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Seasonal Variations in Gross and Net Primary Productivity in Upper Lake, Bhopal Using the Light-Dark Bottle Method

Piyush Soni[1], Mukesh Dixit[2], Vipin Vyas[3]
[1]*Department of Zoology and Applied Aquaculture, Barkatullah University*
[2]*Department of Zoology, Sarojini Naidu Govt. Girls PG (Auto.) College, Bhopal*
[3]*Department of Zoology and Applied Aquaculture, Barkatullah University*

Abstract: This study investigates seasonal variations in Gross Primary Productivity (GPP), Net Primary Productivity (NPP), and community respiration in Upper Lake, Bhopal, using the Light–Dark Bottle method. Monthly sampling was conducted at two ecologically distinct sites, Boat Club and Khanugaon from September 2023 to August 2024. Physico-chemical parameters including temperature, pH, dissolved oxygen, nitrate, phosphate and transparency were analyzed following APHA (2017) protocols. Results indicated the highest primary productivity during summer, associated with elevated temperature and enhanced light penetration, while the lowest productivity occurred in winter. Khanugaon exhibited higher nutrient concentrations and biochemical oxygen demand, reflecting greater anthropogenic influence compared to Boat Club. Correlation analysis revealed that GPP had a strong positive relationship with dissolved oxygen and transparency, and a negative association with nitrate, phosphate and BOD. The findings suggest that Upper Lake is moderately productive but prone to nutrient enrichment and emerging eutrophication risk. Effective catchment management and nutrient load reduction strategies are essential for sustaining ecological health and fisheries potential.
Keywords: Upper Lake Bhopal, Gross Primary Productivity, Net Primary Productivity, Eutrophication, Light–Dark Bottle Method.

I. INTRODUCTION

Primary productivity in freshwater ecosystems the conversion of solar energy into organic matter by phytoplankton and aquatic plants is the fundamental driver of aquatic food-webs and ecosystem functioning (Wetzel 2000). Gross primary productivity (GPP), net primary productivity (NPP) and community respiration are critical metrics for understanding how energy flows through lentic systems and how shifts in environmental conditions influence ecosystem health, fish yields and trophic status (Adoni, 1985; Babar et al., 2015). Urban lakes in India are particularly vulnerable to seasonal fluctuations owing to combined influences of monsoon-rainfall cycles, anthropogenic nutrient inputs (sewage, storm-runoff), shoreline development and changes in water-level. These seasonal drivers often affect light availability, water mixing, nutrient regeneration and hence productivity patterns (Arvind et al., 2013). The light-dark bottle method remains a robust field technique for quantifying the photosynthetic oxygen evolution (GPP) and dark respiration, thus allowing estimation of NPP (Babar et al., 2015). Previous studies have explored its physico-chemical parameters, nutrient status and plankton community structure (Magarde et al., 2011; Parashar et al., 2006). Detailed investigations of seasonal variations in GPP and NPP using the light-dark bottle technique remain limited for this lake. Studying seasonal dynamics of productivity in Upper Lake is important it helps link abiotic drivers (for example water transparency, nutrient concentration, temperature, dissolved oxygen) to biological productivity and ecosystem health. It also provides understanding when productivity peaks, when respiration dominates, when the lake might shift toward eutrophic/hypereutrophic states, thus informing fishery potential, water quality interventions and catchment management. This research therefore aims to quantify the seasonal patterns of GPP, NPP and community respiration in Upper Lake, Bhopal using the light-dark bottle method and to analyse their relationships with key environmental parameters.

II. STUDY AREA

The study area for this research is the Upper Lake, Bhopal (Figure 1) situated on the western side of Bhopal city in Madhya Pradesh, India. The lake lies approximately between latitude 23°12′ to 23°16′ N and longitude 77°18′ to 77°23′ E. It has two sampling sites Boat Club and Khanugaon. Sampling was conducted monthly (Sept 2023 – Aug 2024) across four seasons (Fig 1). It covers a water-spread area of around 31 km² under typical conditions, with some earlier reports citing up to 36 km². Its mean depth is about 6 m, with maximum depth estimates around 11.7 m. The watershed (catchment) area contributing to it is approximately 361 km².

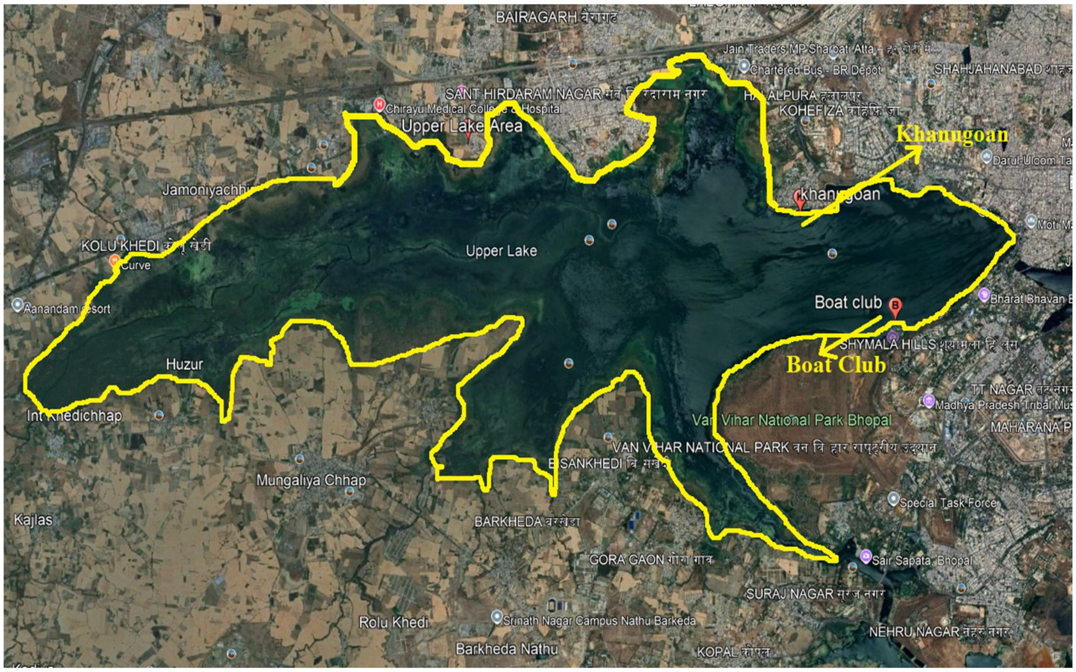

Figure. 1: Upper Lake with sampling sites – Boat club and Khanugaon.

III. METHODOLOGY

Seasonal sampling was carried out during pre-monsoon, monsoon, post-monsoon and winter periods to capture temporal variations in primary productivity. Water samples were collected from surface layers using pre cleaned polyethylene bottles. Parameters including temperature, pH, DO, BOD, nitrate (NO_3^-), phosphate (PO_4^{3-}) and transparency were analysed following APHA (2017) standard methods for water quality analysis. Water samples were collected from selected stations at the surface to euphotic depth using a Van Dorn sampler minimizing atmospheric oxygen exchange. Immediately after collection, samples were transferred to clean 300 mL Biological Oxygen Demand (BOD) bottles, comprising one transparent (light bottle) and one opaque (dark bottle) sealed using airtight stoppers. The initial dissolved oxygen (DO) concentration of the lake water was determined on-site using the Winkler iodometric titration method, which is widely recognized for accuracy in aquatic productivity studies (APHA, 2017). The paired bottles were then incubated in situ under natural sunlight for 4 hours in situ incubation, allowing the light bottle to undergo photosynthesis and respiration, while the dark bottle permitted only respiratory oxygen consumption by eliminating light penetration (Wetzel & Likens, 2000). After incubation, DO was again estimated for both bottles using the same Winkler method. The differences in DO concentrations were used to calculate Net Primary Productivity (NPP) and Community Respiration (CR), while Gross Primary Productivity (GPP) was derived as:

$$\text{NPP} = O_2(\text{Light Bottle}) - O_2(\text{Initial})$$

$$\text{CR} = O_2(\text{Initial}) - O_2(\text{Dark Bottle})$$

$$\text{GPP} = \text{NPP} + \text{CR}$$

The obtained values expressed in mg O_2 L^{-1} hr^{-1} were subsequently converted into mg C m^{-3} hr^{-1} using the standard photosynthetic conversion coefficient of 0.375 mg C per m^3 O_2 (Adoni, 1985). Supporting physico-chemical parameters such as water temperature, pH, dissolved oxygen, conductivity, transparency (Secchi depth), alkalinity and hardness were measured to interpret their influence on productivity dynamics (Upadhyay et al., 2012). All analyses were completed within 24 hours of sample collection to avoid chemical and microbial alteration. The resulting data were compiled seasonally to determine temporal variations in GPP, NPP and CR.

IV. RESULTS

Table 1. Seasonal mean (±SD) physico-chemical parameters at Boat Club (2023–24).

Parameter	Post-monsoon	Winter	Summer	Monsoon
Air temperature (^{0}C)	27.7±3.2	21.25±6.7	37.25±8.1	26±7.0
Water temperature (^{0}C)	25.65±3.4	19.5±3.5	29.6±3.5	23.35±3.0
pH	7.6±0.2	7.55±0.4	8±0.1	7.9±0.1
Conductivity (µS/cm)	223±7.0	194±5.6	291±24.0	236±25.4
DO (mg/l)	5.95±2.3	5.5±1.8	7.3±0.8	6.95±1.7
BOD (mg/l)	4.15±0.9	4.7±0.5	5.3±0.4	5.2±0.5
NO3(mg/l)	1.15±0.2	0.7±0.1	1.95±0.2	1.5±0.2
PO4(mg/l)	0.945±0.04	0.825±1.4	0.96±0.07	1.02±0.08
Cl-(mg/l)	22.1±2.4	19.4±2.8	26±2.8	21±1.4
Total hardness (mg/l)	91.1±6.9	89.5±3.5	98±5.6	95.5±6.3
Total alkalinity (mg/l)	76.5±6.3	76±2.8	78.5±7.7	79±8.4
TDS (mg/l)	146.5±9.1	143.5±21.9	148.5±36.7	147.5±2.1
Transparency (cm)	78±2.8	77.5±2.1	80±2.8	73±4.2

Table 2. Seasonal mean (±SD) physico-chemical parameters at Khanugaon (2023–24).

Parameter	Post-monsoon	Winter	Summer	Monsoon
Air temperature (^{0}C)	28.4±3.6	21.75±6.5	37.1±9.8	26.25±6.0
Water temperature (^{0}C)	25.9±3.2	20.25±3.8	29.95±3.6	23.85±3.1
pH	7.55±0.3	7.45±0.4	8±0.2	7.8±0.1
Conductivity (µS/cm)	227.5±9.1	205.5±10.6	304.4±38.1	245.5±31.8
DO (mg/l)	5.6±2.1	5.05±1.6	7.05±0.6	6.8±0.8
BOD (mg/l)	4.25±0.3	4.85±0.4	5.55±0.3	5.85±0.6
NO3(mg/l)	1.25±0.2	0.75±0.2	2.1±0.2	2.25±0.4
PO4(mg/l)	0.96±0.04	0.855±0.1	1.01±0.1	1.13±0.07
Cl-(mg/l)	18.85±1.0	17.65±2.1	28.5±4.9	26.5±3.5
Total hardness (mg/l)	93.55±7.7	92±2.8	104±11.3	103.5±6.3
Total alkalinity (mg/l)	79±7.0	80±4.2	84.5±4.9	85±4.2
TDS (mg/l)	158±41.0	168.5±41.7	192±18.3	171±36.7
Transparency (cm)	77±1.4	76.5±2.1	78.5±2.1	71±1.4

Seasonal variations in the physico-chemical characteristics of Upper Lake revealed distinct spatial and temporal patterns across the two study sites (Tables 1 & 2). Both air and water temperatures showed clear seasonal fluctuations, peaking during summer (37°C and ~29–30°C) and declining in winter (~21°C and ~19–20°C), consistent with regional climatic trends. The lake water remained slightly alkaline (pH 7.5–8.0) throughout, providing favorable conditions for phytoplankton growth. Dissolved oxygen (DO) levels were highest in summer (7.3 mg/L at Boat Club and 6.8 mg/L at Khanugoan) due to enhanced photosynthetic activity. The lower DO at Khanugoan indicates greater organic and nutrient loading. Biochemical oxygen demand (BOD) showed the reverse pattern, with consistently higher values at Khanugoan (5.8 mg/L in monsoon) than at Boat Club (5.3 mg/L), reflecting greater organic decomposition and microbial activity from agricultural runoff. Nitrate and phosphate concentrations were markedly higher at Khanugoan, particularly during the monsoon and summer seasons (up to 2.3 mg/L NO_3^- and 1.15 mg/L PO_4^{3-}), confirming nutrient enrichment from nearby agricultural fields and domestic inputs. In contrast, Boat Club maintained moderate nutrient levels, suggesting less external loading. Conductivity, hardness, and TDS also rose sharply in summer, especially at Khanugoan, due to evaporation and solute accumulation. Transparency reached maximum values in summer (80 cm at Boat Club; 77 cm at Khanugoan) but decreased substantially during the monsoon (73 cm and 70 cm, respectively) because of sediment inflow and turbidity.

Table 3. Seasonal variation in GPP, NPP and Community Respiration at both sites during 2023-24.

Season	Site	Mean GPP (g C/m^3/day)	Mean NPP (g C/m^3/day)	Mean Respiration (g C/m^3/day)
Post-monsoon	Boat Club	2.15	1.20	0.95
	Khanugoan	2.41	1.28	1.07
Winter	Boat Club	1.68	0.85	0.83
	Khanugoan	1.82	0.91	0.91
Summer	Boat Club	3.10	1.90	1.20
	Khanugoan	3.36	1.96	1.32
Monsoon	Boat Club	2.65	1.34	1.31
	Khanugoan	2.52	1.10	1.42

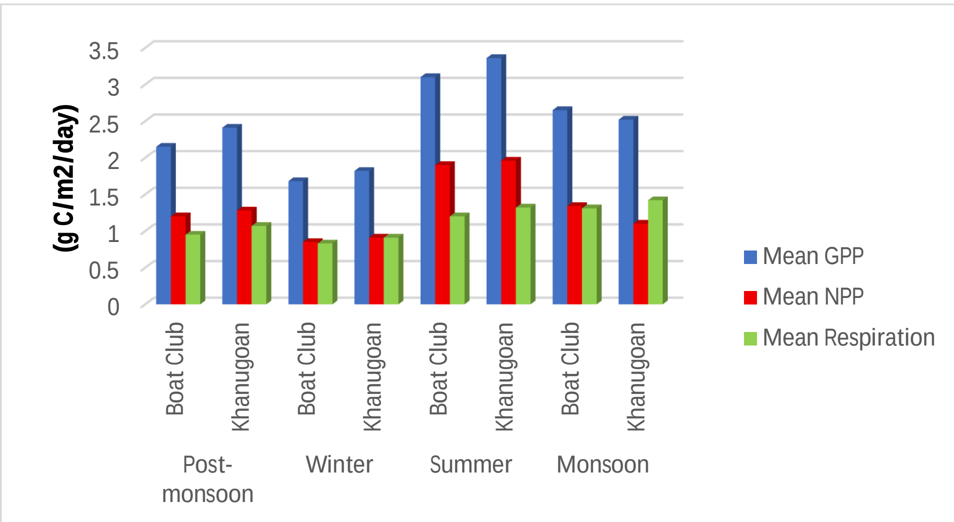

Figure 2. Seasonal variation in GPP, NPP and community respiration in Upper Lake.

The primary productivity of the Upper Lake ecosystem is a critical indicator of its ecological health and energy flow. The recorded GPP and NPP values showed distinct seasonal trends with highest productivity during summer and pre-monsoon months (Table 3). Peak GPP was observed in summer (3.36 gC/m^3/day at Khanugoan) while monsoon months showed comparatively lower values due to reduced light penetration and increased turbidity. Boat club showed a similar seasonal trend though with slightly higher winter productivity than Khanugoan (Figure 2) possibly reflecting site-specific differences in water quality or nutrient availability. Respiration rates (R) closely paralleled GPP across seasons with higher values in summer and monsoon, underscoring the heightened metabolic activity of both autotrophic and heterotrophic communities during periods of increased organic input and temperature (Mishra et al. 2001). The ratio of NPP to GPP was generally lower during periods of high productivity suggesting a greater proportion of fixed carbon were respired a phenomenon commonly observed in productive aquatic systems (Tamot et al. 2006).

Table 4. Correlation Matrix of GPP and Physico-chemical Parameters at Boat Club (2023–24)

Parameters	GPP	DO	BOD	Temp.	pH	NO_3^-	PO_4^{3-}	Transparency
GPP	1.00	+0.74	–0.62	+0.68	+0.43	–0.45	–0.53	+0.59
DO	+0.74	1.00	–0.78	+0.52	+0.41	–0.48	–0.49	+0.67
BOD	–0.62	–0.78	1.00	–0.58	–0.32	+0.56	+0.65	–0.49
Temperature (°C)	+0.68	+0.52	–0.58	1.00	+0.33	+0.29	+0.31	+0.44
pH	+0.43	+0.41	–0.32	+0.33	1.00	–0.38	–0.40	+0.28
Nitrate (NO_3^-)	–0.45	–0.48	+0.56	+0.29	–0.38	1.00	+0.75	–0.41
Phosphate (PO_4^{3-})	–0.53	–0.49	+0.65	+0.31	–0.40	+0.75	1.00	–0.46
Transparency (cm)	+0.59	+0.67	–0.49	+0.44	+0.28	–0.41	–0.46	1.00

Table 5. Correlation Matrix of GPP and Physico-chemical Parameters at Khanugoan (2023–24)

Parameters	GPP	DO	BOD	Temp.	pH	NO_3^-	PO_4^{3-}	Transparency
GPP	1.00	+0.70	–0.58	+0.63	+0.47	–0.49	–0.57	+0.62
DO	+0.70	1.00	–0.74	+0.48	+0.40	–0.52	–0.55	+0.69
BOD	–0.58	–0.74	1.00	–0.50	–0.31	+0.59	+0.68	–0.54
Temperature (°C)	+0.63	+0.48	–0.50	1.00	+0.30	+0.26	+0.35	+0.45
pH	+0.47	+0.40	–0.31	+0.30	1.00	–0.36	–0.39	+0.31
Nitrate (NO_3^-)	–0.49	–0.52	+0.59	+0.26	–0.36	1.00	+0.78	–0.43
Phosphate (PO_4^{3-})	–0.57	–0.55	+0.68	+0.35	–0.39	+0.78	1.00	–0.49
Transparency (cm)	+0.62	+0.69	–0.54	+0.45	+0.31	–0.43	–0.49	1.00

The correlation analysis for both sites of Upper Lake (Boat Club and Khanugoan) reveals strong inter-relationships between phytoplankton productivity and key physico-chemical parameters (Table 4,5). All correlations are significant at $p < 0.05$. At both stations, GPP exhibited a strong positive correlation with dissolved oxygen ($r = +0.74$ at Boat Club; +0.70 at Khanugoan), reflecting direct oxygen evolution from photosynthetic activity. This indicates that phytoplankton productivity is the major contributor to oxygen enrichment in surface waters. GPP showed a negative correlation with BOD ($r = –0.62$ and –0.58), implying that higher organic pollution tends to depress photosynthetic efficiency, possibly due to reduced light penetration and oxygen demand from microbial respiration (Singh & Rai, 2013). Temperature demonstrated a moderate positive relationship with GPP ($r \approx +0.65$), confirming that productivity peaks during warmer months, consistent with findings of Mishra & Tripathi (2001) and Verma et al. (2017). The slight positive association between pH and GPP suggests that alkalinity within the range of 7.5–8.0 favors phytoplankton growth. Nutrient correlations revealed that phosphate ($r = –0.53$ at Boat Club; –0.57 at Khanugoan) and nitrate ($r = –0.45$; –0.49) were inversely related to GPP, consistent with Tamot & Sharma (2006) and Upadhyay et al. (2012), who reported that excessive nutrient loading in Upper Lake induces eutrophic conditions and reduces light penetration, thereby suppressing photosynthesis. The strong positive phosphate–nitrate correlation ($r = +0.75–0.78$) reflects shared anthropogenic sources such as sewage and urban runoff. Transparency was positively correlated with GPP ($r = +0.59$ and +0.62), supporting the role of light availability in enhancing phytoplankton photosynthesis (Wetzel, 2001). Similarly, DO also correlated positively with transparency and temperature, confirming that well-lit and aerated conditions favour higher primary productivity.

V. DISCUSSION

The seasonal evaluation of phytoplankton primary productivity and water quality parameters in Upper Lake, Bhopal, revealed that temperature, dissolved oxygen and nutrient levels were the dominant factors regulating Gross Primary Productivity (GPP) and Net Primary Productivity (NPP). The observed variations across seasons and between the two sites Boat Club and Khanugoan reflect the interplay between climatic conditions, nutrient enrichment and anthropogenic activities affecting the lake ecosystem. The highest productivity was recorded during the summer season, coinciding with elevated temperature and light intensity, while the lowest values occurred in winter. These results are consistent with previous observations in tropical lakes (Mishra & Tripathi, 2001) who observed that higher solar radiation and thermal stability enhance phytoplankton photosynthesis. Elevated water temperatures during summer increased metabolic rates and oxygen evolution, resulting in a strong positive correlation between GPP and dissolved oxygen ($r \approx +0.7$). The concurrent rise in DO during peak productivity months confirms the dominance of photosynthetic oxygenation in the lake's surface layers, consistent with Amarasinghe and Vijverberg (2002). Biochemical Oxygen Demand (BOD) showed a negative correlation with GPP ($r \approx –0.6$), indicating that increased organic load and microbial respiration reduce available oxygen, thus suppressing photosynthesis. Similar negative relationships between productivity and BOD have been reported for other Indian lakes, such as Shahpura and Ambazari (Kumar & Raut, 2008; Tamot & Sharma, 2006). Transparency displayed a positive association with productivity ($r \approx +0.6$), emphasizing the importance of light penetration for algal growth and oxygen production (Wetzel, 2001). Decreased transparency during the monsoon, due to sediment runoff and suspended solids, corresponded with reduced GPP and NPP, a trend also documented by Upadhyay et al. (2012) for Upper Lake. Phosphate and nitrate concentrations, showed inverse correlations with GPP ($r \approx –0.5$), suggesting that excessive nutrient loading from domestic sewage and agricultural runoff leads to turbidity and self-shading, ultimately limiting photosynthetic efficiency. These results are in agreement with Singh and Rai (2013) and Bano and Chauhan (2017), who reported that nutrient oversupply promotes eutrophic conditions and algal bloom dominance in Indian freshwater ecosystems.

The strong positive interrelation between phosphate and nitrate indicates common sources of nutrient influx, primarily anthropogenic discharges. Spatial differences between the two sites further highlight human impact on lake metabolism. Khanugoan, located near agricultural zones, exhibited higher nutrient and BOD concentrations but slightly lower DO and productivity, reflecting organic enrichment and eutrophic tendencies. Boat Club influenced by recreational activity but better water circulation, recorded higher DO and transparency, supporting marginally lesser GPP. These findings corroborate earlier observations by Arvind et al. (2013) and Magarde et al. (2011), who emphasized localized pollution effects in Upper Lake.

VI. CONCLUSION

The present study on seasonal variations in phytoplankton productivity and water quality of Upper Lake, Bhopal highlights the close interdependence between physicochemical conditions and primary productivity. Seasonal fluctuations in temperature, dissolved oxygen, and nutrient concentrations significantly influenced phytoplankton dynamics, with maximum productivity during summer and minimum in winter. Contrasts were observed between the two study sites. Boat Club exhibited comparatively higher dissolved oxygen, greater water transparency and moderate nutrient levels, reflecting better circulation and lower pollution influence. Khanugoan showed higher biochemical oxygen demand, elevated nitrate and phosphate concentrations, and reduced oxygen and transparency attributes indicating greater organic enrichment and nutrient loading from agricultural runoff. Upper Lake can be characterized as a moderately productive but nutrient-stressed ecosystem where sustained anthropogenic pressures may lead to eutrophication. Effective management strategies should focus on controlling nutrient inflow, improving sewage treatment, and conserving the lake’s catchment vegetation to maintain balanced phytoplankton productivity and safeguard the ecological health of this vital freshwater resource.

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