Aquatic Macrophyte Distribution in Response to Physical and Chemical Environment of the Lakes along an Altitudinal Gradient in the Himalayas, Nepal

by

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To the Gurus, for their inexhaustible supply of wisdoms

To the Sherpas, for accepting their physical challenges

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ABSTRACT

Aquatic plants and physical-chemical characteristics were studied in 34 lakes at altitudes ranging from tropical (77 m) to high-alpine (4,950 m) in the Himalayas of Nepal. The water chemistry was dominated by HCO_3^- among anions, and by Ca^{2+} and Mg^{2+} among cations. Criteria related to total phosphorus, total nitrogen, and chlorophyll showed that lakes in the High Himal (HH) and High Mountain (HM) regions are oligotrophic, while those in the Middle Mountains (MM) were oligotrophic to hypereutrophic, and Terai (TE) lakes were eutrophic to hypereutrophic.

Aquatic macrophytes occurred in 28 lakes, up to an altitude of 4,750 m. Both species richness and diversity of aquatic macrophytes showed approximately linear decreases with increasing altitude. The study region exhibits a relatively high proportion of monocotyledonous helophytes and hyperhydates, as is typical of aquatic macrophytes on the Indian subcontinent.

A canonical correspondence analysis of the steepest altitudinal gradient (CCA-1) suggested that the strongest abiotic influences on the distribution of macrophytes are associated with water temperature, substrate quality, altitude, pH, transparency, and conductivity. Two more restricted CCA analyses examined a shorter altitudinal gradient of 70 m to 1500 m. The CCA-2 analysis (all plants) and CCA-3 (only euhydrophytes) found that the most important abiotic influences were associated with temperature, lake surface area, suspended solids, bicarbonate, and dissolved phosphorus. These results suggest that relatively local influences are different from those that have a regional basis, but that climatic influences are key along altitudinal gradients. The temperature gradient in the CCA distinguished Arcto-tertiary floristic elements of the HH and HM regions from the more widely distributed temperate and tropical species of the MM and TE regions. This observation is also supported by the results of a cluster analysis.

LIST OF ABBREVIATION AND SYMBOL USED

AL = agricultural land
ANC = acid-neutralizing capacity
AP = alpine pasture
AS = alpine scrub
BL = barren land
CCA = Canonical Correspondence Analysis
DCA = Detrended Correspondence Analysis
DTF = dry temperate forest
GL = glacial lake
HFF = himalayan frontal fault
HH = high himal
HHCH = high himalayan crystalline series
HM = high mountains
HU = human use
I = impoundments
KTWR = Koshi Tappu Wildlife Reserve
L = natural lake
LRTAP = the long range transport of atmospheric pollutants
LLG =lowland grassland
LM =loose moraine with rocks
max = maximum
MBT = main boundary thrust
MCT = the main central thrust
min = minimum
MM = middle mountains
MTF = moist temperate forest
MY = million years
O = natural oxbow lake
PCA = Principal Component Analysis
PL = natural perched lake
PS = lake with ground water inflow highly probable
RCNP = Royal Chitwan National Park
RF = riverine forest
S = lake with known groundwater inflow
SACF = sub-alpine coniferous forest
SHU = seasonal human use
TE = terai
TSF = tropical sal forest
TWINSPAN = Two-Way INdicator SPecies ANalysis
WSA = watershed area

Water chemistry

ALT = altitude
COND = conductivity
CHL = chlorophyll
Ca^{++} = calcium
Cl^{-} = chloride
DN = dissolved nitrogen
DP = dissolved phosphorus
HCO_3^{-} = bicarbonate
K^{+} = potassium
Mg^{++} = magnesium
Na^{+} = sodium
NVSS = non-volatile suspended solids
SA = surface area
SO_4^{2-} = sulphate
TEMP = temperature
TN = total nitrogen
TP = total phosphorus
TSS = total suspended solids
VSS = volatile suspended solids
Z_{max} = maximum depth
Z_s = Seechi transparency

Symbols and Units

λ = eigen value
p = probability level
< = less than
> = greater than
° = degree
% = percentage
C = centigrade
E = east
N = north
m = meter
mg/l= milligram per liter
µg/l= microgram per liter
me/l= mille equivalents per liter

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1. INTRODUCTION

Plant community ecology deals with variations in the distribution and abundance of assemblages of plant species. It also examines intrinsic characteristics of plant species that affect their acquisition and use of resources, as well as extrinsic factors influencing resource availability, which can be abiotic or biotic in origin. As such, extrinsic and intrinsic factors integrate to affect the structure and dynamics of plant communities.

Among the complex of extrinsic environmental factors, the relative strengths of abiotic and biotic ones vary with the temporal and spatial scales under consideration. However, the integrative quantification of the influences of these factors on biodiversity at various scales has not yet been advanced much (Huston and McBride, 2002). Until common drivers are recognized to allow extrapolation from relatively local to more extensive levels, studies addressing the large scales of landscape or region are required to answer specific questions at these scales (O'Neill and King, 1998). Within this context, studies of regional environmental gradients provide an opportunity to explore ideas and models about influences on the structure and function of ecosystems, allowing assessment of their utility and potential application to large scales (Burke *et al.*, 1998; Burke, 2000).

Spatial variation in the structure and function of ecosystems is profoundly evident on landscapes, at both latitudinal and altitudinal scales. Gradients of resource availability are often parallel to those of climatic factors — on a global scale, more than 80% of the variation of regional plant-species richness is accounted for by climatic factors (Francis and Currie, 2003). A similar phenomenon is apparent for terrestrial vegetation in mountainous regions, where elevation-related climatic gradients ranging from tropical to high-alpine may be expressed over lateral distances of only several tens of kilometers (Whittaker and Niering, 1975; Singh *et al.*, 1994; Martens *et al.*, 2001).

Studies of this sort have not yet, however, been made of aquatic plants in lakes along a steep altitudinal gradient. Within this context, the present thesis examines variations of the distribution and abundance of aquatic plants and assesses them against the physical-chemical characteristics of lakes along a steep altitudinal gradient, ranging from tropical to high-alpine environments, within a lateral distance of less than 100 km.

1.1 Regional limnology and aquatic macrophytes

The study of regional limnology is useful and necessary because the characteristics of lakes and their biota vary according to physical-chemical influences of their geological origin, basin morphometry and climate, as well as biogeographical influences associated with species complement and ecological interactions among taxa (Wetzel, 1983; Naiman *et al.*, 1995; Abell *et al.*, 2000; Riera *et al.*, 2000; Heino, 2002). The study of regional limnology also has important implications for the management of lakes and their resources, including study of the potential effects of climate change on freshwater ecosystems (Schindler, *et al.*, 1990, 1996 a, b; Magnuson *et al.*, 1997).

Lakes vary considerably in their physical, chemical, and biological characteristics, even within a particular so-called "lake-district" having relatively uniform conditions of basin origin, catchment geology, climate, and species complement. Early studies of waterbodies in a particular, relatively uniform, lake-district were made by Birge and Juday (1911), Thienemann (1925), Naumann (1932), and Likens (1985). More recently, limnologists have also been studying much wider gradients of limnological conditions across various lake-districts (Kratz and Frost, 2000; Riera *et al.,* 2000; Webster *et al.,* 2000).

For instance, Seddon (1972) studied more than 70 lakes in Britain ranging from coastal to montane (to several hundred meters of elevation) to investigate the use of aquatic macrophytes as limnological indicators. Similar studies across lake-districts have been made by Rørslett (1991), and Heegaard *et al.* (2001). Trans-district studies of macrophytes have also been made in lotic habitats (Riis *et al.*, 2000; Lougheed *et al.*, 2001; Murphy *et al.*, 2003). In the present study, however, a particularly wide range of limnological habitats and macrophytes is undertaken — along a steep altitudinal gradient ranging from tropical to high alpine in the Himalayan region of Nepal.

1.2 Aquatic macrophytes and their communities

For the purpose of this study, aquatic macrophytes (i.e., larger aquatic plants) were restricted to herbaceous aquatic vascular plants. These plants have important ecological and economic roles in freshwater ecosystems (Sculthorpe, 1967; Carpenter and Lodge, 1986; Engel, 1988; Haslam *et al.*, 1998; Cronk and Fennessy, 2001).

As a group, macrophytes typically increase in abundance and then decline along lake trophic gradients (i.e., ranging from ultra-oligotrophic to hypertrophic). They may also modify cascading trophic interactions in aquatic communities and influence nutrient cycling (Jeppesen *et al.*, 1998). Aquatic plants often have a wide-ranging dispersal ability and they may colonize new habitats, such as reservoirs, within a few years if their habitat requirements are met (Macan, 1977; Odland, 1997). Macrophytes may also be used as indicators of ecological integrity, because of their importance to aquatic invertebrates, fishes, and other animals (Glowacka *et al.*, 1976; Fowler and Robson, 1978; Kovács, 1992; Dvořák, 1996; Palmer and Roy, 2001; Schneider and Melzer, 2003).

Aquatic plants are in intimate contact with the environmental conditions of lakes, through their root system and particularly their foliage, which is immersed in or floating on an aqueous medium. It is well known that patterns of species composition and relative abundance of macrophyte communities respond strongly to variations of environmental conditions within and among waterbodies, and the factors controlling the distribution and abundance of aquatic plants have long been of interest to scientists (e.g., Pearsall, 1920; Sculthorpe, 1967; Spence, 1967; Hutchinson, 1975; van der Valk, 1987; Rodwell, 1995; Moss, 1998). Along these lines, numerous studies have examined variations in the local distribution and abundance of aquatic plants and compared them with environmental conditions. Key North American studies include: Moyle (1945), Catling *et al.* (1986), Jackson and Charles (1988), Srivastava *et al.* (1995), Lougheed *et al.* (2001), while European ones are: Seddon (1972), Palmer *et al.* (1992, 1994), Onaindia *et al.* (1996), Jeffries (1998), Linton and Goulder (2000), Willby *et al.* (2000) Boedeltje *et al.* (2001), Heegaard *et al.* (2001), and Willby *et al.* (2001).

Aquatic macrophytes can indicate the trophic status of a waterbody (Schmedtje and Kohmann, 1987; Schneider and Melzer, 2003). European ecologists have classified aquatic plants into indicator categories according to their relationship with trophic status of their habitats (Linkola, 1933; Seddon, 1972; Pietsch, 1980; Wiegleb, 1981; Mäkirinta, 1989; Jensén, 1994; Toivonen and Huttunen, 1995; Schneider and Melzer, 2003). In ultra-oligotrophic lakes, the number of macrophytes species and their biomass are typically low, while in hypertrophic waters aquatic plants may disappear because of the lack of light penetration (Phillips *et al.*, 1978; Blindow, 1992).

Hydrochemical factors in addition to nutrients also influence the distribution and abundance of aquatic plants. Calcium concentration, alkalinity, and conductivity are considered key influences on macrophytes in oligotrophic Norwegian lakes (Brandrud and Mjelde, 1997). Other studies have found that water pH is a principal factor (Iversen, 1929; Catling *et al.*, 1986; Heitto, 1990; Brandrud and Mjelde, 1997). Depending on the complex of waterbodies and conditions studied, other environmental factors may also be related to variations in macrophyte composition and abundance, including salinity, insolation, light regime within the waterbody (which is influenced by turbidity and shading), temperature, basin slope, physical disturbances affecting water-level fluctuations and substrate stability, and quality and quantity of sediment (Pearsall, 1921; Haller *et al.*, 1974; Hutchinson, 1975; Barko and Smart, 1983, 1986; Keddy, 1983; Chambers and Kalff, 1985; Duarte *et al.*, 1986; Duarte and Kalff, 1986; Chambers, 1987; Nilsson and Keddy, 1990; Barko *et al.*,1991; Ellenberg *et al.*, 1992; Hellsten and Riihimäki, 1996; Andersson, 2001). Also important are the regional species pool, dispersal vectors, and biological influences such as competition, allelopathy, herbivory, and pathogens (Lodge, 1991; Wilson and Keddy, 1991; Gopal and Goel, 1993; Gaudet and Keddy, 1995; Hofstra *et al.*, 1999; Gross *et al.*, 2001). Within any waterbody, macrophytes and their communities are also influenced by the spatial and temporal heterogeneity of the habitats available (Sculthorpe, 1967; Hutchinson, 1975; Duarte *et al.,* 1994).

In mountainous regions, surface waters are exposed to strikingly different environmental conditions, depending on altitude-related factors, the geological nature of the catchment, and the disturbance regime (Jenkins *et al.*, 1998). Although not yet quantitatively studied over a steep altitudinal gradient, these environmental variations can be expected to have a profound influence on the floristic composition and relative abundance of macrophytes in lakes in mountainous regions.

1.3 Influence of environmental gradients on the distribution and abundance of species

Various studies of plant communities have examined species distributions along gradients of resource availability within habitats (Whittaker, 1975; Tilman, 1982; Jongman *et al.*, 1995). Ecologists have often used indirect gradient analysis (Whittaker, 1967) as a non-parametric technique to analyze relationships among plant species, their communities, and environmental factors. The uses of multivariate techniques in studies of ecological gradients have been widely facilitated by the publication of several textbooks (Gauch, 1982; Greig-Smith 1983; Pielou, 1984; Digby and Kempton, 1987; Jongman *et al.*, 1995; Kevin *et al.*, 2000) and the related articles (Hill, 1973; Hill and Gauch, 1980; Palmer, 1993; ter Braak, 1994; ter Braak and Verdonschot, 1995).

Ordination, cluster analysis, and canonical correspondence analysis (CCA) are multivariate methods that have been used to characterize environment gradients in data sets in aquatic ecology (Birks *et al.*, 1994; Toivonen and Huttunen, 1995). CCA is also used as a means to analyze multidimensional niches and to study seasonal and spatial variations in communities (Snoeijs and Prentice, 1989; Bakker *et al.*, 1990; Anderson *et al.*, 1994). Moreover, CCA can be used to assess the degree to which multivariate community patterns can be related to associated variations in environmental factors (Kautsky and van der Maarel, 1990; Heegaard *et al.*, 2001).

The environmental tolerances of species of aquatic plants have been estimated by correspondence analysis of various species-environment data sets (Seddon, 1972; Palmer *et al.*, 1992, 1994; Heegaard *et al.*, 2001). For instance, in a study of Welsh lakes, a principal components analysis was used to derive a gradient explaining the species and communities of macrophytes characteristic of dystrophic, oligotrophic, mesotrophic, and eutrophic waterbodies, as well as species that are generalists (Seddon, 1972). Often, such wide variations of chemical characteristics of lakes are associated with the kinds of anthropogenic activities occurring in local and regional catchments (e.g., Heegaard *et al.*, 2001).

1.4 Objectives

Assessments of freshwater biodiversity are sparse worldwide, and are particularly lacking in developing countries (Crow, 1993; World Resources Institute, 2000). Although the lowlands of the Indian subcontinent are floristically rich in terms of aquatic macrophytes, the mountains of northern India, Nepal, and Tibet have not been well studied (Gopal, 1990). In Nepal, the distribution and abundance of aquatic macrophytes are much less well studied than other taxonomic groups in waterbodies (Bajracharya, 1998; Shrestha and Janauer, 2000).

Understanding the relationships among aquatic macrophytes and altitude-related abiotic environmental factors will be useful in predicting the likelihood of plant invasions of impoundments associated with the development of hydroelectricity, irrigation, and aquaculture. This knowledge is also important to understanding the factors influencing biodiversity patterns in waterbodies.

The present study is intended to examine the following broad objectives related to aquatic plants in Nepal :

- to obtain basic information on regional limnology in relation to variations of altitude, over a range extending from 77 m to higher than 4,980 m in the Himalayas of Nepal;
- to observe the patterns of distribution and abundance of species of aquatic plants in lakes along this steep altitudinal gradient;
- to use statistical and mathematical analyses to determine the apparent influences of key environmental factors on the distribution of macrophytes and their communities.

The following broad research questions were examined in this research:

- How do the physico-chemical attributes of lakes and their local environment vary with changes in altitude in the Himalayas?
- Do the presence and abundance of aquatic plants and their communities vary with altitude in the Himalayas?
- Do variations in the abundance and distribution of aquatic plants mathematically relate to variations in abiotic environmental conditions?

2. MATERIALS AND METHODS

2.1 Introduction to study area

This study was conducted in a region bounded by latitudes 26° 36′ to 28° 13′ and longitudes 84° 05′to 87° 30′, and ranging in altitude from 77m to 4,980m. The study area is in the kingdom of Nepal, within the basins of the Kosi and Narayani Rivers of the greater Ganges drainage (Figures 2.1 and 2.2). The study area is in the central part of the Hindu-Kush Himalayan arc, which stretches from Karakoram in eastern Pakistan to Assam in northeastern India. The 34 lentic habitats studied (hereafter referred to as lakes) are identified using local names according to toponymic criteria, and are also coded with a regional identifier and progressive number from east to west. The geographical coordinates and altitude of each lake are also provided, so its identification is unequivocal (Table 2.1).

2.1.1 Geological background

The geo-morphological history of the Himalayas suggests that the region emerged from the Tethys Sea during Paleocene-Eocene times (58-66 MY ago), as the result of the geological collision of the Indian plate (derived from the breakup of the Gondawana landmass) moving from the south with the more massive Euro-Asian plate (Stocklin, 1980; Zeitler *et al.*, 1982; Molnar, 1986). The higher Himalayas originated in the Miocene (24 MY), as did major river systems and a monsoon climate. During the Pleistocene (1.7 MY), the Mahabharat range was uplifted and later the Churia range (Sharma, 1997). These thrusts developed the high Himalayan ranges lying over the Main Central

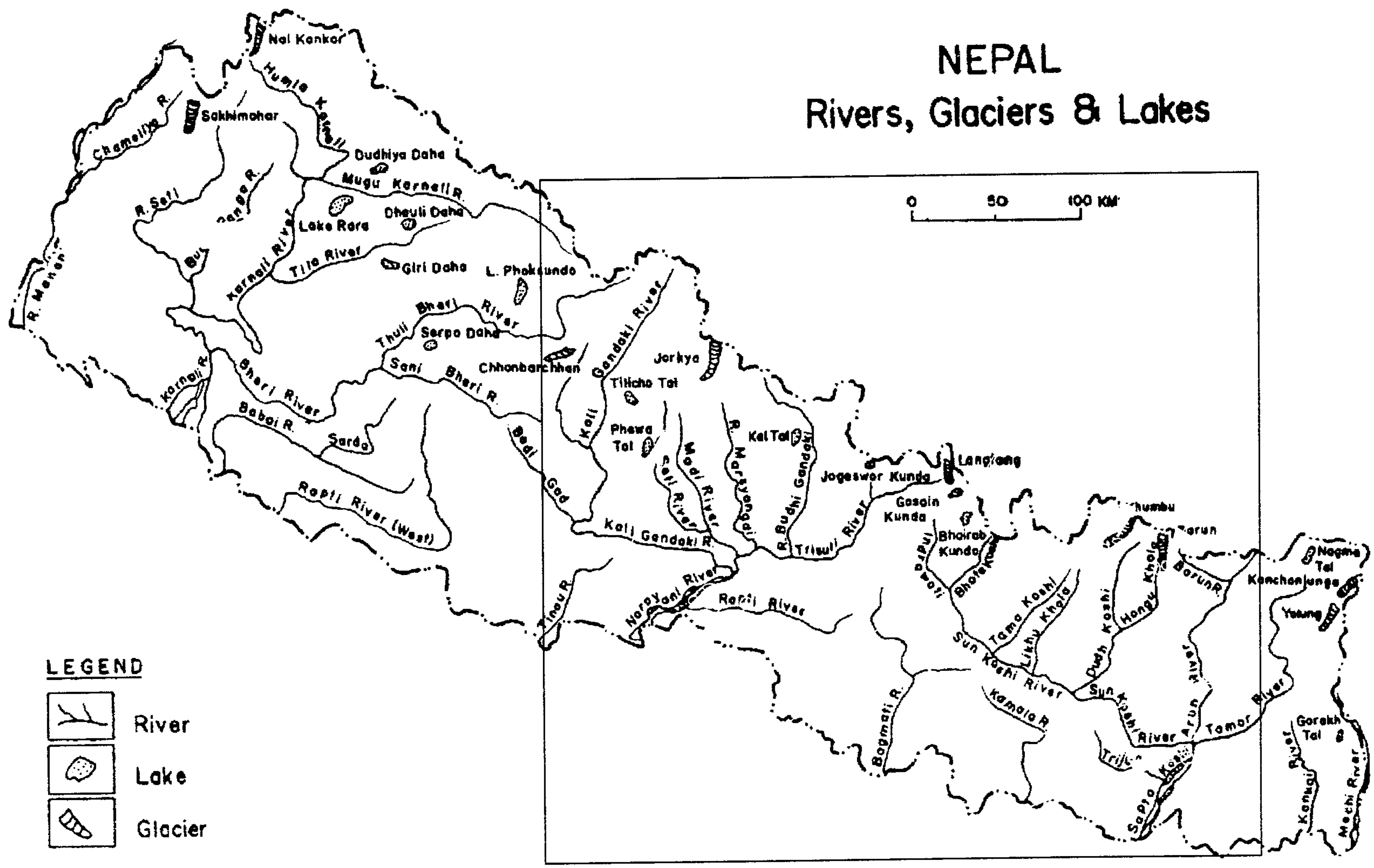


Figure 2.1 A map of Nepal showing the study area in inset.

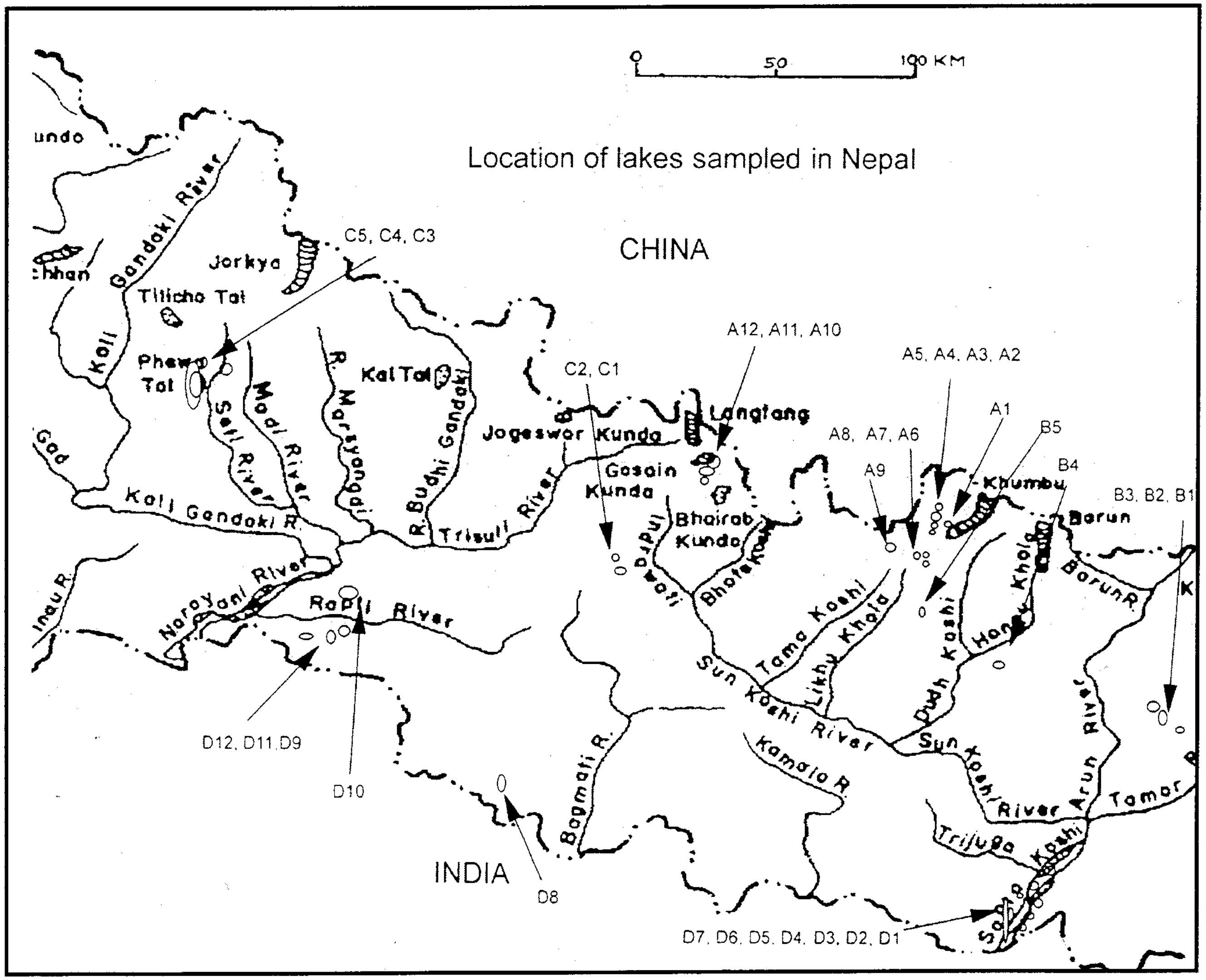


Figure 2.2 Inset portion of map showing lakes with their codes.

Table 2.1 Physical characteristics of lakes sampled and the catchments.

Code	Lake's name	Type	Latitude (N)	Longitude (E)	ALT. (m)	SA (ha)	Z_{max} (m)	WSA (ha)	Surrounding catchments
High Himal (HH)									
A1	Tsola Tso	GL	27°58.383′	86°48.280′	4512	63.3	13.0	2240	LM
A2	Tso Mengma	GL	27°55.089′	86°42.341′	4680	3.4	1.3	7710	LM
A3	Longponga	GL	27°56.647′	86°41.903′	4715	23.8	25.3	7580	AS
A4	Dudh- Pokhari	GL	27°56.932′	86°41.251′	4750	44.1	45.3	7520	AS
A5	Ngojumpa	GL	27°58.383′	86°41.212′	4980	28.0	35.3	7400	LM
A6	Panch-P-1 (Bau)	L	27°36.548′	86°50.851′	4293	22.0	10.0	510*	LM
A7	Panch P-2 (Amma)	L	27°36.596′	86°30.736′	4254	26.1	22.0	630*	LM
A8	Panch P-3 (Bhai)	L	27°36.692′	86°50.851′	4285	18.1	7.5	500*	LM
A9	Tso-Rolpa	GL	27°49.820′	86°28.110′	4580	140.0	56.5	7760	LM
A10	Gosian Kund	L	28°05'213′	85°23'318′	4300	25.0	23.3	4250	AP and SHU
A11	Bhairav Kund	L	28°04.971′	85°24.400′	4250	25.0	60.0	4381	AP and SHU
A12	Sarswati Kund	L	28°04.827′	85°23.954′	4068	12.1	7.5	4680	AP and SHU
High Mountains (HM)									
B1	Gupha Pokhari	PL	27°17.117′	87°30.378′	2965	6.2	6.6	1600*	BL and HU
B2	Ram pokhari	L	27°15.776′	87°29.320′	3003	2.5	1.6	300*	MTF and HU
B3	Mauwa Pokhari	PL	27°05.219′	87°24.950′	2965	6.2	5.6	1200*	DTF
B4	Salpa Pokhari	PL	27°26.772′	86°56.007′	3536	14.1	15.8	1300*	SACF
B5	Phokte Tal	L	27°34.542′	86°49.589′	3364	5.2	3.7	6,500*	MTF
Middle Mountains (MM)									
C1	Nag Daha	L, I	27°37.514′	85°19.90′	1272	2.1	7.2	<100	AL
C2	Tau Daha	L, I	27°38.930′	85°16.860′	1275	4.0	6.2	<100	AL
C3	Rupa Tal	L	28°08.953′	84°06.647′	643	115.7	6.1	3000	DTF and AL
C4	Begnas Tal	L, I	28°10.039′	84°05.562′	694	373.7	10.6	1900	DTF and HU
C5	Phewa Tal	L, I	28°13.145′	83°57.343′	742	524.0	24.0	11,000	DTF and HU

Contd.

Code	Lake's name	Type	Latitude (N)	Longitude (E)	ALT. (m)	SA (ha)	Z_{max} (m)	WSA (ha)	Surrounding catchments
Terai (TE)									
D1	Tower lake (KTWR)	O, L	26°37.436′	87°01.744′	77	2.1	3.1	<50#	RF
D2	Lake 2 (KTWR)	O, L	26°36.917′	87°01.393′	77	1.6	3.1	<50#	RF
D3	Lake 6 (KTWR)	O, L	26°36.261′	87°00.951′	77	2.6	3.0	<50#	RF
D4	Kamal Kund (KTWR)	O, L	26°41.085′	86°57.440′	145	20.0	2.3	>300#	AL and HU
D5	Pathari Pond	O, L	26°38.405′	86°56.410′	140	3.3	1.9	<100#	LLG
D6	Pathari Pool	O, L	26°38.360′	86°56.320′	140	2.2	1.7	<100#	LLG
D7	Kushaha Nahar	L, I	26°36.280′	86°55.210′	134	37.1	1.4	>500#	LLG and HU
D8	Barahawa Tal	L	26°45.512′	85°16.535′	190	10.3	2.9	>50#	AL and HU
D9	Dhakre Tal	O, L	27°34.240′	84°30.102′	182	2.1	3.1	>50#	TSF
D10	Beeshajar Tal	L, I	27°37.046′	84°26.113′	286	59.0	3.6	>100#	TSF
D11	Tamar Tal	L	27°31.590′	84°21.030′	200	7.1	2.7	450	TSF
D12	Devi Tal	L	27°32.000′	84°07.000′	188	14.1	3.1	746	TSF

- Abbreviations used for geo-physical and morphometric characteristics of lakes are; **SA** = surface area, $\mathbf{Z_{max}}$ = maximum depth, **WSA** = watershed area, **ALT** = altitude.

- Abbreviation used for lake types are; **L** = natural lake, **GL** = glacial lake, **PL** = natural perched lake, **O** = natural oxbow lake with intermittent connection to river, **I** = impoundments, **S** = known groundwater inflow, **PS** = groundwater inflow highly probable.

- Abbreviation used for catchments characteristics are; **LM** = loose moraine with rocks, **AS** = alpine scrub, **AP** = alpine pasture, **HU** = human use, **SHU** = seasonal human use, **BL** = barren land, **MTF** = moist temperate forest (birch + rhododendron + mosses), **DTF** = Dry temperate forest (*Schima+ castonopsis*), **SACF** = sub-alpine coniferous forest, **AL** = agricultural land, **RF** = riverine forest (*Dalbergia sisso*), **TSF** = tropical Sal forest (*Shorea robusta*), **LLG** = lowland grassland. * = approximate value calculated from low-resolution maps (1:100000). # = apparent watershed but highly influenced by adjoining river system.

Thrust (MCT) region, successively followed by the Main Bounday Thrust (MBT) and Himalayan Frontal Fault (HFF) to the south (Gansser, 1964). The High Himalaya lies above MCT and is dominated by hard rocks of gneiss and schist beneath a High Himalayan Crystalline Series (HHCS). This complex is also overlain by the Tibetan Himalayas at a transitional contact, which includes a series of epicontinental sedimentary rocks ranging from Lower Paleozoic to Lower Tertiary. The High Mountains and Middle Mountains (Mahabharat range) lie close to the main boundary thrust, and are dominated by Lesser Himalayan metasediments consisting of dolomite, limestone, magnesite, marble, phyllites, quartzite, and schist. To the south of the High Himalaya, the Churia Hills lie above the HFF, and further to the south lies the Indo-Gangetic lowlands and plain.

The Himalayas are the youngest major mountain system in the world, and they are still rising. The ongoing orogeny, coupled with recent and modern advances and retreats of alpine glaciers, result in glacial lakes being formed and suddenly drained by catastrophic outbreaks *(Jokulhlaup)*, perhaps in response to regional and global warming. Presently, most glaciers in the Khumbu region of eastern Nepal are in rapid retreat, and fourteen large outbreaks of glacial lakes have been reported in the region since 1964 (Vuichard and Zimmermann, 1986; Ives, 1986; Yamada, 1993; recently, structures have been installed at some vulnerable lakes to prevent these catastrophic events, and none have occurred in the region since 1993). The recent rate of place impact (or lateral contraction) across the Himalayas is 17.5 mm/yr, and the rate of slip of the Indian plate beneath the Tibetan one is 20.5 mm/yr (Bilham *et al.*, 1997). Uplift of the Himalayas continues at about 1 mm/yr (Zeitler *et al.*, 1982; Iwata *et al.*, 1984).

The average surface warming of the Indian subcontinent was about 0.4 °C during the period 1902-1982 (Hingane *et al.*, 1985). Overall, the warming since 1970 has averaged about 0.03 °C/year in the lowlands of Nepal, but 0.06-0.12 °C/year in alpine environments (Shrestha *et al.*, 1999). The trend in surface warming has been broadly consistent with global climate change, and is expected to further increase by more than 2 °C over the monsoon region during the next century (Lal *et al.*, 1992). In response to the regional warming, the glacial equilibrium elevation in the central Himalayas has been rising at a rate of 10-15 cm per year (Kotlyakov and Lebedeva, 1998). The most recent glacial maximum (GM) is close to 3100 m at Langtang Valley, where glaciers now terminate at about 4500 m (Shiraiwa and Watanabe, 1991). These overall changes during recent Himalayan ontogeny and warming have resulted in the creation of many relatively young lakes in early stages of ecological development (Löffler, 1969; Lami *et al.*, 1998).

2.1.2 Phytogeography

The number of identified flowering plants in Nepal is about 6,500 species, dispersed among 203 families (Hara *et al.*, 1978, 1982; Hara and Williams, 1979; WCMC, 1994; Press *et al.*, 2000). More precisely, Koba *et al.* (1994) list 5,806 species (this has been extended to 6,452 species through new records and different taxonomic treatments; Akiyama *et al.*, 2002; 2003). Nepal ranks tenth among Asian countries in the total richness of plant species (BPP, 1995), and 31st globally (WCMC, 1994).

Nepal lies at an intersection of major floristic regions of Asia — it is the meeting point of the drier western and central Asiatic floral province and the humid Sino-Japanese one.

The southeast Asiatic province also penetrates to the foothills of eastern Nepal, while the African-Indian desert province attenuates in western Nepal. The boreal/montane Palearctic floristic region is extensive in northern Nepal above 3000 m, and the Paleotropical region (Oriental realm) in the southern lowlands. The tropical elements of southern Nepal occur in an east to west running warm belt known as Terai, and they are typical of the floristic regions of the Indo-Gangetic plains and possess widespread north-Indian elements. The somewhat distinctive floras of the eastern and western Himalayas merge in central Nepal (Stearn, 1960).

Phytogeographic classifications of Nepal, based on various authors, show that the study area lies:

1. between the Kali Gandaki and the Sapta Koshi zones in the Central Himalayas (Schweinfurth, 1957);
2. in the Central Region (83° 0′ - 86° 30′ E), slightly overlapping the Eastern Region (Stearn, 1960);
3. between the Gandaki and Koshi river systems (Banerji, 1963); in Terai, Bhabar, dun valleys and outer foothills, and the midlands and southern sides of Himalayan ranges (Stainton, 1972); and
4. in the "Domaine centre nepalais" (from the longitude of Dhaulagiri to that of the Arun valley at about 87° 10′ E; Dobremez, 1972). Dobremez's (1972) central domain in the southern Himalayas has the highest diversity of flowering plants in the region (Shrestha and Joshi, 1996).

2.1.3 Limnology

The study of lakes, or limnology, was established as an area of science in Europe and North America at the end of 19th century. In the 1980s, the International Lakes Environment Committee (ILEC) launched a "Survey of the State of World Lakes," which developed information on more than 500 lakes in 73 countries, including physical-chemical data on limnological conditions and trophic characteristics. Two lakes from Nepal (one of which, Lake Phewa, was sampled in the present study) were included in the ILEC study (http://www.ilec.or.jp).

Synoptic accounts of the limnology of India include those of Ganapati (1957), Tripathi and Srikandar (1989), Mishra and Trivedy (1993) Unni (1993), Sugunan (1995) and Vijaykumar (1999). Accounts of high-altitude Indian lakes of the Kumaun, Kashmir, and Sikkim Himalayas are in Kaul (1977), Zutshi and Vass (1978) Sharma and Pant (1979) Khan and Zutshi (1980), Vass *et al.* (1989) Venu *et al.* (1990) and Zutshi (1991). In comparison, there have been few studies of high-altitude lakes north of Nepal, in the Himalayas of Tibet and adjacent India (Hutchinson, 1937; De Terra and Hutchinson, 1934; Liu and Sharma, 1988).

Lakes in Nepal have been studied sporadically, mostly in the lowlands and middle mountains (Hickel, 1973a,b; Ferro, 1978; Okino and Satoh, 1986; Nakanishi *et al.*, 1988; Aizaki *et al.*, 1987; Lohman *et al.*, 1988; Jones *et al.*, 1989; McEachern, 1994; WMI and IUCN/Nepal, 1994; Rai, 1998, 2000; Bhatt *et al.*, 1999). Löffler (1969) was the first to study high-mountain lakes. In general, lower-altitude tropical and subtropical lakes are shallow oxbows, polymictic, and relatively productive, while high-altitude ones are generally deep, dimictic to cold polymictic, oligotrophic, particularly phosphorus-limited.

2.1.4 Physiographic zones and classification of lakes

The study area covers all major physiographic zones of Nepal (Table 2.2), as described in the official Forest Sector Master Plan (HMG/Nepal, 1988), *viz*:

- High Himal
- High Mountains
- Mahabharat and Midland
- Churia Hills (Siwaliks)
- Terai

The upper regions of the Churia Hills, however, do not have lakes because of their predominant well-drained geomorphology of coarse-textured, stony, shallow soil. In addition, the Churia Hills are similar to Terai in terms of climate and vegetation (and is sometimes referred to as Inner Terai), and so for the convenience of study these two zones are merged here into one (within the altitudinal range of 70 to 500 m). This results in four physiographic study regions, based on gradients of surface temperature, insolation regime, precipitation, and overall climate (Kaddha, 1967; Sharma, 1990; Jha, 1992). The shallow lakes in the study regions range from continuously warm polymictic lakes at low elevation, to cold polymictic lakes at the highest elevation, and the deep lakes are dimictic and monomictic in the HH and MM region, respectively (Figure 2.3). This encompasses much of the global variation of lake types, from equatorial to alpine/arctic, but all occurring within a relatively restricted area of Nepal.

Table 2.2 Summary of the physiographic zones in Nepal where the lakes were sampled.

Physiographic zone	% of Nepal	Climate	Soils *	Natural vegetation	Alt. (m)	Lake type and number studied	Bio-geographic realm
High Himal (HH)	23	Alpine tundra	regosols, leptosols and podzols(entisol, spodosols)	Alpine grassland and tundra	>4000	Glacial and moraine dammed; ice-free water for 5-7 months, (n=12)	Palearctic
High Mountains (HM)	20	Cool temperate	Podzols, cambisols (spodosols and inceptisols)	Evergreen coniferous forest	3000-4000	Tectonic; ice-free water for 9-11 months, (n=5)	Indo-Malayan trans-Gangetic (Himalayan) zone
Middle Mountains (MM)	30	Warm temperate	cambisols (inceptisols)	Deciduous monsoon forest	2000-3000	Tectonic lakes with alluvial deposits; no freezing, (n=5)	Indo-Malayan Trans-Gangetic (Himalayan) zone
Siwalik	13	Sub-tropical	Cambisols, alisols/ acrisols and ferralsols (inceptisols/ Ultisols/alfisols/ oxisols)	Sub-tropical humid forest	120-2000	Zone is devoid of lakes because of porous bedrock	Indo-Malayan; Cis- Gangatic (Indian) zone
Terai (TE)	14	Tropical	ferralsols (oxisols)	Sub-tropical humid forest	60-330	Ox-bow lakes and impoundments in alluvial deposits; no freezing, (n=12)	Indo-Malayan; Cis- Gangatic (Indian) zone
Total	100					Total = 34 lakes	

* Soil types according to FAO–UNESCO (1990); soil types according to US soil taxonomy, Soil Survey Staff (1994) in parenthesis.

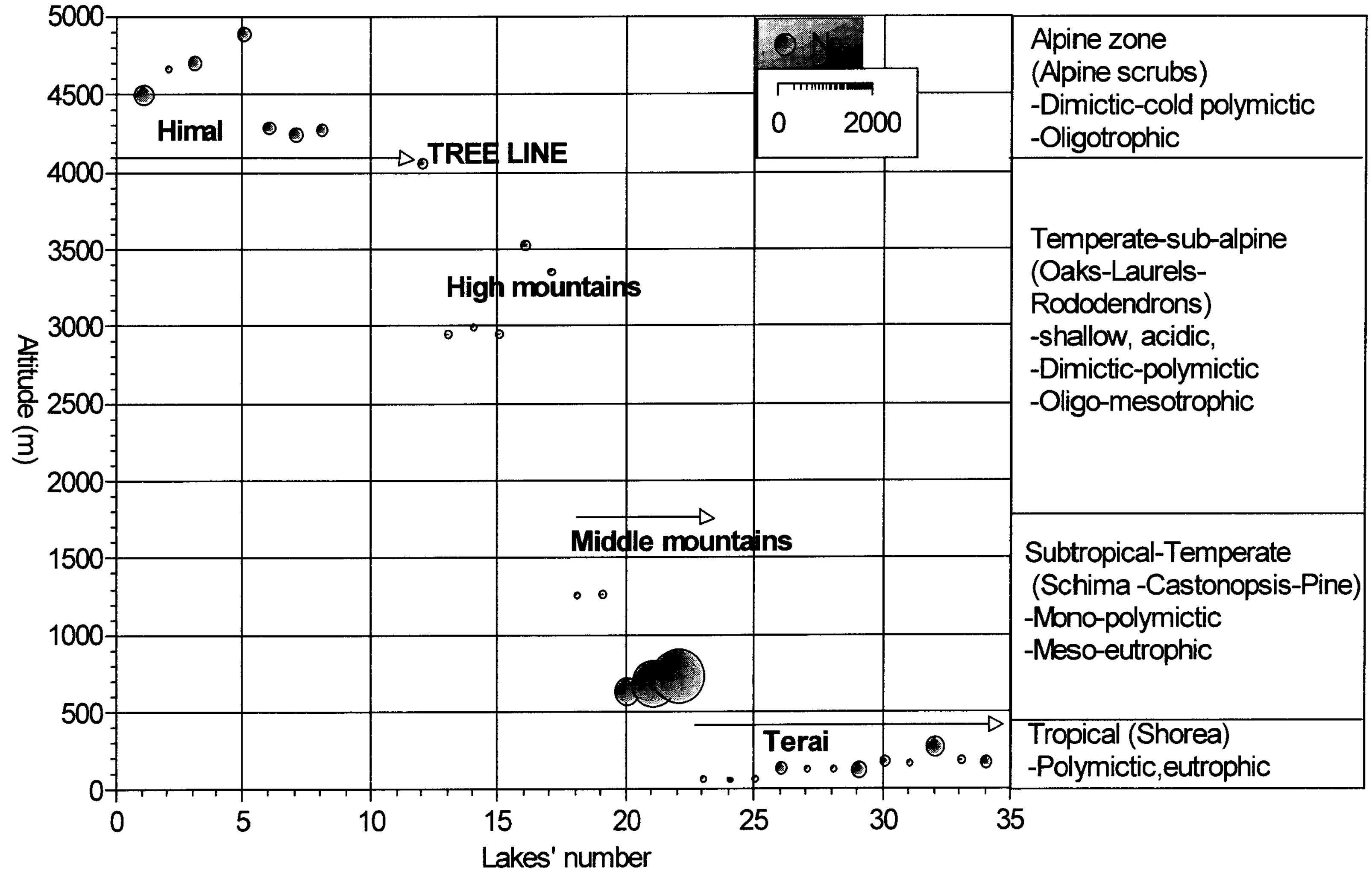


Figure 2.3 Diagrammatic representation of lake dimension and distribution at different altitudes with corresponding geo-geographic and bio-climatic zonation.

2.1.4.1 High Himal lakes (HH)

The sampled lakes in the High Himal (HH) region occur above 4,000 m and are glacial in origin, being dammed by lateral and/or end moraines formed during the most recent advancing stage of the neo-glaciation period between the 15th and 19th centuries. Lakes A1 to A9 are in the Everest region in the eastern Himalayas, and Lakes A10 to A12 are in the Langtang region (Table 2.2).

Tsola Tso (A1) is a lake formed by damming of the lateral moraine of the Tsola Glacier. Tso Rolpa (A9) was formed at the terminus area of the Trakarding Glacier (a debris-covered glacier) and is dammed by its lateral and end moraines. The Gokyo lakes chain (A2, A3, A4, A5) is hydrologically connected by a series of waterfalls and streams that drain the meltwater of the Ngojumpa Glacier on the southern slopes of Cho-Oyu Mountain. All of these lakes have watersheds with bedrock dominated by gneiss with quartz nodules and intrusions of granites (Bortolami, 1998). Their watersheds are sparsely vegetated with alpine tundra.

Three lakes (A6, A7, A8) were sampled from a chain of five waterbodies at Panch Pokhari, in an alpine zone with rocky and scree terrain and scattered tundra. Three other lakes (A10, A11, A12) are located in the Langtang region in the Central Himalaya. The geology of their catchments is pelilite gneiss consisting of mica, garnet, quartz, and feldspar. These lakes occur close to the limit of alpine tundra.

The hydrogeological setting of lakes A1, A6, A7, A8, and A9 have primary (or vertical) porosity associated with their fluvioglacial and fluvial deposits and slope debris. Their permeability determines the residence time of water and fluctuations of depth. These types of lakes are formed as a superficial aquifer supported by alluvial drift from the tributaries, and are hydraulically dependent on their hydrographic network (Bortolami, 1998). The aquifer is recharged by precipitation and snowmelt, and subordinately by seasonal melting of glacial ice. Due to the coarse character of the substrate, the aquifer is subject to glacial lake outbursts and events of mass erosion.

All other lakes sampled in the High Himal occur in aquifers that are impermeable or that have secondary (lateral) porosity that provides more physical stability of the boundary, depth, and bottom substrate (Bortolami, 1998).

2.1.4.2 High Mountain lakes (HM)

The High Mountain (HM) lakes lie between the heavily populated middle mountains and the almost unpopulated High Himal, within an altitudinal range of about 2,900 to 3,600 m. The dominant rock types include schist, quartzite, and gneiss in formations that are relatively resistant to weathering and erosion. This zone is generally covered by temperate evergreen forest dominated by *Abies*, *Pinus*, and *Rhododendron*, but the cover is patchy as a result of disturbances by humans. Lakes are infrequent in this region and mostly occur in perched depressions.

Gupha Pokhari (B1), Ram Pokhari (B2), and Mauwa Pokhari (B3) occur in the eastern districts of Terhathum and Dhankuta. Salpa Pokhari (B4) lies in the Sankhuwasabha district at the border of the Makalu Barun National Park. Phokte Tal (B5) lies in the Solukhumbu district within Makalu Barun National Park.

2.1.4.3 Middle Mountains and midland valley lakes (MM)

This zone comprises a network of ridges and valleys, with the lakes occurring within an altitudinal range of 643 to 1272 m. The lakes are mostly distributed on valley floors and are generally tectonic. Phewa Tal (C5), Begnas Tal (C4), and Rupa Tal (C3) lie in Pokhara valley with watersheds predominantly sedimentary in structure (Gansser, 1964). The Pokhara valley contains extensive quaternary deposits of metasediment of Precambarian to Cambrian age, mainly composed of phyllite. Phewa, Begnas, and Rupa are blocked lakes formed by terraces intruded into rivers. Their sources of water are inflow streams and groundwater springs, and the lakes have potential for fishery development (Hickel, 1973 a; Nakanishi *et al.*, 1988; Lohman *et al.*, 1988; Jones *et al.*, 1989; FDD, 1992). Lakes Tau Daha (C2) and Nag Daha (C1) are located in the southwest of the Kathmandu valley, and are filled by the summer monsoon and by groundwater springs. The catchments of the middle-mountain lakes are covered by a mixture of forest and agricultural land.

2.1.4.4 Siwalik and Terai lakes (Terai; TE)

The Terai zone is a plain at 60 to 330 m extending from Chure and Bhabar to the northern Indian border. Terai represents 14% of Nepal, is composed of quaternary alluvial deposits, and is about 70% under agricultural use.

Most lakes in the Terai region are ox-bows or other natural impoundments of rivers. Seven ox-bow lakes were studied within the Koshi Tappu Wildlife Reserve (KTWR) – a Ramsar site and its vicinity, in a low-lying area with alluvial deposits of fine sand, silt and clay (Ohta and Akiba, 1973). The sampled waterbodies were: D1 (Tower lake); D2 (Lake-2, KTWR); D3 (Lake 6, Titri Gachi), Kamal Kund (D4), Pathari Pond (D5), Pathari Pool (D6), and Kushaha Nahar (D7). The Kushaha Nahar is an impoundment with a relatively high degree of human disturbance in its watershed, while the other waterbodies are natural and have mosaics of subtropical riverine forest and wetlands in their watersheds

Other Terai lakes were Dhakre tal (D9), Tamar tal (D11), and Devi tal (D12) are in the Royal Chitwan National Park (RCNP), in a region of sal forest (sub-tropical humid *Shorea robusta*). These lakes are ox-bow or old-channel lakes with watersheds of wetland within sal forest. Beeshajar tal – a Ramsar site (D10) is outside of RCNP, and was developed by the construction of irrigation works. Barahawa Tal (D8) is located in an urban area of Gaur municipality, and is subject to human influence.

2.1.5 Climate

The study region is characterized by extreme differences of climatic conditions, which can be aggregated into five south-to-north running zones along elevational gradients (Jha, 1992):

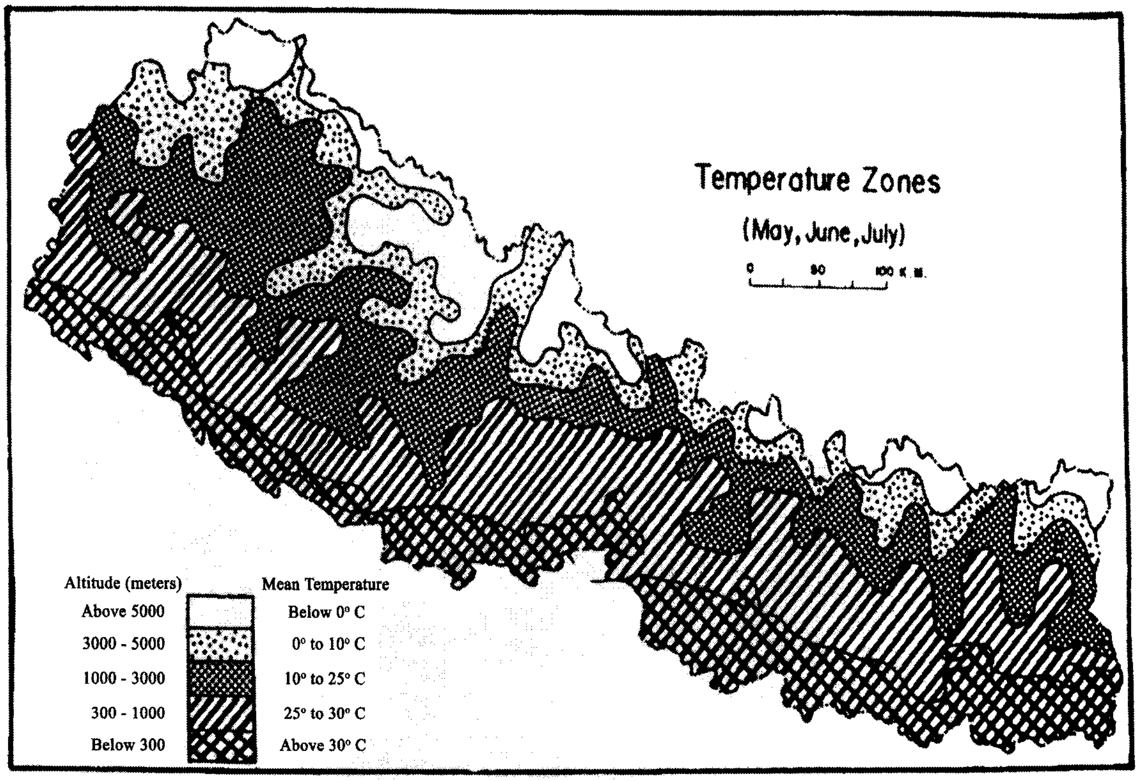
1. tropical and subtropical
2. warm temperate
3. cool temperate (montane)
4. alpine tundra
5. high alpine (little or no vegetation)

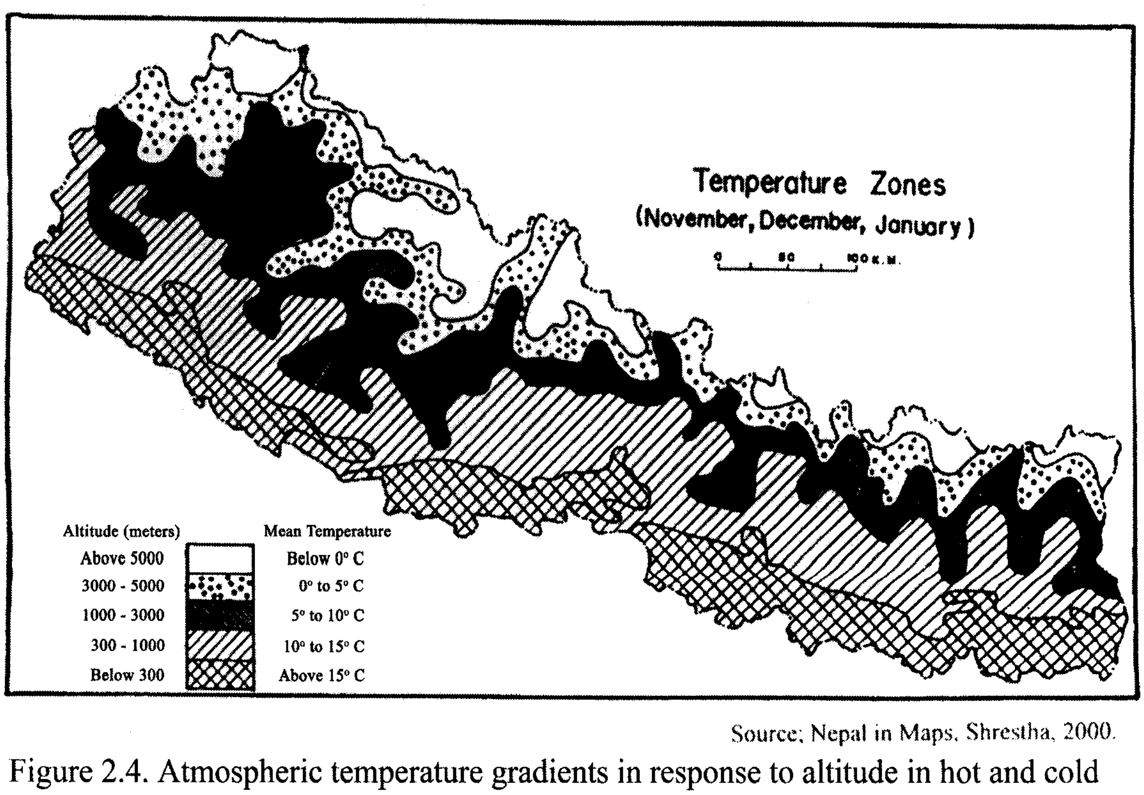
The tropical-subtropical bio-climate zone corresponds to Terai, and the high alpine to the High Himal.

Most of Nepal experiences a monsoon climatic regime typical of South Asia. About 90% of the variation of surface temperature can be statistically explained by elevation (Nayava, 1980; Chalise *et al.*, 1996). The lapse rate of temperature with altitude is 0.52°C/100 m (Dobremez, 1976). Figure 2.4 shows ambient temperature gradients in response to altitude in hot and cold months; these have a great influence on physiographical zones. Figure 2.5 shows the variations of air temperature and precipitation at meteorological stations within my sampling regions; they all indicate pronounced seasonal variations of temperature and rainfall, but the amount of precipitation is lowest at the high altitudes.

Seasonal weather differences in the Himalayas depend on a strong thermal anticyclone known as the "Tibetan High" that occurs in the upper troposphere during the monsoon season, and on the strength and location of the subtropical jet stream during the rest of the year (Yasunari, 1976). From October to May, the axis of the sub-tropical westerly jet stream is generally just south of the Himalayas; disturbances steered by this system travel eastward and cause gales and blizzards on the peaks (Barry, 1981). This cold weather typically freezes the surface of lakes above 5,000 m.

Climate in Nepal consists of wet and dry periods in response to the monsoon, which occurs from mid-June to mid–September and supplies more than 80% of the annual precipitation, most intensely during July and August (Figure 2.5). The drying period starts slowly in the post-monsoon season (September to January) and then intensifies to the pre-monsoon (February to May), by which time some shallow lakes have lost





Source; Nepal in Maps, Shrestha, 2000.

Figure 2.4. Atmospheric temperature gradients in response to altitude in hot and cold months of a year corresponding to various physiographical zones

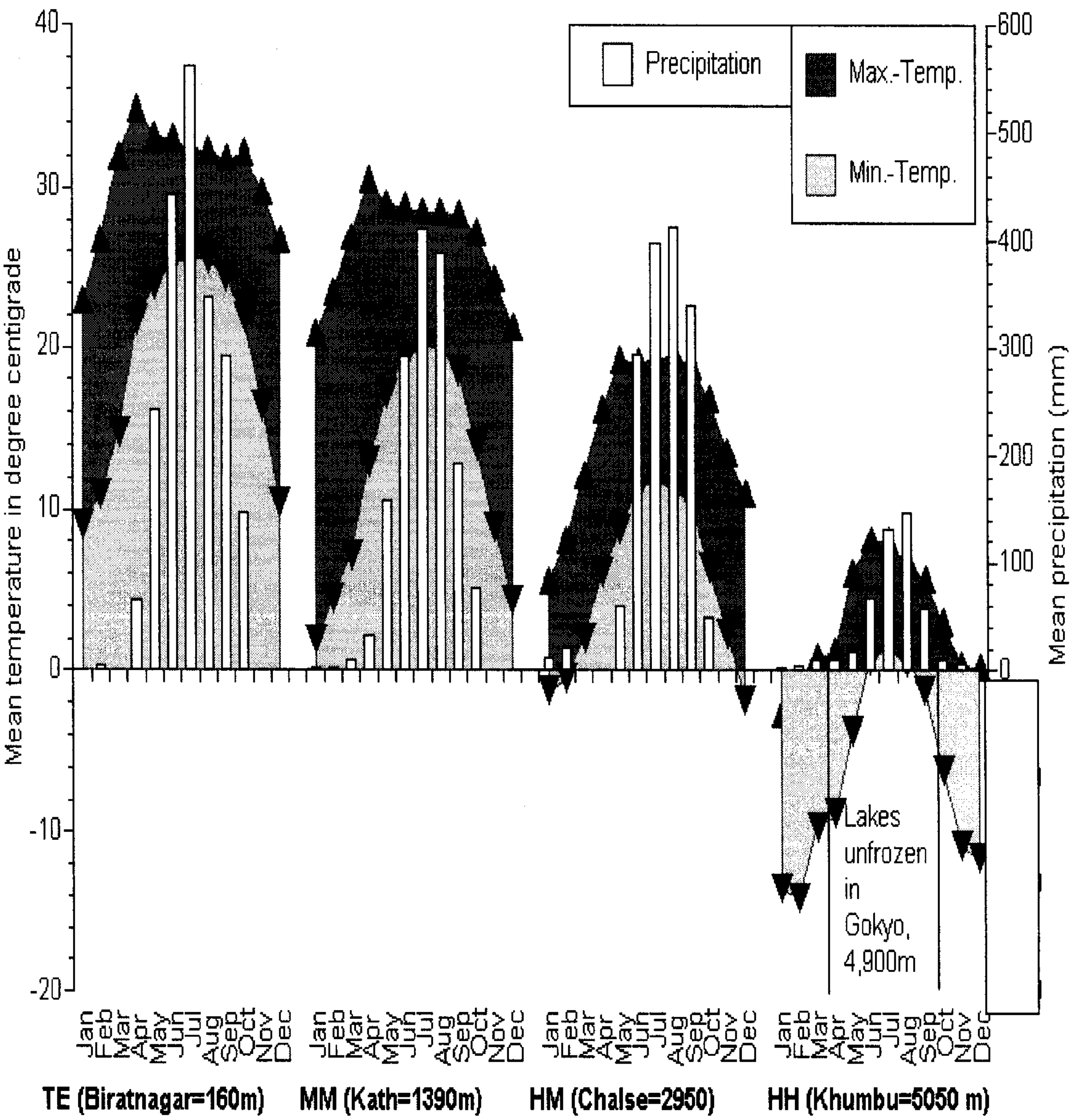


Figure 2.5 Mean temperature and precipitation at the closest meteorological stations from the sampled lakes. Terai (TE) is represented by meteorological data at Biratnagar airport (1999-2001); Middle mountains (MM) is represented by meteorological data at Kathmandu airport (1999-2001); High Mountains (HM) is represented by meteorological data at Chalse station (1995-1996). High Himal (HH) is represented by meteorological data at Khumbu valley (1994-1996).

Sources of data: Biratnagar and Kathmnadu (unpublished meteorological stations reports of the Department of Hydrology and Meteorology, HMG/Nepal); Chalse (Department of Hydrology and Meteorology, HMG/Nepal, 1999); Khumbu valley (Tartari *et al.*, 1998a).

considerable depth and area. Overall, precipitation in Terai averages 1,400mm/year, while the Middle Mountains and High Mountains have less, and the High Himal are relatively dry. Annual precipitation in the Middle Mountains can be variable. For example, the Kathmandu valley had 144-147 mm in 1998 and 1999, but only 117 mm in 2000 (Figure 2.6).

The Terai lakes (70-300 m) are located in a subtropical area and have a mean annual temperature of 24° C, with a monthly high in June of 30° C and a low in January of 14° C. The Middle Mountain lakes (500-2000 m) are in a warm temperate climate and have a mean temperature of 18° C, with a monthly mean of 23° C in July and 10° C in January. The High Mountains (2,900 to 3,600 m) have a cool montane climate with mean temperature of 12° C, a monthly high of 16° C in July, and a low of 10° C in January. The High Himalaya lakes sampled (above 4,000 m) have a mean temperature of 7° C, with 10° C in July and–5° C in January. [Note that the climatic data for the HH region are from the Pyramid Observatory Laboratory at 5,050 m in the Khumbu valley of the Everest region (Tartari *et al.*, 1998 a), and that for the HM are from the Chalse station (Department of Hydrology and Meteorology, HMG/Nepal, 1999)].

2.2.6 Research calendar

The data set consists of seasonal samples collected from the study lakes at various times from October 1998 to June 2001. The sample means were averaged within three climatic seasons:

- pre-monsoon (February to May)

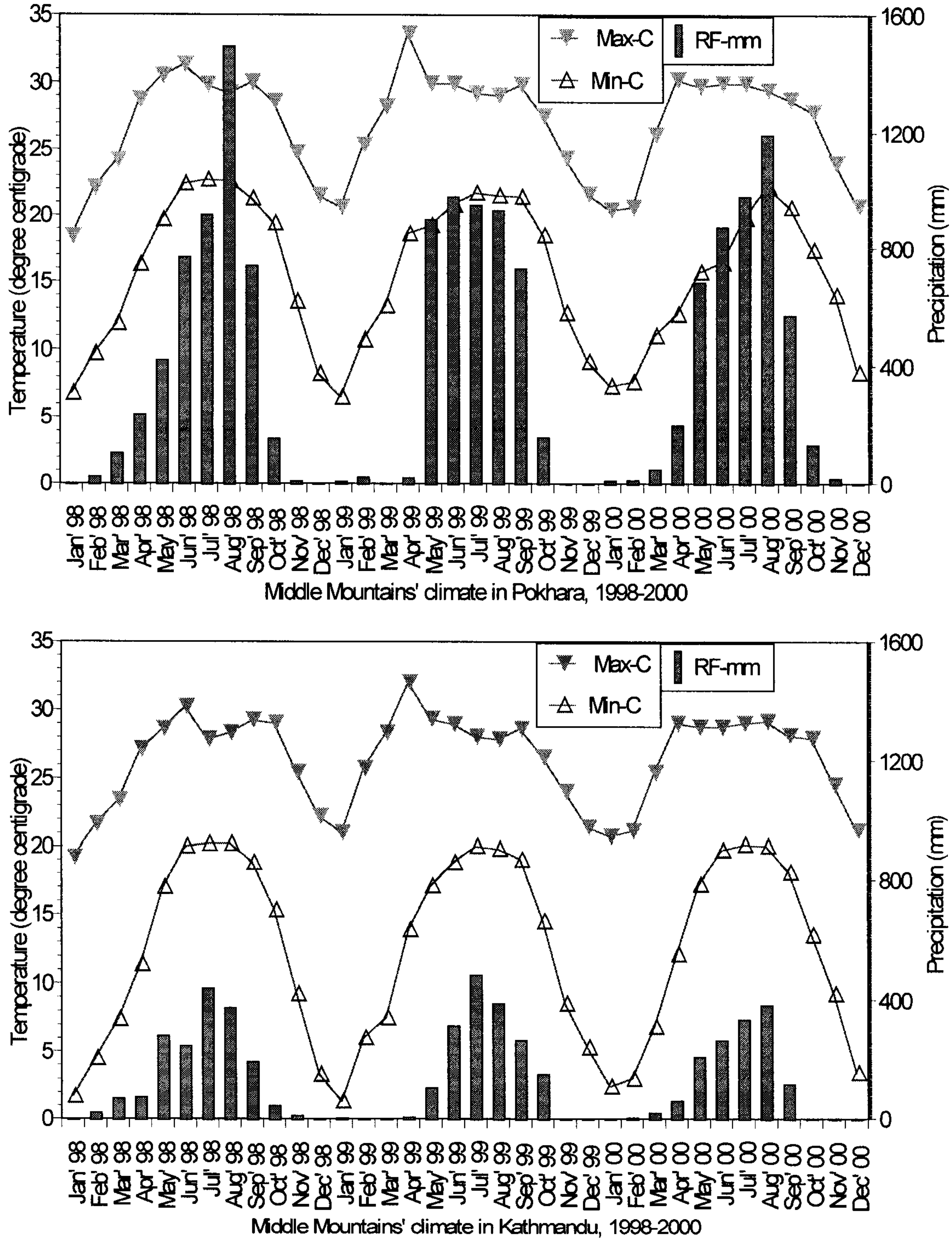


Figure 2.6 Mean temperature and rainfall variation within middle mountains (MM) region. Above and below graphs were made from meteorological data for three years (1988-2000) from Pokhara airport and Kathmandu airport (data source; unpublished meteorological stations reports of the Department of Hydrology and Meteorology, HMG/Nepal; Max-C and Min-C are the maximum and minimum temperatures recorded for a month; RF = rainfall in millimeters/months).

- monsoon (June to September)
- post-monsoon (October to January)

Samplings were done during mid-day hours in calm sunny days to minimize the diurnal effects. Five sub-samples of 0.5 liter of waters were collected from the five random points of a macrophytes bed just above sediment, and were then mixed to make a composite sample for chemical analysis. The seasonal means were the results of five composite samples taken from five different prominent macrophytes beds within a lake for the pre monsoon, monsoon and post monsoon seasons. Only the post monsoon samples were not collected in Lake no A1, A3, A6, A7, A8, A9 due to the thick ice covering.

The seasonal means were averaged over the entire study period to obtain lake means, which were the basic unit for characterization and comparison among lakes and vegetation data. Figure 2.7 shows the times when the various lakes were sampled. Note that all of the lakes sampled in the HM and HH regions were extremely remote, and some of them required as long as one to two weeks of trekking to reach and sample.

2.3.1 Physical and chemical methods of water analysis

The composite water samples collected on macrophyte beds were brought to the laboratory in nalgene bottle pre-cleaned with distilled water and rinsed several times with composite water sample. Analyses of the composite water samples from all lakes were made in the field or laboratory according to standard methods (A.P.H.A., 1995), unless otherwise stated.

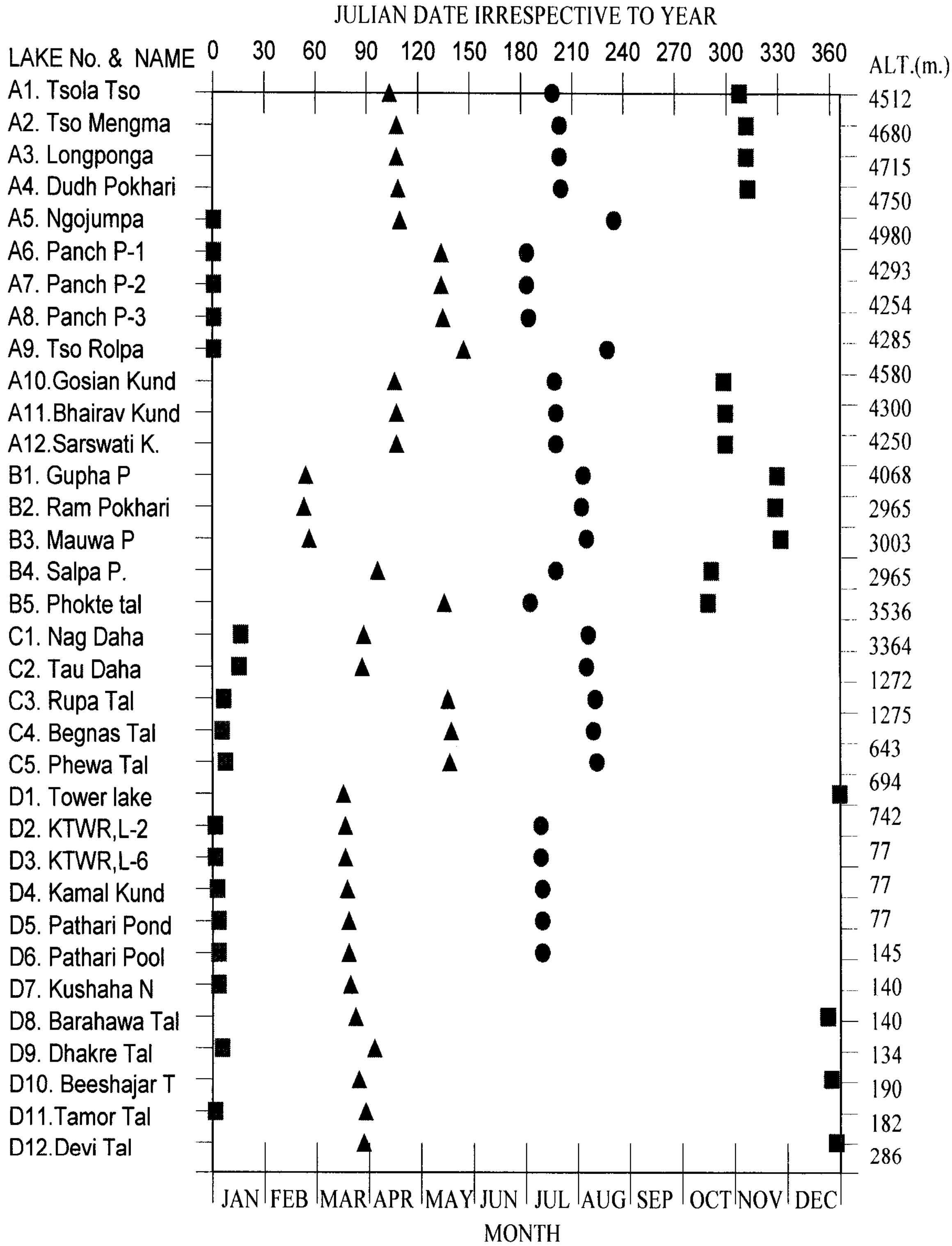


Figure 2.7 Sampling carried out in different lakes shown in Julian dates calendar irrespective of years starting from October 1998 to June 2001 (▲= Pre monsoon; ●= Monsoon ■ = Post monsoon)

Water temperature was measured in epilimnion region only using a handheld thermometer, and conductivity with a temperature-corrected Fisher (C-33) probe. Transparency was determined with a 20-cm Secchi disc, averaged over two measurements. pH was measured with colour-sensitive pH strips (Merck , range 5.5-9.0; graduation 0.5 pH unit) and using a handheld Hannah pH meter (HI 9214). Conductivity and pH were re-analyzed in the laboratory to verify the field results.

Other variables could not be analyzed in the field. The samples were divided into sub-samples of 50 and 100 ml and preserved according to the specific determination to be performed later in the laboratory. The sub-samples were treated following the recommendations of A.P.H.A. (1995), as follows:

- chilling in an icebox, for analysis of calcium, magnesium, sodium, potassium, chloride, sulphate and phosphorus;
- acid preservation (40% H_2SO_4 added in the field to achieve pH <2) for analysis of total and dissolved nitrogen. Samples were neutralized with equivalent additions of NaOH prior to digestion in laboratory.

The chemical determinations used were as follows:

- calcium, magnesium, sodium, and potassium were determined by flame atomic absorption analysis
- bicarbonate was determined by carbonate-hydroxide titration.
- chloride was determined using a spectrophotometric method (argentometric)

- sulphate was determined using a gravimetric method ($BaSO_4$)
- total suspended solids (TSS), non-volatile suspended solids (NVSS), and volatile suspended solids (VSS) were analyzed gravimetrically after passing through Whatman 934 AH filters (particle retention 1.5 μ m).
- Total suspended chlorophyll was collected by filtration through Whatman GF/C filters (particle retention 1.2 μ m) and analyzed according to the fluorometry methods (Knowlton, 1984; Sartory and Grobbelaar, 1986). Samples were stored in dessicant (silica gel) in the field till analyzed in laboratory in Kathmandu. Filtrate from chlorophyll processing was used for dissolved fractions of nutrients (DN and DP) while whole water was used for the total nutrients (TN and TP) by the processes as below:
- phosphorus (total and dissolved) was analyzed after Prepas and Rigler (1982)
- nitrogen (total and dissolved (nitrate plus ammonium) was determined by second derivative analysis of persulphate oxidized samples (Crumpton *et al.*, 1992).

Replicate outliers samples were eliminated prior to data analysis, if their differences from the mean value exceeded the test accuracy ($1 \mu g.L^{-1}$ for P and 50 $1 \mu g.L^{-1}$ for N) and two times the variation observed for all replicates from the lake on the same sampling date. Also, the values observed in the analysis were cross-examined with the values published for the lakes, where they were available.

Substrates (excluding cobbles, boulders and large rock, which were visually estimated) from lakes bottom below each macrophytes bed were sampled. 100 gm sediment from each sample was air dry at 105 ˚C for 24 hours and then broken up with a wooden roller, without grinding, to keep the natural particles unbroken. Then the sediment samples were sieved through tiers of specified size mesh for different grain sizes. Sediment classes were assigned based on the percentage of pedological components (based on size) and their position in the soil triangle (dimensionless units after Soil Survey Staff, 1951) as follows: (I) clay = 0.5; (II) silty clay = 1.0; (III) sandy clay = 1.5; (IV) clay loam = 2.0; (V) silty clay loam = 2.5; (VI) sandy clay loam = 3.0; (VII) loam = 3.5; (VIII) silt loam = 4.0; (IX) sandy loam = 4.5; (X) loamy sand = 5.0; (XI) silt = 5.5; (XIII) sand = 6.0; (XIV) pebble = 7; (XV) cobble = 8; (XVI) boulder = 9; (XVII) large rock = 10.

2.4 Vegetation analysis

In this study, aquatic macrophytes are defined as vascular, non-arborescent, flowering plants, whose photosynthetically active parts are submerged in water permanently or for at least several months each year, or are emergent, or float on the water surface. Aquatic macrophytes have been broadly classified according to life-form and systematics by Sculthorpe (1967), Cronk and Fennessy (2001), and Cook (1996) into the following groups (Table. 3.3.1);

(1) Emergent (Emer);

(I) Helophyte (Hel) = terrestrial plants which tolerate submergence including Tenagophyte (Ten), whose juvenile are submerged and adult usually terrestrial.

(II) Hyperhydate (Hyp) = emergent aquatic whose lower parts always in water.

(2) Submerged (Subm);

(I) Haptophyte (Hap) = macrophytes attached but not penetrating substrate.

(II) Rosulate (Ros) = submerged macrophytes, bottom rooted, leaves in a rosette (eg. Isotids).

(III) Vittate (Vit) = submerged macrophytes, bottom rooted, leaves cauline (eg. Eleodid).

(3) Floating –leaved (F-L)

(I) Ephydate (Eph) = bottom rooted macrophytes with floated leaves.

(4) Free- Floating (F-F);

(I) Plankton (Pla) = Free swimming macrophytes under the surface water.

(II) Pleustophytes = Free floating macrophytes at the surface of water.

Non-destructive sampling measures were used, as is required within the protected areas of Nepal. The frequency of the species presence was scaled into classes based on the ratio of the summed lengths of stands of a particular species to the whole shoreline. The overall abundance was estimated by the average percent cover of the lake surface area by plant species within quadrats placed in representative stands of obvious "communities". Ten to twenty (depending on the size of the lake) quadrats of 1 m^2 were sampled within each community. Total cover could not exceed 100%. The entire water column was considered, but estimation was made of all layers within the column to do this. In shallow water this was done while standing and looking over the quadrat, while in deeper water it was done from a small boat and by snorkel diving. Subsequently seasonal sampling was conducted at the same sites with the help of a geographic positioning system. The mean abundance values within the various communities were used to calculate an area-weighted average for of the lake. Frequency and abundance estimations of the entire lake were subdivided into seven cover-class categories using the classification system of Toivonen and Huttunen (1995) as follows:

Table 2.3 Scales used to quantify the frequency and abundance of plant species in 28 lakes in various altitudinal gradients in Nepal.

Frequency Class	Frequency	Abundance class	Abundance	Percentage range
1	Very rare	1	Very sparse	<1.5 %
2	Rare	2	Sparse	1.5-3 %
3	Fairly rare	3	Fairly sparse	3-6 %
4	Occasional	4	Scattered	6-12 %
5	Fairly frequent	5	Fairly abundant	12-25 %
6	Frequent	6	Abundant	25-50 %
7	Very frequent	7	Very abundant	50-100 %

Quantity index values were used in the multivariate analyses (see below), which were derived values using the formula:

$$Q_i = (f_i + a_i) - 1$$

where Q_i is a quantity index, and f_i and a_i are frequency and abundance values on scales of 1-7 (Table 3.3.1) for the *i*th species. The quantity index employs a geometric scale from 1 (the species being very rare and very sparse) to 13 (very frequent and very abundant). Because frequency and abundance scales are geometric with the multiplication factor 2, a difference of one unit in the index means that the total cover of species is, on average, two times greater (Toivonen and Huttunen, 1995).

2.4.2 Identification

Plant species were identified using published flora and by visiting herbaria in Nepali universities and the national herbarium. Studies of the aquatic flora of Nepal began in the early 19th century, with the surveys of F.B. Hamilton and N. Wallich (Don, 1825), who reported some macrophytes in their collections. Other studies are those of Burkill (1910), various joint expeditions of University of Tokyo and the Department of Plant Resources/HMG/Nepal (1966-1991; published in Bulletins of the Society of Himalayan Botany, Tokyo, and the Department of Plant Resources, HMG, Nepal), Joshi (1973), Rajbahandari (1982), Yadav *et al.* (1983), Regmi and Ranjit (1985), Dangol *et al.* (1986), Sah, (1993, 1997), WMI and IUCN/Nepal (1994), Siwakoti and Verma (1995), Oli (1996), Shrestha, P. (1996), Shrestha, R. (1996), Shrestha (1997), Bhandari (1998), and Dangol and Lacoul (1998), Lacoul and Lacoul (2002). Shrestha (1999) compiled 187 species in a comprehensive list of aquatic macrophytes of Nepal.

A comprehensive "Flora of Nepal" has not yet been published. To identify plants in this study, information was obtained on the taxonomy and distribution of aquatic macrophytes of the region in the works of Hooker (1872 - 1887), Hara (1966, 1971), Hara *et al.* (1978, 1982), Hara and Williams (1979), Shrestha and Joshi (1996), Shrestha (1999), and

Press *et al.* (2000). Cook (1996) also included the aquatic plants of Nepal in their book on macrophytes of the Indian sub-continent. Plant specimens were examined at the National Herbarium (of Nepal), in the Department of Plant Resources (HMG/Nepal), and in the Ministry of Forest and Soil Conservation (HMG/Nepal).

2.4.3 Species diversity and similarity

Species diversity for individual lakes was calculated by Shannon diversity index (Margalef, 1958):

$$H' = -\Sigma p_i \log p_i \qquad \text{where, } p_i = n_i/N;$$

That is, P_i is the proportion of total abundances of all species that occurs as species i.

The community similarity between lakes was calculated by the Jaccard coefficient of community (Mueller-Dombois and Ellenberg, 1974), as follows;

$$CC_j = C/S_1+S_2 - C$$

where S_1 and S_2 are the number of species in communities 1 and 2, respectively, and C is the number of species common to both communities.

2.5.1 Data analysis

2.5.1.1 Descriptive Analyses

Descriptive statistics were calculated for limnological and species data. Averages, standard deviations, regressions, and correlations of variables were calculated using the statistical packages Statistica (version 5.0) and SPSS (version 10.0). ANOVA was used to compare variables in different altitudinal regions, with Tukey post-hoc tests. The non-parametric tests, Kruskal-Wallis followed by Mann-Whitney, were used to examine region-wise seasonal variations of environmental variables.

2.5.1.2 Multivariate Analyses

The classification of species data (the quantity index, Q_i) was done using the TWINSPAN polythetic divisive classification method (Hill, 1979; Gauch, 1982) on PC-ORD (version 4; McCune and Mefford, 1999). The default values of the programme were used, except that the cut levels for the pseudospecies set to 0, 3, 6, 10, and 12 (Qi-values), and the minimum group size for division to 5.

All ordinations were performed using the computer program CANOCO (version 4; ter Braak and Šmilauer, 1998). The theory underlying the statistical approaches used here is summarized in Jongman *et al.* (1995). All environmental variables were tested for non-normal distribution. The data for environmental variables were transformed as $\log_{10}(x+1)$ prior to analysis, to reduce skewness of their distribution, with the exception of pH (which is already a logarithmic variable). Principal component analysis (PCA) was used to summarize the major patterns of variation within the environmental data. PCA is an indirect ordination technique used to obtain a low-dimensional representation of multivariate data, so that they may be examined visually and any obvious structure identified (Everitt, 1978). The results are presented as a PCA correlation biplot, in which variables with high positive correlations generally have acute angles between their biplot arrows. The length of an arrow indicates how strongly the variable is related to the ordination (ter Braak, 1994).

Detrended correspondence analysis (DCA) was used to identify major gradients of variation in the macrophyte species data. DCA data consisted of 28 sites, 177 macrophyte species. DCA is an indirect gradient analysis that summarizes patterns of variation within a complex dataset and reveals relationships among species assemblages (sometimes referred to as "communities") (Hill and Gauch, 1980). DCA provides an effective but approximate ordination for a unimodal response model in two or more dimensions.

Unimodal ordination techniques were used because the length of the environmental gradient was >3 - 4 standard deviation as determined by DCA (ter Braak and Šmilauer, 1998). Data for DCA, CA and CCA were all performed with down-weighting of rare species and biplot scaling (ter Braak and Šmilauer, 1998). Species abundances were not square-root transformed, as this resulted in little difference in the overall variance explained in the CA and CCA compared to the untransformed data. The key variables determining species distributions that were chosen in forward selection also did not change.

First CCA was started with 28 sites, 177 macrophyte species and 23 environmental variables. Prior to CCA analysis, the species and environmental data were screened to identify and eliminate redundant and/or superfluous environmental variables, as well as extreme (outlier) data. In all ordination analyses, samples having extreme values in the environmental variables have more influence on the results than the central samples (ter Braak, 1994). The extremity of the position of the sample in the multivariate space of the environmental variables was examined using leverage diagnostics in CCA (ter Braak and

Šmilauer, 1998). No samples were found in extreme positions for the selected environmental variables having >8-times the average leverage.

The relationships among macrophyte species assemblages and environmental variables were further explored using canonical correspondence analysis (CCA) (ter Braak, 1986, 1996). CCA is a direct gradient technique that enables a simultaneous representation of sites, environmental variables, and species in low-dimensional space (ter Braak, 1987). CCA can be used to identify environmental variables that statistically account for variation in the species data. Species are assumed to have unimodal response surfaces, and the ordination axes are constrained to be linear combinations of the environmental variables. In all CCAs performed in the present study, the species scores were scaled to be weighted averages of their site scores.

Canonical coefficients and intra-set correlations were examined to estimate the relative contributions of particular environmental variables to the CCA ordination axes (ter Braak, 1996). The forward-selection option was used in the CCA to determine the minimal set of environmental variables that explain statistically significant proportions of variation in the macrophyte species data (ter Braak, 1996). This procedure is analogous to the selection process used in stepwise multiple regression (ter Braak, 1996). At each step, the statistical significance of the variable added in the course of the forward selection was tested by means of a Monte Carlo permutation test (500 unrestricted permutations). This test replaces the F-test and t-test used in forward selection in univariate multiple regression (ter Braak and Šmilauer, 1998). Variables were considered statistically significant if the permutation-test derived a P value ≤ 0.05.

To reduce the influence of strongly correlated environmental variables, I performed a series of constrained CCAs in which each environmental variable was selected as the sole variable and the significance of the first axis tested using a Monte Carlo Permutation test. Only significant ($P<0.05$ in a 500-permutation analysis) variables were retained. Following this, the variables were checked for high-variance inflation factors (a VIF =20 indicates a variable is perfectly correlated with another; ter Braak and Šmilauer, 1998) and eliminated sequentially, beginning with the variable having the highest VIF. Of the remaining variables, only those identified as significant ($P<0.05$, 500 permutations) using the forward selection options in CANOCO were included as active variables in the CCA. The same procedures were repeated for the CCA-2 and CCA-3, after removing many redundant variables to maintain the number of variables (n-2), where n is number of samples. For the data set of 17 lakes in CCA-2, only 15 environmental variables were selected after removing redundant variables. CCA-1 involved analysis of all lakes having macrophytes, while CCA-2 involved altitudinal regions TE and MM, and CCA-3 only involved euhydrophyte species (submerged, floating-leaved, and free-floating species).

3. RESULTS

3.1 Physical characteristics of the study lakes

3.1.1 Altitudinal distribution (ALT) and watershed area (WSA)

Figure 2.3 shows the altitudinal distribution of the study lakes, which range from 77 m.a.s.l (in the Koshi Tappu Wildlife Reserve) to 4,980 m (Ngojumba Lake, Gokyo). Table 2.2 illustrates the characteristics of the physiographic zones in which the lakes occur, in terms of climate, vegetation, and bio-geographic realm.

All of the lakes sampled in the High Himal (HH) alpine region lie above the treeline (*ca.* 4,200 m) and below the permanent cover of ice and snow (*ca.* 5,600 m; Figure 2.3). The largest watersheds in HH are those of Tso-Rolpa (7,760 ha) and the four lakes in Gokyo region (7,400-7,710 ha), followed by those in Langtang region (4,250-4,680 ha). The smallest watersheds are those of the three Panch Pokhari lakes (Table 2.1).

The High Mountains (HM) region occurs in the montane (boreal to cool-temperate) climatic zone of the high Himalayas. Phokte Tal (6,500 ha) and Ram Pokhari (300 ha) have the largest and smallest watersheds, respectively, in the HM region (Table 2.1).

The Middle Mountain (MM) lakes occur within a warm-temperate to subtropical climate zone of an extensive valley floor in the middle mountain zone, within densely populated areas of the greater Kathmandu and Pokhara regions. Phewa Tal has the largest watershed (11,000 ha) in the MM region and Tau Daha and Nag Daha have the smallest ones (<100 ha).

The Terai lakes (TE) are in the southern lowlands of Nepal, close to the border with India, in a tropical climatic zone dominated by sal (*Shorea robusta*) and sissoo (*Dalbergia sisso*). The TE region is densely populated, but most of the sampled lakes are within protected areas with relatively small anthropogenic influences. The only exception is Barahawa Tal, located within an urbanized area. It is extremely difficult to estimate the indistinct watershed areas in the Terai region, because most lakes are oxbows affected by seasonal riverine overflow in flat terrain. In general, however, watersheds in the TE region are smaller than in the mountain regions, and generally <500 ha in area. Two lakes, however, Tamar Tal and Devi Tal, have relatively discrete watersheds in hilly sal (*Shorea robusta*) terrain of 450 ha and 746 ha, respectively.

3.1.2 Lake surface area (SA)

In the HH region, Tso Rolpa is the largest lake (140 ha) and Tso Mengma (3.4 ha) the smallest (Table 2.1). Lake Tsola-Tso, also in the HH, has a seasonally variable surface area of 30-110 ha, depending on the timing of the monsoon and snow/glacial melt. In the HM region, the largest lake studied is Salpa Pokhari (14 ha) and the smallest is Ram Pokhari (2.5 ha). Lakes in the MM region have a much larger average surface area than in other study regions. Lake Phewa is the largest lake studied, with a surface area of 524 ha, followed by Lake Begnas (374 ha). The smallest lake studied in the MM region is Nag Daha (2.1 ha). The largest lake studied in the TE region is Beeshajar Tal (59 ha) and the smallest is Lake 2 in the Koshi Tappu Wildlife Reserve (1.6 ha).

A one-way ANOVA with Tukey's HSD (honest significant difference) for unequal N (Spjotvall/Stoline test; Table 3.1) showed that lakes in the HH, HM, and TE regions do not differ significantly in surface area. Lakes in the Pokhara area within the MM region are significantly larger ($p \leq 0.05$) than those in the other altitudinal study regions, including those of the Kathmandu area of MM. The region-wise seasonal areas showed non-significant ($p \leq 0.05$) changes along seasons (Appendix 3).

3.1.3 Maximum depth (Z_{max})

The deepest lake sampled in the HH region is Tso-Rolpa (56 m) and the shallowest Tso-Mengma (1.3 m) (Table 2.1). Tsola-Tso is exceptional in the HH region for its seasonal variations of depth, which ranged from 8 to 16 m (see Löffler (1969) for similar observations of this lake).

The deepest Z_{max} sampled in the HM region is Salpa Pokhari (16 m) and the shallowest Ram Pokhari (1.6 m). In the MM region the deepest Z_{max} was in Lake Phewa (24 m) and the shallowest Lake Rupa (6 m). In the Terai region Z_{max} ranged from 1.4 to 3.6 m. However, the Terai lakes varied seasonally in depth depending on the stormflow from the monsoon. For example, Beeshajar Tal varied in Z_{max} from 1.4 m in the pre-monsoon to 2.5 m during the monsoon season (Appendix 2).

In general, lakes in the HH region are much deeper than those in other altitudinal regions (Table 2.1). A one-way ANOVA (Table 3.1) showed that Z_{max} of the HH lakes is significantly deeper than in other altitudinal groups, while Z_{max} of the TE lakes is significantly shallower, and Z_{max} of lakes in HM and MM do not differ ($p \leq 0.05$). For all

Table 3.1 Comparative mean values (± SD) of selected variables in four physiographically distinct zones. The F ratio is calculated by one-way ANOVA. Post hoc- comparison of mean by Tukey's HSD for unequal N (Spjotvoll/ Stoline test); Different letters denotes the variables that are statistically different to each other ($P<0.05$).

Variable	High Himal (HH)	High Mountains (HM)	Middle Mountains (MM)	Terai (TE)	F- ratio
Altitude (m)	4471 ± 257 $_{A}$	3167± 239 $_{B}$	925 ± 288 $_{C}$	153 ± 59 $_{D}$	13176.0
Surface Area (ha)	36.7 ± 34.5 $_{A}$	6.9 ± 3.9 $_{A}$	203.9 ± 211.1 $_{B}$	13.4 ± 17.1 $_{A}$	99.9
Maximum depth (m)	26.0 ± 19.7 $_{A}$	9.7 ± 5.9 $_{B}$	10.8 ± 6.8 $_{B}$	2.6 ± 0.7 $_{C}$	113.4
Conductivity (µcm2/sec)	25.5 ± 15.6 $_{A}$	31.3 ± 7.8 $_{A}$	101.4 ± 90.1 $_{B}$	157.3 ± 83.6 $_{C}$	146.0
pH	7.0 ± 0.2 $_{A}$	5.9 ± 0.3 $_{B}$	7.8 ± 0.7 $_{CD}$	7.9 ± 0.3 $_{CD}$	587.3
Secchi transparency (m)	5.4 ± 4.1 $_{A}$	2.4 ± 1.8 $_{B}$	1.8 ± 0.9 $_{BC}$	1.0 ± 0.4 $_{C}$	97.6
Temperature (°C)	6.4 ± 3.2 $_{A}$	10.7 ± 3.1 $_{B}$	22.2 ± 6.8 $_{C}$	26.8 ± 5.5 $_{D}$	567.6
Calcium (mg/l)	3.9 ± 2.3 $_{A}$	3.6 ± 0.9 $_{A}$	12.1 ± 13.2 $_{B}$	17.6 ± 12.6 $_{C}$	74.3
Magnesium (mg/l)	0.35 ± 0.1 $_{A}$	0.95 ± 0.3 $_{A}$	2.9 ± 2.7 $_{B}$	5.9 ± 5.2 $_{C}$	86.8
Sodium (mg/l)	0.86 ± 0.3 $_{A}$	1.89 ± 0.4 $_{A}$	4.8 ± 3.3 $_{B}$	5.17 ± 5.3 $_{B}$	50.5
Potassium (mg/l)	0.5 ± 0.4 $_{A}$	0.34 ± 0.06 $_{A}$	1.6 ± 1.5 $_{B}$	2.9 ± 2.0 $_{C}$	111.1
Bicarbonate (mg/l)	11.5 ± 7.2 $_{A}$	12.6 ± 2.2 $_{A}$	63.2 ± 56.2 $_{B}$	93.9 ± 50.9 $_{C}$	157.6
Chloride (mg/l)	0.2 ± 0.7 $_{A}$	1.4 ± 0.6 $_{B}$	4.2 ± 3.7 $_{C}$	0.85 ± 1.8 $_{B}$	83.8
Sulphate (mg/l)	4.6 ± 1.1 $_{A}$	3.1 ± 0.6 $_{B}$	0.36 ± 0.2 $_{C}$	1.0 ± 1.3 $_{D}$	454.8
Total Suspended Solids (mg/l)	20.1 ± 44.2 $_{A}$	9.8 ± 9.7 $_{A}$	7.3 ± 2.8 $_{A}$	54.9 ± 56.6 $_{B}$	35.6
Volatile Suspended Solids (mg/l)	0.91 ± 1.0 $_{A}$	4.9 ± 4.7 $_{AB}$	5.0 ± 2.1 $_{AB}$	7.6 ± 6.4 $_{B}$	64.5
Non-Volatile Suspended Solids (mg/l)	19.1 ± 43.5 $_{A}$	4.95 ± 5.2 $_{A}$	2.3 ± 0.9 $_{A}$	32.6 ± 46.5 $_{A}$	16.3
Total Nitrogen (µg/l)	162.3 ± 87.2 $_{A}$	172.3 ± 48.1 $_{A}$	460.7 ± 283.5 $_{B}$	607.8 ± 144.2 $_{C}$	182.1
Dissolved Nitrogen (µg/l)	111.1 ± 55.1 $_{A}$	122.1 ± 33.9 $_{A}$	305.7 ± 119.1 $_{B}$	394.7 ± 179.3 $_{C}$	146.2
Total Phosphorus (µg/l)	9.1 ± 3.5 $_{A}$	5.5 ± 1.4 $_{A}$	51.8 ± 39.2 $_{B}$	97.9 ± 66.8 $_{C}$	143.8
Dissolved Phosphorus (µg/l)	4.1 ± 1.2 $_{A}$	2.8 ± 0.7 $_{A}$	19.2 ± 11.9 $_{B}$	31.4 ± 14.6 $_{C}$	257.2
Chlorophyll (µg/l)	1.3 ± 0.9 $_{A}$	3.0 ± 1.0 $_{A}$	18.1 ± 11.8 $_{B}$	10.2 ± 7.4 $_{C}$	135.5

lakes (regardless of altitudinal zone), the seasonal variation of Z_{max} was not significant ($p \geq 0.05$). The non-parametric tests of region-wise seasonal data showed that Z_{max} does not differ significantly among the HH, HM and MM regions ($p \leq 0.05$; Appendix 3). But, the TE lakes showed significant differences ($p \leq 0.01$) in their Z_{max} between the monsoon season and the pre- and post-monsoons, but no differences between the pre- and post-monsoon seasons.

3.1.4 Water temperature

Surface water temperature of the lakes changed both seasonally and with altitude. Among the study lakes, the coolest surface temperature during the growing season was in Ngojumba Lake in the HH region (4.8° C; altitude 4,980 m; Appendix 2; note that this was the warmest surface temperature attained by this lake during the study period). Local people informed me that this lake is frozen over for seven months of the year. The warmest surface temperature in the HH region was in Dudh Pokhari (12° C); this is also the highest lake (4,750 m) supporting any macrophytes. According to local people, most lakes in the HH region are frozen over for 5-6 months of the year.

Lakes studied in the HM region ranged in surface temperature from 7.2° C to 7.8° C during the post-monsoon (late autumn), and from 13° C to 16° C during the monsoon. In the MM region, the post-monsoon surface temperature differed between lakes in the Kathmandu valley (8.6° C - 9.4°C) and the Pokhara valley (15.9° C -19.8° C), but they were similar during the monsoon (25.8° C to 29.8° C) and in the pre-monsoon (24.9° C to 29.8°C).

In the Terai lakes surface temperature was 27.5° C - 31.2° C during the pre-monsoon, 30.7° C-33.6° C during the monsoon, and 17.9° C - 21.1° C during the post-monsoon.

For the entire data set, surface temperature differed significantly ($p \leq 0.05$) among the altitudinal regions (Table 3.1). The region-wise seasonal surface water temperature on non-parametric tests also showed significant differences ($p \leq 0.01$; Appendix 3), being warmest during the pre-monsoon to monsoon, and coolest in the post-monsoon season.

The overall relationship between surface water temperature and altitudinal position of the lakes is negative (Figure 3.1). The mean annual surface temperature is about 28°C at 200 m in Terai, and it declines with altitude at a lapse rate of 0.4°C per 100 m.

3.1.5 Transparency (Z_s)

Transparency of lakes in the HH region is highly variable, depending on whether there is a local input of glacial water having a high concentration of suspended solids. Bhairav Kund has the greatest transparency, with a Secchi depth of 14.0 m, while in Tso Rolpa it is only 0.16 m because of the influence of glacial flour (Appendix 1).

The transparency of lakes in the HM, MM, and TE regions is similar (ANOVA and Tukey's comparison; $p \leq 0.05$; Table 3.1). Lakes in the HH region have significantly deeper transparency than in the other regions, although as previously noted this varied greatly among lakes in the HH. The region-wise seasonal transparency is not significantly different for HH and HM lakes. However, transparency was significantly less ($p \leq 0.05$;

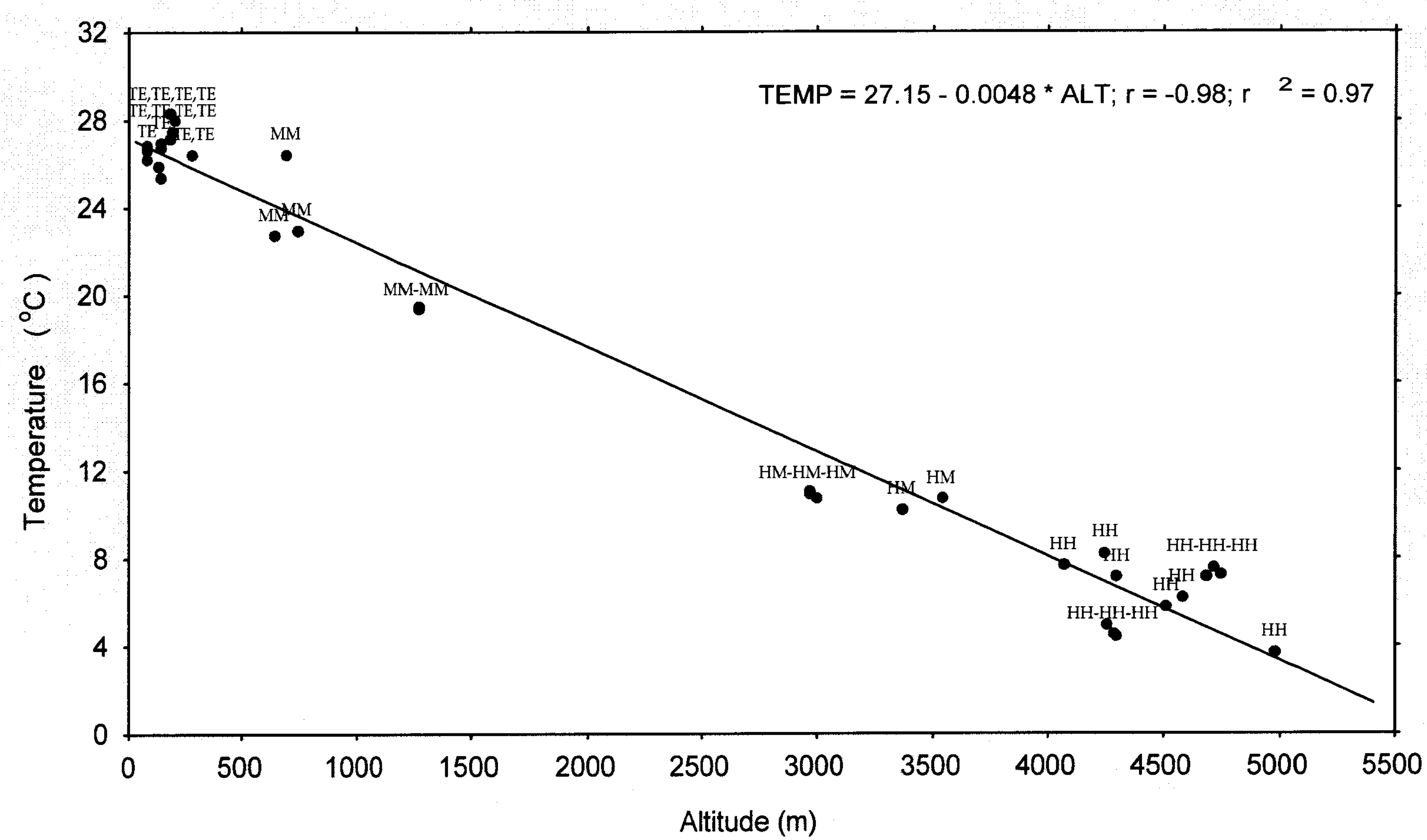


Figure 3.1 Surface water temperatures relationship to the lakes in various altitudinal regions. HH, HM, MM and TE represent the lakes in High Himal, High Mountains, Middle Mountains and Terai regions respectively.

Appendix 3) between the monsoon season and both of the pre- and post-monsoon in MM and TE lakes (the pre- and post-monsoon transparencies were not significantly different).

There was a strong log-linear relationship between transparency and total suspended solids (r^2 = 0.78; Figure 3.2) among the 34 study lakes, but a weak relationship with chlorophyll (r^2 = 0.09; Figure 3.3).

3.2 Chemical characteristics of the study lakes

3.2.1 pH

The pH of lakes in HH region was circumneutral (average pH = 7.0). Lakes in the HM region were acidic (average pH= 5.9), with the most extreme value being pH 5.6 in Salpa Pokhari during the monsoon. Lakes in the MM and TE regions were slightly alkaline, with pHs of 7.8 - 7.9; the most extreme value was pH 9.2 in Rupa Tal in the post-monsoon. The HH and HM regions were significantly different (ANOVA; $p \leq 0.05$) from each other and from the MM and TE regions (MM and TE did not differ). Region-wise seasonal pH values were significantly less ($p \leq 0.05$; Appendix 3) for all lakes during the monsoon compared with other seasons, but the pre- and post-monsoon seasons were not different.

3.2.2 Conductivity

The average conductivity of lakes in the HH region was 25.5 µS/cm, and in HM it was 31.3 µS/cm (difference not significant). The most extreme values were in high-

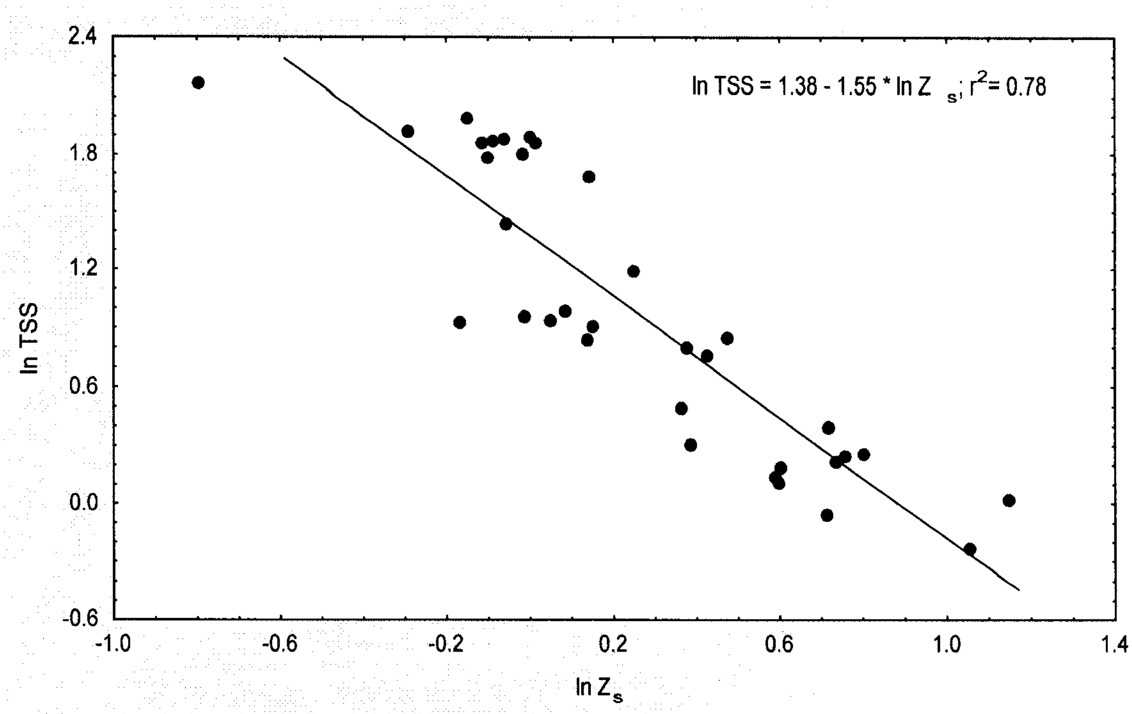


Figure 3.2 Relationship between mean values of log Secchi depth (transparency) and log total suspended solid (TSS) of lakes (n= 34)

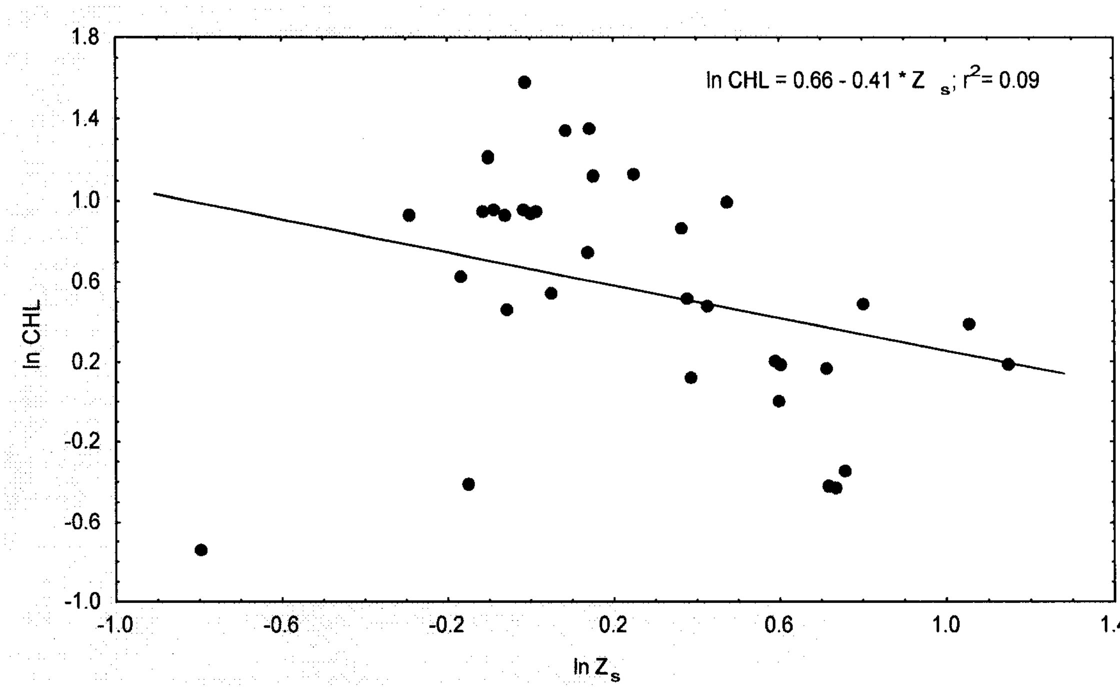


Figure 3.3 Relationship between mean values of log Secchi depth (transparency) and log total chlorophyll of lakes (n= 34)

transparency lakes in the Langtang area of HH, with only 6.9 μS/cm (only about double the conductivity of distilled water). Conductivity was significantly higher ($p \leq 0.05$) in the MM region, averaging 101 μS/cm; the most extreme values were Tau Daha in the Kathmandu valley with 296 μS/cm in the pre-monsoon, and Lake Rupa in the Pokhara region with 25.3 μS/cm during the monsoon. The Terai lakes had an average conductivity of 157 μS/cm (significantly higher than other regions), with a range among lakes of 72 to 360 μS/cm. The seasonal variation of conductivity in the HH region was not significant ($p \geq 0.05$; Appendix 3). In contrast, lakes in the HM, MM and TE regions had significantly different ($p \leq 0.05$) conductivity during the monsoon, compared with the pre- and post-monsoon (the pre- and post-monsoon were not significantly different). Conductivity was lower during the monsoon in HM and MM lakes, but higher than in the TE region.

3.2.3 Ionic concentration

The ranking of total-ion concentrations (in me/l; Table 3.2) shows that calcium and bicarbonate are consistently dominant; in the HH region calcium dominates, and in other regions it is bicarbonate. Sulphate ranks third in total ions in the HH, but is lower in the other regions, while magnesium and sodium are of moderate importance. Potassium and chloride equivalent concentrations are consistently low.

The mean calcium concentration was relatively low in the HH (3.9 mg/l) and HM (3.6 mg/l) regions, being 3-4-times higher in the MM (12.1 mg /l) and TE (17.6 mg/l) (Table 3.1). The differences between HH/HM and MM/TE are significant (ANOVA; $p \leq 0.05$).

Table 3.2 Rank of cations and anions in order of average quantities (me/l) of sampled water from different regions. Parenthesis gives the value with standard deviation.

Region \Rank	1st	2nd	3rd	4th	5th	6th	7th
HH	Ca^{2+} (0.19 ± 0.12)	HCO_3^- (0.19 ± 0.12)	SO_4^{2-} (0.10 ± 0.03)	Na^+ (0.04 ± 0.01)	Mg^{2+} (0.03 ± 0.01)	K^+ (0.01 ± 0.01)	CL^- (0.01 ±0.01)
Pre-monsoon	Ca^{2+} (0.23 ± 0.12)	HCO_3^- (0.22 ± 0.12)	SO_4^{2-} (0.09 ± 0.02)	Na^+ (0.03 ± 0.01)	Mg^{2+} (0.03 ± 0.01)	K^+ (0.01 ± 0.01)	CL^- (0.01 ± 0.01)
Monsoon	Ca^{2+} (0.17 ± 0.09)	HCO_3^- (0.16 ± 0.10)	SO_4^{2-} (0.09 ± 0.02)	Na^+ (0.04 ± 0.01)	Mg^{2+} (0.03 ± 0.01)	K^+ (0.01 ± 0.01)	CL^- (0.01 ± 0.01)
Post-monsoon	Ca^{2+} (0.18 ± 0.13)	HCO_3^- (0.18 ± 0.13)	SO_4^{2-} (0.11 ± 0.02)	Na^+ (0. 04 ±0.01)	Mg^{2+} (0.03 ± 0.01)	K^+ (0.01 ± 0.01)	CL^- (0.01 ± 0.01)
HM	HCO_3^- (0.21 ± 0.03)	Ca^{2+} (0.18 ± 0.04)	Na^+ (0.08 ± 0.02)	Mg^{2+} (0.08 ± 0.03)	SO_4^{2-} (0.06 ± 0.01)	CL^- (0.39 ± 0.02)	K^+ (0.01 ± 0.01)
Pre-monsoon	HCO_3^- (0.23 ± 0.02)	Ca^{2+} (0.21 ± 0.03)	Mg^{2+} (0.08 ± 0.03)	Na^+ (0.08± 0.01)	SO_4^{2-} (0.06 ± 0.01)	CL^- (0.04 ± 0.02)	K^+ (0.01±0.002)
Monsoon	HCO_3^- (0.17 ± 0.03)	Ca^{2+} (0.13 ± 0.02)	Na^+ (0.09 ± 0.02)	Mg^{2+} (0.08 ± 0.03)	SO_4^{2-} (0.06 ± 0.01)	CL^- (0.04 ± 0.02)	K^+ (0.01±0.002)
Post-monsoon	HCO_3^- (0.22 ± 0.01)	Ca^{2+} (0.20 ± 0.02)	Na^+ (0.08 ± 0.01)	Mg^{2+} (0.08 ± 0.03)	SO_4^{2-} (0.06± 0.01)	CL^- (0.04 ± 0.02)	K^+ (0.01±0.001)
MM	HCO_3^- (1.04 ± 0.92)	Ca^{2+} (0.65 ± 0.64)	Mg^{2+} (0.24 ± 0.22)	Na^+ (0.21 ± 0.14)	CL^- (0.12 ± 0.10)	K^+ (0.04 ± 0.04)	SO_4^{2-} (0.01±0.004)
Pre-monsoon	HCO_3^- (1.11 ± 0.97)	Ca^{2+} (0.66 ± 0.72)	Mg^{2+} (0.26± 0.24)	Na^+ (0.22 ± 0.14)	CL^- (0.12± 0.12)	K^+ (0.04± 0.04)	SO_4^{2-} (0.01±0.004)
Monsoon	HCO_3^- (0.93 ± 0.90)	Ca^{2+} (0.51 ± 0.50)	Mg^{2+} (0.2 ± 0.19)	Na^+ (0.18± 0.13)	CL^- (0.11 ± 0.09)	K^+ (0.04 ± 0.03)	SO_4^{2-} (0.01±0.004)
Post-monsoon	HCO_3^- (1.07± 0.92)	Ca^{2+} (0.64± 0.69)	Mg^{2+} (0.26 ± 0.24)	Na^+ (0.22 ± 0.15)	CL^- (0.12 ± 0.11)	K^+ (0.04 ± 0.04)	SO_4^{2-} (0.01±0.005)
TE	HCO_3^- (1.54± 0.83)	Ca^{2+} (0.88± 0.63)	Mg^{2+} (0.49± 0.43)	Na^+ (0.23 ± 0.23)	K^+ (0.07 ± 0.05)	CL^- (0.02 ± 0.05)	SO_4^{2-} (0.02 ± 0.02)
Pre-monsoon	HCO_3^- (1.63 ± 0.9)	Ca^{2+} (0.88± 0.67)	Mg^{2+} (0.52 ± 0.51)	Na^+ (0.24 ± 0.25)	K^+ (0.08± 0.05)	CL^- (0.03 ± 0.04)	SO_4^{2-} (0.02 ± 0.02)
Monsoon	HCO_3^- (1.32 ± 0.58)	Ca^{2+} (0.79± 0.44)	Mg^{2+} (0.41 ± 0.26)	Na^+ (0.19 ± 0.19)	K^+ (0.08 ± 0.04)	CL^- (0.03 ± 0.05)	SO_4^{2-} (0.02 ± 0.02)
Post-monsoon	HCO_3^- (1.66 ± 0.94)	Ca^{2+} (0.98 ± 0.74)	Mg^{2+} (0.52 ± 0.47)	Na^+ (0.24 ± 0.24)	K^+ (0.07 ± 0.05)	SO_4^{2-} (0.02 ± 0.02)	CL^- (0.02 ± 0.04)
Total sites	HCO_3^- (0.82± 0.88)	Ca^{2+} (0.51± 0.56)	Mg^{2+} (0.24 ± 0.34)	Na^+ (0.14 ± 0.17)	SO_4^{2-} (0.05 ± 0.04)	K^+ (0.04 ± 0.04)	CL^- (0.04 ±0.06)
WORLD *	HCO_3^- (0.96)	Ca^{2+} (0.75)	Mg^{2+} (0.34)	Na^+ (0.27)	SO_4^{2-} (0.23)	CL^- (0.22)	K^+ (0.06)

* Mean composition of surface water of the world (Wetzel, 1983).

The highest value (35.9 mg/l) was observed in Tau Daha in the Kathmandu Valley (MM), and the lowest (0.67 mg/l) in Sarswati Kund (HH). Region-wise seasonal calcium values showed no significant differences in TE ($p \geq 0.05$; Appendix 3), but in the HH and HM regions were significantly higher in the pre- and post-monsoon than during the monsoon. The MM region was only significantly higher in the pre-monsoon compared with the monsoon.

The mean magnesium concentration was lower in the HH (0.35 mg/l) and HM (0.95 mg/l) regions than in the MM (2.9 mg/l) and TE (5.9 mg/l) (Table 3.1). The differences between HH/HM and MM/TE are significant (ANOVA; $p \leq 0.05$). The highest value (16.7 mg/l) was observed in Beeshajar Tal in Terai, and the lowest (0.19 mg/l) in Bhairav Kund and Sarswati Kund (HH). Region-wise seasonal magnesium values for the pre-monsoon season was significantly higher ($p \leq 0.05$; Appendix 3) than during the monsoon and post-monsoon in the HH and HM regions. In the MM region both pre- and post-monsoon values were higher ($p \leq 0.05$) than during the monsoon. No significant differences were observed for seasonal values of magnesium in TE lakes.

The mean sodium concentration was lower in the HH (0.86 mg/l) and HM (1.9 mg/l) regions than in the MM (4.8 mg/l) and TE (5.2 mg/l) (Table 3.1). The differences between HH/HM and MM/TE are significant (ANOVA; $p \leq 0.05$). The highest value (20.7 mg/l) was observed in Barahawa Tal in TE, and the lowest (0.68 mg/l) in a glacial lake, Tso Rolpa, in HH. The region-wise seasonal sodium concentration showed lower pre-monsoon values ($p \leq 0.05$; Appendix 3) than during the monsoon in the HH and HM regions. In contrast, in the MM and TE regions sodium values were less ($p \leq 0.05$) during the monsoon than in the pre-monsoon.

The mean potassium concentration was lower in the HH (0.50 mg/l) and HM (0.34 mg/l) regions than in the MM (1.6 mg/l) and TE (2.9 mg/l) (Table 3.1). The differences between HH/HM and MM/TE are significant (ANOVA; $p \leq 0.05$). The highest value (7.3 mg/l) was observed in Barahawa Tal in Terai, and the lowest (0.17 mg/l) in Gosian Kund and Bhairav Kund in HH. The region-wise seasonal potassium concentrations showed no significant differences for most of the regions ($p \geq 0.05$; Appendix 3).

Bicarbonate is the dominant anion in all of the altitudinal regions, followed by sulphate and chloride in much lower equivalent concentrations (Table 3.2). The mean bicarbonate concentration was lower in the HH (11.5 mg/l) and HM (12.6 mg/l) regions than in the MM (63.2 mg/l) and TE (93.9 mg/l) (Table 3.1). The differences between HH/HM and MM/TE are significant (ANOVA; $p \leq 0.05$). The highest value (186 mg/l) was observed in Devi Tal in Terai, and the lowest (2.4 mg/l) in three lakes in HH. The region-wise seasonal concentration were lower during the monsoon than in the pre- and post-monsoon in the HH, HM and MM regions ($p \leq 0.05$; Appendix 3). There was no significant seasonal change in the TE lakes.

The mean sulphate concentration was higher in the HH (4.6 mg/l) and HM (3.1 mg/l) regions than in the MM (0.36 mg/l) and TE (1.0 mg/l) (Table 3.1). All differences among regions are significant (ANOVA; $p \leq 0.05$). The lowest value (0.15 mg/l) was observed in Tau Daha in MM, and the highest (5.6 mg/l) in Tsola Tso in HH. The region-wise seasonal concentrations were not significantly different for HM, MM and TE lakes ($p \geq 0.05$; Appendix 3), but in the HH lakes were higher during the post-monsoon than in the monsoon or pre-monsoon (ANOVA; $p \leq 0.05$).

The mean chloride concentration did not vary consistently among the altitudinal regions. It was higher in the MM (4.2 mg/l), followed by HM (1.4), TE (0.85 mg/l), and HH (0.20 mg/l) (Table 3.1; all differences are significant at $p \leq 0.05$, except HM = TE). The lowest value (0.11 mg/l) was observed in Dudh Pokhari in HH, and the highest (8.8 mg/l) in Nag Daha in MM. The region-wise seasonal concentrations were not different for HM, HM and MM lakes, but in TE lakes were significantly higher ($p \leq 0.05$; Appendix 3) during the monsoon season than in the pre-monsoon and post-monsoon.

The average total cation concentration (Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}; region-wise value dispersion is shown in Figure 3.4) varied as follows:

- HH 5.6 mg/l 0.27 me/l
- HM 6.7 0.35
- MM 21.5 1.1
- TE 31.7 1.7

The differences between HH/HM and MM/TE are significant (ANOVA; $p \leq 0.05$).

The average total anion concentration (HCO_3^- + Cl^- + SO_4^{2-}; region-wise value dispersion is shown in Figure 3.4) varied as follows:

- HH 8.0 mg/l 0.29 me/l
- HM 17.8 0.66

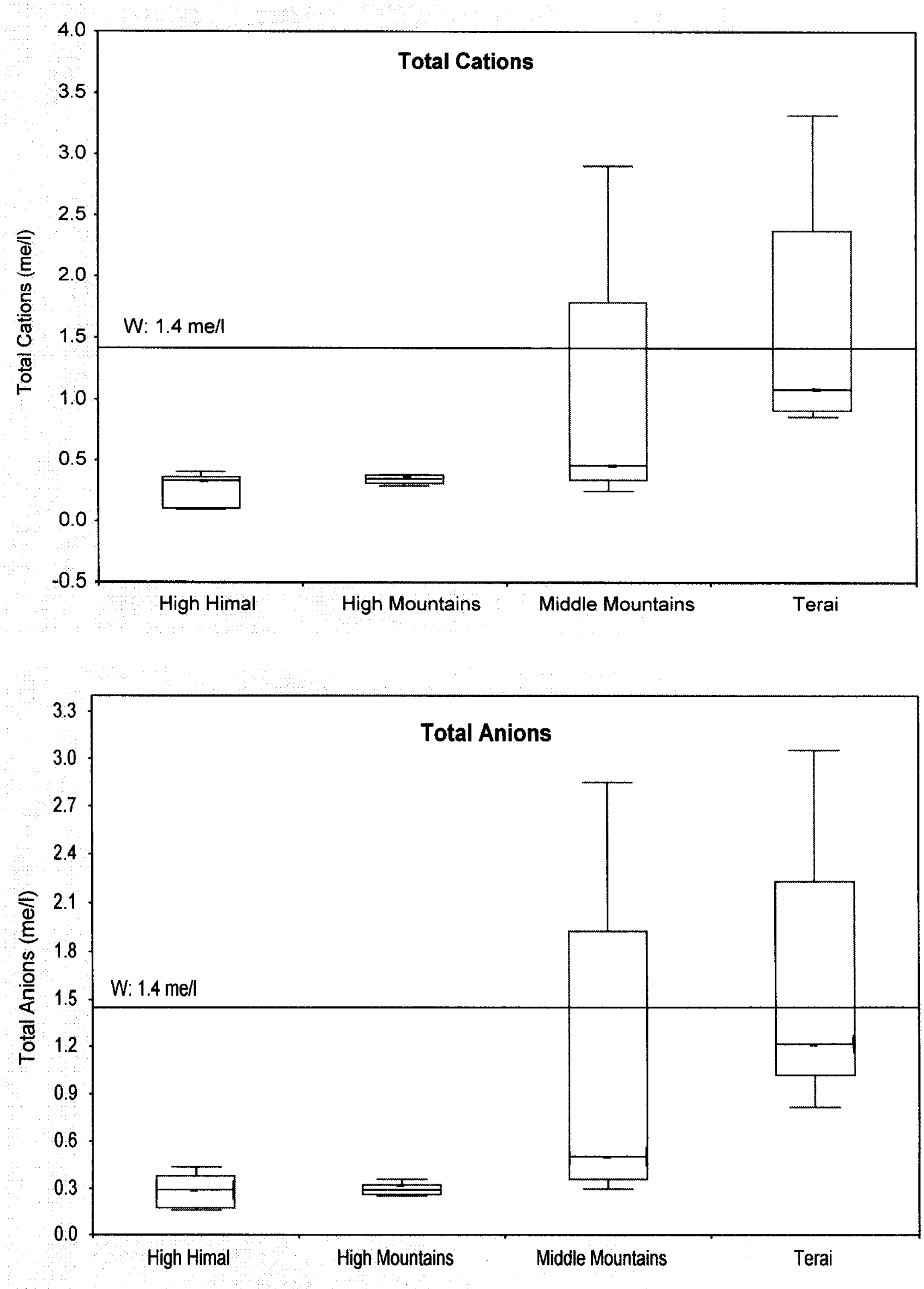


Figure 3.4 Lakes mean total cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and total anions (HCO_3^-, Cl^-, SO_4^{2-}) grouped by physiographic zone. Boxes denote 25th to 75th percentile, a median is the central line, whiskers represent 10th and 90th percentile. W is the mean of surface fresh water after Wetzel (1983).

- MM 67.7 1.16
- TE 95.8 1.58

The differences between HH/HM and MM/TE are significant (ANOVA; $p \leq 0.05$).

In general, the TE region had relatively high concentrations of cations and anions, particularly during the monsoon, while the monsoon values for the HH, HM and TE regions were relatively lower than in other seasons (Figure 3.5).

The overall charge balance between positive and negative equivalents was rarely greater than 15% for the HM, MM and TE regions, but it could be more than 20% in the HH (Figure 3.6). Note, however, that this balance does not account for anion charges attributable to nitrate and organic anions, which were not quantified in this study. Seasonal differences between mean total cations and total anions did not differ significantly among seasons (ANOVA; $p \leq 0.05$; Figure 3.7).

A correlation matrix among ionic species is presented in Figure 3.8. There were strong positive correlations between all cations and bicarbonate ($p \leq 0.01$). Chloride did not show significant relationships with divalent cations, but it did with monovalent ones. Sulphate showed weak or insignificant relationships with other ions. Calcium plus magnesium showed a strong relationship ($r^2 = 0.95$) with bicarbonate (Figure 3.9).

3.2.4 Suspended solids

The mean total suspended solids (TSS) in the HH (20.1mg/l), HM (9.8 mg/l), and MM (7.3 mg/l) regions were lower than in the TE (54.9 mg/l) (Table 3.1). The differences

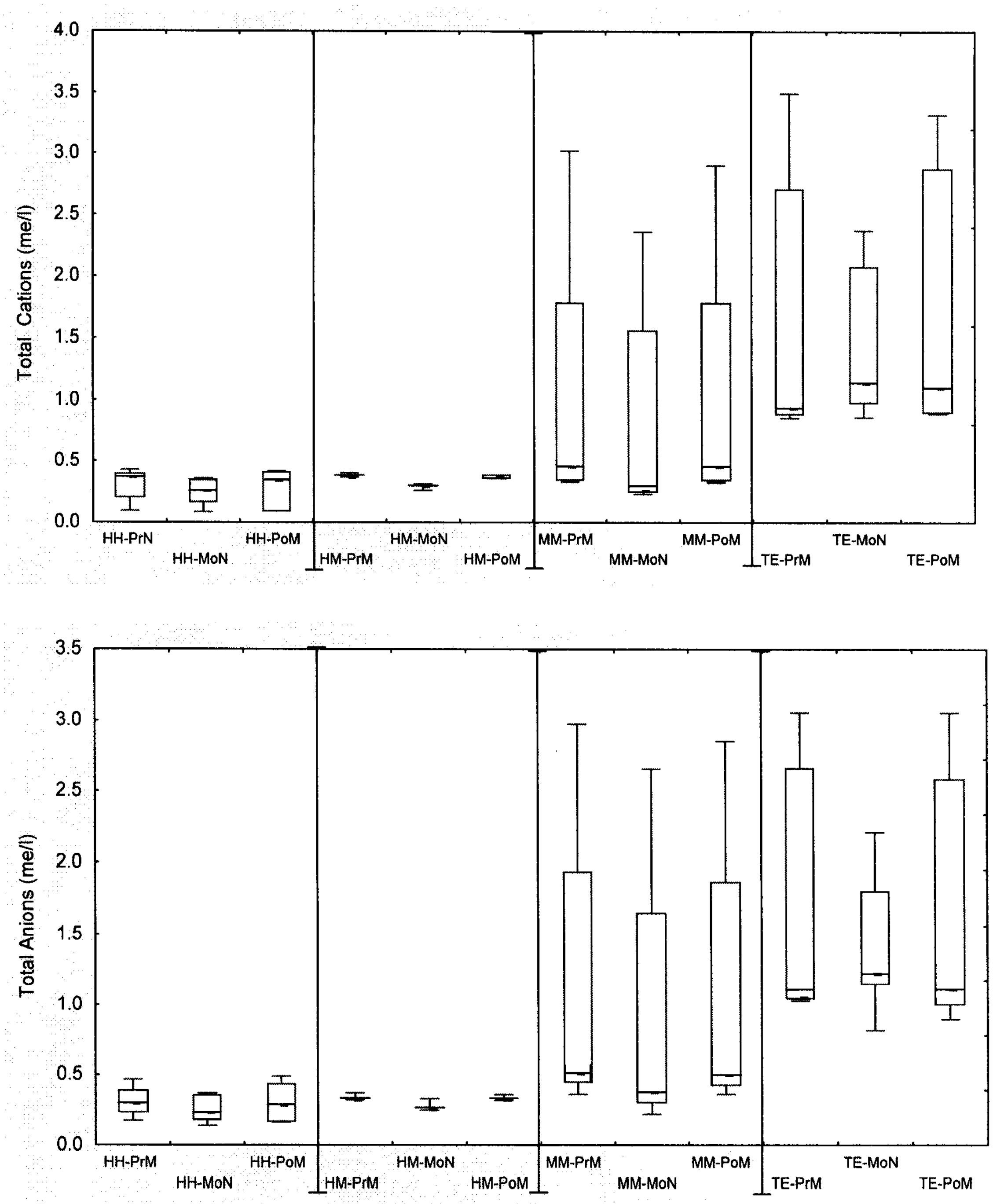


Figure 3.5 Lakes seasonal mean total cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and total anions (HCO_3^-, Cl^-, $SO4^{2-}$) grouped by physiographic zones. Boxes denote 25th and 75th percentile, a median is the central line, whiskers represent 10th and 90th percentile. HH, HM, MM and TE represent physiographic regions high himal, high mountains, middle mountains and Terai respectively. PrM, MoN and PoM represent sampled seasons, pre-monsoon, monsoon and post monsoon respectively.

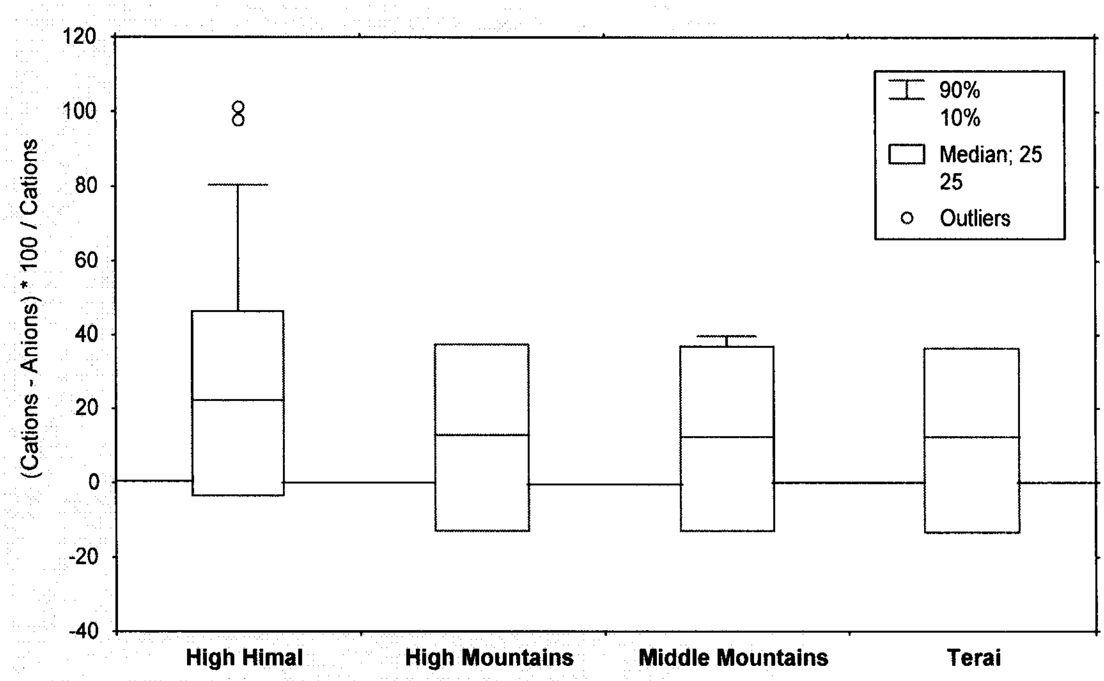


Figure 3.6 Differences between mean total cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and total anions (HCO_3^-, Cl^-, SO_4^{2-}) expressed as a percent of total cations milli-equivalents (n=34).

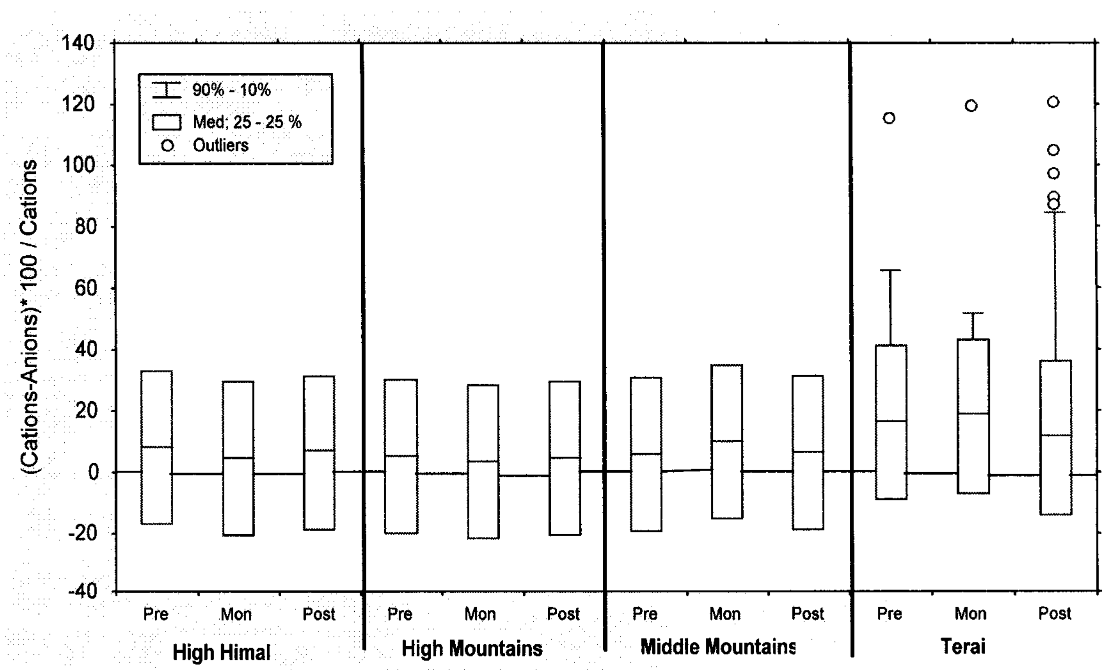


Figure 3.7 Differences between mean total cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and total anions (HCO_3^-, Cl^-, SO_4^{2-}) expressed as a percent of total cations milli-equivalents (n=34) for pre-mosoon (Pre), monsoon (Mon) and post monsoon (Post).

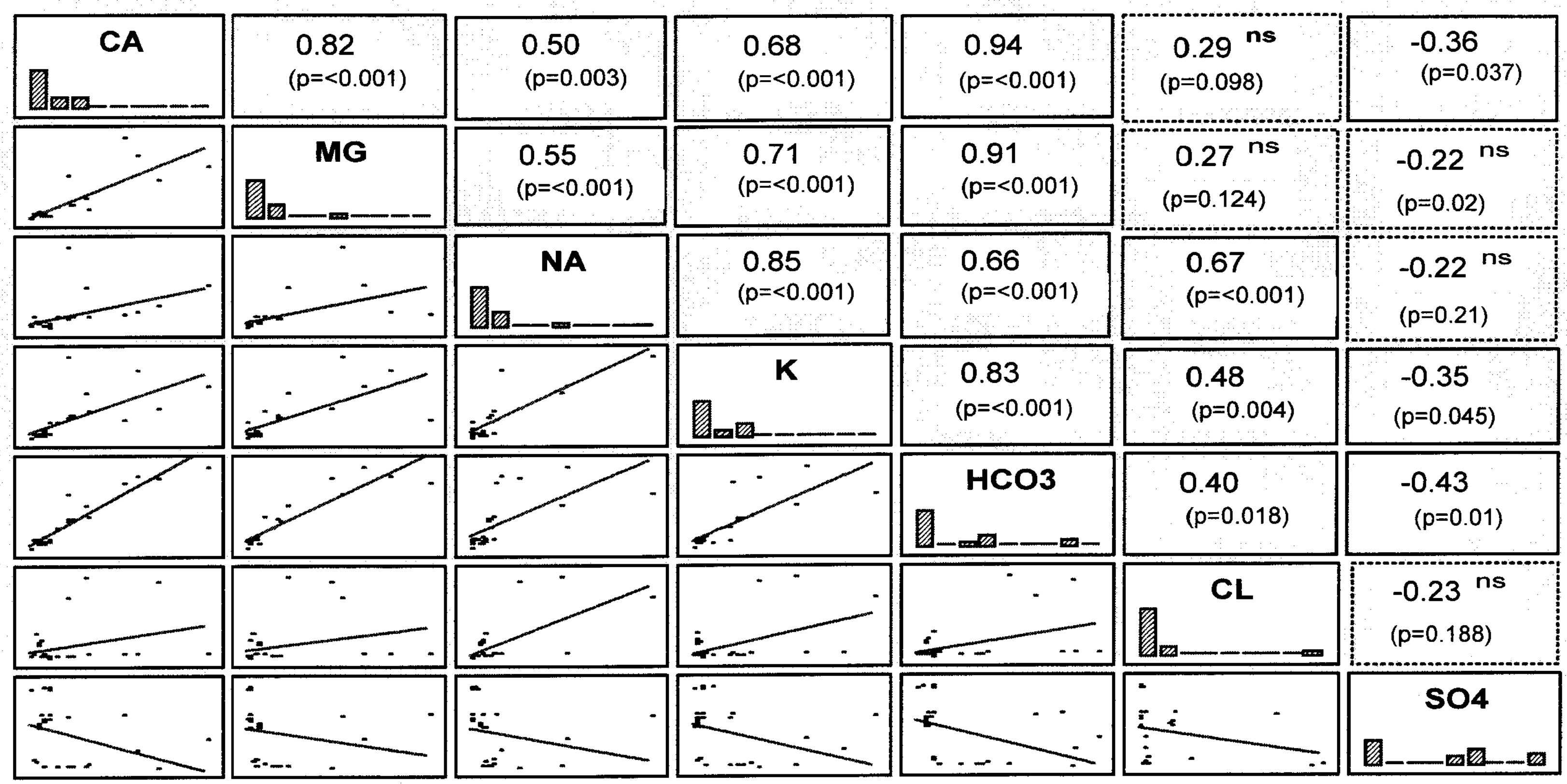


Figure 3.8 Correlations among cations and anions using lake mean ion concentration (me/l, n=34). The values above the diagonal are bivariate correlations, with corresponding scattered plots below the diagonal. Diagonal portrays the distribution of each variable. All correlations excepts those in dashed box with ns are not significant at $p<0.05$.

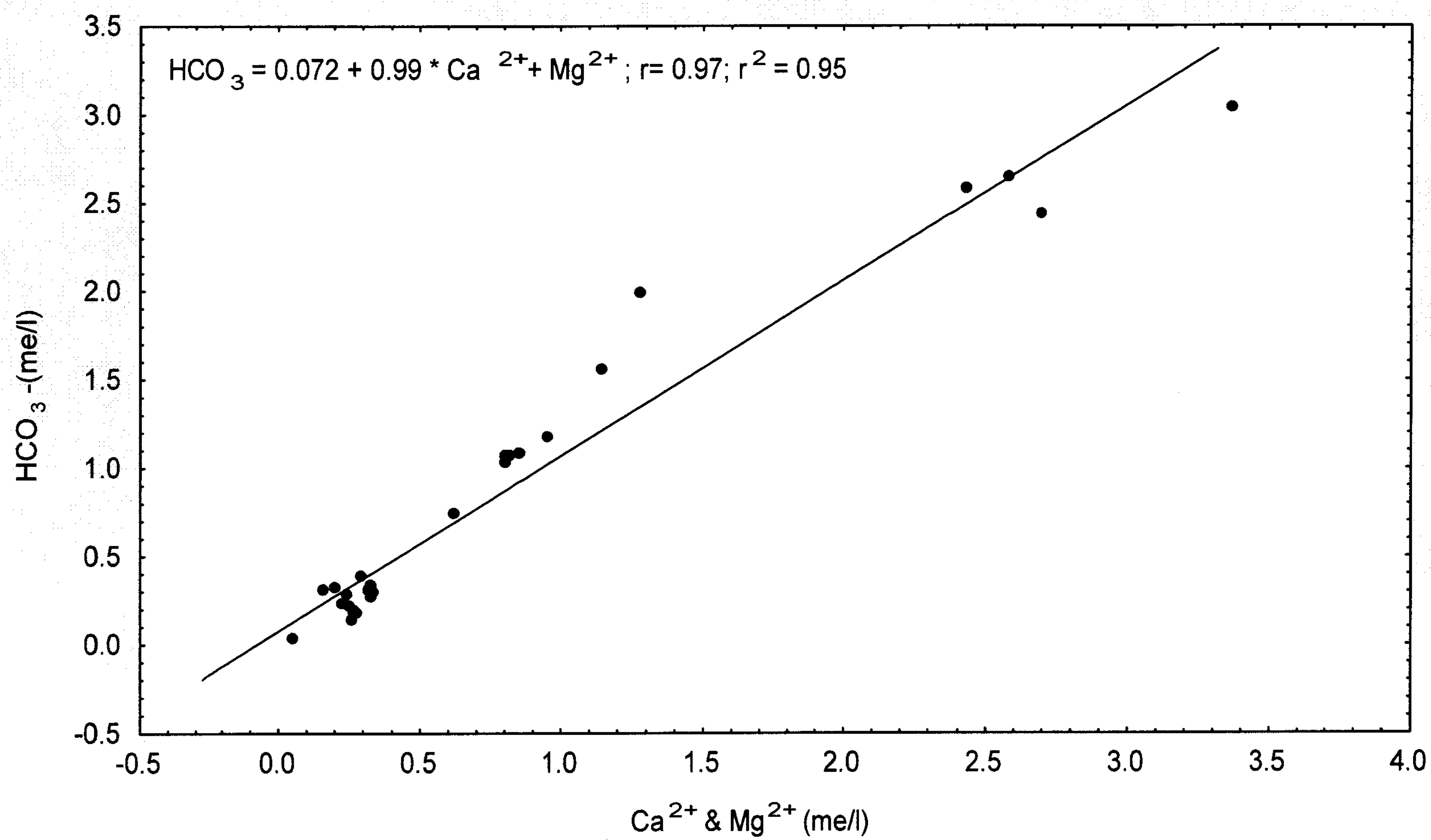


Figure 3.9 Linear regression of $Ca^{2+} + Mg^{2+}$ against HCO_3^- using lake means (n=34).

between HH, HM, and MM are not significant, but all are different from TE (ANOVA; $p \leq 0.05$). The highest values were observed in Tso Rolpa and Tsola Tso lakes (147 and 96 mg/l, respectively) close to melting glaciers in the HH region, and the lowest (0.58 mg/l) in Gosain Kund in HH. The TSS values were significantly higher ($p \leq 0.01$; Appendix 3) during the monsoon than during the pre- and post-monsoon seasons for all regions, except for HM where the post-monsoon values did not showed significant difference with the monsoon values.

The mean volatile suspended solids (VSS) were lower in the HH (0.91 mg/l) region than in the HM (4.9 mg/l), MM (5.0 mg/l) and TE (7.6 mg/l) (Table 3.1). The differences between HH, HM, and MM are not significant, but the HH is different from TE (ANOVA; $p \leq 0.05$). The highest value (15.2 mg/l) was observed in Barahawa Tal in Terai, and the lowest (0.25 mg/l) in Ngojumba in HH. The VSS values were significantly higher ($p \leq 0.01$; Appendix 3) during the monsoon than during the pre- and post-monsoon seasons for TE, MM, and HH, but there were no significant differences among seasons in the HM region.

The mean non-volatile suspended solids (NVSS) were lower in the HH (19.1mg/l) and HM (4.9 mg/l) and MM (2.3 mg/l) regions than in TE (32.6 mg/l) (Table 3.1). However, the differences among the mean regional values were not significant ($F_{0.05, 31} = 16.3$). The highest values (146 and 92 mg/l) were observed in Tso Rolpa and Tsola Tso lakes in HH region, and the lowest were in Salpa Pokhari (0.25 mg/l) and Gosain Kund (0.26 mg/l) in the HM and HH, respectively. The seasonal values of NVSS were significantly higher during the monsoon than during the pre- and post-monsoon in all regions ($p \leq 0.05$; Appendix 3).

3.2.5 Nutrients

The mean total nitrogen (TN) in the HH (162 μg/l) and HM (172 μg/l) regions were significantly lower than in the MM (461 μg/l) and TE (608 μg/l) regions (ANOVA; $p \leq 0.05$; Table 3.1). The highest mean value (983 μg/l) was observed in Tau Daha in MM region and the lowest (35 μg/l) in Tso Rolpa in HH. The values of TN varied seasonally, but the patterns were not consistent among altitudinal regions.

The mean total dissolved nitrogen (DN) in the HH (111 μg/l) and HM (122 μg/l) regions were lower than in the MM (306 μg/l) and TE (395 μg/l) (ANOVA; $p \leq 0.05$; Table 3.1). The highest mean value (656 μg/l) was observed in Tau Daha in MM region and the lowest (24 μg/l) in Tso Rolpa in HH. The values of DN varied seasonally, but the patterns were not consistent among altitudinal regions.

The mean total phosphorus (TP) in the HH (9.1 μg/l) and HM (5.5 μg/l) regions were lower than in the MM (51.8 μg/l) and TE (97.9 μg/l) regions (ANOVA; $p \leq 0.05$; Table 3.1). The highest mean value (160 μg/l) was observed in Barahawa Tal in TE region and the lowest (2.6 μg/l) in Tso Rolpa in HH. The values of TP varied seasonally, but the patterns were not consistent among altitudinal regions.

The mean total dissolved phosphorus (DP) in the HH (4.1 μg/l) and HM (2.8 μg/l) regions were lower than in the MM (19.2 μg/l) and TE (31.4 μg/l) regions (ANOVA;

$p \leq 0.05$; Table 3.1). The highest mean value (43.3 μg/l) was observed in Tamar Tal in TE region and the lowest (1.3 μg/l) in Tso Rolpa in HH. The values of DP varied seasonally, but the patterns were not consistent among altitudinal regions.

There was a moderately strong relationship (r^2= 0.72) between the TN: TP ratio and log TP concentrations among the study lakes (Figure 3.10), but that with log TN was weak (Figure 3.11; r^2= 0.29).

3.2.6 Chlorophyll

The mean total chlorophyll (CHL) was lower in the HH (1.3 μg/l) and HM (3.0 μg/l) regions than in the MM (18.1μg/l) and TE (10.2 μg/l) (ANOVA; $p \leq 0.05$; Table 3.1). The highest mean value (38 μg/l) was observed in Tau Daha in MM region and the lowest (0.18 μg/l) in Tso Rolpa in HH. The values of CHL varied seasonally, but the patterns were not consistent among altitudinal regions.

There was a strong log-linear relationship between CHL and TN (r^2= 0.65; Figure 3.12) among the study lakes, with both variables generally increasing in lower altitudes (i.e., in MM and TE). The relationship is strengthened when Lake Tsola Tso (HH region) is removed from the dataset (r^2 = 0.74); this lake is close to a glacier that contributes high TSS and turbidity that result in anomalous productivity. The relationship of CHL and TP is somewhat weaker (r^2 = 0.57; Figure 3.13), and is also improved (r^2 = 0.61) if Tsola Tso is not included in the dataset.

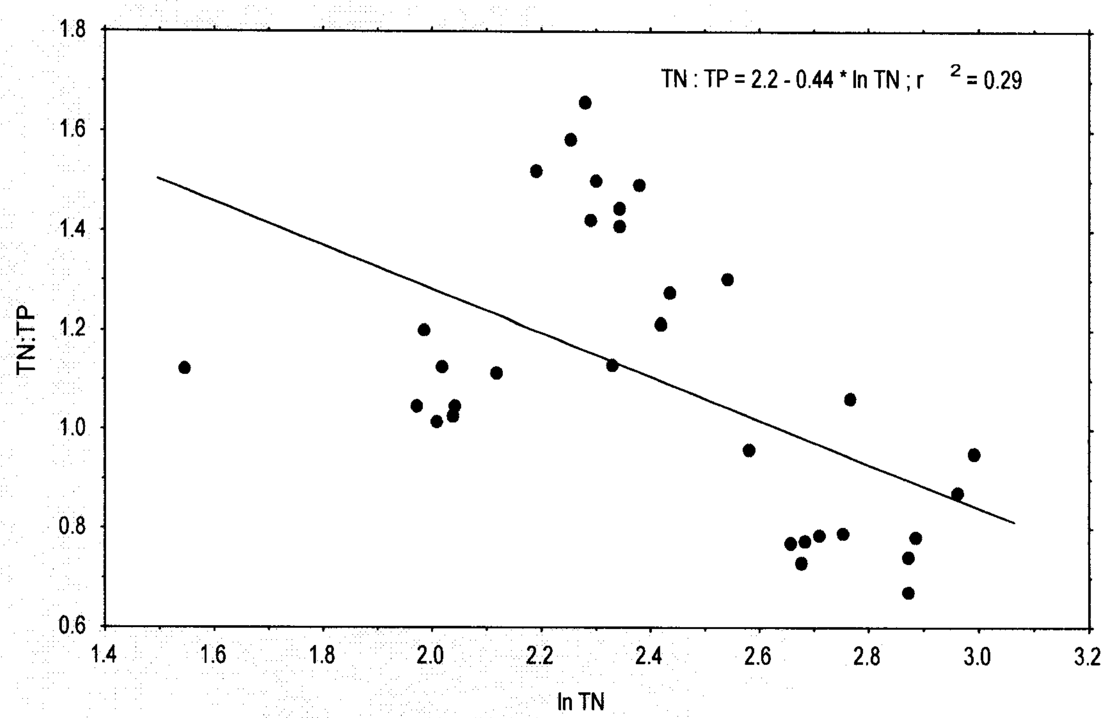


Figure 3.10 A relationship between total nitrogen and total nitrogen by total phosphorus ratio for the lakes.

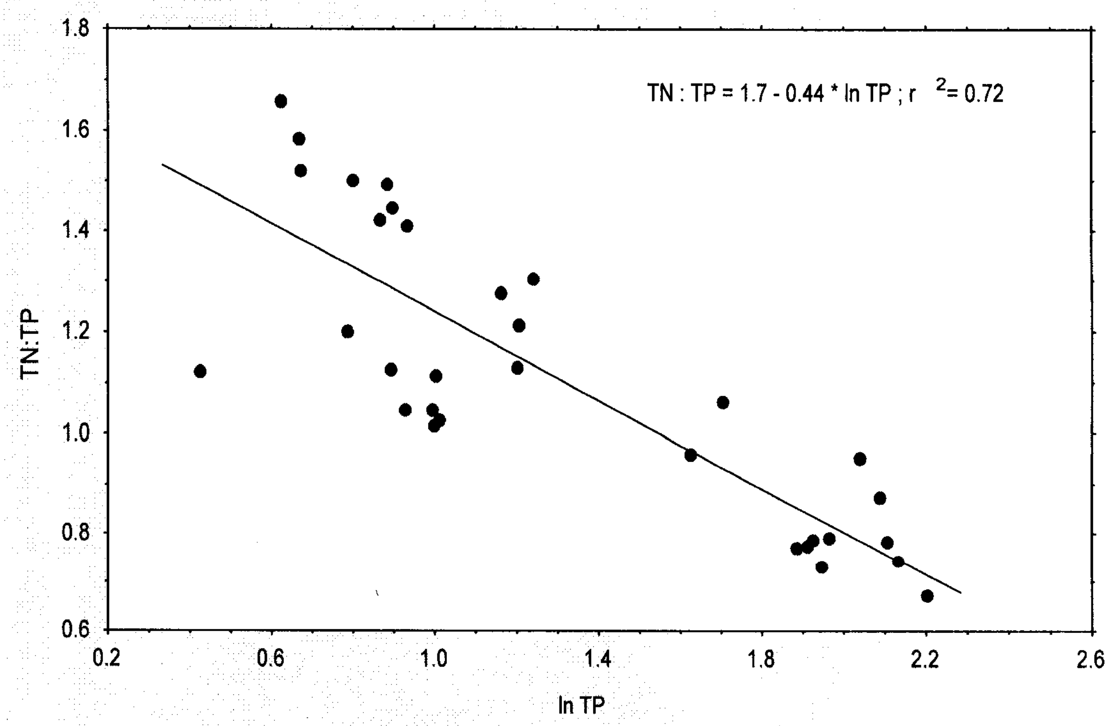


Figure 3.11 A relationship between total phosphorus and total nitrogen by total phosphorus ratio for the lakes.

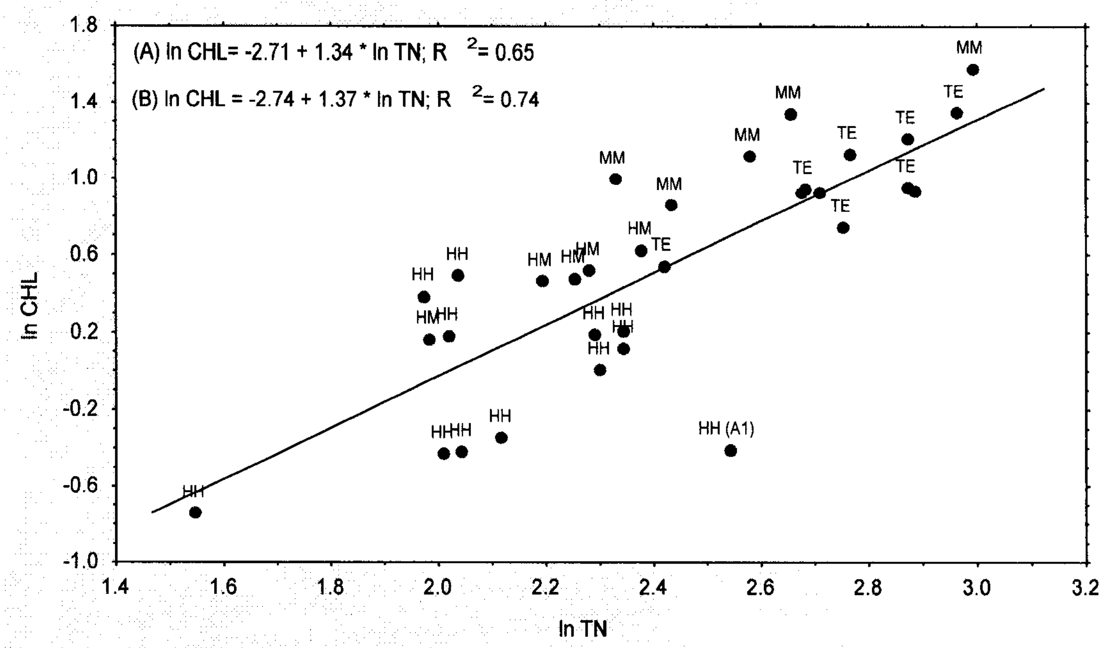


Figure 3.12 (A) Lakes total suspended chlorophyll relationships with total nitrogen (n=34). (B) Same relationships after excluding the sample from Lake Tsola Tso in HH region. Data is identified by physiographic zone to show distribution.

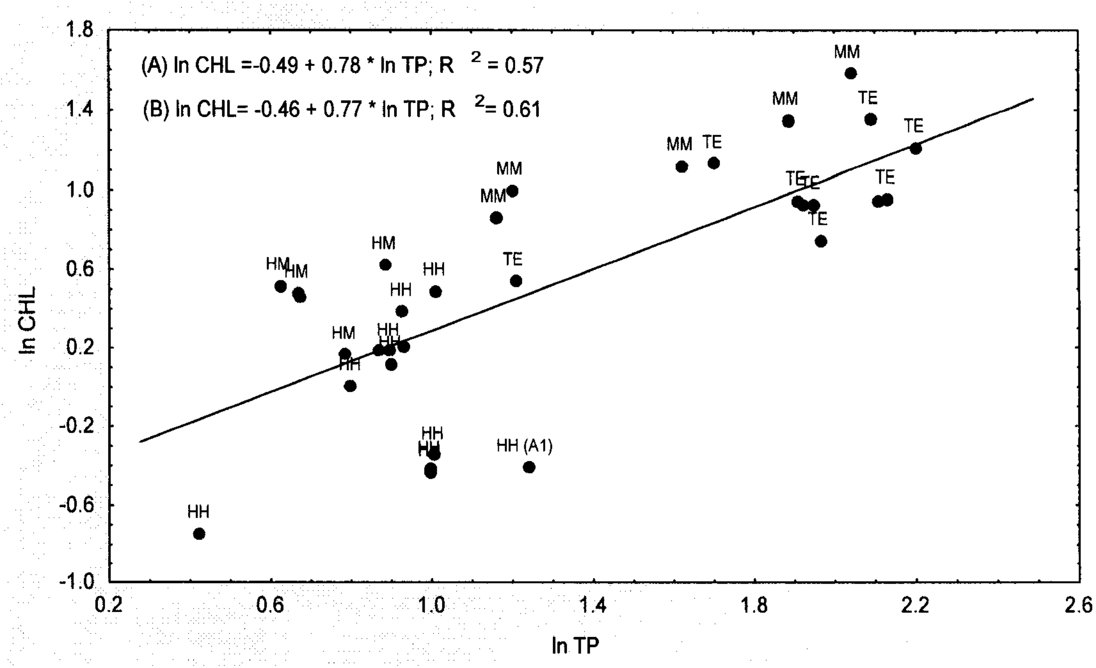


Figure 3.13 (A) Lakes total suspended chlorophyll relationships with total phosphorus (n=34). (B) Same relationships after excluding the sample from Lake Tsola Tso in HH region. Data is identified by physiographic zone to show distribution.

Table 3.3 shows the distribution of lakes among trophic categories based on mean indicator values of TN, TP, CHL, and TRANS. In general, the HH and HM lakes are largely in an oligotrophic condition, with a few being mesotrophic (that is, if anomalous predictions related to TSS associated with glacial flour are disregarded). Lakes in the MM region are more variable, ranging from oligotrophic to hypereutrophic. The TE lakes are generally more productive than waterbodies in the other regions, being mostly in a eutrophic to hypereutrophic condition.

3.3.1 Distribution of aquatic macrophytes

A total of 177 species of aquatic macrophytes was observed in this study. Macrophytes were observed in 28 out of the 34 lakes studied, but were absent in 6 of the highest-altitude waterbodies. The species present comprised: (1) one macroalga, *Nitella* sp.; (2) six Bryophytes in six families; (3) eight Pteridophytes in 7 genera and 6 families; (4) 65 dicotyledonous plants in 39 genera and 26 families; and (5) 97 monocotyledonous plants in 55 genera and 16 families (Appendix 4). Out of the 55 families of aquatic plants observed, 39 families were represented by a single genus, and 23 families by one species. Figure 3.14 shows the number of genera and species among major taxonomic groups. The family Cyperaceae represents 32% of the monocot species and 18% of the genera, followed by Poaceae (28% of monocot species and 34% of genera). The Scrophulariaceae represents 14% of the dicot species and 10% of the genera, followed by Asteraceae (9% of species and 15% of genera).

Six high-altitude lakes in the HH region did not harbor any aquatic macrophytes: Lake Tsola Tso (A1), Lake Ngojumpa (A5), three lakes in Panch Pokhari (A6, A7, A8), and Lake Tso-Rolpa (A9). Other lakes in HH region supported only 1-3 of flowering

Table 3.3 Percentage of lakes in trophic categories based on lake means of TN, TP or CHL (after Forsberg and Ryding ,1980; threshold values are given below variables in parenthesis).

	Oligotrophic %				**Mesotrophic %**				**Eutrophic %**				**Hypereutrophic %**			
Physiographic zone	**TN** (< 400 mg/ m^3)	**TP** (<15 mg/ m^3)	**CHL** (<3 mg/ m^3)	Z_s (> 4.0 m)	**TN** (400 -600 mg/ m^3)	**TP** (15- 25 mg/ m^3)	**CHL** (3-7 mg/ m^3)	Z_s (2.5- 4.0 m)	**TN** (600- 1500 mg/ m^3)	**TP** (25- 100 mg/ m^3)	**CHL** (7-40 mg/ m^3)	Z_s (1.0- 2.5 m)	**TN** (> 1500 mg/ m^3)	**TP** (> 100 mg/ m^3)	**CHL** (>40 mg/ m^3)	Z_s (< 1.0 m)
High Himal (n=12)	100	92	92	66	-	8	8	8	-	-	-	8	-	-	-	17
High Mountains (n=5)	100	100	80	20	-	-	20	20	-	-	-	20	-	-	-	40
Middle Mountains (n=5)	60	20	-	-	20	20	-	20	20	40	100	60	-	20	-	20
Terai (n=12)	8	-	-	-	50	8	8	8	41	50	92	42	-	42	-	50

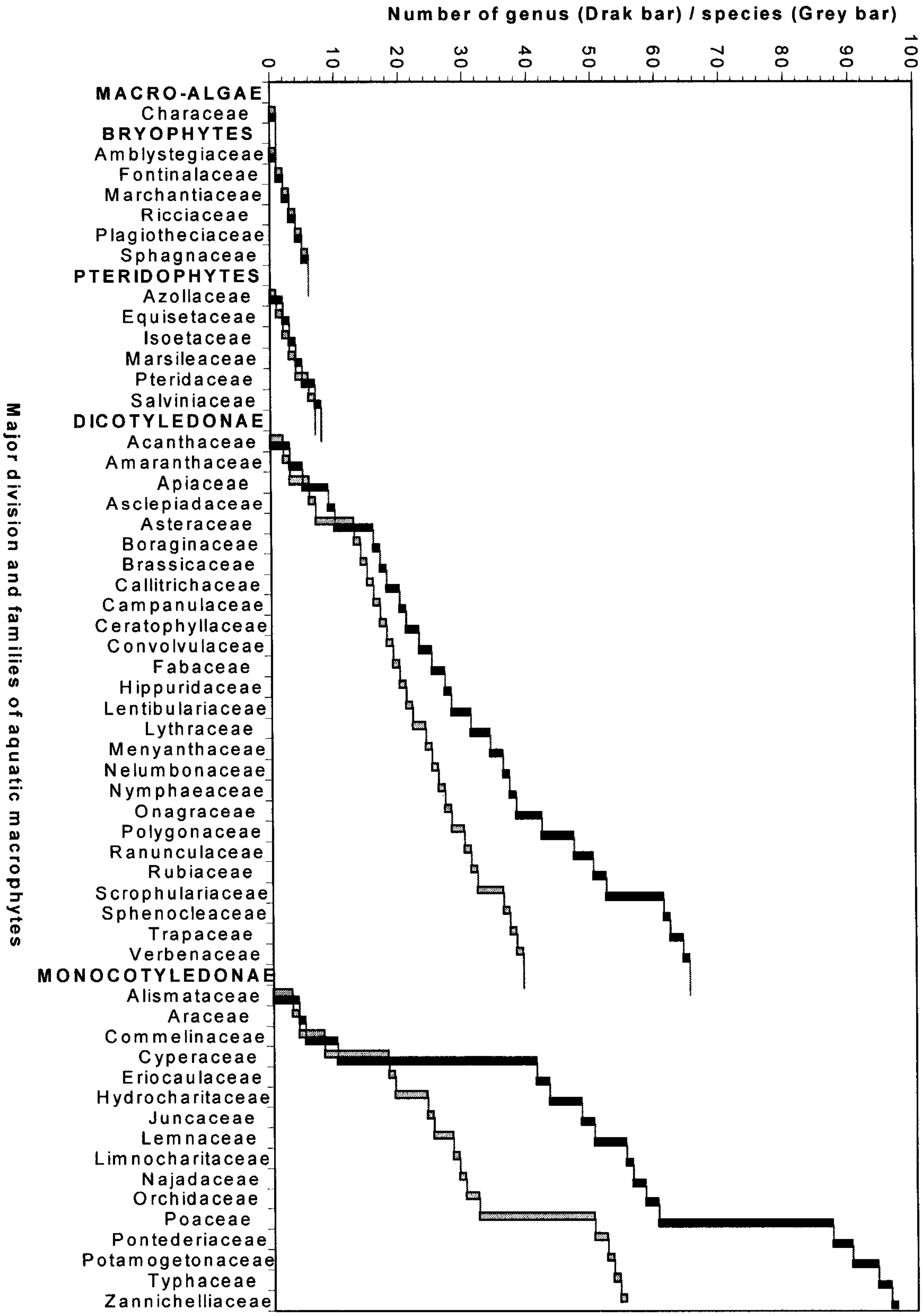


Figure 3.14 Number of genera and species represented by different families of aquatic macrophytes in total sampled lakes.

macrophytes, which are here reported for first time in lakes above 4,700 m anywhere in the world. The highest records are for *Ranunculus trichophyllus*, a submerged eleodid that occurred in three high-altitude lakes (A2, A3, A4; at 4,680-4,750 m) in the Gokyo region of Sagarmatha (Everest) National Park. Another eleodid, *Callitriche palustris*, occurred in Sarswati Kund (A12; 4,068 m) in the Langtang region. In addition, the widespread grass, *Festuca ovina,* occurred sparsely in the shallow littoral zone of lakes in the Langtang region. Other grasses and *Juncus* species were observed in shallow littoral zones of the majority of lakes in HH, particularly close to the inflow and outflow streams.

The HM region is relatively poor in species of aquatic macrophytes. Lakes Salpa Pokhari, Gupha Pokhari, and Mauwa Pokhari had only 4-7 species each, and at a low cover. The *Sphagnum*-fringed lakes Ram Pokhari and Phokte Tal supported macrophytes similar to those in bog habitats, being dominated by bryophytes such as *Sphagnum* spp. and *Drepanocladus* spp. along with graminoids such as *Carex* and *Juncus* species.

The species richness of aquatic macrophytes was much higher in MM lakes, particularly in the Kathmandu and Pokhara valleys, where a total of 78 species was recorded. Lake Rupa was the richest in species (47 present, with a high overall cover), followed by Lake Phewa (40 species). Lake Begnas had the lowest number of species (20 species) in the MM region.

The Terai region (TE) had the greatest species richness, with 139 species recorded. Two lakes with a seasonal, lotic, overflow influence had the highest observed number of macrophytes: Lake Beeshajar Tal had 85 species and Kushaha had 80 species. The species richness in other lakes in the TE region ranged from 17 to 46 species.

Figure 3.15 shows that 55% of the aquatic plants identified were Monocotyledonae followed by Dicotyledonae (37%), Pteridophytes (4%), Bryophytes (3%) and Macroalgae (1%). The percentage distribution of major taxonomic groups in the four altitudinal regions is shown in Figure 3.16. The HH region had 3% of the 65 species of Dicotyledonae in this study, followed by HM (6%), MM (43%), and TE (80%) (note that some species occurred in more than one altitudinal region). A similar trend was seen in Monocotyledonae: HH (2%), HM (13%), MM (41%), and TE (80%).

The depth-range distribution of macrophytes shows that 78% of the species occurred in water shallower than 50 cm (Figure 3.17). Figure 3.18 shows that most species occurrences were in the shallow littoral zone (<15 cm), although this varied by altitudinal region: 50% in HH, followed by 82% in HM, 38% in MM, and 60% in TE.

In Terai, the greatest depth at which macrophytes were found was only 2 meters, due to the commonly murky water and shading effects of floating and emergent plants in the lakes. In the MM region, there is a heterogenous depth distribution of macrophytes, with *Trapa quadrispinosa,* a floating-leaved plant, rooted as deeply as 5 m in Rupa Lake. Among the submerged species, *Ranunculus trichophyllus* in lakes in Gokyo (HH) and *Vallisneria natans* in Lake Phewa (MM) colonized more than 4 m below the surface, although most submerged species occurred no deeper than 2 m.

Overall, the growth form of aquatic macrophytes was dominated by Helophytes (58%), followed by Hyperhydates (17 %), submerged (13 %), floating leaved (6%) and free-

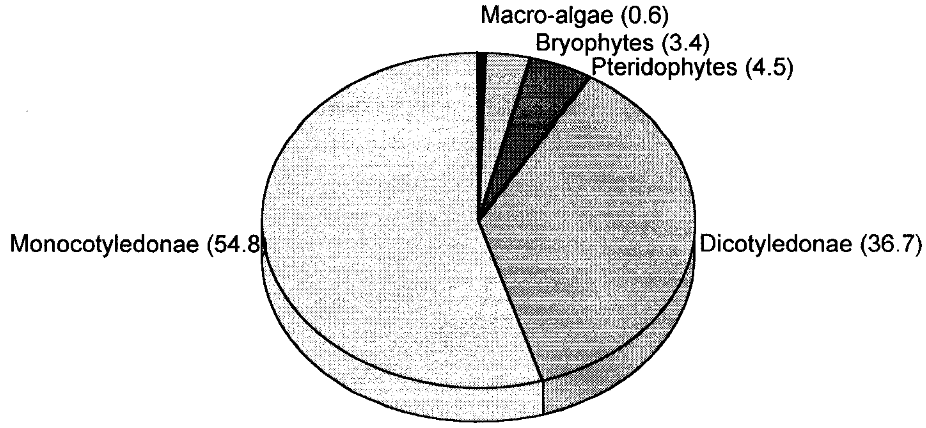


Figure 3.15 Taxonomic groups of aquatic macrophytes in total lakes (percentage values are in parenthesis).

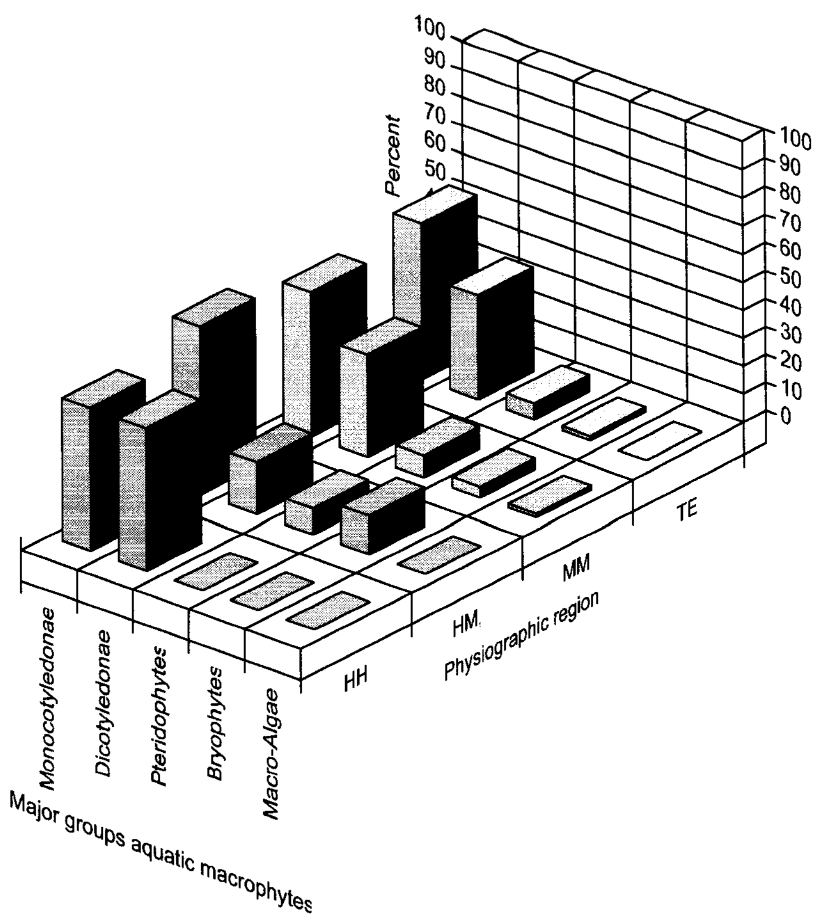


Figure 3.16 Percentage distribution of each taxonomic group in different altitudinal regions.

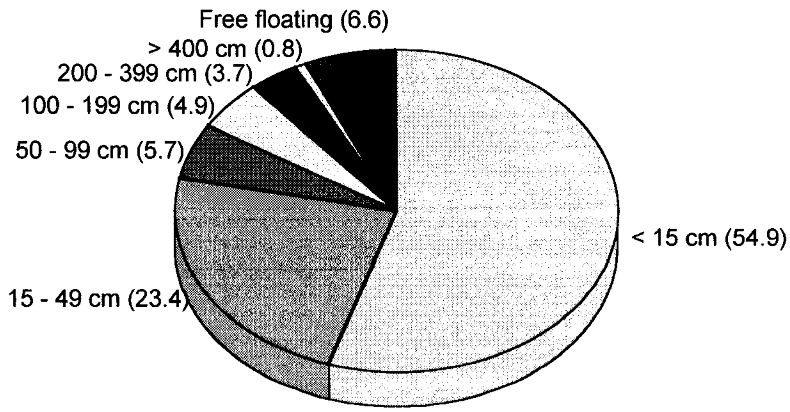


Figure 3.17 Rooting depth range grouping of aquatic macrophytes. Percentage values are in parenthesis.

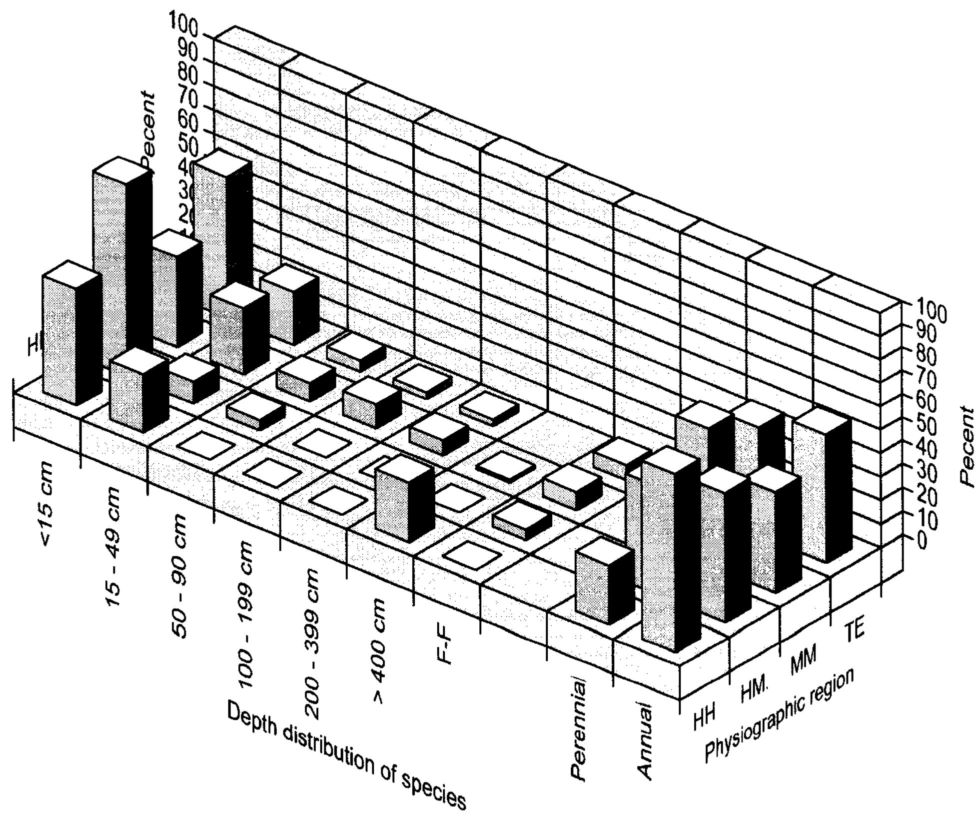


Figure 3.18 Percentage share of different groups categorized on the basis of rooting depth distribution of aquatic macrophytes in different regions with plant growth habit.

floating (6%) (Figure 3.19). The TE region was dominated by shallow-water growth forms such as Helophytes and Hyperhydates, while the MM was rich in submerged forms, The generally shallower lakes in the HM were dominated by Helophytes, and the deep and clear HH lakes by submerged species (Figure 3.20).

Overall, 53% of the macrophyte species are annuals, and 47 % are perennial in lifespan. The annuals were somewhat richer in Terai (80%) and MM (35%), and lower in the HM (35%) and HH (3%) regions of the total annuals (94 species). Perennials also show a similar trend in distribution with altitudinal zones (Figure 3.18).

3.3.2 Macrophytes richness and diversity

Lakes in the TE region have higher levels of Shannon diversity (Figure 3.21). Beeshajar Tal (D10) and Kushaha Nahar (D7) had the highest diversity among the Terai lakes, while the lowest values were in three lakes in the Koshi Tappu Wildlife Reserve (Lakes: D1, D2, D3). In the MM region, Rupa Tal (C3) has the highest species diversity and Begnas Tal (C4) the lowest. In the HM region, Phokte Tal (B5) had the highest diversity and Gupha Pokhari (B1) the lowest. Most lakes in the HH region had only one species; only Sarswati Kund had 3 species.

The Jaccard coefficient of community similarity showed a moderate degree of similarity among lakes in the TE and MM regions ($CC_j = 0.32$). There was little similarity between TE/MM lakes and those in the HM region ($CC_j \leq 0.07$) or in the HH ($CC_j = 0.02$), or between HM and HH ($CC_j = 0.04$).

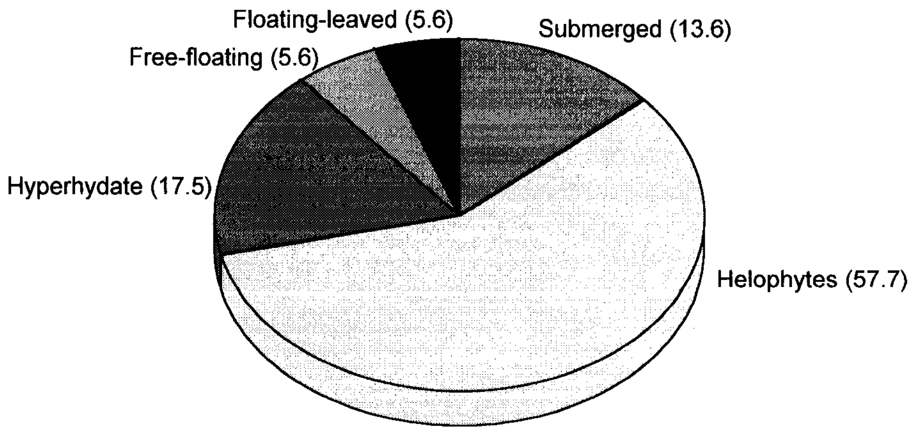


Figure 3.19 Growth forms distribution of aquatic macrophytes in total lakes.

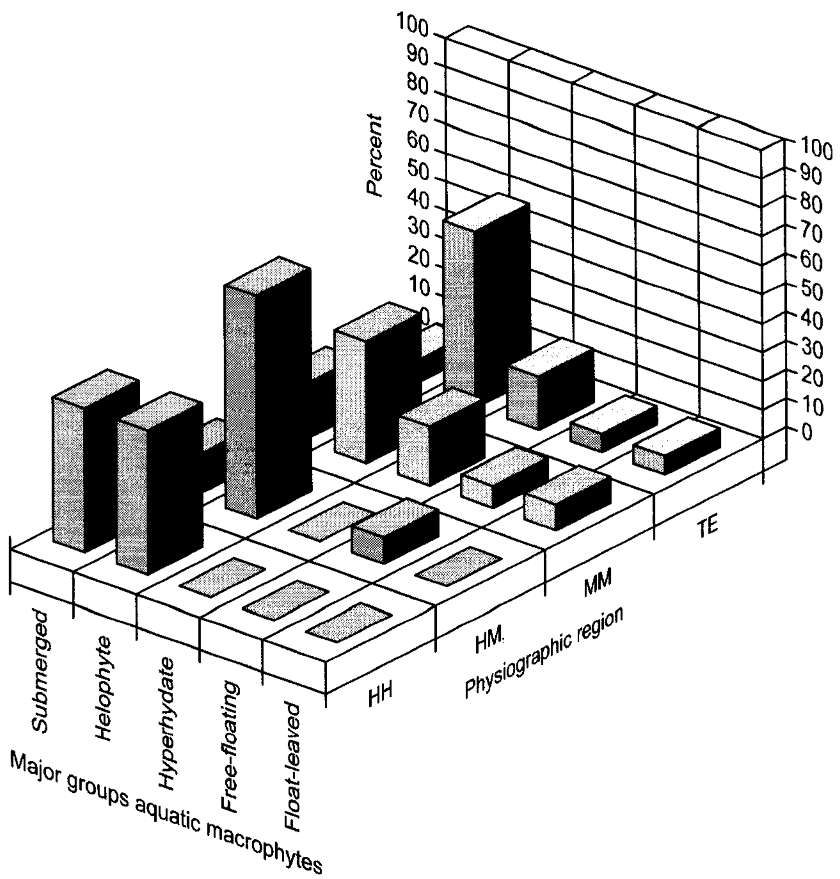


Figure 3.20 Percentage growth forms distribution of aquatic macrophytes in different altitudinal regions.

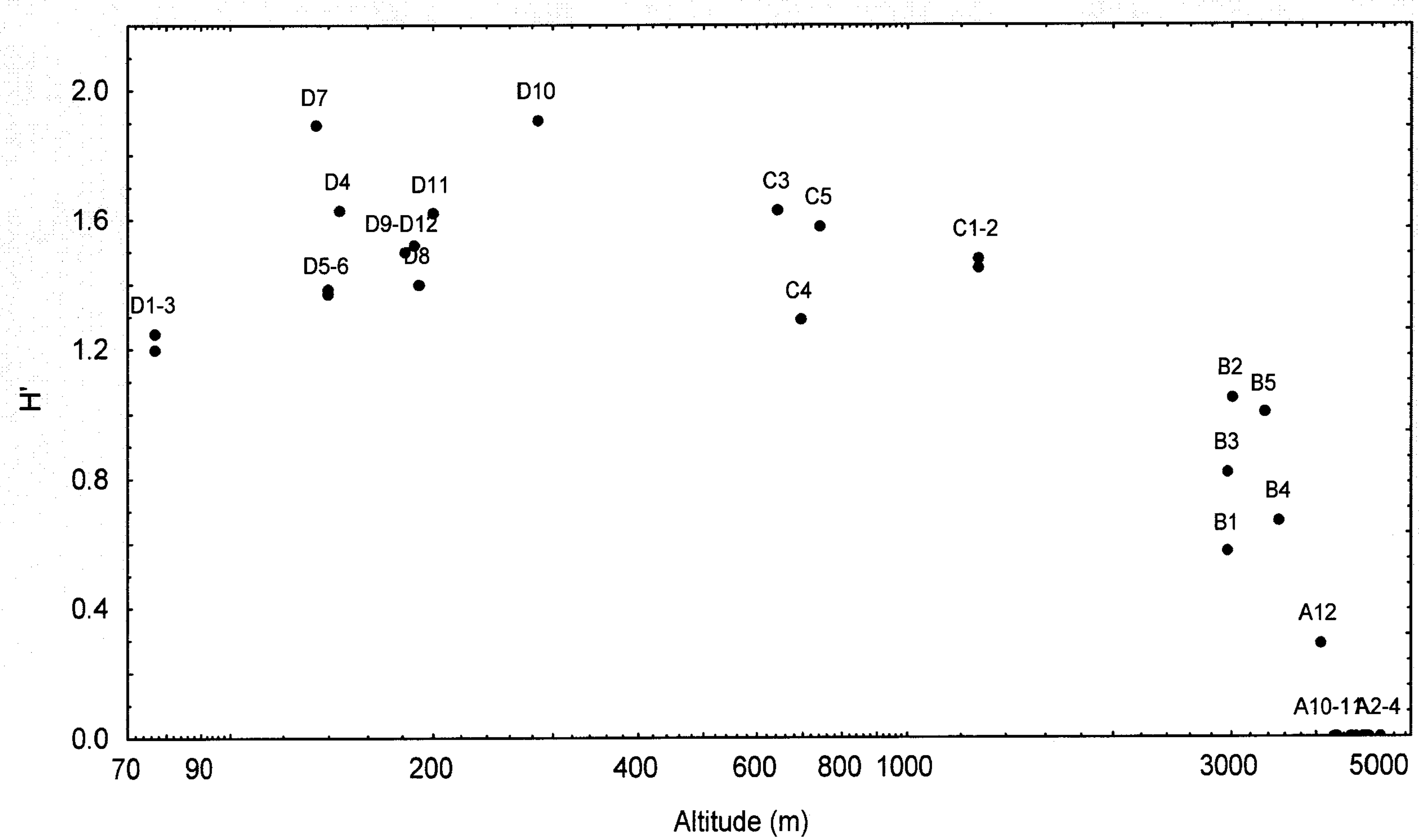


Figure 3.21 Scatterplot of Shannon diversity index for macrophytes species in different lakes at various altitudes.

Spearman rank correlation coefficients among environmental variables and species richness (Appendix 5) show strong relationships with bicarbonate (0.72), substrate quality (-0.71), water temperature (0.70), altitude (r = -0.68), conductivity (0.64), pH (0.62), and nutrients (N and P; range 0.55-0.67), but not for lake surface area (0.11; ns). Altitude, surface water temperature, conductivity, and nutrients showed stronger relationships to the richness of helophytes + hyperhydates, compared to euhydates. However, the euhydrophyte relationships are stronger to pH and substrate quality.

A log-transformed multiple regression analysis (Table. 3.4) between species richness (as dependent variable) and key physical factors (independent variables) showed a negative relationship of macrophytes with altitude, and a positive relationships with water temperature.

Table 3.4 Multiple regression responses of the log species richness as dependable variable to log environmental variable of lakes as independent variables.

Independent variable	β	r^2	F	p
Altitude (m)	-0.77	0.59	38.2	0.01**
Lake surface area (ha)	0.063	0.004	1.2	0.01**
Maximum depth (m)	0.55	0.28	11.42	0.01**
Temperature (°C)	0.91	0.83	127.5	0.01**
Secchi Transparency (m)	-0.72	0.52	28.5	0.01**

The beta and coefficient of determination for surface water temperature showed the strongest relationship (Figure 3.22; β= 0.91; r^2 = 0.83), followed by altitude (Figure 3.23; β= -0.77; r^2 = 0.59) and Secchi transparency (β= -0.72; r^2 = 0.52) (all $p<0.01$). Lake surface area did not have a significant relationship with species richness (β= -0.06; r^2 = 0.004), when considering all lakes in the various altitudinal zones. Within the TE region, however, surface area has a strong relationship with species richness (Figure 3.24; r^2 = 0.79).

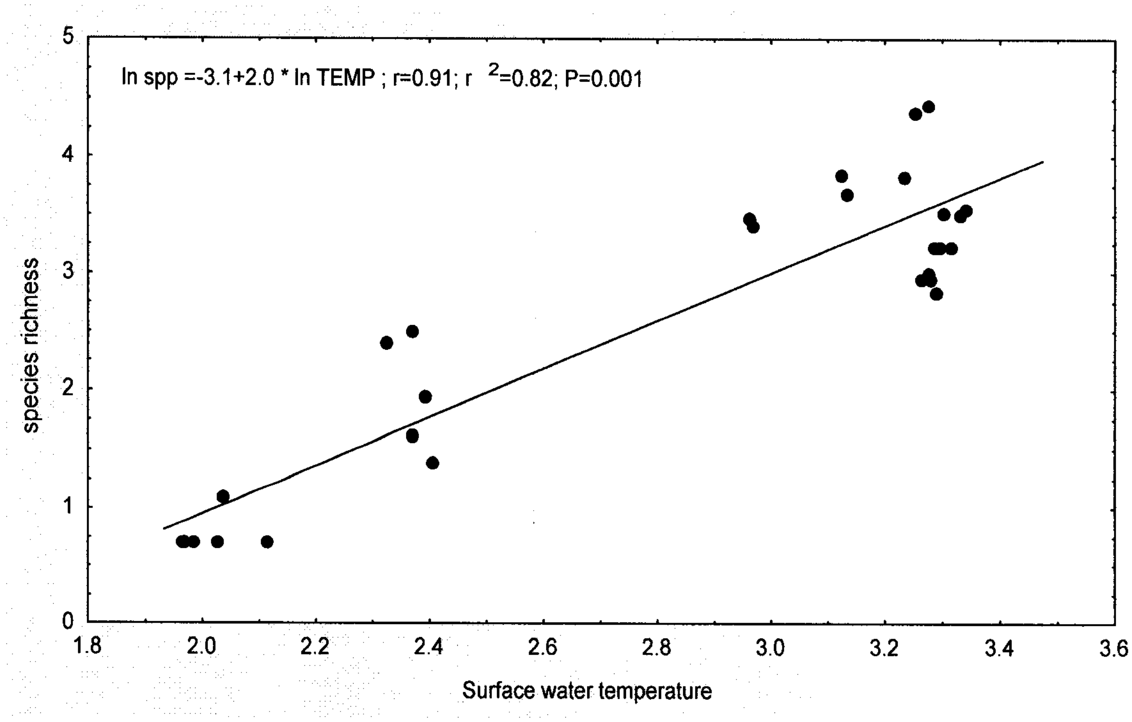


Figure 3.22 Species richness of macrophytes as function of the surface water temperature (n=28).

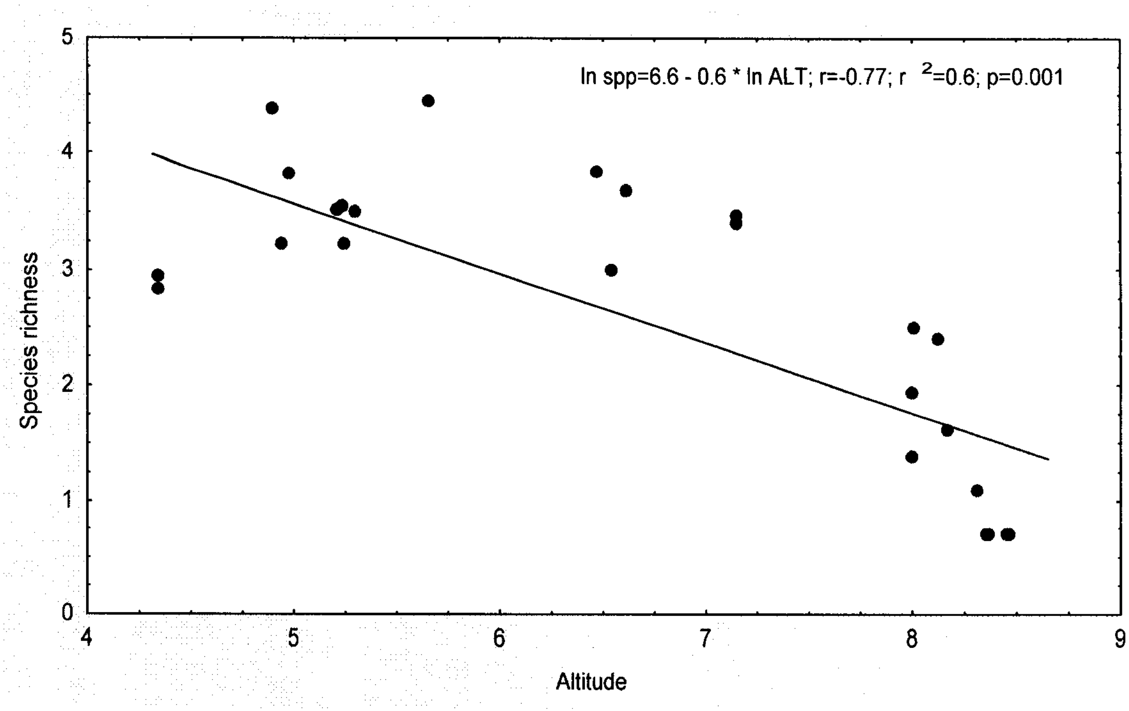
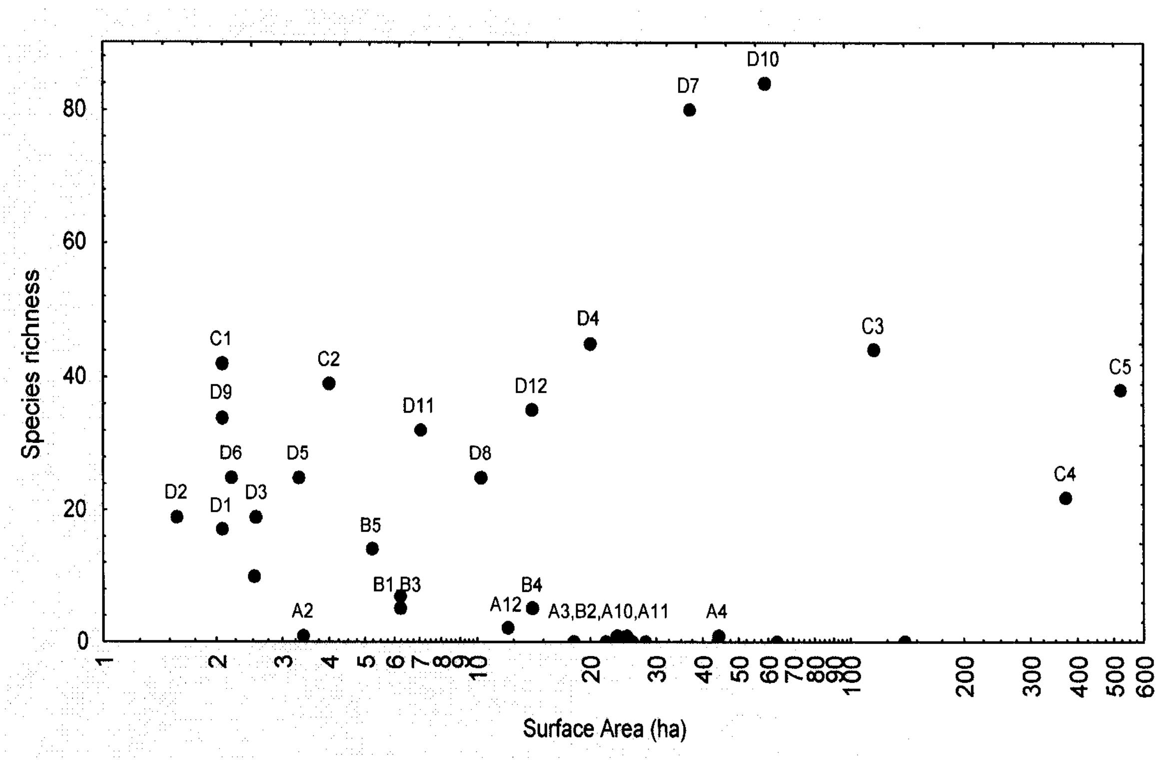


Figure 3.23 Species richness of aquatic macrophytes as function of the altitude (n=28).



Linear regression (n = 28):
SPP = 18.35 + .03 * SA; $r^2 = 0.021$
Linear regression with log transformation:
HH+HM+MM+TE (n = 28); ln SPP = 1.08 + 0.009 * ln SA; r^2 = 0.0001
HM+MM+TE (n = 22); ln SPP = 1.23 + .15 * ln SA; r^2 = 0.10
MM+TE (n = 17); ln SPP = 1.41 + 0.101 * ln SA; r^2 = 0.17
(MM-C4)+TE (n = 16); ln SPP = 1.37 + 0.16 * ln SA; r^2 = 0.38
TE (n=12); ln SPP = 1.2 + 0.37 * ln SA; r^2 = 0.79

Figure 3.24 Species - area relationship for aquatic macrophytes in lakes of various regions with a table with values of the regression analysis with different combinations.

3.4 Mutivariate analyses

3.4.1 Principal Components Analysis (PCA)

A correlation biplot of the principal components analysis (PCA) of the environmental variables is shown in Figure 3.25. The analysis is dominated by the first axis, which had an eigenvalue of λ_1=0.61 and accounted for 69% of the variance (of the first four axes). Eigenvalues for other axes are weaker: second λ_2=0.12; third λ_3=0.10; fourth λ_4=0.055. The first two principal components account for 82% of the variance, and they exhibit the main patterns of variation in the environmental data.

The environmental variables TN, DN, TP, DP, and temperature are positively correlated with axis 1. Altitude, substrate, chloride, maximum depth, Secchi value, and surface area are strongly negatively correlated with axis 1 (Figure 3.25).The variables NVSS, TSS, VSS, calcium, and conductivity are strongly and positively correlated with axis 2, while pH and Secchi depth are most strongly negatively correlated (Figure 3.25).

The first PCA axis contrasts the cold, oligotrophic, amictic/dimictic lakes of high altitude (HH and HM regions), which occur on the left of the diagram, with more eutrophic, mono/polymictic, warm, lower-altitude lakes (TE region; on the right-hand side) (Figure 3.25). Within the group of HH lakes, those having macrophytes present (solid circles) and without (empty circles) ordinate as a broad group. Axis 2 separates acidic, turbid HM lakes from those with circumneutral pH in the HH region and large clear lakes of MM regions.

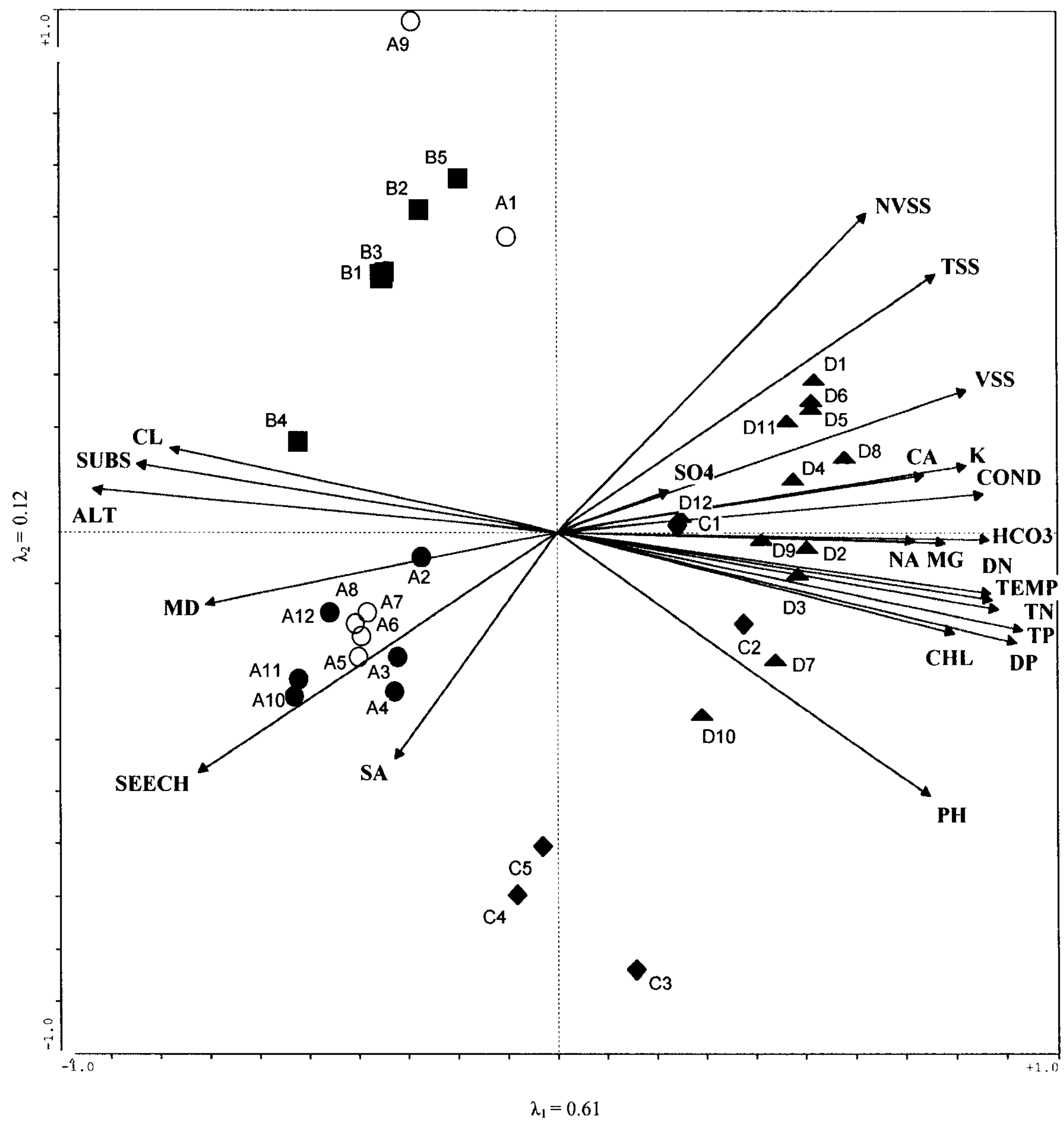


Figure 3.25 Principal component analysis (PCA) correlation biplot of environmental variables among the 34 lakes from all regions. Lakes represented by shaded circle, square, diamond and upright triangle are the lakes in HH, HM, MM and TE regions with macrophytes respectively. The open circles are the lakes without macrophytes in HH region.

The overall display of Figure 3.25 suggests a distinction between high-altitude, oligotrophic, neutral to acidic, coldwater lakes, from low-altitude, higher-conductivity, alkaline, meso-eutrophic, warmwater lakes. This mathematical expression implies a strong influence of altitude and catchment geology on the environmental variables under consideration in this study.

3.4.2 Two-way Indicator Species Analysis (TWINSPAN)

The first three levels of the TWINSPAN clustering of macrophyte species are summarized in Figure. 3.26. The first two major divisions segregate the HH and HM lakes from MM and TE lakes. The indicator species for this main division is *Juncus allioides*. The HM lakes are separated from HH on the basis of *Sphagnum* spp and without it. As an indicator option to *Sphagnum* spp. another species *Fimbristylis schoenoides* further separated the remaining HM lakes, and *Hydrilla verticillata* the MM and TE lakes. The third division segregates the HH lakes on the basis of *Ranunculus trichophyllus*, and the MM from the TE lakes with the indicators *Lemna perpusilla* and *Pistia stratiotes*. The TWINSPAN classification clearly separated the species based on the temperature gradients. The classification separates the cold tolerant arcto-tertiary floral elements of the HH and HM from widely distributed temperate and tropical species of MM and TE regions. Further, it separates the tropical species such as, *Lemna perpusilla* and *Pistia stratiotes* as the indicator species of TE lakes. Except to temperature, pH also showed importance in separating HM lakes with other lakes, with the presence *Sphagnum* species in the former lakes.

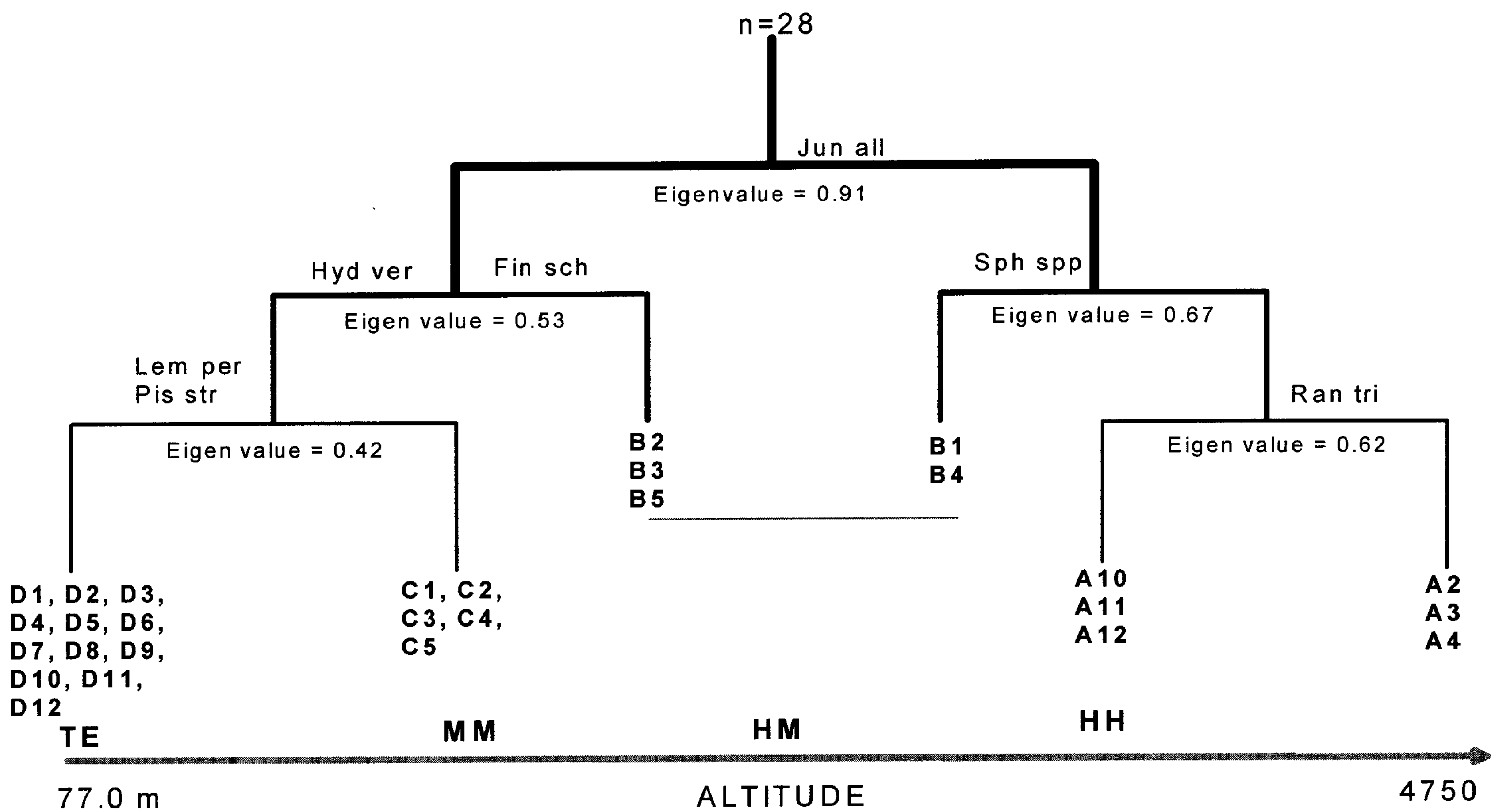


Figure 3.26 TWINSPAN classification of all lakes with macrophytes (n=28). The indicator species for each division are shown in decreasing order of significance.

3.4.3 Detrended Correspondence Analysis (DCA)

The first two axes of the DCA accounted for 26.4% of the total variation (eigenvalues λ_1=0.93 and λ_2=0.49, respectively, and gradient lengths of 7.64 and 3.26 standard deviation units) (Figure 3.27 & 3.28). The length of an environmental gradient >3-4 SD units implies that most taxa in the dataset have a strong unimodal environmental response, and suggests that CCA is an appropriate method for ordination (ter Braak and Šmilauer 1998).

When interpreting the percentage variance accounted for by an ordination, it is important to remember that the objective is not necessarily to achieve 100 %, because part of the variance is due to "noise" in the data (due to a large number of taxa and many zero values; ter Braak, 1994). Therefore, even an ordination that explains a relatively low percentage of the variance (in this case, 26.4%) may represent the data well (ter Braak, 1986). In general, the statistical validity and stability of the ordination is more important than the amount of variance explained (ter Braak, 1988; Pienitz *et al.*, 1995). Moreover, the ordination is more stable if the eigenvalue of the third axis (λ_3=0.191 in the DCA reported here) is smaller than that of the second axis (ter Braak, 1994).

The major purpose of my DCA analysis was to validate the unimodal environmental response, as a prerequisite for proceeding to a canonical correspondence analysis (CCA). As such, the ecological results of the DCA are not discussed here, because this is redundant with the results of the CCA.

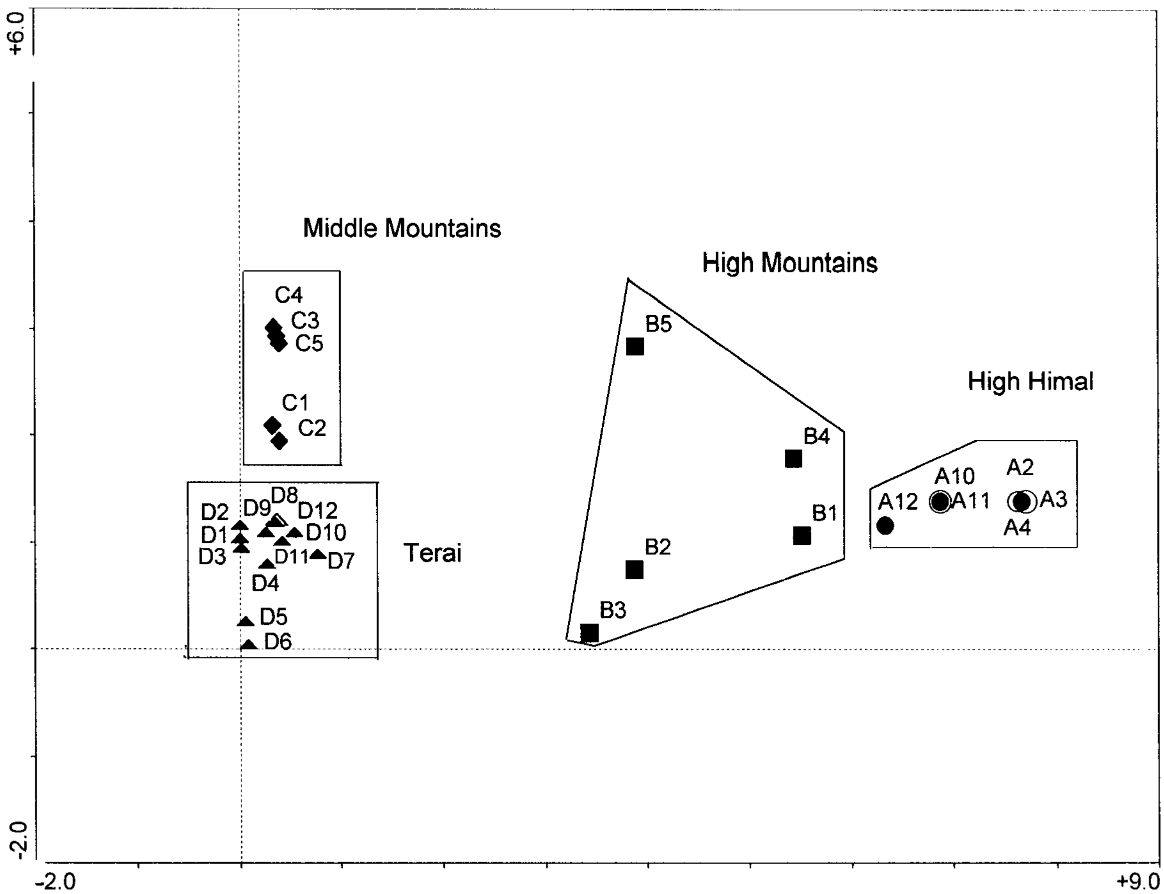


Figure 3.27 Axis 1 (horizontal; λ_1 = 0.93) and 2 (vertical; λ_2 = 0.49) of detrended correspondence analysis, DCA ordination segregating the lakes (based on species data set) on the altitudinal gradient. The lakes represented by shaded circles, squares, diamonds and upright triangles are the lakes in HH, HM, MM and TE regions with macrophytes respectively.

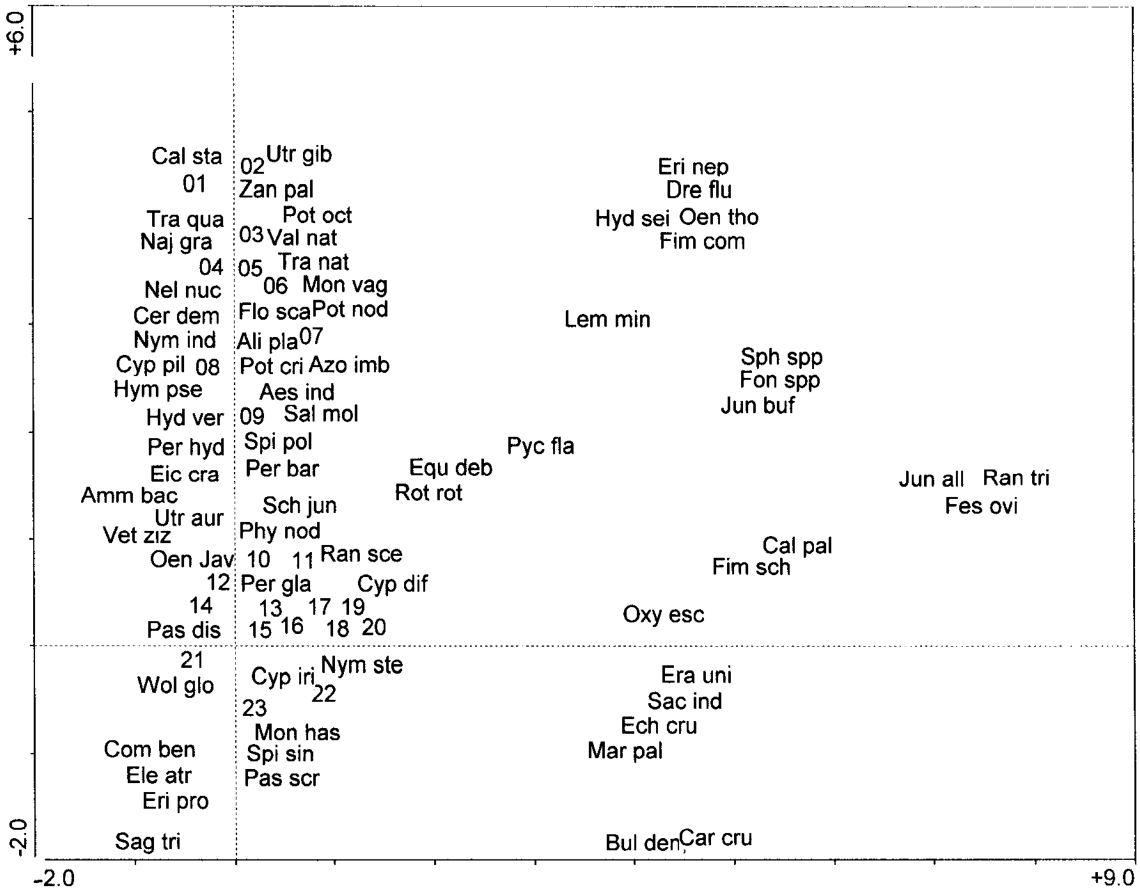


Figure 3.28 Axis 1 and 2 of DCA showing species distribution for the ordinated lakes in figure 3.27. Refer to appendix 4 for an explanation of the species symbols. Some data points were plotted slightly off- center to avoid overlap of symbols. Several species clusters are represented by numbers as below plotted at the location of their overlapping centroids:

01 = Bly aub, Lim ses, Pot pec; 02 = But lat, Cal par, Cyp alt, Cyp esc, Ele con, Ele dul, Naj min, Nit muc, Ric flu, Utr aus; 03 = Ory ruf, Per lap; 04 = Hip vul, Nas off; 05 = Cera tha, Eri cin, Pan rep; 06 = Iso ele, Lee hex; 07 = Alt ses, Hygr ari, Lud ads, Sch muc; 08 = Lem tri, Lob als, Ory sat, Pol ple, Ran rep; 09 = Mar cre; 10 = Fim dic, Pyc san; 11 = Pte vit; 12 = Cen asi, Fim squ, Pha kar, Sac spo; 13 = Alt phi, Cae axi, Com dif, Cyp com, Ecl pro, Hyd dub, Lin ant, Set pal; 14 = Cyp dig, Cyp rot; 15 = Cyp comp, Cyp exa, Cyp ten, Ipo car, Hyg sal; 16 = Cen min, Lud hys, Lud per, Sci kys, Ver aqu; 17 = Cer mur, Nym hyd, Typ ang; 18 = Ami axi, Cent coc, Cyp dis, Ech col, Eny flu, Fim mil, Isa glo, Jus qui, Lin ana, Lim chi, Lin pus, Lip chi, Mur nud, Rot ind, Sph zey; 19 = Aes asp, Hyg aur, Iso cor, Old cor, Old dif, Ott ali, Sac myo, Sag gua, Typ ele, Zeu str; 20 = Coi lac, Cya pur, Ech sta, Hel ind, Lin cil, Lin pro, Lud oct, Pan psi, Pas fla, Pas pun, Pyc pum, Sac int, Spi iab; 21 = Azo pin, Lem per; 22 = Ipo aqu, Kyl ber, Pis str; 23 = Fim aes, Hem com.

3.4.4.1 Canonical Correspondence Analysis (CCA)

The eigenvalues of the first two CCA-1 axes are $\lambda_1 = 0.82$ and $\lambda_2 = 0.41$, and the species–environment correlations for the same axes are high (0.96 and 0.87), indicating a strong relationship between the distribution and abundance of macrophyte species and the measured environmental variables. The first two axes captured 25% of the total variance of the macrophyte data, and 55% of the variance in the species-environment relationship. Monte Carlo permutation tests (500 unrestricted permutations) of the first two axes indicate that both are statistically significant (both $p < 0.01$). Forward-selection and unrestricted Monte Carlo permutation tests indicate that six of the 23 environmental variables made statistically significant contributions to explaining variance in the data of macrophyte species. The most significant of these contributions was surface water temperature (which captured 8.1% of the total variance explained by the initial 23 environmental variables), followed by substrate (8.0%), altitude (5.8%), transparency (5.5%), conductivity (4.6%) and pH (4.5%).

In total, this subset of significant environmental variables extracted 24.4% of the total variance in the species data. The results of the CCA with only these six forward-selected and significant variables are given in Table 3.5 and are illustrated in Figure 3.29 and 3.30 as macrophyte-environmental biplots. On the variable and lakes biplot (Figure 3.29), the length of the environmental vectors indicates their relative importance in explaining variation in the macrophyte data, and their orientation indicates their correlation with the ordination axis. By comparing the arrow lengths, one can examine the relative importance of the measured lakewater variables.

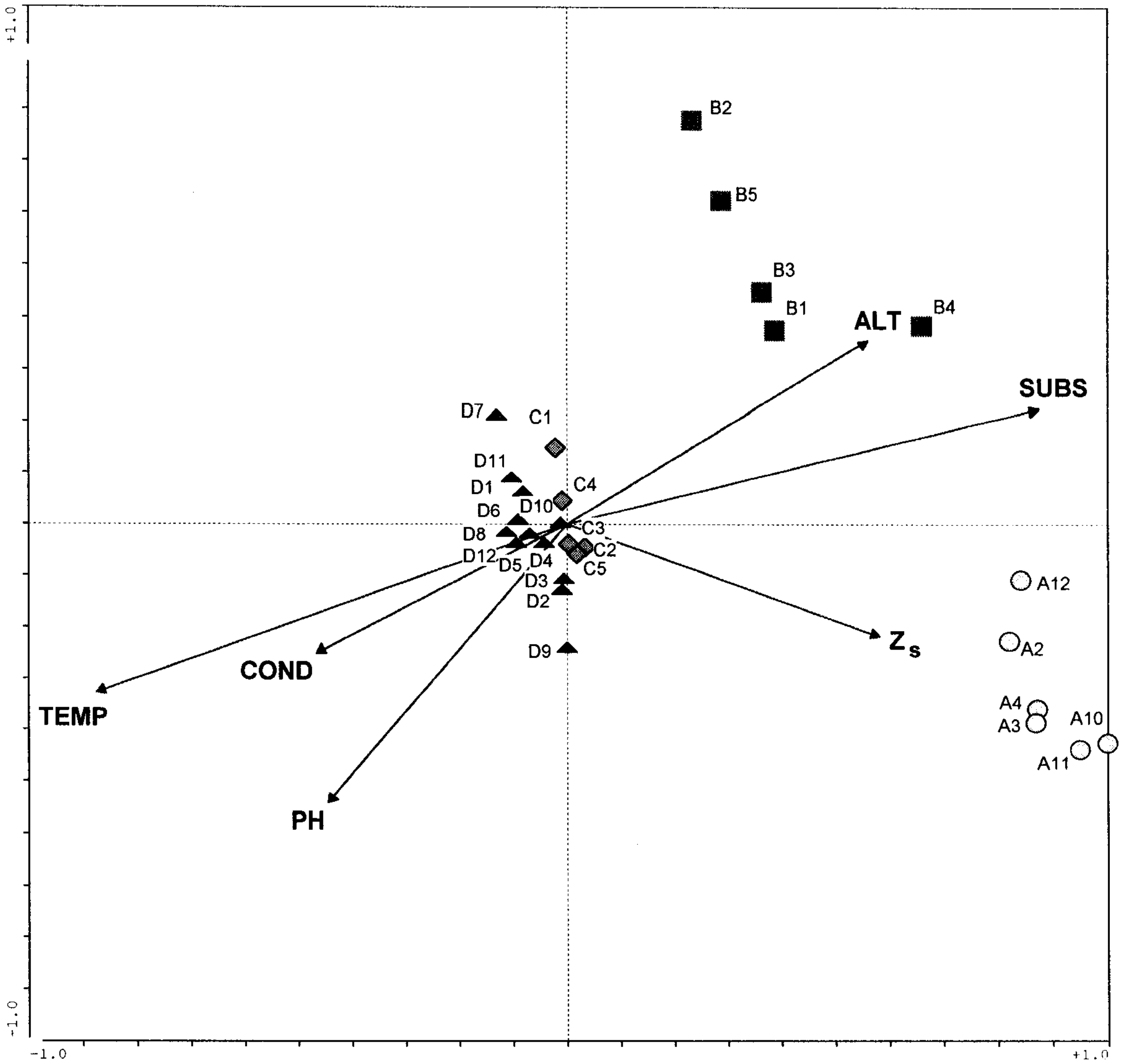


Figure 3.29 Axis 1 (horizontal; λ_1 = 0.82) and 2 (vertical; λ_2 = 0.41) of canonical correspondence analysis (CCA-1) ordination diagram showing the lakes distribution in relation to the six forward selected environmental variables. The filled circle, square, diamond and upright triangle represent the lakes in HH, HM, MM and TE regions respectively.

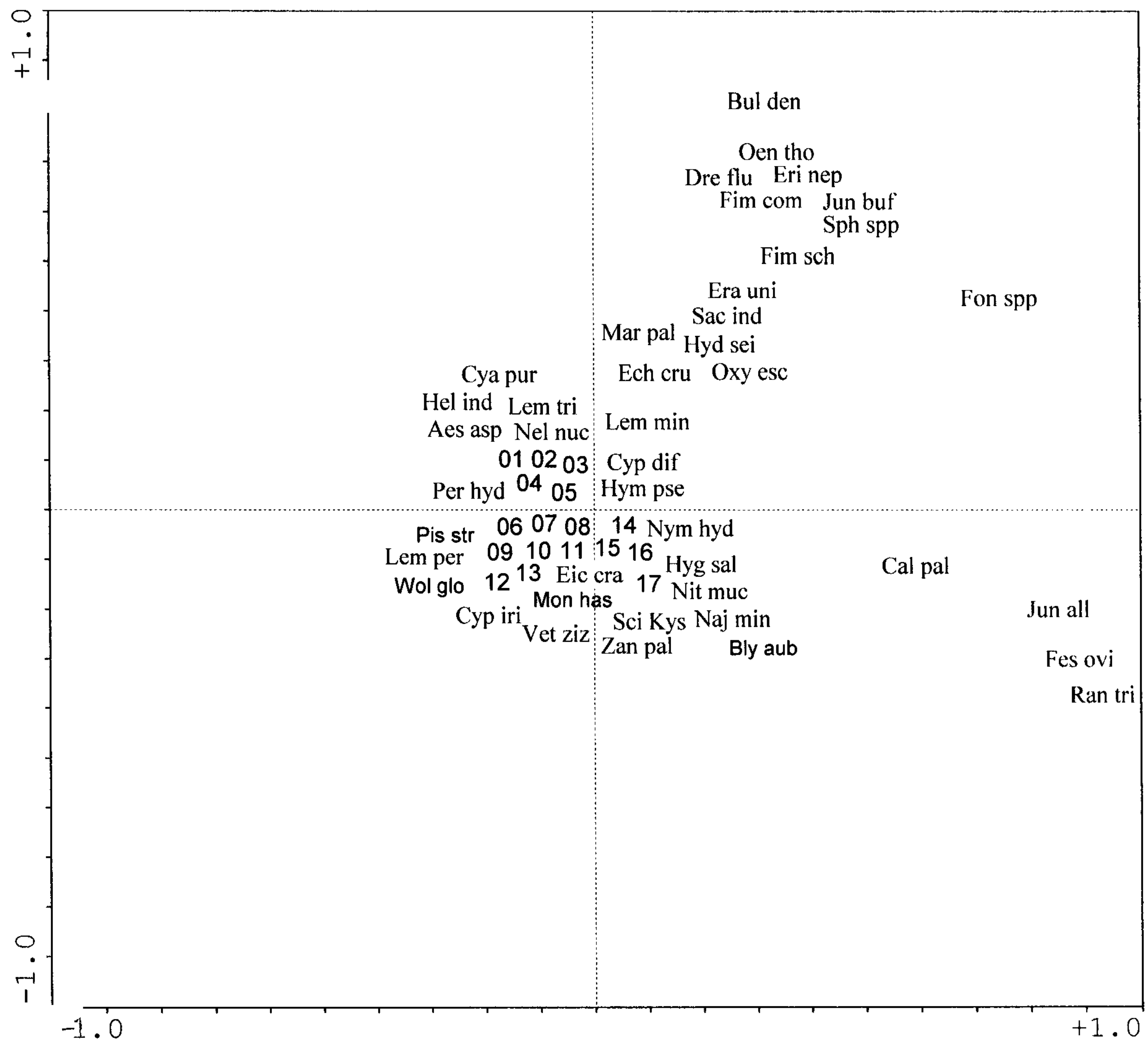


Figure 3.30 CCA-1 ordination diagram showing the species distribution to relate with five forward selected environmental variables in figure 3.29. Refer to appendix 4 for an explanation of the species symbols. Some data points were plotted slightly off-center to avoid overlap of symbols. Several species clusters are represented by numbers plotted at the location of their overlapping centroids as follow:

01 = Aes asp, Cya pur, Cyp pil, Ipo aqu, Lob als, Lud oct, Nym ste, Pas pun, Pol ple, Pyc fla, Sac myo; 02 = Nel nuc, Ory sat, Pan psi, Ran rep, Spi iab, Typ ele; 03 = Cen min, Coi lac, Ech col, Hip vul, Lin cil, Nas off, Naj gra, Old dif, Pot oct, Pot pec, Tra nat, Val nat; 04 = Equ deb, Ech sta, Fim mil, Hel ind, Hygr ari, Iso cor, Lin pro, Mur nud, Old cor, Pas fla, Pyc pum, Rot rot, Sac int, Zeu str; 05 = Aes ind, Azo imb, Cyp rot, Hyg aur, Hyd dub, Lud ads, Nym ind, Per lap, Sal mol, Sch muc,; 06 = Ali pla, Cer dem, Pas scr, Ran sce, Sag tri; 07 = Alt phi, Cent coc, Cyp dis, Fim aes, Fim sqa, Ipo car, Kyl ber, Lin ant, Lip chi, Ory ruf, Per hyd, Pyc san, Sag gua, Spi sin, Sph zey, Utr aur; 08 = Alt ses, Ami axi, Eny flu, Eri cin, Fim dic, Hyd ver, Iso glo, Lee hex, Jus qui, Lim chi, Lin pus, Lin ana, Ott ali, Pot cri, Rot ind,; 09 = Com ben, Cyp dig, Hem com, Mon Vag, Pas dis, Phy nod, Sch jun; 10 = Amm bac, Cae axi, Com dif, Cyp com, Cyp iri, Sac spo; 11 = Cen asi, Ecl pro, Ele atr, Eri pro, Lem per, Mar cre, Oen jav; 12 = But lat, Cyp alt, Ele con, Flo sca, Per bar, Set pal, Spi pol, Utr gib; 13 = Azo pin, Cal par, Cera tha, Cyp esc, Eic cra, Ele dul, Pan rep. Per gla, Pha kar, Pte vit, Tra qua, Utr aus; 14 = Cer mur, Iso ele, Nym hyd, Sci kys, Typ ang; 15 = Lud hys, Lud per, Pot nod, Ver aqu; 16 = Cyp comp, Cyp exa, Cyp ten, Hyg sal; 17 = Naj min, Naj muc, Ric flu, Zan pal.

Table 3.5 Summary statistics for the first four axes of the CCA-1, with 28 active sites from the HH, HM, MM, and TE regions, 177 macrophytes species, and six forward-selected environmental variables.

	Axis 1	Axis 2	Axis 3	Axis 4	Total
Eigenvalue	0.82	0.41	0.38	0.22	
Species–environment correlations	0.96	0.87	0.98	0.91	
Cumulative % variance of species data explained	16.3	24.4	31.9	36.7	
Cumulative % variance of species-environment relation	36.5	54.7	71.4	82.2	
Sum of unconstrained eigenvalues					5.07
Sum of all canonical eigenvalues					2.26
Inter-set correlation of significant environmental variables with axes					
(1) Altitude (Alt.)	0.54	0.31	0.64	-0.31	
(2) Substratum quality (Subs.)	0.84	0.19	-0.17	-0.18	
(3) Conductivity (Cond.)	-0.45	- 0.22	-0.44	-0.42	
(4) pH	-0.43	-0.47	0.14	0.27	
(5) Secchi transparency (Z_s)	0.56	-0.19	0.53	0.26	
(6) Surface water temperature(Temp.)	-0.84	-0.28	-0.19	0.24	

Each taxon on the biplot (Figure 3.30) approximates its weighted average optimum relative to other taxa. However, because we have many species ordinated closely together for lower-altitude lakes (i.e. in MM and TE), the taxa are tightly arranged as a cloud. Therefore, this initial analysis is most useful in separating higher-altitude (HH, HM) lakes from lower-altitude (MM and TE) ones.

The analysis shows that taxa occurring in the HH region are most significantly related to high Secchi transparency and coarse substrate and are positioned on the right side of axis1 (Figure 3.30). In contrast, commonly encountered macrophytes of the MM and TE regions with warmer climate, higher pH, and higher conductivity are located as a tight cluster on the left side of the diagram.

The eigenvalues of the first two CCA axes, constrained to the six most important explanatory variables, are 0.82 and 0.41, and they account for 24.4 % of the total variance of the macrophyte data (Table 3.5). The species-environment correlations of CCA axis 1 (0.96) and axis 2 (0.87) are high, and these two axes capture 54.7 % of the total variance in the species-environment relationship. The eigenvalues for the macrophytes data are only slightly lower than those of a CCA featuring all of the original 23 environmental variables, suggesting that the six forward-selected variables provide a good representation of the overall ecological patterns within the entire dataset. Moreover, the constrained analysis (six variables) yielded higher eigenvalues than a CCA using all 23 environmental variables, also suggesting that the forward-selected variables provide a good representation of the overall ecological patterns.

The first two axes are both significant (p<0.002), as indicated by Monte Carlo permutation tests. Axis 1 is most strongly related to surface water temperature and substrate quality (inter-set correlations are -0.84 and 0.84, respectively), while transparency and altitude have moderate influences (inter-set correlations are 0.56 and 0.54, respectively). The first axis separates alpine and sub-alpine lakes of HH and HM (on the right side of Figure 3.29) from subtropical and tropical lakes in MM and TE regions (on the left).

Axis 2 is most strongly related to pH (inter-set correlation is -0.47), and it helps to segregate acidic lakes of HM region from other lakes. The HM lakes are relatively cold, acidic, and support such cold-tolerant acidophilous species as *Sphagnum* spp, *Fontinalis* spp, *Drepanocladus fluitans*, and generalist grasses and sedges of that climatic belt, such as *Eriocaulon napalense, Fimbristylis complanata, Fimbristylis schoenoides,* and *Juncus bufonius*. In comparison, the HH lakes are circumneutral and cold and have submerged species, such as *Ranunculus trichophyllus* and *Callitriche palustris*, along with high-altitude wetland species, such as *Festuca ovina* and *Juncus allioides* in their shallow littoral zone.

The warmer lakes in MM and TE are separated by an altitude – temperature gradient of axis 1. As the first CCA ordination covered the entire range of climatic zones along a large altitudinal gradient, the many species in these lowland regions clustered tightly together as a data cloud. Therefore, a subsequent ordination was performed using data only for lakes in MM and TE regions, in order to examine the influence of environmental variables in these lower-altitude climatic regions.

3.4.4.2 CCA-2 Ordination of Lakes in the MM and TE Regions

A second ordination was carried out on lakes in the MM and TE regions. All seventeen lakes were incorporated, but redundant environmental factors were removed to bring the variable number to fifteen.

The eigenvalues of the first two CCA-2 axes are $\lambda_1 = 0.39$ and $\lambda_2 = 0.25$, respectively, and the species–environment correlations for the same axes are high (0.98 and 0.97), indicating a strong relationship between the distribution and abundance of macrophyte species and the environmental variables. The first two axes capture 28.3% of the total variance of the macrophyte data, and 55.4% of the variance in the species-environment relationship. A test of significance using Monte Carlo permutation tests (500 unrestricted permutations) showed that the first axis is significant at $p = 0.03$, and the full analysis of four axes at $p = 0.002$. Forward-selection and unrestricted Monte Carlo permutation tests indicate that five of the 15 environmental variables made statistically significant contributions to explaining variance in the macrophyte data. The most significant contribution was surface area (which captured 8.8% of the total variance explained by the 15 environmental variables, followed by TSS (8.3%), temperature (8.0%), bicarbonate (7.5%) and dissolved phosphorus (5.5 %).

In total, the subset of five forward-selected environmental variables extracted 76.0% of the total variance in the species data. The results of the CCA-2 with only these five forward-selected and significant variables are given in Table. 3.6 and are illustrated in Figure 3.31 and 3.32 as macrophyte-environmental biplots. Each taxon on the biplot (Figure 3.32) approximates its weighted average optimum relative to other taxa. However, because many species are ordinated closely together, the taxa are tightly arranged as a data cloud, which have been separated for convenience in the biplot.

Commonly encountered macrophytes of the MM and TE regions are located as a tight cluster on the left side of the diagram in the previous ordination (Figure 3.32). The analysis shows that taxa that occur in the MM have a strong resemblance to those in the TE region. MM taxa and lakes are, however, separated on the basis of multivariate responses to cooler temperature, low bicarbonate, low phosphorus, and low total suspended solids, against the relatively smaller surface areas of lakes in the TE region.

Table 3.6 Summary statistics for the first four axes of the CCA-2, with 17 sites from the MM and TE regions, 15 environmental variables, 165 macrophyte species (helophytes, hyperhydates and euhydrophytes), and five forward-selected environmental variables.

	Axis 1	Axis 2	Axis 3	Axis 4	total
Eigenvalue	0.39	0.25	0.22	0.20	
Species–environment correlations	0.98	0.97	0.90	0.94	
Cumulative % variance of species data explained	17.0	28.3	38.1	46.9	
Cumulative % variance of species-environment relation	33.3	55.4	74.6	92.0	
Sum of unconstrained eigenvalues					2.25
Sum of all canonical eigenvalues					1.15
Inter-set correlation of significant environmental variables with axes					
(1) Surface area (SA)	0.70	-0.61	- 0.10	-0.24	
(2) Surface water temperature (TEMP)	-0.57	-0.72	0.15	0.28	
(3) Bicarbonate (HCO3)	-0.60	0.17	0.55	-0.39	
(4) total suspended solids (TSS)	-0.71	-0.01	-0.59	0.15	
(5) dissolved phosphorus (DP)	-0.51	0.16	-0.18	-0.35	

The eigenvalues of the first two CCA-2 axes, constrained to the five most important explanatory variables, are 0.39 and 0.25, and account for 28.3% of the total variance of the macrophyte data. The species-environment correlations of CCA-2 axis 1 (0.98) and axis 2 (0.97) are high, and these two axes capture 55.4% of the total variance in the species-environment relationship. The eigenvalues for the macrophyte data are only slightly lower than those of a CCA featuring all of the original 15 environmental variables, suggesting that the five forward-selected variables provide a good representation of the overall ecological patterns within the data. In contrast, the

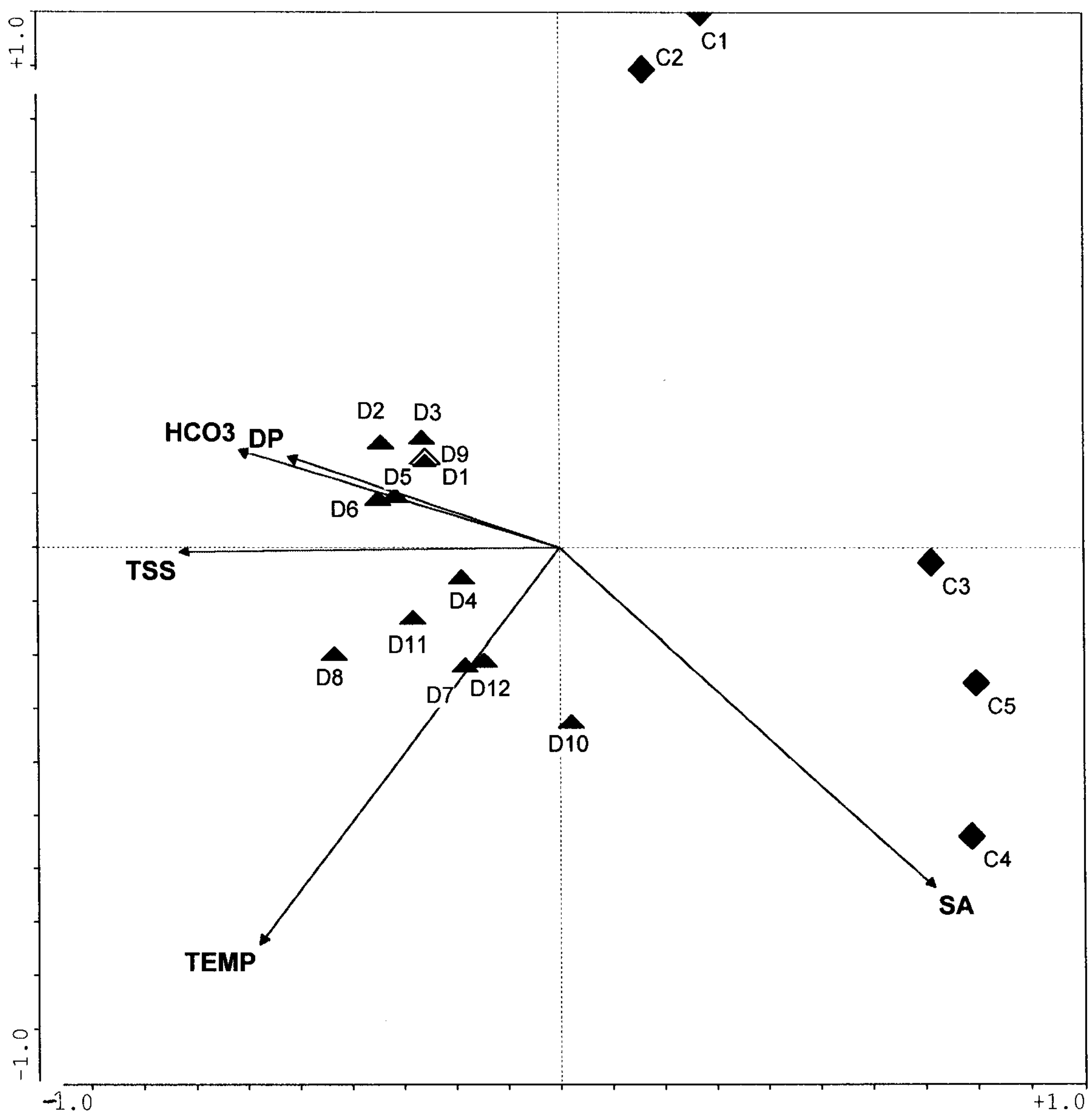


Figure 3.31 Axis 1 (horizontal; λ_1 = 0.39) and 2 (vertical; λ_2 = 0.25) of canonical correspondence analysis (CCA-2) ordination diagram showing the lakes distribution in relation to five forward selected environmental variables to relate with species distribution in lakes of MM and TE regions.

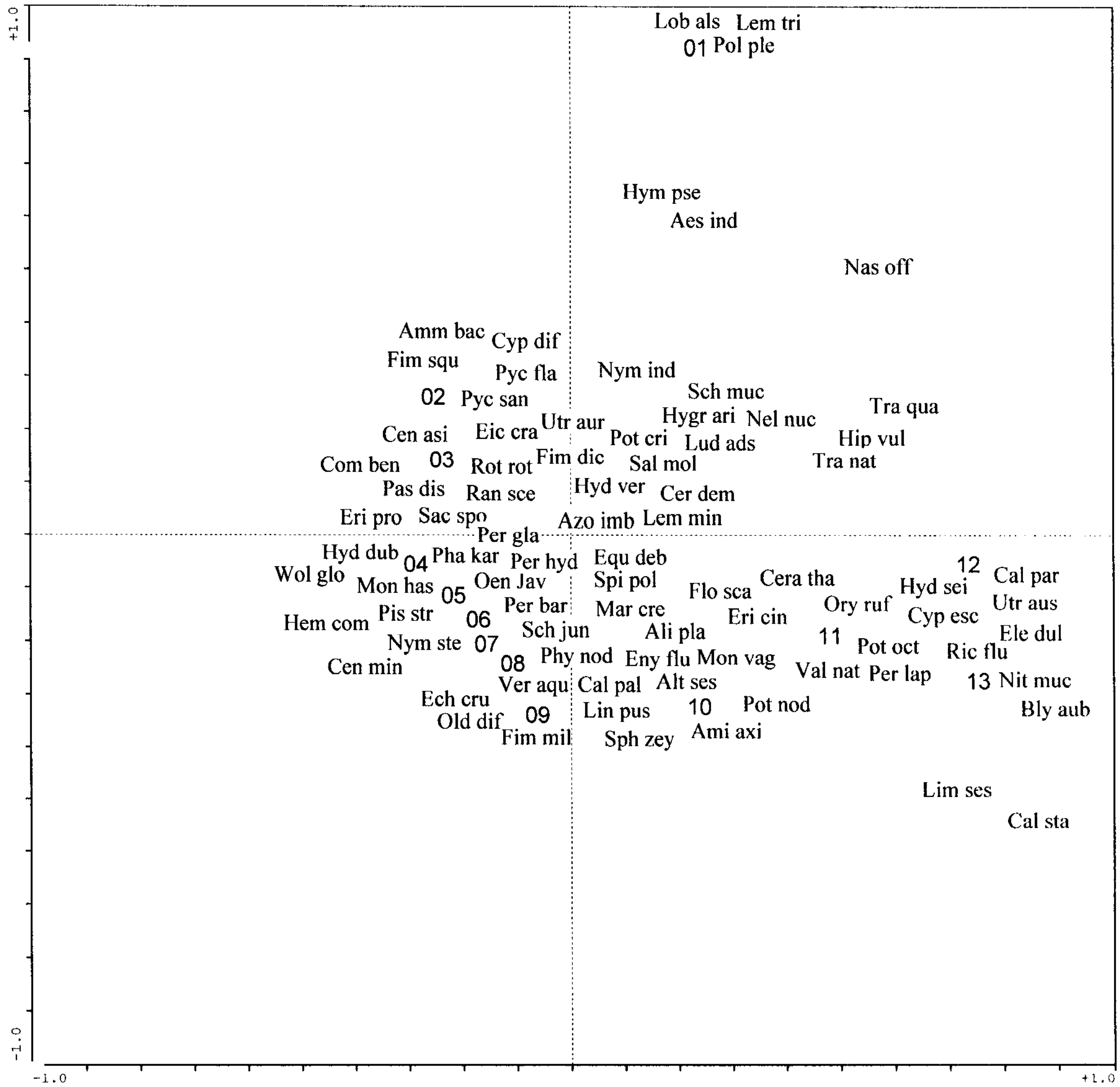


Figure 3.32 CCA-2 ordination diagram showing the species distribution to relate with five forward selected environmental variables in figure 3.31. Refer to appendix 4 for an explanation of the species symbols. Several species clusters are represented by numbers plotted at the location of their overlapping centroids as follow:

01 = Cyp pil, Ory sat, Ran rep; 02 = Cyp rot, Sag tri, Vet ziz; 03 = Azo pin, Ele atr, Pte vit; 04 = Lem per, Pas scr, Spi sin; 05 = Alt phi, Cer mur, Com dif, Cyp comp, Cyp dig, Ecl pro, Era uni, Fim aes, Lud hys, Lud per, Set sal; 06 = Cae axi, Cyp com, Cyp exa, Cyp iri, Cyp ten, Hyg sal, Ipo aqu, Ipo car, Kyl ber, Lin ant, Mar pal, Nym hyd, Sci kys; 07 = Aes asp, Cya pur, Hel ind, Lud oct, Oxy esc, Pas fla, Pas pun, Pyc pum, Spi iab; 08 = Coi lac, Ech sta, Fim sch, Iso cor, Lin cil, Lin pro, Pan psi, Sac int, Sac myo, Typ ang, Typ ele, Zeu str; 09 = Ech col, Hyg aur, Mur nud, Old cor, Sac ind; 10 = Cent coc, Cyp dis, Isa glo, Jus qui, Lim chi, Lin ana, Lip chi, Ott ali, Rot ind, Sag gua; 11 = Iso ele, Lee hex, Naj gra, Pan rep; 12 = But lat, Cyp alt, Ele con, Utr gib; 13=Naj min, Pot pec, Zan pal.

constrained analysis (five environmental variables) yielded higher eigenvalues than a CCA using all 15 variables, also suggesting that the forward-selected variables provide a good representation of the overall ecological pattern.

The first two axes are both significant ($p<0.01$), as indicated by Monte Carlo permutation tests. Axis 1 is most strongly related to total suspended solids, surface area, bicarbonate, and dissolved phosphorus (inter-set correlations are -0.71, 0.70, –0.60 and -0.51, respectively). The first axis separates lakes in the MM region with relatively large surface area, low TSS, and high bicarbonate from the shallow, turbid lakes in the TE region. The large MM lakes are meso-eutrophic and harbor species intolerant of hypereutrophic conditions, such as *Callitriche stagnalis, Zannichellia palustris, Nitella mucronata, Blyxa aubertii, Potamogeton pectinatus,* and *Najas graminea.* These species are absent in small eutrophic MM lakes in the Kathmandu valley, as indicated by their position along the vector for dissolved phosphorus. Many of the widespread species, *viz. Hydrilla verticillata, Potamogeton crispus, Ceratophyllum demersum, Lemna minor, Persicaria barbata,* and *Persicaria hydropiper*, which are able to tolerate increasing levels of eutrophication, occupy a central position in the diagram (Figure 3.32). The majority of species on the left side of the ordination diagram are helophytes and hyperhydates, which require higher amounts of nutrients.

Axis 2 is most strongly related to surface temperature (inter-set correlation -0.72). Within the MM region, axis 2 segregates two lakes in the Kathmandu valley from three largelakes in the Pokhara valley. Some species show a strong affinity to warmer water temperatures on axis 2, particularly *Cyperus iria, Ipomoea aquatica, Ipomoea carnea, Lemna perpusilla,Pistia stratiotes, Sacciolepis myosuroides,* and *Typha elephantina.*

3.4.4.3 CCA-3 Ordination of True Hydrophytes (submerged, floating leaved and free floating macrophytes) **in the MM and TE Regions**

A third ordination, CCA-3, used MM and TE data only for submerged, floating-leaved, and free-floating macrophytes (i.e., for "true" hydrophytes, with helophytes and hyperhydate species eliminated from the dataset).

The eigenvalues of the first two CCA-3 axes were $\lambda_1 = 0.34$ and $\lambda_2 = 0.17$, respectively, and the species–environment correlations for the same axes are high (0.96 and 0.89), indicating a strong relationship between the distribution and abundance of macrophyte species and the measured environmental variables. The first two axes captured 31% of the total variance of the macrophyte data, and 61% of the variance in the species-environment relationship. Monte Carlo permutation tests (500 unrestricted permutations) of the first two axes indicate that both are statistically significant (both $p < 0.01$). Forward-selection and unrestricted Monte Carlo permutation tests indicate that five of the 15 environmental variables made statistically significant contributions to explaining variance in the data for macrophyte species.

The most significant of these contributions was total suspended solids (which captured 7% of the total variance explained by the initial 15 environmental variables), followed by bicarbonate (6.6%), surface area (6.4%) dissolved phosphorus (5.0%) surface water temperature (3.8%).

Table 3.7 Summary statistics for the first four axes of the CCA-3, with 17 sites from the MM and TE regions, 15 environmental variables, 40 macrophytes species (submerged, floating-leaved, and free-floating), and five forward-selected environmental variables.

	Axis 1	Axis 2	Axis 3	Axis 4	total
Eigenvalue	0.34	0.17	0.14	0.11	
Species–environment correlations	0.96	0.89	0.89	0.93	
Cumulative % variance of species data explained	20.8	31.0	39.6	46.3	
Cumulative % variance of species-environment relation	40.8	60.9	78.0	91.1	
Sum of unconstrained eigenvalues					1.64
Sum of all canonical eigenvalues					0.83
Inter-set correlation of significant environmental variables with axes					
(1) Surface area (SA)	0.73	-0.09	-0.50	-0.06	
(2) Surface water temperature (TEMP)	-0.46	0.26	-0.34	0.25	
(3) Bicarbonate (HCO_3)	-0.50	-0.56	0.29	-0.42	
(4) total suspended solids (TSS)	-0.85	0.30	-0.24	0.06	
(5) dissolved phosphorus (DP)	-0.57	0.20	-0.24	0.10	

In total, this subset of five significant environmental variables extracted 76.0% of the total variance in the species data. The results of the CCA with only these five forward-selected and significant variables are given in Table 3.7 and are illustrated in Figure 3.33 as macrophyte-environmental biplots.

Each taxon on the biplot (Figure 3.33) approximates its weighted average optimum relative to other taxa. The TE lakes are remarkably segregated from those of the MM region in terms of vertical gradient; this is an improved result in comparison with the full dataset, which also includes emergent and hyperhydate species. MM lakes are recognized by having relatively low total suspended solids, low bicarbonate, low phosphorus, and low temperature, in comparison to lakes in the TE region.

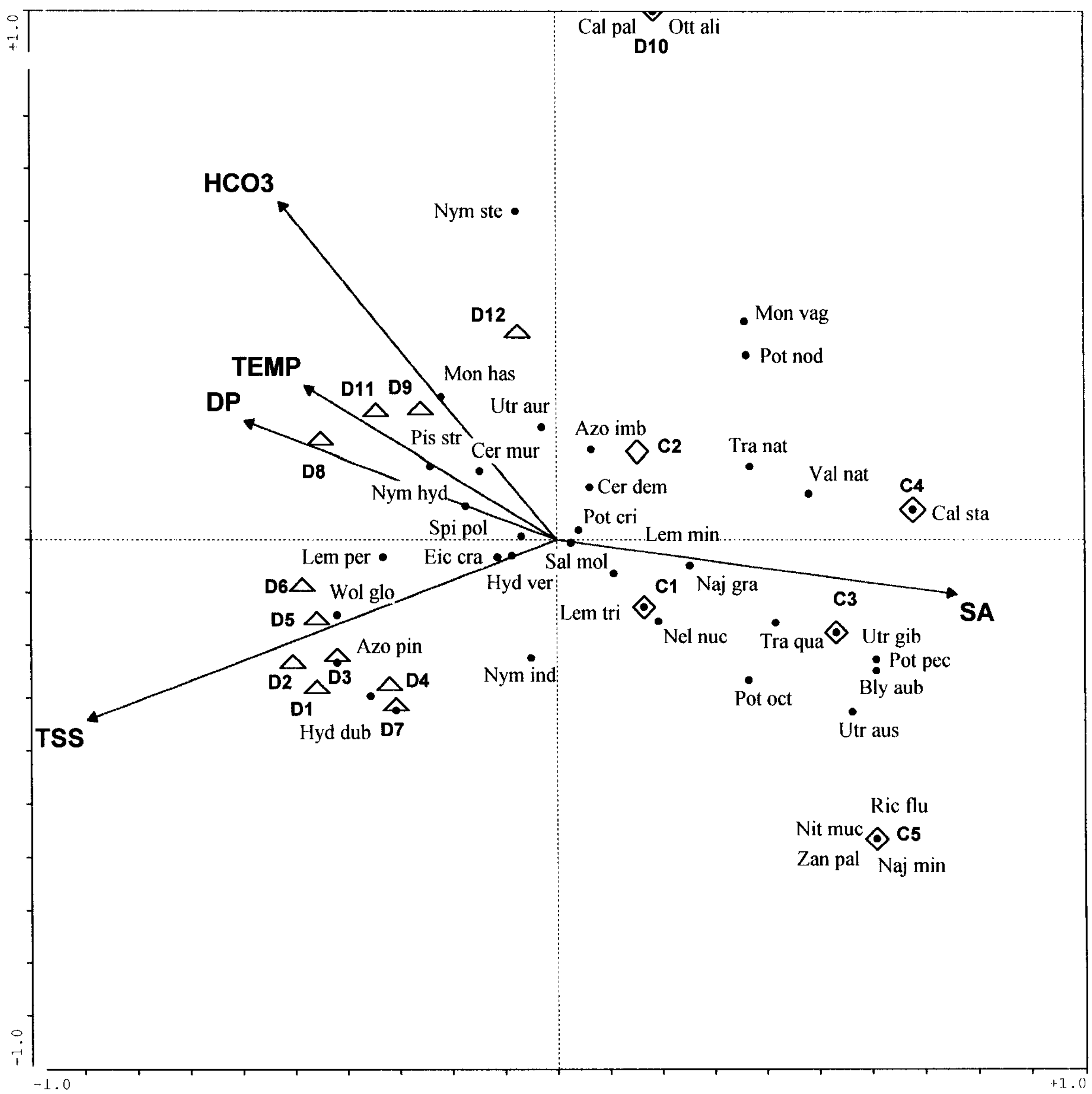


Figure 3.33 Axis 1 (horizontal; $\lambda_1 = 0.34$) and 2 (horizontal; $\lambda_2 = 0.17$) of canonical correspondence analysis (CCA-3) ordination diagram showing the 'true' hydrophytes (submerged, floating leaved and free floating macrophyte species) distribution in relation to the sites and five selected environmental variables from lakes in MM and TE regions.

The eigenvalues of the first two CCA-3 axes, constrained to five explanatory variables, are 0.34 and 0.17, and account for 31% of the total variance of the macrophyte data. The species-environment correlations of CCA-3 axis 1 (0.96) and axis 2 (0.89) are high, and these two axes capture 61% of the total variance in the species-environment relationship. The eigenvalues for the macrophyte data are only slightly lower than those of a CCA including all 15 environmental variables, suggesting that the five forward-selected variables provide a good representation of the overall ecological pattern within the dataset. In contrast, the constrained analysis (five environmental variables) yielded higher eigenvalues than a CCA using all 15 variables, also suggesting that the forward-selected variables provide a good representation of the overall ecological pattern.

The first two axes of CCA-3 are both significant (p<0.01), as indicated by Monte Carlo permutation tests. Axis 1 is most strongly related to total suspended solids, surface area, dissolved phosphorus, and temperature (inter-set correlations are –0.85, 0.73, –0.57, and –0.46, respectively). The first axis separates MM lakes from the TE lakes, similar to the CCA-2 analysis.

Axis 2 is most strongly related to bicarbonate (inter-set correlation is 0.56). The TE lakes are relatively warmer with high total suspended solids and they support many free-floating and fewer floating-leaved species. Relatively nutrient-rich sites were dominated by *Pistia stratiotes, Lemna perpusilla,* and *Nymphoides hydrophylla*, while moderately nutrient-rich sites with high TSS were dominated by *Azolla pinnata, Wolffia globosa, Hydrocharis dubia,* and *Nymphoides indica.* The species at the center of the ordination diagram (Figure 3.33), such as *Eichhornia crassipes, Spirodela polyrhiza, Hydrilla verticillata, Salvinia molesta, Ceratophyllum demersum, Potamogeton crispus* and *Lemna minor*, were widely distributed in both regions. Their abundance depends on the TSS and nutrient content of water bodies, particularly for *Eichhornia crassipes*. The number of submerged species is less and dominated by low light-requiring species such as *Hydrilla verticillata* and *Ceratophyllum muricatum.* Many submerged species that can tolerate deep, clear water, such as *Vallisneria natans*, *Potamogeton pectinatus*, and *Zannichellia palustris*, were absent in TE lakes, possibly because of the high turbidity of the water.

4. DISCUSSION

4.1 Physical limnology

The properties of aquatic habitats in mountainous environments are influenced by regional and local climate, geology, disturbance regime, and land use, including the variations of these factors with altitude. These factors affect critical habitat qualities related to hydrology, morphometry, water chemistry, and benthic substrate, which in turn influence biological diversity and community structure.

In Nepal, most lakes occur in two altitudinal regions: the High Himal (HH) of the glacial mountains and the low-altitude Terai (TE) with ox-bow lakes. There are fewer lakes in the High Mountain (HM) and Middle Mountain (MM) regions, although some of those in the MM are quite large (Bhandari, 1998).

Cole (1979) reported a strong and positive statistical relationship among surface area, mean depth, and volume in an analysis of morphometric data from a world-wide sample of 500 lakes. In this study, however, the relationship between log mean depth and surface area was not strong (r^2= 0.35). In particular, study lakes in the HH region have a higher ratio of depth : area than similar-sized lakes in the HM, MM, and TE regions. This is because the alpine HH lakes are evolved from the deep trenches formed by lateral and end moraines on a glacial tongue.

The largest lake in Nepal, Lake Rara (area 980 ha, altitude 3,000 m), is in the HM region of the far western part of the country, while the deepest lake is Tilicho (95 m) in the HH region (Okino and Satoh, 1986; Aizaki *et al.,* 1987). The deepest lakes samples in the present study were also in the HH region: Bhairav Kund (Z_{max}= 60.0 m), Tso Rolpa (56.5 m), and Dudh Pokhari (45.3 m). Löffler (1969) suggested that 30 m is the maximum depth of lakes in the Mt. Everest region of the HH, but 25% of my lakes in this region were deeper than this, including Lakes Tilicho (95 m), Imja (47 m), Thaulagi (42 m), and Lower Barun (46 m). Hutchinson (1937) also reported deep HH lakes in the Himalayas: Lake Mansarovar (82 m) and Moriri Tso (76 m).

Some of the lakes had remarkable seasonal variations in depth. For instance, Lake Tsola Tso (at 4,512 m in the HH), a natural impoundment in moraine, showed an 8-m difference in water level between the pre-monsoon and post-monsoon seasons. This is similar to the observation of Tartari *et al.* (1998 b), although Löffler (1969) reported an amplitude of 16 m for this lake, suggesting great inter-annual variation (Löffler's observation was the maximum possible, because it corresponds to the height of the moraine barrier forming the lake). The difference between recent observations of Tsola Tso and those of Löffler may be due to differences in the monsoon, or to a reduction of depth by the mass deposition of glacial debris from the surrounding moraine. De Terra and Hutchinson (1934) also reported large annual variations of water levels in HH glacial lakes of nearby Tibet.

The HM lakes in this study are mostly perched waterbodies (i.e., headwater lakes with no obvious surface outflow), and their depth depends on site factors associated with location.

Salpa Pokhari is the deepest lake (15.8 m) studied in the HM region; the others have a maximum depth less than 7 m. The large size of the MM study lakes is due to their location in broad, relatively flat valleys. All of the Terai lakes are ox-bow and shallow (<4 m), with a relatively large surface area. These low-altitude lakes are subject to relatively high rates of siltation associated with soil erosion caused with human activities in their catchments (Ghimire and Uprety, 1990).

Seasonal variations of water temperature occurred in all study lakes, but were most extreme at high altitude. Water temperature has both direct and indirect influences on the physico-chemical and biological characteristics of lakes (Welch, 1952; Hutchinson, 1957). In the Himalayas, seasonal differences of both air and surface-water temperature are caused by variations of a subtropical high-pressure belt, and show marked effects of altitude (Tartari *et al.,* 1998 a). In the HH region, seasonal weather variations depend on a strong thermal anticyclone in the upper troposphere, known as the "Tibetan High," during the monsoon season, and on the strength and location of the sub-tropical jet stream at other times. Within these regional Himalayan influences, particular valleys have distinct climatic conditions, depending on elevation, area, orientation, and presence of a glacier (Yasunari, 1976). These local effects are superimposed on the regional, altitude-related influences on climatic factors. Beyond the local variability, however, there is a strong relationship of altitude and air temperature in the Nepalese Himalayas, with a lapse rate of -0.46 °C/100m (Dobremez, 1976), somewhat smaller than in the Alps of Europe (-0.55 °C/100m; Landolt, 1992). In the present study, the lapse rate of annual-average water temperature of the study lakes was -0.40 °C/100m.

An unusual observation in HH lakes was the minimal changes in water temperature of surface water during the 5-7-month ice-free season. Chikita *et al.* (2000) made a similar observation, and found that it extended to a depth of 10 m. This observation is likely due to these alpine lakes being relatively well-mixed by wind. In addition, solar irradiance is relatively constant during the year in subtropical latitudes (*ca.* 12.4 MJ m^{-2}; Tartari *et al.* 1998 b). Additional factors influencing lakewater temperature include proximity to a glacier, the presence of permafrost, and effects of aspect and watershed morphometry on insolation and wind velocity (Chikita *et al.*, 1999, 2000).

All the HH study lakes displayed dimictic or cold-polymictic variations in their thermal stratification. High-altitude lakes at equatorial latitudes may display amixis, if permanently ice-covered, not affected by stirring by wind, and occurring higher than about 6,000 (Cole, 1994). In the Himalayas, monomictic behavior is observed in deep, cold, high-altitude lakes, although dimictic stratification may occur in HH lakes with moderate depth (Löffler, 1969; Okino and Satoh, 1986; Aizaki *et al.*, 1987). Summer-mixed, dimictic lakes of the type in this study of the HH region are also known as cold thereimictic lakes (Bayly and Williams, 1973).

Lakes Tau Daha, Rupa, and Nag Daha (all in the subtropical MM region) are polymictic and have a similar depth of about 6 m (Hickel, 1973 a & b). Two deeper MM lakes in the Pokhara valley, Phewa and Begnas, however, are warm monomictic (Nakanishi *et al.*, 1988), which is common for deep low-latitude lakes that circulate during the cooler winter but are stratified during the summer. Cole (1994) suggests that warm monomixis is a common occurrence south of about 40° latitude in situations where lakes are deep and sheltered enough to stratify during the summer. The seasonal stratified phase occupies more than 70% of the year in most deep, monomictic, low-latitude, tropical lakes (Talling and Lemoalle, 1998).

The TE lakes were shallow polymictic and had a consistent temperature. Their turnover is influenced more by wind events and daily fluctuations in temperature than by seasonal change. In some of the ox-bow lakes and impoundments studied (D4, D7 and D10), seasonal variations in water temperature were caused by intrusions of river water.

Water transparency has a large influence on light penetration, which in turn greatly affects the distribution and development of aquatic macrophytes. Transparency in lakes is mostly affected by colour of the water, particularly due to dissolved humic substances and phytoplankton, as well as turbidity associated with suspended solids (Hutchinson, 1957; Tilzer, 1983). Secchi-depth is a simple and robust way to characterize the optical properties of lake water (Scheffer, 1998). The lakes in the HH region are much more transparent than those in the HM, MM, and TE regions. The highest Secchi transparency (14 m) was for Bhairav Kund (at 4,250m), a value that ranks among the clearest in the world (Scheffer, 1998).

The studied lakes showed a seasonal variation of transparency (Appendix 3), similar to observations in other studies of Nepalese waterbodies (Aizaki *et al.*, 1987; Nakanishi *et al.*, 1988; Bhatt *et al.*, 1999; Sah *et al.*, 2000; see also Kaushik *et al.*, 1990 and Kant and Raina, 1990 for data from mountainous India). In general, the transparency was lowest during the high-flow of the monsoon season, compared with the pre-monsoon and the post-monsoon. The post-monsoon transparency was generally somewhat higher than in the pre-monsoon, because of the relatively high concentrations of nutrients that favor the productivity of phytoplankton. The dominant effect on transparency during the monsoon is due to suspended silt and clay associated with the high water flows. This influence is greater than that of the phytoplankton minimum during the monsoon, when high water flows cause a washout of algal biomass (Zafar, 1986; Khondker and Parveen 1993).

For lakes that are not excessively turbid or dystrophic, transparency is sometimes used as an indicator of trophic status (Forsberg and Ryding, 1980). According to the proposed transparency threshold values of Forsberg and Ryding (1980), only 67% of the HH and 20% of the HM lakes in my study are in an oligotrophic condition, while in the MM region 80% of the lakes are eutrophic to hypereutrophic, as are 91% of the TE lakes (Table 3.3). In mountain water bodies with high values of suspended inorganic solids (Ghimire and Uprety, 1990), chlorophyll concentration is a preferable indicator of trophic status (see below).

Total suspended solids (TSS) in water bodies are contributed by particles of different sizes, ranging from relatively coarse to fine, and from inorganic to colloids of organic complexes and plankton. In this study, the high TSS during the monsoon season was due to inorganic silt and clay entering the waterbodies with high-flow, erosive runoff of stormwater. A key observation supporting this conclusion is the high ratio (about 6:1) during the monsoon of non-volatile suspended solids (NVSS, an indicator of inorganic particles) to volatile suspended solids (VSS, indicator of organics). During the post-monsoon, the decrease in TSS is due to sedimentation and decreased erosion. During the pre-monsoon, the NVSS is relatively low but VSS is high because of the abundance of phytoplankton (see Appendix 2 for seasonal data on chlorophyll). Similar observations for low-latitude lakes have been made by others working elsewhere on the Indian sub-continent (Shastree *et al.*, 1991; Kaushik and Saksena, 1999).

4.2 Chemical limnology

Biochemical cycles in lakes are not closed systems — substances are imported from the watershed and the atmosphere, and are exported via outflow, evaporation, and sedimentation (Hutchinson, 1957; Drever, 1997; Lampert and Sommer, 1997). Depending on the balance of these processes, a lake may be increasing or decreasing in its stock of particular substances.

Lakewater conductivity, a function of total dissolved ionic substances, increased markedly from high to low altitudes (Table 3.1). High-altitude catchments typically have shallow soil and steep slopes that allow percolating water to pass quickly, reducing the residence time during which ionic substances can be dissolved from the substrate. This, along with a relatively short growing season and predominantly slow-weathering, crystalline, silicate mineralogy, results in ionically dilute lakewater. In contrast, lower-altitude catchments have relatively deep soil and gentle slopes that allow a more extended contact between minerals and percolating water, which along with a perennial and warm growing season and a dominant calcareous mineralogy results in higher rates of weathering and a relatively high ionic strength of lakewater (Drever and Zobrist, 1992; Drever, 1997; Skjelkvåle and Wright, 1998).

As expected, my observations on conductivity are paralleled by those of total ions in the lakewaters studied, which are considerably more dilute in high-altitude waterbodies than in low-altitude ones (Table 3.2; note that sulphate is an exception to this general observation about ions and altitude; see below for additional discussion). The high-altitude HH lakes had the lowest average concentration of total ions (5.6 mg/l), which increased in lakes at lower altitude, as follows: HM lakes (average 6.7 mg/l), MM (21.1 mg/l), and TE (31.7 mg/l). The more-than five-fold difference in total-ion concentration between the high-altitude and low-altitude lakes is due to the same key factors noted above for conductivity.

The strong influence of surficial geology and weathering on water chemistry is suggested by data on ionic composition, which show an almost 1:1 relationship between the concentrations (in microequivalents) of bicarbonate and principal divalent cations (i.e., HCO_3^- versus Ca^{2+} + Mg^{2+}; r^2 = 0.95; Figure 3.9). This observation supports the suggestion of Stallard and Edmond (1983) that the weathering of carbonate minerals would lead to a 1:1 balance between Ca + Mg and bicarbonate on an equivalent basis. A large-scale, regional study of the Ganges-Brahmaputra and Indus Rivers has shown that about two-thirds of the dissolved cations are derived from carbonate weathering, and the rest from silicate minerals (Krishnaswami *et al.*, 1992). Although high-altitude areas of the Himalayas (such as HH and HM) have extensive silicate rocks and little carbonate in their recently deglaciated watersheds, the carbonates are relatively reactive and have a strongly disproportionate influence on the chemistry of surface waters (Blum *et al.*, 1998; Tartari *et al.*, 1998 b ; Thornton *et al.*, 2001). Anderson *et al.* (1997) came to a similar conclusion about alpine watersheds in North America.

The predominance of bicarbonate among anions, and of divalent cations (particularly calcium), is consistent with previous studies of non-acidic lakes in Nepal (Lohman *et al.*, 1988; Jones *et al.*, 1989; McEachern, 1994; Jenkins *et al.*, 1998, Tartari *et al.*, 1998 b), river systems in the Ganges basin (Raymahashay, 1996), and non-polluted lakes in India (Hutchinson, 1937; Kaul, 1977). The results are consistent with regional surveys linking patterns of surface water chemistry with those of surface geology (Naumann, 1929; Duarte and Kalff, 1989; Skjelkvåle and Wright, 1998).

In many parts of the world, regions with dilute, low-alkalinity surface waters (which lave little acid-neutralizing capacity; ANC) are vulnerable to anthropogenic acidification caused by LRTAP (the long-range transport of atmospheric pollutants) (Freedman, 2003). This is true of low-altitude surface waters in regions with silicate rocks, such as much of eastern North America, as well as many alpine areas. This study region in South Asia, anthropogenic emissions of SO_2 are increasing due to rapid industrialization, and the resulting LRTAP could result in acidification of high-altitude surface waters (Thornton *et al.*, 2001). The relatively high concentrations of sulphate in my study lakes in the HH and

HM regions might also be related to LRTAP, or possibly to local effects related to surficial mineralogy.

Most lakes in Nepal are neutral to alkaline in reaction (*Jones et al.*, 1989), but the lakes studied in the HM altitudinal region are slightly acidic (around pH 5.6) and have highly variable concentrations of solutes and nutrients depending on local watershed conditions, including anthropogenic disturbances. Jenkins *et al.* (1998) believe that streams in this region have become acidic because of their dilute water and small ANC (the latter being due to the largely siliceous surficial geology; Thornton *et al*., 2001). However, the acidification of surface waters is also related to other sources of acidity and ANC, such as humic substances, sulfide reduction and oxidation, nitrogen cycling, the ionic chemistry of aluminum and iron, and the influence of acidiphilous *Sphagnum* species (Clymo 1984; Shotyk, 1988; Freedman, 2003). Some of these influences may be important in these lakes in the HM region, which have dilute water and some of which have *Sphagnum* species present.

The HM region of Nepal lacks thorough limnological research, other than a study of Lake Rara in far-western Nepal (Okino and Satoh, 1986). Lakes in eastern Nepal have not been previously examined, although there are a few studies of streams (Jenkins *et al.*, 1998). Therefore, these results on five lakes in the HM region, and the observation that they are somewhat acidic, are unique.

In general, nutrient concentrations in the studied lakes increased with decreasing altitude. The total mean nitrogen (TN) and dissolved nitrogen (DN) were clustered into two regional groups (i.e., HH-HM and MM-TE, with no significant differences within groups), with a 2-4-fold increase in the MM-TE region (Table 3.1). Phosphorus behaved similarly — compared with HH and HM lakes, the mean total phosphorus (TP) in MM-TE lakes was higher by more than 5-fold and 9-fold, respectively (Table 3.1). The difference in dissolved phosphorus (DP) is similar, with MM-TE lakes having an average concentration 5-10-fold higher than the HH-HM. As might be expected on the basis of these differences in nutrient concentration, the mean chlorophyll concentration was 5-9-times higher in the MM-TE lakes than in the HH-MM ones (Table 3.1).

These observations are consistent with the generalization that watersheds with sedimentary or alluvial surficial geology have relatively high rates of nutrient export to lakes (as is typical of the MM and TE regions), while those with igneous and metamorphic geology have lower rates (typical of HH and HM) (Dillon and Kirchner, 1975; Duarte and Kalff, 1989). In addition, anthropogenic influences of agriculture, settlements, and industry mainly occur below 2,000 m in Nepal (Jha and Lacoul, 1999; Lacoul, 2000).

Other researchers working in the region of high Himalayas have suggested that lakes are ultra-oligotrophic, with very low concentrations of dissolved minerals and nutrients, limited biomass of phytoplankton and zooplankton, and no macrophytes (Hutchinson, 1937; Löffler, 1969; Aizaki *et al.*, 1987; Gasso *et al.*, 1993; Manca *et al.*, 1994; Manca *et al.*, 1995; Tartari *et al.*, 1998 b). My observations are generally similar, but with the notable exception that some of my study lakes in the HH region supported species of aquatic macrophytes.

Most limnological studies in Nepal have examined low-altitude lakes in the MM and TE regions (Jones *et al.*, 1989; McEachern, 1994; WMI and IUCN/ Nepal, 1994; Rai, 1998; Bhatt *et al.*, 1999; Rai, 2000). This is because of the potential of those waterbodies for fishery development and their sensitivity to eutrophication caused by the high human populations in their watersheds (more than 70% of the 23 million people in Nepal live in the MM and TE regions; HMG/Nepal, 1988). Lakes in these regions are similar in most characteristics of chemical limnology, even though they occur in different physiographic zones over an altitudinal range of 70 m to 1,400 m.

Lake Titicaca, located in Peru and Bolivia, is the most thoroughly investigated low-latitude, high-altitude lake for nutrient limitation, and nitrogen is considered to be limiting to its primary productivity (Wurtsbaugh *et al.,*1992). In the HH region, both phosphorus and nitrogen concentrations appear to be limiting (Table 3.1). Lake Titicaca has rather high levels of total dissolved phosphorus, possibly because of extensive development of its watershed for agricultural and residential purposes.

In general, the concentration of TP is less than 10 μg/l in waterbodies not affected by anthropogenic influences (Holtan *et al.,* 1988). In this study, Thola Tso and Panch Pokhari-1 (Bau) in the HH and HM regions have a TP concentration higher than 10 μg/l, with Tshola Tso being exceptionally high (17 μg/l), possibly because of an influence of eroded clay and silt from a glacier adjacent to the lake. The mean TP in the HH and HM study lakes (average of 7.3 µg/l) is similar to that of mountain lakes in Europe (around 2-7 µg/l; Psenner, 1989; Marchetto *et al.* 1994; Camarero *et al.*, 1995; Mosello *et al.*, 1995; Skjelkvåle and Wright, 1998; Kopáček *et al.*, 2000) and North America (2.5-14.5 µg/l; Schindler, 2000). In summary, all studied lakes in the HH and HM regions are low in nutrient concentration and are oligotrophic or ultra-oligotrophic (see also Okino and Satoh, 1986; Aizaki *et al.*, 1987; Tartari *et al.*, 1998 b).

The concentrations of TP are considerably higher in lower-altitude waterbodies of the TE and MM zones. The TP concentration of MM lakes averaged 52 µg/l (maximum 110 µg/l in Lake Taudha), while in TE it was 98 µg/l (maximum 159 µg/l in Lake Barahawa Tal) (Table 3.1 and Appendix 1). These TP concentrations support a relatively high productivity and biomass of algae and macrophytes in the generally eutrophic to hypereutrophic lower-altitude lakes.

Both point and non-point sources are important causes of anthropogenic nutrient loading to water bodies in lowland Nepal and elsewhere in South Asia, except for lakes remote from human settlements (Richey, 1983; HMG/Nepal, 1992; Jha and Lacoul, 1999; Lacoul, 2000). Especially important is the nutrient loading associated with human and livestock sewage, runoff of fertilizer, soil eroded from cultivated land, and in some local places, industrial inputs.

The studied lakes in the various altitudinal regions differed in general land-use:

- the TE lakes are mostly located in protected areas with relatively fertile lowland catchments in Sal (*Shorea robusta*) forest and reed-dominated (principally *Phragmites communis* and *Saccharum spontaneum*) floodplains, although some also receive water from agricultural drainage
- the MM lakes are in watersheds supporting intensive agriculture
- the HM lakes are located in catchments dominated by natural mixed-species forest, and the HH lakes are in seasonally grazed alpine tundra or rocky catchments.

It is well known that higher rates of nutrient loading are associated with both pastoral and agricultural land-use, compared with watersheds supporting natural ecosystems (Dillon and Kirchner, 1975; Duarte and Kalff 1989; Collins and Jenkins, 1996). These differences in land-use obviously contributed to the observed patterns of nutrient concentration, and were cumulative with the natural gradient of decreased nutrient loading with increasing elevation (Brylinsky and Mann, 1973; Schindler, 1978). However, the terraced paddy agriculture commonly practiced in the MM region is rather similar in nutrient export to natural wetlands, and exports fewer nutrients than the forested Terai watersheds (Bhandari, 1998).

The primary productivity of the TE lakes appears to be more limited by the availability of nitrogen than of phosphorus, as indicated by an average N:P ratio of 6.2 (range 2-15; Table 3.1; a ratio <10 indicates N limitation; Forsberg and Ryding, 1980). This is similar to observations of lowland lakes throughout southern Asia (Fernando, 1984). All of the TE lakes were eutrophic or hypereutrophic in terms of phosphorus and chlorophyll concentrations; some, however, ranked as mesotrophic or even oligotrophic by nitrogen criteria, further suggesting that their productivity was limited by available N (Table 3.3). The nitrogen-limiting condition of TE lakes is probably the result of relatively high P loading which lower the ratio of N:P as is typical of drainage from landscapes covered with tropical forest (Bruijnzeel, 1991). However, morphometry and internal loadings were also likely important in determining the nutrient status of TE lakes (Osgood, 1988).

Most of the lakes in the MM region (60%) are mesotrophic to eutrophic in terms of criteria related to total phosphorus (Table 3.3). More than 80% of the lakes in HH and HM regions are oligotrophic in terms of all criteria (i.e., those related to total nitrogen, total phosphorus, and chlorophyll).

4.3 Distribution of aquatic macrophytes

A total of 177 species of aquatic macrophytes was encountered in 28 of the 34 lakes studied (the other 6 lakes lacked aquatic plants; Appendix 6). This total includes 48% of the 339 species of aquatic plants known to occur in Nepal where macrophytes comprise about 6% of the total vascular flora of the country. Aquatic angiosperms account for 34% of the macrophyte species (470 species) reported from the Indian subcontinent (Cook, 1996), which represents about 50% of the global species (Lavania *et al.*, 1990). The 91 observed genera of aquatic angiosperms in my study is equivalent to 22% of the global number (407 genera; Cook, 1990).

About 2-3% of the 2.5 x 10^5 species of angiosperms in the world are aquatic plants (Cook, 1990; Philbrick and Les, 1996). In comparison, 6% of the vascular flora of Nepal is comprised of aquatic plants. This is a smaller value than reported for some temperate countries (e.g., 11% in Denmark and 10% in Britain; Moeslund *et al.*,1990; Preston and Croft, 1997), but higher than in neotropical countries (<1% in Ecuador and Peru; Young and León, 1993; Jørgensen and León, 1999). The relatively high richness of aquatic macrophytes in Nepal may be due to the greater richness of Poaceae and Cyperaceae compared to other parts of the world (Table 4.1), as is typical of the Indian sub-continent (Bor, 1960; Jain, 1986).

Only three endemic species of aquatic macrophytes are reported from Nepal: *Eriocaulon exsertum, E. kathmanduense*, and *Rotala rubra* (Shrestha and Joshi, 1996), but none of them were observed in the study lakes. According to Lavania *et al.* (1990), the Indian subcontinent supports 41 endemic species of aquatic macrophytes (although these authors noted only one endemic species from Nepal).

Only 4% of the Nepali species (15 species) have a cosmopolitan distribution (Figure 4.1). As expected, the aquatic and wetland species of Nepal show a strong affinity to those of India. In particular, the macrophyte flora of lowland Terai is a biogeographic extension of that of the Indo-Gangetic plain; many species also occur widely in Southeast Asia (including Indonesia; although few range south of Wallace's Line; Scott, 1989). In contrast, there is relatively little resemblance to the aquatic flora occurring on the dry Tibetan Plateau, even though it is only slightly north of this study area. This reflects both

Table 4.1 Proportional occurrence of monocotyledonae and dicotyledonae macrophytes in world and Nepalese wetland environment.

	Dicot	Monocot	Ratio
World			
Estimated number of species [1]	165,000	50,000	3.3:1
Estimated number of genera [1]	9,515	2,703	3.5:1
Estimated number of family [1]	318	65	4.9:1
Genera with aquatic species	192	212	0.9:1
Families with aquatic species	44	34	1.3:1
Genera with aquatic species (excluding Alismatidae) [2]	192	159	1.2:1
Genera with aquatic species excluding Alismatidae,Cyperaceae and Poaceae) [2]	192	67	2.9:1
Nepal			
Estimated number of species [3]	4603 (75.7 %)	1476(24.3 %)	3.1:1
Estimated number of genera [3]	1168 (77.2 %)	346 (22.8 %)	3.4:1
Estimated number of family [3]	173 (83.6 %)	34 (16.4 %)	5:1
Total wetland species compiled from Flora database	***148 (43.6%)***	***191 (56.4%)***	***0.77:1***
Genera with aquatic species	63	72	0.87:1
Families with aquatic species	36	22	1.6:1
Genera with aquatic species (exl. Alismatidae)	63	69	0.9:1
Genera with aquatic species (excluding Alismatidae, Cyperaceae and Poaceae)	63	36	1.7:1
Species encountered in present study	***65 (40.1%)***	***97 (59.9%)***	***0.67:1***
Genera with aquatic species	39	56	0.7:1
Families with aquatic species	26	16	1.63:1
Genera with aquatic species (excluding Alismatidae)	39	53	0.73:1
Genera with aquatic species (excluding Alismatidae, Cyperaceae and Poaceae)	39	25	1.56:1

Genera for which there is incomplete estimate of the number of aquatic species have been excluded from these comparisons.

[1] compiled from Cronquist, 1981

[2] compiled from Cook, 1990

[3] Press *et al.*, 2000

the differences in aquatic habitat (De Terra and Hutchinton, 1934), as well as the high Himalayas and Tibetan dry plateau serving as barriers to plant migration and distribution.

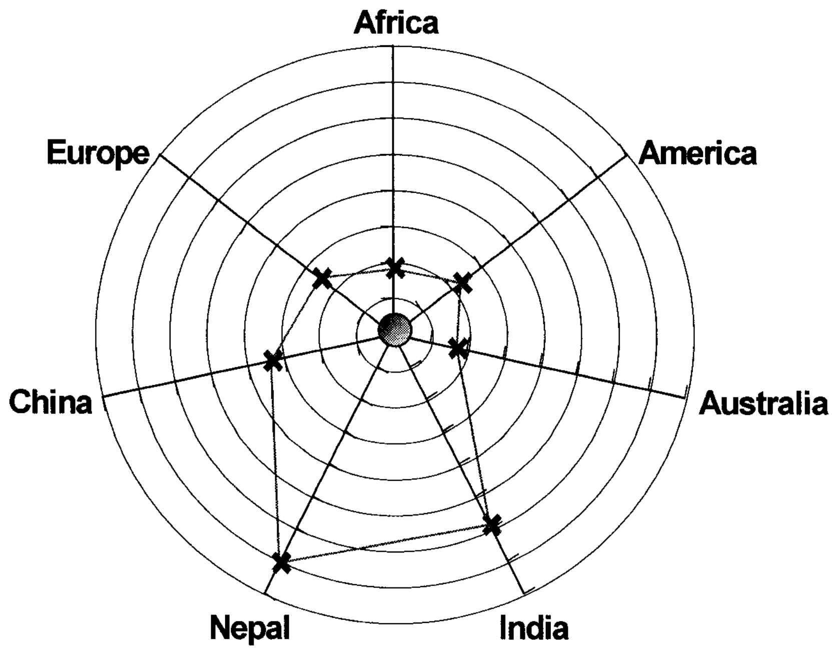


Figure 4.1 Number of aquatic and wetland plants of Nepal, and their distributional similarity to selected regions of the world. Each concentric circle represents 50 shared species; the inner solid circle represents the 15 cosmopolitan aquatic species occurring in Nepal. Regional data were obtained from Cook (1996).

In general, the Himalayan phytogeographic region is a transitional zone between the Palaeotropic and Holarctic realms. The mountainous regions of the Himalayas largely support aquatic plants that are widespread in Central Asia and Eurasia, or that have their closest relatives there. In contrast, aquatic plants of the lowlands of Nepal are mostly widespread in the floodplains of the great rivers draining the Himalayas to the Indian subcontinent (particularly the Brahmaputra, Ganges, Indus, and Sutlej Rivers), and extending to the foothills and middle-altitude valleys of Nepal, particularly where paddy rice is cultivated (Cook, 1996). The distribution of species of aquatic plants in this study is consistent with this pattern.

In Nepal, the ratio of genera of aquatic monocots to that of dicots is 1:0.87, only slightly less than the global pattern (1:0.9; Table 3.2.2; Cook, 1990). The comparable ratio of aquatic dicot:monocot species in Nepal is 1:0.77 (there are no comparable global data). Although monocot genera and species generally dominate wetlands and lakes in Nepal, the patterns differ on an altitudinal basis, with monocots being especially dominant in the HM region (see also Table 4.1):

	monocot:dicot genera	**monocot:dicot species**
TE	1:0.67	1:0.70
MM	1:0.77	1:0.84
HM	1:0.36	1:0.36
HH	1:1.00	1:1.00

In general, shallow lacustrine habitats are dominated by emergent monocotyledon plants (Sculthorpe, 1967; Hutchinson, 1975; Cronk and Fennessy, 2001). The relatively high proportion of moncots in the TE, MM, and HM regions could be due to the prevalence of shallow lakes. The reason for the particularly high dominance of monocots in the HM region is not obvious.

Overall, 53% of the macrophyte species observed in this study are annuals, and 47% are perennial in lifespan. Both the number and proportion of annual species are greater at lower altitudes, and are highest in the TE region (Figure 3.18). The Terai habitats are severely affected by seasonal disturbances and high turbidity associated with the monsoon, which generally favours annuals in aquatic habitats (Shipley *et al.*, 1991).

The ability of species to become established and persist under the prevailing environmental conditions is an obvious factor affecting the diversity of plant communities. The establishment phase is critical, and the conditions that a given species requires to germinate and become established may differ from those that favor older plants. The requirements for germination and establishment have been named the "regenerative niche" (Grubb, 1977). For aquatic plants, variable water levels are important in offering propagules an opportunity to establish and make community composition temporally variable (Keddy, 2001; Cronk and Fennessy, 2001). For example, the seeds and seedlings of many aquatic plants, particularly helophytes and hyperhydates, require drawn-down water levels for germination and establishment. In this region, the particularly low water levels of the pre-monsoon season favor the germination and establishment of many helophytes and hyperhydates in lake-boundary habitats (particularly in TE and MM), and most macrophytes then grow taller in synchronic response to rising water levels with the advent of the monsoon. Shrestha (1999) suggested that the development of annual aquatic plants in Nepal is dependent on the monsoon schedule, and that they produce seed in the post-monsoon season, which then remain dormant until they germinate in the pre-monsoon of March-June.

It has been shown that the stabilization of the water level can reduce the plant species diversity and affect vegetation types in aquatic bodies (Keddy and Reznicek, 1986;

van der Valk *et al.*, 1994; Shay *et al.*, 1999). Lakes and impoundments generally have relatively stabilized water levels. In the MM study region, Lake Begnas, a 374-ha impounded natural lake, supported only 20 species of aquatic plants and Lake Phewa (524 ha) 40 species. In contrast, non-impounded Lake Rupa (47 species; 116 ha) supported considerably more species although being relatively smaller than two lakes.

Overall, the growth-form spectrum of aquatic macrophytes was dominated by Helophytes, followed by Hyperhydates, submerged, floating-leaved, and free-floating forms (Figure 3.19). The high proportion of Helophytes and Hyperhydates may reflect the low transparency and shallow character of many of the study lakes (Appendix 1). The TE region was dominated by shallow-water growth forms, particularly Helophytes and Hyperhydates, while the MM was richer in submerged forms. The generally shallow lakes in the HM region were dominated by Helophytes, and the deep and clear HH lakes by submerged species.

Due to the exponential attenuation of light in water, depth is a critical factor affecting the depth-distribution and species richness of submerged macrophytes (Hutchinson, 1975; Chambers and Kalff, 1985; Duarte *et al.*, 1986; Stewart and Freedman, 1989; Sand-Jensen and Borum, 1991; Middelboe and Markager, 1997). Depending on species, the compensation point of submerged plants is 4-29% of incident light intensity (Dennison *et al.*, 1993). In the present study, 78% of the species encountered occurred in water shallower than 50 cm, and 55% only in shallow littoral water <15 cm deep (Figure 3.17).

As a rule of thumb, submerged macrophytes will grow to depth of 2-3 times the Secchi depth (Canfield *et al.*, 1985; Chambers and Kalff, 1985). The depth-distribution of macrophytes in this study was generally within this range of transparency. In the case of the deepest occurrences of rooted macrophytes (5 m for *Trapa quadrispinus* and *Valisneria natans*), the depths were 4- and 2-times the Sechhi depth, respectively. (Note, however, that *Trapa* establishes from large nuts that sink to the bottom and allow germinants to establish in relatively light-poor conditions. The 5-m depth occurrence of *Trapa* in Lake Rupa is unusually deep for an emergent/floating-leaved plant, which in temperate regions seldom grow in water deeper than 3 m (Canfield and Hoyer, 1992).

In the TE region, rooted macrophytes were not observed deeper than 2 m, due to the prevailing low-transparency water and abundant shade cast by floating-leaved and emergent plants. In the MM region, there was a wider range of depth distribution of macrophytes, including the deepest records in this study, for *Trapa quadrispinosa* (5 m), *Vallisneria natans* (5 m), and *Ranunculus trichophyllus* (4.5 m). In general, water transparency was greater in higher-altitude lakes (Table 3.1), and it likely contributed to the relative richness of submerged species in MM lakes. Transparency of the HM lakes is highly variable; several have a low transparency because of the presence of DOC (humic substances). Although transparency is high in the HH lakes, the cold temperature, ice cover in winter, and ice-scouring in spring contribute to a low species richness.

Although some species in this study occurred at great depth (up to 5 m), there are records of even deeper occurrences of aquatic plants in exceptionally clear lakes, particularly of certain Charophytes and Bryophytes, living plants of which have been found to >100m (Middelboe and Markager, 1997). The deepest occurrence for an angiosperm macrophyte is less, around 12 m, possibly because of intolerance of extreme hydrostatic pressure (Hutchinson, 1975).

Although water clarity is the primary factor affecting the ability of plants to grow in deep water, additional influences include temperature, irradiance, and length of the growing season, all of which are typically greater at lower altitudes (Duarte and Kalff, 1986; Gasith and Hoyer, 1998). In this study, warm water showed a greater depth distribution in the MM region, and caulescent and rosette-forming macrophytes had their deepest occurrences there compared to lakes at higher altitudes. Middelboe and Markager (1997) concluded that the deepest-growing angiosperms are caulescent forms, but in this study of low-latitude lakes they were joined by rosette-forming plants in deep water. Middelboe and Markager (1997) also suggested that angiosperms are the deepest-growing macrophytes in lakes with low transparency (Secchi transparency < 3 m), whereas bryophytes and charophytes grow deepest in more transparent lakes. In this study, however, the deepest and most transparent lakes occur in the HH region, and they support angiosperms rather than bryophytes and macrophytic algae (except for clearwater Salpa Pokhari in the HM region, where bryophytes occurred most deeply). This observation could be related to the low concentrations of ions and nutrients and the persistent ice cover (and consequent low irradiance) of the HH lakes; these factors may restrict the distribution of bryophytes and macroalgae at high altitudes (similar observations have been reported in streams in the Nepalese Himalayas; Ormerod *et al.*, 1994; Suren and Ormerod, 1998).

Examination of the distribution and abundance of macrophytes along gradients of lake size, depth, and other environmental factors is complicated because plant development is highly variable, even within and among lakes of similar morphometry (Sculthorpe, 1967; Hutchinson, 1975). In this study, the species richness of aquatic plants showed negative relationships with altitude, and positive relationships with surface water temperature (Table. 3.4). Other studies have also found declines of species richness with increasing elevation (Rørslett and Hvoslef, 1986; Rørslett, 1989; Rørslett, 1991) and with decreasing temperature (Pip, 1979; Scheffer *et al.*, 1992).

In general, the number of species present increases with area of the habitat (Arrhenius, 1921; Connor and McCoy, 1979; Rørslett, 1991) and decreases with isolation of habitat "islands" (MacArthur and Wilson, 1967). One commonly used relationship of species:area is $S = cA^z$ (the Arrhenius equation; where S is the number of species, c is constant, A is area, and z is the slope of a log/log relationship; Williamson, 1988; Rosenzweig, 1995). In the present study, there is a weak species:area relationship among lakes in the various altitudinal/climatic zones (Figure 3.24). Within the altitudinal regions, however, the relationship is stronger. In the TE lakes, for example, the species:area relationship has a slope of 0.37 ($r^2 = 0.79$). Weiher and Boylen (1994) reported an Arrhenius slope of 0.23 for Adirondak lakes and 0.29 for Danish ponds, and suggested that lower slopes in regional lakes were due to the size of the species pool. However, in a study of 641 lakes in Scandinavia, Rørslett (1991) found little influence of either the regional species pool or latitude on the Arrhenius slope. Rosenzweig (1995), in a wide-ranging review of species:area relationships, concluded that the form of the curve changes with spatial scale. If species are dispersal-limited, then the local species richness will differ from that found by a random sampling of the metacommunity. All species are dispersal limited at some spatial scale, an effect that becomes increasingly important at larger scales (Hubbell, 2001). In this study, the dispersal limitation is particularly pronounced in high-altitude regions (HH and HM), where climate-related barriers and environmental stresses result in a dramatic decrease in the species richness of macrophytes. Moreover, the aquatic plants occurring in my high-altitude lakes are mostly cosmopolitan species as other aquatic organisms (Manca *et al.*, 1998).

The limits to dispersal of macrophytes in high-altitude lakes are related to cold water temperature, seasonal ice cover, littoral scouring, and low concentrations of solutes and nutrients (Suren and Ormerod, 1998), and perhaps to infrequent visitation by animal vectors. Other studies of lakes (Löffler, 1969; Lami *et al.*, 1998) and streams (Suren and Ormerod, 1998) above 4,000 m in the Himalayas of Nepal have not observed aquatic macrophytes. Interestingly, a paleo-limnological study of two lakes above 5,000 m in the Everest region found that macrophytes had been present during several warm periods within the past 2,600 years, but that they are no longer occur (Lami *et al.*, 1998). In this study, six high-altitude lakes in the HH region did not harbor any macrophytes, but others supported 2-3 species: *Ranunculus trichophyllus*, *Callitriche palustris*, *Festuca ovina,* and *Juncus alloides*. Of these species, *J. alloides* is widespread between 2,000-4,650 m in the Sino-Himalayan floristic region and occurs from Punjab in the western Himalayas through Tibet to Shaanxi and Hubei in China, particularly in marshy places, bogs, and streamsides (Miyamoto, 2002). *Festuca ovina* has a similar distribution in rocky slopes and wet places of the high Himalayan region. These helophtes are riparian elements that extend into lakes in shallow depths. *Ranunculus trichophyllus* (up to 4,750 m) and *Callitrichia verna* (up to 4,068 m) are also widespread species, and these altitudinal records appear to be the highest observed for aquatic angiosperms (based on a wide-ranging review of literature on alpine macrophytes).

The unusual occurrence of *Ranunculus trichophyllus* at 4,750 m is noteworthy. The aquatic ecosystems of the HH region are extreme environments, in which physical stressors associated with ice and snow (winter cover, scouring, and avalanche) and severe climate are limiting factors for the dispersal and distribution of aquatic macrophytes — these are habitats utilized by stress-tolerant species, sensu Grime (2001; see also Chambers and Prespas, 1988; Campbell and Grime 1992; Körner, 1999; Yoshida, 2002). In general, the phenology of high-altitude plants in the Himalayas is closely coupled to the timing of snowmelt and other key seasonal events that initiate and end the brief growing season (Pangtey *et al.*, 1990). Moreover, Schindler *et al.* (1990, 1996a) notes that relatively shorter periods of snow- and ice-cover of alpine lakes (as might be caused by climate warming) enhance the exchange of gases and nutrients, wind-driven circulation, and light conditions required to support the productivity of aquatic plants. In fact, there is paleo-limnological evidence that macrophytes were more abundant in lakes in the Everest region during warmer periods within the past 2,600 years (Lami *et al.*, 1998). In the present study, the possibly recent, abundant presence of *R. trichophyllus* in a 44 ha lake at 4,750 m could, in fact, be a signal of recent warming, and warrants further monitoring of aquatic plants in this and other high-altitude lakes in the region (Sommaruga-Wögrath *et al.*, 1997; Kotlyakov and Lebedeva, 1998; Hughes, 2000; Magnuson *et al.*, 2000; IPCC, 2001; Quayle, 2002; Walther *et al.*, 2002).

Crawley (1997) argues that niche specificity is greater under more extreme conditions, and that tolerance of environmental stress and the disturbance regime also plays an important role in the distribution and abundance of species (Grime, 1979; 2001). Out of the six core developmental strategies suggested for alpine plants (Körner, 1999), the one dominant in sites with particularly long snow-and-ice cover is present in *R. trichophyllus* — it involves leaf initiation and expansion before final snowmelt and rapid greening and activation of photosynthesis immediately after release. Additional adaptations of *R. trichophyllus* to its extreme alpine environments include its tolerance of sudden frost; the ability to self-pollinate in bud; the presence of hexaploids that are interfertile with other hexaploids (such as *R. aquatilis*), finely dissected leaves with high chlorophyll on epidermal cells for efficiency of light absorption; an ability to use either CO_2 or HCO_3^- as a source of inorganic carbon for photosynthesis; tolerance of intense irradiation by UV-B; and extreme vagility and colonization ability, including by fragmented vegetative tissues (De-Yuan, 1991; Rascio, 1999; Barrat-Segretain and Gudrun, 2000; Bennike, 2000; Birks, 2000). These attributes are important for *R. trichophyllus* to proliferate in high-altitude Himalayan lakes.

Lakes in the TE region had greater species richness and diversity, particularly those with seasonal lotic (riverine overflow) influences. This observation is consistent with suggestions that diversity increases with an intermediate disturbance regime (Connell, 1978; Tilman, 1988; Wilson and Tilman, 1993, 2002). The lowest diversity among the TE waterbodies was observed in three lakes in the Koshi Tappu Wildlife Reserve in which disturbance is frequent and intense due to wading and wallowing by wild water buffalo (*Bubalus arnae*). Their movements in the lakes make the water turbid and uproot plants, which reduces the diversity of submerged macrophytes. Another TE lake, Devi Tal, had relatively low diversity in its littoral zone, possible related to wallowing and feeding by rhinoceros (*Rhinoceros unicornis*) and elephant (*Elephas maximus*); this effect was less evident in waters deeper than 1 m.

In the MM region, the lowest species richness was in Begnas Tal, likely because of recent reservoir development that increased the water level, reduced shallow-water area by the construction of embankments, and led to low nutrient levels. The effects of increased water level and reduced shallow-water habitat on macrophytes are direct, but those of reduced nutrient levels are more complex. Jeppesen *et al.* (2000) analyzed data for 71 shallow Danish lakes and found increase and decrease of species richness of macrophytes in response to nutrient levels, particularly to the phosphorus gradients. In this study, the three-fold difference in phosphorus concentration between Lakes Rupa (42 μg/l) and Begnas (15 μg/l) in the MM region could be related to the smaller macrophytes richness in the latter.

Species richness and diversity were lower in the HM lakes, and lowest in the HH ones. In the HM region, the highest species richness was in Phokte Tal and the lowest in Gupha

Pokhari, both mesotrophic lakes. These observed differences are possibly caused because Gupha Pokhari is a small lake (6.5 ha) that is frequently disturbed by local people drawing water and washing. The vegetated HH lakes are dominated by only 2-3 species (other HH lakes lack macrophytes). The HH lakes occur in climatically extreme alpine environments, which along with their recent origin (following deglaciation) and oligotrophic status leads to a low level of species richness (Dobson *et al.* 1997; Toivonen, 2000; Lodge, 2001). The glacially recent origin of these HH lakes is notable; other high-altitude lakes that are older have more species of macrophytes present. For example, the ancient alpine Lake Titicaca (Peru, Bolivia) has 23 species of macrophytes present, including an endemic (Dejoux, 1994).

Factors influencing the levels of species richness and diversity within communities have been attributed to the intensities of three clusters of environmental influences: stress, competition, and disturbance regime (Grime, 1979, 2001). In this study, stress was not studied by experimental means; rather, its intensity was inferred by correlative and multivariate investigations. Still, it is apparent that the high-altitude lakes are subject to more intensive and prolonged regimes of severe climatic stress, along with a low nutrient availability, and this has resulted in the presence of few species. In comparison, the lower-altitude lakes in the TE and MM regions, which are typically mesotrophic–eutrophic, are characterized by environmental conditions in which biological interactions (such as herbivory and competition) and disturbance have a greater influence on community composition and the relative abundance of species (Grime, 1979, 2001; Jeppesen *et al.*, 2000). Overall, the high-altitude lakes are characterized by stresstolerators and ruderals (*sensu* Grime, 1979; 2001), while low-altitude lakes are dominated by competitors. In addition, the overall moderate regime of anthropogenic disturbance and nutrient loading in the TE and MM regions appears to have contributed to the dispersal and distribution of species (including non-native ones).

Reviews on the threats to the fresh water biodiversity show the importance of invasion of non-native species, as invasion rate is accelerating with the changes in ecosystem structure due to global warming (Parker *et al.*, 1999; Kolar and Lodge, 2000; Sala *et al.*, 2000). Nepal is poor in endemic aquatic macrophytes (3 species) relative to Indian subcontinent (41 species; Lavania *et al.*, 1990), but many aquatic angiosperms have been naturalized to the aquatic habitats, as a weed in the paddy cultivated field and in wetlands. Many exotics macrophytes observed in the country are either endemic to Europe or Indo-Malayan region, but nuisance exotics are those endemics from South America, such as, water hycinth (*Eichhornia crassipes*) and water cabbage (*Pistia stratiotes*) having extensive cover in many lakes in TE and MM regions. These free-flaoting macrophytes have significant impacts on submerged species distribution in many lakes in the tropical to sub-tropical region.

Despite many aquatic macrophytes are known as weeds in paddy cultivation, they have several important economic and ethno-botanical values. Herodatus, the Greek historian described the practice of lilies seeds use in 5 centaury B.C. Similarly, Ayurveda, Unani and Tibetan medicinal practices extensively use the parts of aquatic plants to cure different ailments. Lacoul and Lacoul (2002) have compiled 77 aquatic species being used for medicinal purposes in Nepal, and about 25% of macrophytes in the present study shows the medicinal values. Except to the medicinal uses, culms of *Trapa* spp are eaten as fresh fruit in Nepal. Also, dried chestnuts are grind to make flour for various delicacies. The roots and seeds of *Nelumbo nucifera* are eaten by local people. Many annual and biannual tall grasses are used as construction material in the villages.

4.4 Multivariate analysis

Hutchinson (1975) highlighted the importance of comparative studies of aquatic macrophytes among waterbodies differing in limnological characteristics; such studies are potentially valuable in understanding community-environment relationships. To this general end, researchers have used multivariate methods to extract relationships among macrophytes and limnological and watershed variables in various parts of the world (Jensén, 1979; Catling *et* al., 1986; Jackson and Charles, 1988; Srivastava *et al.*, 1995; Riis, 2000; Boedeltje *et al.,* 2001; Heegaard *et al.*, 2001; Lougheed *et al.*, 2001; Mackay *et al.*, 2003; Murphy *et al.*, 2003). However, studies of this sort have not previously been done on the steep altitudinal (but narrow latitudinal) gradients of the Himalayas.

In this study, a PCA result involving environmental factors (Figure 3.25) shows that gradients of pH, conductivity, ions, and nutrients all change with altitude. Most of these limnological variables show strong negative correlations with altitude; exceptions are sulphate, chloride, lake area, maximum depth, transparency, and substrate quality (coarser-grained at higher altitudes). In general, the HH and HM lakes have relatively low concentrations of ions and nutrients, are large, deep, and transparent, and their productivity (indicated by chlorophyll) is low. Although investigating a much smaller range of altitude, a study of macrophytes in 574 lakes in Northern Ireland also found strong negative correlations for ions, nutrients, and chlorophyll, and positive ones for lake area, color, and turbidity (Heegaard *et al.*, 2001).

TWINSPAN clustering of lakes by species (Figure 3.26) produced a similar grouping of waterbodies as the PCA based on environmental factors, segregating on the basis of altitudinal-temperature gradients. *Juncus allioides* and *Ranunculus trchophyllus*, the holarctic cold-tolerant species, are the indicator species of the HH region in the TWINSPAN analysis. The HM region, particularly of eastern Nepal, is indicated by *Sphagnum* species and graminoids of temperate bog habitats. MM and TE lakes share cosmopolitan species of temperate and tropical biomes, indicated most strongly by *Hydrilla verticillata*, and by the tropical species *Lemna perpusilla* and *Pistia stratiotes*. The DCA ordination (Figure 3.27 & 3.28) of lakes by species resulted in a grouping similar to that of the TWINSPAN analysis, segregating the waterbodies into four altitudinal groups corresponding to the HH, HM, MM, and TE regions.

I conducted a canonical correspondence analyses on two different altitudinal scales. The initial CCA-1 analysis covered the entire altitudinal gradient from 70m to 5,000 m, extending from tropical to alpine zones (and including the HH, HM, MM and TE regions). The CCA-1 analysis included 28 waterbodies (all with macrophytes present), which supported 177 species, and investigated 23 environmental variables. The first two axis of the CCA-1 analysis accounted for 24.4% of the variance of the species data, while

55% of the variance of the species-environment relationship was accounted for by six forward-selected environmental variables: surface-water temperature, substrate quality, pH, altitude, transparency, and conductivity. The CCA-1 analysis distinctly separated the macrophyte species of the HH and HM regions, but grouped those of the MM and TE regions by forming a data cloud (Figure 3.30; species similarity = 0.44).

A second analysis, CCA-2, involved a more narrow altitudinal gradient (70 m to 1500 m, extending from the tropical to warm-temperate zones, or from TE to MM) and included 17 waterbodies, 165 species, and 15 environmental variables. The intention of CCA-2 was to separate the species of the TE and MM regions that formed a data-cloud in CCA-1. The first two axis of CCA-2 accounted for 28.3% of the variance of species data, while 55.4 % of the variance of the species-environment relationship was accounted for by five forward-selected environmental variables: surface-water temperature, area, total suspended solids, bicarbonate, and dissolved phosphorus. This analysis separated the TE lakes from the MM ones, although the species do not separate as clearly (Figure 3.32).

The results of both analyses (CCA-1 and CCA-2) suggest that surface-water temperature has the strongest influence on the distribution of macrophyte species along the altitudinal gradient studied. This agrees with the generalization of Welch (1952) that: "no other factor has so much profound direct and indirect influence on physico-chemical, biological, metabolic and physiological behaviour of aquatic ecosystems than temperature". The influence of ambient temperature on the distribution of macrophytes and their community structure is well known (Barko and Smart, 1981, Barko *et al.*, 1982; Pip, 1979; Scheffer *et al.*, 1992; Madsen and Brix, 1997; Rooney and Kalff, 2000; Heino, 2002). Also, a good agreement has been inferred between accumulated degree-days sediment temperature for emergence of vegetative propagules and geographical distribution of aquatic macrophytes (Spencer *et al.*, 2000).

High-altitude waterbodies, even in low latitudes, have cold water temperatures and little seasonal variation of solar radiation, which eliminates species of warm water (Löffler, 1964, 1968; Carney *et al.*, 1987; Pollingher and Berman, 1991; Green, 1995; Manca *et al.*, 1995, 1998). In general, the distribution of freshwater organisms and their communities is related to both regional climate, as well as the specifics of geographical location (Heino, 2002). This suggests that large-scale environmental factors determine regional species combinations, by posing constraints on the distribution of species. In Fennoscandia, the species richness of macrophytes decreases with increasing latitude and altitude, and much of the variation (74%) is explained by mean July temperatures (Heino, 2002). In central North America, the species richness of macrophyte communities is also most positively correlated with maximum seasonal water temperature (Pip, 1979).

According to Sculthorpe (1967), about 60% of the world's macrophyte species fall into one of the following three floristic groups: (i) cosmopolitan, (ii) north-temperate (Arcto-tertiary derivatives), and (iii) pan-tropical (tropical-tertiary floral derivatives). The other 40% of species are mostly confined to a single continent, and are either temperate or tropical in distribution. The CCA-1 analysis exhibits a clear demarcation between HH and HM lakes, with dominance of Arcto-tertiary floral derivatives, and the MM and TE lakes, with dominance by cosmopolitans and pan-tropical species. Arcto-tertiary species, such as *Ranunculus trichophyllus, Callitriche palustris,* and *Festuca ovina*, and cold-tolerant high-altitude species, such as *Juncus allioides* of Himalayan distribution, are prevalent in the HH and HM regions. The pan-tropical and cosmopolitan species, such as *Azolla imbricata, Ceratophyllum demersum, Eichhornia crassipes, Hydrilla verticillata, Nymphoides indica, Potamogeton crispus, Salvinia molesta, Spirodela polyrhiza*, and various grasses and sedges of the warm Indian subcontinent are of wide occurrence in the MM and TE regions.

In this study, a gradient of benthic substrate quality was observed among lakes at different altitude. The HH lakes have less clay/silt content and more coarse material, while clay and silt dominate the substrate in MM and TE lakes. Substrate quality has a well-known influence on the distribution and abundance of aquatic plants (Pearsall, 1920; Anderson and Kalff, 1988; Duarte and Kalff, 1990; Barko *et al.*, 1991; Ferreira, 1994; Toivonen and Huttunen, 1995; Suren and Ormerod, 1998; Boedeltje *et al.*, 2001), particularly on emergent macrophytes (Weisner, 1991). In this study, the paucity of clay/silt in sediment in the HH zone may pose a constraint on macrophytes, and may relate to the presence of few helophytes and hyperhydates. The substrate types are related to the geologic influences and human activities in the catchments, which play a decisive role in substrate quality of inflowing streams and the lakes directly (Haslam, 1978; Holmes, 1983; Ferreira, 1994; Toivonen and Huttunen, 1995; Crosbie and Chow-Fraser, 1999; Lougheed *et al.*, 2001). The lakes in the lowland MM and TE regions have a similar geology and intensive agricultural land-use, and their comparable benthic substrates are not significant in segregating species in the CCA-2 analysis.

Some studies have found that pH and related factors (such as alkalinity) can be an important influence on the species richness of macrophytes (Fassett, 1930; Iversen, 1929; Moyle, 1945; Catling *et al.*, 1986; Jackson and Charles, 1988). Various surveys have established floristic gradients extending from low-alkalinity/acidic lakes to strong alkalinity and even saline ones. Here, only the HM lakes were slightly acidic (to pH 5.6), and they are dominated by bryophytes, particularly *Sphagnum* species, as is common in cool-to-temperate acidic lakes (pH 4.5-5.5) (Heitto, 1990). The species richness of elodeids and charophytes is higher in hardwater lakes with pH >7, the latter mostly in small clear ponds (Brandrud and Mjelde, 1997; Vestergaard and Sand-Jensen, 2000). The predominance of isoetids in softwater lakes and of elodeids and charophytes in hardwater ones has been reported from various regions of the world (Fassett, 1930; Moyle, 1945; Spence, 1964; Seddon, 1972; Moeller, 1978; Keeley, *et al.*, 1994). This pattern is reflected in the physiological ecology of species, including their ability to utilize bicarbonate and/or carbon dioxide as a source of inorganic-C nutrition, and nitrate and/or ammonium as inorganic-N (Wium- Anderson, 1971, Moeller, 1978; Keeley *et al.*, 1994). The CCA-1 analysis showed a significant relationship of pH and macrophyte distribution, but this was not important in the CCA-2 analysis because of the relatively narrow pH range (7.4 - 8.9) in that dataset. Similarly, other studies have only found a substantial relationship between macrophytes and pH if a wide range of pH values was examined (Grahn, 1977; Roberts *et al.*, 1985; Yan *et al.*, 1985; Catling *et al.*, 1986; Rørslett, 1991).

Secchi transparency is another important factor in the CCA-1 analysis. This is also reflected in CCA –2 by the influence of total suspended solids (TSS) in water, as the majority of the lakes studied in the MM and TE regions are shallow and turbid. (Across the entire dataset, Secchi transparency is negatively correlated with TSS ($r = -0.44$; $p<0.05$)). In CCA-1, transparency helps to segregate clearwater lakes and species of the HH region from the relatively murky lakes of the HM, MM, and TE regions. Similarly, in CCA-2, the TSS segregates most emergent and free-floating species of low-transparency lakes of TE from clearer lakes of MM with many submerged species (such as *Najas graminea*, *Najas minor*, and *Nitella mucronata*). Transparency has an influence on the relative dominance of light-demanding helophytes and hyperhydates, compared with submerged and floating-leaved species (Canfield *et al.*, 1985; Skubinna *et al.*, 1995; Toivonen and Huttunen, 1995; Vestergaard and Sand-Jensen, 2000; Squires *et al.*, 2002; Nurminen, 2003).

The influence of conductivity on CCA-1 is consistent with other studies of macrophyte communities, likely because of indirect relationships with nutrient availability (Seddon, 1972; Palmer *et al.*, 1992, 1994; Brandrud and Mjelde, 1997; Khedr and El-Demerdash, 1997; Heegaard *et al.*, 2001). In CCA-1, the conductivity gradient is represented by bicarbonate (Appendix 5; $r = 0.93$; $p<0.05$) and dissolved phosphorus ($r = 0.55$; $p<0.05$) and suggests a relationship of nutrients and species richness and distribution. In my CCA-1 analysis, macrophytes aggregate into two broad groups on the basis of conductivity along the altitudinal gradient:

(a) low-conductivity (27 ± 14 $\mu S.cm^{-1}$ (mean $\pm$ SD; n=17), oligotrophic lakes in the HH and HM regions, with *Callitriche palustris* and *Ranunculus trichophyllus* as representative species; and

(b) high-conductivity (140 ± 88 μS.cm^{-1}; n=17), mesotrophic-to-eutrophic lakes in the MM and TE regions, with *Hippuris vulgaris, Hydrilla verticillata, Lemna minor, Lemna trisulca, Eichhornia crassipes, Paspalum distichum, Potamogeton crispus, Potamogeton pectinatus, Urticularia vulgaris,* and *Zannichellia palustris,* being representative species.

The MM and TE regions are dominated by eleodids and emergent monocots, which can utilize bicarbonate for photosynthesis, as can *Hydrilla verticillata*, *Potamogeton crispus*, and many emergent monocots from other parts of the world (Prins and Elzenga, 1989; Krabel *et al.,* 1995).

At low latitudes, high-altitude freshwater ecosystems are characterized by low annual and diurnal temperatures and little variation of solar radiation. The first two factors appear to limit the distribution of most floristic and faunistic elements, resulting in low species richness at higher altitude (Hunter and Yonzon, 1992; Ormerod *et al.*, 1994; Suren and Ormerod, 1998). This pattern of species richness is also observed with aquatic plants in the present study in CCA-1. The decline in species richness is consistent with others findings for macrophytes in temperate and tropical water bodies (Rørslett, 1989, 1991; Ormerod *et al.*, 1994; Suren and Ormerod, 1998; Heegaard *et al.*, 2001; Heino, 2002). One explanation for this altitudinal variation in species richness is the "energy hypothesis," which suggests that areas with greater energy availability provide a wider resource base, allowing more species to occur (Tilman, 1982; Turner *et al.*, 1996). Studies of the relationship between energy availability and species richness tend to fall into two broad groups:

(a) those reporting hump-shaped relationships, in which species richness peaks at an intermediate level of energy availability or productivity (Grime, 1973; Tilman, 1982; Guo and Berry, 1998) (although Rappoport's Rule and hard-boundary theory may provide an alternate explanation; Stevens, 1989; Colwell and Hurtt, 1994; Rahbek, 1995; Colwell and Lees, 2000);

(b) those reporting broadly positive relationships, in which species richness peaks at the highest levels of energy availability, or in the warmest climate (Wright, 1993; Currie, 1991, Turner *et al.*, 1996).

The humped-shaped relationship has been observed by various authors studying terrestrial vegetation along Himalayan altitudinal gradients (Shrestha and Joshi, 1996; Grytnes and Vetaas, 2002; Vetass and Grytnes, 2002). In contrast, my study of aquatic plants in lakes approaches the latter hypothesis, with the highest number of macrophytes species occurring in lowland TE lakes.

Alternatively, the "time hypothesis" of Pianka (1966) suggests that the low richness of some habitats is a consequence of insufficient time available for species to colonize or recolonize after an earlier ecological upheaval (Gaston and Blackburn, 2000). Compared with the low-altitude lakes of the MM and TE regions, those of the HH and HM are relatively young, only being available for post-glacial colonization since about the 17th century. This pattern is also reflected in the small number of endemic aquatic macrophytes in contrast to the higher endemism of the terrestrial vegetation of Nepal (Vetaas and Grytnes, 2002).

The influence of lake surface area is strong in CCA-2, but not in CCA-1. This result is consistent with the view of Rosenzweig (1995) that the form of the species-area curve changes with spatial scale, and shows a strong relationship among lakes within a similar climatic regime (Rørslett, 1991). In addition, Duarte *et al.* (1986) found that the percentage surface area covered by *submerged plants* is not a constant proportion of the lake area, but tends to be smaller in bigger lakes (in a study of 139 lakes). In contrast, *emergent macrophytes* colonized a rather constant proportion (7%) of the area, regardless of lake size (Duarte *et al.*, 1986). The significance of lake area in the CCA-2 analysis of MM and TE lakes could be related to the dominance of those waterbodies by emergent macrophytes.

The key nutrients (nitrogen and phosphorus) affecting trophic status were not significant environmental factors in the CCA-1 analysis, but in CCA-2 dissolved phosphorus (DP) had a significant influence. However, the environmental data are incomplete with respect to these nutrients, because there is no data on sediment chemistry, and this substrate is a primary source of nutrients for rooted macrophytes (Barko and Smart, 1986; Barko, *et al.*, 1991; Jackson *et al.*, 1994; Barko and James, 1998). The significant influence of DP in CCA-2 could be indirect, and related to effects on transparency of high algal biomass at high DP levels. In addition, dense beds of macrophytes may increase the rate of release of DP from sediment, due to locally high pH caused by inorganic carbon dynamics (Boström *et al.*, 1982; James and Barko, 1991; James *et al.*, 1996; Barko and James, 1998).

Several relatively local studies have found that the trophic state of lakes is related to the distribution of macrophyte communities (Jensén, 1994; Srivastava *et al.*, 1995; Toivonen

Huttunen, 1995). In Nordic countries, macrophyte species have been divided into broad categories according to their apparent preference for nutrient availability and trophic status, ranging from low (oligotraphents) to high (eutraphents) nutrient and trophic indicators (Linkola, 1933; Jensén, 1994; Toivonen and Huttunen, 1995; Toivonen, 2000). A similar classification has been used in central European studies (Seddon, 1972; Pietsch, 1980; Wiegleb, 1981; Mäkirinta, 1989).

A third canonical correlation analysis, CCA-3, was conducted with only the euhydrophytes (submerged, free-floating and floating-leaved species) in the MM and TE regions, using 15 environmental variables as in CCA-2. The environmental variables significantly influencing the euhydrophytes were the same as in CCA-2. The first axis clearly segregated the species on the basis of nutrient gradients (HCO_3^- and TP). The oligo-meso eutrophents *Najas minor*, *Callitriche stagnalis*, *Blyxa aubertii*, and *Potamogeton pectinatus* are positioned at the extreme right of the ordination diagram (Figure 3.33). *Hydrilla verticillata* and *Nymphoides indica* were centrally located in habitats featured by high silt load and cultural eutrophication, suggesting a wider ecological amplitude (Singhal and Singh, 1978; Papastergiadou and Babalonas, 1992). In comparison, *Azolla imbricata*, *Ceratophyllum demersum*, *Potamogeton crispus* were centrally located along with habitats with low silt and high nutrient loads (Uotila, 1971; Sahai and Sinha, 1976; Gopal and Sharma, 1990). Ordinating on the left (Figure 3.33) are pan-tropical eutrophents such as *Pistia stratiodes*, *Eichhornia crassipes*, *Monochoria hastata*, *Nymphoides hydrophyllum*, and *Ceratophyllum muricatum* (Little, 1966; Gaudet, 1979; Mitchell and Gopal, 1991).

In any particular habitat, with its unique circumstances of substrate, water quality, climate, and disturbance history, certain species will grow better than others and will be community dominants. This study of a steep altitudinal gradient over a narrow altitudinal range allowed the examination of a large range of environmental influences on species distribution. In a steep altitudinal range of habitats, environmental factors that varied widely had the greatest statistical and mathematical influence on the distribution of aquatic plants (listed in order of relative significance, these are: temperature, transparency, pH, alkalinity, and conductivity). Secondary analyses, involving narrower environmental gradients, revealed that other environmental factors were more influential at those scales, such as nutrients and surface area. It must be borne in mind, however, that this research did not examine other potentially important environmental factors, such as disturbance history and biological interactions among species (competition, herbivory, parasitism, disease, mutualism, and allelopathy).

5. SUMMARY AND CONCLUSION

Physico-chemical characteristics of 34 lakes at altitudes ranging from tropical (77 m) to high -alpine (4,980 m) were studied in the mountainous region of Nepal. The lake water chemistry was dominated by HCO_3^- among anions, and by Ca^{2+} and Mg^{2+} among cations. The average conductivity for the lakes in the High Himal (HH) region was 25.5 µS/cm, compared with 31.3 µS/cm in the High Mountains (HM), 101.4 µS/cm in the Middle Mountains (MM), and 157.3 µS/cm in the low-altitude Terai (TE) region. Lakes in the HH, MM, TE regions had moderate hardness, while those in HM were somewhat acidic. Total suspended solids showed a stronger relationship to Seechi transparency than to chlorophyll concentration, reflecting the inorganic turbidity of many lakes. Criteria related to total phosphorus, total nitrogen and chlorophyll revealed that HH and HM lakes are largely oligotrophic, with a few being mesotrophic. Lakes in the MM region are more variable, ranging from oligotrophic to hypereutrophic, and TE lakes are mostly eutrophic to hypereutrophic.

Aquatic macrophytes were present in 28 lakes, up to a maximum altitude of 4,750 m in the lakes in the Gokyo region within Sagarmatha National Park. The moderate hardness of waters has favored the extensive proliferation of the eleodids in the study region. The only moderately acidic water bodies occurred in the HM region, and these lakes supported *Sphagnum* and *Drepanocladus* as well as certain graminoids.

Species richness and diversity of aquatic macrophytes showed a linear decrease with altitude. The study region exhibits a relatively high proportion of monocotyledonous species, as is typical of aquatic macrophytes in the Indian subcontinent. Helophyte and hyperhydate species are relatively rich compared to other euhydrophytes. The high diversity of helophytes and hyperhydates in the littoral zone of lakes in the region could be due to: (1) the region being rich in the grass and sedge families, (2) generally high turbidity due to high rates of erosion in the region owing to steep mountain catchments, and (3) severe anthropogenic damage, largely associated with extensive agricultural practices that affect lakes by irrigation draw-down, flooding of paddy fields, introduction of aquatic weeds, and trampling of the littoral and riparian zones by human and livestock.

High altitude observations of the species *Ranunculus trichophyllus* (as high as 4,750 m) and *Callitriche palustris* (to 4,250 m) are the highest reports for angiospermic aquatic macrophytes anywhere in the world. Both of these aquatic plants are widely distributed in arctic and alpine environments, as are many species of phytoplankton and zooplankton in the Himalayan region.

A canonical correspondence analysis of the steepest altitudinal gradient (CCA-1) showed that the dominant abiotic environmental influences on the distribution of macrophytes were: water temperature, substrate quality, altitude, pH, transparency and conductivity (listed in order of decreasing strength). In comparison, the CCA-2 and CCA-3 analyses of a shorter altitudinal gradient of 70 m to 1500 m (tropical to warm temperate climate) found that the most important influences were temperature, lake area, total suspended solids, bicarbonate, and dissolved phosphorus. This result suggests that relatively local influences are different from those that have a large-regional basis. However, a strong climatic influence is ubiquitous in all of the gradient studies (CCA-1, CCA-2 and CCA-3). This conclusion is reflected in the fact that surface-water temperature (annual average) had the strongest influence over the altitudinal gradient from tropical to high alpine climate. The temperature gradient distinguished Arcto- tertiary floristic elements of the HH and HM regions from the more widely distributed temperate and tropical species of the MM and TE regions. This observation parallels the distribution of tundra components, such as *Ranunculus trichophyllus*, *Callitriche palustris* in the HH region (these are Holarctic species that also occur in alpine tundra lakes), to the tropical components such as *Spirodela polyrhiza* and *Lemna perpusilla* in TE. This observation is also supported by the results of the TWINSPAN analysis.

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Appendix 1. Mean environmental values of lakes

Lake	Lakes name	ALT (m)	SA (ha)	Z_{max} (m)	COND ($\mu S.cm^{-1}$)	pH	Z_s (m)	TEMP (°C)	Ca^{++} (mg/l)	Mg^{++} (mg/l)	NA^{+} (mg/l)	K^{+} (mg/l)
A1	Tsola Tso	4512	63.3	13.0	27.4	7.24	0.71	5.80	4.34	0.51	0.82	0.95
A2	Tso Mengma	4680	3.4	1.3	45.9	7.25	2.4	7.17	5.85	0.45	1.26	0.54
A3	Longponga	4715	23.8	25.3	44.8	7.24	4.0	7.58	5.68	0.43	1.07	0.57
A4	Dudh-Pokhari	4750	44.1	45.3	42.6	7.18	3.9	7.27	5.97	0.41	0.79	0.57
A5	Ngojumpa *	4980	28.0	35.3	31.9	7.03	3.9	3.70	4.26	0.35	0.81	0.57
A6	Panch-Pokhari 1*	4293	22.0	10.0	17.3	7.12	5.7	4.40	4.61	0.45	0.70	0.35
A7	Panch-Pokhari 2*	4254	26.1	22.0	17.4	7.13	5.2	4.90	4.72	0.47	0.71	0.32
A8	Panch-Pokhari 3*	4285	18.1	7.5	16.4	7.08	5.4	4.50	4.80	0.43	0.70	0.34
A9	Tso-Rolpa*	4580	140.0	56.5	40.2	6.40	0.16	6.20	6.14	0.26	0.68	1.52
A10	Gosain Kund	4300	25.0	23.3	6.7	6.86	11.3	7.13	0.70	0.20	0.83	0.17
A11	Bhairav Kund	4250	25.0	60.0	6.9	6.87	14.0	8.27	0.69	0.19	0.87	0.17
A12	Sarswati Kund	4068	12.1	7.5	7.2	6.87	6.33	7.67	0.67	0.19	0.91	0.18
B1	Gupha Pokhari	2965	6.2	6.6	36.9	5.81	2.67	11.1	3.37	1.18	1.64	0.36
B2	Ram Pokhari	3003	2.5	1.6	41.1	5.75	0.68	10.7	3.36	1.27	1.66	0.36
B3	Mauwa Pokhari	2965	6.2	5.6	30.9	5.83	2.39	10.9	3.41	1.22	1.9	0.38
B4	Salpa Pokhari	3536	14.1	15.8	26.9	5.66	5.19	10.7	3.69	0.51	2.18	0.24
B5	Phokte Tal	3364	5.2	3.7	20.8	6.50	0.88	10.2	3.99	0.59	2.05	0.34
C1	Nag Daha	1272	2.1	7.2	134.1	7.20	1.21	19.3	16.4	3.99	10.5	4.13
C2	Tau Daha	1275	4.0	6.2	258.3	7.57	0.97	19.5	35.9	7.72	6.0	2.68
C3	Rupa Tal	643	115.7	6.1	32.1	8.87	1.41	22.7	1.49	1.01	3.06	0.48
C4	Begnas Tal	694	373.7	10.6	38.8	7.71	2.31	26.5	2.55	0.85	2.31	0.34
C5	Phewa Tal	742	524.0	24.0	43.7	7.81	2.99	22.9	4.26	0.97	2.06	0.59
D1	TowerLake(KTWR)	77	2.1	3.1	100.2	8.06	0.51	26.8	8.36	2.44	2.98	1.56
D2	Lake 2 (KTWR)	77	1.6	3.1	110.3	8.12	1.00	26.6	12.1	2.96	2.97	2.05
D3	Lake 6 (KTWR)	77	2.6	3.0	98.0	8.11	0.96	26.2	11.7	2.83	2.95	2.04

Lake	Lakes name	Alt. (m)	SA (ha)	MD (m)	Cond ($\mu S.cm^{-1}$)	pH	Secchi (m)	Temp. (°C)	Ca^{++} (mg/l)	Mg^{++} (mg/l)	NA^{+} (mg/l)	K^{+} (mg/l)
D4	Kamal Kund(KTWR)	145	20.0	2.3	110.0	8.1	1.0	25.4	11.1	3.01	2.57	1.87
D5	Pathari Pond	140	3.3	1.9	114.8	8.1	0.9	26.8	10.9	3.11	2.57	1.86
D6	Pathari Pool	140	2.2	1.7	121.2	8.1	0.8	27.0	11.1	3.01	2.57	1.87
D7	Kushaha Nahar	134	37.1	1.4	99.9	8.1	0.8	25.9	11.8	2.83	2.95	2.04
D8	Barahawa Tal	190	10.3	2.9	213.8	7.9	0.8	27.5	11.3	8.67	20.7	7.33
D9	Dhakre Tal	182	2.1	3.1	197.9	7.9	1.7	27.1	30.2	13.0	4.05	6.03
D10	Beeshajar Tal	286	59.0	3.6	225.3	7.5	1.4	26.4	26.4	16.7	3.47	1.67
D11	Tamar Tal	200	7.1	2.7	125.4	7.5	1.4	28.0	16.4	1.65	3.14	2.45
D12	Devi Tal	188	14.1	3.1	370.6	7.3	1.1	28.3	49.9	10.6	11.1	4.61

Note: Lakes with * are the mean values of composite samples for two seasons without post-monsoon values (n = 10) and lakes without * include the post-monsoon values too (n =15).

Contd.

Lake	Lakes name	HCO_3^- (mg/l)	Cl^- (mg/l)	SO_4^{2-} (mg/l)	TSS (mg/l)	VSS (mg/l)	NVSS (mg/l)	TN (µg/l)	DN (µg/l)	TP (µg/l)	DP (µg/l)	CHL (µg/l)
A1	Tsola Tso	8.9	0.17	5.62	96.1	3.71	92.43	348.5	201.1	17.4	3.9	.39
A2	Tso Mengma	20.7	0.15	5.47	2.02	0.41	1.59	221.0	161.3	7.9	4.0	1.3
A3	Longponga	19.1	0.14	5.58	1.55	0.33	1.22	195.1	147.6	7.4	4.0	1.5
A4	Dudh Pokhari	18.3	0.11	3.70	1.38	0.35	1.03	219.7	164.7	8.5	4.5	1.6
A5	Nogojumba	17.7	0.19	3.45	1.29	0.25	0.44	199.3	137.8	6.3	2.8	1.0
A6	Panch Pokhari-1	11.0	0.19	3.46	1.76	0.60	1.16	130.8	77.9	10.1	5.1	.45
A7	Panch Pokhari-2	11.3	0.16	3.38	2.45	0.72	1.71	110.4	67.5	9.9	5.3	.38
A8	Panch Pokhari-3	11.3	0.23	3.33	1.64	0.67	0.97	102.2	63.5	9.9	5.0	.37
A9	Tso Rolpa	16.4	0.20	3.49	147.3	1.35	145.9	35.1	23.7	2.6	1.3	.18
A10	Gosain Kunda	2.4	0.25	5.36	0.58	0.32	0.26	94.1	69.8	8.5	4.1	2.4
A11	Bhairav Kunda	2.5	0.27	5.38	1.04	0.72	0.32	104.3	77.7	7.8	3.9	1.5
A12	Sarswati Kunda	2.4	0.26	5.39	1.82	1.17	0.65	109.0	79.3	10.2	5.3	3.1
B1	Gupha Pokhari	11.8	1.57	3.03	5.71	2.49	3.22	179.5	124.5	4.7	2.5	3.0
B2	Ram Pokhari	11.5	1.68	3.12	8.42	5.31	3.33	238.9	153.9	7.7	3.9	4.2
B3	Mauwa Pokhari	11.7	1.70	2.76	6.28	2.88	3.40	191.0	143.6	4.2	2.2	3.3
B4	Salpa Pokhari	14.3	0.16	2.88	0.88	0.63	0.25	96.5	70.2	6.1	2.3	1.5
B5	Phokte Tal	13.4	1.87	3.80	27.6	13.20	14.5	155.6	118.3	4.7	3.1	2.9
C1	Nag Daha	95.1	8.83	0.26	9.58	6.61	2.97	454.2	311.3	77.0	25.6	22.1
C2	Tau Daha	157.9	8.25	0.15	8.98	5.95	3.03	982.6	656.3	109.6	36.6	38.0
C3	Rupa Tal	18.9	0.55	0.67	8.03	5.68	2.35	381.2	239.3	42.0	19.7	13.2
C4	Begnas Tal	20.2	2.63	0.55	3.13	2.29	0.84	272.1	189.0	14.5	7.6	7.3
C5	Phewa Tal	23.7	0.57	0.19	7.01	4.70	2.29	213.3	132.4	15.9	6.7	9.9
D1	Tower Lake(KTWR)	45.4	0.31	0.20	83.05	7.96	75.1	476.3	409.9	88.5	35.5	8.4
D2	Lake-2 (KTWR)	66.7	0.28	0.21	76.98	7.19	6.34	769.6	454.3	127.7	30.8	8.7
D3	Lake-6 (KTWR)	65.5	0.27	0.20	63.53	6.04	6.21	747.4	425.8	135.5	30.9	9.0

D4	Kamal Kund(KTWR)	65.7	0.24	0.21	72.95	8.61	64.34	481.9	417.2	81.3	35.8	8.9
D5	Pathari Pond	63.5	0.24	0.19	75.98	9.65	66.33	514.0	429.7	83.8	37.8	8.5
D6	Pathari Pool	65.7	0.24	0.20	72.95	8.61	64.34	481.9	417.2	81.3	35.8	8.9
D7	Kushaha Nahar	65.5	0.27	0.21	74.40	7.88	6.21	747.4	425.8	135.5	30.9	9.0
D8	Barahawa Tal	121.2	6.65	3.54	59.89	15.16	44.73	747.5	474.1	159.5	36.8	16.2
D9	Dhakre Tal	161.4	0.39	1.34	15.66	6.84	8.09	582.6	222.0	50.5	12.3	13.5
D10	Beeshajar Tal	148.6	0.40	3.71	6.80	1.83	4.91	566.0	345.7	92.2	39.9	5.5
D11	Tamar Tal	72.1	0.44	0.36	48.38	9.60	38.78	917.1	585.0	123.1	43.3	22.4
D12	Devi Tal	185.8	0.45	2.01	8.61	2.21	6.39	262.1	129.5	16.1	7.6	3.5

Note: Lakes with * are the mean values of composite samples for two seasons without post-monsoon values (n = 10) and lakes without * include the post-monsoon values too (n =15).

Appendix 2. Seasonal means environmental values of lakes. (variables are the seasonal mean of five composites samples in each lake)

Lake/ Season	**Alt.** (m)	**SA** (ha)	**Z_{max}** (m)	**Cond.** ($\mu S.cm^{-1}$)	**pH**	**Z_s** (m)	**Temp.** (° C)	**Ca^{2+}** (mg/l)	**Mg^{2+}** (mg/l)	**Na^{+}** (mg/l)	**K^{+}** (mg/l)
A1; Pre-Monsoon	4512	30.0	8.0	23.5	7.3	0.84	6.4	5.3	0.52	0.78	0.84
; Monsoon		110.0	15.0	22.8	7.1	0.44	8.8	2.8	0.49	0.90	0.99
; Post Monsoon		50.0	16.0	29.1	7.2	0.84	2.2	4.9	0.50	0.78	1.0
A2; Pre-Monsoon	4680	3.2	1.1	51.1	7.3	2.6	6.7	6.4	0.49	1.2	0.53
; Monsoon		3.8	1.6	41.0	7.1	2.2	10.4	4.9	0.37	1.7	0.57
; Post Monsoon		3.3	1.2	45.0	7.3	2.5	4.4	6.3	0.48	0.89	0.51
A3; Pre-Monsoon	4715	23.7	25.0	47.2	7.3	4.2	6.0	6.2	0.47	0.90	0.57
; Monsoon		24.0	26.0	38.0	7.1	3.4	11.9	4.9	0.38	1.4	0.62
; Post Monsoon		23.8	25.0	45.2	7.3	4.4	4.9	5.9	0.45	0.92	0.52
A4; Pre-Monsoon	4750	44.0	45.0	44.9	7.3	4.1	5.4	6.2	0.43	0.72	0.59
; Monsoon		44.2	46.0	36.0	7.3	3.0	12.0	5.1	0.39	0.79	0.58
; Post Monsoon		44.0	45.0	43.0	7.2	4.5	4.4	6.6	0.42	0.84	0.53
A5; Pre-Monsoon	4980	28.0	35.0	35.5	7.0	3.7	2.6	4.4	0.36	0.80	0.63
; Monsoon		28.0	35.5	32.3	7.0	4.2	4.8	4.2	0.34	0.82	0.50
A6; Pre-Monsoon	4293	22.0	9.0	16.1	7.0	6.7	3.2	5.8	0.49	0.64	0.33
; Monsoon		22.1	11.0	17.5	7.0	5.3	5.6	3.4	0.40	0.76	0.37
A7; Pre-Monsoon	4254	26.0	21.0	16.0	7.0	5.2	3.2	5.7	0.54	0.67	0.29
; Monsoon		26.2	23.0	17.8	7.2	5.2	6.6	3.7	0.40	0.75	0.36
A8; Pre-Monsoon	4285	18.0	7.0	14.0	7.1	5.7	3.4	5.6	0.48	0.65	0.33
; Monsoon		18.3	8.0	18.0	7.0	5.2	5.6	4.0	0.38	0.76	0.36
A9; Pre-Monsoon	4580	139.0	55.1	40.2	6.5	0.20	6.8	7.0	0.29	0.66	1.4
; Monsoon		140.0	57.8	43.2	6.3	0.12	5.6	5.3	0.23	0.69	1.6
A10; Pre-Monsoon	4300	25.0	23.0	6.5	7.0	12.0	8.0	0.82	0.22	0.75	0.16
; Monsoon		25.0	24.0	7.0	6.9	9.8	9.6	0.54	0.16	0.91	0.19
; Post Monsoon		25.0	23.0	6.8	6.8	12.2	3.8	0.74	0.21	0.84	0.17

Lake/ Season	**Alt.** (m)	**SA** (ha)	**Z_{max}** (m)	**Cond.** ($\mu S.cm^{-1}$)	**pH**	**Z_s** (m)	**Temp.** (° C)	**Ca^{2+}** (mg/l)	**Mg^{2+}** (mg/l)	**Na^+** (mg/l)	**K^+** (mg/l)
A11; Pre-Monsoon	4250	25.0	60.0	6.9	7.0	14.4	9.6	0.77	0.22	0.85	0.17
; Monsoon		25.0	60.0	7.1	6.9	13.0	10.6	0.55	0.16	0.90	0.18
; Post Monsoon		25.0	60.0	7.0	6.9	14.7	4.6	0.74	0.19	0.84	0.17
A12; Pre-Monsoon	4068	12.0	7.0	7.1	7.0	6.8	7.0	0.78	0.21	0.84	0.17
; Monsoon		12.2	8.0	7.3	6.9	5.2	11.4	0.50	0.16	0.97	0.17
; Post Monsoon		12.0	7.5	7.0	6.9	7.0	4.6	0.73	0.19	0.91	0.18
B1; Pre-Monsoon	2965	6.2	13.0	37.5	5.8	2.9	10.4	3.8	1.2	1.7	0.37
; Monsoon		6.3	14.5	35.5	5.7	2.2	15.7	2.4	1.1	1.5	0.35
; Post Monsoon		6.2	13.3	38.5	5.7	2.9	7.2	3.9	1.2	1.7	0.36
B2; Pre-Monsoon	3003	2.5	1.5	45.0	6.0	0.74	11.6	3.8	1.2	1.7	0.36
; Monsoon		2.5	1.8	35.4	5.0	0.54	13.3	2.4	1.4	1.6	0.32
; Post Monsoon		2.5	1.6	40.1	5.9	0.76	7.2	3.8	1.2	1.7	0.40
B3; Pre-Monsoon	2965	6.2	13.0	35.5	5.8	2.6	10.8	4.1	1.3	1.8	0.38
; Monsoon		6.3	14.5	25.8	5.7	1.7	14.6	2.3	1.1	2.1	0.38
; Post Monsoon		6.2	13.3	36.1	5.8	2.9	7.4	3.8	1.3	1.8	0.39
B4; Pre-Monsoon	3536	14.0	15.0	26.5	5.7	5.8	10.9	4.4	0.60	2.1	0.24
; Monsoon		14.3	17.0	25.2	5.6	4.9	13.4	2.5	0.40	2.3	0.25
; Post Monsoon		14.0	15.3	27.5	5.7	4.9	7.8	4.2	0.53	2.2	0.21
B5; Pre-Monsoon	3364	5.2	3.2	22.2	6.5	1.1	10.2	4.6	0.63	1.9	0.35
; Monsoon		5.3	4.4	19.8	6.4	0.66	12.9	2.8	0.53	2.6	0.33
; Post Monsoon		5.2	3.5	20.5	6.5	0.92	7.6	4.5	0.60	1.7	0.33
C1; Pre-Monsoon	1272	2.0	7.0	145.0	7.5	1.3	21.2	17.2	4.1	10.9	4.2
; Monsoon		2.2	7.5	94.6	6.8	1.0	28.2	15.0	3.6	9.7	3.8
; Post Monsoon		2.0	7.0	135.0	7.5	1.2	8.6	16.9	4.3	11.1	4.4
C2; Pre-Monsoon	1275	4.0	6.0	296.0	7.5	0.96	21.6	39.3	8.5	6.5	3.1
; Monsoon		4.1	6.5	214.0	7.3	0.88	27.4	30.9	6.5	5.2	2.3
; Post Monsoon		4.0	6.0	259.0	8.0	1.1	9.4	37.6	8.2	6.3	2.7
C3; Pre-Monsoon	643	115.0	6.0	36.8	8.4	1.2	24.9	1.6	1.1	3.4	0.55

Lake/ Season	**Alt.** (m)	**SA** (ha)	**Z_{max}** (m)	**Cond.** ($\mu S.cm^{-1}$)	**pH**	**Z_s** (m)	**Temp.** (° C)	**Ca^{2+}** (mg/l)	**Mg^{2+}** (mg/l)	**Na^{+}** (mg/l)	**K^{+}** (mg/l)
; Monsoon		117.0	6.2	25.3	9.0	1.0	27.4	1.2	0.85	2.5	0.38
; Post Monsoon		115.0	6.0	34.5	9.2	2.0	15.9	1.6	1.1	3.3	0.51
C4; Pre-Monsoon	694	373.0	10.6	40.9	8.1	2.5	29.8	3.1	0.85	2.4	0.33
; Monsoon		375.0	10.7	30.0	7.2	2.1	29.8	1.4	0.77	2.1	0.29
; Post Monsoon		373.0	10.6	48.4	7.9	2.3	19.8	3.1	0.94	2.4	0.41
C5; Pre-Monsoon	742	523.0	24.0	58.2	8.1	3.7	26.3	4.9	1.2	2.2	0.66
; Monsoon		526.0	24.2	25.8	7.2	2.0	25.8	2.7	0.54	1.8	0.48
; Post Monsoon		523.0	24.0	42.5	7.8	3.3	16.9	5.2	1.1	2.1	0.62
D1; Pre-Monsoon	77	2.0	3.0	97.1	8.1	0.56	28.1	7.9	2.5	3.0	1.3
; Monsoon		2.2	3.5	121.2	7.9	0.24	31.2	9.7	2.3	2.8	2.4
; Post Monsoon		2.0	2.9	81.0	8.0	0.74	21.1	7.5	2.5	3.1	0.94
D2; Pre-Monsoon	77	1.5	3.0	99.5	8.3	1.1	28.4	11.1	2.7	3.1	1.5
; Monsoon		1.7	3.3	152.0	8.0	0.82	31.3	10.1	2.6	3.0	1.7
; Post Monsoon		1.5	3.0	83.5	8.0	1.1	20.1	15.1	3.5	2.8	3.0
D3; Pre-Monsoon	77	2.5	3.0	87.5	8.2	1.1	28.5	9.5	2.5	3.0	1.8
; Monsoon		2.7	3.2	120.0	8.1	0.76	30.9	14.7	3.4	2.7	3.0
; Post Monsoon		2.5	2.8	75.6	8.0	1.1	19.1	11.1	2.7	3.1	1.3
D4; Pre-Monsoon	145	18.0	2.1	102.8	8.1	1.1	27.5	10.4	2.8	2.6	1.8
; Monsoon		22.0	2.7	125.0	8.0	0.82	30.8	12.7	3.5	2.4	2.3
; Post Monsoon		20.0	2.0	95.4	8.0	1.1	17.9	10.3	2.7	2.7	1.4
D5; Pre-Monsoon	140	3.2	1.8	122.0	8.1	0.92	29.4	10.2	3.0	2.6	1.8
; Monsoon		3.6	2.1	129.0	8.0	0.72	31.8	12.2	3.4	2.4	2.4
; Post Monsoon		3.2	1.7	98.0	8.0	0.98	19.1	10.4	2.9	2.7	1.4
D6; Pre-Monsoon	140	2.1	1.5	135.0	8.2	0.78	30.1	10.4	2.8	2.6	1.8
; Monsoon		2.4	2.0	132.0	8.1	0.64	31.8	12.7	3.5	2.4	2.3
; Post Monsoon		2.1	1.5	105.8	8.0	0.88	19.0	10.3	2.7	2.7	1.4
D7; Pre-Monsoon	134	35.5	1.3	91.2	8.1	0.84	28.4	9.5	2.5	3.0	1.8
; Monsoon		40.2	1.8	152.0	8.0	0.70	30.9	14.7	3.4	2.7	3.0

Lake/ Season	**Alt.** (m)	**SA** (ha)	**Z_{max}** (m)	**Cond.** ($\mu S.cm^{-1}$)	**pH**	**Z_s** (m)	**Temp.** (° C)	**Ca^{2+}** (mg/l)	**Mg^{2+}** (mg/l)	**Na^+** (mg/l)	**K^+** (mg/l)
; Post Monsoon		35.5	1.2	72.0	8.1	0.92	18.4	11.1	2.7	3.1	1.3
D8; Pre-Monsoon	190	10.0	2.8	225.7	7.8	0.86	29.7	9.5	8.9	22.5	7.5
; Monsoon		10.8	3.0	153.0	8.0	0.66	32.4	12.8	8.3	17.6	6.8
; Post Monsoon		10.0	2.8	245.0	8.0	0.86	20.4	11.6	8.8	21.9	7.7
D9; Pre-Monsoon	182	2.0	3.0	198.0	7.9	2.0	30.3	30.7	13.9	4.4	6.9
; Monsoon		2.2	3.2	183.8	7.8	1.2	32.6	25.3	10.1	3.4	5.0
; Post Monsoon		2.0	3.0	181.3	7.9	2.1	18.6	34.6	15.1	4.4	6.1
A10; Pre-Monsoon	286	58.0	3.5	202.0	7.5	1.6	29.4	30.2	21.4	3.9	2.1
; Monsoon		61.0	3.7	183.8	7.5	1.0	31.5	18.3	9.8	3.1	1.3
; Post Monsoon		58.0	3.5	262.5	7.7	1.5	18.4	30.9	19.0	3.4	1.5
A11; Pre-Monsoon	200	7.0	2.0	125.2	7.6	1.5	31.0	18.5	1.7	4.0	3.0
; Monsoon		7.2	2.2	121.0	7.5	1.1	33.6	7.6	1.1	3.0	2.5
; Post Monsoon		7.0	2.0	121.0	7.3	1.5	19.5	23.0	2.2	2.5	1.9
A12; Pre-Monsoon	188	14.0	3.0	335.0	7.3	1.1	31.2	52.8	11.7	11.9	5.2
; Monsoon		14.3	3.2	360.0	7.3	0.92	33.2	38.7	8.3	9.2	3.6
; Post Monsoon		14.0	3.2	330.0	7.5	1.3	20.5	58.3	11.8	12.2	5.0
All Grps	**2118.**	**48.5**	**12.3**	**84.9**	**7.3**	**4.8**	**17.1**	**10.2**	**2.9**	**3.2**	**1.6**

Contd.

Lake/ Season	**HCO_3^{--}** (mg/l)	**Cl^-** (mg/l)	**SO_4^-** (mg/l)	**TSS** (mg/l)	**VSS** (mg/l)	**NVSS** (mg/l)	**TN** (µg/l)	**DN** (µg/l)	**TP** (µg/l)	**DP** (µg/l)	**CHL.** (µg/l)
A1; Pre-Monsoon	10.34	.16	5.72	95.64	3.16	92.48	368.80	219.80	16.20	3.84	.44
; Monsoon	6.82	.18	4.82	103.76	4.34	99.42	305.20	180.80	19.60	4.24	.33
; Post Monsoon	9.49	.16	6.32	89.00	3.62	85.38	371.60	202.80	16.26	3.72	.39
A2; Pre-Monsoon	24.66	.14	5.11	1.30	.22	1.04	211.80	162.20	7.50	3.70	1.20
; Monsoon	15.14	.17	5.64	3.48	.78	2.70	246.00	167.00	9.30	4.80	1.48
; Post Monsoon	22.40	.14	5.65	1.28	.24	1.04	205.20	154.60	7.00	3.50	1.24
A3; Pre-Monsoon	21.22	.12	5.48	.56	.21	.35	207.20	154.20	6.40	3.40	1.53
; Monsoon	16.64	.14	5.69	2.74	.46	2.28	227.00	173.20	8.20	4.40	1.75
; Post Monsoon	19.34	.16	5.58	1.36	.32	1.04	151.20	115.40	7.50	4.20	1.35
A4; Pre-Monsoon	19.80	.09	3.43	.83	.31	.52	211.40	164.00	7.80	4.00	1.31
; Monsoon	16.26	.14	3.91	2.40	.41	1.99	244.00	173.40	9.46	5.10	2.10
; Post Monsoon	18.70	.09	3.75	.90	.32	.58	203.60	156.80	8.34	4.40	1.42
A5; Pre-Monsoon	18.36	.19	3.53	1.90	.24	.44	163.00	120.40	6.30	2.70	.91
; Monsoon	17.12	.20	3.38	.68	.26	.44	235.60	155.20	6.30	3.00	1.10
A6; Pre-Monsoon	12.85	.23	3.68	1.62	.54	1.08	144.20	87.00	9.00	4.40	.47
; Monsoon	9.22	.15	3.25	1.90	.66	1.24	117.40	68.80	11.20	5.70	.43
A7; Pre-Monsoon	13.16	.17	3.30	2.20	.68	1.52	101.80	59.80	8.80	5.20	.36
; Monsoon	9.44	.15	3.46	2.70	.76	1.90	119.00	75.20	11.00	5.50	.40
A8; Pre-Monsoon	13.32	.28	3.29	1.52	.68	.84	101.60	63.40	9.20	4.60	.42
; Monsoon	9.20	.17	3.36	1.76	.66	1.10	102.40	63.60	10.64	5.46	.32
A9; Pre-Monsoon	17.62	.17	3.59	133.42	1.20	132.22	39.20	26.80	2.82	1.42	.17
; Monsoon	15.14	.23	3.40	161.20	1.50	159.70	31.00	20.60	2.48	1.20	.20
A10; Pre-Monsoon	2.74	.22	5.72	.52	.24	.28	90.60	64.00	8.20	4.00	2.68
; Monsoon	1.54	.27	5.04	.64	.43	.21	99.80	82.40	8.56	4.02	2.54
; Post Monsoon	2.86	.24	5.32	.58	.28	.30	91.40	63.00	8.58	4.22	2.08

Lake/ Season	**HCO_3^{--}** (mg/l)	**Cl^-** (mg/l)	**SO_4^-** (mg/l)	**TSS** (mg/l)	**VSS** (mg/l)	**NVSS** (mg/l)	**TN** (µg/l)	**DN** (µg/l)	**TP** (µg/l)	**DP** (µg/l)	**CHL.** (µg/l)
A11; Pre-Monsoon	2.97	.28	5.78	.94	.66	.28	111.80	85.20	8.26	4.28	1.54
; Monsoon	1.58	.29	4.98	1.22	.84	.38	94.80	64.20	7.26	3.40	1.72
; Post Monsoon	2.92	.25	5.38	.96	.66	.30	106.40	83.60	8.02	4.04	1.30
A12; Pre-Monsoon	2.94	.26	5.74	1.66	1.06	.60	116.00	92.80	10.90	5.64	3.52
; Monsoon	1.58	.27	5.10	2.06	1.36	.70	98.00	64.80	8.98	4.60	2.96
; Post Monsoon	2.76	.25	5.34	1.74	1.08	.66	113.00	80.40	10.80	5.56	2.80
B1; Pre-Monsoon	13.38	1.63	2.96	4.98	2.22	2.76	189.00	129.20	4.92	2.66	3.00
; Monsoon	9.10	1.54	3.02	6.58	2.98	3.60	169.00	119.00	4.38	2.30	2.78
; Post Monsoon	13.06	1.53	3.12	5.56	2.26	3.30	180.40	125.40	4.70	2.54	3.24
B2; Pre-Monsoon	12.64	1.70	3.10	7.16	3.98	3.18	248.60	157.00	8.00	4.04	4.48
; Monsoon	8.92	1.58	3.06	10.08	7.10	3.64	224.00	149.20	6.94	3.50	3.56
; Post Monsoon	12.98	1.77	3.20	8.02	4.84	3.18	244.00	155.40	8.14	4.10	4.54
B3; Pre-Monsoon	13.16	1.73	2.76	5.88	2.70	3.18	195.20	152.60	4.50	2.38	3.68
; Monsoon	8.86	1.69	2.70	6.98	3.26	3.72	180.20	124.60	3.92	2.08	2.82
; Post Monsoon	13.12	1.69	2.82	5.98	2.68	3.30	197.60	153.60	4.20	2.22	3.36
B4; Pre-Monsoon	15.62	.17	2.80	.58	.38	.20	98.40	71.40	6.62	2.50	1.47
; Monsoon	12.00	.16	2.94	1.16	.84	.32	93.20	67.60	5.70	2.08	1.36
; Post Monsoon	15.28	.16	2.90	.90	.66	.24	97.80	71.60	6.00	2.28	1.55
B5; Pre-Monsoon	14.12	1.86	4.14	21.80	10.40	11.40	158.80	119.80	5.36	3.44	3.37
; Monsoon	12.16	1.82	3.74	35.20	16.80	18.40	151.80	113.60	4.00	2.64	2.52
; Post Monsoon	14.06	1.92	3.52	25.80	12.40	13.80	156.20	121.40	4.76	3.14	2.78
C1; Pre-Monsoon	101.40	9.08	.28	8.56	5.62	2.94	504.00	327.60	76.60	25.74	22.66
; Monsoon	86.40	8.28	.26	11.18	7.86	3.32	368.60	282.20	75.40	25.00	21.50
; Post Monsoon	97.60	9.14	.24	9.00	6.34	2.66	490.00	324.00	79.00	25.98	22.14
C2; Pre-Monsoon	165.82	8.84	.18	8.20	5.20	3.00	992.00	635.20	110.60	37.80	39.77
; Monsoon	148.76	7.54	.12	10.68	7.64	3.04	866.00	613.80	82.74	28.36	36.64
; Post Monsoon	159.24	8.38	.16	8.06	5.02	3.04	1089.8	720.00	135.40	43.52	37.72
C3; Pre-Monsoon	20.15	.54	.68	6.02	3.94	2.08	384.20	272.80	36.80	17.20	12.77

Lake/ Season	**HCO_3^-** (mg/l)	**Cl^-** (mg/l)	**SO_4^-** (mg/l)	**TSS** (mg/l)	**VSS** (mg/l)	**NVSS** (mg/l)	**TN** (µg/l)	**DN** (µg/l)	**TP** (µg/l)	**DP** (µg/l)	**CHL.** (µg/l)
; Monsoon	16.36	.61	.62	11.48	8.76	2.72	370.00	167.80	62.00	21.60	18.43
; Post Monsoon	20.27	.49	.70	6.58	4.34	2.24	389.40	277.40	27.20	20.20	8.25
C4; Pre-Monsoon	21.14	3.06	.58	3.06	2.28	.78	306.40	210.20	13.00	6.60	5.70
; Monsoon	19.36	1.90	.50	3.52	2.54	.98	224.40	139.60	16.70	9.10	6.24
; Post Monsoon	20.20	2.93	.58	2.82	2.06	.76	285.60	217.20	13.80	7.10	9.84
C5; Pre-Monsoon	29.59	.67	.20	6.12	3.92	2.20	236.00	153.20	14.80	6.40	9.90
; Monsoon	12.28	.49	.14	8.96	6.44	2.48	185.40	124.80	17.80	7.60	6.92
; Post Monsoon	29.16	.56	.22	5.94	3.74	2.18	218.40	119.20	15.00	6.20	12.96
D1; Pre-Monsoon	46.68	.28	.22	38.12	5.42	32.70	752.80	662.40	55.00	30.80	14.28
; Monsoon	48.96	.36	.16	190.74	14.82	175.92	288.60	254.60	182.20	60.60	7.06
; Post Monsoon	40.58	.30	.22	20.28	3.64	16.64	387.40	312.80	28.40	15.00	3.98
D2; Pre-Monsoon	61.76	.28	.22	32.46	5.02	5.00	768.00	448.60	70.40	25.40	6.40
; Monsoon	64.02	.26	.26	170.00	12.06	5.76	846.00	514.00	87.80	29.60	10.68
; Post Monsoon	74.26	.31	.16	28.48	4.48	8.26	694.80	400.20	225.00	37.40	8.96
D3; Pre-Monsoon	63.50	.24	.24	31.60	4.92	5.70	809.00	431.60	82.40	27.80	12.56
; Monsoon	73.10	.30	.16	123.40	8.14	7.98	701.20	401.00	248.00	38.40	9.12
; Post Monsoon	59.94	.27	.20	35.60	5.06	4.94	732.00	444.80	76.00	26.60	5.42
D4; Pre-Monsoon	63.36	.21	.24	34.94	5.38	29.56	704.20	636.80	56.60	31.00	11.98
; Monsoon	73.70	.26	.16	159.40	16.30	143.10	297.60	263.40	143.00	50.40	7.02
; Post Monsoon	60.10	.24	.22	24.50	4.14	20.36	444.00	351.40	44.20	26.00	7.58
D5; Pre-Monsoon	63.06	.21	.20	40.14	6.42	33.72	767.20	658.60	61.60	35.60	10.78
; Monsoon	73.76	.26	.16	159.40	16.30	143.10	301.60	263.60	143.60	51.00	7.04
; Post Monsoon	53.76	.24	.22	28.40	6.22	22.18	473.20	366.80	46.20	26.80	7.58
D6; Pre-Monsoon	63.36	.21	.22	34.94	5.38	29.56	704.20	636.80	56.60	31.00	11.98
; Monsoon	73.70	.26	.16	159.40	16.30	143.10	297.60	263.40	143.00	50.40	7.02
; Post Monsoon	60.10	.24	.22	24.50	4.14	20.36	444.00	351.40	44.20	26.00	7.58
D7; Pre-Monsoon	63.50	.24	.26	44.80	5.76	5.70	809.00	431.60	82.40	27.80	12.56
; Monsoon	73.10	.30	.16	136.20	12.14	7.98	701.20	401.00	248.00	38.40	9.12

Lake/ Season	**HCO_3^{--}** (mg/l)	**Cl^-** (mg/l)	**SO_4^-** (mg/l)	**TSS** (mg/l)	**VSS** (mg/l)	**NVSS** (mg/l)	**TN** (µg/l)	**DN** (µg/l)	**TP** (µg/l)	**DP** (µg/l)	**CHL.** (µg/l)
; Post Monsoon	59.94	.27	.22	42.20	5.74	4.94	732.00	444.80	76.00	26.60	5.42
D8; Pre-Monsoon	138.00	6.40	3.84	29.60	6.40	23.20	831.20	511.80	138.20	42.80	18.66
; Monsoon	103.80	7.49	3.14	123.80	33.18	90.62	694.80	401.00	225.00	37.40	17.62
; Post Monsoon	121.76	6.07	3.64	26.28	5.90	20.38	716.60	509.40	115.20	30.20	12.43
D9; Pre-Monsoon	168.02	.32	1.32	14.28	6.50	6.90	577.00	203.40	48.20	11.90	16.09
; Monsoon	132.18	.51	1.42	19.04	7.56	9.42	635.60	270.40	60.20	13.78	11.04
; Post Monsoon	184.10	.35	1.29	13.66	6.46	7.96	535.20	192.20	43.00	11.08	13.39
D10; Pre-Monsoon	180.96	.39	3.78	4.40	1.58	2.82	451.60	265.20	76.80	33.60	6.05
; Monsoon	93.28	.48	3.20	11.80	2.52	9.28	807.40	527.00	109.80	46.20	3.62
; Post Monsoon	171.66	.33	4.14	4.20	1.40	2.64	439.00	244.80	90.00	39.80	6.96
D11; Pre-Monsoon	82.66	.72	.41	27.72	6.04	21.68	1010.4	673.40	73.60	28.40	11.19
; Monsoon	11.62	.41	.32	100.72	19.02	81.70	1152.0	774.80	140.60	54.80	41.34
; Post Monsoon	121.90	.20	.33	16.70	3.73	12.97	589.00	306.80	155.00	46.80	14.61
D12; Pre-Monsoon	200.50	.42	2.12	7.08	2.00	5.08	215.60	112.00	16.78	7.20	3.52
; Monsoon	146.38	.49	1.84	11.50	2.66	8.84	385.60	187.80	17.48	8.68	4.14
; Post Monsoon	210.76	.43	2.08	7.24	1.98	5.26	185.20	88.60	14.12	6.86	2.76
All Grps	**50.27**	**1.24**	**2.40**	**29.45**	**4.66**	**19.35**	**375.32**	**248.14**	**48.09**	**16.40**	**7.46**

Appendix 3. Seasonal differences of environmental values.

	High Himal				High Mountains				Middle Mountains				Terai			
	χ^2	(A) Pr=Mo	(B) Pr=Po	(C) Mo=Po	χ^2	(A) Pr=Mo	(B) Pr=Po	(C) Mo=Po	χ^2	(A) Pr=Mo	(B) Pr=Po	(C) Mo=Po	χ^2	(A) Pr=Mo	(B) Pr=Po	(C) Mo=Po
Alt.(m)	ns	4512.0	4512.0	4512.0	ns	3003.0	3003.0	3003.0	ns	742.0	742.0	742.0	ns	142.5	142.5	142.5
SA(ha)	ns	25.0	25.0	25.0	ns	6.2	6.3	6.2	ns	115.0	117.0	115.0	ns	5.1	5.4	5.1
Z_{max}	ns	23.0	23.5	23.0	ns	13.0	14.5	13.3	ns	7.0	7.5	7.0	ns	2.9**	3.1	2.80**
Cond	ns	23.5	20.7	27.4	ns	30.0*	26.1	34.1*	ns	58.5**	32.8	47.5**	**	110.6**	138.7	104.0**
pH	**	7.10**	7.0	7.20**	**	5.8**	5.7	5.9**	**	8.0**	7.3	8.0**	**	8.1**	8.0	8.1**
Z_s	ns	4.50	5.0	4.5	ns	2.1	1.7	2.5	ns	1.4*	1.1	2.0**	**	1.0**	0.80	1.1**
Temp	**	6.0**	8.0**	4.0**	**	11.0**	14.0**	7.0**	**	25.0**	28.0**	16.0**	**	29.15**	31.8**	19.1**
Ca^{2+}	**	4.5**	3.8	4.9*	**	3.8**	2.4	4.0**	ns	5.1*	2.6	5.1	**	10.5	13.0	11.5
Mg^{2+}	**	0.38**	0.35	0.39	ns	1.14*	1.1	1.18	ns	1.25*	0.9	1.2*	**	2.8	3.5	2.9
Na^+	**	0.85**	0.87**	0.9	ns	1.8*	2.0	1.75	ns	3.30*	2.49	3.4	*	3.15**	2.9	3.1*
K^+	ns	0.45	0.44	0.5	*	0.35*	0.32	0.36	ns	0.66	0.5	0.61	**	1.9*	2.7*	1.65**
HCO_3^-	*	12.8**	9.7**	9.8	**	13.0**	10.0	13.3**	ns	30.9*	19.6	29.1*	ns	64.5	74.0	67.35
Cl^-	ns	0.19	0.2	0.19	ns	1.65	1.6	1.65	ns	3.1	1.9	2.8	ns	0.27**	0.32	0.29**
SO_4^{2-}	**	5.0	4.45**	5.5**	ns	3.10	3.1	3.0	ns	0.30	0.30	0.30	ns	0.3	0.20	0.22
TSS	**	1.16**	2.1	1.2**	*	6.30*	7.2	6.0	**	6.4**	10.2	7.2**	**	32.2**	130.5**	22.5**
VSS	*	0.60**	0.7	0.3*	ns	3.0	3.2	2.7	**	4.2**	7.4	4.9**	**	5.3**	14.0**	4.35**
NVSS	*	1.00**	1.45	0.7**	ns	3.3*	3.6	3.3	*	2.2	2.8	2.2*	ns	12.5**	42.5	10.2**
TN	ns	125.0	116.0	148.0	ns	180.0	170.0	180.0	**	385.0*	365.0	391.0*	**	750.0**	605.5**	542.5
DN	ns	101.0	85.0	115.0	*	125.0*	121.0	127.0	ns	274.0*	270.0	278.0	**	491.5**	322.0**	329.0
TP	*	8.5*	9.0	8.5	ns	5.0*	4.5	5.0	ns	38.0	61.0	25.0	**	61.0**	155.0	56.0**
DP	*	4.1*	4.45	4.0	ns	2.6**	2.3	2.6	ns	17.0	21.0	20.0	**	29.0**	41.0	27.5**
CHL	ns	1.20	1.20*	1.3	ns	3.0*	2.8	3.6	ns	12.5	16.5	13.5	**	12.2**	7.5**	6.85

Note: Kruskal-Wallis test followed by Mann-Whitney U test showing difference median value of variables; ns = not significant ($p>0.05$); * = significant at $P>0.05$; ** = significant at $P>0.01$. A, B, C are values in pre-monsoon (Pr), monsoon (Mo) and post-monsoon (Po); Pr=Mo, Pr=Po and Mo=Po signify the comparison of two seasonal values with Mann- Whitney U test.

Appendix 4. Species list of aquatic macrophytes

Explanation of life-form terms: Broad classification of life-forms of aquatic macrophytes is adopted (Sculthrope, 1967 (LFS); Cronk and Fennessy, 2001), with further details from Cook (LFC; 1996). Species name followed by the authority abbreviated according to R.K. Brummitt & C.E. Powell (1992). Vaucher specimens were contributed to the National Herbarium, Godawari and the herbarium in the Central Department of Botany, TU, Nepal.

(1) **Emer = Emergents**:
- (I) Hel = Helophytes- Terrestrial plants which tolerate submergence.
  - Ten = Tenagophyte- Juvenile submerged, adult usually terrestrial.
- (II) Hyp= Hyperhydate- Emergent aquatic (lower parts always in water).

(2) **Subm = Submerged**:
- Hap = Haptophyte – Attached to but not penetrating the substrate.
- Ros = Rosulate – Submerged, bottom rooted, leaves in a rosette (E = Isotids).
- Vit = Vittate – Submerged, bottom rooted, leaves cauline (Eleodid).

(3) **F-L = Floating –Leaved Plants**
- Eph = Ephydate – Bottom rooted with floated leaves

(4) **F-F = Free- Floating Plants**
- Pla = Plankton – Free- swimming below the water surface.
- Ple = Pleustophyte – Free-floating (at the water surface)

		Species	Code	Perr	Life-forms (LFC)	Life – forms (LFS)	Total lakes with spp.			
							HH	HM	MM	TE
1		**MACRO-ALGAE** **Characeae**								
	1	*Nitella mucronata* (Thuill.) Kuetz	Nit muc	Per	Hap	Sub			1	
1		**BRYOPHYTES** **Amblystegiaceae**								
	2	*Drepanocladus fluitans* (Hedio.) Warnst.	Dre flu	Per	Hap	Sub		1		

		Species	Code	Perr	LFC	LFS	HH	HM	MM	TE
2	**Marchantiaceae**									
	3	*Marchantia palmata* Nees	Mar pal	Per	Ten	Hel			2	1
3	**Fontinalaceae**									
	4	*Fontinalis* spp.	Fon spp	Per	Hap	Sub		1		
4	**Ricciaceae**									
	5	*Riccia fluitans* L.	Ric flu	Per	Hap	Sub			1	
5	**Plagiotheciaceae**									
	6	*Isopteris* spp.	Iso spp	Per	Hel	Hel			1	1
6	**Sphagnaceae**									
	7	*Sphagnum* spp.	Sph spp	Per	Hap	Sub		4		
	PTERIDOPHYTES									
1	**Azollaceae**									
	8	*Azolla imbricata* (Roxb.) Nakai.	Azo imb	Ann	Ple	F-F		1	5	5
	9	*A pinnata* Fr. & Sav (R.Br.)	Azo pin	Ann	Ple	F-F				7
2	**Pteridaceae**									
	10	*Ceratopteris thalictroides* (L.) Brongniart.	Cera tha	Per	Ple/Hyp	Hyp			2	2
	11	*Pteris vittata* L.	Pte vit	Per	Hel	Hel			1	8
3	**Salviniaceae**									
	12	*Salvinia molesta* Mitchell	Sal mol	Per	Ple	F-F			3	2
4	**Equisetaceae**									
	13	*Equisetum debile* Vaucher	Equ deb	Per	Hel	Hel		2	4	8
5	**Isoetaceae**									
	14	*Isoetes coromandelina* L.	Iso cor	Per	Ros	Sub				1
6	**Marsileaceae**									
	15	*Marsilea crenata* Presl	Mar cre	Per	Ten	Hel			2	5

		Species	Code	Perr	LFC	LFS	HH	HM	MM	TE
		<u>**ANGIOSPERMAE (DICOTYLEDONAE)**</u>								
1		**Acanthaceae**								
	16	*Hygrophila auriculata* (K. Schumacher) Heine	Hyg aur	Per	Ten/Hyp	Hel				2
	17	*H salicifolia* (Vahl) Nees	Hyg sal	Ann	Hyp/Ten	Hyp				1
	18	*Justicia quinqueangularis* J. König ex Roxb.	Jus qui	Per	Hel	Hel				1
2		**Amaranthaceae**								
	19	*Alternanthera philoxeroides* (Martius) Grisebach	Alt phi	Per	Hyp	Hyp				6
	20	*A sessilis* (L.) DC.	Alt ses	Ann	Hel/ Ple	Hel			2	3
3		**Apiaceae** (Umbelliferae)								
	21	*Centella asiatica* (L.) Urban	Cen asi	Per	Hel	Hel			2	12
	22	*Hydrocotyle sibthorpioides* Lamarck	Hyd sib	Per	Hel	Hel		1	2	
	23	*Oenanthe javanica* (Blume) DC.	Oen Jav	Per	Hyp /Hel	Hyp			2	12
	24	*O thomsonii* C.B. Clarke	Oen tho	Per	Hel	Hel		1		
4		**Asclepiadaceae**								
	25	*Oxystelma esculentum* (L.f.) R.Brown ex J.A. Schultes	Oxy esc	Per	Hel	Hel		1		1
5		**Asteraceae**								
	26	*Caesulia axillaris* Roxburgh	Cae axi	Per	Hel/hyp	Hel				4
	27	*Centipeda minima* (L.) A. Braun et Ascherson	Cen min	Ann	Hel	Hel				2
	28	*Cyathocline purpurea* (Buch.-Ham.ex D.Don) O. Kuntze	Cya pur	Ann	Hel	Hel				1
	29	*Eclipta prostrata* L.	Ecl pro	Ann	Hel	Hel				6
	30	*Enydra fluctuans* Loureiro	Eny flu	Ann	Hel	Hel				1
	31	*Spilanthes iabadicensis* A.H. Moore	Spi iab	Ann	Hel	Hel				1
6		**Boraginaceae**								
	32	*Heliotropium indicum* L.	Hel ind	Ann	Hel	Hel				1
7		**Brassicaceae** (Cruciferae)								
	33	*Nasturtium officinale* R.Brown	Nas off	Per	Hyp/ Hel	Hyp			2	

		Species	Code	Perr	LFC	LFS	HH	HM	MM	TE
8	**Callitrichaceae**									
	34	*Callitriche palustris* L.	Cal pal	Ann	Vit/ Ros	Sub	1			1
	35	*C stagnalis* Scopoli	Cal sta	Ann	Vit/Eph	Sub			1	
9	**Campanulaceae**									
	36	*Lobelia alsinoides* Lamark	Lob als	Ann	Hel	Hel			2	
10	**Ceratophyllaceae**									
	37	*Ceratophyllum demersum* L.	Cer dem	Per	Pla-Vit	Sub			5	6
	38	*C muricatum* Chamisso	Cer mur	Per	Pla-Vit	Sub				3
11	**Convolvulaceae**									
	39	*Ipomoea aquatica* Forsskal	Ipo aqu	Per	Hyp	Hyp				4
	40	*I carnea* Martius ex Choisy	Ipo car	Per	Hel	Hel				5
12	**Fabaceae** (Leguminosae)									
	41	*Aeschynomene asper* L.	Aes asp	Per	Hel/Hyp	Hyp				1
	42	*A indica* L.	Aes ind	Per	Hel/Hyp	Hyp			2	1
13	**Hippuridaceae**									
	43	*Hippuris vulgaris* L.	Hip vul	Ann	Hel	Hel			2	
14	**Lentibulariaceae**									
	44	*Utricularia aurea* Loureiro	Utr aur	Ann	Pla	Sub			3	5
	45	*U australis* R.Brown	Utr aus	Per	Pla/ten	Sub			2	
	46	*U gibba* L.	Utr gib	Per	Pla/ten	Sub			1	
15	**Lythraceae**									
	47	*Ammannia baccifera* L.	Amm bac	Ann	Hyp/Hel	Hyp			1	3
	48	*Rotala indica* (Wildenow) Koehne	Rot ind	Ann	Ten/Hyp	Hel				1
	49	*R rotundifolia* (Buch.-Ham.) ex Roxb.	Rot rot	Per	Hyp/Ten	Hel		1	4	9
16	**Menyanthaceae** (Gentianaceae)									
	50	*Nymphoides hydrophyllum* (Loureiro) O. Kuntze	Nym hyd	Per	Eph	F-L				3

		Species	Code	Perr	LFC	LFS	HH	HM	MM	TE
	51	*N indica* (L.) Kuntze	Nym ind	Per	Eph	F-L			4	4
17	**Nelumbonaceae** (Nymphaeaceae)									
	52	*Nelumbo nucifera* Gaertner	Nel nuc	Ann	Eph/Hyp	F-L			3	1
18	**Nymphaeaceae**									
	53	*Nymphaea stellata* (Sims) Hook.f & Thomson	Nym ste	Per	Eph	F-L				2
19	**Onagraceae**									
	54	*Ludwigia adscendens* (L.) H.Hara	Lud ads	Per	Hyp	Hyp			2	2
	55	*L hyssopifolia* (G.Don) Exell	Lud hys	Ann	Hyp	Hyp				2
	56	*L octovalvis* (Jacquin) Raven	Lud oct	Per	Hel	Hel				1
	57	*L perennis* L.	Lud per	Ann	Hel	Hel				2
20	**Polygonaceae**									
	58	*Persicaria barbata* (L.) H. Hara	Per bar	Ann	Hel	Hel			2	8
	59	*P glabra* (Willdenow) Gomez de la Maza	Per gla	Ann	Hel	Hel				6
	60	*P hydropiper* (L.) Spach	Per hyd	Ann	Hel	Hel			3	8
	61	*P lapathifolia* (Schrank) H. Gross	Per lap	Ann	Hel/Hyp	Hel			3	1
	62	*Polygonum plebeium* R. Brown	Pol ple	Ann	Hel	Hel			2	
21	**Ranunculaceae**									
	63	*Ranunculus repens* L.	Ran rep	Ann	Hel	Hel			2	
	64	*R sceleratus* L.	Ran sce	Ann	Ten/Eph	Hel			1	5
	65	*R trichophyllus* Chaix	Ran tri	Per	Ros	Sub	3			
22	**Rubiaceae**									
	66	*Oldenlandia corymbosa* L.	Old cor	Ann	Hel	Hel				2
	67	*O diffusa* (Willdenow) Roxb.	Old dif	Per	Hel	Hel				2
23	**Scrophulariaceae**									
	68	*Centranthera cochinchinensis* (D.Don)	Cent coc	Ann	Hel	Hel				1
	69	*Limnophila chinensis* (Osbeck) Merrill	Lim chi	Ann	Ten/Hel	Hel				1

		Species	Code	Perr	LFC	LFS	HH	HM	MM	TE
	70	*L sessiliflora* (Vahl) Blume	Lim ses	Ann	Hel	Hel			1	
	71	*Lindernia anagallis* (Burm.f.) Pennell	Lin ana	Ann	Hel	Hel				1
	72	*L antipoda* (L.) Alston	Lin ant	Ann	Hel	Hel				5
	73	*L ciliata* (Colsmann) Pennell	Lin cil	Ann	Hel	Hel				1
	74	*L procumbens* (Krocker) Borbas	Lin pro	Ann	Hel	Hel				1
	75	*L pusilla* (Willdenow) Boldingh	Lin pus	Ann	Hel/Ten	Hel				1
	76	*Veronica anagallis-aquatica* L.	Ver ana	Per	Hel/Ple	Hel				2
24	**Sphenocleaceae**									
	77	*Sphenoclea zeylanica* Gaertner	Sph zey	Ann	Hel/ Hyp	Hel				1
25	**Trapaceae**									
	78	*Trapa quadrispinosa* Roxb.	Tra qua	Ann	Eph	F-L			3	
	79	*T natans L. Var. bispinosa* (Roxb.) Makino	Tra nat	Ann	Eph	F-L			3	1
26	**Verbenaceae**									
	80	*Phyla nodiflora* (L.) E. Greene	Phy nod	Per	Hel	Hel			1	6
	ANGIOSPERMAE (MONOCOTYLEDONAE)									
1	**Alismataceae**									
	81	*Alisma plantago-aquatica* L.	Ali pla	Ann	Eph/Hyp	Hyp			2	4
	82	*Caldesia parnassifolia* (L.) Parl	Cal par	Per	Eph/Hyp	Hyp			2	
	83	*Sagittaria guayanenesis* D.Don	Sag gua	Ann	Hyp	Hyp				1
	84	*S trifolia* L.	Sag tri	Per	Hyp	Hyp				1
2	**Araceae**									
	85	*Pistia stratiotes* L.	Pis str	Per	Ple	F-F				8
3	**Commelinaceae**									
	86	*Amischophacelus axillaris* (L.) Roa & Kammathy	Ami axi	Ann	Hel	Hel				1
	87	*Commelina benghalensis* L.	Com ben	Per	Hel	Hel				3
	88	*C diffusa* N.L. Burman	Com dif	Ann	Hel	Hel				5

		Species	Code	Perr	LFC	LFS	HH	HM	MM	TE
	89	*Floscopa scandens* Loureiro	Flo sca	Per	Hel	Hel			2	4
	90	*Murdannia nudiflora* (L.) Brenan	Mur nud	Ann	Hel	Hel				2
4	**Cyperaceae**									
	91	*Bulbostylis densa* (Wallich) Handel-Mazzetti	Bul den	Ann	Ten/ Hel	Hel		1		
	92	*Carex cruciata* Wahlenb.	Car cru	Ann	Hel	Hel		1		
	93	*Cyperus alternifolius* (Rottb.) Kük	Cyp alt	Ann	Hel	Hel			1	
	94	*C compactus* (Retzius) Boldingh	Cyp com	Ann	Hel	Hel				5
	95	*C compressus* L.	Cyp comp	Ann	Ten/ Hel	Hel				1
	96	*C difformis* L.	Cyp dif	Ann	Ten/ Hel	Hel		1	2	4
	97	*C digitatus* Roxb.	Cyp dig	Per	Ten/Hel	Hel				1
	98	*C distans* L.	Cyp dis	Per	Ten/Hel	Hel				1
	99	*C esculentus* L.	Cyp esc	Per	Hel	Hel			2	
	100	*C exaltatus* Retzius	Cyp exa	Per	Ten/ Hel	Hel				1
	101	*C iria* L.	Cyp iri	Ann	Ten/Hel	Hel				8
	102	*C pilosus* Vahl	Cyp pil	Per	Ten/hel	Hel			2	
	103	*C rotundus* L.	Cyp rot	Per	Hel	Hel			2	5
	104	*C tenuispica* Steudel	Cyp ten	Ann	Hyp/ Hel	Hel				1
	105	*Eleocharis atropurpurea* (Retzius) Kunth	Ele atr	Ann	Hyp/Ten	Hyp				3
	106	*E congesta* D.Don	Ele con	Ann	Hyp/Hel	Hyp			1	
	107	*E dulcis* (N.L.Burman) Trinius ex Henschel	Ele dul	Per	Hyp/Ten	Hyp			2	
	108	*Fimbristylis aestivalis* (Retz.) Vahl	Fim aes	Ann	Hel	Hel				4
	109	*F complanata* (Retzius) Link	Fim com	Per	Ten/Hel	Hel		1		
	110	*F dichotoma* (Linn.) Vahl.	Fim dic	Per	Ten/Hel	Hel			1	2
	111	*F miliacea* (L.) Vahl	Fim mil	Ann	Ten/Hel	Hel				2
	112	*F schoenoides* (Retzius) Vahl	Fim sch	Ann	Ten/Hel	Hel		5		1
	113	*F squarrosa* Vahl	Fim squ	Ann	Ten/Hel	Hel			2	5

		Species	Code	Perr	LFC	LFS	HH	HM	MM	TE
	114	*Kyllinga bervifolia* Rottboll	Kyl ber	Per	Hyp/Hel	Hel				6
	115	*Lipocarpha chinensis* (Osbeck) Kern	Lip chi	Ann	Ten/Hel	Hel				1
	116	*Pycreus flavidus* (Retz.) T. Koyama	Pyc fla	Ann	Hel	Hel		1	2	4
	117	*P pumilus* (L.) Domin	Pyc pum	Ann	Ten/Hel	Hel				1
	118	*P sanguinolentus* (Vahl) Nees ex C.B.Clarke	Pyc san	Ann	Ten/Hel	Hel			2	5
	119	*Schoenoplectus juncoides* (Roxb.) Palla	Sch jun	Ann	Hyp/ten	Hyp			1	6
	120	*S mucronatus* (L.) Palla ex Kerner	Sch muc	Per	Hyp/Ten	Hyp			2	3
	121	*Scirpus kysoor* Roxb.	Sci Kys	Ann	Hyp/Hel	Hyp				2
5	**Eriocaulaceae**									
	122	*Eriocaulon cinereum* R.Brown	Eri cin	Ann	Ten/Ros	Hel			2	1
	123	*E nepalense* Prescott ex Bong	Eri nep	Ann	Ten/Hel	Hel		1		
6	**Hydrocharitaceae**									
	124	*Blyxa aubertii* L.C. Richard	Bly aub	Per	Ros	Sub			3	
	125	*Hydrilla verticillata* (L.f.) Royle.	Hyd ver	Per	Vittate	Sub			5	11
	126	*Hydrocharis dubia* Bl. (Backer)	Hyd dub	Ann	Vittate	Sub				3
	127	*Ottelia alismoides* (L.) Persoon	Ott ali	Ann	Ros	Sub				1
	128	*Vallisneria natans* (Lour.) H.Hara	Val nat	Per	Ros	Sub			3	1
7	**Juncaceae**									
	129	*Juncus bufonius* L.	Jun buf	Ann	Helo	Hel		3		
	130	*J allioides* Franch	Jun all	Ann	Helo	Hel	6	2		
8	**Lemnaceae**									
	131	*Lemna minor* L.	Lem min	Per	Ple	F-F		2	5	3
	132	*L perpusilla* Torr.	Lem per	Per	Ple	F-F				11
	133	*L trisulca* L.	Lem tri	Per	Pla/ Ple	F-F			1	
	134	*Spirodela polyrhiza* (L.) Schleiden	Spi pol	Per	Ple	F-F			4	12
	135	*Wolffia globosa* (Roxb.) Hartog & Plas	Wol glo	Ann	Ple/ Pla	F-F				7

		Species	Code	Perr	LFC	LFS	HH	HM	MM	TE
9	**Limnocharitaceae** (Butomaceae)									
	136	*Butomopsis latifolia* (D.Don) Kunth	But lat	Ann	Hyp	Hyp			1	
10	**Najadaceae**									
	137	*Najas graminea* Raffeneau-Delile	Naj gra	Per	Vittate	Sub			3	1
	138	*N minor* Allioni	Naj min	Ann	Vittate	Sub			1	
11	**Orchidaceae**									
	139	*Spiranthes sinensis* (M.bieb.) H.Hara	Spi sin	Per	Hel	Hel				4
	140	*Zeuxine strateumatica* (L.) Schlechter	Zeu str	Ann	Hel	Hel				1
12	**Poaceae**									
	141	*Coix lachryma-jobi* L.	Coi lac	Ann	Hel	Hel				1
	142	*Echinochloa colona* (L.) Link	Ech col	Ann	Hel	Hel				2
	143	*E crus-galli* (L.) Palisot de Beauvois	Ech cru	Ann	Hel	Hel		1		2
	144	*E stagnina* (Retzius) Palisot de Beauvois	Ech sta	Ann	Hel	Hel				1
	145	*Eragrostis unioloides* (Retzius) Nees ex Steudel	Era uni	Ann	Hel	Hel		3		2
	146	*Eriochloa procera* (Retzius) C.E. Hubbard	Eri pro	Ann	Hel	Hel				3
	147	*Festuca ovina* L.	Fes ovi	Ann	Hel	Hel	3			
	148	*Hemarthria compressa* (L.f.) R. Brown	Hem com	Per	Hel	Hel				4
	149	*Hygroryza aristata* (Retzius) Nees ex Wright et Arnott	Hygr ari	Per	Hyp	Hyp			2	2
	150	*Hymenachne pseudointerrupta* C. Mueller	Hym pse	Per	Hyp/ Hel	Hyp			2	1
	151	*Isachne globosa* (Thunberg) O.Kuntze	Isa glo	Ann	Hel/ Hyp	Hel				1
	152	*Leersia hexandra* Swartz	Lee hex	Per	Hel/Ple	Hel			2	2
	153	*Oryza rufipogon* Griffith	Ory ruf	Ann	Hyp/ Ep	Hyp			2	1
	154	*O sativa* L.	Ory sat	Ann	Hel	Hel			2	
	155	*Panicum psilopodium* Trinius	Pan psi	Ann	Hel	Hel				1
	156	*P repens* L.	Pan rep	Per	Hel	Hel			2	1
	157	*Paspalidium flavidum* (Retzius) A. Camus	Pas fla	Per	Hel	Hel				1

		Species	Code	Perr	LFC	LFS	HH	HM	MM	TE
	158	*P punctatum* (N.L. Burman) A. Camus	Pas pun	Per	Hel	Hel				1
	159	*Paspalum distichum* L.	Pas dis	Per	Hyp	Hyp			1	7
	160	*P scrobiculatum* L.	Pas scr	Per	Hyp	Hyp				3
	161	*Phragmites karka* (Retz.) Trinius ex Steudel	Pha kar	Per	Hel	Hel				8
	162	*Saccharum spontaneum* L.	Sac spo	Per	Hel	Hel				7
	163	*Sacciolepis indica* (L.) A. Chase	Sac ind	Ann	Hel	Hel		2		2
	164	*S interrupta* (Willdenow) Stapf.	Sac int	Per	Hyp/ Hel	Hyp				1
	165	*S myosuroides* (R.Brown) A. Camus	Sac myo	Ann	Hyp/ Hel	Hyp				1
	166	*Setaria pallidefusca* (Schumach.) Stapf &C.E. Hubbard	Set pal	Ann	Hel	Hel				5
	167	*Vetivera zizanioides* L.	Vet ziz	Ann	Hel	Hel				1
13	**Pontederiaceae**									
	168	*Eichhornia crassipes* (Mart.) Solms-Laubach	Eic cra	Ann	Ple/ Ten	F-F			3	6
	169	*Monochoria hastata* (L.) Solms-Laubach	Mon has	Per	Hyp/Ten	F-L				2
	170	*M vaginalis* (N.L. Burman) Kunth	Mon vag	Ann	Hyp/Ten	F-L			1	1
14	**Potamogetonaceae**									
	171	*Potamogeton crispus* L.	Pot cri	Per	Vittate	Sub			5	6
	172	*P nodosus* Poiret	Pot nod	Per	Eph/vit	F-L			1	1
	173	*P octandrus* Poiret	Pot oct	Per	Eph/vit	F-L			3	1
	174	*P pectinatus* L.	Pot pec	Per	Vittate	Sub			3	
15	**Typhaceae**									
	175	*Typha angustifolia* L.	Typ ang	Ann	Hyp	Hyp				3
	176	*T elephantina* Roxb.	Typ ele	Ann	Hyp	Hyp				1
16	**Zannichelliaceae**									
	177	*Zannichellia palustris* L.	Zan pal	Ann	Vittate	Sub			1	

Appendix 5. Spearman rank correlations between environmental variables and the species richness.

Variables	**N**	**R**	**t(N-2)**	**p-level**
ALT & TSPP	28	-.68	-4.73	.001
ALT & EUHY	28	-.59	-3.73	.001
ALT & HELO	28	-.70	-5.08	.001
SA & TSPP	28	.11	0.55	.59
SA & EUHY	28	.20	1.05	.30
SA & HELO	28	.01	.017	.987
MD & TSPP	28	-.39	-2.20	.037
MD & EUHY	28	-.26	-1.35	.188
MD & HELO	28	-.46	-2.62	.014
SUBS & TSPP	28	-.71	-5.11	.001
SUBS & EUHY	28	-.71	-5.16	.001
SUBS & HELO	28	-.68	-4.77	.001
COND & TSPP	28	.64	4.22	.001
COND & EUHY	28	.58	3.62	.001
COND & HELO	28	.66	4.45	.001
PH & TSPP	28	.62	4.07	.001
PH & EUHY	28	.64	4.27	.001
PH & HELO	28	.60	3.82	.001
SECC & TSPP	28	-.48	-2.76	.010
SECC & EUHY	28	-.41	-2.31	.029
SECC & HELO	28	-.52	-3.13	.004
TEMP & TSPP	28	.70	5.0	.001
TEMP & EUHY	28	.61	3.9	.001
TEMP & HELO	28	.70	5.03	.001
HCO3 & TSPP	28	.72	5.22	.001
HCO3 & EUHY	28	.67	4.64	.001
HCO3 & HELO	28	.72	5.36	.001
TN & TSPP	28	.65	4.43	.001
TN & EUHY	28	.61	3.96	.001
TN & HELO	28	.68	4.76	.001
DN & TSPP	28	.55	3.37	.002
DN & EUHY	28	.53	3.18	.004
DN & HELO	28	.57	3.57	.001
TP & TSPP	28	.63	4.19	.001
TP & EUHY	28	.61	3.92	.001
TP & HELO	28	.66	4.44	.001
DP & TSPP	28	.67	4.60	.001
DP & EUHY	28	.64	4.22	.001
DP & HELO	28	.69	4.81	.001
CHL & TSPP	28	.77	6.15	.001
CHL & EUHY	28	.73	5.41	.001
CHL & HELO	28	.77	6.28	.001

Note: TSSP = total species; EUHY = euhydrophytes only (submerged, +free floating + floating leaved species) and HELO = helophytes + hyperhydates.

Appendix 6. Species abundances in the lakes (each cell has two values, first represents the frequency class and second represents the cover class).

Code	D1	D2	D3	D4	D5	D6	D7	D8	D9	D 10	D 11	D 12	C1	C2	C3	C4	C5	B1	B2	B3	B4	B5	A2	A3	A4	A 10	A 11	A 12
Nit muc																	2+2											
Dre flu																						5+6						
Mar pal											2+3								1+1	1+1								
Fon spp																					1+1							
Ric flu																	2+2											
Iso ele							2+2										2+3											
Sph spp																		1+1	1+1		1+2	1+2						
Azo imb								4+5	4+5	4+5	5+6	5+6	3+5	3+5	4+5	2+3	2+5		1+1									
Azo pin	3+4	3+4	3+4	3+4	3+4	3+4	4+4																					
Cera tha			1+1							1+1					1+2		1+2											
Pte vit	3+2	3+2	3+2				3+2		3+3	3+2	3+2	3+2		2+2														
Sal mol				2+4			2+4			2+3			2+3		2+3													
Equ deb	2+3	2+3	2+3				3+3		2+3	3+4	3+5	3+5		2+3	2+3	2+2	2+2		1+2	1+2								
Iso cor							2+4																					
Mar cre							2+4		2+4	2+5	2+3	2+3			2+3		2+3											
Hyg aur							2+4			2+4																		
Hyg sal				2+4																								
Jus qui										2+4																		
Alt phi							2+5	2+4	2+4	2+5	2+4	2+4																
Alt ses							2+4	3+4		2+4					2+4		2+4											
Cen asi	1+2	1+3	1+2	1+3	1+2	1+2	1+3	1+2	1+2	2+3	1+3	1+3	1+3	1+3														
Hyd sei															1+3		1+3					4+4						
Oen Jav	2+4	3+4	2+4	2+4	2+4	2+4	2+4	2+4	2+4	2+4	2+4	2+4			2+4		2+4											
Oen tho																						2+2						

Code	D1	D2	D3	D4	D5	D6	D7	D8	D9	D 10	D 11	D 12	C1	C2	C3	C4	C5	B1	B2	B3	B4	B5	A2	A3	A4	A 10	A 11	A 12
Oxy esc							2+4													2+4								
Cae axi									2+3	2+3	2+3	2+3																
Cen min							3+3	3+3																				
Cya pur							3+3																					
Ecl pro							3+4	3+4	3+3	3+4	3+4	3+3																
Eny flu										2+3																		
Spi iab							2+3																					
Hel ind							3+3																					
Nas off													3+3		3+3													
Cal pal										2+3																		4+4
Cal sta																2+4												
Lob als													3+3	3+3														
Cer dem					4+5			4+5	4+5	4+4	4+5	4+5	4+4	4+5	5+6	3+4	5+4											
Cer mur				3+3			3+3			3+3																		
Ipo aqu						3+4	4+4	3+3		3+3																		
Ipo car			3+2	3+2			3+3	3+2		3+2																		
Aes asp							3+3																					
Aes ind										3+3			3+3	4+6														
Hip vul														2+2		2+2												
Utr aur						3+4			3+4	3+4	3+4	3+5	3+4	3+3	3+3													
Utr aus															4+4		3+2											
Utr gib															3+2													
Amm bac	3+2	3+2	3+2											3+2														
Rot ind										3+3																		

Code	D1	D2	D3	D4	D5	D6	D7	D8	D9	D 10	D 11	D 12	C1	C2	C3	C4	C5	B1	B2	B3	B4	B5	A2	A3	A4	A 10	A 11	A 12
Rot rot				3+2	3+2	3+2	3+3	3+2	3+2	3+2	3+2	3+2	3+3	3+3	2+2		2+3					2+2						
Nym hyd				5+5			4+4			3+4																		
Nym ind	5+5	3+3		3+3			3+3						4+5	3+3	3+3		3+2											
Nel nuc				5+6									5+6		4+5	3+3												
Nym ste										4+4	4+4																	
Lud ads				2+2						2+3			2+2		2+2													
Lud hys				3+2						3+2																		
Lud oct							2+3																					
Lud per				3+3						3+4																		
Per bar	3+2	3+2	3+3				3+3		3+4	3+3	3+3	3+4			3+2		3+2											
Per gla	2+3	2+3	2+3	3+3			2+3			2+3																		
Per hyd	5+5	3+4	3+4	2+3	2+3	2+3	3+5			2+3					2+3	2+3	2+3											
Per lap										4+3					4+3	2+3	4+3											
Pol ple													3+3	3+3														
Ran rep													3+3	2+3														
Ran sce							3+2		3+2	3+2	3+2	3+2	3+2															
Ran tri																							4+4	4+5	5+5			
Old cor							2+2			2+3																		
Old dif							2+2			2+2																		
Cent coc										3+3																		
Lim chi										4+4																		
Lim ses																3+5												
Lin ana										3+4																		
Lin ant							2+2		2+2	3+4	4+3	4+3																
Lin cil							3+3																					
Lin pro							2+3																					

Code	D1	D2	D3	D4	D5	D6	D7	D8	D9	D 10	D 11	D 12	C1	C2	C3	C4	C5	B1	B2	B3	B4	B5	A2	A3	A4	A 10	A 11	A 12
Lin pus										2+3																		
Ver aqu				2+2						2+3																		
Sph zey										2+3																		
Tra qua														5+7	6+7		4+5											
Tra nat										5+2			5+6		4+4	4+3												
Phy nod							2+3	2+4	2+3	2+3	2+3	2+3					2+2											
Ali pla									2+3	2+3	3+2	3+2			2+2	3+2												
Cal par															4+3		4+2											
Sag gua										4+3																		
Sag tri						3+4																						
Pis str				4+2	4+2	2+3	4+4		4+2	4+4	4+2	3+2																
Ami axi										4+2																		
Com ben				3+4	3+4	3+4																						
Com dif								4+4	3+4	4+4	3+3	3+3																
Flo sca									1+2	1+2	1+2	1+2			2+2		2+2											
Mur nud							3+2			3+2																		
Bul den																			3+2									
Car cru																			4+3									
Cyp alt															3+2													
Cyp com				3+2					3+2	3+2	3+2	3+3																
Cypcomp				3+2																								
Cyp dif				3+2	3+3	3+3	3+3						3+4	3+4						1+2								
Cyp dig								1+2																				
Cyp dis										2+3																		
Cyp esc															3+3		2+3											

Code	D1	D2	D3	D4	D5	D6	D7	D8	D9	D 10	D 11	D 12	C1	C2	C3	C4	C5	B1	B2	B3	B4	B5	A2	A3	A4	A 10	A 11	A 12
Cyp exa				2+2																								
Cyp iri					1+2	1+2	2+2	2+2	3+3	2+2	3+2	3+2																
Cyp pil													2+2	2+2														
Cyp rot				3+3	2+3	3+4	2+3	2+3					2+2	2+2														
Cyp ten				2+3																								
Ele atr				2+3	2+3	2+3																						
Ele con															3+3													
Ele dul															2+3		3+4											
Fim aes				3+3	2+3	2+3	3+4																					
Fim com																						2+3						
Fim dic							3+4			3+4				3+4														
Fim mil							2+3			2+3																		
Fim sch							2+2											1+2	3+3	1+2	1+2	1+2						
Fim squ	3+4	3+4	3+4		3+4	3+4							2+2	2+2														
Kyl ber				2+2	1+2	1+2	2+2	2+2		3+3																		
Lip chi										2+2																		
Pyc fla									2+2	2+2	2+2	2+2	2+2	2+3								1+2						
Pyc pum							1+2																					
Pyc san							2+2		2+3	2+3	2+2	2+2	2+2	2+2														
Sch jun							2+2	2+2	2+2	2+2	2+2	2+2			2+2													
Sch muc				2+3						2+3			3+2	2+2	2+3													
Sci Kys				2+3			2+3																					
Eri cin							2+2								2+2		1+2											
Eri nep																						2+2						
Bly aub															2+2	2+2	2+2											
Hyd ver	4+5	5+6	4+4	4+4	4+3		4+4	4+4	4+4	4+4	4+4	4+4	4+4	4+5	3+3	3+3	5+7											

Code	D1	D2	D3	D4	D5	D6	D7	D8	D9	D 10	D 11	D 12	C1	C2	C3	C4	C5	B1	B2	B3	B4	B5	A2	A3	A4	A 10	A 11	A 12
Hyd dub	2+2			3+3			2+2																					
Ott ali										2+4																		
Val nat										3+4					2+2	2+2	4+4											
Jun buf																			2+3		2+3	2+3						
Jun all																		2+3			2+3		3+2	3+2	3+2	3+2	3+2	3+2
Lem min							4+5	3+4				2+3	2+4	2+4	3+3	2+3	2+3		2+3			2+3						
Lem per	3+5	2+2	3+3	3+4	4+3	4+3	4+3		2+3	2+3	2+2	2+2																
Lem tri													2+2															
Spi pol	1+3	1+3	1+3	2+2	2+2	2+2	3+4	2+2	2+2	3+4	2+2	2+2		2+2	4+3	2+3	2+3											
Wol glo		1+2	1+2	1+2	1+2	1+2	2+2	2+3																				
But lat															1+1													
Naj gra								2+3							2+2	2+2	1+1											
Naj min																	2+3											
Spi sin				2+2	2+3	2+2	2+2																					
Zeu str							2+2																					
Coi lac							2+3																					
Ech col							3+3			2+3																		
Ech cru							2+3			2+3									2+2									
Ech sta							2+2																					
Era uni				2+2			2+3											1+1	2+3	2+3								
Eri pro				2+2	2+3	2+2																						
Fes rub																										2+2	2+2	2+3
Hem com				2+2	2+2	2+2				2+3																		
Hygr ari				2+2			2+3						2+3		2+3													
Hym pse				2+2									2+2	2+2														
Isa glo										2+2																		

Code	D1	D2	D3	D4	D5	D6	D7	D8	D9	D 10	D 11	D 12	C1	C2	C3	C4	C5	B1	B2	B3	B4	B5	A2	A3	A4	A 10	A 11	A 12
Lee hex							3+4			3+4					4+4		4+4											
Ory ruf							1+2								2+3		1+3											
Ory sat													2+2	2+2														
Pan psi							2+2																					
Pan rep										3+4					3+4		2+2											
Pas fla							3+4																					
Pas pun							2+3																					
Pas dis					3+4	3+3		3+4	3+4	2+3	2+2	2+2	2+3															
Pas scr					2+3	2+3				2+3																		
Pha kar	3+5	3+4	3+4	3+4			2+2		4+4	4+4		4+4																
Sac spo	4+5	4+5	4+5						3+4	4+4	3+4	4+5																
Sac ind							2+2			2+2									2+2	2+2								
Sac int							2+2																					
Sac myo							2+2																					
Set pal							2+2		2+2	2+2	2+2	2+2																
Vet ziz		2+2																										
Eic cra			5+7	6+7			3+3	7+7	6+6			5+7	5+6	5+7			5+5											
Mon has					5+7					3+4																		
Mon vag										3+4					3+4													
Pot cri		5+5		3+5			3+5		3+3	4+5		3+5	4+5	3+4	2+4	2+4	2+5											
Pot nod										3+4							2+3											
Pot oct							3+3								2+4	2+3	2+4											
Pot pec															2+3	2+3	2+4											
Typ ang				4+4			3+4			3+3																		
Typ ele							3+3																					
Zan pal																	2+2											