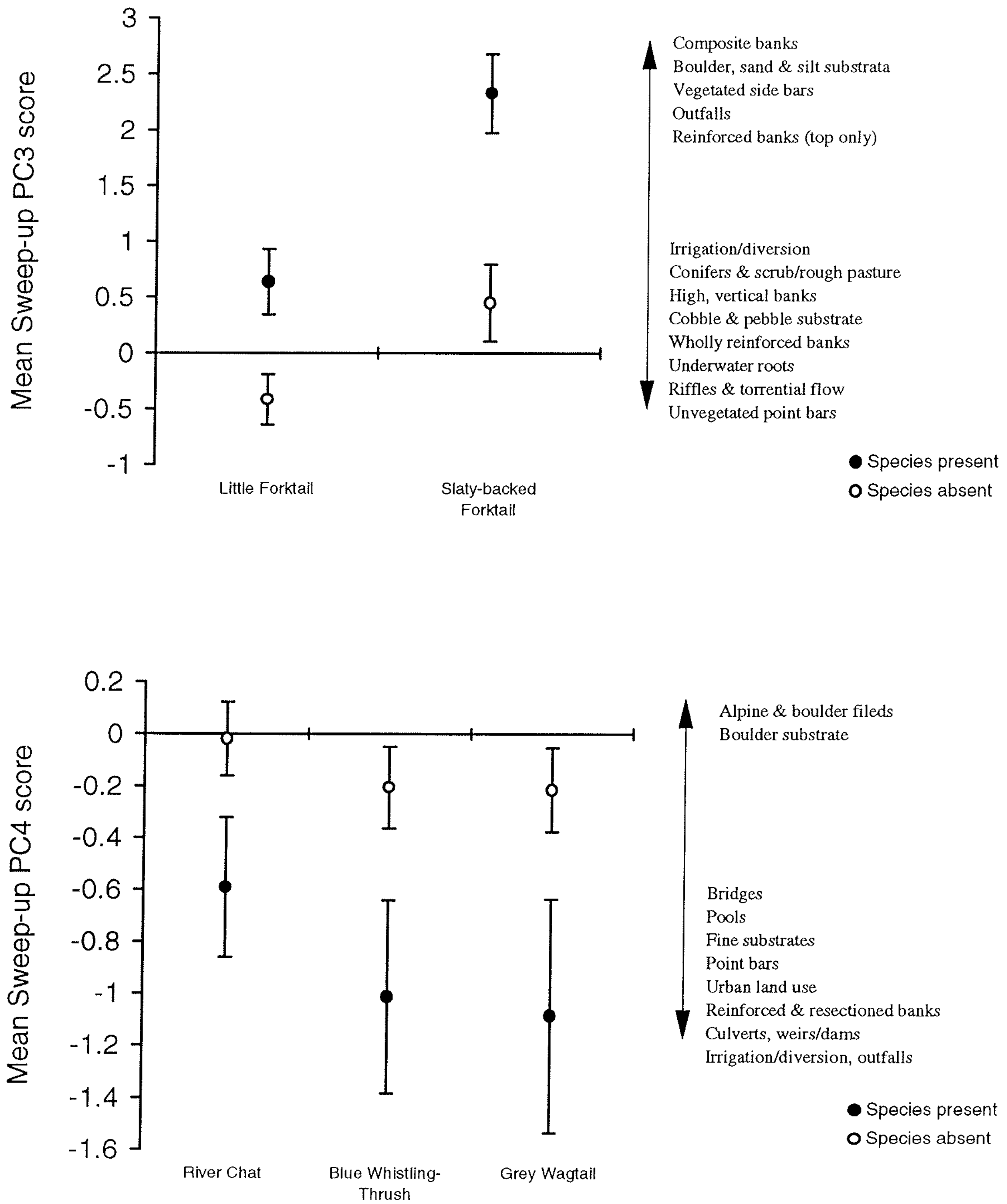
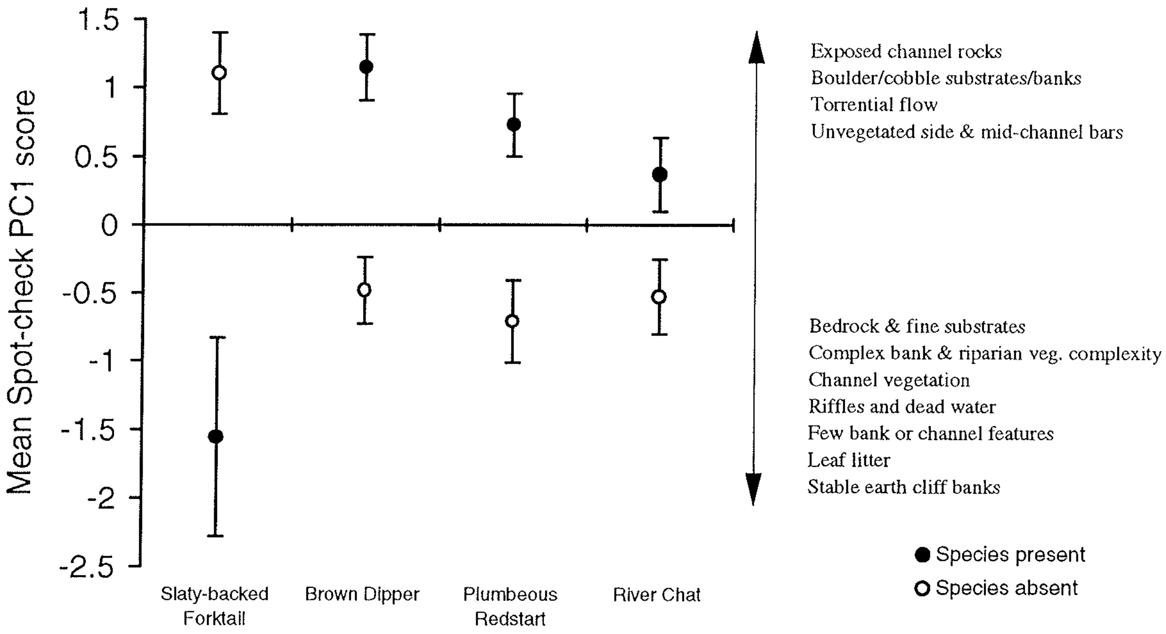


Figure 6.36(b) *Mean sweep-up PC scores from RHS of 182 sites occupied and unoccupied by river bird species in the Indian and Nepalese Himalaya, 1994-1996. Error bars indicate ± 1 S.E.*



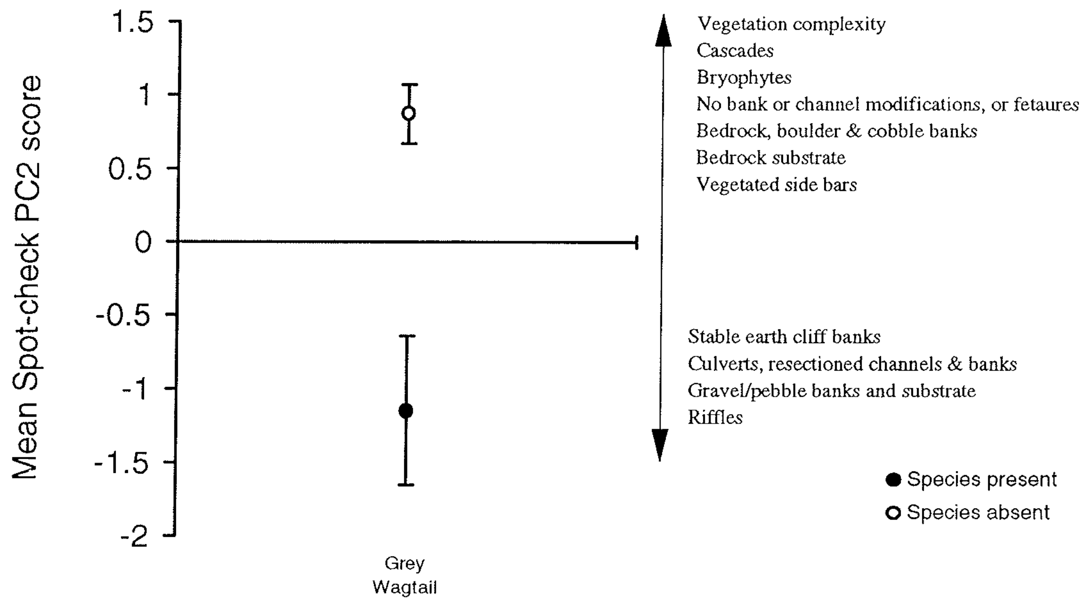
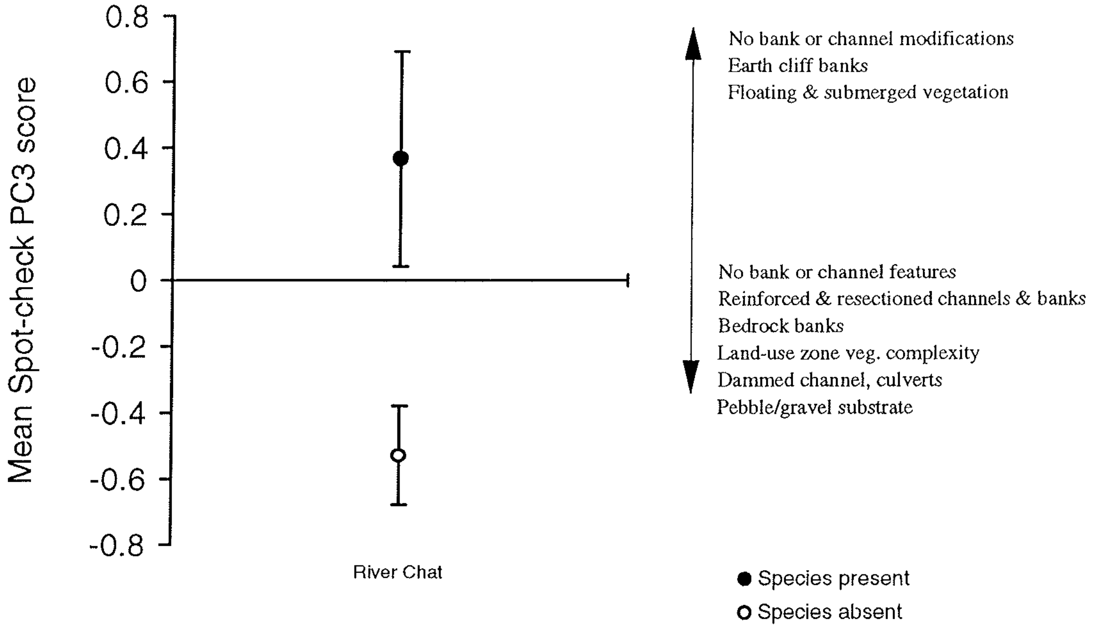


Figure 6.36(c) *Mean spot-check PC scores from RHS of 182 sites occupied and unoccupied by river bird species in the Indian and Nepalese Himalaya, 1994-1996. Error bars indicate ± 1 S.E.*



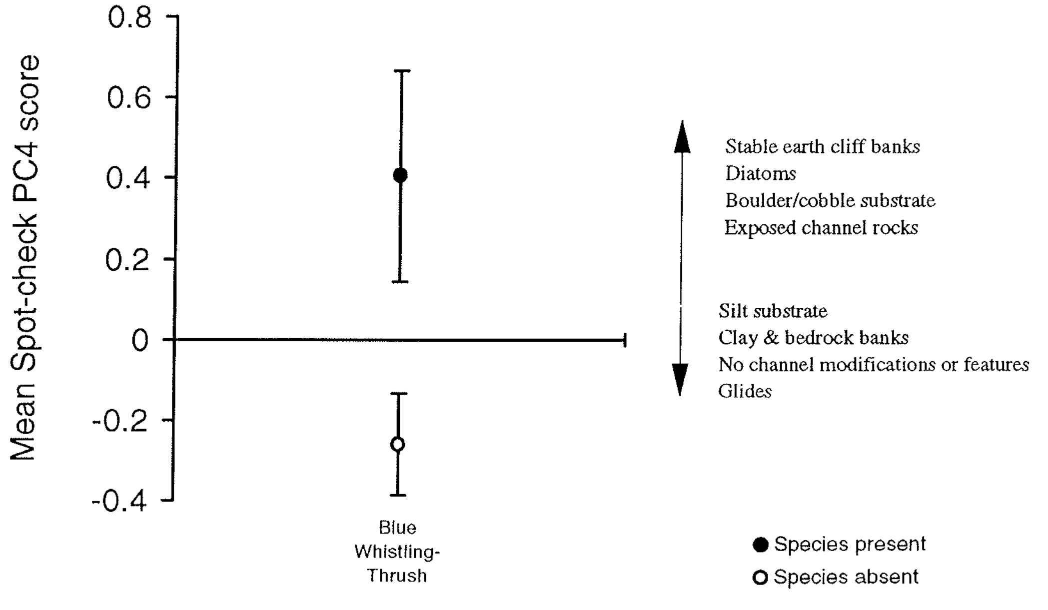


Figure 6.36(d) *Mean spot-check PC scores from RHS of 182 sites occupied and unoccupied by river bird species in the Indian and Nepalese Himalaya, 1994-1996. Error bars indicate ± 1 S.E.*

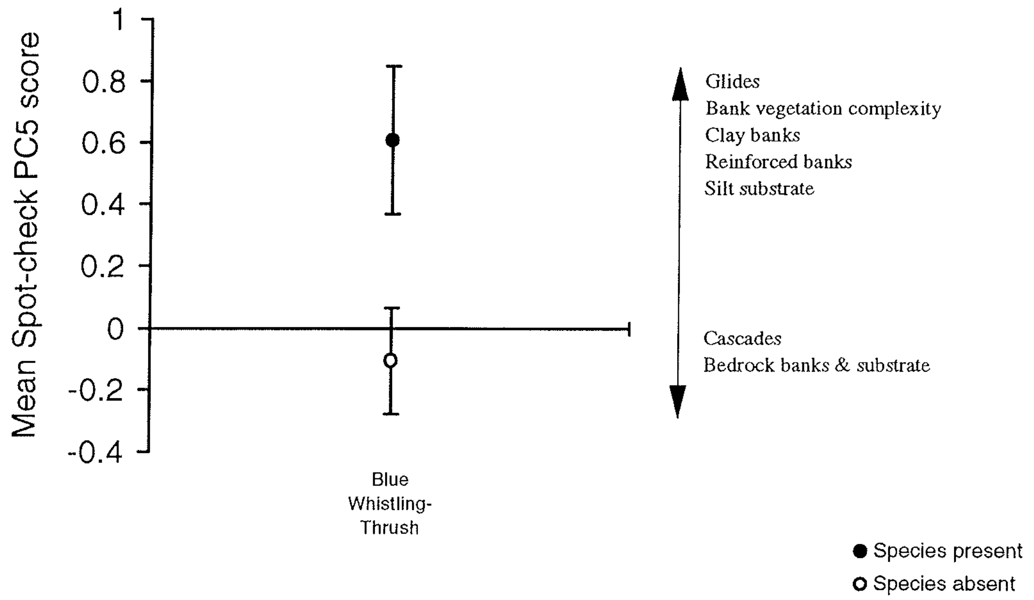


Figure 6.36(e) *Mean spot-check PC scores from RHS of 182 sites occupied and unoccupied by river bird species in the Indian and Nepalese Himalaya, 1994-1996. Error bars indicate ± 1 S.E.*

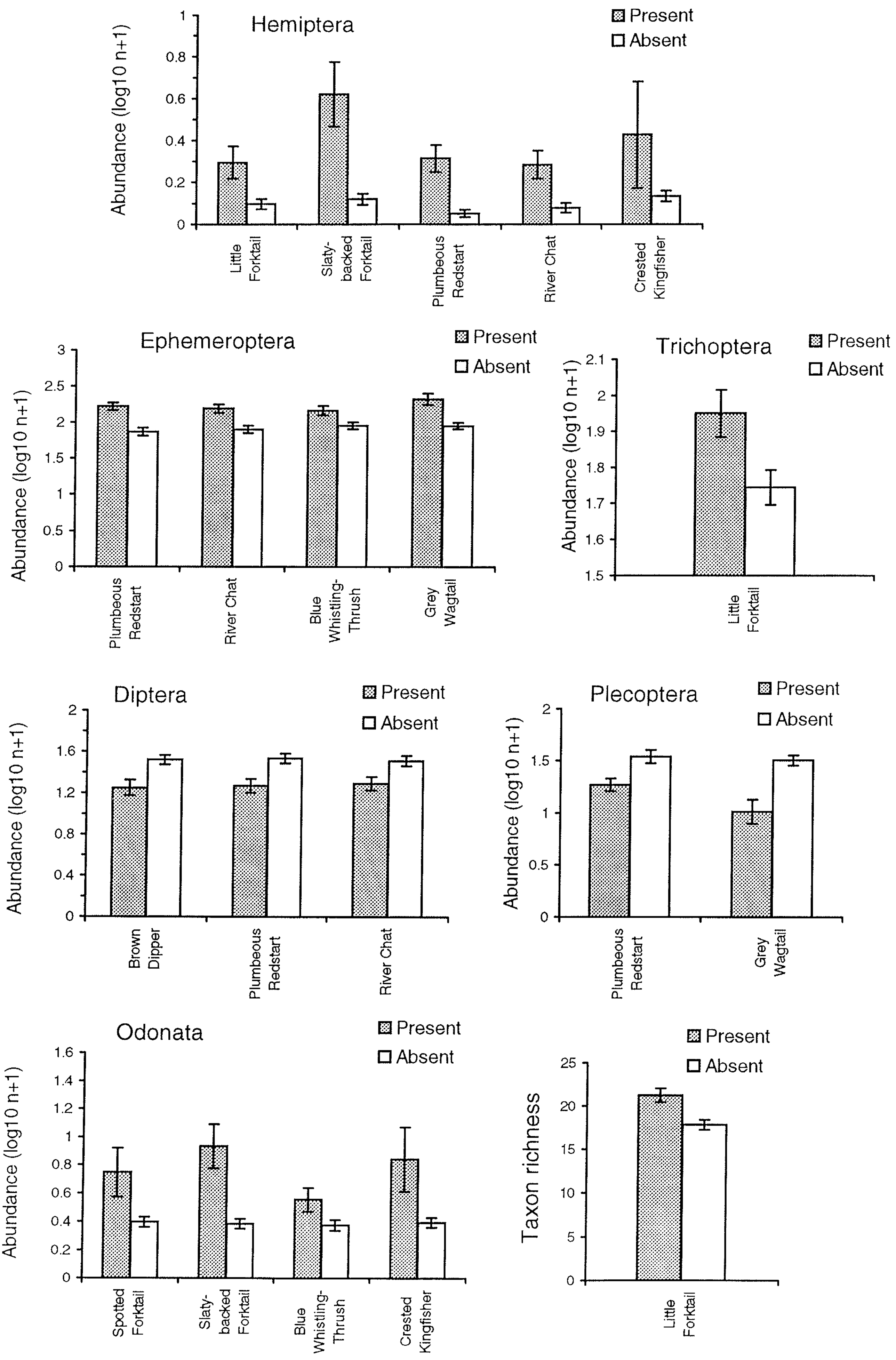


Figure 6.37 *Mean abundances (log_{10} (n+1)) of Ephemeroptera, Piecoptera, Trichoptera, Odonata, and Hemiptera in riffles at 182 sites with and without 9 species of river birds in the Indian and Nepalese Himalaya, 1994-1996. Error bars indicate ± 1 S.E.*

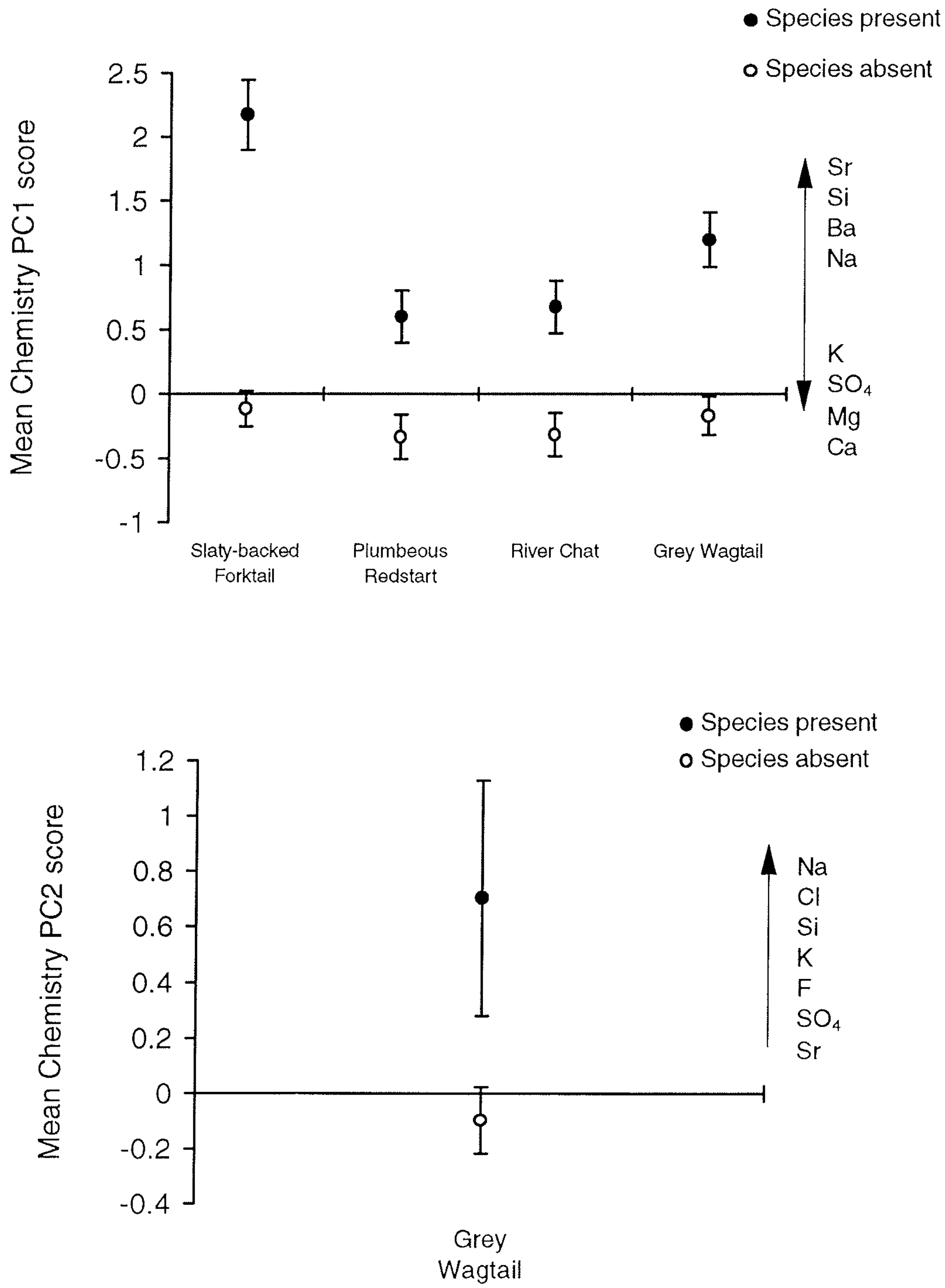


Figure 6.38 *Mean chemistry PC1 and PC2 scores at 182 sites either occupied or unoccupied by river bird species in the Indian and Nepalese Himalaya. Error bars indicate ± 1 S.E.*

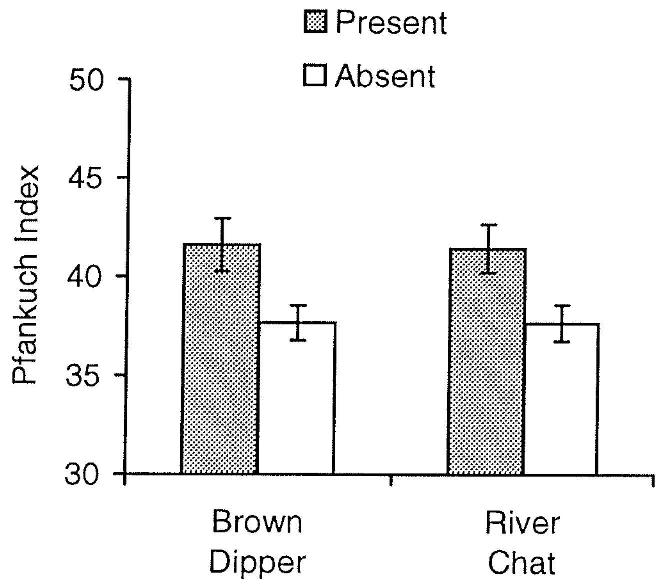


Figure 6.39 *Pfankuch Index at 182 sites in the Indian and Nepalese Himalaya with and without Brown Dipper and River Chat, 1994-1996. Error bars indicate ± 1 S.E.*

7 Context, Synthesis and Next Steps

Recent concern about interactions between global population growth, water use and food production has refocussed attention on areas like the Himalaya, where debate about human effects on ecosystems has been long-standing (Eckholm, 1975; Greenland *et al*, 1997). There are important questions about the extent to which river and catchment ecosystems will be resilient against change where water use and food production must increase to sustain human need (Falkenmark, 1997). Potential impacts on aquatic biodiversity are paramount. This is particularly the case in the Himalaya, where contributions to global biodiversity are disproportionately large (Myers, 1988; 1990). So far, however, results about effects of Himalayan land use change have been gathered from the perspective of terrestrial ecosystems, where effects have been profound (Inskipp, 1989; Hunter and Yonzon, 1993).

The results from this programme therefore represent an important advance in understanding. First, they illustrate natural pattern in stream character across a significant part of the Himalaya Second, they confirm that the Himalaya also hold significant stocks of global biodiversity of river organisms - such as birds (Buckton & Ormerod, unpubl.). Third, they provide insight into effects on Himalayan stream ecosystems from land-use change. In this latter context, one possible interpretation is that the consequences of converting forest to agriculture in this region have been less marked than previously expected (Eckholm, 1975): effects from terracing were apparently insufficient to change chemistry substantially, nor were all stream organisms adversely affected. Much more realistic, however, is a view that change in catchment land use has affected Himalayan rivers, but the influences have so far been subtle, localised or confined to more sensitive biota. In addition to modest increases in invertebrate abundance, agricultural streams have altered diatom communities consistent with increased nutrient load (see also Jüttner *et al*, 1996(a)). They also have reduced benthic bryophyte cover (Appendix 2), and substantially altered habitat structure (this study). Bird distribution did not vary markedly between streams, but the apparent influence of habitat character on most bird species provides a pathway through which further intensification in catchment land use could affect species occurrence. In and around the Kathmandu valley, for example, where human population densities are larger than anywhere in Nepal, streams from peri-urban and intensively terraced areas are characterised by large alterations in habitat structure and water quality (e.g *Jüttner et al,* 1996(b), Collins and Jenkins, 1996). Given the current rate of human population growth and resource needs in the region (e.g. Greenland, Gregory and Nye, 1997), and the risk that continued growth will be greatest at the lower altitude where aquatic biodiversity is concentrated (Hunter and Yonzon, 1993), the possibility of future change will remain an important issue. For this reason, our study represents an important baseline for future change. Continuing the work in more intensively used and degraded catchments therefore will represent an important next step in research progress. Apparently pronounced and widescale sensitivity to acidification revealed by the chemical data illustrate also the importance of continued vigilance to assess whether projected increases in acid deposition in the region might also impact aquatic resources.

Despite calls by some authors for careful examination using field data or experimentation, the early concepts about Himalayan degradation have never been robustly tested (Eckholm, 1975; Ives and Messerli 1989; Messerli and Ives, 1997). There are clearly difficulties in finding a scientific approach that is sufficiently rigorous to faithfully represent variations over spatiotemporal scales that match those involved in change in mountain environments. Experimental manipulation with appropriate replication is clearly difficult at large spatial scales (Likens, 1992), and yet broad scale approaches are required to match the scale of the phenomena involved (May and Webb, 1994). Site-specific catchment studies are powerful in allowing some understanding of catchment-scale problems (Hornung and Reynolds, 1995): however, they also risk limited representativeness, and failure to capture episodic effects with long return periods, such as intense monsoonal floods (Reeve, 1996). The approach in this project, involving extensive survey across many catchments, provides at least one method of representing the status of a wide range of sites with contrasting land use, altitude, habitat character, and disturbance history. Assessments of river ecosystems at the catchment to regional scale are being increasingly advocated in river ecology generally in order to represent important large-scale phenomena (Allan and Johnson, 1997).

At the same time, however, catchment survey approaches like these have potential disadvantages: they rely on correlation to infer cause and effect; they result in the collection of complex sets of data involving many uncontrolled variables; they are constrained logistically in Himalayan environments, so that site selection cannot be easily randomised. In our case also, data collection was restricted to one visit. However, we were careful in stratifying data collection across several regions and altitudes, and ensuring that data were collected only in independent sub-catchments. The survey was designed also to reflect the nested hierarchy of scale factors (i.e. stream, catchment and region) that influence stream ecosystems (Frissel *et al*, 1986). A further important need, nevertheless, is that these correlative data should be supported by improved understanding about cause-effect links between chemical change, land use pattern, stream dynamics and biota. Augmenting the synoptic data by studies at different seasons and under different conditions is clearly crucial.

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Appendix 1 Habitat features recorded by the River Habitat Survey

INSTRUMENT READINGS:

Altitude, slope

PREDOMINANT VALLEY FORM:

e.g. deep v-shaped valley, asymmetrical floodplain, etc.

RIFFLES, POOLS AND POINT BARS:

Numbers counted

SPOT CHECKS:

bank material - e.g. bedrock, boulder, cobble etc. - presence recorded at 10 points
bank modifications - e.g. reinforced, resectioned.
bank features -e.g. side bars, eroding or stable cliffs.
channel substrate - e.g. bedrock, boulder, etc.
flow type - e.g. free fall (waterfalls), chutes, broken standing waves, smooth.
channel modification - e.g. culverted, resectioned, reinforced, dam, ford.
channel feature - e.g. exposed rocks, mid-channel bars, mature islands.
riparian land use within 5m of bank - e.g. urban, broad-leaved woodland, rough pasture, Sal Forest, terraced agriculture etc.
bank top and bank face vegetation structure based on presence of bryophytes, short herbs, grasses, tall herbs, scrub, and trees - bare (none), uniform (1 type), simple (2 or 3 types), complex (4 or more types).
channel vegetation types - e.g. bryophytes, emergent reeds / rushes, floating.

SWEEP-UP:

land use within 50m of banktop - as spot-check definitions recorded as present or extensive (> 33 % of reach) unless otherwise statedbank profiles (natural / modified) - e.g. vertical, vertical and toe, steep, gentle, composite (mixture)
extent of tree and associated features - 6 point scale from none to continuous
extent of channel features - e.g. waterfalls, cascades, riffle-pools, runs, exposed boulders, channel bars, side bars etc.

DIMENSIONS AND INFLUENCES:

channel dimensions (m): bank height, banktop width, water width, water depth
artificial features - e.g. numbers of culverts, weirs, bridges, fords etc.
evidence of recent management - e.g. dredging, mowing, weed-cutting
features of special interest - e.g. braided channel, debris dams, water meadow, bog
brief description

Appendix 2

Aquatic bryophytes in Himalayan streams: testing a distribution model in a heterogeneous environment

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SUMMARY

1. Aquatic bryophytes were sampled from 108 streams spanning over 3000 m of altitude in 4 regions of Nepal. Richness, cover and community composition were related to physico-chemistry using multiple regression, DECORANA ordination and TWINSPAN. We examined the performance of a hierchically-scaled descriptive model, developed in New Zealand for predicting bryophyte distribution, in this highly heterogeneous Himalayan region.

2. Community composition and cover varied highly significantly with altitude, streambed stability and base-richness, with evidence of effects of riparian land use on bryophyte cover. Cover was greatest in streams at low to middle altitudes with steep slopes (> 15°), high stability and low conductivity (< 60 uS cm^{-1}), where communities were dominated by two *Isopterygium* spp, two *Philonotis* spp., *Mnium punctatum* and Lejeunaceae.

3. Richness, by contrast, increased significantly but weakly at high altitude and moderate stability, where streams were dominated by *Eurynchium praelongum*, *Rhynchostegium* spp., *Fissidens grandifrons* and *Hygroamblystegium* spp.

4. Richness and cover were lowest in unstable streams at the lowest altitude, where no single taxon was consistently most abundant.

5. Although these results were similar to those in the descriptive model developed for bryophytes in New Zealand, subtle differences were apparent. Substrate size, although influencing the presence of bryophytes in New Zealand streams, appeared unimportant in Nepal. By contrast, streambed stability was more important in Nepal than New Zealand, perhaps reflecting pronounced monsoonal floods in the former. A suggested habitat template indicates that large size and vegetative reproduction may be responsible for the widespread dispersal of some species, even into unstable Himalayan streams.

Introduction

Headwater streams are perceived as harsh environments for benthic organisms. They are generally steep, and characterised by turbulent cascades over riffles, steps, chutes, or other large substrata. Intense rainfall and discharge sometimes occur, but at the most extreme altitudes, elevated UVB radiation, icing, nutrient scarcity, low ionic strength, low catchment productivity, reduced barometric pressures, and accompanying low gas concentrations, may combine to restrict diversity (Ward, 1994).

Conditions of this type are not favourable to aquatic plant growth. Macrophytes are generally absent (Sheath *et al.*, 1986; Howard-Williams et al, 1987; Haslam, 1978), while periphyton biomass is often low and transient (Suren, 1991; Biggs, 1995; and see Stevenson et al., 1996 for reviews). Aquatic bryophytes, however, are a common feature of headwaters (Glime, 1970; Sheath *et al.*, 1986; Ormerod *et al.,* 1987; Suren, 1996; Bowden *et al*, 1997), and may be the major autotroph and contributor to nutrient dynamics (Meyer, 1979; Steinman & Boston, 1993). Bryophytes support high invertebrate densities (e.g., Percival & Whitehead, 1929; Suren 1991) and enhance periphyton and detrital biomass (Suren 1992), presumably reflecting increased surface area, but reduced nearbed water velocities and turbulence (Nikora *et al.* 1997). As such, aquatic bryophytes have important ecological roles in headwater streams, representing stable islands in otherwise unstable ecosystems (but see Steinman & Boston, 1993). Due to their temporal persistence and resistance to grazing (Gerson, 1972; Suren & Winterbourn, 1991), bryophytes can be sampled at any time of the year without compounding influences of community changes due to floods or life cycles. They thus act as good integrators of antecedant conditions, and represent useful organisms in which to test ecological theory (During & van Tooren, 1987; Muotka & Virtanen 1995).

Despite their obvious ecological importance, attempts at modelling bryophyte distribution - even conceptually - are in their infancy (Bowden *et al* 1997). Recent studies have reported the restriction of aquatic bryophytes to large, stable substrata (McAuliffe, 1983; Slack & Glime, 1985; Englund, 1991; Steinman & Boston, 1993), reflecting their slow recolonisation rates after disturbances (Glime *et al.* 1979; Englund, 1991). In a broad scale survey on New Zealand's South Island, Suren (1996) investigated the effects of macroscale (i,e, geology and land use), mesoscale (i.e., hydrology and water quality) and microscale (i.e., substrate size, localised flow type, streambed stability and stream slope) features on aquatic bryophytes. In a summary model, he suggested that microscale variables, especially streambed stability, substrate size, slope, and lack of low flow events appeared fundamental to bryophyte occurrence. Macro and mesoscale variables, by contrast, seemed to influence community type. So far, however, this hierarchically-scaled conceptual model is untested elsewhere.

The Himalayan mountains represent an ideal location in which to extend bryological studies, both to assess communities in their own right, and to test Suren's (1996) conceptual model. Streams here display pronounced environmental heterogeneity, occurring over an extreme altitudinal range (300 - >5000 m) through which many taxonomic groups vary (Rundle, Jenkins & Ormerod, 1993; Ormerod *et al*, 1994; Suren, 1994; Rothfritz *et al.*, 1997); marked geological complexity and anthropogenic activities combine to cause inter-catchment variations in stream chemistry; stream geomorphology is also variable and dynamic, and there are marked variations in climate across latitudes and altitudes (Ormerod *et al.* 1994; 1997). Reflecting its dynamic character, structural heterogeneity and situation on the borders of the Oriental and Palaearctic biogeographical regions, the region is characterised by high biodiversity and pronounced endemism (Shengji, 1996).

In this paper, we report the results of the most extensive survey of Himalayan river bryophytes ever undertaken. A wide range of macro, meso and microscale data were collected across 3000 m of altitude, and around 900 km of latitude, allowing us to test Suren's (1996) model.

Study Area and Methods

The Simikot, Dunai, Makalu (Rothfritz *et al.* 1997) and Langtang regions (Ormerod *et al.* 1994) of Nepal provided all 108 sites for this work, and their catchment vegetation, climate and land use have been described previously (op. Cit.). Land uses were mostly low intensity, including rough seasonal pasture or subsistence crops of barley, wheat, millet and potatoes, with some terracing at lower altitudes. Most catchments still contain semi-natural vegetation, however, including mixed or Sal (*Shorea robusta)* forest at low altititudes (350 m above sea level), pines at medium altitude, and scrub, alpine meadows and boulderfields at higher altitudes (to 4000m). Streams in the four remote regions were surveyed during November - December 1994, all reached by teams walking for approximately 150-200 km.

Chemistry

At each site, water samples were filtered through a 0.45 μm membrane filter, with aliquots for metal analysis fixed in 1% ARISTAR nitric acid. Concentrations of anions and cations were determined respectively by ion chromatography and inductively coupled plasma spectrometry (Jenkins *et al.*, 1995). Sampling was timed to occur at least two months after the mid-summer monsoon, under stable flow, so that antecedent chemical conditions experienced by bryophytes were likely to be faithfully reflected (Jenkins *et al.*, 1995 and unpubl. data).

Physical features

Stream width and maximum depth were measured at 10 cross sections, and slope measured at each site with Abney levelling instruments over a 20 m reach. Streambed sediments were characterised by Wolman sampling (Wolman, 1954; Mosely, 1982), measuring at least 100 particles per stream. The resultant substrate data were grouped into five qualitative size classes (Jowett *et al.* 1991):

- bedrock (solid rock surface > 2056 mm that would rarely move during a flood)
- boulders (> 256 mm)
- cobbles (64 - 255 mm)
- gravel (10 - 63 mm)
- sand (10 - 63 mm)

All substrate measurements were then converted to a single substrate index such that low values represented streams with smaller substrates, and high values represented streams with coarser substrate particles (see Suren 1996).

Streambed stability was assessed by the bottom component of the Pfankuch score (Suren 1996). Catchment valley form, land-use, channel form, flow type, bank structure and other aspects of habitat character over a 200 m reach at each site was assessed using a modified version of the U.K. Environment Agency's River Habitat Surveys (RHS; Ormerod *et al.*, 1997; Raven *et al.*, 1997; Buckton & Ormerod, 1997; see Table 1). Altitudes were determined on-site using altimeters pre-calibrated at locations of known elevation.

Bryophytes

Aquatic bryophyte cover was estimated by eye along a 50 m reach at each site and assigned to one of 6 cover classes: 1 = absent, 2 = rare (1 - 5%), 3 = occasional (6 - 25%), 4 = common (26-50%), 5 = abundant (51-75%), 6 = extensive (>76%). Only those bryophytes that were permanently submerged, or continually wetted by splash or spray were included in this assessment. Finally, representative samples of aquatic bryophytes were collected from a variety of microhabitats within each stream to ensure that no taxa were missed. Samples were air dried and stored in plastic bags pending identification.

In the laboratory, all samples were rehydrated and washed free of accumulations of detritus / periphyton, and identified using keys of Gangulee (1969-1980), Vohra (1983), and Kattel & Adhikari (1992).

Statistical analysis

Our survey gave us data on bryophyte cover classes and taxonomic richness at each site, as well as information about physical variables (altitude, slope, Pfankuch stability score, substrate index), water quality (pH, conductivity, nutrients (PO_4 and NO_3) and 14 major anions / cations) and catchment variables (valley shape, channel form, flow type, landuse and bank structure). This represented a large data set of both quantitative (physical and water quality) and semi-quantitative (catchment variables) data. To simplify this data set, a Principal Components Analysis (PCA) was performed on data for all anions / cations and data for catchment variables. Landuse data were essentially ordinal in nature, with 4 classes for each land use type ranging from 'absent' to 'extensive'; the use of ordinal data in this way parallels their use in modern logit regression, or as dummy variables in multiple regression, and is acceptable in PCA (Jongman *et al.*, 1995; Hair *et al.*, 1995). Resulting gradients from the PCA of anions/cation data from all streams were expressed as PCWATER1 and PCWATER2, while PCA gradients for catchment variables were expressed as PCLAND1 and PCLAND2.

All bryophyte data were ordinated by DECORANA to produce information on beta diversity (i.e. changes in diversity along environmental gradients (Whittaker, 1972)) in bryophyte communities, represented by the DECORANA scores for each sample. Following this, all environmental data were correlated with the DECORANA scores to assess which variables might influence bryophyte community composition.

Many of the physicochemical variables identified by Suren (1996) as influencing bryophyte distribution in New Zealand streams were measured in this survey. Relationships between these variables, and bryophyte communities in the Nepalese streams were therefore examined by classifying all streams by TWINSPAN into groups of similar physicochemical conditions, and then comparing the bryoflora across the resulting groups. Streams were classified into groups on the basis of physical variables (altitude, slope, Pfankuch stability score, substrate index), water quality (pH, conductivity, NO_3 and PO_4, PCWATER1 and PCWATER2), and catchment variables (PCLAND1 and PCLAND2). All variables were first standardised by ranks prior to the TWINSPAN analysis. Differences between TWINSPAN groups in all physicochemical variables, bryophyte taxonomic richness, and DECORANA axis scores were assessed by ANOVA. Differences in bryophyte cover between TWINSPAN groups were assessed by Kruskal-Wallis test. A *post-hoc* Tukey's test, corrected for unequal sample sizes, was used to assess pairwise differences. The distribution of the most common bryophyte taxa (i.e., those collected more than 7 times) was examined to assess whether any taxa were more common in any of the defined TWINSPAN groups.

Suren (1996) suggested that streams in New Zealand had to be of a minimal "stability threshold" before bryophytes occurred. Furthermore, he showed that streams without bryophytes differed from streams with bryophytes in certain macro, meso and microscale variables This observation was also tested in the Nepalese streams by *a priori* assigning all streams to bryophyte cover classes. ANOVA was used to determine whether environmental variables differed between streams with, and without bryophytes, and between streams supporting different bryophyte cover.

Finally, the relative strengths of physico-chemical variables putatively influencing DECORANA ordination scores, bryophyte cover classes and taxonomic richness was investigated by stepwise regression analysis. All variables were first examined for collinearity, and slope was removed as it was highly correlated with seven of the 10 variables.

Results

Physicochemical conditions

Stream altitudes ranged from 350 m to 4000 m; those in the Makalu region generally lower than in the Langtang or Simikot regions, while the highest streams were in Dunai (Table 2). Stream gradient was lowest in the Simikot and Makalu regions, and greatest in Dunai and Langtang. The largest streams were sampled in the Makalu area. These streams also had the lowest pH and conductivity (Table 2). Stability of streams in each region was similar.

PCA of the anion / cation data explained 47% of the variation in sample spread. On the basis of factor loadings (Table 3), high PCWATER1 scores represented high concentrations of SO_4 and base cations, whereas low PCWATER1 scores indicated high concentrations of Al and F. High PCWATER2 scores represented high concentrations of electrolytes such as Na, Cl, K, SO_4, and also Si (Table 3).

PCA of the landuse data explained 57% of the variation in sample spread. Correlations of each variable with PCAs showed that channel variables were negatively correlated, and landuse and flow variables positively correlated, with the factor 1 scores. Samples with high PCLAND1 scores were from turbulent natural streams flowing through relatively unmodified valleys (Table 4). Samples with low PCLAND1 scores were from modified streams flowing through catchments where landuse changes were quite apparent. Valley form and landuse were positively correlated with the factor 2 scores, while bank structure and dominant flow were negatively correlated (Table 4). Streams with high PCLAND2 scores thus flowed through coniferous forest or alpine vegetation in natural valleys, and had pristine channels where torrential water flows were common. Streams with low PCLAND2 scores were from terraced catchments where stream channels had been modified, dug or dammed, and where water flows were predominantly smooth (Table 4).

Bryophyte communities

Of 108 streams surveyed, 31 contained no bryophytes. A total of 44 taxa was recognised, with a maximum of 7 at any site. Mosses were dominant (38 taxa), while only 6 liverwort taxa were collected. The most diverse genera were *Fissidens* and *Rhynchostegium* (5 species each) and *Philonotis* (4 species each).

Community composition: DECORANA analysis.

DECORANA axis 1 and 2 explained 77% of the variation in sample spread, with Axis1 explaining 46%. DECORANA axis 1 scores were strongly negatively correlated with altitude, PCWATER1 scores (i.e. base status), conductivity, slope, PO_4 concentration, but positively correlated with the Pfankuch stability score (Table 5). Three bryophyte taxa declined significantly along DECORANA Axis 1, suggesting that they were more common in the higher altitude and base-rich sites; five bryophyte taxa increased significantly along DECORANA Axis 1 (Table 5), suggesting that these taxa were restricted to the lower, base-poorer sites, predominantly in the Makalu region.

Bryophyte communities: TWINSPAN analysis

DECORANA implicated altitude, stability and water quality in regulating bryophyte community structure, and these results were generally corroborated by TWINSPAN on physico-chemical attributes.

TWINSPAN revealed 4 distinct groups after 2 divisions (Fig. 1). Groups 1 and 2 were from small high altitude streams with steep slopes, intermediate stability, and catchments with little modification. They were the most alkaline streams, had high conductivity, and high scores on PCWATER1 scores (Fig. 1). Bryophytes were relatively common, in taxonomically rich communities with low DECORANA scores (Fig. 2).

TWINSPAN Group 3 streams were assessed as being the most stable (Fig. 1). They drained moderately low catchments in terraced valleys (i.e., low PCLAND2 scores). Despite surrounding catchment modification, the stream channels were unmodified, and were generally steep, narrow, and shallow. They had the lowest conductivity, pH, PCWATER1 scores, indicating low base-richness but modestly elevated Al concentrations (Fig. 1). They supported the highest bryophyte cover and taxonomic richness, but high DECORANA scores indicated strong differences in community from TWINSPAN Groups 1 and 2 (Fig. 2).

Streams in TWINSPAN Group 4 had the lowest altitudes and PCLAND1 scores from terraced, semi-improved grazing or rough pasture land; channels were often modified. They were low gradient, wide and deep, with high Pfankuch score suggesting physical instability. They also had a low conductivity and pH (Fig. 1). Bryophyte cover and richness were the lowest of any streams (Fig. 2), but high DECORANA scores suggested similar bryophyte communities to streams in Group 3.

Species distribution patterns

Out of 11 taxa widespread enough for analysis, five were collected mostly from streams in the high altitude, intermediately stable and base-rich TWINSPAN Group 1 (Table 6). Of these five, the moss *Hygroamblystegium tenax* was also common in Group 2 (Table 6), where it occurred with the congeneric *H. obtulosum*. Five different taxa were common in streams in Group 3, but none was most common in Group 4, and four were not found there (Table 6)

Three taxa, *Rhynchostegium riparioides*, *Fissidens grandifrons*, and *Eurhynchium praelongum*, were found in all TWINSPAN groups, although much less frequently in Groups 3 and 4 than in Groups 1 and 2 (Table 6).

A priori *bryophyte cover classes*

Of all measures related to bryophyte cover, the most obvious was a relationship with Pfankuch stability score, with cover increasing with increasing stability (Fig. 3). Otherwise, there were only subtle differences in physico-chemistry between cover classes. Larger streams generally did not support bryophytes, which were restricted more to smaller streams (Fig. 3). Streams without bryophytes were significantly lower than streams where cover was abundant, and streams without bryophytes were less steep than streams where these plants were common (Fig. 3).

Stepwise regression analysis

Among the variables correlating with DECORANA axes scores (see Table 5), stepwise multiple regression showed that altitude, Pfankuch stability score, and PCWATER1 could explain a highly significant 60.7% of the variance in ordination spread (Table 7).

Over 65% of the variance in bryophyte cover was explained by Pfankuch stability rating, PCLAND2, altitude, substrate index and PCWATER1 scores, with all these variables having significant effects on cover values.

For taxonomic richness, however, altitude (positive effects) and Pfankuch stability (negative effects) explained only 18.5% of the variation in sample spread, indicating either marked stochasticity or some other unmeasured influence (Table 7).

All models were examined by regressing predicted and observed values of each bryophyte feature. There was a highly significant relationship between observed and predicted DECORANA score (Fig. 4; $r = 0.549$), and between observed and predicted bryophyte cover (Fig. 4, $r = 0.473$). Observed and predicted taxonomic richness were not closely related (Fig. 4; $r = 0.185$).

Discussion

Overall trends in distribution

This study has highlighted the importance of altitude and streambed stability to aquatic bryophyte communities in Nepal. These two variables were the most important predictors for community composition and taxonomic richness, and were among the three most important predictor variables for bryophyte cover. Water quality and landuse were also implicated as influencing bryophyte communities, but their effects appeared secondary.

The influence of altitude on bryophyte communities confirms previous similar observations of altitudinal trends in benthic invertebrates and periphyton in Himalayan streams (Rundle *et al.*, 1993; Ormerod *et al.,* 1994, Suren 1994). In particular, our results were similar to those of Ormerod *et al.,* (1994), who reported a decline in bryophyte taxon richness and cover with increased altitude. This was attributed to scouring from anchor ice and possible abrasion from glacial flour, and indeed both anchor ice and abrasion from suspended sediments are well known to be detrimental to bryophytes (Glime, 1970; Lewis, 1973; Muotka & Virtanen, 1995). Headwater streams are generally colder and less enriched chemically than low altitude streams, but these conditions are not necessarily detrimental to these communities; bryophytes commonly attain high biomass even in oligotrophic waters (Sheath *et al.*, 1986; Suren, 1991), and in polar regions (Longton 1988) where both nutrients and temperatures are low.

In addition to high altitude effects on bryophytes, Ormerod *et al.* (1994) reported a decline in richness and cover with decreasing altitude in the Langtang-Likhu Khola region of Nepal, such that streams below 1000 m supported the fewest bryophytes. A similar pattern was found in this study, where bryophytes were either absent, or where a few taxa occurred rarely in low altitude streams. Similar distribution patterns are common in many other countries (e.g, England: Haslam 1978; USA: Sheath *et al.*, 1986; New Zealand: Suren, 1991), and may reflect the lack of sufficient free CO_2 in these non-turbulent lowland streams for the plants to photosynthesise (Bain & Proctor, 1980; Allen & Spence, 1981). Lowland streams also have finer substrates, and a high ratio of water depth to substrate height. Substrate movement in these systems is thus likely to be more common, reflecting their greater stream power (Moutka & Virtanen, 1994; Suren, 1996).

Some nutrient concentrations at lower altitudes in Nepal are higher than in headwater streams, reflecting increased catchment modification and increased human population at lower altitudes (Ormerod et al., 1994). Under such eutrophic conditions, benthic algae may proliferate, smothering bryophytes, leading to their eventual loss (Miller, 1990; Suren, 1996). Here, however, landuse *per se* had little impact on bryophyte communities, and were only weakly related to bryophyte cover within a stream. Cover was related to PCLAND2 scores, whereby bryophytes were more common in natural valleys with predominantly coniferous or alpine landuse, and in relatively pristine streams where torrential flows and riffle - pool morphology. Streams in terraced valleys where the channel had been dug or modified supported little or no bryophytes.

Effects of water quality involved streams with high base cations concentrations (i.e., high PCWATER1 scores) supporting different bryophyte communities than streams with low base cations. Vitt *et al.* (1986) also found that bryophyte distributions in 11 streams in the Rocky Mountains, Canada, were correlated with Ca ions. Streams draining the eastern Rockies flowed over dolomitic rock, and supported different bryophyte communities to streams draining the western Rockies, flowing over non-calcareous sediments. Geological differences have also been implicated in influencing algal communities in Nepal (Jenkins et al. 1995).

Assessing a descriptive model for bryophyte distributions

This survey examined many of the variables identified by Suren (1996) as important in regulating bryophyte distribution patterns in New Zealand streams (Table 8). While some similarities existed between our results and those in New Zealand, differences were also apparent.

Suren (1996) reported that bryophytes were more common in stable than unstable streams, but that there were no differences in stability between streams supporting different bryophyte communities (Table 8). In the present study, we also found that bryophytes were more common in stable streams. However, we also found that bryophyte community composition was related to stability. Taxa such as *Isopterygium*, *Philonotis* and Lejeuneaceae were more common in unstable streams, while *Eurhunchium*, *Hygroamblystegium*, and *Bryum were* more common in stable streams.

Our results reflect those of Muotka and Virtanen (1995) who examined community composition of bryophytes in north-eastern Finland. They found that frequently disturbed sites were dominated by small, potentially fast colonising bryophytes such as *Blindia*, while stable sites were dominated by large, perennial species such as *Fontinalis*. Disturbance in their study was related to either substrate movement or water level fluctuations, as they sampled both aquatic and semi-aquatic bryophytes. We restricted our survey to submerged bryophytes only, and so could only consider streambed stability, as assessed by the Pfankuch score.

Stability is a consequence of substrate size, and the propensity for substrates to move during high discharge. In New Zealand, streams without bryophytes had smaller substrates than streams with bryophytes (Suren 1996), yet we found that substrate size was similar in all the Nepalese streams, irrespective of bryophyte cover. Although substrate size is often equated with stability (Carling, 1983; Komar, 1988; Townsend, Doledec & Scarsbrook, 1997), this may not always be the case. Large particles protrude more into the water column and are thus subject to higher velocities and turbulent shear stress than small particles, which may lie in hydrologically quiescent areas of the streambed. Additionally, large particles become mobile when random, high energy turbulent eddies hit them, so the longer a stream is in flood for, the more likely this is to occur. Flow regimes in New Zealand and Nepal are very different, with New Zealand streams characterised by frequent, unpredictable short lived floods, and Nepalese streams characterised by long, seasonal increases in discharges as a result of monsoonal rainfall. The longer flood durations in Nepalese streams would thus increase the likelihood of a particular substrate element in being moved by random high energy turbulent eddies. Since even large particles - up to metres in diameter - are sometimes moved during monsoonal floods (SJO, pers. observation), the presence of large particles in Himalayan streams does not necessarily equate with extra stability.

The highly predictable pattern of monsoonal rainfall, and resultant regular hydrographs may, however, provide an alternative explanation as to why substrate size appeared unimportant for bryophytes in Nepalese streams. Aquatic bryophytes are intolerant of desiccation (Kimmerer & Allen, 1982; Glime & Vitt, 1984; Bowden at al, 1997) and so would be absent from streambed material that becomes exposed during the winter low flows. Differences in water level would be expected to be more pronounced on larger boulders, and if these become exposed during the winter low flow, aquatic bryophytes would not be able to successfully colonise them.

Streambed slope was identified by Suren (1996) as important for aquatic bryophytes in New Zealand (Table 8), with bryophyte cover increasing with increasing slope. A similar trend was observed in our study. We did however, observed a decline in bryophyte cover in very steep streams, reflecting either a decline in streambed stability, or the loss of continually submerged areas of the streambed.

Macroscale and mesoscale variables in New Zealand streams appeared to influence both the presence of aquatic bryophytes in streams, and the resultant community (Suren 1996). We found similar patterns in our study, although landuse played a less important role than in New Zealand. Not surprisingly, altitude played a more important role in structuring bryophyte communities in Nepal than in New Zealand, reflecting the much greater altitude range and the number of altitude related variables. Additionally, with the exception of substrate size, all microscale variables examined by Suren (1996) were implicated in regulating the presence of bryophytes in the Nepalese streams. Subtle differences in how these might influence bryophyte communities in Nepal were evident, as streambed stability had no influence on bryophyte community composition in New Zealand, but correlated strongly with communities in Nepal.

From our results, it is clear that the summary model presented by Suren (1996) is generally valid for aquatic bryophytes in these Nepalese streams, despite the greater heterogeneity in the Himalaya. Differences between the behaviour of bryophyte communities in the two countries with respect to stability and substrate size can be explained by the fundamental differences in the hydrological regimes of the two countries. and the greater stream power of the Nepalese streams during the monsoon.

A habitat template for Nepalese bryophytes

The above results enabled us to develop a conceptual habitat template for bryophytes in Nepalese streams. On the basis of the TWINSPAN and DECORANA results, altitude and streambed stability were identified as the major axes on this template (Fig. 5), although other secondary environmental gradients such as conductivity, pH, PCWATER1 and PCLAND1 which also identified. These variables showed a high correlation with altitude, and so are represented on the same axis. Although altitude (and related variables) is thought to be the dominant variable for aquatic bryophytes in these streams, stability was also of major importance, yet the two were not correlated. This variable thus forms the secondary axes of our habitat template model.

Bryophyte cover was least in low altitude streams which were also the least stable. Cover was highest in streams at a moderate altitude, which were also the most stable. Streams at higher altitudes were less stable and so supported fewer bryophytes. Notwithstanding any effects of altitude, the effects of streambed stability in these streams were the same as predicted by both Muotka & Virtanen (1995) and Suren (1996). Our model shows how bryophyte communities changed with respect to both altitude and stability, confirming observations by Ormerod *et al.*, (1994) of the importance of altitude, and Muotka & Virtanen (1995), of the importance of stability to bryophytes.

Some taxa such as *Isopterygium distichaceum,* and Lejeunaceae were restricted to lower sites, where they were more common in stable streams. Other taxa such as *Rhynchostegium vagans* and *Hygroamblystegium obtulosum* were restricted to only high altitude streams. Three taxa, *Fissidens grandifrons* and *Rhynchostegium riparioides*, and *Eurhynchium praelongum* were notable in their broad distribution across a wide range of both altitude and stability (Table 6 and Figs 5), and indeed were collected the most. The wide spread distribution of *F. grandifrons* in Nepal mirrors that of the distribution of *F. rigidulus* in New Zealand, where it was found in almost half of the 118 streams surveyed throughout the South Island. These 2 species of *Fissidens* must have broad niches, and efficient means of reproduction and dispersal to explain their ubiquitous distribution patterns in these highly dynamic environments.

Traditional plant theory predicts that stable environments will be dominated by large, long lived perennial species which rely mainly on asexual reproduction, while more disturbed environments would be dominated by smaller, short lived 'shuttle' species that regularly produce spores (During, 1979; Grime *et al.*, 1990). It is interesting to note that sporophyte production in *F. rigidulus* is relatively rare (Suren 1996, pers obs), as it is in *F. grandifrons* (Hill, 1902). Presumably, these species rely on vegetative propagation. The widespread occurrence of these vegetatively producing plants throughout the two countries where disturbance by substrate movement is common suggests that the importance of sexual reproduction in unstable environments may not be as relevant for aquatic bryophytes as is commonly assumed (Muotka & Virtanen, 1995).

Intuitively, sexual reproduction in an unstable stream environment would be difficult. High flows would result in high levels of suspended sediments, which are known to reduce the production of antheridia and archegonia (Lewis, 1973). Fertilisation may also be difficult, especially on dioecious plants where high currents may wash sperm away from the separate female plant. Sporophyte production, successful release of spores, their subsequent entrapment in a suitable place, and their germination to form protonema and then a new gametophyte would be conceptually difficult in an unstable environment such as the Himalayas. Vegetative reproduction, however, only requires a plant fragment to lodge in a suitable area for sufficient time to enable rhizoid production to occur. Although our results imply that vegetatively dispersing plants are ubquitous throughout Nepal, more studies are needed to see whether reproductive strategies for aquatic bryophytes do indeed match those as predicted by traditional theory. Alternatively, populations of the same species may use different reproductive strategies in habitats of different stability.

Overall, our results show clearly that bryophyte communities in the Nepalese Himalaya are regulated mainly by altitude (and altitude related variables) and by stability. We have also shown that the summary discriptive model developed by Suren (1996) to explain bryophyte distributions in New Zealand is relevant here, although some discrepencies occur. Altitude appears to play a much more important role in these Nepalese streams than it does in New Zealand, and so this forms a major axis of our habitat template model. As predicted by Suren (1996), and Moutka & Virtanan (1995), stability is also fundamental to the occurrence of bryophytes within Nepalese streams, and forms the second axis of our template. Species distributions vary in apparently consistent patterns along these two axes, although some species appear to have wider distributions than predicted by traditional ecological theory. Better knowledge of the ecology and life cycles of the common species encountered would provide valuable information and help in terms of developing a clearer understanding between species traits and their relationship to the habitat template we have proposed for these plants.

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Table 1 Catchment and habitat details were assessed at all sites, with information collected on valley shape, channel form, flow type, landuse, and bank structure. All qualitative categories used in these assessments are given below.

Catchment varaible	Category	Catchment variable	Category
Valley	1. vee	**Dominant flow**	1. torrential / white water
	2. concave		2. riffle / pool
	3. terraced		3. step / pool cascade
	4. symmetrical		4. run
	5. assymmetrical		5. glide
	6. gorge		
Landuse	1. terrace / agriculture	**Bank**	1. vertical / undercut
	2. (semi)-improved grazing		2. vertical + toe
	3. scrub / rough pasture		3. steep (>45°)
	4. sal forest		4. gentle
	5. broad leaf / mixed forest		5. composite
	6. coniferous forest		
	7. alpine		
Channel	1. pristine		
	2. semi-natural		
	3. dammed		
	4. artificially dug		
	5. resectioned / realigned		

Table 2: 108 streams were surveyed from 4 geographically distinct areas in Nepal, two regions in western Nepal (Simikot and Dunai), one region in north-central Nepal (Langtang region) , and the Makalu region in eastern Nepal. Streams in these regions differed with respect to their altitude, physical nature (e.g., slope, stability, size) and chemistry ($x \pm$ 1sd).

Variable	Dunai (n = 20)	Simikot (n = 32)	Langtang (n = 23)	Makalu (n = 33)
Altitude (m)	3087 ± 487	2222 ± 418	2430 ± 666	1212 ± 4739
Slope (°)	16 ± 9	8 ± 5	15 ± 9	11 ± 6
Width (m)	1.2 ± 0.9	2.6 ± 2.2	2.0 ± 0.9	6.8 ± 6.4
Depth (cm)	11 ± 13	22 ± 17	17 ± 14	36 ± 45
pH	8.1 ± 0.4	7.7 ± 0.6	7.9 ± 0.4	7.3 ± 0.5
Conductivity (μScm^{-1})	128 ± 49	137 ± 124	60 ± 53	39 ± 28
Stability	41 ± 6	35 ± 10	37 ± 9	38 ± 9

Table 3 Factor loadings for the water anion / cation data on axes 1 and 2 of the PCA. * indicates those variables whose concentrations were significantly correlated to the PCA factor loading scores ($P < 0.05$).

Anion / cation	Axis 1	Axis 2
Ca	0.250 (*)	0.016
Sr	0.259 (*)	-0.073
Al	-0.249 (*)	0.093
Ba	0.185 (*)	0.013
Mn	0.178 (*)	-0.024
SO_4	0.149 (*)	0.123 (*)
Na	-0.063	0.319 (*)
K	0.051	0.277 (*)
Cl	-0.060	0.287 (*)
Mg	0.105 (*)	0.147 (*)
Si	-0.028	0.121 (*)
F	-0.088 (*)	0.113 (*)
Fe	0.124 (*)	-0.030

Table 4 Factor loadings for the catchment and stream characterisation data on axes 1 and 2 of the PCA conducted on landuse variables. The table shows those variables which were significantly correlated with the PCA factor loading scores ($P < 0.05$), and shows what variables were indicative of samples with high or low PCA scores.

Catchment / stream variable (correlation coefficient r)	High scores	Low scores
PCA Axis 1		
Channel (-0.842)	Pristine	Dammed
	Semi-natural	Artificially dug
Landuse (0.652)	Broad leaved forest	Terraced
	Coniferous forest	Semi (improved) grazing
	Alpine	Scrub / rough pasture
Dominant flow (0.260)	Torrential	Riffle / pool
	Step / pool cascade	Glide
PCA Axis 2		
Valley form (0.626)	Symmetrical	Concave
	Assymetrical	Terraced
	Gorge	Vee-shaped
Bank structure (-0.604)	Vertical / undercut	Gentle
	Vertical plus toe	Composite
Landuse (0.486)	Coniferous forest	Terraced
	Alpine	
Dominant flow (-0.355)	Torrential	Glide
	Step / pool cascade	

Table 5: Correlation coefficients (*r*) of measured environmental variables and bryophyte species to DECORANA ordination scores of species in sample space, and of sites to DECORANA ordination scores of samples in species space. Only significant correlations to DECORANA Axis 1 scores are shown ($P < 0.05$).

	Negative correlations	Positive correlations
Variables ($n = 76$)	Altitude (-0.659)	Pfankuch stability (0.224)
	PCAWATER1 (-0.479)	
	Conductivity (-0.476)	
	Slope (-0.290)	
	PO_4 concentration (-0.229)	
Species ($n = 76$)	*Eurhynchium praelogum* (-0.500)	*Isopterygium distichaceum* (0.617)
	Hygroamblystegium obtulosum (-0.397)	*Philonotis glomerata* (0.511)
	Bryum pseudotriquetrum (-0.281)	*Philonotis hastata* (0.314)
		Lejeuneaceae (0.310)
		Isopterygium albecens (0.267)
Sites ($n = 27$)	Dunai 1 (-0.374)	Makalu 28 (0.528)
	Dunai 6 (-0.370)	Makalu 34 (0.368)
	Dunai 19 (-0.461)	Makalu 41 (0.475)
	Dunai 38 (-0.391)	Makalu 43 (0.388)
		Makalu 64 (0.365)
		Makalu 65 (0.368)
		Makalu 81 (0.463)
		Makalu 84 (0.611)

Table 6: Streams in the different TWINSPAN groups supported different species assemblages. The table shows the relative percentage occurrence of 11 common taxa in streams in each of the 4 TWINSPAN groups.

	TWINSPAN GROUP			
Bryophyte taxa	Group 1	Group 2	Group 3	Group 4
Bryum pseudotriquetrum	20	20	60	0
Eurhynchium praelongum	45	23	18	14
Fissidens grandifrons	44	30	19	7
Hygroamblystegium obtulosum	27	64	9	0
Hygroamblystegium tenax	50	50	0	0
Isopterygium distichaceum	0	0	78	22
Lejeunaceae	0	0	86	14
Lophocolea sp	38	0	46	16
Mnium punctatum	25	12	44	19
Rhynchostegium riparioides	44	25	19	12
Rhynchostegium vagans	50	13	17	0

Table 7: Stepwise multiple regression analysis of Bryophyte cover, taxonomic richness and community composition as expressed as DECORANA axis 1 scores against measured physico-chemical parameters from the 108 streams. Significant ($P < 0.01$) values for the resultant model test for each equation are also given.

Variable	Coefficient	*t*-value	*P*- value	*F* - value
A. DECORANA scores (n = 78, r^2=0.607)				
Altitude	-0.108	-6.290	0.001	
Stability	-3.753	-2.536	0.014	
PCAWATER(1)	-29.765	-2.536	0.015	
Substrate index	-1.698	-1.177	0.245	17.08
B. Taxonomic richness (n = 108, r^2=0.158)				
Altitude	0.001	3.637	0.001	
Stability	-0.043	-2.309	0.023	9.64
C. Bryophyte cover (n=62, r^2=0.651)				
Stability	-0.809	-7.613	0.001	
PCALAND(2)	-0.313	-3.468	0.001	
Altitude	-0.013	2.859	0.006	
Substrate index	-0.031	-2.437	0.018	
PCAWATER(1)	-0.525	-2.133	0.037	19.28

Table 8: Comparison of the results that examine the interactions of macro, meso, and microscale variables on aquatic bryophytes in streams in New Zealand (Suren 1996) and in Nepal (this study). Table shows the major relationships obtained in each study, and highlightes those variables seen to regulate both the presence of aquatic bryophytes in streams, as well as the resultant community composition.

Variable	Suren (1996)		This study	
	Presence / Absence	Community composition	Presence / Absence	Community composition
Macroscale				
Altitude	✓		✓	✓
Geology	✓	✓	not examined	
Landuse	✓	✓	✓	
Mesoscale				
Hydrology	✓	✓	not examined	
Water quality	✓	✓	✓	✓
Microscale				
Substrate size	✓		not important	
Water nature	✓		not examined*	
Stability	✓		✓	✓
Slope	✓		✓	

* Water nature was not examined directly in this study, but all bryophytes were collected from fast flowing, highly turbulent areas. As such, this gave the same result as in Suren (1996)

Captions to figures

Fig. 1 TWINSPAN analysis of the 108 streams produced 4 discrete groups. Streams within these groupings differed significantly ($P < 0.05$) with respect to many variables, including altitude ($F_{(3, 104)} = 32.61$), slope, ($F_{(3, 104)} = 12.36$), depth ($F_{(3, 104)} = 16.79$), width ($F_{(3, 104)} = 14.11$), and stability ($F_{(3, 102)} = 7.29$), as assessed by the Pfankuch score. Streams in TWINSPAN groups also differed with respect to landuse, as expressed as PCLAND1 and PCLAND2 ($F_{(3, 83)} = 17.29$ and 16.25 respectively), and water chemistry, both in terms of ionic composition (PCWATER1; $F_{(3, 104)} = 17.668$), pH and conductivity ($F_{(3, 103)} = 23.81$ and 18.51 respectively). Letters above each group indicate that they were not significantly different to each other (Tukey's test; $P < 0.05$)

Fig. 2 Streams in the defined TWINSPAN groups had significantly different ($P < 0.05$) bryophyte cover ($F_{(3, 102)} = 13.69$), taxonomic richness ($F_{(3, 104)} = 5.31$) and community composition, as expressed by DECORANA ordination numbers ($F_{(3, 72)} = 11.39$); conventions as in Fig. 1.

Fig. 3 Relationships between *a priori* defined bryophyte cover classes, and environmental variables which were significantly different ($P < 0.05$) between streams in each class, conventions as in Fig. 1.

Fig. 4 Stepwise regression analysis gave resultant regression models from which to predict DECORANA scores, cover classes and taxonomic richness from some of the environmental data.

Fig. 5 Conceptual habitat template model of the TWINSPAN groups showing their position on the altitude - stability axes. Bryophyte cover and richness varied between these groups, as did the distribution patterns of common taxa, some of which were restricted to particular TWINSPAN groups, while others were found in all streams.

Figure 1

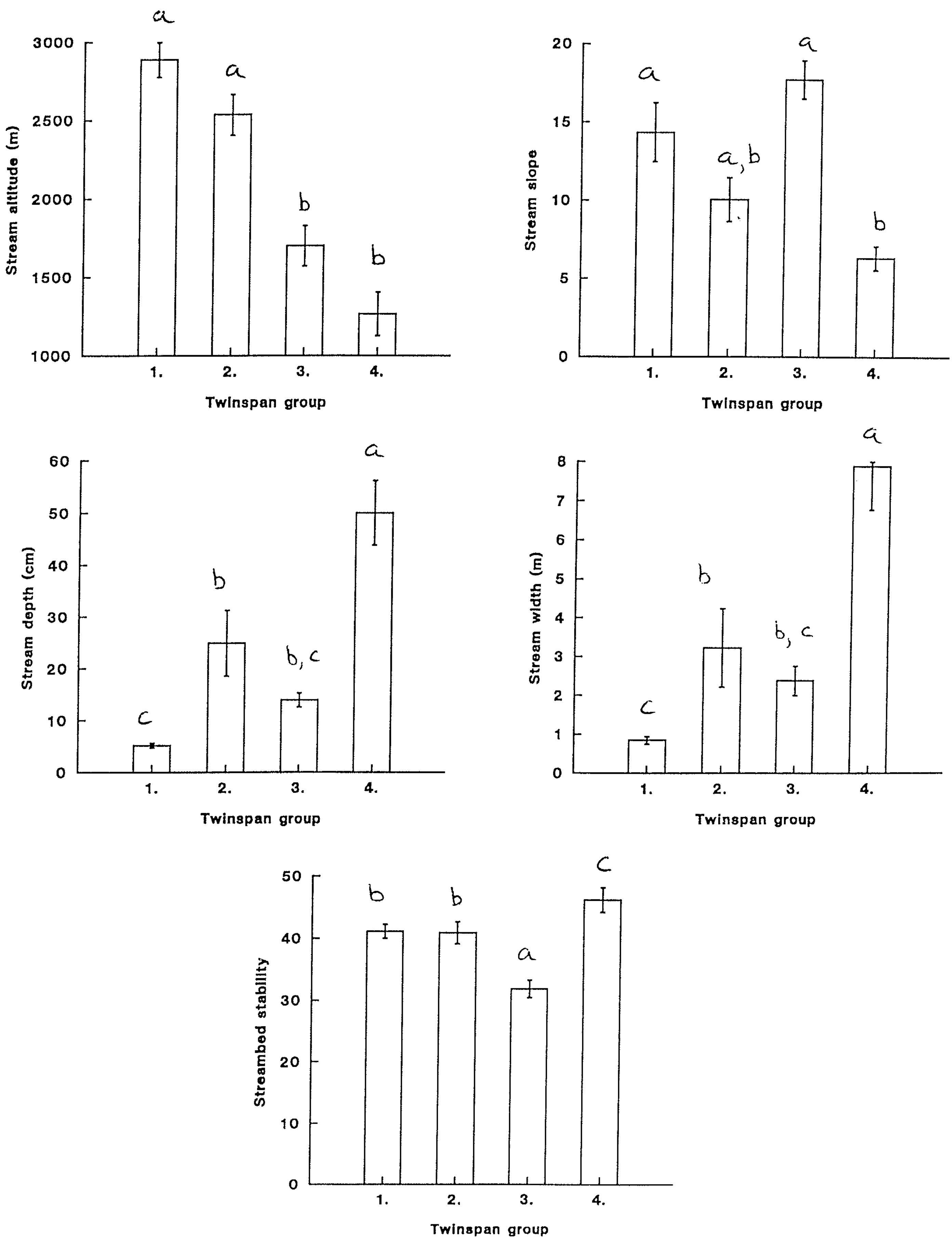
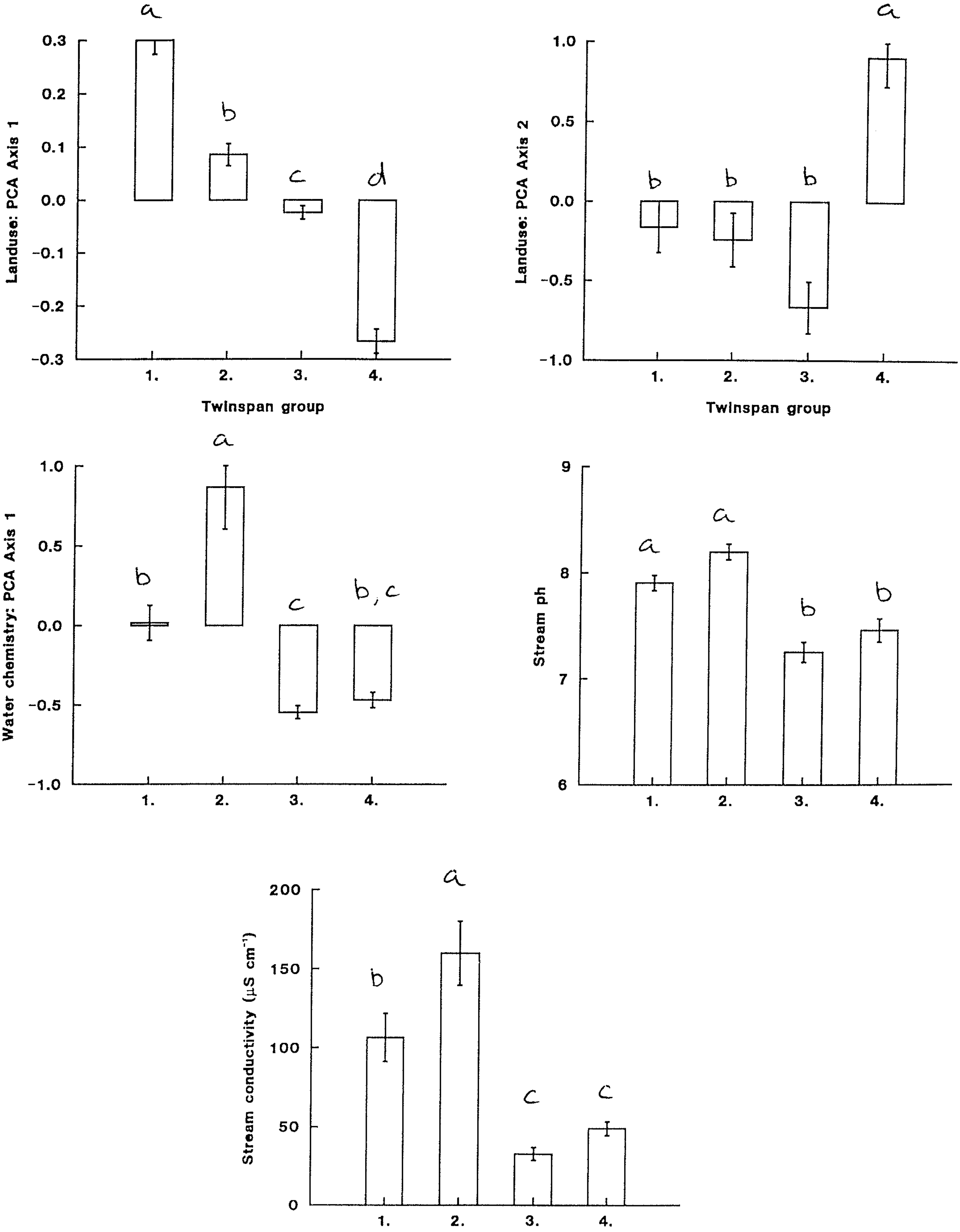

Stream altitude (m)
3000
2500
2000
1500
1000
1.
2.
3.
4.
Twinspan group
a
a
b
b
Stream slope
20
15
10
5
0
1.
2.
3.
4.
Twinspan group
a
a, b
a
b
Stream depth (cm)
60
50
40
30
20
10
0
1.
2.
3.
4.
Twinspan group
c
b
b, c
a
Stream width (m)
8
7
6
5
4
3
2
1
0
1.
2.
3.
4.
Twinspan group
c
b
b, c
a
Streambed stability
50
40
30
20
10
0
1.
2.
3.
4.
Twinspan group
b
b
a
c

Figure 1



a
b
c
d
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
Landuse: PCA Axis 1
1.
2.
3.
4.
Twinspan group
a
b
b
b
1.0
0.5
0.0
-0.5
-1.0
Landuse: PCA Axis 2
1.
2.
3.
4.
Twinspan group
a
b
c
b, c
1.0
0.5
0.0
-0.5
-1.0
Water chemistry: PCA Axis 1
1.
2.
3.
4.
a
a
b
b
9
8
7
6
Stream ph
1.
2.
3.
4.
a
b
c
c
200
150
100
50
0
Stream conductivity (µS cm⁻¹)
1.
2.
3.
4.

Figure 2

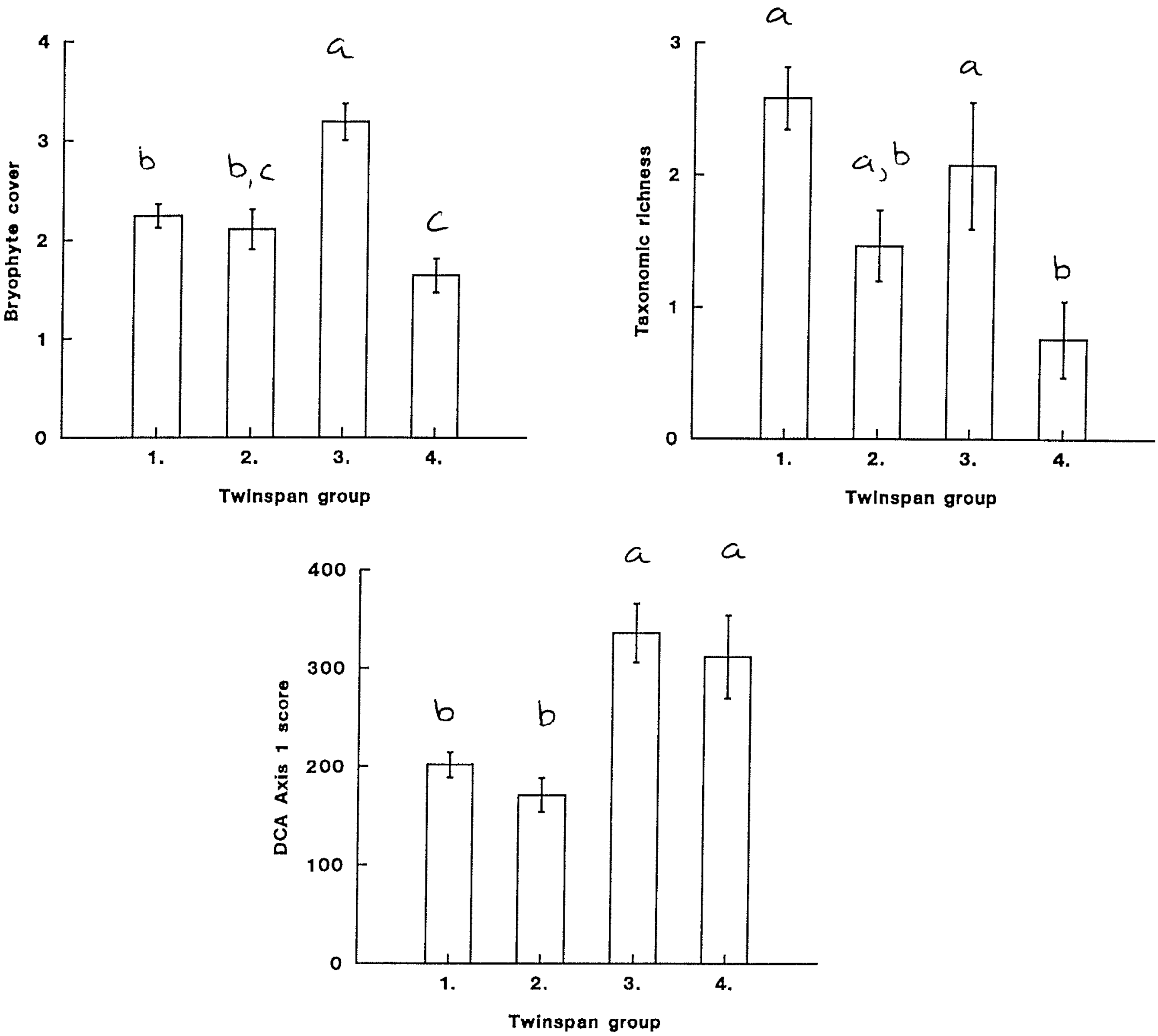

Bryophyte cover
0
1
2
3
4
1.
2.
3.
4.
Twinspan group
b
b,c
a
c
Taxonomic richness
0
1
2
3
1.
2.
3.
4.
Twinspan group
a
a,b
a
b
DCA Axis 1 score
0
100
200
300
400
1.
2.
3.
4.
Twinspan group
b
b
a
a

Figure 3

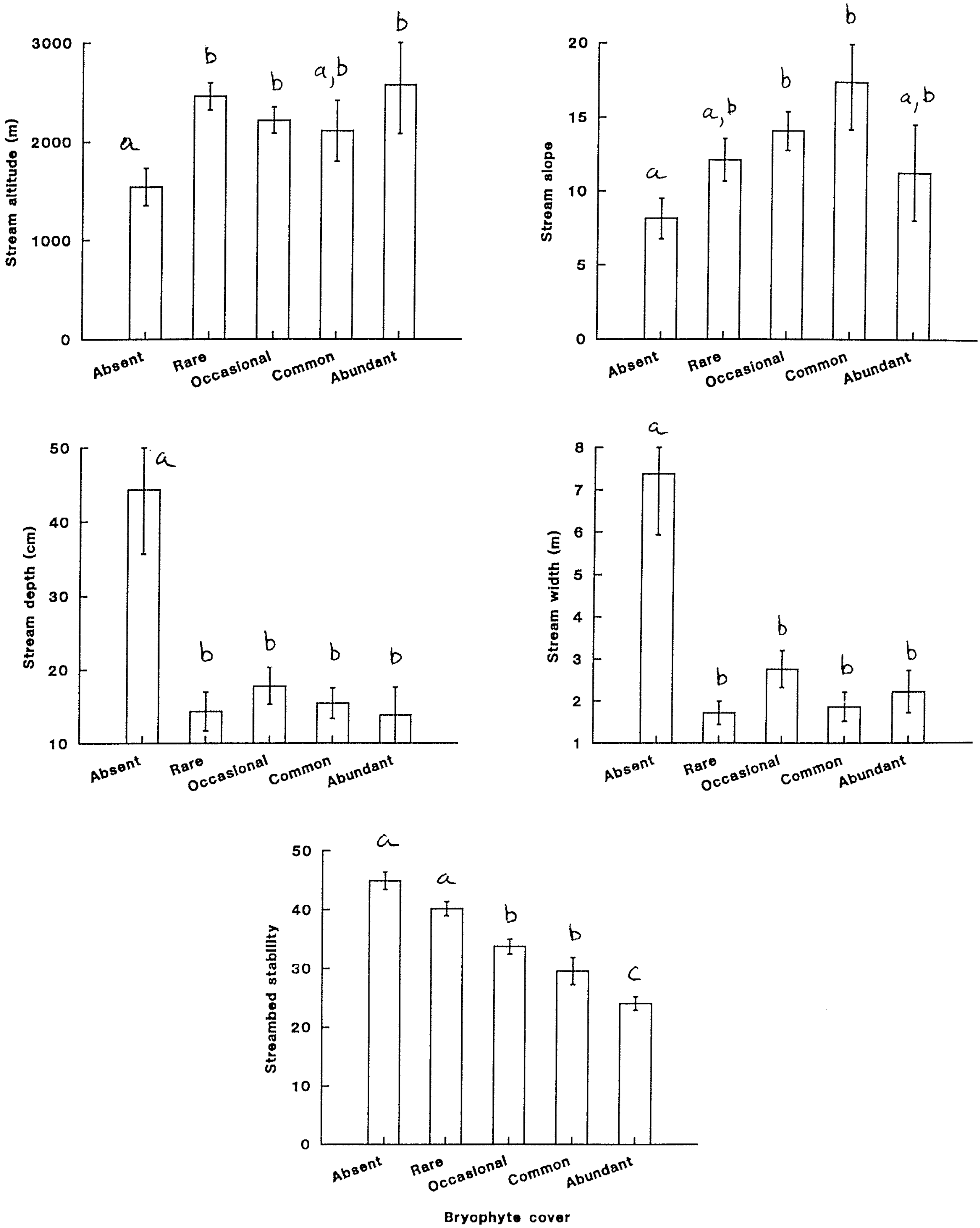
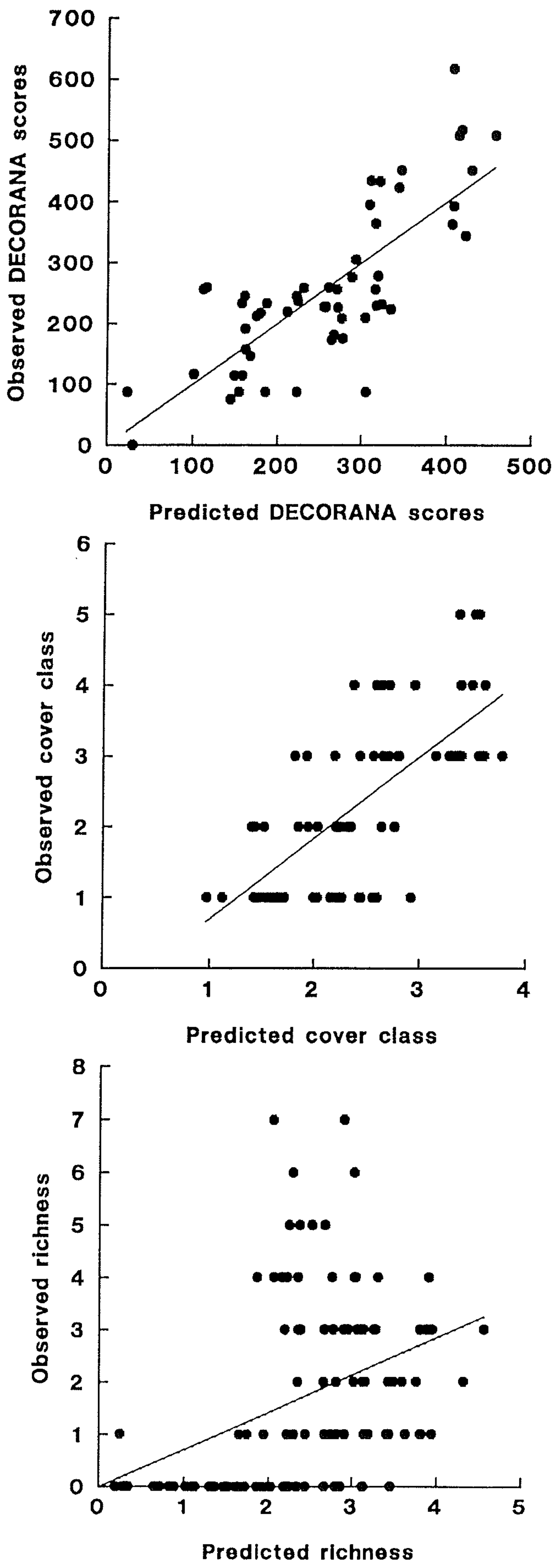
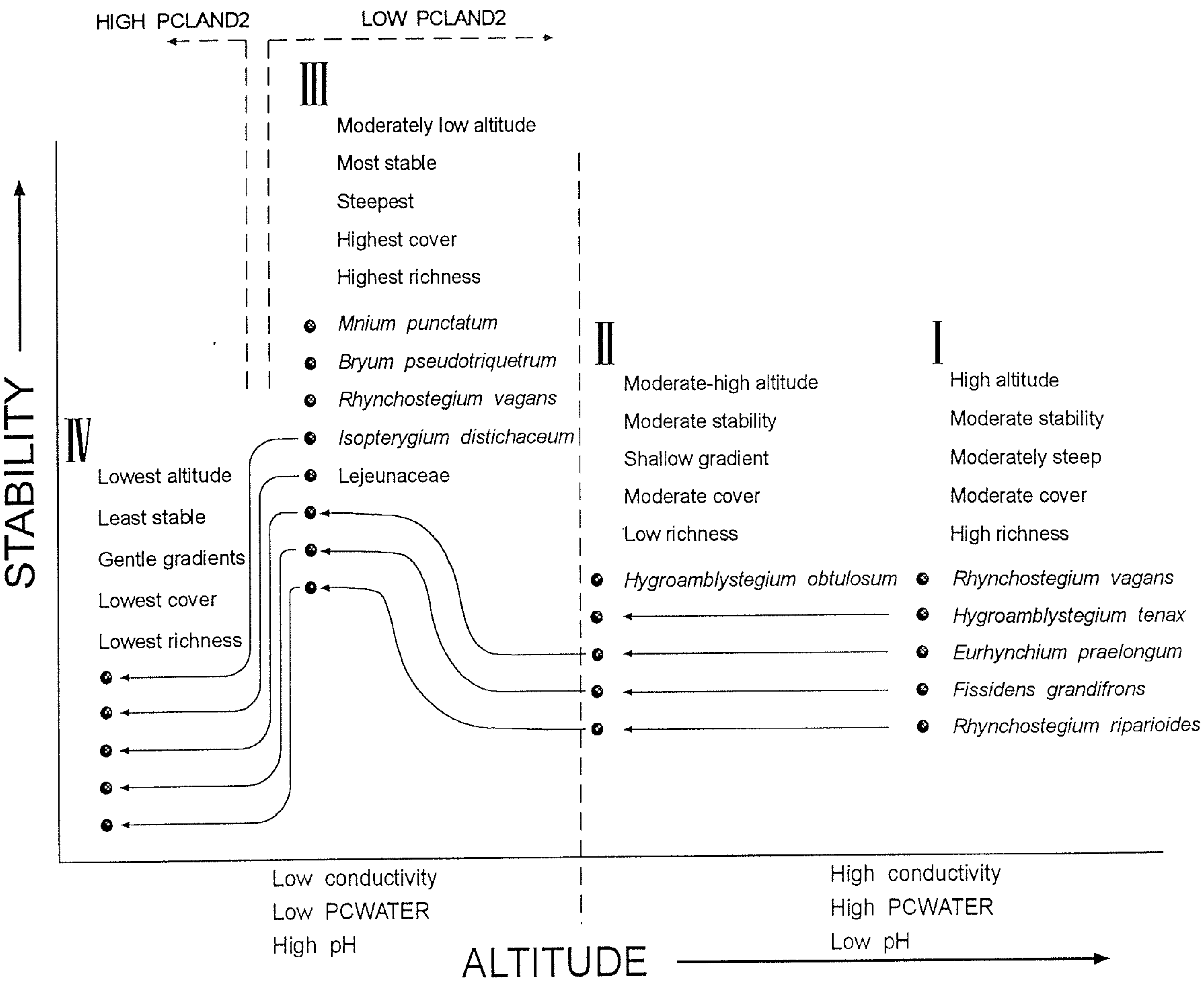

Stream altitude (m)
Stream slope
Stream depth (cm)
Stream width (m)
Streambed stability
Absent
Rare
Occasional
Common
Abundant
Bryophyte cover

Figure 4



Observed DECORANA scores
Predicted DECORANA scores
Observed cover class
Predicted cover class
Observed richness
Predicted richness

Figure 5



HIGH PCLAND2
LOW PCLAND2
III
Moderately low altitude
Most stable
Steepest
Highest cover
Highest richness
Mnium punctatum
Bryum pseudotriquetrum
Rhynchostegium vagans
Isopterygium distichaceum
Lejeunaceae
II
Moderate-high altitude
Moderate stability
Shallow gradient
Moderate cover
Low richness
Hygroamblystegium obtulosum
I
High altitude
Moderate stability
Moderately steep
Moderate cover
High richness
Rhynchostegium vagans
Hygroamblystegium tenax
Eurhynchium praelongum
Fissidens grandifrons
Rhynchostegium riparioides
IV
Lowest altitude
Least stable
Gentle gradients
Lowest cover
Lowest richness
STABILITY
Low conductivity
Low PCWATER
High pH
High conductivity
High PCWATER
Low pH
ALTITUDE