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Environmental Characterization of Two Ecologically Distinct Gangetic Oxbow Lakes using Zooplankton Taxonomic Indices Through Comparative Approach for Wetland Monitoring

Suman Kumari[1] · Lianthuamluaia Lianthuamluaia[1] · Uttam Kumar Sarkar[1] · Mishal Puthiyottil[1] · Gunjan Karnatak[1] · Dharmendra Kumar Meena[1] · Sandhya Kavitha Mandhir[2] · Md Abul Hassan[1] · Ashok Kumar Jaiswar[3] · Anil Prakash Sharma[4] · Basanta Kumar Das[1]

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Abstract

The present investigation is an attempt for environmental characterization of two ecologically distinct oxbow lakes using zooplankton taxonomic indices following a comparative approach. These closed and seasonally open oxbow lakes are subjected to eutrophication, impacting their nutrient concentration and eco-hydrological characteristics. The zooplankton are closely linked with environment throughout their life cycle, hence are a potential indicator of eutrophication. The study examined the assemblage pattern of zooplankton community and trophic state of two ecologically distinct oxbow lakes based on eco-hydrological factors and community structure of rotifers and planktonic crustaceans. Comprehensive trophic state index (mTSI), rotifer trophic state indices ($mTSI_{ROT}$) and crustacean based indices (TSI_{CR}) were used to assess the degree of eutrophication. The Kruskal–Wallis test confirmed the heterogeneity in eco-hydrological factors between the oxbow lakes. The studied lakes were in transition from high meso-eutrophic to moderately eutrophic state. The mTSI, $mTSI_{ROT}$ and $mTSI_{CR}$ for Khalsi (seasonally open) and Akaipur (closed) were 54.90 ± 11.71, 56.95 ± 15.64, 59.55 ± 4.54 and 60.26 ± 4.48, 55.79 ± 4.76, 60.00 ± 4.03 respectively. The Canonical Correspondence Analysis (CCA) revealed NO_3^-N, water temperature and pH positively impacted abundance of eutrophication indicator species *Brachionus* and *Keratella*. An overview of worldwide use of rotifer and crustacean based indices in assessment of TSI has also been discussed. The use of these zooplankton indices to evaluate the trophic status of the ecologically distinct lakes is highly recommended for water quality assessment and management.

Keywords Oxbow Lake · Ecological health · Zooplankton-based indices, fisheries management

Introduction

The oxbow lakes are characterized by shallow depth, high sediment nutrient and productivity (Janseen et al. 2014; Tang et al. 2018, 2019). These lakes offer a plethora of ecosystem services for livelihood and nutritional security to the riparian communities (Sarkar et al. 2020; Das et al. 2021). These wetland ecosystems provide safety from natural calamities, serve as habitat for larval rearing, nutrient recycling, water for domestic and irrigation purpose, fishing activities and are considered as "Kidney of ecosystem" due to its efficient sinking capacity to inhale major agricultural runoff (Sarma and Dutta 2012; Meena et al. 2019; Karnatak et al. 2020; Sarkar et al. 2020, 2021a, b).

Oxbow lakes, mainly distributed in eastern and north-eastern India are important fishery resources. These lakes

✉ Uttam Kumar Sarkar
uksarkar1@gmail.com

1 Indian Council of Agricultural Research-Central Inland Fisheries Research Institute, Barrackpore, Kolkata 700120, India

2 Indian Council of Agricultural Research-Central Institute of Fisheries Technology, Kochi, Kerala 682029, India

3 Indian Council of Agricultural Research-Central Institute of Fisheries Education, Versova, Andheri West, Mumbai, Maharashtra 400061, India

4 G. B. Pant, University of Agriculture & Technology, Pantnagar, India

are under integrated management practices including fisheries (culture-based fisheries, enclosure culture), agriculture and horticulture (Chaudhuri et al. 2008; Ghosh and Biswas 2015). Despite huge potential, these water bodies are neglected and used irrationally. Anthropogenic pressures resulting from agriculture and industrial developmental activities have accelerated degree of eutrophication of freshwater ecosystem worldwide (Junk et al. 2014). Different types of bioindicators are widely used to assess the aquatic ecosystem health using physical, chemical and biological parameters comprehensively (Oh et al. 2017). Several tools such as macrobenthos based multimetric indices (Meena et al. 2019), phytoplankton indices (Roshith et al. 2018), water quality index (WQI) (Sharma and Bora 2020), biomonitoring and bioassessment (Sanyal et al. 2015), fish assemblage and fisheries (Sandhya et al. 2016, 2019) etc. have been used for wetland health assessment. These have limitations in terms of real time application such as high fluctuations due to climatic and water quality factors. Trophic state is one of the most important characteristics to classify nutritional load of an aquatic ecosystem (Jekatierynczuk-Rudczyk et al. 2014; Dembowska et al. 2015; Ejsmont-Karabin et al. 2016; Wen et al. 2017; Smaoune et al. 2021). Various environmental parameters are used to measure the trophic status of a lake. One of the most widely used trophic state index for classifying lakes is Carlson trophic status index that is based on total phosphorus (TP), Secchi depth (SD) and concentration of Chlorophyll *a* (Carlson and Havens 2005; Abell et al. 2020).

Chlorophyll *a* concentration proxies the phytoplankton biomass which signifies the production functions of aquatic ecosystem (Das Sarkar et al. 2021). Easiest one is based on SD but its measures are inclined by both algal and non-algal particulate matters. Zooplankton are one of the important biotic components and a sensitive indicator of water quality, vital for maintaining overall ecosystem productivity and stability of food web (Branco et al. 2002; Kumari et al. 2017; Doukhandji and Arab 2017; Tang et al. 2019; Smaoune et al. 2021).

Although, several reports are available on zooplankton abundance and community structure from water bodies of India (Ganesan and Khan 2008; Sharma 2009, 2011; Sharma and Sharma 2012) and Bangladesh (Biswas and Panigrahi 2015), most are limited to the diversity indices. Only a few studies have attempted to study the relation between species richness and assemblage pattern based on macro-zoobenthos and rotifers to evaluate the wetland health (Kumari et al. 2017; Meena et al. 2019; Ejsmont-Karabin 2012; Dembowska et al. 2015), crustacean (Jekatierynczuk-Rudczyk et al. 2014; Xiong et al. 2016). Rotifer is a tiny, short generation time organism which quickly responds to the environmental changes (Segers 2008) and acts as an effective tool to indicate the ecological status of the lakes and reservoirs (Jiang et al. 2017). Initially taxon-based indicator such as *Brachionus:Trichocerca* ratio (BT) was used to assess the trophic status of lake, but this has its own limitation of not working in absence of either species (Sládeček 1983). Trophic status of lakes based on zooplankton such as rotifers and crustaceans have been found to be promising to assess the degree of eutrophication in shallow lakes worldwide (Ejsmont-Karabin 2012; Jekatierynczuk-Rudczyk et al. 2014; Dembowska et al. 2015; Ejsmont-Karabin et al. 2016; Smaoune et al. 2021). Rotifer based indicator of trophic status was highly recommended for anthropogenic impacted water bodies (Lodi et al. 2011). Rotifer and crustacean based indices such as TSI_{ROT} and TSI_{CR} are potential tool for evaluating the degree of eutrophication (Liang et al. 2020a, b).

Therefore, in the present study rotifer trophic state index (TSI_{ROT}) and crustacean trophic status index (TSI_{CR}) developed by Ejsmont-Karabin (2012) and modified by Ejsmont-Karabin and Karabin (2013) respectively have been used to estimate ecological quality standards of the two different type of shallow open water bodies. The present investigation is an attempt to determine the spatio-temporal patterns and trends of physico-chemical factors by perusal of zooplankton structured taxonomic indices. The findings will reflect spatio-temporal eutrophication in two lower Gangetic Oxbow lakes in relation to zooplankton dynamics.

Materials and Methods

Study Area

Two Oxbow lakes of West Bengal namely Khalsi ($25^{0}59'54.02''$N $88^{0}38'27''$E) and Akaipur ($23^{0}05'14.14''$N $88^{0}42'56.22''$E) were selected for study (Fig. 1). The study was conducted seasonally covering pre-monsoon (March to May), monsoon (June to August), post-monsoon (September to November) and winter seasons (December to February) during March 2014 to February 2016. Major activities in the catchments of both lakes included intensive agriculture, habitat for birds, cattle, orchards, and human habitation (Sandhya et al. 2016). These lakes are subjected to culture based fisheries management practices involving stocking of both indigenous and exotic carp seed providing livelihood support to the 500 and 300 fishers families in Khalsi and Akaipur respectively. (Meena et al. 2019). Both the lakes are in the lower Gangetic deltaic region and receive runoff from agricultural land, domestic waste, silt and other wastes from jute retting, bathing, washing etc. Both lakes are ecologically distinct. Akaipur has lost its perennial connectivity with the parent river, while Khalsi still maintains a feeble connectivity with the adjacent rivulet facilitating annual flushing. Dominant submerged macrophytes (*Hydrilla verticillata* (L.f.)

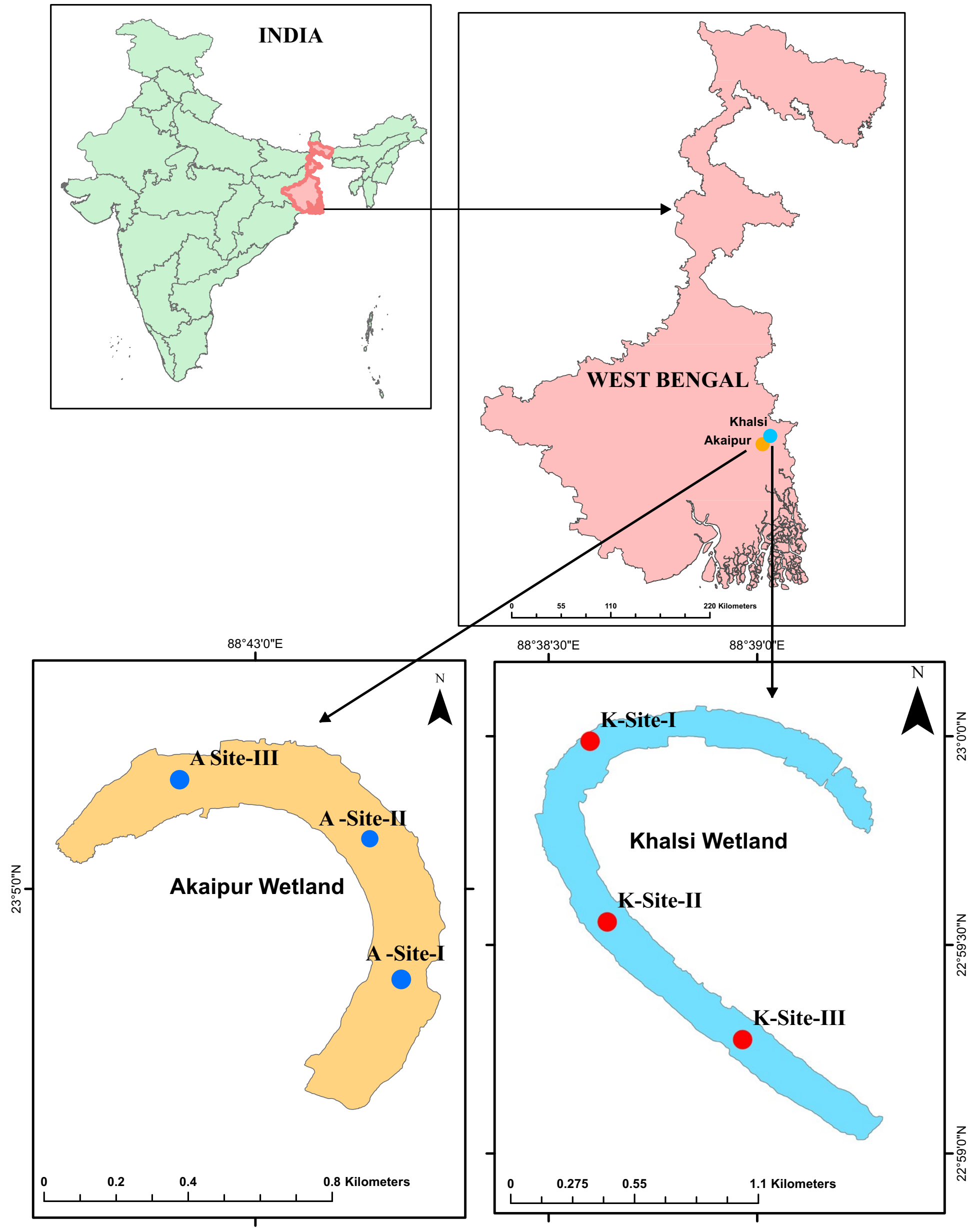

Fig. 1 The Khalsi and Akaipur oxbow lakes and their sampling locations

Royle, *Ceratophyllum demersum* L., *Vallisneria* sp. and floating aquatic vegetations (*Eichhornia crassipes* Mart., *Pistia stratiotes* L., *Nelumbo nucifera* Gaertn., *Salvinia molesta* D. Mitch., *Lemna* sp. etc.) have occupied a greater part of Khalsi wetland (40–45%) distinguishing it from Akaipur, where only sporadic occurrence of aquatic plants was noticed (10–15%) during the study period. Floating and submerged macrophytes provide shelter and breeding habitat for many small indigenous fish species in lakes. Standard sampling frequency to effectively monitor biotic and abiotic variables, seasonal variability and inter-annual changes was chosen following Water Framework Directive (WFD) guidelines (European Commission 2000).

Water Sample Collection

Seasonal water quality parameters such as water temperature, transparency (SD), pH, dissolved oxygen (DO), electrical conductivity (EC), total alkalinity (Alk), total hardness (Hard), major dissolved nutrients such as nitrate (NO_3-N) and phosphate (PO_4-P) and Chlorophyll *a* (Chl *a*) concentrations were analysed from 3 different fixed sites in each lake. To analyze the physicochemical quality, major nutrients and Chl *a* concentration, 1000 ml water was collected in plastic bottles with double stoppers from each sampling station. Water temperature, pH, conductivity was measured using a multi-parameter pcstestr 35 (Eutech) in situ; water transparency was measured by using Secchi-disc. Dissolved oxygen was measured following modified Winkler's method (Strickland and Parsons 1972). The dissolved inorganic nutrients (NO_3-N and PO_4-P), total alkalinity and total hardness were analysed in laboratory following standard methods (APHA 2005). For chlorophyll *a* measurement standard spectrophotometric method (HACH Spectrophotometer, DR 2800, Germany) was used (APHA 2005).

Plankton Data Collection and Analysis

The sampling of zooplankton was done following Sharma and Sharma (2012). Taxonomic identification to the lowest possible taxon was done using standard keys for rotifers (Koste 1978; Battish 1992; Segers 1995; Nogrady & Segers 2002) and cladocerans and copepods (Edmondson 1959; Victor and Fernando 1979; Sehgal 1983; Benzie 2005; Dussart & Defaye 2001). Verification and confirmation of taxonomic nomenclature was done following International Commission on Zoological Nomenclature for rotifers (http://iczn.org/lan/rotifer), Cladocerans (Kotov et al. 2013) and Copepods (Walter and Boxshall 2015). Abundance of zooplankton was expressed as ind/l. Aliquot of 5 ml sample out of 50 ml sample (50 ml sample concentrated from 5 l of lake water) were taken randomly after mixing, and used for counting in a Sedgewick-Rafter chamber under an inverted microscope (Zeiss-Winkel).

Biovolumes of zooplankton were assessed following equations based on geometrical formulae best fitted for each body shape (Ruttner-Kolisko 1977; McCauley 1984). Thirty organisms of each selected species of same taxon were selected randomly. Length, width and height were measured and best fitted geometrical shape formulae were applied. Biovolume of each taxon was converted to fresh weight assuming a specific density of (1×10^{-6}). The fresh weight (FW) was later converted to dry weight (DW) (Schindler and Noven 1971; Bottrell et al. 1976). Biomass of ostracods was calculated following Lehette and Hernández-León (2009). Biovolume of Copepod nauplii were assumed 0.400 μg as suggested by Hawkins and Evans (1979). Zooplankton biomass was calculated by multiplying wet weight of individual zooplankton with abundance. Phytoplankton biomass was assessed based on chlorophyll *a* estimation following Vörös and Padisak (1991).

To determine the ecological indices, number of zooplankton taxa present in each season was included in calculation excluding copepod nauplii and unidentified zooplankton. The commonly used index for biological system was Shannon–Wiener diversity index (H') to characterize species diversity of zooplankton community. Shannon–Wiener diversity index was used both for comparing two distinct water bodies on temporal and spatial scale and to evaluate the health of water bodies. Index value greater than 3 indicates clean water while values in the range of 1–3 indicate moderate pollution (Mason 1966).

Species diversity and homogeneity were calculated using the Shannon–Wiener diversity index H' (Shannon and Weaver 1949), Margalef's richness index (Margalef 1958) and Evenness index J' (Pielou 1966).

The trophic state index (TSI) was used for qualitative assessment of trophic state of the lakes (Carlson 1977; Adamovich et al. 2016). The wetland trophic status classified on a numerical scale between 0–100 is given in Table 1.

$$mTSI = (TSI_{CHla} + TSI_{TP} + TSI_{SD})/3$$

The individual trophic state index (TSI) of Chlorophyll *a* (Chl *a*), total phosphorus (TP) and Secchi disk transparency (SD) were calculated as follows.

(1) $TSI_{Chl\,a} = 9.76\ln(Chl\ a) + 30.91$
(2) $TSI_{TP} = 14.43\ln(TP) + 4.15$
(3) $TSI_{SD} = -14.39\ln(SD) + 59.91$

Rotifer community structure have been used for rotifer trophic status index (TSI_{ROT}) by following equations given by (Ejsmont-Karabin 2012).

(1) $TSI_{ROT1} = 5.38\ln(Nr) + 19.28$; where Nr number of rotifer (ind/l)
(2) $TSI_{ROT2} = 5.38\ln(B) + 64.47$; where B biomass of rotifer (mgww/l)
(3) $TSI_{ROT3} = 3.85(B/Nr).^{-0.318}$
(4) $TSI_{ROT4} = 0.144\ TECTA + 54.8$; percentage of spineless form (tecta) in abundance of *Keratella cochlearis*
(5) $TSI_{ROT5} = 0.203IHT + 40.0$; number of species contributed to the high trophic status indicator group

The mean value of TSI ($mTSI_{ROT}$) obtained from of above five equation is used as an indicator of ecological status of lakes.

Crustacean based indices (TSI_{CR}) developed by Ejsmont-Karabin and Karabin (2013) for estimation of Crustacean based trophic status indices have been followed for Trophic index of lakes is given below;

(6) $TSI_{CR1} = 25.5\ Nr.^{0.142}$; where Nr number of crustacean abundance (ind/l)
(7) $TSI_{CR2} = 57.6B.^{0.081}$; where B total wet cyclopoid biomass (mg/l)
(8) $TSI_{CR3} = 40.9CB^{0.097}$; percentage of cyclopoid biomass in the total crustacean biomass
(9) $TSI_{CR4} = 58.3(CY/CL).^{0.071}$; CY/CL: ratio of cyclopoids (CY) to cladoceran biomass (CL)
(10) $TSI_{CR5} = 5.08Ln(CY/CA) + 46.6$; ratio of cyclopoids (CY) to calanoid biomass (CA)

Table 1 The topographic details and land use pattern of Oxbow lakes

Information	Khalsi	Akaipur
Area of lakes (Ha)	65	28
Coordinate	$25^0$59′54.02¨N $88^0$38′27¨E	$23^0$05′14.14¨N $88^0$42′56.22¨E
Bio-climate	Semi-Arid	Semi-Arid
Pre-monsoon season	March–May	March–May
Monsoon season	June–August	June–August
Post-monsoon	September–November	September -November
Winter	December-February	December-February
Mean depth (cm)	177	160
Managed by society	Khalsi Udvastu Matsyjivi Samanvaya Samittee Ltd	Akaipur Dwarvasini Fishermen Cooperative Society Ltd
River connectivity	Icchamati river	Ganga river
Water salinity	Freshwater	Freshwater
Connectivity with river channel	Seasonally open	Closed
Macro-vegetation	Floating, submerged and marginal	Floating, submerged and marginal
Water use	Irrigation, Fisheries, Domestic, Cattle bathing, washing and Jute retting	Fisheries, Cattle bathing, washing and Jute retting
Fisheries management	Culture based fisheries, enclosure culture	Culture based fisheries, enclosure culture
Dominant species	Small Indigenous fish *Pethia* sp. *Puntius* sp. *Chanda nama*	Small Indigenous fish *Pethia* sp. *Puntius* sp. *Chanda nama*

The mean value of TSI ($mTSI_{CR}$) obtained from of above five equation is used as an indicator of ecological status of lakes.

Statistical Analysis

Statistical analysis was applied on dataset of environmental and biological factors to know the spatio-temporal variability. The Spearman's bivariate correlation test was performed to explain the level of significant relationship among the environmental factors. Krushkal- Wallis test at the level of significance (5%) were used for analysis of difference among the physico-chemical water quality parameters between the oxbow lakes using SPSS 16.0. One–way ANOVA test was performed at 1% level of significance to determine the annual significant differences between the lakes using SPSS 16.0. Canonical correspondence analysis (CCA) is well known multivariate method to explain the biological identified assemblage and environmental factors. The CCA analysis was performed in R (R Development Core Team 2018).

Results

Variations among Environmental Factors

During the study period, the physical and chemical water quality parameters were assessed seasonally taking average of two years for each station. Correlogram of environmental variables based on their relationship is depicted (Fig. 2). The size of a circle indicates the strength of the correlation and the colour indicates the direction of correlation (that is, blue = positive, orange to red = negative). Only significant correlations ($p < 0.01$) are shown in the Fig. 2. The correlation analysis shows high correlation between the variables EC and Alk ($p < 0.01$, $r = 0.85$), between EC and Hard ($p < 0.01$, $r = 0.83$), Hard and Temp ($p < 0.01$, $r = 0.73$). It was also found that $PO_4 - P$ was positively correlated with Depth ($p < 0.01$, $r = 0.66$), Hard, Alk and EC. On the other hand, N:P were negatively correlated with $PO_4 - P$ ($p < 0.01$, $r = -0.72$).

The spatio-temporal variations of each physico-chemical parameter are given in the Fig. 3. The physico-chemical parameters measured for each lake reflect a spatial difference in majority of variables except Temp ($p = 0.81$), Depth ($P = 0.085$), Chl *a* (0.61), NO_3-N ($p = 0.24$) and N:P ($p = 0.13$) as confirmed by Kruskal–Wallis test ($p < 0.05$).

Spatio-temporal Variation of Diversity and Community Characteristics of Zooplankton

Altogether 68 species of zooplankton were identified in the two oxbow lakes: Khalsi (54 species) and Akaipur (45 species) (Table 2). Out of 68 species listed: Rotifera (47 species), Cladocera (12 species), Copepoda (2 orders), Ostracoda (2 species) and Protozoa (5 species), only 3 species of rotifer (*Filinia longispina, B. fulcatus, Keratella cochlear*) were recorded throughout the study period. Species richness was higher in Khalsi than Akaipur lake. Relative abundance of *B. fulcatus* and *B. budapestiensis* were more than 10%

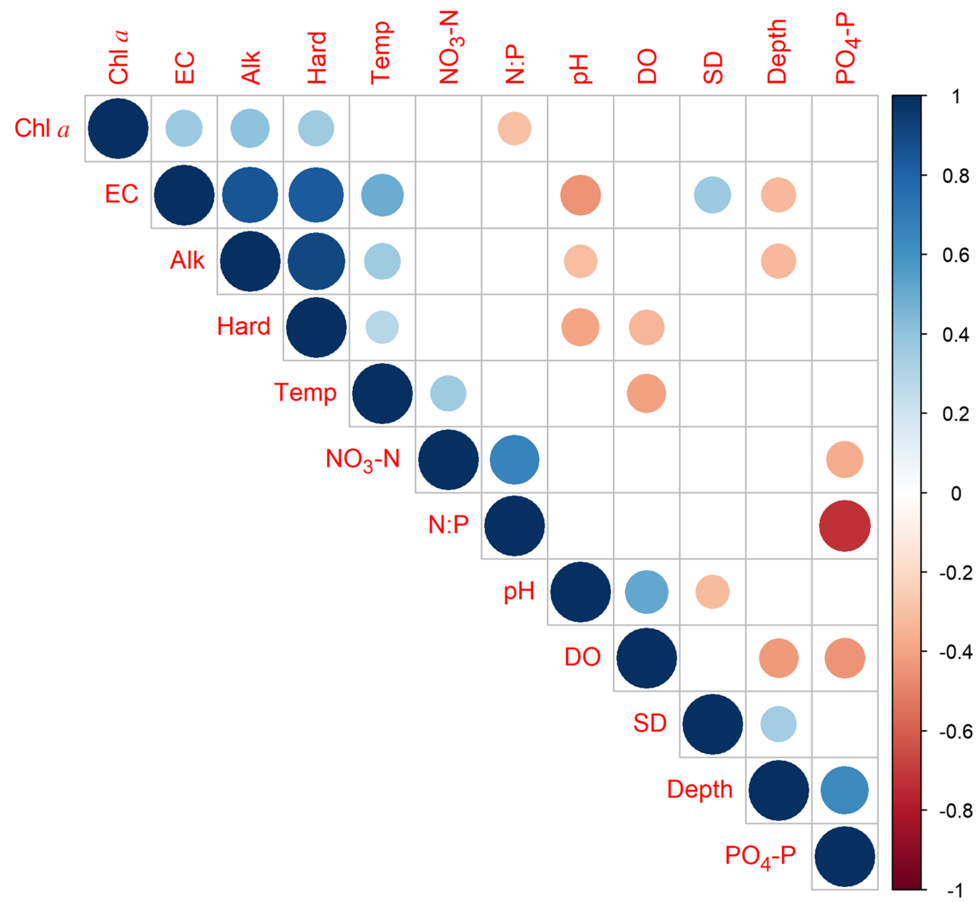

Fig. 2 Correlogram of environmental variables of lakes. Note: Chl *a* = Chlorophyll *a*; EC = electrical conductance; Alk = alkalinity; Hard = hardness; Temp = water temperature; NO_3-N = nitrate nitrogen; N/P = nitrate/phosphate; DO = dissolved oxygen; SD = Secchi depth; PO_4-P = phosphate phosphorus

each while *B. budapestiensis* was absent in Khalsi lake. *K. longiseta* was recorded in all seasons except premonsoon in Khalsi lake while absent in Akaipur lake. *K. quadrata* was found abundant in Akaipur lake whereas absent in Khalsi lake. Maximum species (14): *Filinia longispina, Brachionus rubens, B. fulcatus, B. forficula, Keratella cochlearis, K. tropica, Bosmina longirostris, Polyarthra vulgaris, Ceriodaphnia cornuta, Moina branchiate, M. micrura, Mesocyclops* sp., *Phyllodiaptomus* sp. and *Centropyxis aculeate* were commonly found in both the lakes. *Polyarthra vulgaris* was occasionally recorded in warmer season from premonsoon to post-monsoon and absent in winter (Table 2).

The 21 species/genera viz. *Polyarthra dolicoptera, Filinia longiseta, F. opoliensis, T. longiseta, P. quadricornis, B. Calyciflurous, B. caudatus f. austerogenitus, K. longiseta, K. tropica, Mytilina mucronata, M. ventralis, Lecane ungulate, Testudinella patina, Synchaeta* sp., *A. herricki, Leydigia* sp., *Cypris* sp., *Stenocypris* sp., *Difflugia corona, Vorticella* sp. and *Colpodia colpodia* were recorded only in Khalsi lake with varying abundance and frequency. A total of 10 species /genera viz. *K. quadrata, T. cylindrica P. multiappendiculata, Lepadella patella, L. ploenensis L. luna, Alona verrucosa, Notholca* sp., *Asplanchna brightwelli* and *Diaphanosoma* sp. were observed only in Akaipur lake with varying seasonal abundance and frequency (Table 2). Out of 12 species/taxa of cladocerans *Ceriodaphnia cornuta, Moina branchiate* and *M. micrura* were recorded in few numbers during monsoon seasons in Khalsi lake. *Mesocyclops* sp. and *Phyllodiaptomus* sp. were recorded throughout the study period but had higher abundance during monsoon and post-monsoon. Number of nauplii decreased in 2015–16 as compared to 2014–15. The result of the various indices such as diversity (Shannon–Wiener H′), richness (Margalef D), evenness (Pielou J′) of both lakes varies significantly (Table 3).

Degree of Eutrophication (TSI)

Trophic status was calculated based on three water parameters- transparency (secchi disk depth), total phosphorus and total chlorophyll *a*, and two taxa: rotifer and crustaceans. TSI results show that TSI (Chl *a*) varies significantly from 33.57 (pre-monsoon of 1st year) to 53.48 (premonsoon of 2nd year). The study indicated Khalsi lake is in transition phase from oligotrophic to higher mesotrophic state. In Akaipur lake TSI (Chl *a*) oscillate from 37.14 (pre-monsoon of 1st year) to 54.4 (monsoon of 1st year), indicating similar condition to Khalsi lake. The value of TSI (SD) varies from 53.03 (post monsoon of 1st year) to 70.51 (pre-monsoon of 2nd year) in

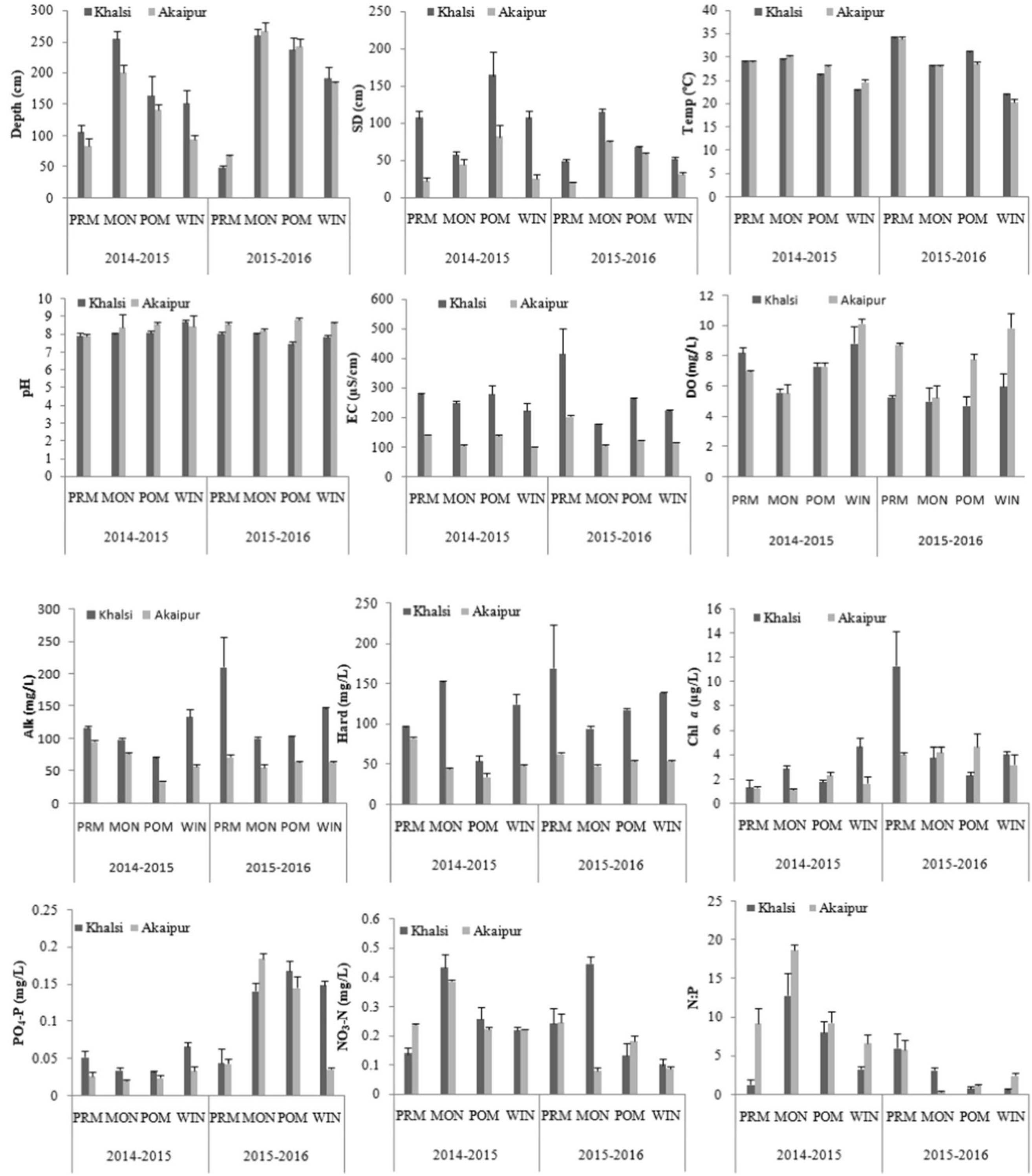

Fig. 3 Spatio-temporal variations of environmental parameters viz: Depth, Secchi depth (SD), Water temperature (Temp), pH, Electrical conductivity (EC), Dissolved oxygen (DO), Total Alkalinity (Alk), Total Hardness (Hard), Chlorophyll *a* (Chl *a*), Phosphate (PO_4-P), Nitrate (NO_3-N), Nitrate: phosphate (N:P). Note: PRM: Pre-monsoon season; MON: Monsoon season; POM: Post-monsoon season; WIN: Winter season

Table 2 Relative abundance, frequency, and seasonality of rotifers encountered in the different oxbow lakes between April 2014 and March 2016

S.N	Name of Species	Khalsi Oxbow lakes					Akaipur Oxbow lakes				
		RA	RFSeasonally				RA	RF Seasonally			
			PRM	MON	POM	WIN		PRM	MON	POM	WIN
1	*Scaridium longicaudum*	+	C	-	-	O	+	A	-	R	-
2	*Polyarthra vulgaris*	+	O	O	O	-	+	O	O	O	-
3	*P. multiappendiculata*	-	-	-	-	-	+	R	-	-	A
4	*P. dolichoptera*	+	O	O	-	F	-	-	-	-	-
5	*Filinia longispina*	+	O	R	O	O	+	O	R	R	O
6	*F. terminalis*	+	-	O	F	O	+	R	R	F	F
7	*F. longiseta*	+	-	-	C	O	-	-	-	-	-
8	*F. opoliensis*	+	-	-	-	A	-	-	-	-	-
9	*Trichocerca similis*	+	-	O	C	-	+	-	-	F	F
10	*T. longiseta*	+	-	-	-	A	-	-	-	-	-
11	*T. cylindrica*	-	-	-	-	-	+	-	R	A	-
12	*Trichocerca* sp.	+	O	R	O	R	-	-	-	-	-
13	*Anuraeopsis fissa*	-	-	-	-	-	+	-	-	A	-
14	*Platyias polycanthus*	+	O	R	O	R	+	-	A	-	R
15	*P. quadricornis*	-	-	-	-	-	-	-	-	-	-
16	*Cephalodella gibba*	+	R	F	O	-	+	-	-	A	-
17	*Brachionus rubens*	+	R	O	R	O	+	-	C	R	O
18	*B. falcatus*	+	R	O	R	O	+ +	R	F	R	O
19	*B. forficula*	+	-	O	R	O	+	R	R	R	F
20	*B. budapestiensis*	-	-	-	-	-	+ +	C	R	R	R
21	*B. Calyciflurous*	+	R	F	-	O	-	-	-	-	-
22	*B. patulus*	+	F	-	-	F	+	-	F	-	O
23	*B. quadridentatus*	-	-	-	-	-	+	R	O	R	O
24	*B. caudatus f. austerogenitus*	+	-	O	-	F	-	-	-	-	-
25	*B. caudatus*	+	-	O	R	F	+	O	R	R	O
26	*B. diversicornis*	+	R	O	-	F	+	O	-	O	F
27	*B. angularis*	+	-	O	-	C	+	-	-	-	A
28	*Keratella cochlearis*	+	O	F	O	R	+	R	F	R	O
29	*K. quadrata*	-	-	-	-	-	+	O	R	O	O
30	*K. longiseta*	+	-	R	F	F	-	-	-	-	-
31	*K. tropica*	+	O	O	O	A	+	-	C	R	O
32	*Mytilina mucronata*	+	O	O	O	A	-	-	-	-	-
33	*M. ventralis*	+	O	O	O	A	-	-	-	-	-
34	*Monostyla* spp.	+	-	O	-	C	-	-	-	-	-
35	*Lecane ungulata*	+	-	O	-	C	-	-	-	-	-
36	*L. bulla*	+	-	-	-	A	+	R	-	-	A
37	*L. ploenensis*	-	-	-	-	-	+	-	-	-	A
38	*L. luna*	-	-	-	-	-	+	F	O	-	-
39	*Lecane* sp.	-	-	-	-	-	+	-	R	F	F
40	*Testudinella patina*	+	O	-	-	F	-	-	-	-	-
41	*Lepadella patella*	-	-	-	-	-	+	O	O	-	O
42	*Lepadella* sp.	+	-	-	-	A	-	-	-	-	-
43	*Synchaeta* sp.	+	F	-	-	F	-	-	-	-	-
44	*Notholca* sp.	-	-	-	-	-	+	-	-	O	O
45	*Asplanchna brightwelli*	-	-	-	-	-	+	O	-	O	O
46	*A. herricki*	+	-	F	-	F	-	-	-	-	-
47	*Asplanchna* sp.	+	F	-	O	O	+	O	-	O	C

Table 2 (continued)

S.N	Name of Species	Khalsi Oxbow lakes					Akaipur Oxbow lakes				
		RA	RFSeasonally				RA	RF Seasonally			
			PRM	MON	POM	WIN		PRM	MON	POM	WIN
48	*Bosmina longirostris*	+	O	-	O	F	+	R	-	O	C
49	*Bosmina* sp.	+	-	-	O	C	+	R	R	R	C
50	*Ceriodaphnia cornuta*	+	R	O	F	R	+	O	-	R	F
51	*Moina branchiata*	+	-	R	R	C	+	-	-	F	F
52	*M. micrura*	+	R	O	O	O	+	F	-	O	F
53	*Moinodaphnia macleayi*	+	-	-	-	A	+	-	-	-	A
54	*Alona verrucosa*	-	-	-	-	-	+	-	R	R	C
55	*Alona* sp.	+	R	-	-	A	-	-	-	-	-
56	*Leydigia* sp.	+	-	-	-	A	-	-	-	-	-
57	*Daphnia lumholtzi*	+	-	R	-	A	+	-	F	R	F
58	*Daphnia* sp.	+	-	-	-	A	+	-	-	-	A
59	*Diaphanosoma* sp.	-	-	-	-	-	+ +	F	R	R	O
60	*Mesocyclops* sp.	+ +	R	O	F	R	+	O	F	O	-
61	*Phyllodiaptomus* sp.	+ +	R	R	F	F	+	R	R	O	F
62	*Cypris* sp.	+	-	-	A	-	-	-	-	-	-
63	*Stenocypris* sp.	+	F	-	F	-	-	-	-	-	-
64	*Stylonychia pustulata*	+	O	-	C	-	-	-	-	-	-
65	*Centropyxis aculeata*	+	O	-	C	-	+	R	-	O	C
66	*Difflugia corona*	+	-	R	F	F	-	-	-	-	-
67	*Vorticella* sp.	+	-	-	-	A	-	-	-	-	-
68	*Colpodia colpodia*	+ + +	-	-	O	C	-	-	-	-	-

RF relative frequency (A, abundant with RF = 100–81%, *C* common with RF = 80–61%, *F* frequent with RF = 60–41%, *O* occasional with RF = 40–21%, *R* rare with RF = 20–0%), *RA* relative abundance (+ + + with RA > 11%, + + with RA = 6–10%, + with RA = 5–1%), *PRM* Pre-monsoon, *MON* monsoon, *POM* post-monsoon, *WIN* winter; -: absent

Khalsi lake, and 63.09 (post-monsoon of 1st year) to 82.51 (pre-monsoon of 2nd year) in Akaipur. The total phosphorus based TSI (TSI (TP)) ranged from 52.18 (pre-monsoon of 1st year) to 75.43 (post-monsoon of 2nd year) (Fig. 4a & b). The mTSI varied between the lakes ($p > 0.05$) ranging from 47.28 ± 10.28 to 62.53 ± 13.14 in Khalsi and 51.00 ± 16.23 to 62.91 ± 15.06 in Akaipur. The mTSI values indicated that both the lakes are becoming moderately eutrophic (Table 4).

The TSI_{ROT} values varied from 56.41 ± 2.38 to 62.70 ± 6.70 and 58.73 ± 2.10 to 61.80 ± 6.87 in Khalsi and Akaipur lake, respectively (Fig. 4a & b). The calculated $mTSI_{ROT}$ values indicated both the lakes were in transition stage from slightly eutrophic to moderately eutrophic condition. The $mROT_{CR}$ value varied from 49.26 ± 3.44 to 62.32 ± 6.08 and 52.63 ± 5.68 to 67.38 ± 2.38 in Khalsi and Akaipur lake, respectively (Fig. 4a & b). The variation of $mROT_{CR}$ in Akaipur lake indicate shifting from meso-eutrophic to hyper eutrophic condition. Single peak value in $mROT_{CR}$ was observed during monsoon of 2014–2015.

Pearson's correlations among taxonomic diversity indices (D, J, H`), trophic status indices ($mTSI_{ROT}$ and $mTSI_{CR}$) and environmental parameters were analysed. The $mTSI_{ROT}$ of both lakes were found to exhibit a significantly positive correlation with PO_4-P and Chl *a,* and significantly negative correlation with N:P and DO concentration. The $mTSI_{CR}$ were also significantly negatively correlated with N:P and positively correlated with PO_4-P and Chl *a* d in both lakes. These indices were also

Table 3 Annual average value of taxonomic indices (± SD) of studied lakes

Index	Khalsi		Akaipur		One-way ANOVA	
	2014–15	2015–16	2014–15	2015–16	F	*p*
Species number (S)	24.41 ± 10.35	18.83 ± 2.69	22 ± 5.72	13.16 ± 4.04	7.147	0.000
Margalef index (D)	2.51 ± 0.98	1.97 ± 0.24	2.45 ± 0.57	1.44 ± 0.49	7.749	0.000
Pielou's evenness (J)	0.33 ± 0.09	0.38 ± 0.06	0.78 ± 0.10	0.70 ± 0.05	89.35	0.000
Shannon Wiener (H`)	2.01 ± 0.20	1.96 ± 0.10	2.80 ± 0.30	2.017 ± 0.32	30.39	0.000

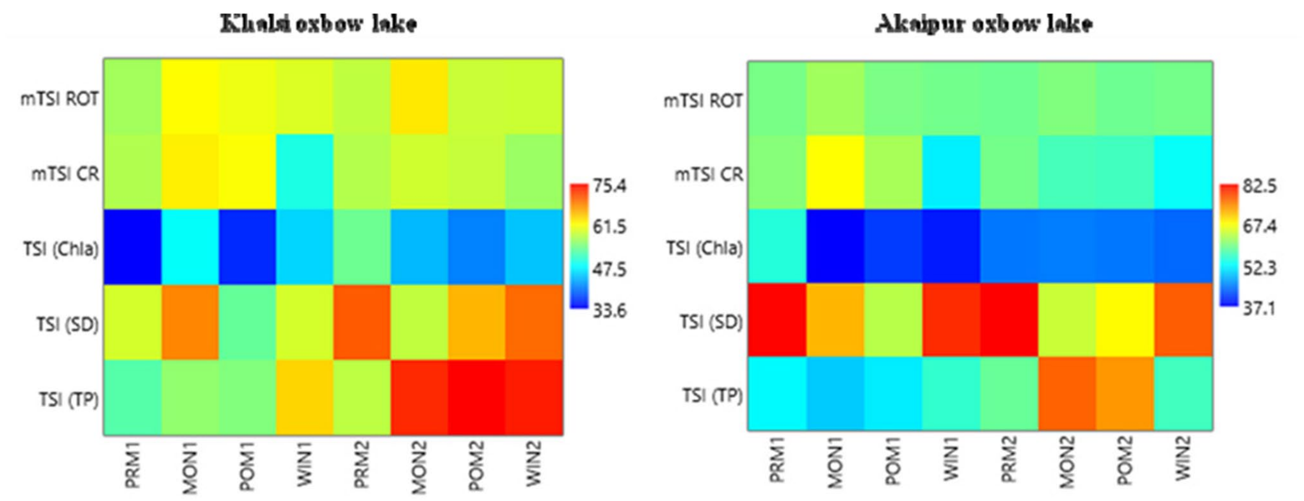

Fig. 4 Temporal variation of TSI in seasonally opens (Khalsi) and closed (Akaipur) oxbow lakes. Note: 1: 2014–2015; 2: 2015–2016; PRM: Pre-monsoon season; MON: Monsoon season; POM: Post-monsoon season; WIN: Winter season; mTSI ROT: mean trophic status index based on Rotifer; mTSI CR: mean trophic status index based on Crustaceans; TSI (Chl *a*): trophic status index based on Chlorophyll *a*; TSI (SD): trophic status index based on secchi depth; TSI (TP): trophic status index based on total phosphorus

significantly and negatively correlated with Temp and DO in Khalsi lake and insignificantly correlated in Akaipur lake. The Shannon Wiener (H`) is significantly positively correlated with DO concentration in both lakes but negatively correlated with PO_4-P and Chl *a* concentration. Pielou's evenness (J) of both the lakes was significantly and negatively correlated with water depth and positively correlated with EC. The significance of Margalef index (D) in both lakes was highly variable (Table 5). Assessment of ecological status based on trophic staus of the lakes have been widely used worldwide (Table 6).

CCA was carried out to identify the important environmental factors influencing the zooplankton abundance in Khalsi and Akaipur lake. The first axis of the CCA (CCA1) explained 23% of the total variation of the model and 15% of the variability was explained by the second component. The first two component CCA indicated that the environmental parameters including phosphate, Secchi disk depth (transparency), alkalinity, hardness, electrical conductivity, chlorophyll *a* and water depth are the important parameters influencing the zooplankton abundance in Khalsi lake. On the other hand, nitrate, temperature, pH, N:P and DO are the important parameters influencing the zooplankton abundance in Akaipur lake. CCA also indicated that the assemblage pattern of zooplankton in Akaipur lake was distinct from Khalsi lake (Fig. 5).

Table 4 Numeric scale of trophic status index (TSI) based on Chl *a*, SD, TSI_{ROT} and TSI_{CR} following Tang et al. (2019), Ejsmont-Karabin & Karabin (2013) and Ejsmont-Karabin (2012)

Sl. No	TSI	$mTSI_{ROT}$	Ecological status
1	0- 20	< 35	oligotrophic
2	20–30	35–40	low mesotrophic
3	30–40	40–45	high mesotrophic
4	40–50	45–50	low meso-eutrophic
5	50–55	50–55	high meso-eutrophic
6	55–60	55–60	slight eutrophic
7	60–70	60–65	moderately eutrophic
8	> 70	> 65	hyper eutrophic

Discussion

The ecological state exclusively depends on physico-water quality parameters and is highly variable in shallow lakes which are disconnected from river. Both studied oxbow lakes were significantly different based on electrical conductivity, phosphorus concentration, DO, pH, alkalinity and hardness. Differences in hydrological parameters may be attributed to riverine connectivity of lakes (Amoros and Bornette 2002) and other climatological factors (Sarkar et al. 2020). Seasonal fluctuation of water depth was significantly different in both lakes due to rainfall of the region and latitudinal connectivity to river channel. Water temperature is one of the most influencing affecting chemical and biological process of ecosystem (Cremona and Blank 2021). Fluctuations in temperature were related to regional climatic conditions and air temperature. The pH value in both the lakes was alkaline with limited fluctuation indicating optimum level (BIS 2003) for productivity. The pH is a vital component for biochemical function of aquatic ecosystem (Jena et al. 2013). Slightly higher pH value in Akaipur lake might be due to oscillation of metabolic activity of aquatic organism,

Table 5 The Pearson correlations between taxonomic indices (Margalef index (D), Pielou's eveness (J), Shannon Wiener (H`), $mTSI_{ROT}$, $mTSI_{CR}$ and environmental factors (* $p<0.05$ and ** $p<0.01$)

	Khalsi Oxbow Lake					Akaipur Oxbow Lake				
	$mTSI_{ROT}$	$mTSI_{CR}$	D	J	H	$mTSI_{ROT}$	$mTSI_{CR}$	D	J	H
Depth (cm)	0.053	-0.162	-.663**	-.896**	-0.245	0.222	0.086	-0.115	-.354*	-0.2
SD (cm)	-0.021	0.221	0.005	-0.23	0.022	0.161	0.001	-0.337	-.604**	-.427*
Temp (^{0}C)	-0.221	-.599**	.388*	-.382*	0.186	0.004	-0.301	0.001	-.544**	-0.2
pH	0.291	0.049	.622**	-0.11	.759**	-0.024	-0.069	0.051	-0.2	0.02
EC (μS/cm)	-0.137	-0.294	-.440*	.590**	-0.301	0.282	0.22	-0.281	-0.1	-0.2
DO (mg/L)	-.471*	-.532**	.684**	-.534**	.365*	-0.057	0.103	0.295	.531**	.379*
Alk (mg/L)	0.136	0.039	-0.246	.578**	0.022	-0.094	0.394*	-0.262	0.25	-0.1
Hard (mg/L)	0.071	0.27	-0.302	.641**	0.079	0	0.620**	-0.244	.446*	-0.1
NO_3-N(mg/L)	0.326	-0.207	-0.013	0.21	0.284	-.405*	-0.415*	.366*	0.03	.388*
PO_4-P (mg/L)	0.275*	.613**	-0.101	-0.06	-0.028	.495**	.0424*	-0.339	-.464*	-.448*
N:P	-0.193	-.456*	-0.126	0.15	-0.09	-.462*	-.577**	0.292	0.04	0.32
Chl *a* (μg/L)	.656**	.468*	0.002	0.29	0.226	.573**	.414*	-.434*	-.479**	-.485**

and photosynthetic activity (Saha et al. 2021). The coverage of macrophytes in lakes also attributed to diurnal fluctuations in pH value (Rameshkumar et al. 2019). Comparatively lower pH value in Khalsi might be due to decomposition of macrophyte which is in corollary to the study of Tang et al. (2019). Bala and Mukherjee (2010) observed similar finding in Nadia wetland of West Bengal. Dissolved oxygen (DO) is one of the health indicators of aquatic ecosystem. DO of both lakes were well within acceptable range (above 5 mg/L) for ecological wellbeing. DO fluctuations depends on temperature and mixing of nutrient due to influx of runoff from surroundings (Ouhmidou et al. 2015). DO concentration in both the lakes was lowest in monsoon and highest in winter season. Heavy rain during monsoon season brings organic matter such as plant leaves, grasses and other organic matters into the lakes, causing enhanced microbial activity to decompose the vegetation and accelerate the use of oxygen (Mandal et al. 2012).

Chl *a* is an important component to assess overall algal biomass of lakes and classify their trophic level (Gregor and Mařsalek 2004). Chl *a* was very high in pre-monsoon (PRM) in both the lakes due to decreased water depth and increased light penetration. Das Sarkar et al. (2021) studied and reported environmental factors influencing Chl *a* concentration in Gangetic wetlands were water temperature, total alkalinity, electrical conductivity, and pH. The concentration of Chl *a* in pre-monsoon season was higher due to favourable environmental factors. Annual average Chl *a* was higher in 2015–16, which might be due to higher influx of organic nutrient in the lakes. Enclosure culture (pen culture) practice was initiated during 2015–16 in both the lakes that might be the source of higher PO_4-P leading to eutrophication. Similar observations were made in Baiyangdian lake by Wang et al. (2013). Nutrient concentration (NO_3-N and PO_4-P) increased from 2014–15 to 2015–16 in both the lakes, with higher deviation in Akaipur. The enhanced organic nutrients particularly, NO_3-N and PO_4-P due to unscientific pen culture practice in Akaipur as compared to the Khalsi during 2015–2016 is in line with results of Beveridge (1984). The highest concentration of NO_3-N during monsoon (June to September) in the present study may also be due to the allochthonous organic input and the decomposition of the aquatic macrophytes and jute retting (Ghosh and Biswas 2018). Enhanced nutrient (NO_3-N and PO_4-P) concentration during second year of the study, which might be the reason for transition from high mesotrophic to slight eutrophic state. N:P value have decreased significantly in 2015–16 in both the lakes. Tang et al. (2019) suggested N as the only limiting factor in Baiyangdian lake and McCarthy et al. (2013) suggested P as limiting factor in Taihu lake, China for eutrophication. The deviation of the result in our study in contrast to these studies might be due to the fact that supply of both nitrogen and phosphorus from atmospheric deposition, non-point source as agriculture runoff has potentially contributed to increasing nutrients loads in the lakes.

The pattern of zooplankton community structure and abundance are very important for the maintenance of the ecological health of an aquatic ecosystem. Zooplankton are ecological indicators of aquatic environment health (Neto et al. 2014). Rotifers respond quickly to aquatic environmental changes due to their short life cycle and are therefore used as indicators of overall health or condition (Carriack and Schelske 1977). Three common species *Filinia longispina, Brachionus fulcatus, Keratella cochlearis* of rotifer was recorded throughout the study period. Sharma et al. (1992) noted *Filinia longispina* is a eurytopic alkaline species. Two commonly occurring species *Brachionus fulcatus, Keratella cochlearis* of the genus *Brachionus* and

Table 6 The overview of selected trophic status indices methods used in various parts of world for the assessment ecological status of lakes

Country	Aquatic ecosystem type	Frequency of sampling	Period of sampling	Taxon- and trait-based trophic indices	Reference
North Eastern Poland	41 dimictic and 33 polymictic lakes	Once a year, during the summer stagnation period	1976- 2005	Rotifer based Trophic status indices (TSI_{ROT})	Ejsmont-Karabin 2012
Poland	12 lakes within Suwałki Landscape Park	Once	23–31 July 2009	TSI_{SD}, $TSI_{Chl\ a}$, TSI_{TP} Rotifer trophic state indices (TSI_{ROT}) Crustacea trophic state index (TSI_{CRU})	Jekatierynczuk-Rudczyk et al. 2014
Eastern Poland	Jeziorak, a postglacial lake	Summer	2011–12	TSI_{ROT} $TSI_{TP+SD+Chl\ a}$	Dembowska et al. 2015
India	Osmansagar Reservoir	Monthly	December 2010 to November 2012	Based on presence of specific indicator rotifer species	
Poland	Suwalki Landscape Park: Typical deep channel lakes, moraine lakes and shallow polymictic lakes	Once a year	July/August 1983–1985, 2009, 2012 and 2015	Rotifer trophic state indices (TSI_{ROT})	Ejsmont-Karabin et al. 2016
China	2 Shallow lakes	Twice a month	July 2012 to June 2013	Comprehensive trophic state index (TSI) based on Chl *a*, SD (Secchi disk), TN (total nitrogen) and TP (total phosphorous) Tait-based indices: rotifer community Guild ratio	Wen et al. 2017
Algeria	Three reservoirs: Sidi Yacoub, Bakhadda, Hammam Boughrara		December 2015 to November 2017	Carlson index and TSI_{ROT}	Smaoune et al. 2021
China	Han river downstream (HD), Reservoir (RE) and Tidal creek (TC)	Seasonal	July 2015, November 2015, January 2016 and May 2016	Rotifer abundance and the rotifer trophic state	Liang et al. 2020a, b

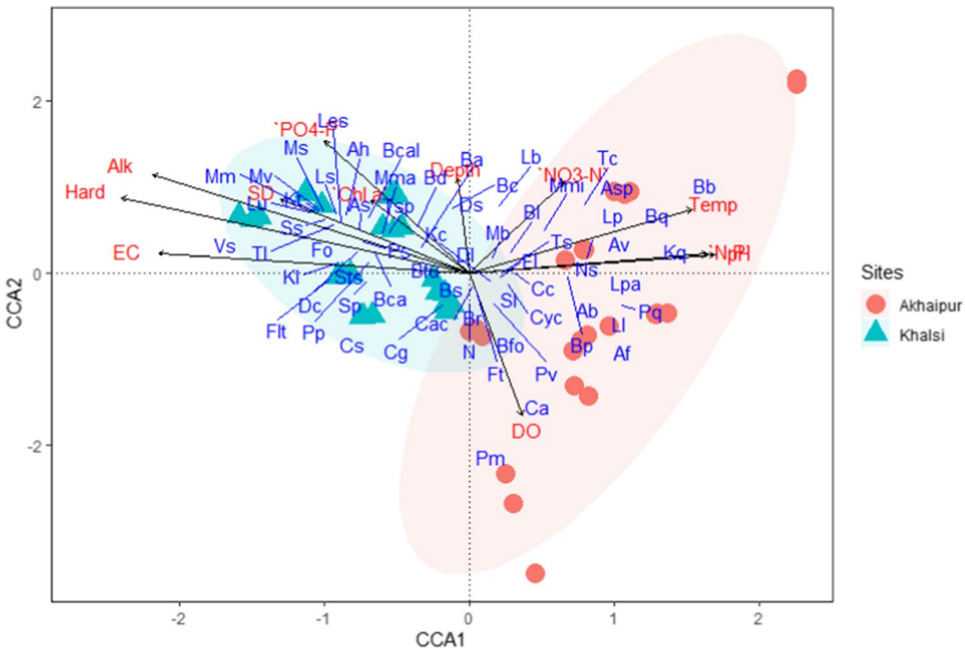

Fig. 5 A canonical correspondence analysis (CCA) of zooplankton species and physicochemical parameters. Sl, *Scaridium longicaudum*; Pv, *Polyarthra vulgaris*; Pm, *Polyarthra multiappendiculata*; Ps, *Polyarthra* sp.; Fl, *Filinia longispina*; Ft, *Filinia terminalis*; Flt, *Filinia longiseta*; Fo, *Filinia opoliensis*; Ts, *Trichocerca similis*; Tl, *Trichocerca longiseta*; Tc, *Trichocerca cylindrical*; Ts, *Trichocera* sp.; Af, *Anuraeopsis fissa*; Pp, *Platyias polycanthus*; Pq, *Platyias quadricornis*; Cg, *Cephalodella gibba*; Br, *Brachionus rubens*; Bfu, *Brachionus fulcatus*; Bfo, *Brachionus forficula*; Bb, *Brachionus budapestiensis*; Bc, *Brachionus Calyciflurous*; Bp, *Brachionus patulus*; Bq, *Brachionus quadridentatus*; Bca, *Brachionus caudatus f. austerogenitus*; Bc, *Brachionus caudatus*; Bd, *Brachionus diversicornis*; Ba, *Brachionus angularis*; Kc, *Keratella cochlearis*; Kq, *Keratella quadrata*; Kl, *Keratella longiseta*; Kt, *Keratella tropica*; Mm, *Mytilina mucronata*; Mv, *Mytilina ventralis*; Ms, *Monostyla* spp.; Lu, *Lecane ungulate*; Lb, *Lecane bulla*; Lp, *Lecane ploenensis*; Ll, *Lecane luna*; Lpa, *Lepadella patella*; Ls, *Lepadella* sp; Ss, *Synchaeta* sp.; Ns, *Notholca* sp.; Ab, *Asplanchna brightwelli*; Ah, *Asplanchna herricki*; Asp, *Asplanchna* sp.; Bl, *Bosmina longirostris*; Bs, *Bosmina* sp.; Cc, *Ceriodaphnia cornuta*; Mb, *Moina brachiata*; Mmi, *Moina micrura*; Mma, *Moinodaphnia macleayi*; Av, *Alona verrucosa*; As, *Alona* sp.; Les, *Leydigia* sp.; Dl, *Daphnia lumhottzi*; Ds, *Daphnia* sp.; Cyc, Cyclopoid copepod; Cac, Calanoid copepod; Cs, *Cypris* sp.; Sts, *Stenocypris* sp.; Sp, *Stylonychia pustulata*; Ca, *Centropyxis aculeate*; Dc, *Difflugia corona*; Vs, *Vorticella* sp.; Coc, *Colpodia colpoda*

Keratella are considered as cosmopolitan and eurytopic species (Branco et al. 2002; Kumari et al. 2017) due its broader ecological value, thermal tolerance, and geographical distribution (Bennett et al. 2019). Rotifer species *Filinialon gispina, Brachionus rubens, B. fulcatus, B. forficula, Keratella cochlearis, K. tropica, Bosmina longirostris* and *Polyarthra vulgaris* were present in both lakes with varying degree of abundance. *Keratella cochlearis* and *K. tropica* have been recorded from many freshwater bodies such as ponds to reservoir (Doukhandji and Arab 2017). The seven species of rotifers from both lakes have wide range of pollution tolerance (Sládeček 1983; Sharma et al. 1992; Branco et al. 2002; Kumari et al. 2017). Genus *Keratella* and *Brachionus* are considered as indication of eutrophic state of the lake due to their close association with nutrient rich environment (Branco et al. 2002; Kumari et al. 2017; Doukhandji and Arab 2017; Smaoune et al. 2021). Genus *Polyarthra* was less abundant in both the lakes due to high nutrient availability, as it is less tolerant. Occurrence of *Polyarthra* is found in oligotrophic, mesotrophic as well as eutrophic lakes (García-Chicote et al. 2018; Obertegger et al. 2008, 2014; Karpowicz et al. 2020). In the present study, in winter (higher PO_4-P), *Polyarthra* were absent, therefore this genus is indicator of oligotrophic to mesotrophic state. Genus *Trichocerca* was recorded only in post monsoon and winter when nutrient concentration was higher. Castro et al. (2005) also reported this genus from eutrophic environment. Genus *Bosmina* was relatively abundant throughout the seasons except in monsoon. In monsoon season, generally flow of water is higher compared to other seasons and Cladocerans usually prefer lentic water (littoral zone with macrophytes) (Maia-Barbosa et al. 2008; Jeong et al. 2015), therefore the genus was absent in both lakes in monsoon. Only cladocerans *Ceriodaphnia cornuta, Moina branchiate* and *M. micrura* were recorded during monsoon seasons in Khalsi because of their preference towards clear water and macrophyte dominant reasons. Mergeay et al. (2006) have also found similar results and confirmed their association in macrophyte dominated reasons in shallow lakes of southern Kenya. Higher abundance of copepods in monsoon and post-monsoon indicated well mixing of nutrients and favorable temperature. Yin et al. (2018) also reported higher abundance of copepod in mesotrophic lake. Copepod adults have greater preference towards nutrient rich environment than nauplii. Mathews et al. (2018) have reported that favorable temperature range of 25-28^{0}C for growth and reproduction of copepod. In this context monsoon and post-monsoon season is most favorable season for higher abundance of copepods. Ostracod communities have close association with aquatic macrophytes (Matsuda et al. 2015) and higher ecological tolerance (Kiss 2007). *Centropyxis, Difflugia* and *Arcella* were dominant in Khalsi lake but *Centropyxis* in Akaipur lake, throughout the study period. All these protozoans have wide range of tolerance to nutrient and are found in oligotrophic to eutrophic conditions (Madoni 2011).

Measuring zooplankton species diversity is one of the most important characteristics of aquatic ecosystem to maintain stability as means of coping with any environmental changes. We have compared the value of various indices between two lakes. We have found that lowest diversity indices H′ and D from Akaipur during winter. Diversity has decreased due to unscientific enclosure culture practice and lack of connectivity with main river channel along with abiotic factor, natural predation by copepod and cladoceran, competition for food and increasing eutrophication (Marcus 2004; Perbiche-Neves et al. 2016; Arcifa et al. 2020).

The $mTSI_{ROT}$ and $mTSI_{CR}$ values were determined annually for both the lakes but spatial as well as temporal difference was not significant. Rotifer community among the zooplankton shows quick response to the environmental changes and is considered as highly suitable for assessing degree of eutrophication (Jekatierynczuk-Rudczyk et al. 2014; Dembowska et al. 2015; Ejsmont-Karabin et al. 2016; Wen et al. 2017; Smaoune et al. 2021). In this study trophic state index was assessed based on rotifer and crustacean groups. The $mTSI_{ROT}$ and $mTSI_{CR}$ had significantly positive relationship with phosphorus concentration (PO_4-P) in both the lakes. Similar finding was reported by Xiong et al. (2016) from two subtropical lakes. Although, there are cumulative effect of many abiotic factors in changing the trophic dynamics of ecosystem PO_4-P and Chl *a* showed significantly positive relationship with eutrophication.

The composition and diversity of zooplankton species with higher trophic state have well explained by combination of environmental parameters with Pearson's correlations and CCA analysis. García-Chicote et al. (2018) explained the dominance of some of the species in ecological stressful environment. Our result also shows dominance of genus *Brachionus* influenced by NO_3-N rich environment also supported by favorable temp and pH. According to Branco et al. (2002) and Kumari et al. (2017) dominance of genus *Brachionus* is a considered as good indicator of eutrophication. Present study also reveals the fluctuation in species composition with high level of eutrophication and reported by Obertegger and Manca (2011). The density of rotifers is much more prevalent in both the lakes.

Conclusion

Rotifers proved their strong sensitivity to nutrient load in freshwater ecosystem based on the scientific evidence and fluctuation in species diversity. The present investigation advocates the suitability of rotifers based TSIs, integrating with physico-chemical parameter of the lakes which is first of its kind. The estimated mTSIs value has validated biological indices to suggest an indicator species for determination of water quality and ecosystem health of the lakes. Based on the findings of hydro biological parameters, the degree of eutrophication varies between the lakes. The $mTSI_{CR}$ and mTSI based combination of environmental factors have revalidated our finding to assess degree of eutrophication of oxbow lakes. The study highlights the importance riverine connectivity of lakes and short-term impact of enclosure culture on eutrophication of lakes. The present investigation could further help to understand the phenological mechanisms of water quality and rotifer abundance for scientific management of lakes. Nutrient concentration PO_4-P, temperature, Chl *a*, EC, Hard, Alk and SD was found to be most influencing factor influencing trophic state.

Khalsi lake, a partially open wetland has more sinking capacity as compared to Akaipur (closed wetland) having scope for continuation of enclosure culture practices provided impact assessment for long term culture are carried out. Khalsi lake has more fish production potential and essential water quality parameters for open water fisheries emphasizing upon the scientific management and ecosystem-based approach for sustainable fish production. Khalsi lake can be more promising than the Akaipur lake towards biodiversity conservation and enhancement in the present climate change scenario through sustainable management interventions. Akaipur lake requires immediate intervention in terms of restriction of irrational culture practices, management of point source of organic load. Akaipur lake might be succeeding towards super eutrophication if same practices continue for long term without considering scientific management. Present study is first of its kind to validate the physico-chemical and biotic factors with rotifer and crustacean based indices advocating rotifers as excellent indicator organism for ecological assessment, water quality monitoring and assessment of degree of eutrophication for better policy decisions. Thus, addressing the issues related to the eco-hydrological alteration taking place in the closed and semi-closed lakes for ensuring sustainable fisheries enhancement and to carry forward the ecosystem services for wellbeing of the riparian community must be prioritized in the context of degraded ecosystem health, anthropogenic pressures and climate change.

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Authors Contributions Conceptualization: Uttam Kumar Sarkar, Suman Kumari and Ashok Kumar Jaiswar, Formal analysis and data collection: Lianthuamluaia Lianthuamluaia, Mishal Puthiyottil, Sandhya Kavitha Mandhir, Data collection: Archan Kanti Das, Darmendra Kumar Meena,, Data Support: Md. AbulHassan, Methodology: Suman Kumari and Mishal Pudyottil, Original draft preparation: Suman Kumari, Lianthuamluaia Lianthuamluaia, Review and editing: Gunjan Karnatak, Uttam Kumar Sarkar, Mishal Puthiyottil, Funding acquisition: Anil Prakash Sharma and Basanta Kumar Das, All the au-thors read and approved the final manuscript.

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Data Availability Data will be available based on request.

Declarations

Ethics Approval The submitted manuscript is not submitted in any other journal.

Consent to Participate Not applicable.

Consent for Publication The approval for submitting the manuscript was received from the ICAR-Central Inland Fisheries Research Institute.

Competing Interests The authors declare no competing interests.

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