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ORIGINAL ARTICLE

Seasonal behaviour of thermal stratification and trophic status in a sub-tropical Palustrine water body

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Abstract
Thermal and chemical stratification of water bodies has a strong bearing upon the water quality since it regulates mixing of nutrients/pollutants and affects the aquatic life in it. The present study was undertaken in a shallow pond ecosystem to study thermal stratification and trophic status over a period of 4 months (January–April, 2015) to understand the seasonal variations associated with. Chemical stratification with respect to dissolved oxygen was also observed along the depth. The pond was weakly to strongly thermally stratified throughout the study. The redox potential of water varied from −246 mV (February 15) to 137 mV (March 15) indicating dominantly reducing conditions. The dissolved oxygen profile with depth confirmed that reducing conditions prevailed in the hypolimnion. The surface epilimnion represented higher values of Trophic State Index for total phosphate (TSI-TP) and relatively lower values of total chlorophyll (TSI-Chl). The value of buoyancy frequency (N) and Richardson number (R) indicated complete and strong mixing in surface epilimnion due to the temperature, wind velocity, and current speed during the study with relatively stronger stratification and lower surface mixing during early summer (March–April). The higher value of TSI-TP compared to TSI-Chl indicated that zooplankton grazing or limitation of nitrogen plays a role in limiting eutrophication and algal growth. Although the wind velocity may be higher during summer, stronger thermal stratification can be formed due to temperature difference between upper layer and lower layer resulting in lower mixing of surface epilimnion, which may be a cause of concern if dissolved phosphate levels are high.

Keywords Trophic State Index · Thermal stratification · Eutrophication · Water quality · Buoyancy frequency (N) · Richardson number (R)

Introduction

Cultural eutrophication is a process that speeds up the rate of natural eutrophication by increasing the inflow rate of nutrients (nitrogen and phosphorous) into the water body. Enrichment of nutrients can lead hyper-eutrophication. Similarly, turbidity of the water body is an important parameter to determine the water quality, and most of the eutrophicated lakes have low transparency because of algal growth, and dead and decomposing organic matter. It results in reduced sunlight penetration, reduced photosynthesis, and low productivity of the lake (Haritash et al. 2015a, b). This process may result in oxygen depletion in the water body as a response to reduced photosynthesis and increased level of nutrients (Balakrishnan et al. 2017). The algal blooms have a number of adverse effects on water users, because algae can reduce dissolved oxygen, affect nutrient cycle produce toxins, and decrease aesthetic water quality (Brown et al. 1998; Haritash et al. 2016). Lakes are generally classified as oligotrophic, mesotrophic, eutrophic, and hypertrophic based on the trophic status. Trophic state is defined as the total weight of the biomass in a water body at a specific location and time (Devi Prasad and Siddaraju 2012). Carlson (1977) used algal biomass as key description for measuring the Trophic State Index because algal blooms are of concern to the public. Many physical factors are responsible of the trophic state of water body; thermal stratification is one of them where density difference in the lake is primarily due to

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the temperature variation (Yang et al. 2018). Thermal stratification leads to reduction in turbulent mixing and accumulation of algal population in the surface layer. Blooms do not occur under complete mixing of the water column (Bormans et al. 1997). Permanent stratification has decisive impact on redistribution of dissolved substances, in deep lakes complete mixing rarely occurs, and it leads to anoxic condition at bottom of the lake (Boehrer and Schultze 2008; Mellios et al. 2015). A lake is classified as stratified if the temperature difference of 0.2 °C/m or higher with depth is present near the surface of the water body (Pernica and Wells 2012). Thermal stratification is affected by factors, such as solar radiation, turbidity, discharge, and wind speed; and to lower extent to humidity and air temperature. Wind-driven mixing in epilimnion of deep lakes has been studied by Pernica and Wells (2012), and a positive correlation of wind-induced mixing with thermal stratification using gradient Richardson number is mentioned. In this study, thermal stratification is correlated with wind-induced mixing and trophic state to see the effect of thermal stratification on eutrophication.

Materials and methods

This study was carried out from January 15 to April 15 in a shallow pond located in the campus (28°44′58.55″N, 77° 0.6′46.75″E) of Delhi Technological University, Delhi. The pond has total area of 9468 m^2 and average depth of 1.8 m. It receives wastewater from neighbouring residential colony and partially from a university hostel.

In order to achieve average water quality, the pond was divided into 09 grids, and a sample was collected from each grid to evaluate the spatial variations, if any. The samples were collected in pre-rinsed PET bottles and were immediately transported to laboratory (within 10 min) for its characterisation. The samples were characterised for pH, oxidation–reduction potential (ORP), temperature, dissolved oxygen (DO), available phosphate (AP), total phosphate (TP), nitrogen (as nitrate and total Kjeldahl nitrogen TKN), calcium, magnesium, chlorophyll (Chl), Secchi depth (SD) as per standard methods in triplicates using analytical grade (AR) chemicals and ultrapure (type I) water. The parameters like pH, temperature (°C), DO (mg/l), ORP (mV) were measured on the site using Orion make Star A329 model multiparameter meter, and SD (m) and total depth (meter) were also measured on site using Secchi disc and a graduated steel rod, respectively. TKN (mg/l) was measured using Kjeldahl nitrogen estimation system. Extraction and determination of chlorophyll were performed according to the method prescribed by Arnon (1949). Other parameters were determined within 24 h using standard methods as prescribed by APHA (1995).

Trophic status

A popular method for examining trophic state of a water body uses the Trophic State Index (TSI) developed by Carlson (1977) to determine Carlson Trophic State Index (CTSI). Chlorophyll was calculated by using following equation given by Arnon (1949).

$$\text{Chlorophyll 'a'(mg/ml)} = (0.0127) \times (A663) - (0.00269) \times (A645) \quad (1)$$

where A663 and A645 are the absorbance of extract at 663 nm and 645 nm wavelength using spectrophotometer (LabIndia make UV3092 model). The formulae for calculating the TSI values where SD is Secchi depth (m), Chl is chlorophyll (mg/m^3), and TP is total phosphorus (mg/l) are as follows:

$$\text{Secchi disk:} \quad \mathrm{TSI(SD)} = 60 - 14.41 \ln(\mathrm{SD}) \quad (2)$$

$$\text{Chlorophyll a:} \quad \mathrm{TSI(CHL)} = 9.81 \ln(\mathrm{Chl}) + 30.6 \quad (3)$$

$$\text{Total phosphorus:} \quad \mathrm{TSI(TP)} = 14.42 \ln(\mathrm{TP}) + 4.15 \quad (4)$$

The following equation can be used to compute the CTSI:

$$\mathrm{CTSI} = \{(\mathrm{TSI} - \mathrm{SD}) + (\mathrm{TSI} - \mathrm{Chl}) + (\mathrm{TSI} - \mathrm{TP})\}/3 \quad (5)$$

Wind

Data of wind speed (u) of the study area were taken from the Indian Meteorological Department (IMD) for the months of January 15 to April 15. Wind-induced current was empirically calculated, for wind speeds between 100 and 500 cm/s "the wind factor (current speed/wind speed) decreased linearly with wind speed". At wind speeds above 500 cm/s, "the wind factor remained in the range of 1–3%" (George 1981). For the present study, the wind factor was considered as 2% of wind speed (cm/s). The occurrence of stable stratification depends on the relative strengths of turbulent mixing and thermally induced density gradients (Richardson 1926). The relative magnitudes of these two processes have been calculated by the non-dimensional ratio known as the Richardson number, R, expressed as:

$$R = N^2/(\mathrm{d}u/\mathrm{d}z)^2 \quad (6)$$

where buoyancy frequency N is define as $N = ((g/\varrho)\,(\mathrm{d}\varrho/\mathrm{d}z))^{1/2}$, g =acceleration due to gravity (9.81 m/s^2), ϱ = density of fluid (water, kg/m^3), u =velocity (m/s) and z=depth (m) (Pernica and Wells 2012). Denominator of Eq. (6) is the vertical velocity shear. According to (Pernica and Wells 2012), there will be little or no turbulent mixing for $R < 0.25$.

Results and discussion

Based on the results obtained, the shallow pond in DTU receives significantly high concentration of dissolved phosphate and it undergoes thermal stratification seasonally. The water body was classified as eutrophic throughout the study, and the details of water quality, thermal stratification, and the trophic status are discussed in the following sections.

Water quality

The water quality on the basis of physico-chemical characterisation of collected water samples revealed that the water lies in slightly alkaline range with average pH ranging from 7.6 to 8.7 (Table 1) with dominantly reducing conditions based on values of oxidation–reduction potential (ORP). The average ORP varied from − 246 (February 15) to 137 mV (March 15). The concentration of available and total phosphate was observed to be significantly high considering its potential (more than 1.0 mg/l) for eutrophication. Phosphorous which is generally recognized as the key nutrient for algal growth is an essential element to determine the fertility of ponds (Shah and Pandit 2012). The concentration of available phosphate (orthophosphate phosphorus) during the study period ranged from a maximum of 9.4 ± 1.2 mg/L under reducing condition (ORP − 299 mV) in February to a minimum of 7.1 ± 0.9 mg/l under oxidising condition (ORP 137 mV) in March. The concentration of dissolved phosphate remains lower under oxidising conditions since binding of PO_4^{3-} takes place with Fe^{3+} and Al^{3+} ions which forms an insoluble metal–phosphate complex under oxidising conditions, whereas under reducing conditions Fe^{3+} ions are reduced to Fe^{2+} which breaks the metal–phosphate complex resulting in remobilisation of phosphate in water (Haritash et al. 2017). Increase in the orthophosphate concentration during highly reducing conditions has also been observed by Olila and Reddy (1997). In the present study, phosphate concentration was significantly high compared to the other nutrient, i.e. nitrogen expressed as nitrate (mg/l) and TKN (mg/l); most of the nitrogen was present as ammoniacal or organic (as TKN) in the form relatively lower concentration of nitrate (from 1.1 to 6.9 mg/l) compared to ammoniacal nitrogen further strengthens the observation that the condition in the pond were chiefly reducing during the study.

Trophic status of pond

The trophic state indices for phosphate (TSI-TP), chlorophyll (TSI-Chl), and Secchi depth (TSI-SD) are used to arrive at an aggregated average referred to as Carlson's Trophic State Index (CTSI). The TSI values of different parameters are given in Table 2. It is observed that TSI-TP has maximum value followed by TSI-Chl and TSI-SD. The combined CTSI was observed to more than 100 (Table 3) in all the cases indicating that the pond is eutrophic throughout the study; CTSI value from the observation was found to be maximum in April (117) and minimum in March (113) due to low concentration of phosphate in water during March. Since TSI-TP > TSI-Chl > TSI-SD, the transparency of water is not affected significantly limiting the effects of eutrophication. This may also be attributed to zooplankton grazing and/or limitation of nitrogen. In this study, both the factors were observed to play a significant role in keeping TSI-SD values less than the other parameters (Fig. 1).

Stratification of pond

The observed values of temperature and dissolved oxygen with respect to depth revealed that the pond remained stratified (weak to strong) during the study (Fig. 2). The temperature lapse was observed to be 0.8, 1.1, 4.4, and 3.0 during months January, February, March, and April of 2015 (Table 1), respectively. As per the literature available,

Table 2 TSI values for SD, TP, Chl(a) in pond during the study

TSI/months	Jan 15	Feb' 15	Mar 15	Apr 15
TSI(SD)	80	82	79	82
TSI (Chl)	127	128	124	133
TSI(TP)	135	137	136	137
CTSI	114	116	113	117

Table 1 Monthly variations of physico-chemical characteristics, thermal stratification (d*T*/d*z*), buoyancy frequency (*N*), Richardson number (*R*) during the study

Parameters/months	pH	ORP (mV)	Temp. (°C)	AP (mg/l)	TP (mg/l)	Nitrogen (mg/l)		d*T*/d*z* (°C/m)	*N* (s^{-1})	*R*
						NO_3^-	TKN			
Jan 15	8.1 ± 0.1	108 ± 48	14.2 ± 0.5	8.4 ± 0.3	9.3 ± 2	3.2 ± 0.5	13.0 ± 4.5	0.8	0.031	2.18
Feb 15	7.6 ± 0.1	− 246 ± 32	15.3 ± 0.1	10.3 ± 2.3	13.7 ± 1.9	1.1 ± 1.0	16.3 ± 1.2	1.1	0.039	1.37
Mar 15	8.7 ± 0.2	137 ± 26	21.1 ± 1.3	9.3 ± 0.9	11.6 ± 1.7	6.9 ± 0.8	9.5 ± 2.1	4.4	0.101	1.91
Apr 15	8.3 ± 0.1	120 ± 74	26.3 ± 0.9	8.6 ± 1.7	14.3 ± 1.9	2.0 ± 0.4	10.3 ± 0.5	3.0	0.085	1.02

Table 3 Carlson's Trophic State Index values and classification of lakes (Devi Prasad and Siddaraju 2012)

TSI values	Trophic status	Attributes
< 30	Oligotrophic	Clear water, oxygen throughout the year in the hypolimnion
30–40	Oligotrophic	A lake will still exhibit oligotrophy, but some shallower lakes will become anoxic during the summer
40–50	Mesotrophic	Water moderately clear, but increasing probability of anoxia during the summer
56–60	Eutrophic	Eutrophic lower boundary of classical eutrophy: decreased transparency, warm-water fisheries only
60–70	Eutrophic	Eutrophic dominance of blue–green algae, algal scum probable, extensive macrophyte problems
70–80	Eutrophic	Eutrophic heavy algal blooms possible throughout the summer, often hypereutrophic
> 80	Hypereutrophic	Eutrophic algal scum, summer fish kills, few macrophytes

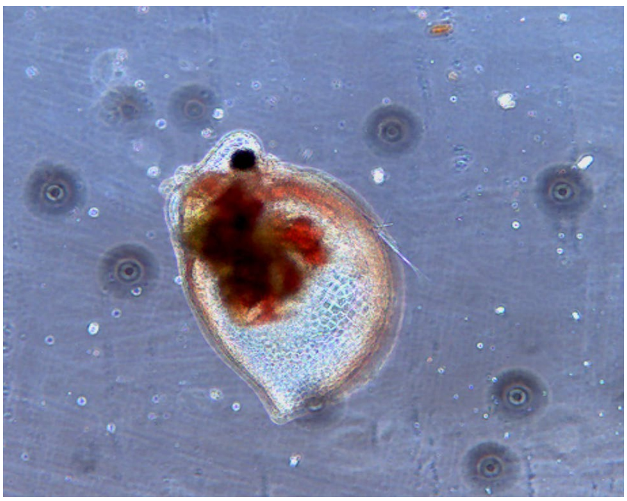

Fig. 1 Microscopic view (100×) of *Ceriodaphnia* spp. present in the DTU pond

a water body is classified as thermally stratified if dT/dz is greater than 0.1 °C/m. Based on the values of thermal stratification, it was observed that the pond was weakly stratified during winter (January and February) as compared to the summer (March and April). Physical and chemical both forces are responsible for the process of stratification. Temperature and dissolved substances contribute to density difference in water (Boehrer and Schultze 2008; Mellios et al. 2015). Variation of temperature with depth is described in Fig. 2. A sharp change of temperature from surface to bottom was observed during summer with the temperature difference of 8.1 °C in March and 6.5 °C in April; as against the difference of 1.4 °C in January and 2.1 °C in February. If temperature of surface water falls below the temperature of the underlying layer, the entire water body can overturn (Boehrer et al. 2008). Starting from homogeneous conditions in winter, surface water is heated by radiation and contact with the atmosphere, and mixing usually driven by wind due to which, overturning was not found in the pond. Thermocline was found at approximately same depth of 3 °cm during the study.

Wind-induced stratification

Temperature, wind velocity, current speed and dissolved oxygen data are compared in this section, and observations are described in Table 1 and Fig. 2. Anoxic hypolimnion was observed during the study. Further analysis of this data, including calculation of Buoyancy frequency and Richardson number (R), is also included. Buoyancy frequency and Richardson number having its critical value $N_{cri} = 0.025\ s^{-1}$, $R_{cri} = 0.25$ (Pernica and Wells 2012) below which little or no mixing is observed, ranged from maximum of 2.18 during January to a minimum of 1.02 in April (Table 1). Near-surface stratification was found to be weak during April with minimum R value, because epilimnion gets completely mixed due to the high wind speed. Strong winds (above about 3 m/s) induce Langmuir circulations (large-scale counter-rotating helical vortices) which is largely responsible for mixing of the surface layer and deepening of the epilimnion, but an average wind speed (1–2 m/s) can cause a complete mixing of stratified surface layer of the water body (Chubarenko et al. 2010).

Conclusion

Based on the physico-chemical characteristics, the water body was observed to be rich in phosphate and deficient of nitrogen. Although the Trophic State Index (TSI) due to phosphate was high, its CTSI values were lower than TSI-TP, indicating that eutrophication in the ecosystem is regulated by limited nitrogen and zooplanktons grazing. Based on temperature profile with depth, the pond was classified as stratified with temperature lapse more than 0.1 °C/m throughout the study. Significant difference between surface and bottom temperature confirmed the thermal stratification. Moreover, chemical stratification in terms of DO concentration was also observed with significant low concentration of DO at bottom within the average depth of 1.8 m, indicating the strong stratification may have severe impact on bottom-dwelling aerobic organisms. The prevalence of reducing conditions in bottom layer resulted in solubilisation/mobilisation of phosphate

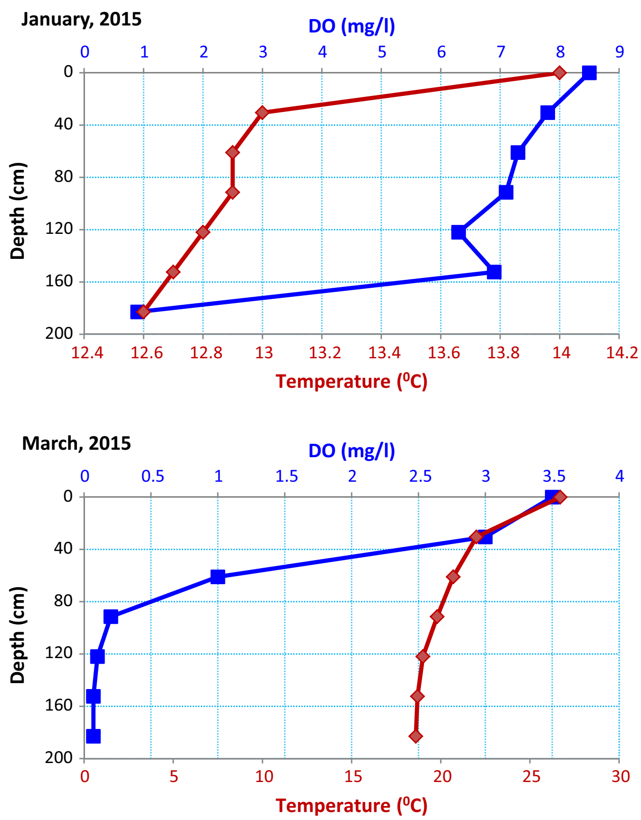

Fig. 2 Thermal (temperature—°C) and chemical (DO—mg/l) stratification in DTU pond during the study

in bottom layer. This may result in excessive algal growth upon overturning of the lake (when the thermal stratification breaks). Therefore, it becomes important to adopt effective interventions which result in reduction in import of phosphate and enhance its export, e.g. chemical precipitation of phosphate followed by sediments dredging and/or promoting aquaculture and fish catch. Managing water quality even of shallow ponds is ecologically important to maintain its water quality especially in respect of eutrophication and sustain natural ecosystem within it.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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