



Catchment Land Use Drives Seasonal Water Quality and Phytoplankton Community Structure in Six Freshwater Bodies of Amravati District, Maharashtra, India

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ABSTRACT

Reservoirs, tanks and ponds on the Deccan plateau serve irrigation, domestic supply, livestock and fisheries at once, but few studies have compared their algal communities with measured water quality. This study followed six water bodies in Amravati District, Maharashtra, selected to represent forested, agricultural, urban and village catchments. Littoral and open-water stations were sampled monthly from July 2024 to June 2026, which produced 288 station-month records of seventeen physico-chemical variables together with quantitative phytoplankton counts. The water bodies formed a clear spatial gradient. Mean dissolved oxygen fell from 8.00 mg/L in the hill-catchment reservoir to 3.43 mg/L in the urban tank. Over the same sequence, biochemical oxygen demand rose from 1.84 to 7.07 mg/L, phosphate-P from 0.120 to 0.568 mg/L and chlorophyll a from 7.11 to 79.15 µg/L. For most variables of ionic content, organic load and nutrients, site accounted for more than 80 per cent of the variance (partial η^2). Twenty-eight taxa in seven classes were recorded. Desmids, dinoflagellates and green algae were typical of the forested reservoirs, while cyanobacteria (41.0 per cent of density) and euglenoids (30.7 per cent) dominated the urban tank. Diatoms peaked in winter (38.3 per cent of density) and cyanobacteria in summer (45.1 per cent). Shannon diversity was highest in the forest-fringe reservoir ($H' = 2.736$) and lowest in the urban tank (2.116). A redundancy analysis of Hellinger-transformed densities explained 41.1 per cent of community variation ($p = 0.001$), and forward selection retained nitrate-N, water temperature, total dissolved solids, transparency and magnesium.

Keywords: phytoplankton; water quality; land use; seasonal succession; redundancy analysis; eutrophication; Vidarbha

1. INTRODUCTION

Small standing waters account for most of the surface water that rural India uses. Irrigation tanks, village ponds and medium reservoirs fill during the south-west monsoon and drain through the long dry season, and their depth, chemistry and biology can change sharply within one year. Fertiliser runoff reaches them from cultivated catchments, and domestic wastewater, washing and cattle affect their margins. Nutrient enrichment in such systems usually raises algal biomass, lowers transparency and depletes oxygen; at later stages it favours bloom-forming cyanobacteria (Paerl & Otten, 2013; Huisman et al., 2018). Phytoplankton respond to these pressures within days because their generation times are short, and their composition reflects conditions over the weeks before a sample is taken. Each group has its own ecological tendencies. Desmids are associated with clear, nutrient-poor

water; chlorococcalean green algae increase with moderate enrichment, euglenoids with organic loading, and cyanobacteria with warm, stable, nutrient-rich water (Reynolds, 2006; Bellinger & Sige, 2015). Comparisons across climates have shown that warmer shallow lakes hold a larger share of cyanobacteria, especially where nutrients are not limiting (Kosten et al., 2012), and tropical waters can support blooms for much of the year (Mowe et al., 2015). The algal community thus provides a biological record of water quality alongside periodic chemical measurement. India has a large literature on phytoplankton and water quality, but most studies describe one water body over one annual cycle and report chemistry and biology side by side without testing how they are related (Giripunje et al., 2013). Some recent studies have begun to use ordination. In a reservoir of the Ganga basin, bicarbonate, dissolved solids, oxygen demand and pH emerged as the main correlates of phytoplankton succession (Kumar et al., 2020). In Nachiketa Tal, a Himalayan lake, phytoplankton density peaked in winter and was lowest in the monsoon, and *Navicula*, *Nitzschia*, *Oscillatoria* and *Microcystis* were reported as pollution indicators (Sharma & Tiwari, 2018). For Vidarbha, the most detailed account covers two urban lakes of Nagpur, where *Microcystis* dominated a toxic cyanobacterial assemblage and chlorophyll *a* ranged from 1.44 to 71.74 mg/m³ (Maske et al., 2010). The rural reservoirs, irrigation tanks and village ponds that make up most of the region's water bodies are still largely undocumented. Amravati District is well placed to fill this gap. One administrative unit, under one monsoon regime, contains the forested Melghat hills, an intensively cultivated basaltic plain, a large town and many villages (Lamsoge, 2013). Recent geospatial work on lakes of Vidarbha and Marathwada has also linked land-use pattern with lake water quality in the region (Diwate et al., 2025). Sampling water bodies along this catchment gradient for more than one year makes it possible to separate the effect of catchment condition from that of season.

2. MATERIALS AND METHODS

2.1 Study area

Amravati District (20°32' to 21°46' N, 76°37' to 78°27' E; 12,210 km²) is in the Vidarbha region of north-eastern Maharashtra. Deccan Trap basalt underlies about 70 per cent of the district, and alluvium of the Purna valley covers the rest. The climate is hot and dry outside the south-west monsoon (June to September), and normal annual rainfall ranges from about 709 mm at Daryapur to 1647 mm at Chikhaldara (Lamsoge, 2013). Forest is concentrated in the northern Melghat tract, while cotton, soybean and pulses dominate the southern plain. Six water bodies (S1 to S6) were chosen purposively to cover this gradient (Figure 1; Table 1).

Table 1. Characteristics of the six water bodies studied

Site	Water body (taluka)	Area (ha)	Max. depth (m)	Catchment (km ²)	Dominant land cover (%)	Main pressure
S1	Shahanur Reservoir (Anjangaon Surji)	312.0	14.5	186.0	Forest (68.4)	Monsoon silt; marginal grazing

Site	Water body (taluka)	Area (ha)	Max. depth (m)	Catchment (km ²)	Dominant land cover (%)	Main pressure
S2	Chandrabhaga Reservoir (Achalpur)	246.0	11.2	142.5	Forest (46.7)	Turbid inflow; fishing
S3	Minor irrigation tank (Nandgaon Khandeshwar)	38.5	4.2	18.4	Cultivation (71.2)	Fertiliser runoff; drawdown
S4	Sawanga Lake (Chandur Railway)	64.2	5.6	41.6	Cultivation (55.6)	Washing ghats; village runoff
S5	Chhatri Lake (Amravati)	17.6	3.8	6.2	Built-up (62.7)	Storm-drain inflow; immersion
S6	Village pond (Bhatkuli)	2.4	2.1	1.4	Cultivation (49.6)	Cattle, dung and detergent

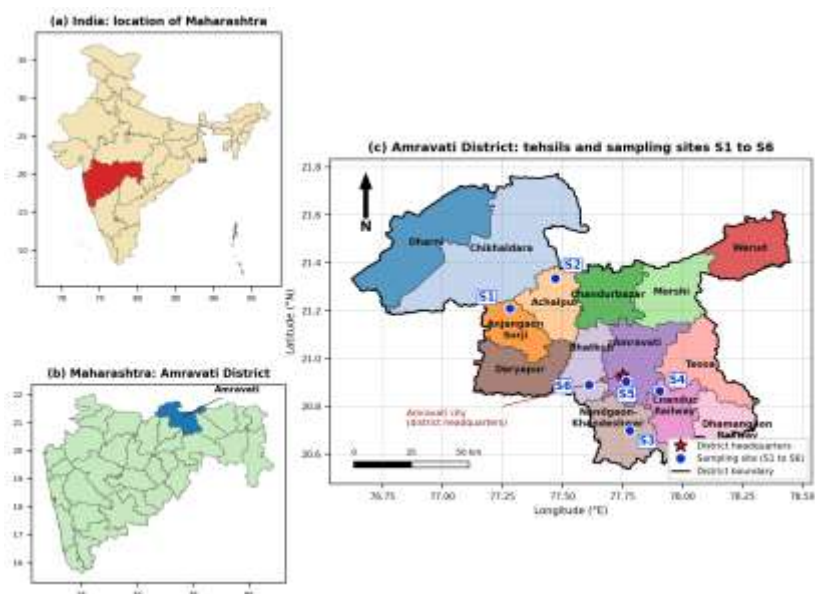


Figure 1. Location of Amravati District and the six sampling sites (S1–S6)

Source: Prepared by the authors from Census of India 2011 administrative boundaries.

2.2 Sampling design

Each water body had two fixed stations, one littoral and one in open water, which were relocated by GPS at every visit. Both were sampled once a month between 07:00 and 10:00 h for 24 consecutive months, from July 2024 to June 2026. The year was split into three seasons of four months each: monsoon (June to September), winter (October to January) and

summer (February to May). This gave 288 station-month records, balanced across six sites, three seasons, two stations and two annual cycles, with 16 records in each site-season cell.

2.3 Physico-chemical analysis

Water temperature, pH, electrical conductivity (EC) and Secchi transparency were measured in the field, and dissolved oxygen (DO) was fixed on site by the Winkler azide method. In the laboratory, biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), total alkalinity, total hardness, calcium, magnesium, chloride, nitrate-N, phosphate-P, sulphate, total dissolved solids (TDS) and chlorophyll a (acetone extraction, trichromatic method) were determined by standard methods (American Public Health Association et al., 2017). Nitrate and phosphate values refer to the dissolved fractions. Each batch included blanks, calibration standards and duplicate analysis of one sample in ten. Results were compared with the acceptable limits of the Indian drinking water standard (Bureau of Indian Standards, 2012).

2.4 Phytoplankton analysis

At each station a 5 L surface sample was collected. One litre was fixed with Lugol's iodine (10 mL/L), concentrated to 20 mL by 48 h of sedimentation and counted in a Sedgewick-Rafter cell, using three fillings of 0.25 mL per sample. A single cell, a colony or 100 µm of filament counted as one unit. Identification used net (25 µm) and periphyton samples preserved in 4 per cent formalin, and followed standard Indian monographs and Bellinger and Sigee (2015).

2.5 Community indices

Taxa richness (S), Shannon-Wiener diversity (H'), Simpson's diversity (1 - D), Margalef's richness (d) and Pielou's evenness (J') were calculated for each sample. Diversity was also converted to effective numbers of species, Hill N1 = exp(H') and N2 = 1/D. These are measured in species and are easier to compare than entropy values (Jost, 2006). Trophic state was estimated from chlorophyll a and Secchi depth with Carlson's (1977) index.

2.6 Statistical analysis

Site and season differences were tested by two-way analysis of variance (ANOVA), with site, season, their interaction and annual cycle as factors (269 residual degrees of freedom); algal densities were log-transformed first. Since the same stations were visited every month, the residuals were checked for lag-1 autocorrelation, and as a conservative check each significant F value was divided by (1 + r)/(1 - r). Tukey's HSD test identified homogeneous groups, and Kruskal-Wallis tests confirmed the results where the assumptions were doubtful. Associations were examined with Spearman rank correlation.

Detrended correspondence analysis of the 288 × 28 sample-by-taxon matrix gave a first-axis gradient length of 2.73 SD units, so a linear constrained method, redundancy analysis (RDA), was chosen (ter Braak & Verdonschot, 1995). Densities were Hellinger-transformed (Legendre & Gallagher, 2001) and explanatory variables standardised. Chlorophyll a was left out of the explanatory set because it is itself a measure of algal biomass. Variables with variance inflation factors above ten were dropped one at a time. The remaining variables went through forward selection with permutation tests, and variation was then partitioned

between the selected environmental variables and the site and season design factors using adjusted R^2 (Borcard et al., 2018).

3. RESULTS

3.1 Spatial and seasonal gradient in water quality

All 288 planned samples were collected, and Table 2 gives the site means of the main variables. For almost every variable the water bodies fell in the same order from S1 to S5. Transparency at S1 (141.3 cm) was 3.8 times that at S5 (37.1 cm), and DO was 2.3 times higher. BOD, phosphate-P and chlorophyll a were 3.8, 4.7 and 11.1 times higher at S5 than at S1. EC, TDS, alkalinity, hardness, chloride and sulphate increased along the same sequence. S2 was close to S1, S6 was close to S5, and S3 and S4 sat between the two groups.

Table 2. Site means of selected physico-chemical variables (n = 48 per site)

Variable (unit)	S1	S2	S3	S4	S5	S6	All sites
Water temperature (°C)	27.44	27.59	27.66	27.47	27.51	27.90	27.59
Transparency (cm)	141.3	122.3	79.5	74.1	37.1	49.1	83.9
pH	7.24	7.37	7.67	7.68	8.04	7.92	7.65
Electrical conductivity ($\mu\text{S}/\text{cm}$)	241.4	313.8	483.7	514.3	673.9	615.9	473.8
Dissolved oxygen (mg/L)	8.00	7.38	5.64	5.38	3.43	4.21	5.67
BOD ₅ (mg/L)	1.84	2.78	4.99	5.16	7.07	6.43	4.71
COD (mg/L)	15.24	18.60	29.85	29.98	39.45	36.78	28.32
Total hardness (mg/L as CaCO_3)	114.8	148.0	218.9	227.4	288.6	269.0	211.1
Chloride (mg/L)	40.8	60.2	104.2	109.3	147.8	136.3	99.8
Nitrate-N (mg/L)	0.627	0.977	2.200	2.026	2.832	2.560	1.870
Phosphate-P (mg/L)	0.120	0.196	0.408	0.388	0.568	0.499	0.363
Total dissolved solids (mg/L)	156.9	199.7	309.0	331.5	433.5	396.3	304.5
Chlorophyll a ($\mu\text{g}/\text{L}$)	7.11	11.24	32.85	33.40	79.15	56.01	36.62

The two-way ANOVA supported these patterns (Table 3). Site affected 16 of the 17 variables, all except water temperature, and its partial η^2 was above 0.80 for the variables of ionic content, organic loading and nutrients. Season was significant for every variable but dominated only water temperature (partial $\eta^2 = 0.958$), which rose from 22.83 °C in winter to 32.10 °C in summer. The site $\times$ season interaction was significant for transparency, DO, nitrate-N, phosphate-P and chlorophyll a, so the seasonal course of these five variables was not the same in every water body. For 13 variables the residuals showed lag-1 autocorrelation

beyond ± 0.118 , yet every significant site and season effect survived the conservative adjustment. Only four variables (temperature, EC, sulphate and TDS) differed between the two annual cycles, and those differences were small.

Table 3. Two-way ANOVA of physico-chemical variables: F values and effect sizes

Variable	Site F(5, 269)	Season F(2, 269)	Site $\times$ Season F(10, 269)	Partial η^2 site	Partial η^2 season
Water temperature	2.06 ns	3035.43***	1.69 ns	0.037	0.958
Transparency	563.50***	417.28***	3.83***	0.913	0.756
pH	247.72***	76.04***	1.33 ns	0.822	0.361
Electrical conductivity	748.46***	255.62***	0.63 ns	0.933	0.655
Dissolved oxygen	456.39***	245.30***	3.65***	0.895	0.646
BOD ₅	558.27***	22.80***	0.49 ns	0.912	0.145
Chloride	667.22***	130.70***	0.99 ns	0.925	0.493
Nitrate-N	685.46***	178.72***	14.60***	0.927	0.571
Phosphate-P	775.83***	184.00***	15.09***	0.935	0.578
Total dissolved solids	616.35***	214.74***	0.73 ns	0.920	0.615
Chlorophyll a	245.16***	90.27***	12.05***	0.820	0.402

Note: *** $p < 0.001$; ns, not significant. Annual cycle was included as an additional factor.

Dissolved oxygen was highest in winter (6.64 mg/L) and lowest in summer (4.82 mg/L) at every site (Figure 2). At S5, DO was below 4 mg/L in 68.8 per cent of records and BOD was above 3 mg/L in all of them, whereas DO at S1 never dropped below 6 mg/L. Nutrients behaved differently. Nitrate-N (2.157 mg/L) and phosphate-P (0.420 mg/L) peaked in the monsoon and were lowest in winter. The monsoon peak was sharpest at the irrigation tank S3, where phosphate-P reached 0.538 mg/L (Figure 3).

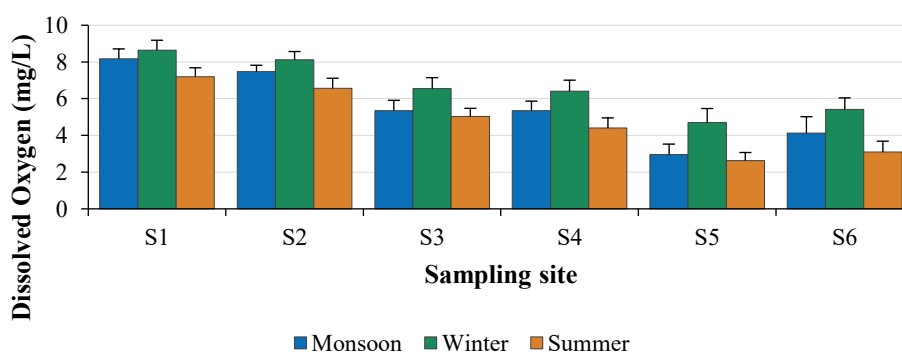


Figure 2. Season-wise mean dissolved oxygen at the six sites

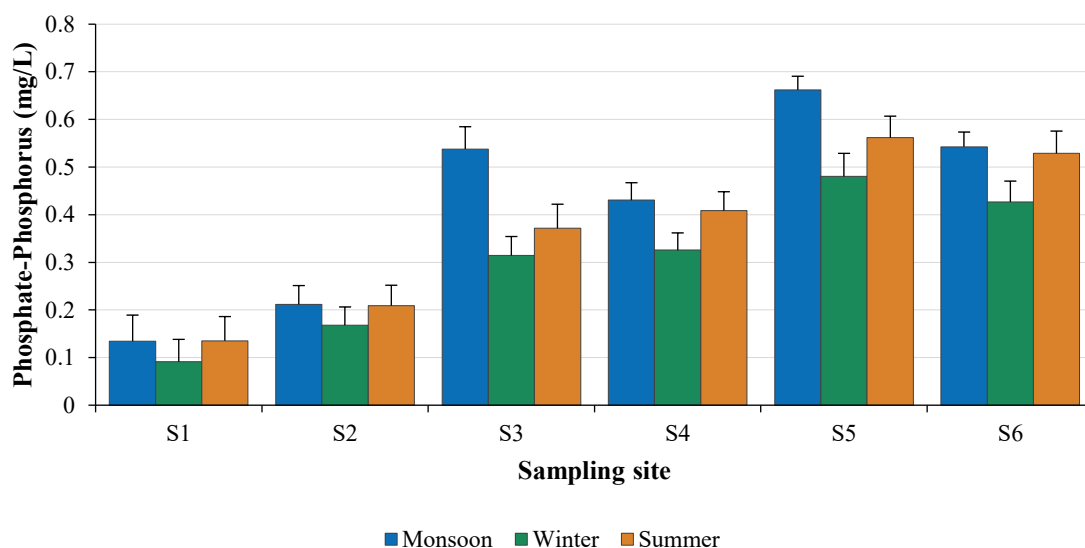


Figure 3. Season-wise mean phosphate-P at the six sites

Chlorophyll a was lowest in winter (23.10 $\mu\text{g/L}$) and about the same in the monsoon (43.16 $\mu\text{g/L}$) and summer (43.61 $\mu\text{g/L}$) (Figure 4). Its seasonal range widened with enrichment. At S1 the seasonal means varied only from 5.41 to 8.14 $\mu\text{g/L}$, but at S5 they varied from 47.22 to 97.34 $\mu\text{g/L}$. By Carlson's chlorophyll-based index, S1 was mesotrophic in 29 of 48 samples (mean TSI 49.25), S2, S3, S4 and S6 were mostly eutrophic, and S5 was hypereutrophic in 35 of 48 samples (mean TSI 72.65). During the monsoon the Secchi-based index was on average 8.07 units higher than the chlorophyll-based index, a sign of non-algal turbidity from runoff. Hardness exceeded the acceptable drinking-water limit of 200 mg/L in 60.4 per cent of all records, all of them from S3 to S6. No record from the reservoirs S1 and S2 exceeded any limit, and nitrate, chloride and sulphate stayed within their limits at every site.

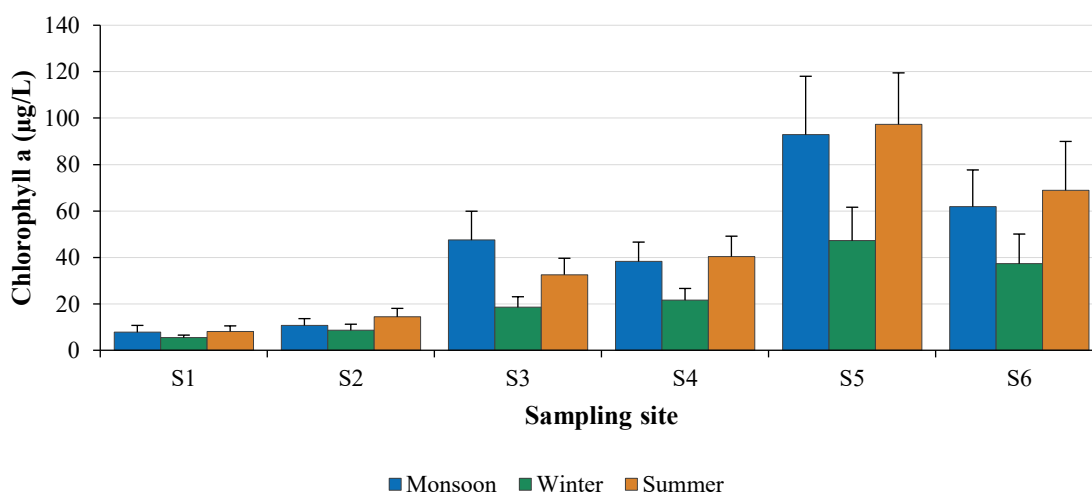


Figure 4. Season-wise mean chlorophyll a at the six sites

3.2 Composition and seasonal succession of the phytoplankton

Twenty-eight taxa from seven classes were recorded: six Cyanobacteria, six Chlorophyceae, six Bacillariophyceae, four Zygnematophyceae, three Euglenophyceae, two Dinophyceae and one Cryptophyceae. Every taxon turned up at every site at least once during the two years, so the water bodies differed in how abundant the taxa were, not in which taxa were present. *Chlorella vulgaris* was the most frequent taxon (72.9 per cent of samples), followed by *Navicula cryptocephala* (72.2 per cent) and *Scenedesmus quadricauda* (71.5 per cent). *Euglena viridis* had the highest mean density (13.15×10^3 org/L).

Mean total density was $209,248 \pm 95,975$ org/L. Density was highest at the agricultural sites S4 (294,178 org/L) and S3 (265,520 org/L) and lowest at S1 (125,098 org/L), and it increased from the monsoon (159,610 org/L) through winter (202,908 org/L) to summer (265,227 org/L). Class composition changed sharply along the catchment gradient (Table 4; Figure 5). At S1, Zygnematophyceae (31.1 per cent), Chlorophyceae (25.2 per cent) and Bacillariophyceae (21.4 per cent) dominated, and cyanobacteria made up only 5.2 per cent. At S5, cyanobacteria (41.0 per cent) and euglenoids (30.7 per cent) together formed nearly three-quarters of the community, and desmids fell below 0.5 per cent.

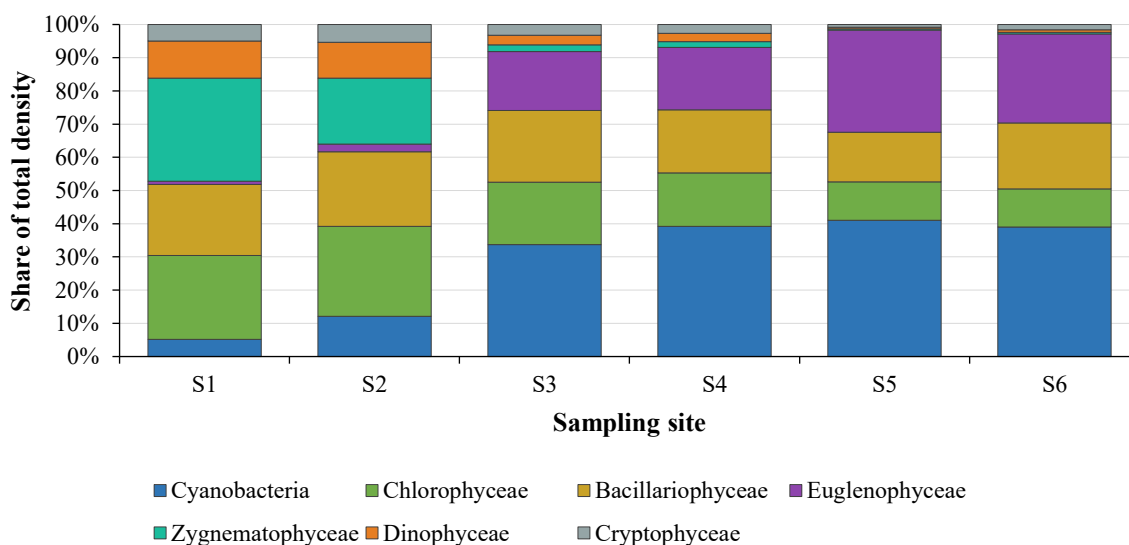


Figure 5. Percentage composition of algal classes at the six sites

Table 4. Percentage contribution of algal classes to total density by site and season

Class	S1	S2	S3	S4	S5	S6	Monsoon	Winter	Summer
Cyanobacteria	5.22	12.08	33.73	39.20	41.02	39.04	27.71	15.70	45.08
Chlorophyceae	25.21	27.10	18.75	16.12	11.55	11.43	22.59	15.10	16.53
Bacillariophyceae	21.37	22.53	21.67	19.03	14.99	19.93	13.55	38.33	9.65
Euglenophyceae	0.98	2.23	17.67	18.78	30.72	26.75	20.97	10.52	20.95
Zygnematophyceae	31.12	19.92	2.08	1.75	0.39	0.49	7.54	10.88	3.27
Dinophyceae	11.17	10.82	2.86	2.47	0.48	0.81	3.23	6.55	2.49

Class	S1	S2	S3	S4	S5	S6	Monsoon	Winter	Summer
Cryptophyceae	4.94	5.31	3.24	2.66	0.86	1.55	4.42	2.92	2.03

Source: Field and laboratory data of the present study. Values are shares of pooled mean density.

The seasonal succession was the same in all six water bodies (Figure 6). Diatoms had their highest share in winter at every site and made up 38.3 per cent of pooled winter density, with *Navicula cryptocephala*, *Nitzschia palea* and *Gomphonema parvulum* the leading taxa. Cyanobacteria had their highest share in summer at every site, rising from 15.7 per cent in winter to 45.1 per cent in summer, when *Microcystis aeruginosa* (24.29×10^3 org/L), *Spirulina major* and *Oscillatoria limosa* were the most abundant taxa. At the enriched sites cyanobacteria formed more than half of summer density (S4 53.1, S5 50.6 and S6 53.1 per cent), while at S1 their share stayed below 17 per cent in every month. The monsoon community was mixed, and Chlorophyceae (22.6 per cent) and Euglenophyceae (21.0 per cent) contributed most. Log-transformed densities of all seven classes differed significantly among sites and seasons, with significant site $\times$ season interactions ($p < 0.001$ in every case except the season effect for Cryptophyceae, $p = 0.040$).

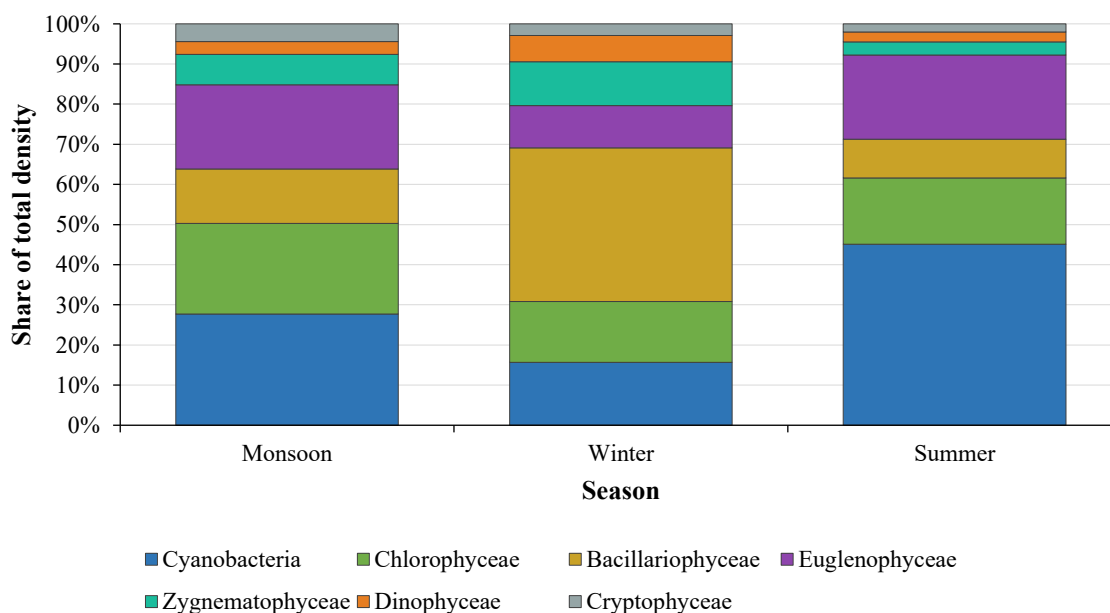


Figure 6. Percentage composition of algal classes in the three seasons

3.3 Diversity

Every diversity measure placed S5 lowest and S6 next, while S2, S3 and S4 shared the highest values (Table 5). Taxa richness per sample ranged from 12.52 at S5 to 19.73 at S4, and Shannon H' from 2.116 at S5 to 2.736 at S2. In effective numbers, a typical sample at S2 behaved as if it held 15.6 equally common taxa, compared with 8.9 at S5. H' was affected by site ($F(5, 269) = 89.53$, $p < 0.001$) and by season ($F(2, 269) = 25.62$, $p < 0.001$), and the interaction was significant ($F(10, 269) = 19.46$, $p < 0.001$). Kruskal-Wallis tests gave the same result (site $H = 122.52$; season $H = 10.54$, $p = 0.005$).

Table 5. Site means of diversity indices

Index	S1	S2	S3	S4	S5	S6	Mean $\pm$ SD
Taxa richness (S)	17.08	19.27	19.58	19.73	12.52	15.04	17.20 $\pm$ 4.13
Shannon-Wiener (H')	2.565	2.736	2.717	2.712	2.116	2.360	2.534 $\pm$ 0.336
Simpson (1 - D)	0.909	0.922	0.921	0.919	0.845	0.883	0.900 $\pm$ 0.044
Margalef (d)	1.372	1.517	1.491	1.493	0.962	1.140	1.329 $\pm$ 0.320
Pielou (J')	0.908	0.927	0.917	0.912	0.850	0.883	0.899 $\pm$ 0.051
Hill N1	13.29	15.62	15.28	15.29	8.90	11.06	13.24 $\pm$ 3.70
Hill N2	11.53	13.39	12.87	12.82	7.57	9.36	11.26 $\pm$ 3.27

Source: Field and laboratory data of the present study (n = 48 samples per site).

The two groups of water bodies followed different seasonal patterns of diversity (Figure 7). Across all sites H' was highest in winter (2.643). At the reservoirs S1 and S2, however, winter was the least diverse season (2.398 and 2.619), because desmids and diatoms became strongly dominant. At S3 to S6 the pattern was reversed: H' peaked in winter and fell to its lowest values in the monsoon or summer, reaching 1.847 at S5 in summer.

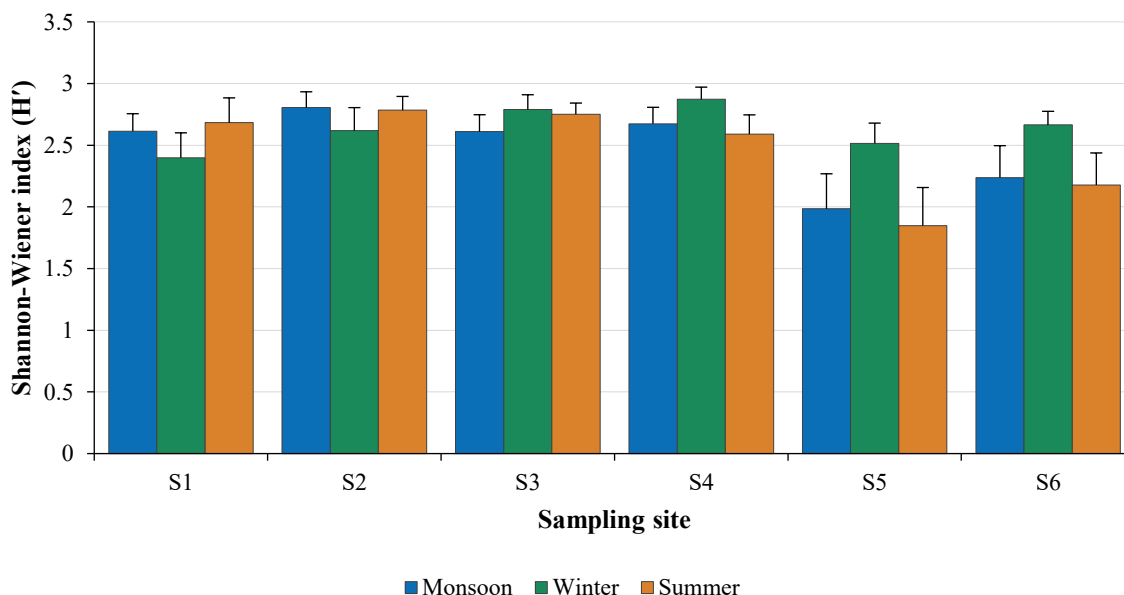


Figure 7. Season-wise mean Shannon-Wiener index (H') at the six sites

Source: Field and laboratory data of the present study. Error bars show +1 SD.

3.4 Relationships between community structure and water quality

The environmental variables were strongly collinear, with 112 of the 136 pairwise Spearman coefficients at $|\rho| \geq 0.70$. The community measures followed the same enrichment axis (Table 6). The share of cyanobacteria rose with pH, EC, nitrate-N and phosphate-P and fell with DO and transparency, and Zygnematomyxaceae showed the opposite pattern. Euglenophyceae were most closely linked with nitrate-N ($\rho = 0.85$) and chlorophyll a ($\rho = 0.84$). Bacillariophyceae were negatively correlated with water temperature ($\rho = -0.74$), which fits their winter maximum. Shannon H' fell as phosphate-P, BOD and chlorophyll a rose, and increased with DO and transparency.

Table 6. Spearman correlations between physico-chemical variables and community measures (n = 288)

Variable	Cyano-bacteria (%)	Bacillario-phyceae (%)	Eugleno-phyceae (%)	Zygnemato-phyceae (%)	Shannon H'	Total density
Water temperature	0.49*	-0.74*	0.23*	-0.24*	-0.18*	0.12*
Transparency	-0.63*	0.37*	-0.82*	0.77*	0.44*	-0.10
pH	0.74*	-0.40*	0.76*	-0.79*	-0.44*	0.28*
Electrical conductivity	0.76*	-0.33*	0.74*	-0.80*	-0.42*	0.38*
Dissolved oxygen	-0.81*	0.53*	-0.82*	0.82*	0.49*	-0.27*
BOD ₅	0.71*	-0.31*	0.78*	-0.81*	-0.45*	0.26*
Nitrate-N	0.75*	-0.44*	0.85*	-0.83*	-0.48*	0.17*
Phosphate-P	0.74*	-0.43*	0.84*	-0.84*	-0.48*	0.18*
Total dissolved solids	0.76*	-0.34*	0.74*	-0.80*	-0.41*	0.38*
Chlorophyll a	0.77*	-0.47*	0.84*	-0.83*	-0.49*	0.25*

Note: * $p < 0.05$. Source: Computed from the data of the present study.

Chlorophyll a was very strongly associated with phosphate-P (Spearman $\rho = 0.940$; Pearson $r = 0.857$; Figure 8), and the relationship held within each of the six sites (within-site r from 0.320 to 0.792). Total density, by contrast, was only weakly correlated with nitrate-N ($\rho = 0.173$, $p = 0.003$) and phosphate-P ($\rho = 0.176$, $p = 0.003$). The cyanobacterial share increased with water temperature both across all samples ($\rho = 0.495$) and within every site (0.489 to 0.884).

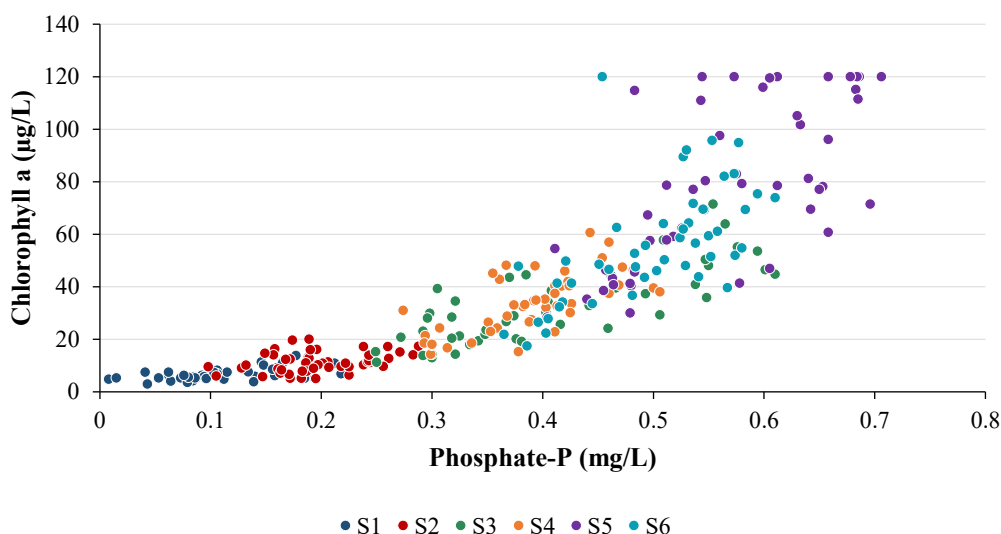


Figure 8. Relationship between phosphate-P and chlorophyll a (n = 288)

3.5 Constrained ordination, variance partitioning and clustering

Stepwise screening removed nine variables with variance inflation factors above ten. Total hardness (VIF = 100.1) and EC (87.8) went first, and BOD, phosphate-P and DO were among the others removed. The seven variables that remained (water temperature, transparency, pH, COD, magnesium, nitrate-N and TDS) explained 41.13 per cent of the variation in the Hellinger-transformed community data (adjusted $R^2 = 0.397$; permutation test, $p = 0.001$). The first canonical axis alone accounted for 36.25 per cent of total variation, which is 88.1 per cent of the explained variation. Forward selection kept five variables (Table 7), and nitrate-N by itself explained 34.70 per cent.

Table 7. Forward selection of explanatory variables in the redundancy analysis

Step	Variable	Variation added (%)	Cumulative (%)	Cumulative adjusted R^2	p
1	Nitrate-N	34.70	34.70	0.3447	0.002
2	Water temperature	2.93	37.63	0.3719	0.002
3	Total dissolved solids	2.02	39.65	0.3901	0.002
4	Transparency	0.53	40.17	0.3933	0.002
5	Magnesium	0.32	40.50	0.3944	0.048

Source: Computed from the data of the present study; p values from 499 permutations at each step.

In the biplot (Figure 9), samples from S1 and S2 lay on the negative side of the first axis and samples from S5 and S6 on the positive side, with S3 and S4 between them. Nitrate-N ($r = 0.980$), TDS ($r = 0.906$) and transparency ($r = -0.887$) had the strongest correlations with this axis. Water temperature loaded on the second axis ($r = 0.923$), which separated samples by season within each site. The highest positive taxon scores on axis 1 belonged to *Euglena*

viridis (0.319), *Microcystis aeruginosa* (0.286), *Oscillatoria limosa* (0.248) and *Phacus pleuronectes* (0.230), and the most negative to *Closterium moniliferum* (−0.273), *Pinnularia gibba* (−0.248), *Volvox aureus* (−0.248) and *Staurostrum gracile* (−0.242).

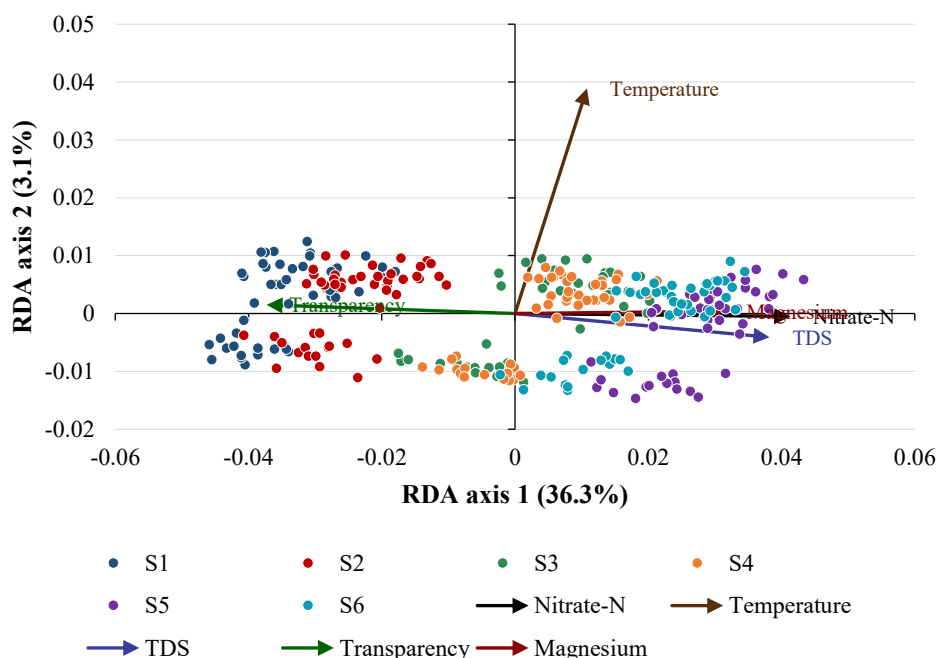


Figure 9. RDA biplot of samples (coded by site) and the selected environmental variables

Variance partitioning showed that most of the explained variation (38.20 per cent) was shared between the environmental variables and the site-season design. The environment alone explained 1.24 per cent and site and season alone 6.12 per cent, leaving 54.44 per cent unexplained. UPGMA clustering of the eighteen site-season communities (cophenetic correlation 0.850) gave three groups. The first held all seasons of S1 and S2, and the second combined the monsoon and summer communities of S3 and S4 with all seasons of S5 and S6. The third contained the winter communities of S3 and S4, which stood apart because of their high diatom share and joined the reservoir branch before the enriched group.

4. DISCUSSION

4.1 Catchment condition sets the level of enrichment

All six water bodies share one climate and one monsoon, yet they differed from one another far more than any single water body differed between seasons. Site accounted for over 80 per cent of the variance in most variables of ionic content, organic load and nutrients, and the water bodies ranked in the same order, from the forested reservoir to the urban tank, for oxygen, oxygen demand, nitrate, phosphate, chloride, dissolved solids and chlorophyll a. This fits the view that land use affects phytoplankton mainly through the delivery of nutrients, solutes, suspended matter and organic material, not by acting on the algae directly. Diwate et al. (2025) have recently documented this link between land use and lake water quality in Vidarbha and Marathwada.

The low dissolved oxygen and high BOD at S5 and S6 point to chronic organic loading rather than occasional events; at S5, DO was below 4 mg/L in more than two-thirds of the morning samples. The combination of high chlorophyll a and low DO also suggests that respiration and decomposition of algal biomass added to the oxygen stress. This feedback can release phosphorus from sediments and sustain further blooms (Paerl & Otten, 2013). Mean chlorophyll a at S5 (79.15 µg/L) was above the upper end of the range reported for the Nagpur urban lakes (1.44 to 71.74 mg/m³; Maske et al., 2010), which places this urban tank among the more productive water bodies documented in Vidarbha.

4.2 Season decides how enrichment is expressed

Season had a significant effect on every variable, but these effects played out around levels that each site kept through the year. The monsoon brought the highest nitrate and phosphate concentrations along with the lowest transparency and total density. During inflow, dilution, flushing and light limitation from suspended silt hold back algal growth, and the monsoon excess of the Secchi-based over the chlorophyll-based trophic index points the same way. The low monsoon density matches the pattern reported for Nachiketa Tal (Sharma & Tiwari, 2018) and the wider observation that the monsoon acts as a reset for phytoplankton in Indian lakes (Giripunje et al., 2013).

Winter water was clear, cool and well oxygenated, and diatoms formed more than a third of total density, as expected from their need for mixing and their tolerance of lower temperature (Reynolds, 2006). Summer brought the highest temperature, ionic concentration and chlorophyll a together with the lowest oxygen, and cyanobacteria reached their largest share at every site. Temperature and cyanobacterial share were positively related within each of the six sites, which supports the conclusion of Kosten et al. (2012) that warmth increases cyanobacterial dominance in shallow lakes. The effect depended on enrichment, though. In summer the cyanobacterial share stayed below 17 per cent at S1 but passed half of total density at S4, S5 and S6. Temperature and nutrients acted together rather than as competing explanations. In these tanks the low-flow summer months carry the greatest bloom risk, as is typical of tropical waters where warmth lasts for much of the year (Mowe et al., 2015).

4.3 The algal community as a record of enrichment

Community composition followed the chemical gradient closely. Desmids, dinoflagellates and green algae such as *Volvox aureus* were typical of the forested reservoirs, and cyanobacteria and euglenoids dominated the enriched water bodies. These tendencies are familiar. Desmids favour clear, weakly enriched water, euglenoids use dissolved organic matter, and colonial cyanobacteria such as *Microcystis* gain from buoyancy in warm, stable, nutrient-rich water (Reynolds, 2006; Bellinger & Sigeo, 2015; Huisman et al., 2018). The prominence of *Microcystis aeruginosa*, *Oscillatoria limosa* and *Euglena viridis* at the enriched sites matches the pollution indicators reported from Nachiketa Tal (Sharma & Tiwari, 2018) and the *Microcystis*-dominated assemblage of the Nagpur lakes (Maske et al., 2010). Their presence indicates a potential toxin hazard, not a confirmed one (Huisman et al., 2018).

Total density peaked at the agricultural sites S3 and S4 and not at the more enriched urban tank, even though chlorophyll a was highest at S5. A cell count gives small and large units the same weight, while chlorophyll a reflects pigment biomass, so a shift toward large colonies or pigment-rich taxa can raise chlorophyll without a matching rise in counted units.

4.4 Diversity does not decline uniformly with enrichment

Diversity was highest in the moderately enriched water bodies S2, S3 and S4 and dropped sharply only at S5 and S6. A modest nutrient supply can support extra taxa without letting a few of them exclude the rest, whereas heavy organic and nutrient loading favours a small set of tolerant organisms. Effective numbers show the size of the loss: the urban tank held little more than half the effective number of species found in the forest-fringe reservoir (Jost, 2006). The seasonal contrast between the two groups of water bodies is also informative. At the reservoirs, winter diversity was lowest because desmids and diatoms became strongly dominant, while at the enriched sites winter brought relief from cyanobacterial and euglenoid dominance and diversity peaked. A single diversity value can mislead on its own and needs to be read together with the identity of the dominant taxa.

4.5 Drivers of community composition

The measured environment explained 41 per cent of compositional variation. For field community data, where dispersal, grazing and short-term events also play a part, this is a substantial fraction. The first axis described an enrichment gradient, with the heaviest loadings for nitrate-N, dissolved solids and transparency, and the second axis described seasonal thermal forcing. Kumar et al. (2020) likewise found dissolved solids, oxygen demand and pH among the main correlates of phytoplankton succession in a tropical reservoir of the Ganga basin, which suggests that the mix of nutrient, ionic and light gradients seen here is typical of Indian standing waters.

The selected variables are best read as stand-ins for environmental dimensions, not as sole causes. Phosphate-P is an example. It was removed during collinearity screening because it varied almost in step with nitrate-N ($\rho = 0.960$), yet it had the strongest correlation with chlorophyll a of any variable. The large shared fraction in the variance partitioning (38.2 per cent) says the same thing: differences in water quality among sites and seasons largely coincided with differences in community composition, so an observational design cannot fully separate the effects of catchment and measured chemistry (Borcard et al., 2018). The clustering showed that the irrigation tank and the perennial lake change state with the season, resembling the reservoirs in winter and the urban tank in the monsoon and summer. These two water bodies are therefore the most likely to respond to nutrient management.

5. CONCLUSIONS

In six water bodies sharing one climate, catchment condition was the main control on water quality, producing a gradient from clear, oxygen-rich forested reservoirs to nutrient-rich, oxygen-depleted urban and village waters. Season modified this gradient. The monsoon raised nutrients but held back algal growth through turbidity and flushing, winter favoured diatoms, and summer favoured cyanobacteria wherever nutrients were high. The phytoplankton reflected these differences closely: desmids, dinoflagellates and green algae



marked the least disturbed waters, and cyanobacteria and euglenoids the most enriched. The measured environmental variables, led by nitrate-N, temperature, dissolved solids and transparency, explained about two-fifths of community variation.

For management, the results support protecting forest cover in reservoir catchments, reducing fertiliser runoff to irrigation tanks before the monsoon, and diverting wastewater and controlling washing and cattle access at urban tanks and village ponds. Chlorophyll a, dissolved oxygen, transparency and the cyanobacterial share together make a compact set of indicators for routine surveillance, and the summer months should be the priority for monitoring and bloom advisories.

REFERENCES

1. American Public Health Association, American Water Works Association, & Water Environment Federation. (2017). Standard methods for the examination of water and wastewater (23rd ed.). American Public Health Association.
2. Bellinger, E. G., & Sigeo, D. C. (2015). Freshwater algae: Identification, enumeration and use as bioindicators (2nd ed.). Wiley-Blackwell. <https://doi.org/10.1002/9781118917152>
3. Borcard, D., Gillet, F., & Legendre, P. (2018). Numerical ecology with R (2nd ed.). Springer. <https://doi.org/10.1007/978-3-319-71404-2>
4. Bureau of Indian Standards. (2012). Indian standard: Drinking water specification (IS 10500:2012, 2nd rev.). Bureau of Indian Standards.
5. Carlson, R. E. (1977). A trophic state index for lakes. Limnology and Oceanography, 22(2), 361–369. <https://doi.org/10.4319/lo.1977.22.2.0361>
6. Diwate, P., Lavhale, P., Singh, S. K., Kanga, S., Kumar, P., Meraj, G., Debnath, J., Sahariah, D., Bhuyan, M. S., & Chand, K. (2025). Impact of land use pattern and heavy metals on lake water quality in Vidarbha and Marathwada Region, India. Water, 17(4), Article 540. <https://doi.org/10.3390/w17040540>
7. Giripunje, M. D., Fulke, A. B., Khairnar, K., Meshram, P. U., & Paunekar, W. N. (2013). A review of phytoplankton ecology in freshwater lakes of India. Lakes, Reservoirs and Ponds, 7(2), 127–141.
8. Huisman, J., Codd, G. A., Paerl, H. W., Ibelings, B. W., Verspagen, J. M. H., & Visser, P. M. (2018). Cyanobacterial blooms. Nature Reviews Microbiology, 16(8), 471–483. <https://doi.org/10.1038/s41579-018-0040-1>
9. Jost, L. (2006). Entropy and diversity. Oikos, 113(2), 363–375. <https://doi.org/10.1111/j.2006.0030-1299.14714.x>
10. Kosten, S., Huszar, V. L. M., Bécáres, E., Costa, L. S., van Donk, E., Hansson, L.-A., Jeppesen, E., Kruk, C., Lacerot, G., Mazzeo, N., De Meester, L., Moss, B., Lüring, M., Nöges, T., Romo, S., & Scheffer, M. (2012). Warmer climates boost cyanobacterial dominance in shallow lakes. Global Change Biology, 18(1), 118–126. <https://doi.org/10.1111/j.1365-2486.2011.02488.x>
11. Kumar, J., Alam, A., Sarkar, U. K., Das, B. K., Kumar, V., & Srivastava, S. K. (2020). Assessing the phytoplankton community and diversity in relation to physico-



- chemical parameters in a tropical reservoir of the River Ganga basin, India. *Sustainable Water Resources Management*, 6(6), Article 110. <https://doi.org/10.1007/s40899-020-00470-z>
12. Lamsoge, B. R. (2013). Ground water information: Amravati district, Maharashtra (Report No. 1757/DBR/2013). Central Ground Water Board, Ministry of Water Resources, Government of India.
 13. Legendre, P., & Gallagher, E. D. (2001). Ecologically meaningful transformations for ordination of species data. *Oecologia*, 129(2), 271–280. <https://doi.org/10.1007/s004420100716>
 14. Maske, S. S., Sangolkar, L. N., & Chakrabarti, T. (2010). Temporal variation in density and diversity of cyanobacteria and cyanotoxins in lakes at Nagpur (Maharashtra State), India. *Environmental Monitoring and Assessment*, 169(1–4), 299–308. <https://doi.org/10.1007/s10661-009-1171-7>
 15. Mowe, M. A. D., Mitrovic, S. M., Lim, R. P., Furey, A., & Yeo, D. C. J. (2015). Tropical cyanobacterial blooms: A review of prevalence, problem taxa, toxins and influencing environmental factors. *Journal of Limnology*, 74(2), 205–224. <https://doi.org/10.4081/jlimnol.2014.1005>
 16. Paerl, H. W., & Otten, T. G. (2013). Harmful cyanobacterial blooms: Causes, consequences, and controls. *Microbial Ecology*, 65(4), 995–1010. <https://doi.org/10.1007/s00248-012-0159-y>
 17. Reynolds, C. S. (2006). *The ecology of phytoplankton*. Cambridge University Press. <https://doi.org/10.1017/CBO9780511542145>
 18. Sharma, R. C., & Tiwari, V. (2018). Phytoplankton diversity in relation to physicochemical environmental variables of Nachiketa Tal, Garhwal Himalaya. *Biodiversity International Journal*, 2(2), 102–110. <https://doi.org/10.15406/bij.2018.02.00052>
 19. ter Braak, C. J. F., & Verdonschot, P. F. M. (1995). Canonical correspondence analysis and related multivariate methods in aquatic ecology. *Aquatic Sciences*, 57(3), 255–289. <https://doi.org/10.1007/BF00877430>