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Limnological reconnaissance of waterbodies in central and southern Nepal[1]

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Abstract

Ionic composition of waterbodies in central and southern Nepal sampled in spring 1985 differed from that normally found in freshwater. Distinguishing characteristics were: 1) predominance of bicarbonate among the anions – accounting for $>90\%$ of the negative equivalents in two-thirds of the waterbodies, 2) the near absence of sulfates – accounting for $<1\%$ of the anions in half the samples so that chloride exceeded sulfate (as meq/L) in three-fourths of the waters tested and 3) calcium was the dominant cation, although in certain waters the relative proportion of either magnesium or the monovalent cations was much higher than the world average. Regional patterns in water chemistry were apparent and are largely explained by differences in local geology, inputs from artesian wells or extensive use by humans. Most ionic salinity values were <400 mg/L. Using conventional criteria to assess trophic state, most waterbodies were eutrophic or hypereutrophic when judged by total phosphorus and chlorophyll content but as a whole the lakes sampled were low in nitrogen. Nitrogen: phosphorus ratios (generally <10) and a significant empirical relation for chlorophyll-nitrogen provide evidence that nitrogen limited algal biomass. Secchi transparency values indicate light regimes were affected by nonalgal materials.

Introduction

This paper describes basic survey information from some 50 waterbodies located in central and southern Nepal (Fig. 1). Sampling was conducted in spring 1985 as part of a nationwide inventory of the limnological characteristics of lakes and impoundments in this Kingdom (Swar, 1980). With the exception of lakes in the Pokhara and Kathmandu valleys, which we describe elsewhere (Lohman *et al.*, 1988), detailed information from individual waterbodies was not paramount interest; rather our purpose was to sample as many waterbodies as possible over a broad geographic area to obtain an overview of chemical composition and fertility of lentic systems in the country. Emphasis was given to measurements of ionic salinity, suspended solids, plant nutrients and algal chlorophyll values in surface waters.

These data provide preliminary information with which we describe patterns of regional limnology based on the content and composition of dissolved salts, generalize on lake trophic state and assess nutrient limitation. This information

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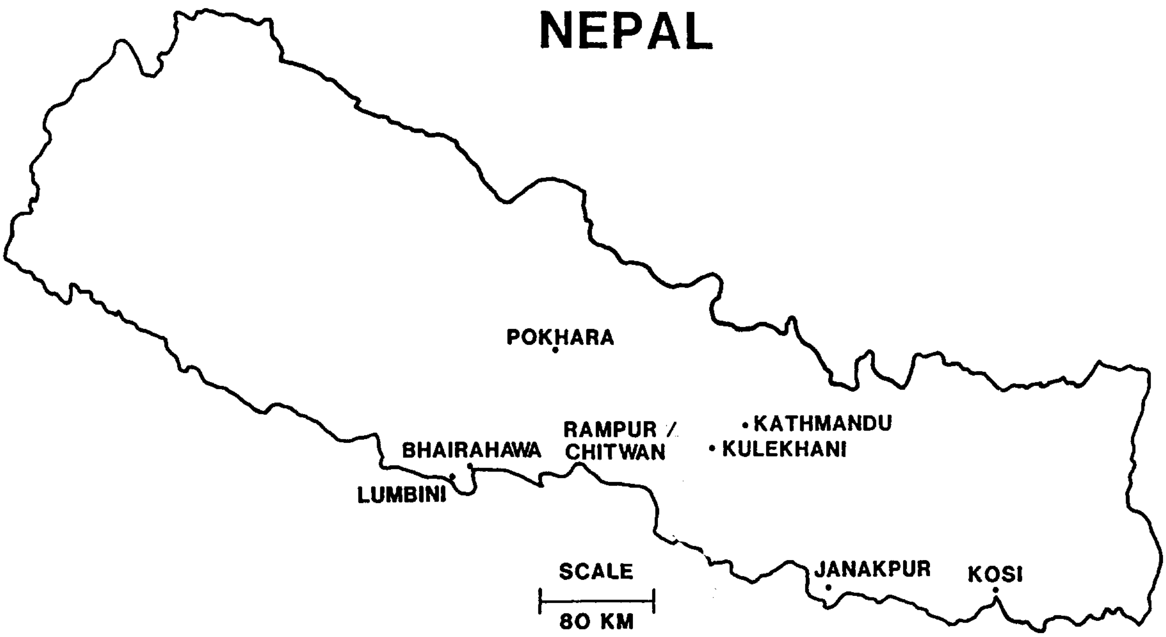

Fig. 1. Map of Nepal showing the regions where lakes were sampled in spring 1985.

also allows us to compare characteristics of the lakes we sampled with mountain lakes in Nepal, lakes on the Indian sub-continent and lake districts of the world.

General description of the physiographic regions and sites sampled

From south to north, Nepal consists of parallel physiographic zones which run the breadth of the country (Kaddah, 1967; Sharma, 1977a). The Terai, the southernmost zone (elevation 70–300 m) is an alluvial plain composed of sands, silts and clays. The Churia Hills which lie to the north (average elevation 1200 m) are principally sedimentary rocks containing sand, shale and gravels derived from weathering of northern ranges. Within the Churia Hills lie several tectonic valleys known as the Inner Terai. Further north the Mahabharat Lekh (elevation 600–4500 m) is composed of metamorphic rocks – mostly phyllite, slatey limestone, cherty dolomite and quartzite – and igneous rocks (granite). Within the Mahabharat range, a fourth physiographic zone, the Midlands, constitutes a large area of intermountain valleys and ridges in the central region of the nation. North of the Midlands lies the Himalayan Range (average elevation 6100 m).

We sampled waterbodies in seven distinct regions located in four physiographic zones (Terai, Inner Terai, Mahabharat Lekh and Midlands) in central and southern Nepal (Fig. 1, Table 1). Lakes were selected for sampling on the basis of local importance and potential for fishery development (Swar, 1980). Many are shallow ponds and some had extensive macrophyte cover. The hydrology of all the waterbodies sampled is closely tied to the summer monsoon and subsequent dry-period during winter and spring. Flushing rate, however, is extremely variable. Some small ponds have limited watersheds and are filled directly by rainwater, while the volume of lakes with extensive watersheds can be replaced up to 15 times during the monsoon (Lohman *et al.*, 1988). A general description of the lakes and local physiographic characteristics of the regions sampled follows:

Table 1. Averages of limnological measurements made on the surface waters of waterbodies in Nepal during Spring 1985.

Region and lake	Lake[a] type	Area ha	Ca	Mg	Na	K	HCO_3	Cl	SO_4	SI Units[b]	CHL *a*	Total N	Total P	SiO_2 mg l^{-1}	pH	Color	OSS mg l^{-1}	ISS mg l^{-1}	Secchi m
			mg l^{-1}								mg m^{-3}								
Pokhara Valley-Midlands																			
Phewa Tal	NL-I	400	7	1	1.5	0.6	28	0.7	0.2	−1.1	11	143	24	<1	8.2	<1	2.3	1.8	2.5
Begnas Tal	NL	244	3	1	2.2	0.4	20	1.0	0.6	−1.6	21	314	47	9	8.2	15	3.7	1.2	1.6
Rupa Tal	NL	117	4	2	3.2	0.8	28	1.3	0.7	−2.0	40	416	41	1	7.5	10	4.9	2.6	1.1
Maidi Tal[c]	W	7	2	2	–[d]	–	23	1.8	n.d.[e]	–	20	450	49	5	6.7	35	3.4	0.5	–
Deepang Tal[c]	NL	4	3	2	–	–	27	1.0	n.d.	–	14	370	29	3	7.1	33	2.9	0.5	1.5
Khaste Tal[c]	NL	18	2	1	–	–	19	2.0	n.d.	–	24	473	41	3	6.9	15	4.1	0.7	1.2
Kathmandu Valley-Midlands																			
Nav Pokhari[f]	P	<1	23	7	114	138	200	216	n.d.	1.8	637	20000	4060	23	9.7	130	182.0	26.7	–
Nag Pokhari[f]	P	<1	35	16	98	137	356	134	8.0	1.8	1308	22000	4160	19	9.3	120	270.5	105.9	–
Sidha Pokhari[f]	P	<1	16	7	9.6	7.6	93	11	n.d.	0.3	298	4700	438	7	8.7	100	55.7	85.7	–
Kamal Pokhari[f]	P	<1	45	9	70	19	261	73	n.d.	−0.1	56	8800	3570	7	7.4	70	10.3	5.2	–
Bheepukhu[f]	P	<1	56	41	188	190	578	274	28.0	1.2	2286	37600	5340	35	8.3	160	308.0	116.0	–
Tau Daha	NL-I	4	26	7	3.4	1.2	107	4.4	0.2	−0.5	6	450	31	5	7.6	10	0.7	1.1	2.6
Nag Daha	I	2	11	3	10.4	4.4	68	8.0	n.d.	−1.2	8	330	22	5	7.5	15	1.5	2.6	1.4
Pokhari Tar	P	<1	23	5	6.9	10.7	102	5.2	n.d.	−0.8	54	1600	406	4	7.4	85	20.0	158.0	0.2
Kulekhani Valley-Mahaharat Range																			
Indrasarewar Reservoir	I	220	16	2	3.3	1.5	64	1.1	1.3	0.3	32	254	43	7	8.9	5	4.9	2.1	2.2
Rampur/Chitawan Region-Inner Terai																			
Kehurani Tal	OB-S	1	37	35	3.5	5.1	285	3.2	9.1	0.7	5	405	146	13	8.3	20	4.6	28.1	–
Satra Hajar Ghol	P	7	31	23	3.6	1.9	205	0.8	0.6	0.5	20	405	66	8	8.3	20	4.3	7.9	–
Beeshajar Ghl	P	11	29	20	4.7	1.3	195	0.8	n.d.	0.3	15	390	53	5	8.1	20	1.6	2.9	–
Bhiashajar Ghol	P	7	20	20	3.3	1.2	154	1.3	4.7	0.6	5	355	71	8	8.7	20	1.7	5.9	–
Chaubishajar Ghol	P	2	15	20	2.9	0.3	134	1.5	n.d.	0.8	7	370	96	9	7.8	30	2.0	3.8	–
Sanu Mardi Ghol	P-S	<1	57	15	3.4	3.4	239	1.8	1.7	0.8	3	150	33	16	8.3	5	0.8	5.5	–
Panchakanya Tal	P-S	2	28	15	2.2	0.9	149	0.7	2.9	−0.6	5	870	46	15	7.4	<1	0.7	2.8	–
Tamar Tal	OB	7	21	2	5.1	1.9	88	0.4	0.3	−0.5	20	730	178	18	8.0	53	4.9	29.3	0.2
Lami Tal	OB	1	35	19	6.1	7.6	227	0.4	n.d.	0.3	17	600	93	1	8.3	15	3.3	16.7	0.3
Dhankre Tal	OB	4	36	16	5.5	8.3	200	0.3	1.3	0.6	29	540	46	1	8.3	15	2.4	2.0	–
Devi Tal	OB	17	21	11	13.0	3.7	145	0.5	2.0	0.2	10	470	78	<1	8.3	20	1.6	2.1	1.1
Bhairahawa/Lumbini Region-Terrai																			
Jagadishpura Ghol I	P	2	47	25	7.3	2.7	259	2.0	11.2	0.9	5	170	33	10	8.4	15	0.6	2.3	1.5
Jagadishpura Ghol II	P	2	52	24	7.1	2.5	280	1.5	13.1	1.0	11	240	33	12	8.4	10	5.1	10.3	–
Bakulla Ghat Tal I	P-B	<1	71	35	15.8	4.3	417	0.5	n.d.	0.6	80	780	216	9	7.7	30	10.0	52.5	0.4
Bakulla Ghat Tal II	P-B	<1	84	37	14.6	3.6	459	0.5	21.3	0.7	23	540	236	19	7.7	20	7.8	47.5	0.3
Bakulla Ghat Tal III	P-B	3	75	42	18.5	5.9	464	1.5	17.9	1.2	64	330	436	14	8.3	40	16.8	63.2	0.2
Gajedi Tal I	P-B	1	66	24	10.6	2.4	337	0.3	8.8	1.1	29	1030	126	10	8.3	20	4.2	19.6	0.4
Gajedi Tal II	P	1	35	7	3.3	3.7	144	0.9	n.d.	−0.3	35	710	86	3	7.6	25	5.4	10.7	–
Lumbini	P-B	<1	40	30	46.4	2.5	417	2.7	3.7	1.1	15	550	38	14	8.4	20	1.2	0.9	–
Bhairahawa Well Water	B	–	78	33	7	1.1	416	0.3	7.3	–	–	190	30	22	7.9	–	–	–	–

Table 1. Continued.

Region and lake	Lake[a] type	Area ha	Ca	Mg	Na	K	HCO$_3$	Cl	SO$_4$	SI Units[b]	CHL *a*	Total N	Total P	SiO$_2$ mg l^{-1}	pH	Color	OSS mg l^{-1}	ISS mg l^{-1}	Secchi m
			mg l^{-1}								mg m^{-3}								
Janakpur Region-Terai																			
Nochha Pokhari	P	4	7	4	11.4	8.5	51	11	6.3	−1.3	22	690	160	2	7.7	40	8.0	47.0	0.2
Parshi Pokhari	P-B	1	11	11	28.0	2.9	166	0.4	n.d.	0.5	11	670	51	2	8.8	25	2.0	7.7	0.5
Narahi Pokhari	P-B	4	9	11	26.0	6.0	137	7.6	5.5	−0.7	65	1100	406	8	7.8	45	16.7	125.6	0.1
Purni Pokhari	P-B	6	22	13	27.6	3.8	212	4.4	1.8	0.3	13	720	140	13	8.2	35	4.4	22.7	0.3
Labka Pokhari	P	6	3	3	34.0	8.5	51	35	n.d.	−2.0	74	770	140	9	7.4	20	10.6	12.5	0.5
Akaura Thukur Pokhari	P	5	6	4	11.8	10.6	68	11	n.d.	−1.2	33	570	91	4	7.7	25	4.0	11.5	0.5
Bateshwar Pokhari[f]	P	5	4	8	48.5	37.5	112	49	n.d.	−0.5	248	2100	435	9	8.5	55	43.3	43.3	0.2
Subba Pokhari[f]	P	2	10	10	43.5	52.5	163	67	7.6	0	161	3300	676	8	8.4	140	16.7	81.1	0.2
Didiya Pokhari[f]	P	1	12	12	51.5	43.0	161	60	3.6	0	166	2100	504	20	8.3	100	22.5	105.0	0.1
Gangasagar Pokhari[f]	P-B	3	30	14	107.0	78.0	344	145	n.d	1.8	245	4000	1695	24	9.4	60	55.0	15.0	0.2
Koshi Region-Terai but drainage extends into Himalayan Range																			
Bantibari Lagoon	P	–	35	6	3.0	3.1	163	2.0	n.d.	0.6	3	230	219	17	8.4	10	1.8	4.8	–
Koshi Band East	W	–	15	4	3.6	2.3	66	1.2	0.3	0	5	200	51	2	8.6	20	1.5	9.0	–
Tin Kouwan	P	–	16	4	3.7	2.6	73	1.2	0.6	−0.6	7	160	32	3	7.9	20	1.3	2.8	–
Puran Daha	P	–	39	8	3.3	4.2	188	1.0	n.d.	0.6	4	190	91	18	8.3	20	1.4	3.3	–
Koshi Band West	W	–	29	8	5.8	6.1	139	1.2	n.d.	0.3	–	200	81	9	8.3	30	4.8	9.6	–
Jumula Region-Himalayan Range																			
Rara Tal	NL	980	20	12	0.9	1.6	116	1.5	–	–	–	–	–	–	–	–	–	–	–

[a] NL = natural lake, I = impoundment, W = wetland, P = pond, OB = oxbow or abandoned channel, S = known spring water addition, B = water added from a boring

[b] Positive values for the Langelier saturation index (SI) signify the water is overstaturated and can be precipitate calcium carbonate. A negative value indicates otherwise (Larson and Buswell 1942).

[c] Ca and Mg estimated from hardness titrations.

[d] A dash indicates data were not collected.

[e] Not detectable

[f] Received extensive human use.

Terai

We sampled man-made ponds on the Terai in two areas near Bhairahawa/Lumbini and Janakpur. Ponds northwest of Bhairahawa were bermed structures located in carbonate-rich alluvial materials derived from the nearby Churia range. At Lumbini (Fig. 1) we sampled a brick bordered pool in alluvial sands and silt (Sharma, 1977a). Ponds near Janakpur either have a clay berm or are depressions in the alluvium and many have limited watersheds. Both areas are artesian zones and many ponds receive supplemental water from deep wells (Table 1).

Sapt Kosi River at Kosi Barage

The headwaters of the Sapt Kosi River are in Tibet, making it an antecedent drainage which predates the Himalayan range (Sharma, 1977a). This river system is the largest in Nepal and drains portions of each major physiographic region. We sampled several backwaters at Kosi Barage on the Terai near the Indo-Nepal border (elevation 70 m) which were created by the impoundment of the Sapt Kosi River in India.

Inner Terai (Rapti Valley)

We sampled bermed ponds, oxbow lakes and ponds formed in abandoned river channels in the Rapti Valley near Rampur and within Chitawan National Park. This elongated valley formed by fault activity is the largest area of Inner Terai in central Nepal (elevation 150 m). Sediments along the margins of this valley are derived from the Churia Hills, whereas the central portion of the valley is composed of alluvium derived from the Mahabharat range (Sharma, 1981).

Mahabharat Lekh

We sampled Indrasarewar Reservoir located near Kulekhani (elevation 1575 m). It was formed in 1981 by the diversion and impoundment of the Balung Khola and several smaller rivers for hydropower generation.

Midlands

The Pokhara and Kathmandu valleys are tectonic formations in the Mahabharat range.. Six lakes (Table 1) which lie along the margin of the Pokhara Valley (average elevation 900 m) were formed by obstructive depositional processes as fluvio-glacial sediments were deposited in the central valley (Sharma, 1977b). Landslides and upwarping near the outlets of these lakes may also have contributed to their formation (Ferro & Swar, 1978). Recently several limnological surveys have been conducted on the three largest lakes (Hickel, 1973a; Daems & Dumont, 1974; Dumont & Van de Velde, 1977; Swar, 1980; Ferro, 1981/82; Swar 1981; Swar & Fernando, 1979a, 1979b, 1980; Kato & Hayashi, 1982; Nakanishi, 1986). Sharma (1977b) estimates the lakes are presently about half their original size due to sedimentation resulting from deforestation but that the dam on Phewa Tal doubles its surface area.

Of the ponds sampled in the Kathmandu Valley (average elevation 1349 m) the two largest – Tau Daha and Nag Daha – were studied previously by Hickel (1973b). The zooplankton of Tau Daha and other ponds in the valley have also been studied (Daems & Dumont, 1974; Dumont & Van de Velde, 1977). Tau Daha is a natural pond with a control structure on the outlet. Nag Daha has an extensive berm along one margin. Six man-made ponds are identified in Table 1 by the term Pokhari and are known locally as tanks. They are either depressions with a clay berm or pools with a masonry perimeter.

Lake Rara, western Nepal

Lake Rara is located in western Nepal (Fig. 1) about 300 km west-northwest of Kathmandu within the Himal range. It is the largest lake in

Nepal, having an area of 9.8 km^2 and a mean depth of 100 m. It was studied by Ferro (1978/79) and more recently by Okino & Satoh (1986). Samples for certain analyses were collected for us by Peace Corps Volunteers and data are included in Table 1 to further document conditions in this remote waterbody. The values are referred to in the discussion but were not included elsewhere in the data analyses.

Waters with extensive human contact

Nepal, like much of southeast Asia, is a region where daily human contact with fresh waters is extensive (Fernando, 1984). We recognize that all waters sampled had some degree of human use, but in several ponds in Kathmandu and Janakpur we had reason to believe human activities – and use by livestock – were having a decided effect on water quality. We have identified these waters in Table 1 and treat them seperataly from other waterbodies in these two regions in certain analyses. A similar approach was used by Khan & Quajjam (1966) in their study of Indian ponds. This designation is subjective and is based on location of the ponds in relation to human density and their apparent use by the local population; it should be considered an ordinal scale with two categories. We have no basis to further subdivide the degree of human contact that waterbodies in these categories receive or compare human use of waters among ponds or regions. Exceptions were three interconnected ponds near the village of Bakulla Ghat (near Bhairahawa) that were continuously flushed by artesian inflow. Water quality did not seem affected by villagers so we did not include them in this category.

Materials and methods

Most waterbodies in this survey are represented by data from one or two surface samples (< 0.5 m) collected on a single date between 2 April and 14 May 1985 by wading out from shore or from a boat. Exceptions were lakes in the Pokhara, Kathmandu and Kulekhani valleys (lakes Phewa, Begnas, Rupa, Tau Daha and Indrasarewar Reservoir) which were sampled on more than one date and at several locations. Data from these waterbodies have been averaged.

Spectrophotometric tests were conducted in Nepal by using a Beckman Mini 20 and the following methods: Chlorophyll *a* (ethanol extractions – Sartory & Grobbelaar, 1984) was determined from absorbance at 663 nm using a standard curve prepared from purified chlorophyll *a* (Sigma Chemical Co., St. Louis) which was necessary to correct for the wide spectral band width (20 nm) of the Mini 20. Total phosphorus (ascorbic acid method after persulfate oxidation – A.P.H.A., 1980), total nitrogen (cadmium reduction after persulfate oxidation – D'Elia *et al.*, 1977), silica (molybdosilicate method – A.P.H.A., 1980) and sulfate (barium turbidimetric method – A.P.H.A., 1980). The sulfate test was not as reproducible as the others and we have the least confidence in those measurements. We did, however, repeat some analyses in our laboratory by using the methyl thymol-blue method and a Technicon Auto Analyzer and found that sulfate values judged as not-detectable by using the turbidimetric method were indeed low (< 1 mg/L).

In Nepal alkalinity was determined by titration with sulfuric acid using phenolphthalein and bromcresol green-methyl red indicators. Total alkalinity is expressed as bicarbonate (mg/L) in Table 1. Chloride was determined by titration with mecuric nitrate and diphenylcarbazone indicator (A.P.H.A., 1980). Hach color disc kits (Hach Chemical Co., Loveland, CO) were used to measure pH and color (platinum-cobalt units). Water transparency was determined by using a 20-cm Secchi disk.

In our laboratory, cation concentrations were determined on acid-preserved samples by using a flame photometer or atomic absorption spectrophotometer. Suspended solids were measured after Hoyer & Jones (1983).

Results

Ionic salinity and composition

Ionic salinity of waters sampled in Nepal (Fig. 2) varied from 28 mg/L in the Pokhara Valley (Begnas Tal) to 1356 mg/L in a tank near Kathmandu (Bheepukhu, Kirtipur). In about 80% of the waterbodies sampled values were <400 mg/L. Regional differences in mineral content are apparent (Fig. 2) and are largely a function of geology. Salinity values in those waterbodies draining metamorphic materials (Kulekhani and Kathmandu-waters with least human use), waterbodies at Kosi Barage, and waterbodies near Janakpur (without artesian inputs or extensive human use) most closely approximated the average mineral content found in the world's freshwaters (105 mg/L, Wetzel, 1983) and in rivers in India (191 mg/L, Handa, 1980). Whereas values for waterbodies on sedimentary and alluvial materials in the Inner Terai (Chitawan & Rampur) and Terai (Bhairahawa) generally exceeded these averages; in many cases by several fold (Table 1, Fig. 2). This pattern was expected because waters draining metamorphic rocks are generally much lower in soluble salts (Hem, 1985) than runoff from sedimentary deposits and alluvial materials. Values on the Terai near Bhairahawa were high, in part, because of leaching of the calcareous formation in this region (Sharma, 1981). Values were lowest in the Pokhara Valley (<40 mg/L) where low grade metamorphic rocks (slate and phyllite), which resist weathering, are dominant.

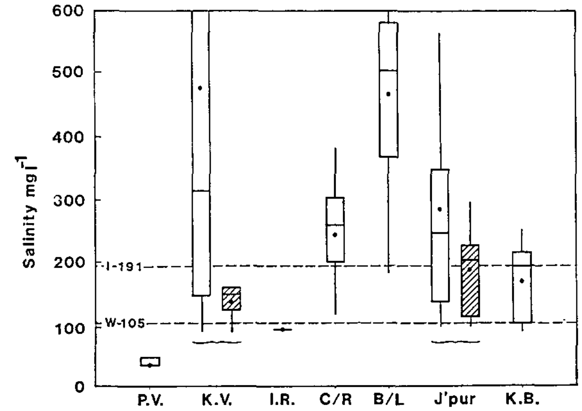

Fig. 2. Box plots of salinity values $(\mathrm{mg\,l^{-1}})$ in the various regions sampled. P.V. = Pokhara Valley; K.V. = Kathmandu Valley (left box = all lakes; right box with lines = lakes with least human use); I.R. = Indrasarewa Reservoir; C/R = Chitawan and Rampur; B/L = Bhairahawa and Lumbini; J'pur = Janakpur (left box = all lakes; right box with lines = lakes with least human use); K.B. = Kosi Barage. Also shown are the average salinity in the world's freshwaters (W) and in runoff from India (I).

Locally, additions from artesian wells and degree of human use are important factors affecting salinity. Near Bhairahawa and Janakpur waterbodies which received additions from artesian wells generally had salinity values about two-fold greater than nearby ponds receiving only atmospheric inputs and surface flow (Table 1). Overall, however, values were highest in waterbodies heavily used by humans. Near Janakpur, ponds with extensive human contact (Table 1, Fig. 2) had higher salinity than those without, and the highest value in this region was from a pond with both human use and artesian inputs (Gangasagar Pokhari). In the Kathmandu Valley there was a 3–13 fold difference in salinity between waterbodies heavily used by humans and those receiving less human use (Table 1, Fig. 2).

These data were collected near the end of the dry season and prior to the onset of monsoon rains when water levels were noticeably low due to evaporation, and Saturation Index values (Larson & Buswell, 1942) suggest that certain waters were oversaturated with calcium carbonate (Table 1). For these reasons we expect that salinity values presented herein probably represent near maximal values in an annual cycle tied to the summer monsoon. Ionic dilution by the monsoon has been measured in several Indian lakes (Singh, 1981, 1985; Banerjee *et al.*, 1983), and Lohman *et al.* (1988) have shown salinity decreased pre- to post-monsoon in lakes sampled in the Pokhara and Kathmandu valleys.

Overall we found a high correlation between the cations and anions (as meq/L) in individual waterbodies ($r = 0.99$, $n = 46$, $P < 0.001$). In about half the samples agreement between positive and negative equivalents in an ion balance of major elements (expressed as an absolute percentage value of the cations) was $<5\%$; a range found acceptable by Golterman & Clymo (1969). In about one-third of the samples this value was >5 to 10%, and >10 to 17% in the remaining waters. In three-quarters of these comparisons cations exceeded anions (n = 33, median difference = 0.171 meq/L or 6.5% of the cation equivalents). Several factors may account for this tendency to measure more cations. Difficulties measuring sulfate (see methods section) may have caused an underestimate of anions in some samples. Also, high pH, silica and color values (Table 1) in waters with the largest measured excess in cations suggest that organic acid anions and ionized silicic acid may have been quantitatively important in some samples (Hutchinson, 1957).

Ionic composition differed among regions (Figures 3 and 4) and in many cases from that normally found in freshwaters (Wetzel, 1983). Distinguishing characteristics of the waters sampled were: 1) predominance of bicarbonate among the anions – accounting for $>90\%$ of the negative equivalents in two-thirds of the samples, 2) the near absence of sulfates – accounting for $<1\%$ of the anions in half the samples so that chloride (meq/L) exceeded sulfate (meq/L) in three-fourths of the waters tested, and 3) calcium was the dominant cation in most waters although in certain samples the relative proportion of either magnesium or the monovalent cations was much higher than the world average (Fig. 3 and 4). These findings are generally consistent with measurements of ionic composition of freshwaters in India (Handa, 1980, 1983; Fig. 3 and 4).

Among these waterbodies, the divalent cations (as a proportion of total cation equivalents) were not correlated with one another (Table 2), but collectively (Ca% + Mg%) have a strong positive relation with bicarbonate and a strong negative relation with the monovalent cations and chloride (expressed as percent of equivalents). Whereas the correlation between the monovalent cations was strong (Table 2) and each element (as percent) had a strong negative correlation with bicarbonate and strong positive correlation with chloride. None of these mineral elements (as percent) was strongly correlated with ionic salinity (Table 2) suggesting that the proportions of these elements relative to one another did not change in a consistent fashion with increasing mineral content.

Ionic composition of most waters was dominated by divalent cations and bicarbonate anions so that a plot of calcium against magnesium (as percent of total cation equivalents, Fig. 5a) and a plot of these cations collectively (Ca% + Mg%) against the relative proportion of bicarbonate anions (Fig. 5b) provide two-dimensional generalizations of their overall mineral content. To simplify the discussion of general trends in ionic composition we have distinguished three categories, though arbitrary, over the continuum of conditions between divalent-dominated and monovalent-dominated waters (Fig. 5a). In the first category calcium and magnesium accounted for $>75\%$ of the positive equivalents, wich describes conditions in over half the waters sampled (Fig. 5a). Within this category ($Ca + Mg = >75\%$ cation equivalents) the relative proportion of these two elements ranged over a continuum of possible combinations from waters dominated by calcium (up to 71%) to those dominated by magnesium (up to 65%). Anions in these waters were almost entirely bicarbonate (91–99.8% of negative equivalents, Fig. 5b). Waterbodies from each area sampled in Nepal are represented in this first category except for ponds on the Terai near Lumbini and Janakpur (Fig. 1). Considering only cations, this first category also includes the average value for the world's freshwaters, the average for Indian rivers and average for runoff from sedimentary materials (Wetzel, 1983).

Waterbodies in this first category with the highest proportion of magnesium were located on sedimentary formations within the inner Terai near Rampur (Fig. 1). High magnesium values are characteristic of drainage from this geologic type (Hutchinson, 1957). In several ponds near Rampur, magnesium equivalents exceeded calcium suggesting the presence of magnesite

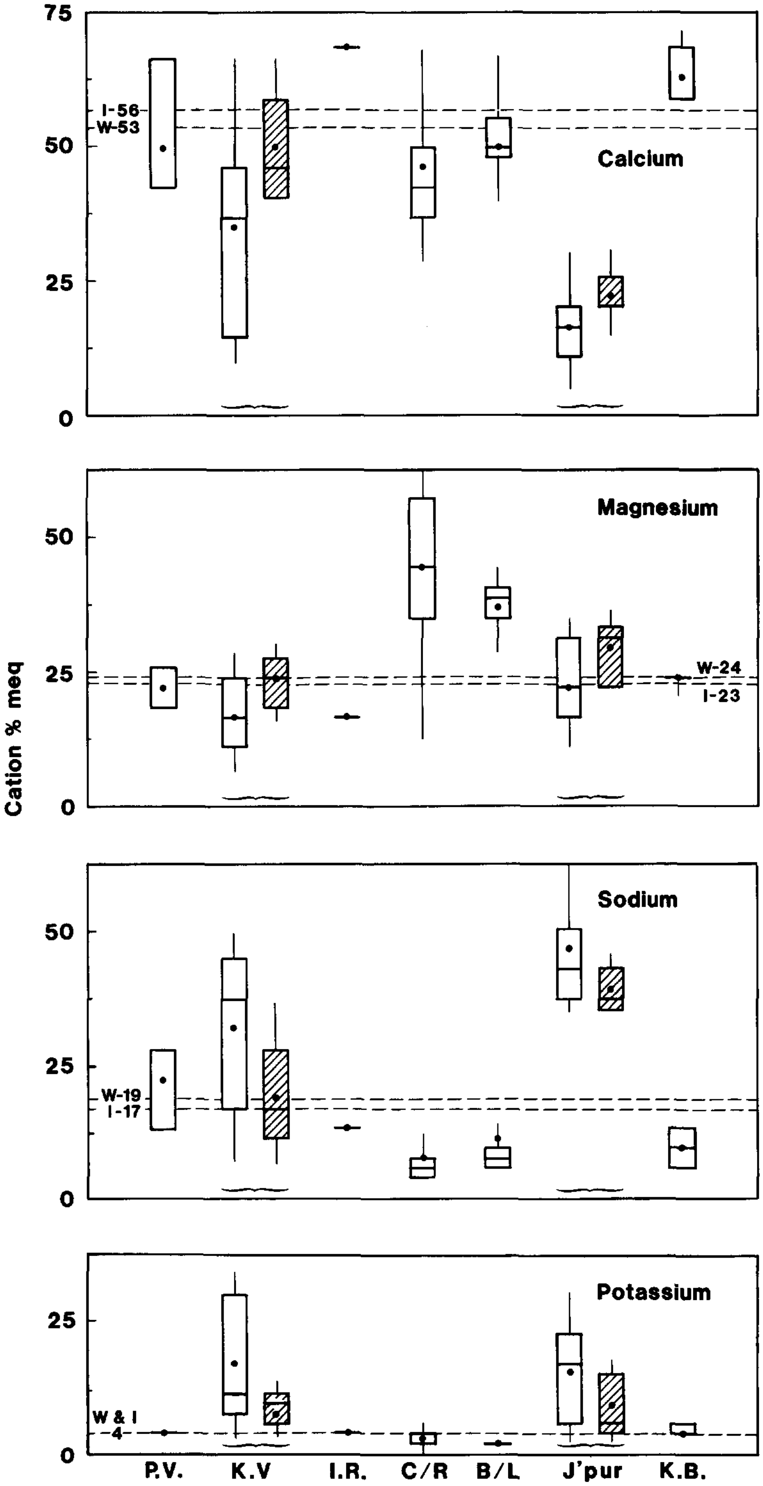

Fig. 3. Box plots of cation elements expressed as a percentage of total cation equivalents. Labels identifying the various regions are identical to those in Figure 2. The percentage of cations in the world's freshwaters (W) and in runoff from India (I) are also shown.

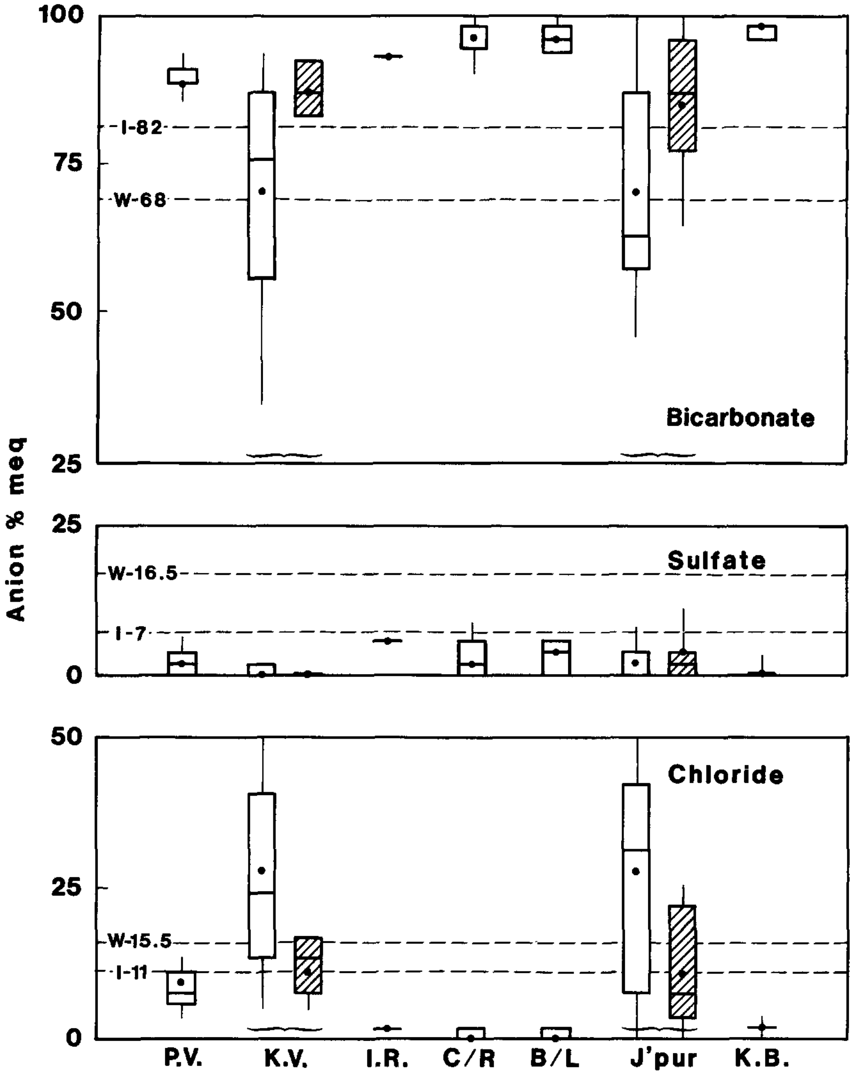

Fig. 4. Box plots of anions expressed as a percentage of total anion equivalents. Labels identifying the various regions are identical to those in Figure 2. The percentage of anions in the world's freshwaters (W) and in runoff from India (I) are also shown.

($MgCO_3$) in the alluvium. Magnesite occurs in Nepal (Sharma, 1977a) but has not specifically been reported in this area. Also, Saturation Index values indicate carbonates were precipitating from many of these waters (Table 1) and, being more soluble than calcium, magnesium complexes would remain in solution. Sodium and potassium accounted for a small fraction of the cations in these waterbodies which has the highest ratio of divalent to monovalent cations (as equivalents) of any in this survey. The relative proportion of divalent cations in oxbow and abandoned channel lakes sampled in the inner Terai within Royal Chitawan National Park (Tamar, Lami, Dhankre, Devi; Table 1), however, was more similar to that measured in waterbodies in the uplands. This finding suggests that alluvium from metamorphic material carried into this tectonic valley by river action (Sharma, 1977a) may influence their water chemistry. Also, several of

Table 2. Correlation matrix for elements comprising salinity expressed as a percentage of either the positive or negative equivalents and ionic salinity (mg l^{-1}).

	Mg	Ca + Mg	Na	K	Na + K	HCO_3	SO_4	Cl	Ionic salinity[a]
Ca	n.s.[b]	0.84	- 0.82	- 0.68	- 0.84	0.76	n.s.	- 0.75	- 0.36
Mg		0.65	- 0.60	- 0.60	- 0.65	0.58	0.30	- 0.62	n.s.
Ca + Mg			- 0.96	- 0.85	- 1.0	0.90	n.s.	- 0.92	- 0.32
Na				0.68	0.96	- 0.82	n.s.	0.83	n.s.
K					0.85	- 0.88	n.s.	0.89	0.44
Na + K						- 0.91	n.s.	0.92	0.32
HCO_3							n.s.	- 0.99	0.42
SO_4								n.s.	n.s.
Cl									0.41

[a] $n = 46$, if $r \geq 0.30$ then $P \leq 0.05$, if $r \geq 0.36$ then $P \leq 0.01$.

[b] Not significant

these lakes are occasionally inundated by river water originating in the uplands.

Young alluvial materials near Bhairahawa are rich in dolomite (Sharma, 1977a) and with one exception (Gajedi II, Table 1), waterbodies in this formation were also high in magnesium (> 34% of cation equivalents) and bicarbonate (> 93% of anion equivalents), and their ionic composition was nearly identical to that found in artesian wells near Bhairahawa (this study Table 1, Swarzenski & Babcock, 1968). The calcareous formation in this region is extensive (Sharma, 1977a) and in such alluvial materials it is common for surface and groundwaters to be chemically similar (White *et al.*, 1963).

The second category depicted in Figure 5a (> 50 < 75% divalent cations) includes waterbodies located in the intermountain valleys (Midlands) and ponds on the Terai near Lumbini and Janakpur. In these waters sodium accounted for about one-third of the cations (range 14–44%) and the anions were principally bicarbonate (83–99% of anion equivalents, Fig. 5b). Handa (1983) refers to waters of this type in India as having mixed-cations. In the Midlands edaphic factors such as the predominance of slate and chloritic phyllite (e.g., lakes Begnas and Rupa, Sharma, 1977b) may account for the proportionately high sodium values of some waterbodies (White *et al.*, 1963) but we cannot discount the influence of human activity on their water chemistry. Lumbini (Fig. 1) is located in older alluvium composed of sand, silt and clay and the pool we sampled received wellwater. These materials typically yield water rich in sodium (White *et al.*, 1963). High sodium values in the groundwater near Lumbini have previously been reported by Sharma (1981) and were found in nearby areas of India (Handa, 1983). Sodium and bicarbonate values were also high in ponds on the Terai near Janakpur (Fig. 3 and 4), perhaps due to weathering of sodium carbonate salts that occur in that region (Sharma, 1981). Ponds near Janakpur that fall into this second category (Fig. 5a) received artesian water and had the lowest relative sodium content of any waterbodies sampled in that region.

Waterbodies in the third category depicted in Fig. 5a (< 50% divalent cations) were located near Kathmandu or Janakpur and had high concentrations of sodium (36–72% of cation equivalents) and in most cases potassium (7–35% of cation equivalents). In all cases potassium was present in smaller amounts than sodium. Two types of waterbodies fall into this last category. They either receive extensive human use and have high proportions of sodium, potassium and chloride from anthropogenic sources (Fig. 3 and 4) or lie within sodium-carbonate materials near Janakpur and therefore are high in sodium and bicarbonate from edaphic sources (Figs 3, 4 and 5b).

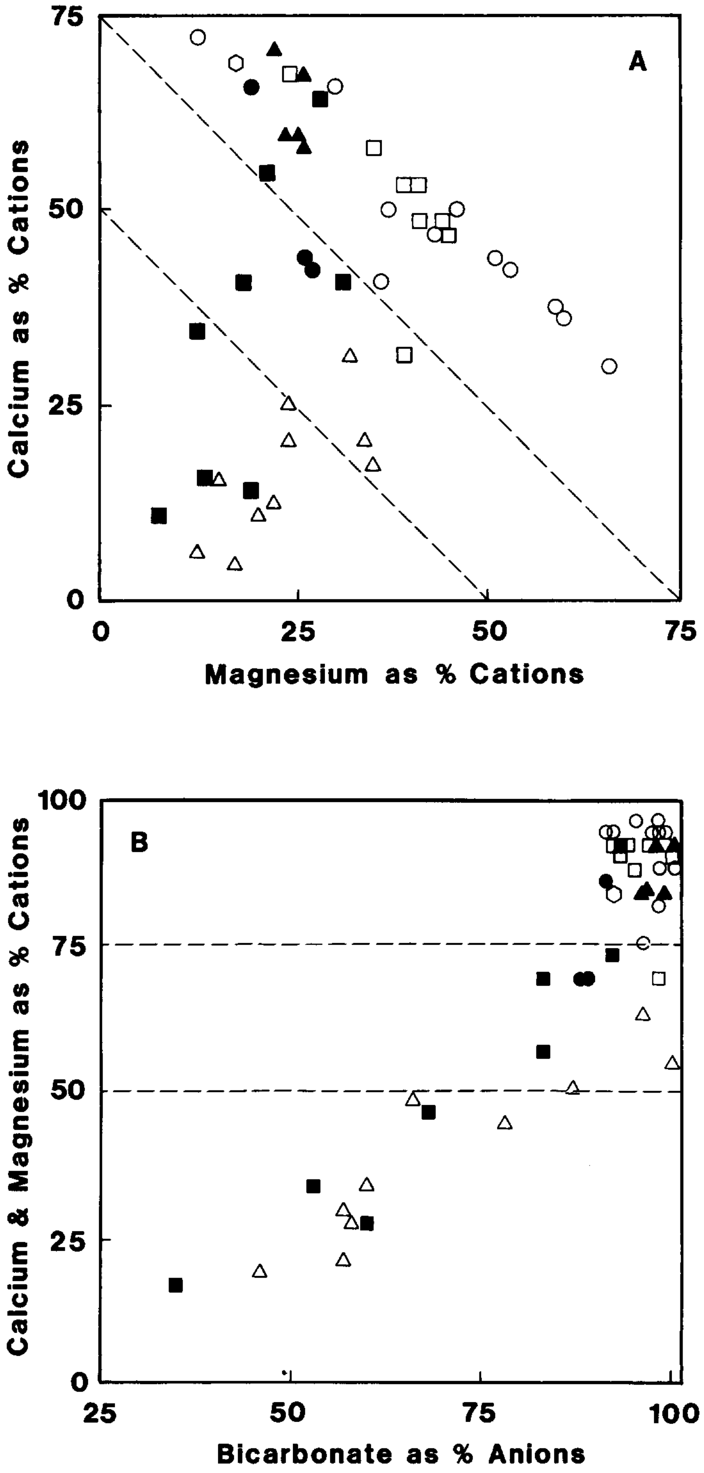

Fig. 5. a) Plot of calcium vs. magnesium expressed as a percentage of total cation equivalents for each lake sampled. Symbols represent regions: closed circles = Pokhara Valley; closed boxes = Kathmandu Valley; hexagon = Indrasarewar Reservoir; open circle = Chitawan/Rampur; open squares = Bhairahawa/Lumbini; open triangles = Janakpur; closed triangles = Kosi Barage. b) Plot of the divalent cations (calcium plus magnesium) expressed as a percentage of total cation equivalents against bicarbonate content expressed as a percentage of total anion equivalents. Symbols are the same as in panel a.

Trophic state and nutrient limitation

Chlorophyll (CHL), total phosphorus (TP) and total nitrogen (TN) ranged over 3–4 orders of magnitude in the waterbodies sampled in Nepal (Tables 1 and 3). Most lakes were fertile and values were highest in those waters receiving extensive human contact near Kathmandu and Janakpur – measuurements from them are among the highest reported in the literature for these parameters. Lowest values generally occurred in the Pokhara Valley lakes, ponds near Bhairahawa and the backwaters at Kosi Barage (Table 1) but there are many individual exceptions to this generalization so that there were no clear cut differences among regions, as was the case for ion concentration and composition.

Using criteria proposed by Forsberg & Ryding (Table 3) to assess trophic state, most waterbodies were either eutrophic or hypereutrophic when judged by their TP or CHL content but as a whole the Nepalese waterbodies seem low in nitrogen. Based on their TN to TP ratios (N : P) most are clearly N-limited (Table 3, Forsberg & Ryding, 1980); a condition suggested as characteristic of Asian lakes (Dussart, 1974). Values of N : P range from 1 to 19 with about half <5 and 85% of them <10. In only one lake was this ratio >17 which is the point where phosphorus is thought to regulate algal biomass (Forsberg & Ryding, 1980).

To further assess nutrient limitation we tested the ability of empirical chlorophyll-nutrient models derived with our data, and several from the literature, to describe algal biomass in these waterbodies. We restricted this analysis to waters with CHL <300 mg/m^3 to: 1) eliminate extreme values that could unduly influence the analysis, 2) more closely match the range of our data base to the range of values used to derive the published models (e.g., Canfield, 1983) and 3) delete those lakes in which algal biomass was least likely limited by nutrients. This restriction required us to drop the three most fertile lakes from the data set (Nav Pokhari, Nag Pokhari & Bheepukhu; Table 1). We also deleted the data from Kamal Pokhari (Kathmandu, Table 1) because when we sampled this lake it was covered with a dense growth of duck weed.

From this analysis we found CHL values from our data set strongly correlated with TP and TN ($r = 0.70$ and 0.81 respectively, $n = 44$, $P < 0.001$, log transformed data, regression equations given in Table 4) but when both plant nutrients were used in a multiple regression analysis TN was the only statistically significant variable. This finding is expected given the low N : P ratios and we conclude the correlation between CHL and TP is mostly due to intercorrelation of TN and TP values ($r = 0.77$, $n = 44$, $P < 0.001$). These analyses and the N : P values strongly suggest that the Nepalese lakes surveyed had an adequate supply of phosphorus and that nitrogen limited algal biomass.

Based on a comparison with empirical chlorophyll-nutrient models from the literature (Table 4) the Nepalese lakes are most dissimilar to equations derived with predominantly P-limited

Table 3. Trophic state criteria based on chlorophyll *a*, total-P and total-N proposed by Forsberg & Ryding (1980) and the percentage of lakes from our data set that fall within various trophic state designations.

Trophic state	Chlorophyll *a* mg m^{-3}		Total-P mg m^{-3}		Total-N mg m^{-3}	
	Criterion	% of lakes	Criterion	% of lakes	Criterion	% of lakes
Oligotrophic	<3	0	<15	0	<400	35
Mesotrophic	3–7	24	15–25	4	400–600	25
Eutrophic	7–40	47	25–100	51	600–1500	20
Hypereutrophic	>40	29	>100	45	>1500	20

Table 4. Chlorophyll-nutrient models from the literature and for the data from Nepal (n = 44, lakes with chlorophyll > 300 mg m^{-3} were eliminated from this analysis along with data from Kamal Pokhari) and comparisons of predicted and observed chlorophyll values using each of these models. Mean square error was calculated as the sum of the mean difference squared and the variance.

Model	Equation for log chlorophyll *a*			Mean difference between predicted and observed chlorophyll (bias)	Mean square error
	Intercept	Slope log TP	Slope log TN		
Nitrogen Only					
Pridmore et al (1985)	−2.56	-	1.22	−33.9	4,095
Canfield (1983)	−2.99	-	1.38	−31.4	3,324
White et al. (1985)	−3.05	-	1.45	−24.7	2,057
Nepal data	−1.96	-	1.19	−9.0	934
Phosphorus Only					
Jones and Bachmann (1976)	−1.09	1.46	-	205.4	417,813
Dillon and Rigler (1974)	−1.14	1.45	-	164.3	277,377
Pridmore et al. (1985)	−1.31	1.35	-	68.7	55,567
Schindler (1978)	−0.848	1.213	-	48.0	23,889
White et al. (1985)	−0.52	0.85	-	−21.9	3,111
Canfield (1983)	−0.15	0.744	-	−14.9	2,682
Vollenweider and Kerekes (1980)	−0.57	0.99	-	1.6	2,428
Nepal data	−0.36	0.83	-	−14.9	2,518
Nitrogen and Phosphorus					
Smith (1982) #6–Florida lakes	−2.488	0.374	0.935	−31.1	3,404
Canfield (1983)	−2.49	0.269	1.06	−26.0	2,465
Smith (1982) #5–northern lakes	−1.517	0.653	0.548	−6.4	1,522

lakes having a high yield of CHL per unit of TP (e.g., Dillon & Rigler, 1974; Jones & Bachmann, 1976; Pridmore *et al.*, 1985). These models greatly overestimate the observed CHL values (Table 4); however, TP models with lower yields of CHL per unit of TP and higher background levels of CHL (larger intercepts, e.g., Vollenweider & Kerekes, 1980; Canfield, 1983; White *et al.*, 1985) predict CHL reasonably well in our N-limited lakes. This reduced response to TP has been pointed out previously in data sets that include N-limited lakes (Smith, 1982; Canfield, 1983) and can occur when in-lake N : P values are low (Sakamoto, 1966; Smith & Shapiro, 1981).

Nepalese lakes behave most similarly to published TN and TN-TP models (Table 4) derived, in part, with data from N-limited lakes (Smith, 1982; Canfield, 1983) or lakes where phytoplankton was occasionally growth limited by N (White *et al.*, 1985). The confidence limits around the slope and intercept values for our TN model encompass the coefficients of these other CHL-TN models (except for the small intercept value of White *et al.*, 1985).

The reasonably good fit of the Nepal data to these models is somewhat surprising given differences among the data sets. Most models in Table 4 were based on annual or seasonal mean concentrations in the pelagic zone of the lakes represented, whereas our data are mostly single samples – many of which were from small, shallow waterbodies with a varying degree of macrophyte dominance and varying concentration of inorganic suspended solids (ISS). Nevertheless, these differences had little discernible effect on nutrient-chlorophyll relations.

Concentrations of ISS in the Nepalese lakes averaged 27 mg/L (range 0.5–158 mg/L; Table 1) which is over four-times the average found by Hoyer & Jones (1983) in relatively turbid midwestern reservoirs (ISS range 0.3–48 mg/L). Secchi transparency values strongly suggest the light regimes of waterbodies in Nepal were affected by ISS. The relation with Secchi transparency was stronger with ISS (Table 5) than either CHL or organic suspended solids (OSS). And in these turbid systems Secchi transparency averaged only 60% of the value predicted with an empirical relation for Secchi-CHL (Jones & Bachmann, 1978) derived with data from lakes low in ISS. Similar to the findings of others, there is a negative relation in our data between transparency and color (Canfield & Hodgson, 1983) such that a two variable model with ISS and color explains 91% of the variation in Secchi depth. These findings suggest light extinction was largely due to nonalgal materials.

In midwest lakes, Hoyer & Jones (1983) found a negative effect of ISS on ratios of CHL to TP (the limiting element in those lakes), presumably because of shading and nutrient binding by nonalgal particulates. This same effect, however, was not seen in the Nepal data set – adding ISS (linear, log transformed, or as a ratio ISS : TN – after Hoyer & Jones, 1983) to a model already containing TN and CHL provided no significant reduction in the mean square error. It may be that light induced reductions in algal biomass (Straskraba, 1980) may not occur in shallow waterbodies like those sampled in Nepal. In fact, ratios of CHL : TN in the data from Nepal were generally greater than values reported by Forsberg & Ryding (1980) and values predicted from models developed with data from less turbid lakes (e.g., Table 4). Under some circumstances nonalgal shading can induce physiological responses such as an increase in pigment content or photosynthetic capacity of phytoplankton (Brown & Richardson, 1968; Grobbelaar, 1984) that could account for the CHL : TN values measured in Nepal, but our data are not sufficient to test this hypothesis directly. Much more work will be needed to determine the interrelations of algae, nutrients, nonalgal particulates and light in these and other lakes. The present analysis does, however, suggest an overriding similarity of nutrient-algal relations in lakes covering a wide range of limnological conditions and geographic setting.

Table 5. Regression equations of Secchi depth (SD, M) on the following independent variables: chlorophyll (CHL, mg m^{-3}), organic suspended solids (OSS, mg l^{-1}), color (C, Pt. units), inorganic suspended solids (ISS, mg l^{-1}) and total suspended solids (TSS, mg l^{-1}) for lakes in Nepal.

Dependent variable	Equation	R^2
Secchi depth (n = 27)		
	Log SD = 0.624 – 0.627 (Log CHL)	0.47
	Log SD = 0.214 – 0.684 (log OSS)	0.58
	Log SD = 0.819 – 0.811 (log C)	0.63
	Log SD = 0.258 – 0.583 (log ISS)	0.86
	Log SD = 0.572 – 0.677 (log TSS)	0.89
	Log SD = 0.564 – 0.417 (log ISS) – 0.313 (log C)	0.91

Discussion

Waterbodies sampled in Nepal (Fig. 2) were, with one exception, within the range considered fresh (ionic salinity < 1000 mg/L) and none were the inland saline type described by Hutchinson (1937) in Tibet or in regional surveys on other continents (Hutchinson, 1957). Most salinity values (median = 220 mg/L) compared closely with the average measured in Indian rivers (191 mg/L, Handa, 1980) and are within the range of values reported for Indian lakes (e.g., Khan & Quajjum, 1966; Kaul, 1977; Handa *et al.*, 1982). Based on values for alkalinity, calcium and magnesium (median = 119, 23 and 8 mg/L, respectively) the ion content of waterbodies we surveyed in Nepal is similar to values found for these variables in the surface waters of reservoirs in central and southern India (Sreenivasan, 1970; Uhlmann *et al.*, 1982; Unni, 1985). Our salinity values are generally greater than Loffler (1969) found in high altitude lakes near Mt. Everest. He measured conductivities of 7–42 μS/cm which indicate salinity values were <30 mg/L (A.P.H.A., 1980). But recent studies of Lake Rara (Okino & Satoh, 1986: Table 1) and Lake Tilitso (Aizaki *et al.*, 1987) suggest that not all high altitude lakes in Nepal are low in electrolytes. Conductivity in these lakes was >130 μS/cm which equates to salinity values >90 mg/L (A.P.H.A., 1980).

The mineral composition of most waters we sampled in Nepal can be broadly characterized by one of the following categories: 1) bicarbonate-dominated waters high in divalent cations and low in monovalent cations and halides – within this type cations can be mainly calcium or magnesiun, 2) bicarbonate-dominated waters with near equal equivalents of calcium, magnesium and sodium but low in halides or 3) waters high in monovalent cations and either chloride or bicarbonate anions (Fig. 5a and b). These categories are identical to those used by Handa (1983) to characterize mineral composition of ground water in northern India and also describe the relative ion composition found in many Indian lakes (e.g., Khan & Quajjum, 1966; Kaul, 1977; Handa *et al.*, 1982) and rivers (Fig. 3 and 4). Most of the waters we sampled are in the first category – dominated by bicarbonates and divalent cations. Nepalese mountain lakes Rara and Tilitso (Okino & Satoh, 1986; Aizaki *et al.*, 1987; Table 1) also fit in this first category. Differences in edaphic factors among geographic regions in central and southern Nepal, along with degree of human use and inputs of artesian water largely explain the range of values measured (Fig. 3 and 4).

Sulfate was not a major component of any of the waters sampled in this study nor in other surface waters in the region suggesting a mineral source for this element is not abundant. Sulfate-dominated waters do not occur in an adjoining region in India (Uttar Pradesh, Handa, 1983) and most lakes (e.g., Zutshi *et al.*, 1980) and rivers (Fig. 4) in India also have low sulfate values. Loffler (1969) found sulfate <4 mg/L in lakes near Mt. Everest while Aizaki *et al.* (1987) report values of 8 mg/L (14% of the anion equivalents) in Lake Tilitso. Relative chloride content was highest in those waters receiving extensive human use, which is consistent with surveys conducted in India (Khan & Quajjum, 1966; Unni, 1985). In waterbodies sampled near Kathmandu receiving heavy human use the equivalent ratios of sodium to chloride was near unity suggesting an anthropogenic source for these elements. Potassium values in the lakes we sampled and lakes Rara (Table 1) and Tilitso (Aizaki *et al.*, 1987) were lower than values reported by Loffler (1969) from Himalayan lakes.

Collectively, lentic systems in central and southern Nepal are fertile as judged by nutrient and algal biomass values in their surface waters. Data from the surface water, however, probably underestimates the fertility of macrophyte-dominated ponds within the data set. In these systems planktonic production can be minor compared to that of macrophytes (e.g., Vass & Zutshi, 1983), and measurements from surface water in these systems underestimate their nutrient content and plant biomass (Canfield *et al.*, 1983). An assessment of macrophyte abundance, however, was beyond the scope of this survey.

Values of TP and CHL measured in this study cover a broad range (Table 1). Extreme values occurred in urban waterbodies impacted by humans which is consistent with studies of similar systems in India (Khan & Quajjum, 1966; Sreenivasan, 1976). But TP and CHL in most waterbodies are within the ranges found in regional studies conducted elsewhere (Sakamoto, 1966; Forsberg & Ryding, 1980, Canfield, 1983) and large data sets from temperate lakes (Jones & Bachmann, 1976; Vollenweider & Kerekes, 1980; Canfield & Bachmann, 1981; Smith, 1982). Based on TP and algal CHL values none of the lakes we sampled are oligotrophic as are high mountain lakes in Nepal (Loffler, 1969; Okino & Satoh, 1986; Aizaki *et al.*, 1987).

Based on primary production measurements, most lakes studied thus far in India are also mesotrophic or eutrophic (e.g., Sreenivasan, 1976; Zutshi *et al.*, 1980; Khan, 1986). Few measurements of total plant nutrients and algal CHL have been published for Indian or Asian lakes so rigorous comparisons using these variables are not possible. Most lakes in our data set (Table 1), however, had CHL values similar to freshwater systems in Sri Lanka (range 15 to 79 mg/m^3, Silva & Davies, 1986, 1987) but generally greater than Uhlmann *et al.* (1982) found in reservoirs in southern India (range 2 to 17 mg/m^3) or Sharma & Pant (1979, 1987) found in a high altitude lake in India (range 1–8.5 mg/m^2). Values of TP published by Zutshi *et al.* (1980) for lakes in Jammu and Kashmir (20 to 200 mg/m^3), however, are similar to many values we found in Nepal.

The N : P ratios and the significant empirical relation for chlorophyll-nitrogen strongly suggest lakes we sampled were limited by nitrogen. This finding contrasts with temperate lakes which are largely limited by phosphorus (Schindler, 1977; Bachmann, 1980) but is consistent with the suggestion that Asian lakes are nitrogen limited (Dussart, 1974). Nitrogen limitation has been inferred from low nitrate concentrations which are characteristic of lakes throughout the region (Sreenivasan, 1965; Lewis, 1978; Khan & Zutshi, 1980). Nakanishi (1986) has also found low TN and low N : P ratios in the Pokhara Valley lakes. Their N : P values from the post-monsoon period range from 11–18 and are similar to post-monsoon values for these lakes reported by Lohman *et al.* (1988) but generally are higher than values we measured during the pre-monsoon period (range 6–10, Table 1). This difference suggests that nutrient ratios may vary seasonally.

In summary, these data should be considered a preliminary generalization of regional limnology in central and southern Nepal; one emphasizing water chemistry and fertility. The data base is largely comprised of measurements from individual waterbodies collected on a single date prior to the monsoon. There is extensive evidence that within individual waterbodies certain limnological parameters measured in this survey can vary in the short-term by several fold (Knowlton *et al.*, 1984) and that the monsoon can drastically alter water chemistry and fertility (Singh, 1981, 1985; Banerjee *et al.*, 1983; Lohman *et al.*, 1988; Silva & Davies, 1987). Given this potential for temporal variability within and among seasons our data should not be considered precise estimates of average conditions within the lakes sampled. This caveat aside, these data are a initial contribution to the comparative limnology of this region.

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