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Hydrology and nutrient dynamics of a sacred lake in Sikkim Himalaya

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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

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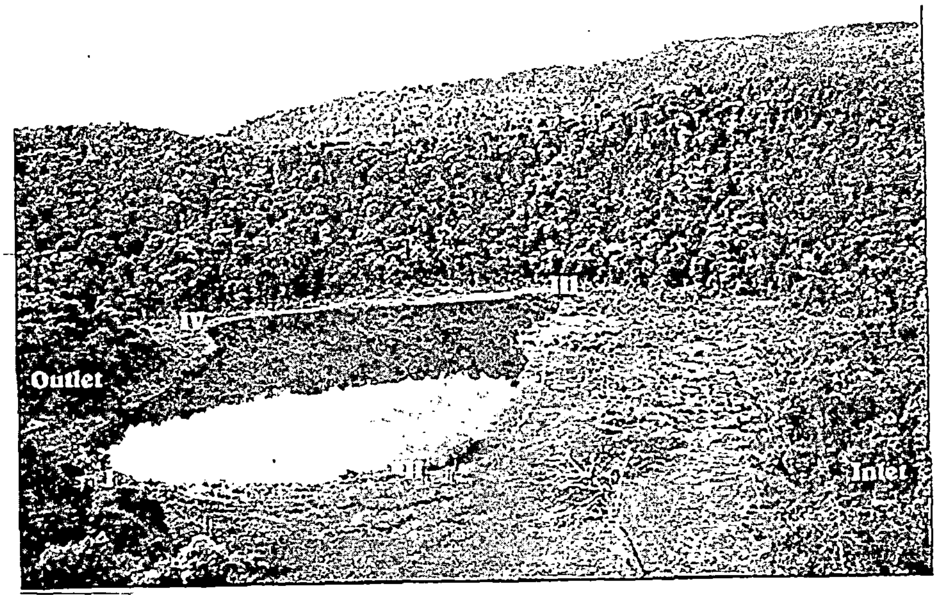


Photo 1. Khecheopalri lake in the Sikkim Himalaya showing boggy area, surrounding watershed and sampling sites.

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.

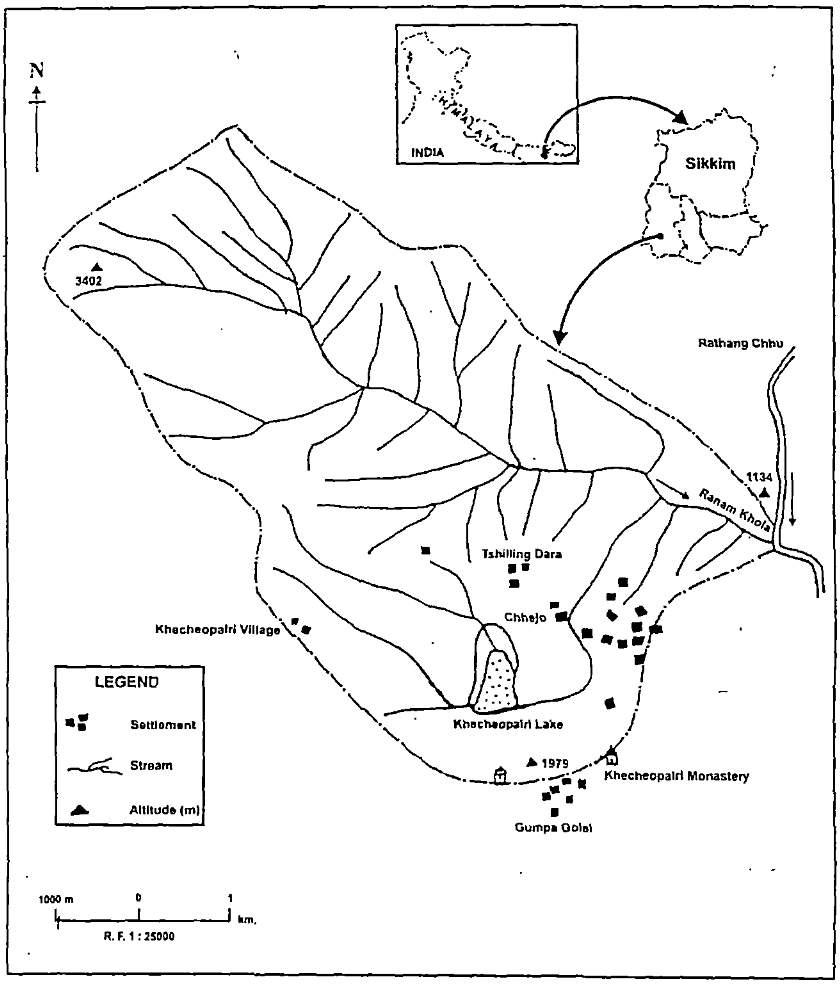


Figure 1. Location map of the Khecheopalri lake and its surrounding watershed.

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	Bog		Watershed forest	Aquatic biodiversity			Type of disturbance
	Aspect*	Peat depth (cm)	Dominant vegetation	dominant tree species*	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

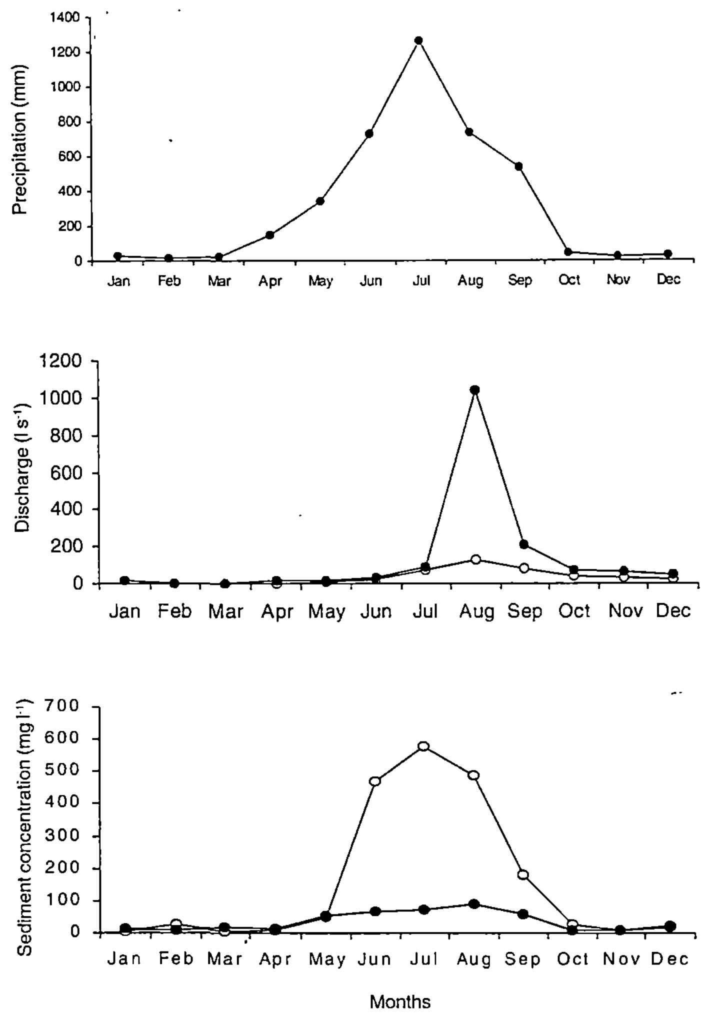


Figure 2. Monthly precipitation, discharge and sediment concentration at the inlets (○—○) and outlet (●—●) of the Khecheopalri lake in Sikkim.

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).

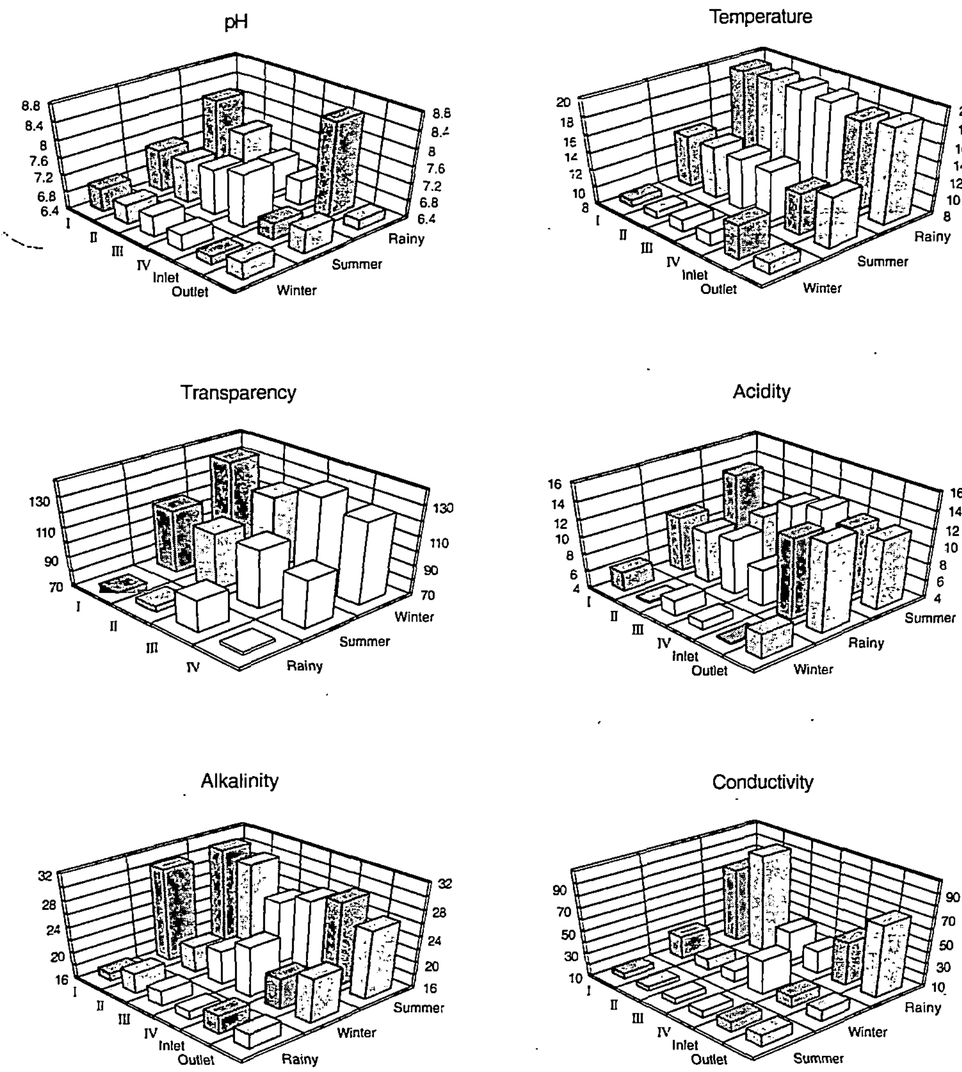


Figure 3. Seasonal variation in pH, temperature, transparency, acidity, alkalinity and conductivity of water at six sites in the Khecheopalri lake. *ANOVA*: pH- Site $F_{5,36}$=28, P<0.001; Season $F_{2,36}$=142, P<0.001; Site × Season $F_{10,36}$=45, P<0.001, LSD(0.05)=0.082; Temperature- Site $F_{5,36}$=8, P<0.001; Season $F_{2,36}$=38872, P<0.001; Site × Season $F_{10,36}$=277, P<0.001, LSD(0.05)=0.071; Transparency- Site $F_{3,24}$=278, P<0.001; Season $F_{2,24}$=9653, P<0.001; Site × Season $F_{6,24}$=156 P<0.001, LSD(0.05)=0.759; Acidity- Site$F_{5,36}$=37, P<0.001; Season $F_{2,36}$=670, P<0.001; Site × Season $F_{10,36}$=15, P<0.001, LSD(0.05)=0.395; Alkalinity- Site $F_{5,36}$=29, P<0.001; Season $F_{2,36}$=812, P<0.001; Site × Season $F_{10,36}$=36, P<0.001, LSD(0.05)=0.498; Conductivity- Site $F_{5,36}$=177, P<0.001; Season $F_{2,36}$=7665, P<0.001; Site × Season $F_{10,36}$=455, P<0.001, LSD(0.05)=0.855.

The main source of phosphorous in the lake was runoff from agriculture land and the forest. Its concentration increased considerably during the rainy season and varied significantly between sites and seasons (Figure 4).

Plankton productivity and respiration

GPP of the lake ranged from 16 mg C m^{-2} d^{-1} to 247 mg C m^{-2} d^{-1}. GPP and net primary productivity was greatest in the rainy season (Figure 5). GPP showed a strong positive correlation with temperature and negative with alkalinity, free CO_2 and total nitrogen. GPP in winter was lowest. Step-wise multiple regression analysis showed that the logarithm of GPP was significantly related to temperature, free CO_2 and total nitrogen [ln GPP = 1.588 + 0.213 T − 0.127 CO_2 + 0.041 TN; R^2 = 0.956, F = 230, P<0.001].

Respiration values of lake water varied between 16 mg C m^{-2} d^{-1}in winter and 160 mg C m^{-2} d^{-1}in the rainy season. Site I showed a relatively higher

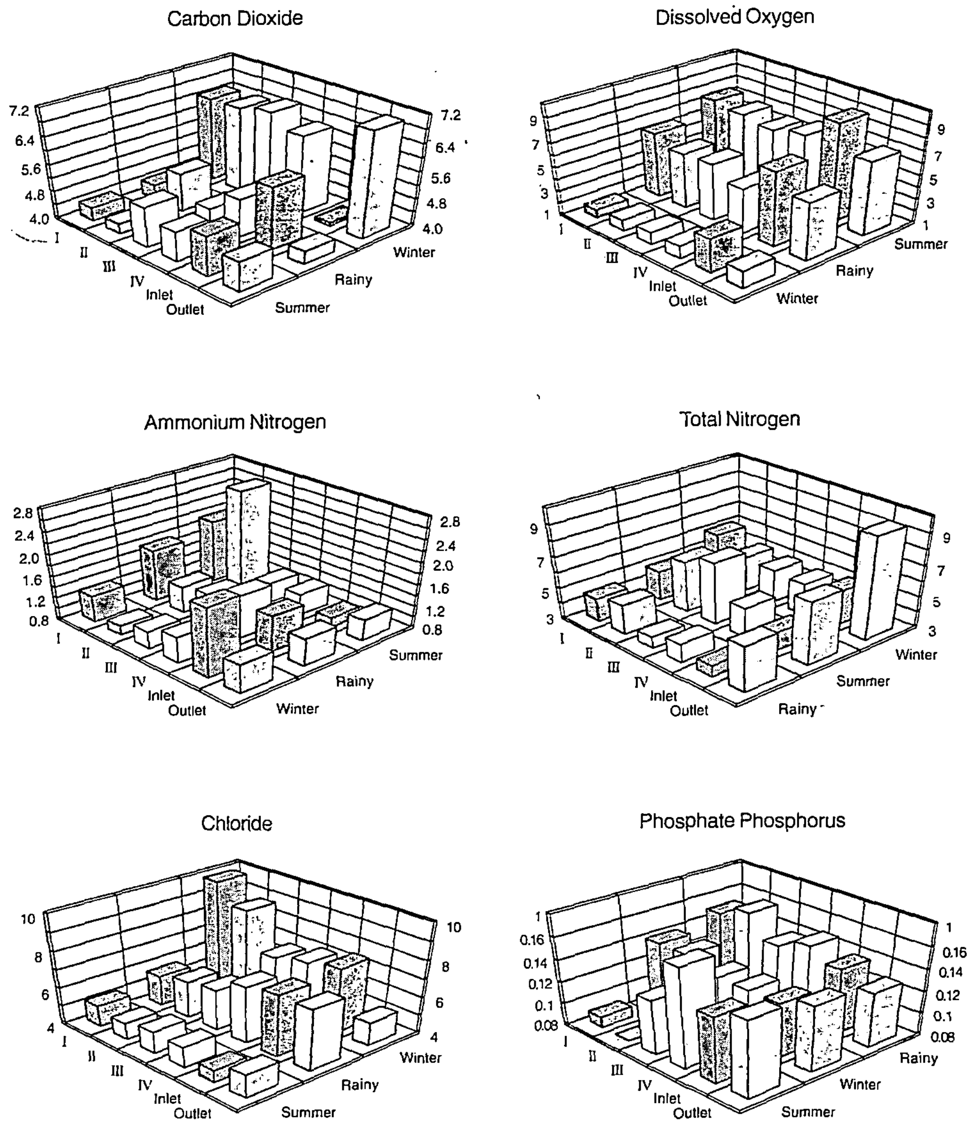
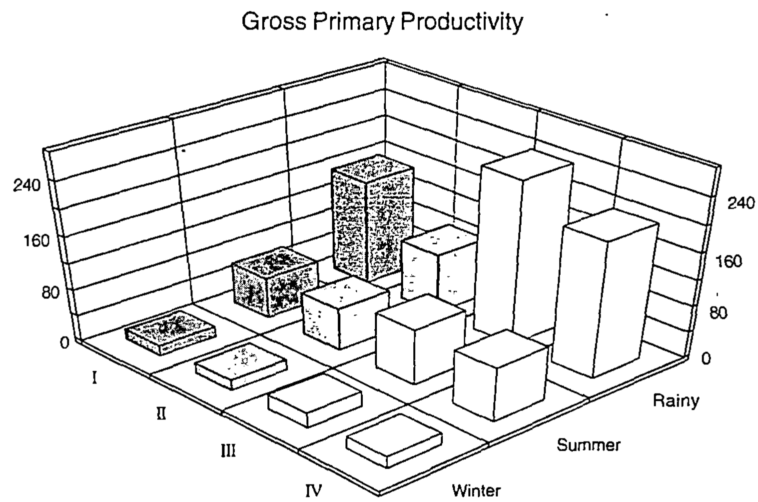


Figure 4. Seasonal variation in free CO_2, DO, NH_4–N, total nitrogen, chloride and PO_4–P of water at six sites in the Khecheopalri lake. *ANOVA*: Free CO_2- Site $F_{5,36}=7$, $P<0.001$; Season $F_{2,36}=181$, $P<0.001$; Site × Season $F_{10,36}=36$, $P<0.001$, LSD(0.05)=0.164; DO- Site $F_{5,36}=37$, $P<0.001$; 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 step-wise 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.



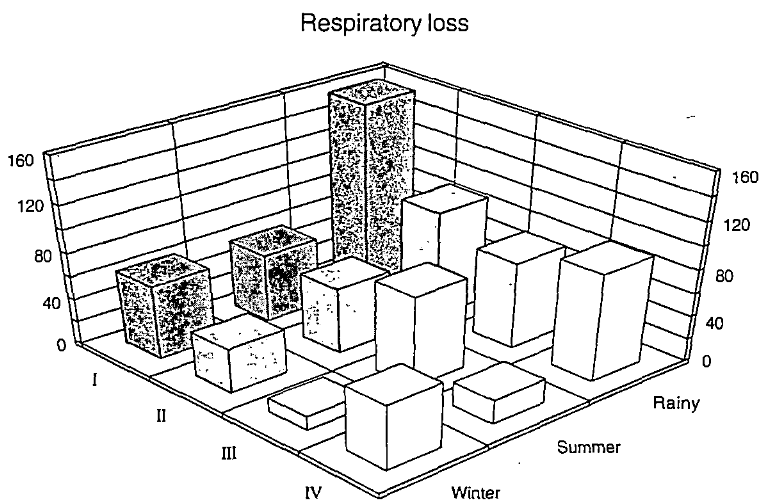


Figure 5. Seasonal variation in GPP and respiration by plankton in the water at four sites of the Khecheopalri lake. *ANOVA*: GPP – Site $F_{3,24}$=5.5. P<0.005; Season $F_{2,24}$=206. P<0.001: Site × Season interaction not significant; Respiration – Site $F_{3,24}$=24, P<0.001; Season $F_{2,24}$=101. 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 $m^{-2}d^{-1}$).

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Hydro-ecological analysis of a sacred lake watershed system in relation to land-use/cover change from Sikkim Himalaya

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Abstract

The hydrology and ecological linkages between Khecheopalri lake and its surrounding watershed (area: 12 km^2) in Sikkim were investigated to assess the long-term impacts of land-use/cover change on the hydrology of the lake ecosystem and bog formation around the glaciated lake. Significant land-use/cover change occurred in the past 4 decades. The bog area expanded by 67%, while the area under agriculture land in the lake watershed grew by 63% between 1988 and 1997. Overland flow was highest on the bare land (4.77% of the precipitation) and lowest in areas of cardamom-based agroforestry (1.79%). Soil and nutrient losses were highest in the cultivated area and least in the cardamom agroforestry system. Sediment loads of 345 Mg $year^{-1}$ were recorded at the lake inlet and of 316 Mg $year^{-1}$ at the outlet. Annual soil loss from the lake watershed was 502 Mg km^{-2} and a net sediment deposition in the lake was 141 Mg $year^{-1}$. The lake received high nutrient loads (organic carbon of 10.2 Mg $year^{-1}$, total nitrogen of 1.01 Mg $year^{-1}$ and total phosphorus of 0.51 Mg $year^{-1}$) from soil erosion and overland flow. The pH, total phosphorus and bulk density of the peat increased from the lake towards the bog-forest edge. This reflects the trapping of sediments and nutrients around the bog forest margin, although their retention is limited. Agricultural practices should be minimized in the upper part of the watershed and agroforestry practices should be encouraged to maintain the health and longevity of the lake. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Discharge; Land-use/cover; Nutrients; Overland flow; Peat bog; Soil loss

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1. Introduction

The land-use/cover changes from forest to other uses have been widespread in the last few decades in the Himalayan region (Singh et al., 1983; Rai et al., 1994). Population growth and tourism have encouraged agricultural expansion unto steep, marginal slopes causing depletion of forests providing fuel, timber and fodder. Such changes in land-use/cover lead to environmental degradation through soil erosion and nutrient loss. Bare, tree-less soil in steep upland farming areas suffers soil erosion and fertility decline (Rai and Sharma, 1995). Therefore, the relationship between land-use/cover change and soil erosion and hydro-ecological processes is a key element in understanding the little known local, regional, and global biospheric disruptions. Such information at the lake watershed level could be highly useful to policy planning and management of the fragile ecosystems of the Himalaya. No such information is available for the lake ecosystems of the Himalayan region. Therefore, the present study was designed to understand the different ecological processes in the sacred Khecheopalri Lake watershed in relation to land-use/cover change. The study investigated (i) the dynamics of land-use/cover change detection; (ii) precipitation, discharge and sediment movement; (iii) overland flow and soil loss; (iv) precipitation partitioning pathways in forest and agroforestry systems and (v) the factors contributing to the development of bog and peatland–lake systems.

2. Study area, material and methods

The famous "Wish fulfilling Lake" Khecheopalri is considered by the Sikkimese as the most sacred. There are many folklores and legends associated with the formation and shape of this lake. The lake being considered sacred, the water is not used for any other purposes except for rites and rituals. Fishing and boating are strictly prohibited in the lake. It is situated in the midst of forest revealing its pristine set up at 27°22′24″N and 88°12′30″E with an altitude of 1700 m amsl in the western part of Sikkim. The lake represents the original "neve" region of the ancient hanging glacier, the depression being formed by the scooping action of hanging glacier (Raina, 1966). The Ramam watershed has mixed broad leaved forests and agriculture land with a total area of 12 km^2 having two villages, which includes 91 ha area specifically as the lake watershed (Fig. 1). Although there are few settlements, the high influx of tourists has led to some disturbance of the lake and its watershed. There are two perennial and five seasonal inlets to the lake and one major outlet (Fig. 2). The lake has been a resting-place for Trans-Himalayan migratory birds and supports commercial and recreational tourism.

Geologically, the local rocks belong to the Darjeeling group. This group mainly comprises high-grade gneisses containing quartz and feldspar with streaks of biotite (GSI, 1984). Pollen analysis of a sedimentary profile from Khecheopalri lake with three ^{14}C dates, i.e., 2280 ± 110, 2380 ± 110, and 1680 ± 130 years BP at different depths (C. Sharma [1]) shows that around 2500 years ago, the lake surroundings had dense mixed

[1] C. Sharma, 1996 (personal communication), Birbal Sanhi Institute of Palaeobotany, Lucknow, India.

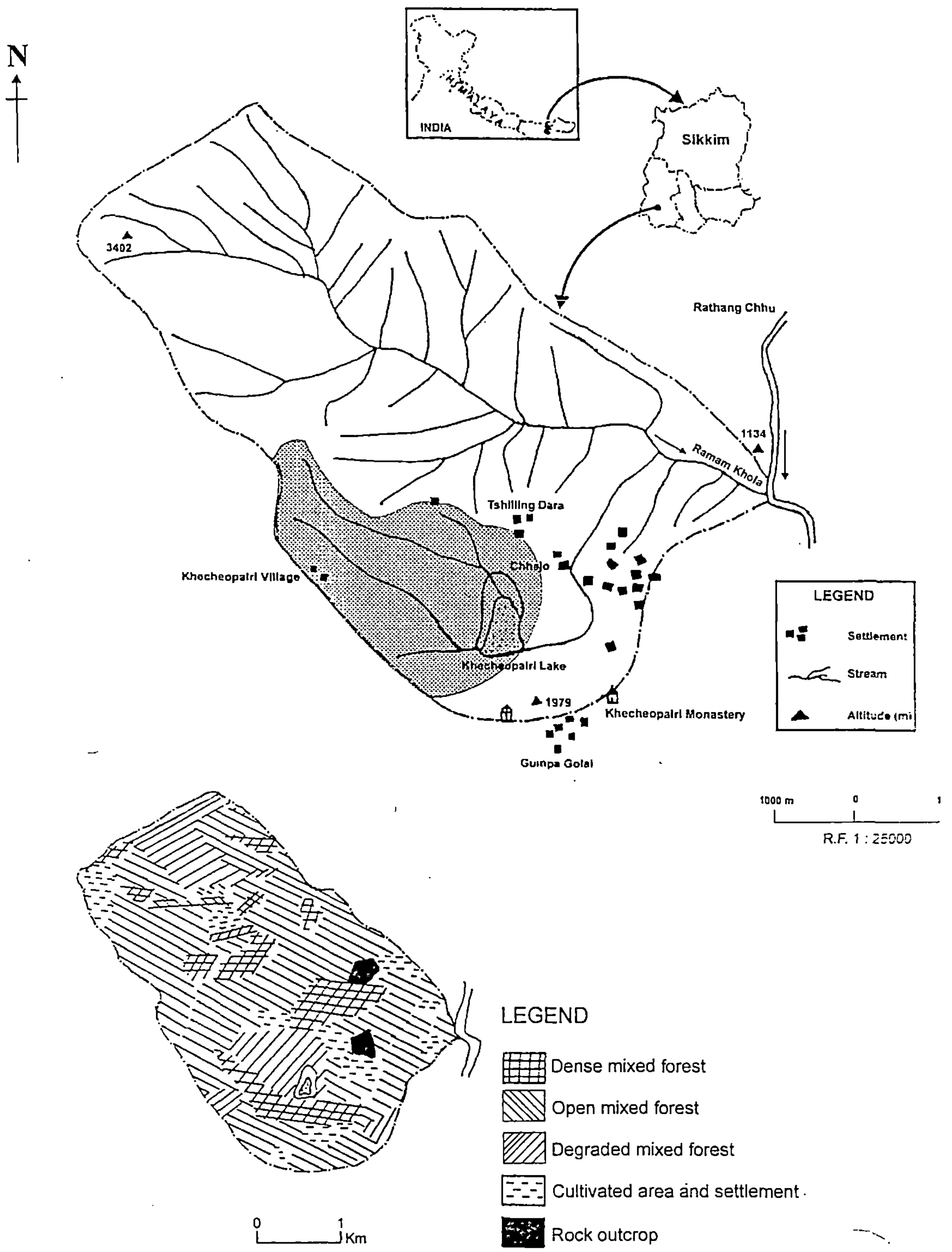

Fig. 1. Location map of the Khecheopalri lake and Ramam watershed. The darkly shaded portion is the lake watershed. Land use/cover of the watershed in 1997 is presented.

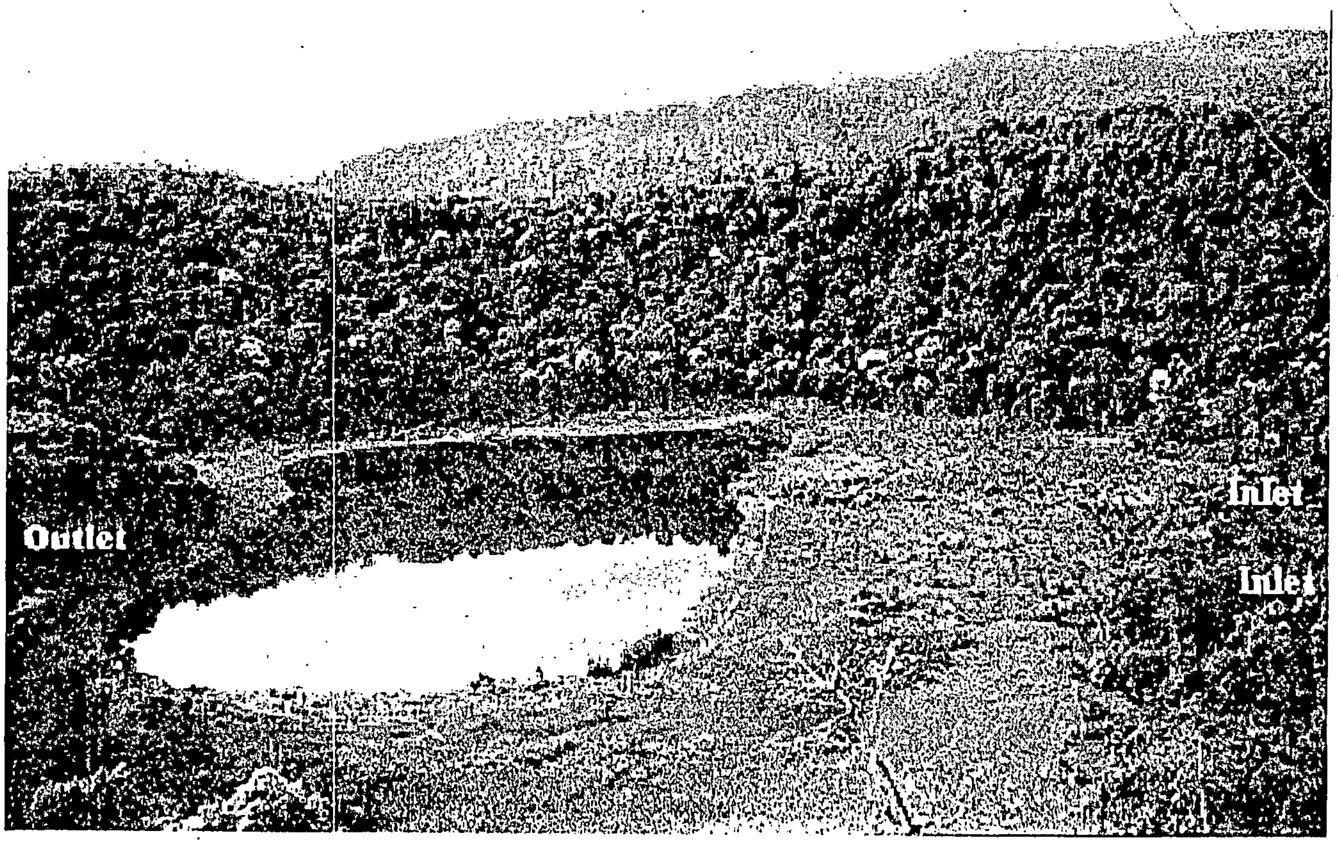

Fig. 2. Khecheopalri lake showing boggy area, surrounding watershed and inlets/outlet.

broad-leaved forests and poorly developed ground vegetal growth. This is indicated by exceedingly high pollen values of *Quercus*, followed by *Alnus* and *Pinus* and other arboreal elements. The soil is sandy loam in nature. Climate of the area is monsoonic and divisible into three seasons: rainy (June to October); winter (November to February); and summer (March to May). Annual precipitation was 3837 mm and mean daily temperatures ranged from 4°C to 24°C during 1997 and 1998.

A land-use/cover map of the sacred Khecheopalari lake watershed was prepared from satellite images, IRS-1A/1B, LISS-II and IRS-1C, LISS-III, FCC of bands 2, 3, and 4 at 1:50 000 for the year 1988 and 1997 and Survey of India topographical maps. Intensive field investigations were carried out to check the land-use/cover classification.

Precipitation was recorded on a monthly basis since 1997 in a non-recording rain gauge located near the lake and pooled into three seasons. Discharge of the inlets and outlet was measured twice daily and values were pooled for three seasons during 1997. Sediment concentration was calculated by filtering water samples collected fortnightly.

Overland flow and soil losses were estimated from 12 experimental plots under different land-use/cover combinations in the lake watershed during 1997 and 1998 on three monsoon (pre-monsoon, mid-monsoon, and post-monsoon) seasons. Three rainfall events were considered for each monsoon period totaling 18 events during 2 years of study. These were estimated using natural shallow surface runoff channels and artificially delineated plots (Pandey et al., 1983; Singh et al., 1983; Rai and Sharma, 1998a). The delineated plot size was 10×3 m^2 for estimation of overland flow and soil loss, and three plots were laid in each type of land-use/cover practice. These plots were bounded with aluminum sheets (6 cm inserted in the soil and remaining 15 cm exposed in air) on all sides to prevent water from entering from adjacent areas. The plots were located on slopes ranging from 20° to 35°. The overland flow and soil losses along the slope were estimated from the collecting tank after each rainfall event. Soil samples were taken down to a 30-cm depth adjacent to each of the delineated plots and were mixed together to form composite samples of the soil at each site. These samples were collected just before the rainy season at the time of plot delineation. The eroded soils were sampled in the form of sediment settled at the bottom of the collecting tank and as-suspended clay material.

Sediment texture analysis of eroded soil was done using mesh sieve. Suspended clay material was separated by filtration using Whatman filter paper from the sample water. The soil for nutrient analyses comprised of both bed-load sediment and suspended clay material for eroded soils. Organic carbon of the soil was estimated following the Walkley–Black method, total nitrogen by the modified Kjeldahl method and the total phosphorus by ascorbic acid method (Anderson and Ingram, 1993). The runoff water samples were analyzed for phosphate–phosphorus by stannous chloride method (Eaton et al., 1995) and total nitrogen by AOAC method (Cunniff, 1995). The organic debris loss was estimated from the overland flow. Net deposition of the sediment in the lake and bog was calculated using delivery ratio (Sharada et al., 1992).

A total of nine stands comprising three each in forests, cardamom-based agroforestry, and traditional crop-based agroforestry systems was selected to investigate pathways of incident precipitation through the plant cover (Table 1). Incident precipitation was recorded during 18 rainfall events during 1997 and 1998. Partitioning of incident

Table 1
Land use based stand characteristic for the hydro-ecological studies in the Khecheopalri lake watershed

Land-use	Altitude (m)	Slope (deg)	Tree height (m)	Basal cover (m^2/ha)	Canopy cover (m^2/ha)	Dominant tree species
Forest	1700–2375	25–35	16 ± 1	58	6805	*Castanopsis tribuloides*, *Symplocos theifolia*, *Machilus edulis*, *Eurya acuminata*, *Viburnum cordifolium*
Cardamom agroforestry	1700–1850	20–30	8.8 ± 1	92	1406	*Prunus cerasoides*, *Eurya acuminata*, *Alnus nepalensis*, *Ficus hookeri*
Traditional crop based agroforestry	1775–2375	30–35	5.5 ± 4	35	727	*Prunus chinensis*, *Ficus nemoralis*, *Ficus hookeri*, *Prunus persica*, *Saurauia napaulensis*, *Machilus edulis*
Bare land	1700–1900	25–35	–	–	–	–

precipitation into throughfall, stemflow, canopy interception, floor leachate, floor interception, and biomass incorporation was made. Trees of dominant species were tagged for stemflow measurement in each of the systems. Stemflow was collected by attaching aluminum collars to three trees of different diameter classes in each stand. Within each plot, three throughfall collectors and three floor leachate collectors were established. Each throughfall collector was placed on the soil surface so that its upper rim was horizontal and was about 20 cm above the ground. Floor leachate collectors were covered by a 2-mm mesh nylon net. The litter carefully removed from below the collector was placed on the net. Floor leachate collectors were inserted into the soil surface such that the rim of the container was horizontal and level with the surface of the litter. Nine throughfall and floor leachate collectors were randomly located. Measurements were made during pre-, mid- and post-monsoon periods. Following each sampling, all throughfall and floor leachate collectors were randomly relocated. This technique produces more accurate estimates of annual volumes than fixed collectors (Kimmins, 1973; Rai and Sharma, 1998a). Throughfall and floor leachate volumes were calculated considering the width of the upper rim of the collecting vessel. Average stemflow was calculated with the basal area of the trees. Biomass incorporation was calculated on dry weight basis of woody biomass. Canopy interception was calculated by subtracting throughfall and stemflow values from the incident precipitation. Forest-floor interception was derived from the difference of the forest-floor leachate, overland flow and biomass incorporation with the added value of throughfall and stemflow.

In order to understand the factors responsible for bog area formation and expansion, four sites were selected considering distance and depth in relation to disturbed and undisturbed upland conditions. Soil cores were taken at 0–50 and 50–100 cm depth intervals below the peat surface at a distance of 2, 30, 60, and 90 m from the lake edge to bog forest edge in 1998 for evaluating the horizontal continuity of the peat strata and the strata boundary. Wet samples were transformed immediately to polyethylene bags to avoid excessive air contact. The peat samples were dried and sieved with a 2-mm mesh for total nutrient analysis. Peat bulk density was determined along the transect at a depth of up to 50 cm. Peat pH was determined using a digital pH meter, total nitrogen by the modified Kjeldahl method and total phosphorus by the chlorostannous reduced molybdophosphoric blue color method (Jackson, 1967). Percent organic matter of oven-dried peat samples was determined by ignition at 450°C for 6 h (Kratz and Dewitt, 1986). Stastical analysis (ANOVA) was done using Systat (1996).

3. Results

3.1. Dynamics of land-use / cover change

The existing land-use/cover pattern of the sacred Khecheopalri lake watershed in 1997 was dense mixed forest (22.53%), open mixed forest (40.69%), degraded forest (21.00%), cultivated land and settlements (13.44%), rock out crop (1.45%) and lake including bog (0.89%). Most of the lake watershed is under forest, with cultivation confined to the upper ridges (Fig. 1).

The major land cover changes from 1963 to 1997 were the expansion of the bog area, of agriculture land and settlements. The cultivated land area increased by 10.29% (Table 2), most of the changes occurring after 1988. Degraded forest increased by 13.42% during 1988–1997. The total forest covers both dense mixed and open mixed decreased by 3.17% and 16.6%, respectively, during the same period. In the case of the lake area, major changes were recorded in the form of bog area expansion (Fig 3). In 1963, the bog was 3.4 ha that increased to 7.0 ha in 1997 (Table 2). The land area, which drained to the lake, comprised of forest (82.5 ha), cultivated land (7.5 ha) and cardamom agroforestry (1 ha).

Table 2
Comparison of land-use/cover change detection of Khecheopalri lake watershed.
Total watershed area 1209 ha.
– Land use not demarcated.

Land-use/cover	Years							
	1963 (area)[a]		1976 (area)[a]		1988 (area)[b]		1997 (area)[b]	
	ha	%	ha	%	ha	%	ha	%
Dense mixed forest	1160.00	95.94	1145.00	94.70	310.80	25.70	272.20	22.53
Open mixed forest[c]	–	–	–	–	693.20	57.33	492.01	40.69
Degraded forest	–	–	–	–	91.70	7.58	254.00	21.00
Settlement and cultivated area	38.20	3.15	53.20	4.40	100.00	8.27	162.50	13.44
Rock out crop	–	–	–	–	2.50	0.21	17.50	1.45
Lake water surface	7.40	0.61	6.80	0.56	6.60	0.54	3.79	0.31
Bog area	3.40	0.28	4.00	0.33	4.20	0.34	7.01	0.58

[a] Based on survey of India map.
[b] Based on satellite imageries.
[c] Large cardamom agroforestry has been included in open mixed forest category.

3.2. Precipitation, discharge and sediment movement

In 1997 and 1998, 85% of the 3837-mm mean annual precipitation was received during rainy season. Annual inflow of water in the lake was estimated at 1103×10^6 l, while the outflow was 4279×10^6 l. The highest discharge of 3835×10^6 l (90%) was

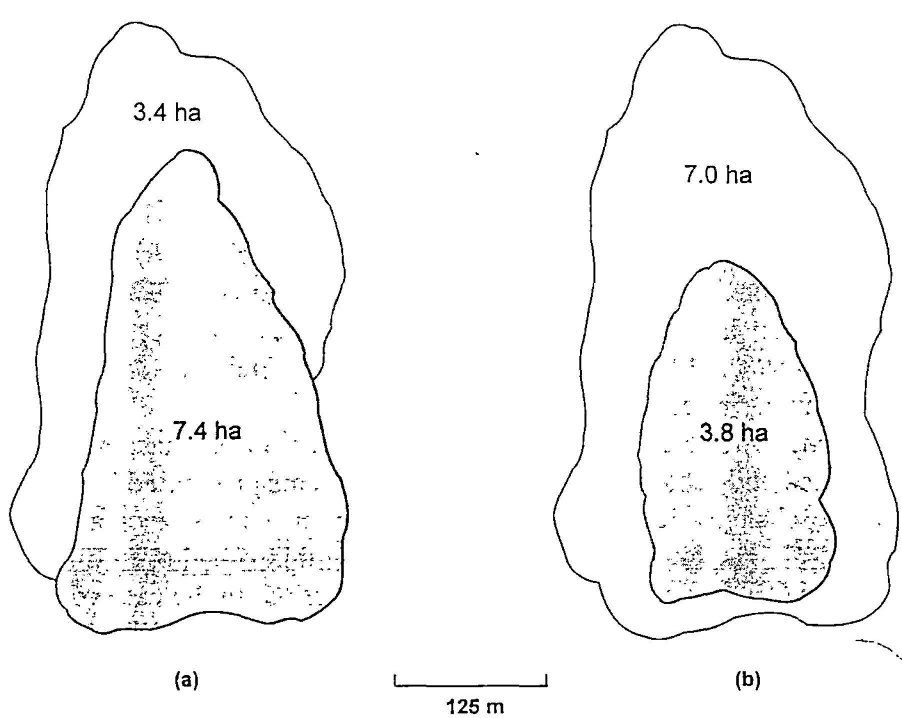

Fig. 3. Extent of open water surface (shaded) and peat bog area in 1963 (a) and 1997 (b) of Khecheopalri lake.

Table 3
Seasonal variation of discharge and sediment movement at the inlets and outlet of the Khecheopalri lake. Values in parentheses are percentages

Season	Inlet flow ($\times 10^6$ l)	Inlet sediment (kg)	Outlet flow ($\times 10^6$ l)	Outlet sediment (kg)
Summer	25 (2.26)	776 (0.22)	94 (2.19)	3173 (1)
Rainy	906 (82.13)	343046 (99.29)	3835 (89.6)	307810 (97.33)
Winter	172 (15.59)	1661 (0.48)	350 (8.23)	5250 (1.66)
Total	1103	345483	4279	316233

recorded in rainy season and the lowest value of 94×10^6 l (2%) in summer season at the outlet (Table 3). Subsurface flow and seepage from the watershed and precipitation on the lake probably cause the outflow to exceed the tributary inflow. At the inlet, the sediment influx ranged from 0.776 Mg during the summer to 343 Mg in the rainy season and the outlet the sediment flow ranged from 3.17 Mg during summer to 308 Mg in rainy season (Table 3). About 29 Mg of soil was deposited annually in the lake and bog through stream sediment.

3.3. *Overland flow and soil loss*

Overland flow was greatest over bare land (4.8%) and smallest in cardamom-based agroforestry (1.8%). Soil loss was highest on the cropped area, while it was lowest in the cardamom based agroforestry system (Table 4). The runoff of organic debris was highest in the forest, followed by cardamom agroforestry, bare land and the least from cropped

Table 4
Rainfall, runoff and eroded soil characteristics of different land-uses of the Khecheopalri lake watershed

Runoff parameter	Forest	Cardamom agroforestry	Cultivated area	Bare land
Overland flow (% of precipitation)	2.06	1.79	3.79	4.77
Runoff ($\times 10^5$ l/ha/year)	6.7	5.8	12.4	15.6
Soil loss[a] (kg/ha)	25	15	405	156
Soil loss (Mg/ha/year)	6.39	1.19	28.42	19.92
Sediment fractionation of eroded soil (%)				
Gravel (> 2 mm)	12	7	2	12
Sand (2–0.04 mm)	74	84	86	67
Silt (0.04–0.09 mm)	9	3	11	14
Clay (< 0.09 mm)	5	6	1	7
Eroded soil nutrient (kg/ha/year)				
Organic carbon	328	38	969	739
Total nitrogen	41	5	91	122
Total phosphorus	13	2	51	39
Runoff water nutrient (kg/ha/year)				
Total nitrogen	7.81	7.03	6.64	6.55
Phosphate-phosphorus	0.12	0.07	0.11	0.19
Runoff organic debris				
(g/l)[a]	1.96	1.75	1.28	1.29
(Mg/ha/year)	1.31	1.13	1.59	2.01

[a]Mean of six rainfall events.

Table 5
Nutrient concentration of parent and eroded soils under different land use in the Khecheopalri lake watershed. Values are mean ($n = 6$) composite samples

Land use	Soil type[a]	Organic carbon (%)	Total nitrogen (%)	Total phosphorus (%)
Forest	PS	4.51	0.47	0.146
	ES	5.13	0.65	0.197
Cardamom agroforestry	PS	3.11	0.35	0.199
	ES	3.19	0.40	0.187
Open cultivated area	PS	2.27	0.28	0.225
	ES	3.41	0.32	0.179
Bare land	PS	2.15	0.15	0.676
	ES	3.71	0.61	0.197
ANOVA P values[b]				
Land-use		0.005	0.05	NS
Soil type		0.05	0.005	0.05
Land-use × Soil type		NS	0.001	NS
LSD (0.05)		–	0.07	–

[a] PS = Parent soil; ES = eroded soil.
[b] Beneath each column P values associated with analysis of variance (ANOVA) are given with LSD values ($P = 0.05$) applicable for means of land use and soil type. NS is not significant.

area. Organic debris in forest runoff was mainly leaf litter. Sediment fractionation of eroded soil from different land-use ranged 67%–86% sand. 2%–12% gravel, 3%–14% silt and 1%–7% clay (Table 4). Total area that drained in the lake was 91 ha, whose 68-ha area drained through two perennial streams and the remaining 23-ha area by overland flow directly to the lake. Soil loss from the 23-ha area that drained directly in the lake was 112 Mg year^{-1}.

Concentrations of nitrogen and organic carbon were higher in eroded soil than the parent soil in all the land-uses, while total phosphorus was mostly higher in the parent than the eroded soil (Table 5). Analysis of variance of organic carbon and total nitrogen showed significant variation between land-uses and soil types, while in the case of total phosphorus, significance between soil types only was recorded (Table 5).

3.4. Precipitation partitioning

Analysis of variance showed that throughfall, canopy interception, overland flow, floor interception and floor leachate varied significantly between the pre-, mid- and post-monsoon periods. Stemflow did not show significant variation between rainfall timings. In case of overland flow, significant variation between land-use was recorded (Table 6). Throughfall ranged from 54% in the cardamom-based agroforestry to 73% in natural forest. The partitioned throughfall positively correlated with the incident precipitation ($r = 0.76$; $df = 8$; $P < 0.01$). The stemflow was recorded highest in traditional agriculture-based agroforestry (6%) followed by natural forest (2%) and lowest in large cardamom-based agroforestry (1%) of the total rainfall. Canopy interception accounted for 45% in cardamom-based agroforestry system followed by 31% in traditional agriculture-based agroforestry and 25% in natural forest (Table 6). About 62% of

Table 6
Precipitation partitioning in three major land uses of the Khecheopalri lake watershed. Values in parentheses are percentages
Rainfall time: PM = pre-monsoon; M = mid-monsoon; POM = post-monsoon; ANOVA: throughfall – rainfall time $F_{3,8} = 63.5$, $P < 0.005$; stemflow – rainfall time $F_{3,8} = 1.72$, NS; canopy interception – rainfall time $F_{3,8} = 16.5$, $P < 0.005$; overland flow – land-use $F_{3,20} = 3.2$, $P < 0.05$; rainfall time $F_{3,20} = 9.8$, $P < 0.005$; floor interception – rainfall time $F_{3,8} = 10$, $P < 0.005$; floor leachate – rainfall time $F_{3,8} = 10.1$, $P < 0.005$. Land-use did not show significant variation for all parameters except overland flow.

Partition components	Land-use											
	Forest				Cardamom agroforestry				Traditional crop based agroforestry			
	PM	M	POM	Total	PM	M	POM	Total	PM	M	POM	Total
Incident precipitation (mm)	1068	1998	572	3638	1068	1998	572	3638	1068	1998	572	3638
Through fall (mm)	566	1548	501	2615 (73)	525	1338	268	2131 (54)	452	1351	453	2256 (63)
Stem flow (mm)	31	72	7	109 (2)	10	30	8	47.4 (1)	11	309	7	327 (6)
Canopy interception (mm)	471	378	64	914 (25)	533	630	296	1460 (45)	606	338	112	1055 (31)
Overland flow (mm)	18	41	6	65	8	39	4	51	9	81	9	100
Floor interception (mm)	458	977	367	1804	17	676	76	769	5	1059	98	1162
Floor leachate (mm)	120	601	133	854	510	653	196	1359	449	520	353	1332
Biomass incorporation (mm)				0.63				0.52				0.10

throughfall and stemflow was collected as leachate in large cardamom-based agroforestry system followed by 51% in traditional agriculture-based agroforestry and 31% in natural forest. Floor interception was highest (66%) in forest, followed by traditional crop-based agroforestry (44%) and cardamom-based agroforestry (35%).

3.5. Bog development and peat nutrient analysis

The peatland of the Khecheoplari lake was formed by the inflow of organic debris and sediments from the upland forest that elevated the periphery of the lake surface, affecting the inundation regimes and colonization by a wide spectrum of vegetation. *Sphagnum* spp. dominated the bog. The lake has a single outlet, which restricts the export of the peat. Seasonal precipitation also favours peat development in the Khecheopalri lake. The peat consists of well-decomposed material with an organic matter content of 12% to 93% (Table 7). The material was dark brown and, in some cases, jelly-like. The organic content of the peat samples gradually decreases from the lake periphery towards the forest margin. Analysis of variance showed significant differences of organic matter content between sites, depth and distance, except for site and depth interaction being not significant (Table 7).

Two relatively discrete vertical peat strata were found in the lake bog. The bulk density varied widely (0.074–0.917 g/cm^3) with distance across the transect, showing

Table 7
Nutrient concentration of bog at two depths of four sites along the distance from lake periphery to forest edge
TN = total nitrogen (%); TP = total phosphorus (%); and OM = organic matter (%); dash = no bog at this distance. ANOVA: pH – site $F_{3,48} = 34.62$, $P < 0.001$; distance $F_{3,48} = 167$, $P < 0.001$; depth $F_{1,48} = 82.4$, $P < 0.001$; site × distance $F_{9,48} = 37.3$, $P < 0.001$; site × depth $F_{3,48} = 12$, $P < 0.001$; distance × depth $F_{3,48} = 13.7$, $P < 0.001$; site × distance × depth $F_{9,48} = 11.3$, $P < 0.001$, LSD (0.05) = 0.14. Total nitrogen – site $F_{3,48} = 80.3$, $P < 0.001$; distance $F_{3,48} = 13.8$, $P < 0.001$; depth $F_{1,48} = 63.2$, $P < 0.001$; site × distance $F_{9,48} = 45.4$, $P < 0.001$; site × depth $F_{3,48} = 11.3$, $P < 0.001$; distance × depth $F_{3,48} = 8.2$, $P < 0.001$; site × distance × depth $F_{9,48} = 16.9$, $P < 0.001$, LSD (0.05) = 0.075. Total phosphorus – site not significant; distance $F_{3,48} = 83.3$, $P < 0.001$; depth $F_{1,48} = 26.6$, $P < 0.001$; site × distance not significant; site × depth not significant; distance × depth $F_{3,48} = 14.3$, $P < 0.001$; site × distance × depth $F_{9,48} = 2.99$, $P < 0.05$, LSD (0.05) = 0.006. Organic matter – site $F_{3,48} = 347$, $P < 0.001$; distance $F_{3,48} = 1488$, $P < 0.001$; depth $F_{1,48} = 740$, $P < 0.001$; site × distance $F_{9,48} = 182.5$, $P < 0.001$; site × depth interaction not significant, site × distance × depth $F_{9,48} = 14$, $P < 0.001$, LSD (0.05) = 1.

Site	Depth (cm)	Distance (m)															
		2				30				60				90			
		pH	TN	TP	OM	pH	TN	TP	OM	pH	TN	TP	OM	pH	TN	TP	OM
I	0–50	4.2	0.44	0.003	89	3.4	1.43	0.007	86	5.3	1.12	0.008	43	–	–	–	–
	50–100	4.9	0.53	0.004	75	3.7	1.42	0.001	82	5.8	0.83	0.069	14	–	–	–	–
II	0–50	3.4	1.29	0.017	93	4.9	1.70	0.015	91	4.5	1.46	0.028	45	5.1	1.10	0.026	53
	50–100	3.7	0.91	0.018	76	5.0	1.17	0.025	83	4.9	0.83	0.045	13	5.2	1.26	0.022	13
III	0–50	4.5	1.10	0.013	88	4.2	1.40	0.022	46	5.7	0.61	0.025	42	5.5	1.21	0.069	54
	50–100	4.8	0.85	0.032	65	4.9	0.64	0.033	24	5.5	1.24	0.046	13	5.9	1.15	0.047	12
IV	0–50	4.1	1.38	0.001	73	4.8	0.37	0.003	40	5.0	0.36	0.026	54	–	–	–	–
	50–100	4.5	0.78	0.003	70	4.9	0.20	0.005	16	5.1	0.34	0.069	13	–	–	–	–

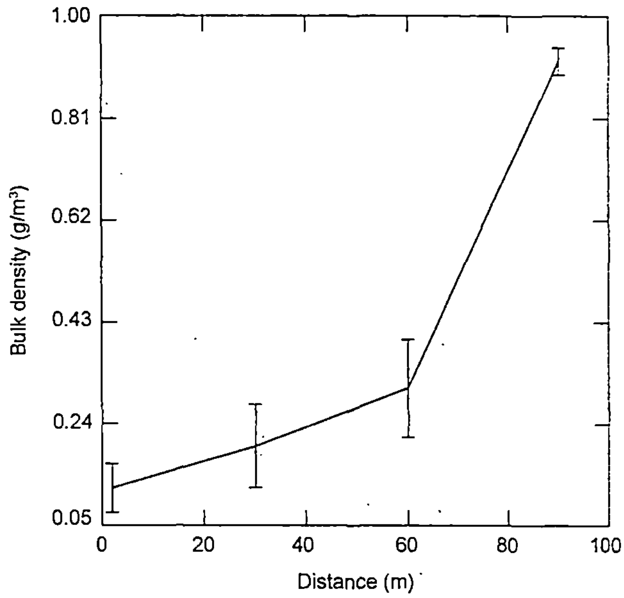

Fig. 4. Variation of bulk density with distance along a transect from lake edge towards bog forest edge.

low values towards the lake edge (Fig. 4). The nutrient contents of the bog samples are presented in Table 7. The pH of the peat materials was acidic, ranging from 4.2 (at 2 m distance) to 5.9 (at 90 m distance). Total nitrogen concentration was generally higher in the upper layer (0–50 cm) compared to the lower depth (50–100 cm). Total phosphorus was low and ranged from 0.003% to 0.069% (Table 7). Analysis of variance of pH and total nitrogen varied significantly with sites, depth and distance, while total phosphorus varied significantly only with distance and depth, and not with sites (Table 7).

4. Discussion and conclusions

The conspicuous land-use/cover changes in the lake watershed in the past 35 years have led to the expansion of the bog area. Agriculture land expansion in the watershed had a major impact on the lake by increased sediment deposition. Areas under dense and open mixed forests have decreased and degraded forest increased remarkably during 1988 and 1997. Nearly a threefold increase in settlements and agriculture area has been recorded in the past 20 years. The conversion of dense mixed forest to open mixed forest and then to degraded forests has been mainly attributed to fuel wood and timber extraction, fodder collection and grazing.

Discharge into and out of the lake is highly seasonal and is directly related to precipitation. Most of the annual rainfall was received in monsoon and the discharge was highest in this period. Seasonal inlets dried completely in the summer season. Sediment concentration also showed a seasonality similar to that of discharge. Sediment flow was high and around 29 Mg was deposited annually in the lake through streams. Greater sediment concentration in the rainy season was attributed to high rainfall and extensive cultivation practices during this period. High sediment in the rainy season turned the lake water turbid. Deposition of sediment in the bog edges resulted in vertical and lateral expansion, threatening the longevity of the lake.

The overland flow from the bare land was greatest compared to other land-uses. Soil loss from the open cropped area was maximum followed by bare land, forest, and minimum from large cardamom agroforestry. The overland flow and the soil loss in the large cardamom-based agroforestry system were less because of good tree canopy and under-storey thick large cardamom bush coverage. The low overland flow recorded in natural forest and cardamom-based agroforestry was comparable with values reported for the Central Himalayan forest and Mamlay watershed of the Sikkim Himalaya (Pathak et al., 1983; Negi et al., 1998; Rai and Sharma, 1998a). On steep forested slopes in Australia. Bren and Turner (1979) found that the overland flow was only 0.005% of the rainfall. That was quite low compared to the present study. The soil loss from the 23-ha area that drained directly in the lake was 112 Mg year^{-1} and sediment load from the remaining 68 ha through the inlet was 345 Mg year^{-1}. Total soil loss from the lake watershed was 502 Mg km^{-2} year^{-1}. Soil deposition in the lake was 141 Mg year^{-1}. This is lower than 616 Mg km^{-2} year^{-1} from a watershed in south Sikkim (Rai and Sharma, 1998b), however, it was at the lower side of the range of 500–1000 Mg km^{-2} year^{-1} reported for the Himalayan region by Milliman and Meade (1983).

The soil loss from the agricultural land was greatest followed by bare land, forest and cardamom agroforestry. Cultivated area occupied 13.4% of the total lake watershed and contributed 22.7% runoff, 42.5% soil loss, 33.2% organic carbon, 27.1% total nitrogen and 39.6% of total phosphorus. The agriculture practice, although small in area, contributed significant amounts of soil and nutrient loss. Therefore, agriculture practice in the form of open cropped area in the lake watershed has to be minimized and should encourage agroforestry practices that showed lower rates of soil and nutrient loss.

The throughfall, stemflow, and canopy interception results are similar to those of the forests of the Central Himalaya and the Mamlay watershed in south Sikkim (Pathak et al., 1983: Negi et al., 1998; Rai and Sharma, 1998a). Throughfall in natural forest was highest as a result of more canopy coverage. Throughfall of similar magnitude has been reported by several workers (Henderson et al., 1977; Rai and Sharma, 1998a). Canopy interception was recorded highest in large cardamom-based agroforestry, which showed good tree canopy and under-storey cardamom coverage. Pathak et al. (1983) reported positive relationship of interception with canopy cover in the Oak forest of the central Himalaya. Waring et al. (1981) argued that the surface area of the forest is an important determinant in interception processes. Comparison between forest and agroforestry systems showed that totality of canopy and floor interception is a very important determinant for water availability with respect to floor leachate. Floor interception of precipitation was directly related with the floor litter composition and quantity. The forest had more floor interception as a result of its thicker litter layer.

The sediment and nutrient inputs from the watershed are filling up the lake, gradually leading to elevation of surface and growth of vegetation. The vegetation in turn affects the flow regimes decreasing the frequency and depth of flooding, so that less organic production is exported and it is deposited as peat. The marshy plants of the peat land trap the sediment to some extent. But it has a negative role to play as it is spreading centripetally towards the open water surface of the lake, forming a kettle hole bog.

Peat soils from bog have many characteristics that distinguish them from the other soils such as low bulk density (Boelter, 1974), high water holding capacity (Thorpe, 1968) and low percent ash and high organic matter content (Pollett, 1972). Our results show that peat contained high organic matter and had low bulk density. The nutrient content of the peat is often an indicator (especially if the peat is drained) of its nutritive value for plant growth (Stanek, 1975). Highly acidic peat showed low contents of the total phosphorus (Lucas and Davis, 1961) and it was reported that highly acidic peat often contained as little as 0.01% phosphorus. Our results showed similar trends, when the peat was highly acidic (pH 4.2) the total phosphorous was recorded very low (0.003%) and with the increase of pH, total phosphorus also increased along the distance from the lake edge towards the forest. Peat acidity and organic matter decreased with depth and distance from the lake periphery towards the forest margin.

Differences in the hydro-ecological attributes of the land-use/cover investigated in this study can form a background for soil and water conservation in the lake watershed. Our findings suggest that the dense mixed forest cover should be maintained on the ridges of the lake watershed to regulate stream flow. The conversion of forests to agriculture land has been quite conspicuous in the past few decades and it has to be reversed immediately. Agroforestry may be encouraged in place of open cropping practice. Successional development in the bog area should be arrested through minimizing sediment accretion from the lake watershed. Agricultural land not only promotes sediment inflow but also adds to the nutrient enrichment through overland flow transport that increases the productivity of the bog, which needs to be stopped. A few rhizomatous species such as *Alocasia* may be grown at the edge of the forest to restrict the sediment from entering the lake and bog.

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