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Hydrology and nutrient dynamics of a sacred lake in Sikkim Himalaya

Alka Jain[1], S. C. Rai[1], J. Pal[2] & E. Sharma[1,*]
[1]*G.B. Pant Institute of Himalayan Environment and Development, Sikkim Unit, P.O. Tadong, Sikkim-737 102, India*
[2]*Department of Zoology, University of North Bengal, Rajarammohunpur, West Bengal-734430, India*
Fax: [+91]-3592-31090. Tel: [+91]-3592-31090 (office); [+91]-3592-31627 (home). E-mail: gbp.sk@sikkim.org

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Abstract

The hydrology and nutrient dynamics of a sacred lake in the western part of the Sikkim Himalaya were studied. The lake watershed has broad-leaved mixed forest and agriculture land, two perennial and five seasonal inlets, and one major outlet. Annual inflow was 1103×10^6 l while outflow was 4279×10^6 l. About 70% of its water was from subsurface flow and seepage. More than 50% of the discharge was recorded in August (peak rainy season month) and the least in March (lean month). Sediment flow to the lake was 346 Mg y^{-1} and outflow 316 Mg y^{-1}. The remaining 30 Mg was deposited in the lake. High sediment runoff in the rainy season turned the lake turbid and caused expansion of the bog. The nutrient (dissolved oxygen, carbon dioxide, total-N, ammonium-N, phosphate-P and chloride) levels of the lake, inlets and outlet varied between seasons and sites. Plankton productivity ranged from 16 mg C m^{-2} d^{-1} in winter to 247 mg C m^{-2} d^{-1} in the rainy season. Its respiratory loss was 12 mg C m^{-2} d^{-1} in winter and 160 mg C m^{-2} d^{-1} in the rainy season. Religious activities, agriculture, cattle grazing and forestry in the watershed should be controlled for maintaining the longevity of the lake.

Introduction

Human population growth and associated land use/cover change have led to increased wastewater discharges to aquatic environments. Enhanced inputs of soil nutrients and other contaminants have hastened the eutrophication process in many lakes and ecological changes that naturally occur over thousands of years are now expressed in decades. Himalayan lakes have a prominent place in mythology and religion. A large number of natural freshwater lakes exist in the Himalayan region which are of great scientific and socioeconomic value (Zutshi, 1985). The increasing anthropogenic pressure in recent years, in and around aquatic ecosystems including their watersheds have contributed to the mineral enrichment of these systems, leading to accelerated eutrophication (Ishaq & Kaul, 1988). Studies on such lakes have been done by various workers (Zutshi et al., 1972; Zutshi & Khan, 1977; Kaul, 1977; Pant et al., 1985; Trisal, 1987; Khulbe, 1992; Joshi & Sundriyal, 1995; Gopal & Zutshi, 1998). But the lakes of the Sikkim Himalaya have not been well documented except for a preliminary report by Roy & Thapa (1998). A quantification of the influence of the surrounding watershed on lake nutrient dynamics are lacking for the Himalayan region. The present study was designed to understand the hydrology and nutrient dynamics of a lake in Sikkim and the inputs from the watershed. This study involves hydrological processes, sediment runoff to the lake and the impact thereof on water quality and plankton productivity.

Study area

The famous 'Wish fulfilling Lake' Khecheopalri is considered by the Sikkimese people as most sacred. Many folklores and legends are associated with its formation and shape. The lake water is used for rites and rituals only. Fishing and boating are strictly prohibited. It is situated in the midst of a pristine forest

* (author for correspondence)

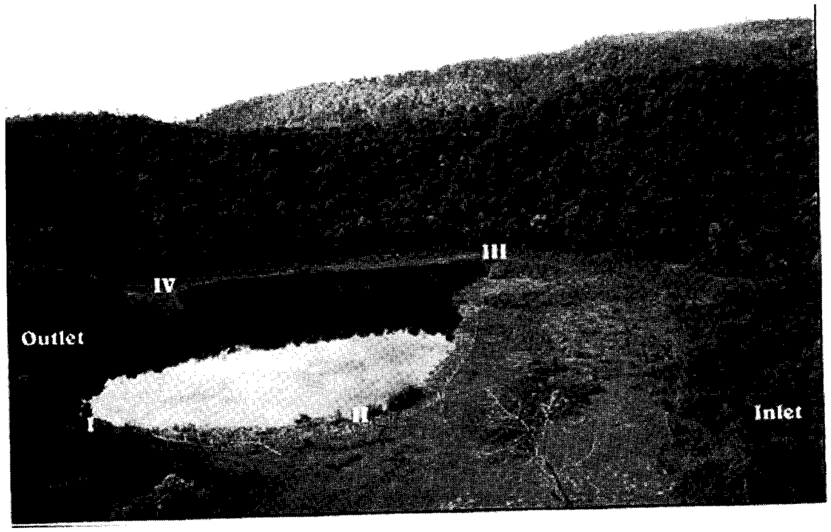

Photo 1. Khecheopalri lake in the Sikkim Himalaya showing boggy area, surrounding watershed and sampling sites.

Table 1. Morphometry of the Khecheopalri lake

Latitude (N)	27° 22′ 24″
Longitude (E)	88° 12′ 30″
Lake elevation (m)	1700
Lake watershed elevation range (m)	1700–2375
Open water area of the lake (m^2)	37 900
Maximum depth (m)	11.2
Minimum depth (m)	3.2
Mean depth (m)	7.2
Water volume (m^3)	272 880
Boggy area (m^2)	70 100
Total boggy and lake water area (m^2)	108 000
Lake watershed area (km^2)	12

(Photo 1) at an altitude of 1700 m asl (27° 22′ 24″ N and 88° 12′ 30″ E) in the western part of Sikkim state, India. The lake represents the original 'neve' region of an ancient hanging glacier, the depression being formed by the scooping action of the glacier (Raina, 1966). The lake watershed (12 km^2), in addition to a broad-leaved mixed forest, has some agriculture land with two villages. The influx of tourists is high with visible impacts of disturbance on the lake and its watershed. Morphometric data are summarized in Table 1. There are two perennial and five seasonal inlets and one major outlet (Figure 1). The lake is a resting-place for Trans-Himalayan migratory birds and supports commercial and recreational tourism.

Geologically, the rocks belong to Darjeeling group, which mainly comprises high-grade gneisses containing quartz and feldspar with streaks of biotite (GSI, 1984). The soil of the watershed is sandy loam. Climate is monsoonic and divisible into three seasons, viz., rainy (June–October), winter (November–March) and summer (April–May). The annual rainfall is 3838 mm and temperature ranges from 4 °C to 24 °C within the annual cycle.

Six sites were selected for measurements. Of these, four were located along the periphery of the lake representing disturbed and relatively less disturbed conditions and one each at the inlet and outlet positions. Slope aspects, bog condition, floral and faunal composition and types of disturbance are given in Table 2.

Methods

Discharge was measured at the inlets and outlet with the help of wooden rectangular weirs installed at the sites. The height of the water was measured twice each day and the values pooled on a monthly basis. Measurements on the seasonal inlets were confined to the rainy season. Sediment concentration was estimated bimonthly by filtering samples through Whatman filter paper 42. Sediment weight was measured on air-dry basis.

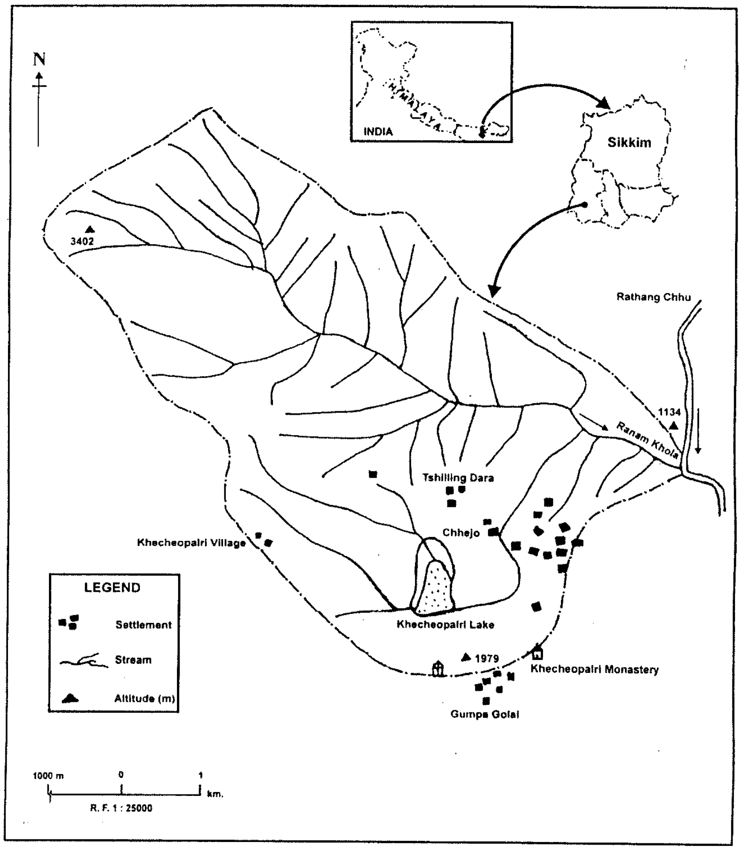

Figure 1. Location map of the Khecheopalri lake and its surrounding watershed.

Water samples from inlets, outlets and the lake were collected bimonthly during 1997 and 1998 for chemical analyses. These samples were collected between 9 and 11 h from 5–10 cm depth and were transported to the laboratory within 24 h of collection. Water temperature and transparency were measured at mid-day (between 12 and 13 h) at all the sites. Temperature was measured using a mercury thermometer and transparency by Secchi disc (21 cm diameter).

Bimonthly data were pooled to seasonal values. The pH values and conductivity were determined using a digital pH meter and conductivity meter on non-filtered samples within a day of collection. Remaining samples were filtered and stored in a refrigerator. All analyses were completed within seven days. Total acidity and alkalinity as $CaCO_3$ were measured gravimetrically. Dissolved oxygen (DO) was estimated by the azide modification method, phosphate–phosphorus (PO_4–P) by stannous chloride method and chloride by argentometric method (Eaton et al., 1995). Ammonium–nitrogen (NH_4–N) was estimated by Kjeldahl method following Allen (1989) and the total-nitrogen by AOAC method (Cunniff, 1995). A gas exchange method using light, dark and initial bottles was followed for estimation of plankton gross photosynthesis and respiration (Gardner & Graan, 1917). The free carbon dioxide was measured following method given by Eaton et al. (1995).

Results and discussion

Precipitation, runoff and sediment concentration

Precipitation of the Khecheopalri area was recorded

Table 2. Characteristic of sampling sites for hydrological studies in the Khecheopalri lake

Site	Slope Aspect*	Bog		Watershed forest dominant tree species*	Aquatic biodiversity			Type of disturbance
		Peat depth (cm)	Dominant vegetation		Ducks	Fishes	Planktons	
I	NW	175	*Arundo donax*, *Sphagnum* sp., *Polygonum* sp.	*Castanopsis* sp., *Beilschiemedia sikkimensis*.	Eastern Goosander, Common Teal, Barheaded Goose, Baer's Pochard	*Cyprinus carpio*, *Danio acquipantus*, *Schizothrax* sp. *Garra* sp.	*Mougeotia* sp., *Cosmarium* sp., *Spirogyra* sp., *Navicula* sp., *Gammurus* sp., *Cyclopoid* sp.	Tourism, pilgrimage and settlement
II	W	500	*Acorus calamus*. *Sphagnum* sp., *Bracharia* sp. *Potentilla*. *pedencularis*	*Eurya acuminata* *Symplocos* sp. *Castanopsis* sp.	–do–	–do–	–do–	Trampling, grazing; fodder, fuel-wood, timber collection; agricultural practices; settlements and cow-sheds
III	SE	153	*Saccharum* sp., *Sphagnum* sp.,	*Castanopsis tribuloides*, *Machilus edulis*	–do–	–do–	–do–	Fuel-wood and timber collection
IV	NE	207	*Rohododendron* sp., *Sphagnum* sp., *Cyperus* sp.	*Machilus* sp., *Symplocos* sp. *Castanopsis* sp.	–do–	–do–	–do–	Fuel-wood and timber collection
Inlet	SW		*Acorus calamus* *Sphagnum* sp., *Bracharia* sp.	*Machiluis* sp., Eurya acuminata *Symplocos* sp. *Castanopsis* sp.				Fuel-wood and fodder collection; trampling, grazing
Outlet			*Acorus calamus* *Rhododendron* sp., *Aponogeton* sp.					Settlements and tourism activity

*Site background aspect and watershed forest.

during 1997 and 1998. Mean annual precipitation was 3899 mm of which 85% was received between June and September (Figure 2).

The annual inflow of water contributed by the two perennial and five seasonal streams was estimated at 1103×10^6 l, while the outflow was 4279×10^6 l. More than 50% (2775×10^6 l) of the discharge at the outlet occurred in August and the lowest (7.36×10^6 l) in March. The excess water outflow compared to the inflow was due to subsurface flow, seepage from the watershed and precipitation on the lake, which could not be measured in this study.

Khecheopalri lake is gradually silting and the major contributor is sediment from the surrounding watershed. Sediment buildup in the lake was rapid in recent years. Sediment flow into the lake was 346 Mg y^{-1} and outflow 316 Mg y^{-1}. The remaining 30 Mg is deposited in the lake. This deposition has contributed to the expansion of the bog. Sediment concentration of discharge at the inlets and outlet was highest in the rainy season (Figure 2). It was much higher at the inlets compared to the outlet, however outflow was far greater contributing to substantial sediment exit. Impact of livestock grazing, trampling, deforestation and agricultural practices in the watershed area contribute to higher sediment concentration in the inlet water. High sediment deposition in the rainy season turns the lake turbid and causes expansion of the bog threatening the longevity of the lake.

Nutrient dynamics

The pH of the lake, inlets and outlet was alkaline with a highest value of 8.6 at the inlet. It was highest in the rainy season and lowest in winter. It showed positive correlation with temperature, acidity, DO and

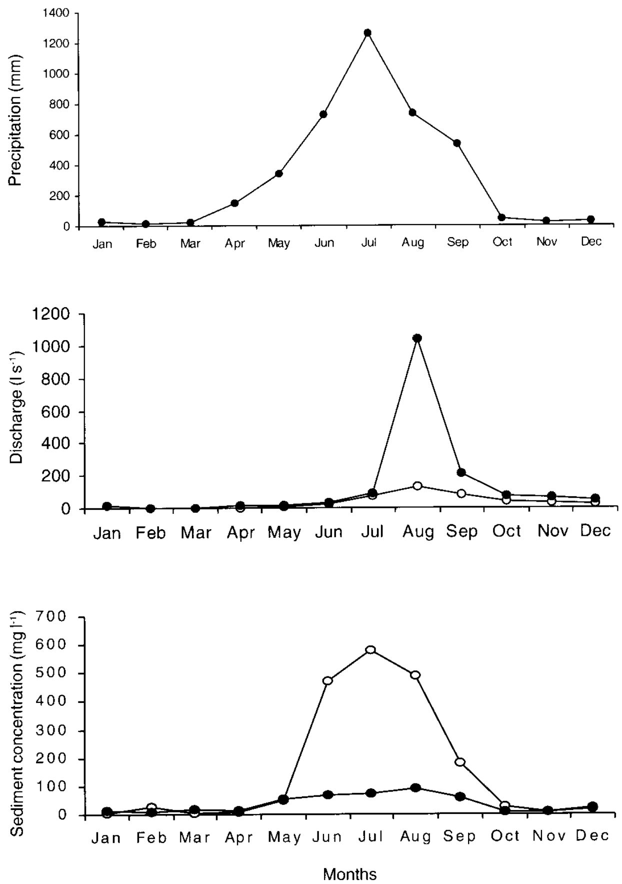

Figure 2. Monthly precipitation, discharge and sediment concentration at the inlets (○—○) and outlet (●—●) of the Khecheopalri lake in Sikkim.

respiration (Table 3). Higher pH was attributed to the presence of carbonates (Purohit & Singh, 1981; Pant et al., 1985). In the lake, pH ranged from 6.8 to 8.2. It was lowest during winter (Figure 3).

Water temperature ranged from 8.8 °C in winter to 19.6 °C in the rainy season (Figure 3). Variation in temperature was significant between sites and seasons. Since their interaction was also significant, LSD value difference between means showed that site to site variation in a season was not apparent except for inlet water compared with other sites (Figure 3). Water temperature was positively correlated with gross primary productivity (GPP), respiration, acidity, pH, DO and conductivity, but negatively with transparency, free CO_2 and alkalinity (Table 3).

The marked seasonal variation of transparency was controlled by varying amounts of sediments, algae, illumination and suspended organic matter. Average transparency for all sites was 104 cm. Low transparency was caused by sediment from the watershed. The highest turbidity (70 cm) was recorded in the rainy season at Site I (Figure 3). Site III showed the highest transparency (range 92–131 cm). A negative correlation between transparency with GPP and respiration reflected seasonal effects rather than a functional relationship. Sediment concentration in the lake was higher in the rainy season, while GPP and respiration peaked in this season. Positive correlation of transparency with alkalinity can be explained by the

Table 3. Pearson's correlation coefficient for physio-chemical characteristics, plankton productivity and respiration of the Khecheopalri lake (n = 12, $d.f.$ = 10 for transparency, gross primary productivity and respiration, and for all other parameters n = 18, $d.f.$ = 16)

Parameters	Transparency	Temperature	pH	Conductivity	Acidity	Alkalinity	DO	Free CO_2	Total nitrogen	NH_4-N	PO_4-P	Chloride	GPP	Respiration
Transparency	–	−0.949	−0.631	−0.630	−0.445	0.690	−0.538	0.654	0.508	−0.327	−0.390	0.426	−0.869	−0.708
Temperature	0.01	–	0.518	0.634	0.624	−0.511	0.549	−0.639	−0.458	0.381	0.197	−0.257	0.944	0.681
pH	0.05	0.05	–	0.328	0.490	−0.134	0.494	−0.172	−0.340	0.409	0.120	−0.230	0.396	0.620
Conductivity	0.05	0.01	NS	–	0.198	−0.602	−0.008	−0.165	−0.272	0.082	0.347	0.144	0.488	0.598
Acidity	NS	0.01	0.05	NS	–	0.158	0.833	−0.516	−0.146	0.254	0	−0.558	0.412	0.272
Alkalinity	0.05	0.05	NS	0.01	NS	–	0.274	0.001	0.292	0.120	−0.424	−0.286	−0.630	−0.327
DO	NS	0.05	0.05	NS	0.01	NS	–	−0.665	−0.270	0.308	−0.086	−0.728	0.445	0.391
Free CO_2	0.05	0.01	NS	NS	0.05	NS	0.01	–	0.331	−0.454	0.214	0.403	−0.620	−0.566
Total nitrogen	NS	NS	NS	NS	NS	NS	NS	NS	–	−0.074	−0.135	−0.170	−0.622	−0.113
NH_4-N	NS	NS	NS	NS	NS	NS	NS	NS	NS	–	−0.602	−0.279	0.226	0.563
PO_4-P	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.01	–	0.138	0.351	−0.002
Chloride	NS	NS	NS	NS	0.05	NS	0.01	NS	NS	NS	NS	–	−0.339	−0.245
GPP	0.01	0.01	NS	NS	NS	0.05	NS	0.05	0.05	NS	NS	NS	–	0.560
Respiration	0.01	0.05	0.05	0.05	NS	NS	NS	NS	NS	NS	NS	NS	NS	–

NS= Not significant; Lower matrix = Probability values; Upper matrix = Correlation coefficients.

decrease in alkalinity due to the formation of a $CaCO_3$ precipitate, decreasing transparency.

Acidity showed a strong positive correlation with temperature, pH and DO but was negative with free CO_2 and chloride (Table 3). It was highest (14.2 mg l^{-1}) in the rainy season and lowest (4.2 mg l^{-1}) in winter. It showed significant variation between sites and seasons, and interaction was also significant. LSD value difference showed that mostly the means varied significantly in each season (Figure 3). Acidity was highest at Site I, due to various offerings made here. People burn leaves of *Cryptomeria japonica, Juniperus recurva* and *Juniperus indica* as incense and the remains are acidic. Offerings like flowers, leaves and fruits on decomposition lead to increased acidity too.

Alkalinity was lowest in the rainy season at all sites, because of higher rates of photosynthesis. Total alkalinity varied significantly between sites and seasons (Figure 3).

The highest electrical conductivity (94 μS) was recorded at Site II, the lowest (15 μS) at Site III. The higher value in the rainy season at Site II was attributed to greater ionic concentration of the inlet flow. This variation in conductivity with seasons and sites was significant (Figure 3) and positively correlated with temperature and respiration, but negatively with alkalinity (Table 3). The free CO_2 values were highest in winter when pH was low (Figure 4).

A positive correlation was observed between DO and temperature, pH and acidity, a negative one with free CO_2 and chloride. DO at the inlet and outlet streams, and in the lake varied significantly between sites and seasons (Figure 4). It was highest in summer, resulting from increased photosynthesis. It was low in winter. These results are consistent with a report on a central Himalayan lake (Khulbe, 1992).

NH_4–N varied significantly between sites and seasons, and it showed a negative correlation with only PO_4–P. The most important source of nitrogen is the ammonification of organic matter. The inlet source in winter showed high ammonium from the watershed forest. Total nitrogen of lake, inlet and outlet waters varied significantly among sites and seasons. It ranged from 3.7 to 9.6 mg l^{-1} showing high values at the outlet in all the seasons. Comparison between seasons showed that it was lower in the rainy season, attributable to a dilution effect. It had an inverse relationship with GPP indicating uptake of nitrogen from water with increased productivity.

The chloride concentration was highest in winter, decreasing in the rainy season and lowest in summer. Less water flowing from and to the lake in winter season caused the accumulation of chloride, released from debris. High chloride values in winter at sites I and II are correlated with animal waste from cattle grazing in the bog during this season. Chloride varied significantly between sites and seasons (Figure 4).

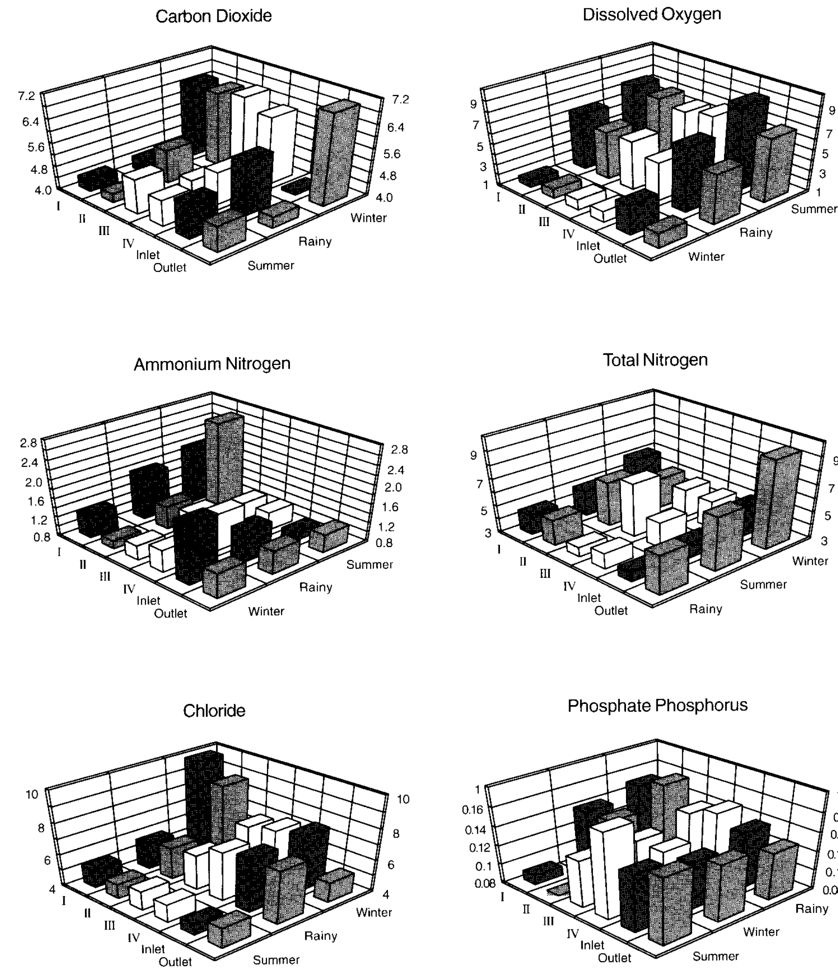

Figure 4. Seasonal variation in free CO_2, DO, NH_4–N, total nitrogen, chloride and PO_4–P of water at six sites in the Khecheopalri lake. *ANOVA*: Free CO_2- Site $F_{5,36}=7$, $P<0.001$; Season $F_{2,36}=181$, $P<0.001$; Site × Season $F_{10,36}=36$, $P<0.001$, LSD(0.05)=0.164; DO-Site $F_{5,36}=37$, $P<0.001$; Season $F_{2,36}=703$, $P<0.001$; Site × Season $F_{10,36}=4$, $P<0.002$, LSD(0.05)=0.28; NH_4-N - Site $F_{5,36}=15$, $P<0.001$; Season $F_{2,36}=10$, $P<0.001$; Site × Season $F_{10,36}=49$, $P<0.001$, LSD(0.05)=0.082; Total nitrogen- Site $F_{5,36}=181$, $P<0.001$; Season $F_{2,36}=228$, $P<0.001$; Site × Season $F_{10,36}=47$, $P<0.001$, LSD(0.05)=0.157; Chloride- Site $F_{5,36}=38$, $P<0.001$; Season $F_{2,36}=987$, $P<0.001$; Site × Season $F_{10,36}=113$, $P<0.001$, LSD(0.05)=0.115; PO_4–P – Site $F_{5,36}=6$, $P<0.001$; Season $F_{2,36}=2$, not significant, Site × Season $F_{10,36}=2.5$, $P<0.02$, LSD(0.05)=0.013.

respiration than other sites. This site was disturbed by offerings made by pilgrims in the form of plant materials and incense. Respiratory loss significantly varied between seasons and sites (Figure 5). The stepwise multiple regression analysis depicted significant relation of respiratory loss with total nitrogen, pH, temperature and carbon-dioxide [ln RES = 2.376 + 0.297 TN – 0.188 pH – 0.131 T – 0.066 CO_2; R^2= 0.475, F = 7.004, $P<0.001$].

Comparison of GPP and respiratory loss showed that there was a gain in productivity in the rainy and summer seasons, but a loss in winter, except at the undisturbed site III.

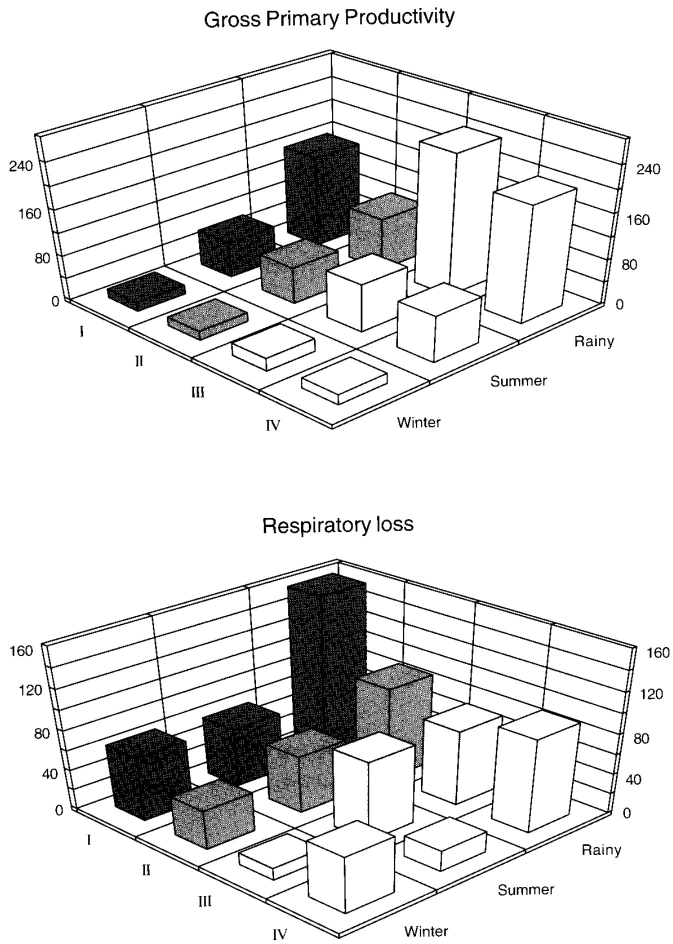

Figure 5. Seasonal variation in GPP and respiration by plankton in the water at four sites of the Khecheopalri lake. *ANOVA*: GPP – Site $F_{3,24}=5.5$, $P<0.005$; Season $F_{2,24}=206$, $P<0.001$; Site × Season interaction not significant; Respiration – Site $F_{3,24}=24$, $P<0.001$; Season $F_{2,24}=101$, $P<0.001$; Site × Season $F_{6,24}=20$, $P<0.001$, LSD(0.05)=9.45.

Conclusions

Natural freshwater lakes in the Himalayan region are slowly disappearing because of runoff sediment deposition and other pressures. Sacred lakes have great values in mythology and religion of mountain people. The longevity of such sacred lakes is now threatened by cultural practices in the surrounding watersheds, as observed in the Khecheopalri lake in Sikkim. High sediment deposition in the lake has enhanced the expansion of the surrounding bog. The boggy area retains much sediment. Nutrient analyses showed that some of the nutrients are imported from agricultural land and forest and from cattle dung in the grazed bog area. Water at the site of worship shows eutrophication. Therefore, offerings should be organized such as to restrict debris from entering the lake. Agricultural activities, grazing and forest resource extraction from the watershed should also be controlled.

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Units: temperature (°C); transparency (cm); acidity (mg l^{-1}); alkalinity (mg l^{-1}); conductivity (μS); CO_2 (mg l^{-1}); DO (mg l^{-1}); NH_4-N (mg l^{-1}); total-N (mg l^{-1}); Cl (mg l^{-1}); PO_4-P (mg l^{-1}); GPP (mg C $m^{-2}d^{-1}$); and respiration (mg C $m^{-2}d^{-1}$).