

Seasonal dynamics of zooplankton in a shallow eutrophic, man-made hyposaline lake in Delhi (India): role of environmental factors

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Abstract Old Fort Lake, a small (1.6 ha), shallow, and recreational water body in Delhi (India) was studied through monthly surveys in two consecutive years (January, 2000–December, 2001). Precipitation is the major source of water for this closed basin lake. In addition, ground water is used for replenishing the lake regularly. This alkaline, hyposaline hard water lake contains very high ionic concentration, especially of nitrates. Based on overall ionic composition, this lake can be categorized as chloride–sulfate alkaline waters with the anion sequence dominated by $\text{SO}_4^{2-} > \text{Cl}^- > \text{HCO}_3^-$, and the cations by $\text{Mg}^{++} > \text{Ca}^{++}$. The overall seasonal variability in physicochemical profile was largely regulated by the annual cycle of evaporation and precipitation, whereas the ground water largely influences its water quality. The lake

exhibited phytoplankton-dominated turbid state due to dominance of the blue green alga, *Microcystis aeruginosa*. The persistent cyanobacterial blooms and the elevated nutrient levels are indicative of the cultural eutrophication of the lake. This study focuses on the relative importance of eutrophic vis-à-vis hyposaline conditions in determining the structure and seasonal dynamics of zooplankton species assemblages. A total of 52 zooplankton species were recorded and rotifers dominated the community structure qualitatively as well as quantitatively. The genus *Brachionus* comprised a significant component of zooplankton community with *B. plicatilis* as the most dominant species. The other common taxa were *B. quadridentatus*, *B. angularis*, *Lecane grandis*, *L. thalera*, *L. punctata*, *Mesocyclops* sp., and *Alona rectangula*. Multivariate data analysis techniques, Canonical Correspondence Analysis (CCA) along with Monte Carlo Permutation Tests were used to determine the minimum number of environmental factors that could explain statistically significant ($P < 0.05$) proportions of variation in the species data. The significant variables selected by CCA were $\text{NH}_3\text{-N}$ followed by percent saturation of DO, COD, SS, BOD, $\text{NO}_2\text{-N}$, rainfall, silicates, and $\text{PO}_4\text{-P}$. The results indicate that the seasonal succession patterns of the zooplankton species were largely controlled by physicochemical factors related directly or indirectly to the process of eutrophication, whereas hyposaline conditions in the lake determined the characteristic species composition.

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Introduction

Eutrophication of aquatic ecosystems is increasing worldwide because of the pressure of anthropogenic activities, which are related to nutrient inputs from agriculture, livestock production, urbanization, and industry (Codd, 2000). It is often accompanied by structural changes in the food webs as also in the community structure of zooplankton, phytoplankton, and macrophyte assemblages (Tallberg et al., 1999). This study is on a shallow man-made recreational water body that showed marked signs of cultural eutrophication as evidenced by elevated nutrient levels and frequent or persistent cyanobacterial blooms of *Microcystis aeruginosa*. This alkaline, hyposaline (TDS: 3.0–10.3 g l⁻¹; Hammer, 1986) and hard water lake contains very high concentrations of ions. We studied the relative impact of a hyposaline and eutrophic environment in structuring zooplankton communities in this lake. Multivariate data analysis techniques, Canonical Correspondence Analysis (CCA) along with Monte Carlo permutation tests were used to elucidate the role played by different environmental variables in modulating the structure and seasonal succession of zooplankton assemblages.

In India, zooplankton communities have been investigated in numerous reservoirs, lakes, and shallow water bodies (see reviews by Gopal & Zutshi, 1998; Jana, 1998). Most of these studies have focused on the relationship of zooplankton with water quality, particularly that of eutrophication and organic pollution. This study, however, is not comparable to earlier investigations on eutrophic ecosystems, as none of the latter was hyposaline. The composition of biological communities in salt lakes is different from that in fresh waters with differences in composition becoming more pronounced as salinity increases (Williams, 1998). In hyposaline waters, most taxa present are generally halotolerant freshwater forms, and species richness and composition are highly correlated with salinity. Despite the well-known impact of salinity as a determinant of community structure, studies have indicated that the most distinctive physicochemical feature of salt lakes i.e.,

elevated ionic concentrations may not be as distinctive as an ecological factor in determining community structure in salt lakes (Williams et al., 1990; Williams, 1998). On the contrary, a variety of factors other than salinity could be playing a more important role in controlling community complexity. This article draws attention to the relative impact of hyposaline vis-à-vis eutrophic conditions in structuring zooplankton community in a shallow lake.

Materials and methods

Study area

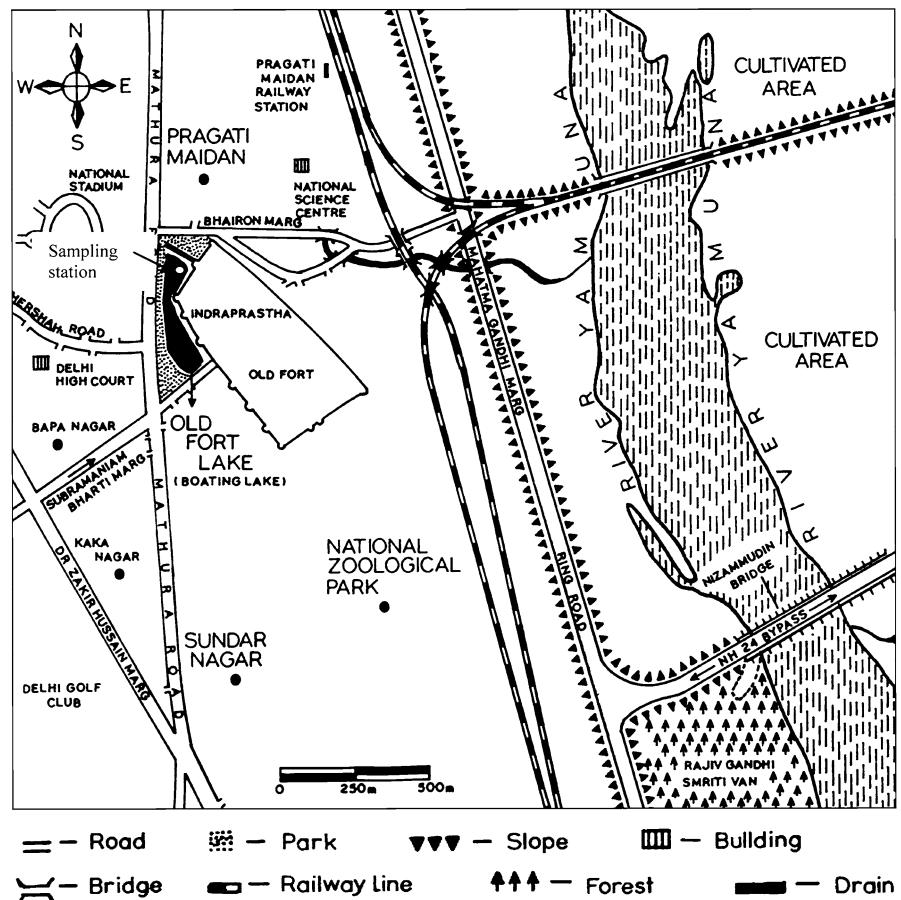
Old Fort Lake is located in the semiarid, subtropical region of northern India near National Zoological Park in Delhi (Fig. 1). The Mughal emperor, Sher Shah Suri constructed this Fort during 1538–1545 A.D. It is believed that originally this water body was a wide moat around the Old Fort connected with the river Yamuna. At present, it is a small, roughly oblong, shallow ($z = 0.8$ m) water body having an average area of ca. 1.6 ha and a shoreline of 771 m, and it represents a closed hydrological basin without any inlet from the river. The lake substratum is largely made up of mud and supports a luxuriant growth of emergent macrophyte (*Typha angustifolia*) along the lake margins. Rainwater is the major source of water and groundwater is frequently pumped into the lake to maintain water level during the dry periods. Delhi Tourism department has made arrangements for recreational activities such as paddle and canoe boating in the lake.

The water as well as plankton samples were collected once a month over a period of 2 years (January, 2000–December, 2001) from a station near the boating complex (Fig. 1).

Physicochemical analysis

Water samples for the estimation of DO were collected directly in BOD bottles, and were fixed immediately. Parameters such as air and water temperature (using dial thermometer), hydrogen ion concentration (using portable pH meter, Cole-Parmer Instrument Co., Chicago, Illinois), and free carbon dioxide (CO₂) were measured in the field, and DO was determined immediately upon returning to the

Fig. 1 Map showing the location of the Old Fort Lake toward northern and western side of the Fort, and its position in relation to the River Yamuna. Note the location of sampling station towards the northern shore end of the lake



laboratory. For analysis of the remaining parameters, surface water samples were collected in clean 1-l and 250-ml polyethylene bottles. For ammonia estimation, samples were fixed with conc. sulfuric acid. In the laboratory, all the parameters were analyzed within 4–6 h of collection, and whenever overnight storage was required, samples were stored at 4°C to minimize microbial activity. Conductivity was recorded using Control Dynamics conductivity meter (Control Dynamics, APX 185). The procedures adopted for analysis of all the physicochemical parameters except nitrates, color, and turbidity were according to the ‘Standard Methods for the Examination of Water and Wastewater’ (APHA, 1989). Nitrates were analyzed according to ‘Water Analysis’ (Fresenius et al., 1988), and color as well as turbidity using Hellige’s aquatester and turbidimeter, respectively. Climatological data were obtained from the Meteorological Department (Government of India) in Delhi.

Plankton analysis

The plankton was concentrated for quantitative analysis by filtering 25 l of water through a 35- μ m mesh plankton net. In order to collect the relatively rare species, 50 l of water was also filtered for qualitative analysis. All the concentrated plankton samples were preserved with 4% neutral formalin for subsequent examination and quantification. For identifying zooplankton species, each sample was scanned critically by using a stereoscopic binocular microscope (Leitz Wetzlar), and the selected specimens were transferred by a micropipette to a watch glass containing a drop of glycerin. Semi-permanent mounts of the selected specimens were prepared by mounting the entire specimen in glycerin on a glass slide, sealed with ‘nail polish’, and examined under 50 \times or 100 \times magnifications. In order to prevent compression and deformation of the specimen, small plasticine “legs” were fixed on each of the four

corners of the cover slip before putting it on the slide. For identification of rotifers, trophi were isolated, whenever necessary, by dissolving the soft tissue with 4% sodium hypochlorite (NaOCl). Organisms were enumerated using a modified Sedgewick-Rafter cell equipped with a grid base. For quantification, the concentrate was thoroughly mixed and diluted to a desired volume. Three counts taking 1 ml aliquots each time were examined and their averages taken. Densities were expressed as Individuals l^{-1} . Zooplanktons were identified to the species level using standard books and keys (e.g., Koste, 1978; Michael & Sharma, 1988; Segers, 1995).

Data analysis

Species diversity of zooplankton was calculated using Shannon–Weiner Index (H') (Brower et al., 1990). Species evenness or equitability was also calculated, which has a minimum value of 0 when evenness is low, and a maximum value of 1 when evenness is high (Brower et al., 1990). The data were analyzed using a software package, SIMDISS version 2.0 by Salmaso (2001).

The temporal variations in physicochemical parameters, plankton abundance, H' , α diversity, and equitability were analyzed by one-way ANOVA using a software package, SYSTAT version 10.2 (SYSTAT Software Inc.).

Principal Component Analysis (PCA), an indirect gradient analysis technique, was used to detect the major environmental variables in the lake (PCA; CANOCO version 4.5; ter Braak, 2002). PCA is an ordination technique used to reduce the dimensionality of multivariate data sets and enable graphical presentation of the relationships between the factors (Waite, 2000). All the variables were $\log_{10}(x + 1)$ transformed to approximate a normal distribution prior to analysis.

Canonical Correspondence Analysis (CCA), using a multivariate direct gradient analysis technique to elucidate the relationships between biological assemblages of species and their environment (ter Braak & Verdonschot, 1995; Waite, 2000), was undertaken with $\log_{10}(x + 1)$ transformation. The data sets used for CCA consisted of monthly species abundance values and correspondent variables. For CCA, 17 zooplankton taxa along with 33 environmental factors (28 physicochemical as listed in Table 1, and five

biological, which include total abundance values of Bacillariophyceae, Cyanobacteria, Chlorophyceae, Xanthophyceae, and Dinophyceae) were considered. Both the species of *Hexarthra* has been considered together as single taxa for CCA due to difficulty in differentiating the two species while quantifying zooplankton. The forward selection of CCA, which is analogous to step-wise multiple regression, was used to determine the minimum number of explanatory factors that could explain statistically significant ($P < 0.05$) proportions of variation in the species data. The significance of these variables was assessed using Monte Carlo permutation tests (with 999 unrestricted permutations). All the ordinations were performed using CANOCO version 4.5 (ter Braak, 2002).

Results

Physicochemical analysis

Physicochemical analysis of water indicated that Old Fort Lake is as an alkaline (pH: 8.3–9.4) and hard water lake (total hardness: 1,420–3,720 $mg\ l^{-1}$) with relatively high ionic concentration (conductivity: 4.9–10.6 $mS\ cm^{-1}$). Throughout the study period, free carbon dioxide was absent at the study site. Among the basic nutrients, exceptionally high values for NO_3-N were recorded, whereas the concentration of PO_4-P was relatively low (Table 1). The predominant anions can be arranged in the following sequence in decreasing order of their average concentration: $SO_4^{2-} > Cl^- > HCO_3^-$. Among cations, values for Mg^{++} were higher than for Ca^{++} (Table 1). Values for DO, % saturation of DO, and silicates were generally high during the study period.

The monthly data for different physicochemical variables were analyzed using Principal Component Analysis (PCA) (Fig. 2). PCA axis 1 (horizontal) explained 37.8% of the variations in the environmental data, whereas PCA axis 2 (vertical) accounted for a further 22.6% variability, and finally the first four PCA axes together explained 80.2% variability (Table 2).

PCA biplot clearly indicates the correlation between different variables as also the relative importance of each variable in explaining the overall variability in the environmental data (Fig. 2). In

Table 1 Physicochemical parameters with their mean and range of variations observed at Old Fort Lake during the study period

Parameters	Symbol	Mean	Range of variation
Rainfall (mm)	Rainfall	59.8	0–295.8
Air Temperature (°C)	AT	28.5	15–38
Water temperature (°C)	WT	24	12–31
Conductivity ($\mu\text{S cm}^{-1}$)	Cond	7514	4886–10583
color (APHA units)	Col	35.2	15–75
Turbidity (APHA units)	Turb	36.5	12–72
Hydrogen-ion concentration (pH)	pH	8.8	8.3–9.4
Free CO_2 (mg l^{-1}) ^a	–	0	
Total hardness (mg l^{-1})	T-Hard	2470	1420–3720
Magnesium hardness (mg l^{-1})	Mg-Hard	1584	870–2540
Calcium hardness (mg l^{-1})	Ca-Hard	887	400–1340
Total alkalinity (mg l^{-1})	T-Alk	141	46–312
Bicarbonate alkalinity (mg l^{-1})	$\text{HCO}_3\text{-Alk}$	118	16–292
Carbonate alkalinity (mg l^{-1})	$\text{CO}_3\text{-Alk}$	23	10–38
DO (mg l^{-1})	DO	10.7	5.9–16.6
% Saturation of DO	%DO	127	56–208
COD (mg l^{-1})	COD	26	15–36
BOD (mg l^{-1})	BOD	6.8	4–12
Total solids (mg l^{-1})	TS	6427	3720–10600
Total dissolved solids (mg l^{-1})	TDS	6121	3320–10220
Suspended solids (mg l^{-1})	SS	306	160–610
Chlorides (mg l^{-1})	Chlor	1733	1000–2620
sulfates (mg l^{-1})	sulf	1985	1450–3100
Orthophosphates (g l^{-1})	$\text{PO}_4\text{-P}$	31	8–105
Silicates (mg l^{-1})	SiO_2	9.7	0.4–19
Nitrates (mg l^{-1})	$\text{NO}_3\text{-N}$	346	75–765
Nitrites (g l^{-1})	$\text{NO}_2\text{-N}$	2635	100–6400
Ammonia (g l^{-1})	$\text{NH}_3\text{-N}$	563	89–1450

Symbols used in PCA biplot are indicated against each variable

^a Free CO_2 always absent

general, similar variables clustered together e.g., (i) those associated with ionic concentration such as conductivity, sulfates, chlorides, total, calcium and magnesium hardness, TS, and TDS; (ii) Turbidity and suspended solids; (iii) pH and carbonate alkalinity; (iv) DO and % saturation of DO; (v) COD and BOD; (vi) Total and bicarbonate alkalinity. In contrast, inverse associations between nitrites, nitrates versus ammonia; BOD, COD versus DO, and % saturation of DO; total, and bicarbonate alkalinity versus carbonate alkalinity and pH can be noticed in the ordination diagram (Fig. 2).

The distribution of each parameter along different months can be analyzed by the positions of the

triangles with respect to the environmental factors (arrows). For example, all the months seen in the lower right quadrant are those in which high values for parameters i.e., turbidity, SS, pH, carbonate alkalinity, and ammonia were obtained, whereas months in the lower left quadrant tend to be associated with higher concentrations of variables such as total and dissolved solids, conductivity, total, calcium and magnesium hardness, chlorides, and sulfates.

Variables such as TS, TDS, conductivity, total, calcium and magnesium hardness, chlorides, $\text{NO}_2\text{-N}$, and $\text{NO}_3\text{-N}$ are significantly correlated with axis 1 (Fig. 2). Besides, factors such as pH, carbonate

Table 2 Eigen values and cumulative percent variance of environmental data for the first four PCA axes obtained for Old Fort Lake (see Fig. 2)

PCA axis	Eigen values (λ)	Cumulative percentage variance of environmental data
1	0.378	37.8
2	0.226	60.4
3	0.113	71.8
4	0.084	80.2

$n = 24$

alkalinity, $\text{NH}_3\text{-N}$, Silicates, SS, $\text{PO}_4\text{-P}$, and turbidity, which are inversely related to the former group, also contributed significantly to axis 1. In contrast, factors i.e., DO, % saturation of DO, COD, BOD, total, and bicarbonate alkalinity are significantly associated with axis 2 (Fig. 2). Thus, it seems that the first axis is somewhat related to the cycle of precipitation and evaporation or wet or dry periods which tend to increase or decrease the ionic concentrations. In contrast, the second axis is likely to be related with the process of degradation of organic matter which influences the DO, BOD, and COD values, and also to some process which bring about changes in the total alkalinity (Fig. 2).

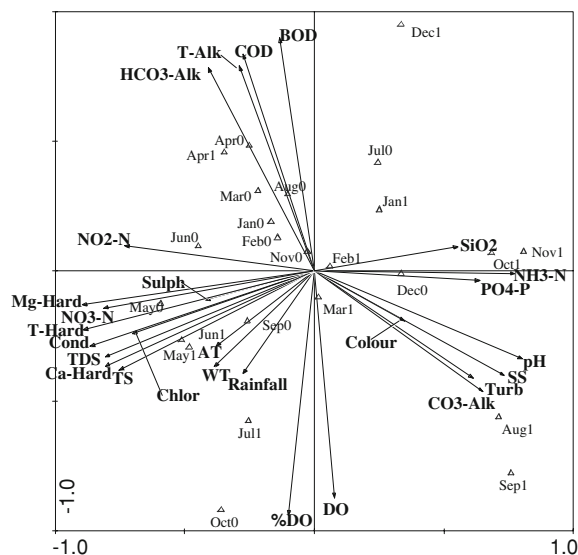


Fig. 2 PCA ordination diagram for the Old Fort Lake with months (white triangle) and environmental factors (arrows); first axis is horizontal and second axis is vertical. The abbreviations used for environmental variables are given in Table 1. The month0 (Jan0–Dec0) and month1 (Jan1–Dec1) refer to the months of the years 2000 and 2001, respectively

Plankton analysis

A total of 52 zooplankton species were recorded, and were represented by rotifers (46 species), cladocerans (5 species), and cyclopoid copepod (1 genus) (Table 3). The species have been classified as common, occasional, frequent, and rare on the basis of the frequency of their occurrence in plankton samples. The α diversity of zooplankton ranged between 5 and 17, and Shannon–Weiner diversity index (H') of zooplankton was relatively low with values ranging between 0.67 and 2.55 bits Ind.^{-1} . The species evenness or equitability of zooplankton varied from 0.20 to 0.78, and exhibited patterns of spatio-temporal variations similar to H' .

The major peak in zooplankton density was recorded during early winter ($9.03 \times 10^3 \text{ Ind. l}^{-1}$) in the year 2000 and during mid-summer ($7.2 \times 10^3 \text{ Ind. l}^{-1}$) in the year 2001. The relative percent contribution of rotifers to the zooplankton was high and that of cladocerans relatively low during major part of the study period. The contribution of cyclopoid copepods and nauplii varied widely during different seasons.

During the 2-year study, genus *Brachionus* comprised a significant component of the zooplankton community. The most dominant brachionid species was *Brachionus plicatilis* during the major part of the study period; however, it disappeared completely from October to December of 2001. Besides, *B. angularis* and *B. quadridentatus*, *Lecane grandis*, *L. thalera*, *L. punctata*, *Mesocyclops* sp., and *Alona rectangula* were commonly observed. Though, the relative contribution of these species to the total density varied widely during different season.

Factors regulating seasonal dynamics of zooplankton assemblages

The influence of environmental variables on seasonal succession and composition of zooplankton species were analyzed using Canonical Correspondence Analysis (CCA). In the ordination biplots, arrows represent environmental variables and points depict either the species or the months. With forward selection and Monte Carlo permutation tests, CCA identified a minimal subset of environmental variables that explained significant proportions ($P < 0.05$) of the variations in the species data and only these variables are shown on the biplots.

Table 3 List of zooplankton species recorded from Old Fort Lake during January 2000–December 2001

Rotifers		
<i>Asplanchna intermedia</i> Hudson	Aint	O
<i>Brachionus angularis</i> Gosse	Bang	F
<i>B. caudatus</i> (Hauer)		R
<i>B. calyciflorus</i> Pallas	Bcaly	O
<i>B. plicatilis</i> (O.F. Müller)	Bplic	C
<i>B. quadridentatus</i> Hermann	Bquad	C
<i>B. rubens</i> (Ehrb.)		O
<i>B. urceolaris</i> (O.F. Müller)		O
<i>Cephalodella catellina</i> (Müller)		O
<i>C. exigua</i> (Gosse)		R
<i>Colurella uncinata f. bicuspidata</i> (Ehrb.)		O
<i>C. adriatica</i> Ehrb.		O
<i>C. oxycauda</i> Carlin		O
<i>Encentrum</i> sp.		R
<i>Eosphora najas</i> Ehrb.	Enaja	O
<i>Euchlanis dilatata</i> Ehrb.		R
<i>Filinia longiseta</i> (Ehrb.)		O
<i>F. terminalis</i> (Plate)		O
<i>Hexarthra intermedia</i> Wiszniewski	Hex	F
<i>H. mira</i> (Hudson)	Hex	F
<i>Keratella tropica</i> (Apstein)	Ktrop	O
<i>Lecane bulla</i> (Gosse)	Lbul	O
<i>L. closteroerca</i> (Schmarida)		O
<i>L. curvicornis</i> (Murray)		O
<i>L. grandis</i> (Murray)		C
<i>L. hamata</i> (Stokes)		O
<i>L. hastata</i> (Murray)		R
<i>L. luna</i> (Müller)	Llun	O
<i>L. papuana</i> (Murray)		R
<i>L. punctata</i> (Murray)		C
<i>L. signifera</i> (Jennings)	Lsign	R
<i>L. stenroosi</i> (Meissner)		O
<i>L. thalera</i> (Harring & Myers)		C
<i>Lepadella eurysterna</i> Myers		O
<i>L. ovalis</i> (Müller)		R
<i>L. patella</i> (Müller)		R
<i>Liliferotrocha subtilis</i> (Rodewald)	Lsubt	O
<i>Limnias melicerta</i> Weisse		R
<i>Philodina citrina</i> (Ehrb.)		R
<i>Proales</i> sp.		R
<i>Rotaria macroceros</i> (Gosse)	Rmacr	O
<i>R. rotatoria</i> (Pallas)		O
<i>Synchaeta oblonga</i> Ehrb.		O
<i>S. pectinata</i> Ehrb.		R

Table 3 continued

<i>Testudinella patina</i> (Hermann)		R
<i>Trichocerca pusilla</i> (Lauterborn)	Tpus	F
Cladocerans		
<i>Alona rectangula</i> Sars (♀ & ♂)	Arect	C
<i>A. taraporevalae</i> Shigur and Naik		R
<i>A. pulchella</i> King		R
<i>Ceriodaphnia cornuta</i> Sars		O
<i>Moina micrura</i> Kurz	Mmicr	O
Copepods		
<i>Mesocyclops</i> sp.	Cycop	C

Symbols used in CCA biplots are indicated against the species. (C = Common; O = Occasional; F = Frequent and R = Rare)

Table 4 Summary statistics for the first four axes of CCA performed between environmental variables and selected zooplankton species for the Old Fort Lake (see Figs. 3, 4)

CCA axis	Eigen values (λ)	Cumulative percentage variance of species–environment relationship
1	0.330	25.5
2	0.236	43.7
3	0.172	57.0
4	0.125	66.6

$n = 24$; No. of zooplankton species = 17; No. of environmental variables = 33 (28 physicochemical as listed in Table 1, and five biological, which include total abundance value of Bacillariophyceae, Cyanobacteria, Chlorophyceae, Xanthophyceae, and Dinophyceae)

The eigenvalues (λ) for CCA axis 1 (λ : 0.330) and CCA axis 2 (λ : 0.236) explained 43.7% of variance in the species data. Altogether, the first four CCA axes explained a total of 66.6% variability (Table 4). Further, Monte Carlo permutation tests and forward selection indicated that out of the total 33 variables, nine made independent and significant contributions to the variance in the zooplankton species assemblages. The maximum variability in the species data was explained by NH₃-N (18.50%), percent saturation of DO (12.34%), COD (10.02%), SS (8.48%), BOD (6.17%), NO₂-N (6.17%), rainfall (5.39%), silicates (3.85%), and PO₄-P (3.85%) (Table 5). Variables, viz., SS ($r = +0.687$), NO₂-N ($r = -0.415$), Silicates ($r = +0.613$), PO₄-P ($r = +0.715$), and NH₃-N ($r = +0.754$) related strongly to axis 1, whereas rainfall ($r = -0.562$) and percent

Table 5 The environmental variables identified by CCA with forward selection and Monte Carlo permutation tests explaining significant proportions of the variance in the zooplankton species–environment relationship at Old Fort Lake (see Figs. 3, 4)

Variables	Sum of all the eigen values (λ_s) = 1.297	
	Eigen values (λ_v)	% Variance explained = $\lambda_v/\lambda_s \times 100$
NH ₃ -N ^b	0.24	18.50
% Saturation of DO ^b	0.16	12.34
COD ^b	0.13	10.02
SS ^b	0.11	8.48
BOD ^b	0.08	6.17
NO ₂ -N ^b	0.08	6.17
Rainfall ^b	0.07	5.39
SiO ₂ ^a	0.05	3.85
PO ₄ -P ^a	0.05	3.85

$n = 24$

^a $P < 0.05$

^b $P < 0.01$

saturation of DO ($r = -0.466$) associated significantly with axis 2 (Figs. 3, 4). However, the biological factors considered for CCA were not found to be significant.

The species such as *Rotaria macroceros*, *Alona rectangula* and *Brachionus plicatilis*, and *Hexarthra* sp. highlighted on the left-hand side were associated with high levels of NO₂-N, whereas species such as *Brachionus angularis*, *B. quadridentatus*, *B. calyciflorus*, *Lecane bulla*, *Moina micrura*, and *Asplanchna intermedia* shown on the right-hand side were associated with high values for SS, PO₄-P, NH₃-N, Silicates, COD, and BOD. In addition, all the species shown in the lower half of the biplot were strongly correlated with high rainfall and percent saturation of DO (Fig. 3).

The ordination diagrams between selected zooplankton species and months clearly demonstrates the distribution pattern of each species along various months of the study period. For example, rotifer species *Liliferotrocha subtilis* occupies an aberrant position and is closely associated with December 2000, indicating that it was abundant only during this period. Similarly, rotifer species, *Brachionus calyciflorus* and *Lecane bulla* were abundant only during

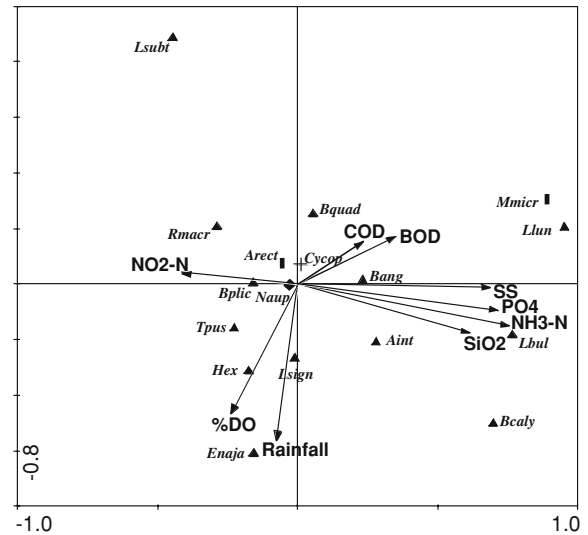


Fig. 3 Ordination biplot of zooplankton species assemblages and environmental variables obtained by CCA for Old Fort Lake. Abbreviations used for different zooplankton taxa are enlisted in Table 3 and Naup represents nauplii. The symbols indicate ▲—rotifers, ■—cladocerans, +—copepods, and ◆—Nauplii

September 2001 when high values for variables like silicates, NH₃-N, PO₄-P and SS were observed (Figs. 3, 4). In addition, *Brachionus angularis* was found to be more abundant in the second year of the investigation (Fig. 4).

In the ordination diagrams, *Moina micrura*, a cladoceran species, occupies an aberrant position due to its occurrence only during October–December of 2001 when a substantial increase in the NH₃-N levels was evident (Figs. 3, 4).

Discussion

Closed basin lakes are particularly sensitive to climatic changes and therefore, respond more quickly to precipitation and to changes in temperature (Richardson, 1969). Wetzel (1999) has pointed out that the most important factor responsible for water loss in closed lake basins of semi-arid regions is evaporation or evapotranspiration. Also, water loss by evapotranspiration in tropical lakes with extensive littoral vegetation is significantly higher than by evaporation from an open water surface. Other investigators have made similar observations with regard to the water economy of closed basin lakes

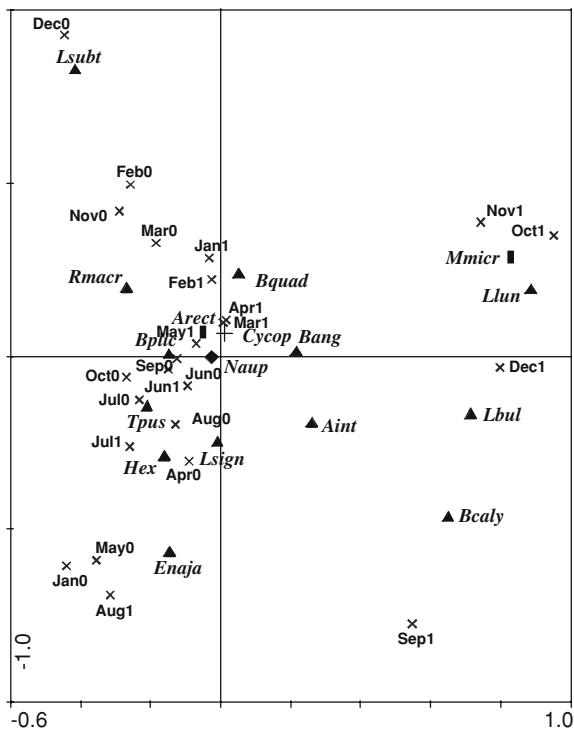


Fig. 4 Ordination biplot of zooplankton species assemblages and months obtained by CCA for Old Fort Lake. Abbreviations used for different zooplankton taxa are enlisted in Table 3 and Naup represents nauplii. The month0 (Jan0–Dec0) and month1 (Jan1–Dec1) refer to the months of the years 2000 and 2001, respectively. The symbols indicate ▲—rotifers, ■—cladocerans, +—copepods, and ◆—Nauplii

(e.g., Hutchinson, 1957; Street-Perrot & Harrison, 1984; Bos et al., 1999). In Old Fort lake with dense stands of actively growing littoral vegetation dominated by emergent macrophyte (*Typha angustifolia*), evapotranspiration could be playing more important role in water loss than evaporation.

In this lake, the seasonal cycles of precipitation and evaporation determine temporal variations in different physicochemical parameters, whereas the elevated ionic concentrations could be due to frequent pumping of groundwater into the lake. The ground water inputs are mostly responsible for the higher values of variables i.e., chlorides, $\text{NO}_3\text{-N}$, sulfates, and hardness. Earlier reports have also indicated that groundwater plays an important role in the solute budgets of the receiving surface waters (e.g., Furch, 2000; La Baugh et al., 2000; Magnuson & Kratz, 2000). In addition, numerous studies have confirmed that groundwater inputs tend to increase

the concentrations of chlorides (Allen et al., 1999), $\text{NO}_3\text{-N}$ (Berka et al., 2001; Piirsoo, 2001; Narula et al., 2002), sulfates (Drever, 1996; Kaçaroğlu et al., 2001), and cations, Mg^{++} as well as Ca^{++} (Furch, 2000; Magnuson & Kratz, 2000), thereby increasing the values for total hardness.

In the closed lake basins, the pattern of geochemical changes follows a path from carbonate source waters to mostly chloride and sometimes to sulfato-chloride composition (Herbst, 2001). On the basis of overall ionic composition, Old Fort Lake can be categorized as chloride–sulfate alkaline earth waters with the anions sequence dominated by $\text{SO}_4^{2-} > \text{Cl}^- > \text{HCO}_3^-$ and the cations by $\text{Mg}^{++} > \text{Ca}^{++}$. Similar ionic compositions have also been reported for some sulfate-rich water bodies in Spain (Armen-gol et al., 1991) and Sicily (Naselli-Flores, 1999). In general, saline lakes may be regarded as a terminal stage in the aging of endorheic lake basins (Herbst, 2001). Thus, the hyposaline Old Fort Lake can be considered to have reached the terminal stage in the aging of its closed basin.

Shallow lakes usually support highly diverse biota due to more extensive littoral zone. The maximum diversity of freshwater ecosystems occurs where wet-land and littoral habitat heterogeneity interfaces with the open waters of lakes (Wetzel, 1999). However, the species richness decreases with increasing salinities (e.g., Leland & Berkas, 1998; Wetzel, 2001). Also, the species diversity is generally greater in larger ecosystems because of the higher spatial heterogeneity and ecological diversity (Carney, 1998). Thus, relatively smaller basin size, absence of varied macrophytes, and high ionic concentrations are probably responsible for comparatively low species richness at Old Fort Lake.

In the planktonic communities, the continual temporal changes as well as succession are usually recognized as the main mechanism by which diversity is maintained (Lewis, 1987). In addition, Carney (1998) has pointed out that in an aquatic ecosystem, the number of “functional species” or “abundant species” is far less than the total number of species actually present. Further, Padišák (1991) suggested that the greater the variability, the higher the persistence of a large number of rare, fast growing species “ready to develop” when the ecological conditions of the environment become suitable. Since the present lake was also subjected to high environmental variability with wide variations in water level, flooded area, and macrophyte development,

it usually supported large number of rare and occasional species.

During the major part of the study period, the lake under observation exhibited phytoplankton-dominated turbid states due to the dominance of blue green algae, *Microcystis aeruginosa* (Arora, 2003). A spring peak of diatoms was observed only in the year 2000, and thereafter their density remained low due to the development of persistent cyanobacterial blooms, which is another important indication of highly eutrophic status of the lake (Arora, 2003). Also, zooplanktons were found to be ineffective in controlling these cyanobacterial blooms. This can possibly be ascribed to avoidance of ingestion of *M. aeruginosa* by zooplankton because of physiological and behavioral problems and/or because *M. aeruginosa* might have escaped predation by zooplankton by increasing the colony size or by forming surface scums. Numerous other studies have reported somewhat similar interactions between blue green algae and zooplanktons (e.g., Gilbert & Bogdan, 1984; de Mott et al., 1991; Henning et al., 1991; Carmichael, 1996).

In waters with salinities between 3 and 20 g l⁻¹ (hyposaline waters), the biota comprises halotolerant freshwater forms, and species richness and composition correlate highly with salinity (Williams, 1998). In particular, the species richness of cladocerans (Bos et al., 1999) and rotifers (Egborge, 1994) decreases with increasing levels of total dissolved solids/salinity of the water body. The high salinity at this Lake also restricted the occurrence of varied rotifers and cladocerans species. However, the characteristic saline waters species such as, *Alona rectangula*, *Brachionus plicatilis*, *B. quadridentatus*, *B. angularis*, *Lecane grandis*, *L. thalera*, and *L. punctata* were recorded. This is in agreement with the observations of Williams (1978), Walker (1981), Egborge (1994), Segers (1995), Naselli-Flores et al. (1998), Bos et al. (1999), and Swadling et al. (2000). Altogether, rotifers had the maximum species representation followed by cladocerans, whereas copepods were represented by a single cyclopoid, i.e., *Mesocyclops* sp. These observations relating to the structure of zooplankton community are in agreement with those of Fernando (1994), Dumont (1994), and Branco et al. (2000).

It is likely that hyposaline condition and the known physiological stress resulting from a saline *milieu exterieur* were playing an important role in determining the distinctive composition of the biota

in this lake. However, a more important driving force controlling the zooplankton species community structure and dynamics possibly was eutrophic environment. It is well established that eutrophication leads to decrease in the percentage of calanoids, while promote the development of cyclopoid copepods in the crustacean community (e.g., McCauley & Kalff, 1981; Maier, 1996; Kasprzak & Koschel, 2000). In addition, eutrophication results in marked increase in the density of zooplankton, especially rotifers (Stemberger, 1974; Walz et al., 1987). The predominance of rotifers in eutrophic environments has been attributed to availability of a wide range of natural sestonic food particles (e.g., Dumont, 1977; Pouriot, 1977; Starkweather, 1980). Similar observations have been made from this lake, wherein there was a complete absence of calanoid copepods, and rotifers dominated the community structure. Also, there was a complete absence of large-bodied cladocerans like *Daphnia*. *Daphnia* populations are usually absent at higher salinities (Moss, 1994; Jeppesen et al., 1994; Scheffer, 1999) but eutrophic environment as manifested by abundance of blue-green algae could also be responsible for its absence from this lake. In many eutrophic lakes, species of *Daphnia* do not seem to thrive when blue-green algae are abundant, either because the algal colonies are too large for them to eat, or because they may not be able to digest some types of blue-green algae even though the cells are small. Thus, in the absence of most of the predators like large-bodied cladocerans that cannot tolerate highly eutrophic conditions, rotifers (euryhaline *B. plicatilis* in this lake) grow and reproduce very well in eutrophic waters.

Sommer et al. (1986) and Michaloudi et al. (1997) have emphasized that in shallow lakes there could be unpredictability in the patterns of seasonal succession of zooplankton. Similarly, no definite pattern of seasonal variations in the population of zooplankton was observed and the zooplankton community was dominated by rotifers, mostly *B. plicatilis*. Similar observations have also been made from the other saline lakes (e.g., Green et al., 1979; Green & Mengistou, 1991; Pejler, 1995). In addition, the relative contribution of crustaceans to the zooplankton was low, except during spring. The increase in crustaceans during spring was possibly due to high fecundity of the over wintering population and the hatching of resting eggs, as reported also by

Hutchinson (1967), Brandl et al. (1989), and Michaloudi et al. (1997).

In lacustrine habitats, zooplankton community structure and their seasonal dynamics are determined by a variety of factors such as morphometry, hydrology, climatic conditions, salinity, littoral complexity, and the presence of macrophytes. Several authors, who have investigated the biota of salt lakes over a range of salinities, have pointed to the fact that salinity generally has little impact in determining species occurrences (e.g., Wood & Talling, 1988; Colburn, 1988; Williams et al., 1990; Williams, 1998). Factors invoked by them to explain distributions included differences in macrophyte community structure, food resources, predation, and competition, and other forms of biological interaction, and interactions between particular physical and chemical factors. A variety of other factors other than salinity such as oxygen concentration, ionic composition, pH, hydrological patterns, geographical position, past climatic events, chance, human intervention, and various forms of biotic interaction may in various combinations or individually, be significant in determining the structure of community in salt lakes. However, in order to single out the major forces driving zooplankton succession remains a difficult task, as at any instance, varied factors can be exerting their influence on the zooplankton community structure. Thus, multivariate data analyses such as CCA, which can elucidate a minimal subset of factors that explain a significant proportion of seasonal variations in zooplankton species assemblages, provide a reasonable solution to this problem. In this study, similar approach to the problem has been taken up.

The significant environmental variables identified by CCA that explain maximum variability in zooplankton species at Old Fort Lake include abiotic factors, viz., $\text{NH}_3\text{-N}$, $\text{NO}_2\text{-N}$, $\text{PO}_4\text{-P}$, % saturation of DO, COD, BOD, silicates, SS, as well as rainfall. Several earlier studies have also confirmed that abiotic factors such as temperature, turbidity, SS, nutrients (N and P), SiO_2 , pH, and ionic concentrations influence directly or indirectly the seasonal dynamics of zooplankton species assemblages (e.g., Berzins & Pejler, 1989; Pinel-Alloul et al., 1990, 1995; Dodson, 1992; Shaw & Kelso, 1992; Beaver et al., 1999; Wolfenbarger, 1999; Swadling et al., 2000). Besides, there are reports that rainfall can also influence the zooplankton community structure (e.g., Burgis, 1973; Gaviria,

1993; Maia-Barbosa et al., 1998). It is important to note that all these significant physicochemical factors are related directly or indirectly more strongly with the process of eutrophication than with the hyposaline condition of the water body.

As pointed out by Williams (1998), salinity should be seen as one of the several other factors responsible for the structure of biological communities in salt lakes, and as one with perhaps less direct impact than in the past has often been assumed a priori. Its impact can be strongly modified by other factors, and there are also indirect mechanisms by which it may exert its effects e.g., by imposing osmoregulatory stress, or by eliminating predators. In this lake, hyposaline condition dictated the unique and distinctive species composition but had little influence on the seasonal dynamics of zooplankton species. Finally, the eutrophic environment played a more decisive role in determining the overall species abundances and seasonal succession.

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