
Assessment of treatment capabilities of Varthur Lake, Bangalore, India

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Abstract: Manmade waterbodies have traditionally been used for domestic and irrigation purposes. Unplanned urbanisation and ad-hoc approaches have led to these waterbodies receiving untreated sewage. This enriches and eutrophies the waterbody. A physico-chemical and biological analysis of sewage-fed Varthur Lake in Bangalore was carried out and its treatment capabilities in terms of BOD removal, nutrient assimilation and self-remediation were assessed. Anaerobic conditions (0 mg/L) prevail at the inlet which improves towards the outlets due to algal aeration. This removed >50% BOD in the monsoon season but was inhibited by floating macrophytes in all other seasons. Alkalinity, TDS, conductivity and hardness values were higher when compared to earlier studies. This study shows the lake behaves as an anaerobic~aerobic lagoon with a residence time of 4.8 d treating the wastewater to a considerable extent. Further research is required to optimise the system performance.

Keywords: nutrients; eutrophication; lagoon; sewage; urban lakes.

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Three different types of biomass-based biogas plants are being disseminated – the plug-flow like biogas plants, solid-state stratified bed (SSB) biogas fermenter and biomass immobilised bioreactors for coffee and agro-processing waste waters.

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1 Introduction

Rapid urbanisation coupled with industrialisation in urban areas has greatly stressed the available water resources qualitatively and quantitatively in India. This has also resulted in the generation of enormous sewage and wastewater after independence. Unplanned urbanisation and ad hoc approaches in planning are evident everywhere, be they settlements or sanitary systems and networks. Urban areas in India lack the infrastructure for sanitation, leading to inappropriate management of the wastewater generated. Most of the sewage and wastewater generated is discharged directly into storm water drains that ultimately link to waterbodies. Since Bangalore is located on a ridge with natural water courses along the three directions of the Vrishabhavaty, Koramangala–Challaghatta (KC) and Hebbal–Nagavara valley systems, these water courses are today being used for the transport and disposal of the city's sewage. The shortfall or lack of sewage treatment facilities has contaminated the majority of surface and ground waters. These aquatic resources are now unfit for current as well as future use and consequently pose critical health problems. Central Pollution Control Board (CPCB, 2006; CPCB, 2009) estimate indicates that about 26,254 million litres per day (MLD) of wastewater are generated in 921 Class I cities (Population > 1,00,000) and Class II (Population 50,000–1,00,000) towns in India (housing more than 70% of the urban population). However, only 27% (7044 MLD) of wastewater is treated.

Bangalore is the principal administrative, cultural, commercial, industrial and knowledge capital of the state of Karnataka. Greater Bangalore, an area of 741 km² including the city, neighbouring municipal councils and outgrowths, was 'notified' (established) in December 2006 (Figure 1). Bangalore is one of the fastest growing cities in India, and is also known as the 'Silicon Valley of India' for heralding and spearheading the growth of Information Technology (IT) based industries in the country. With the advent and growth of the IT industry, as well as numerous industries in other sectors and the onset of economic liberalisation since the early 1990s, Bangalore has taken the lead in service-

based industries, which have fuelled the growth of the city both economically and spatially. Bangalore has become a cosmopolitan city attracting people and business alike, within and across nations (Sudhira et al., 2007; Ramachandra and Kumar, 2008).

The undulating terrain in the region facilitated the creation of a large number of tanks in the past, providing for the traditional uses of irrigation, drinking, fishing and washing. This led to Bangalore having hundreds of such waterbodies through the centuries. In 1961, the number of lakes and tanks in the city stood at 262. A large number of waterbodies (locally called lakes or tanks) in the city had ameliorated the local climate, and maintained a good water balance in the neighbourhood. A current temporal analysis of wetlands, however, indicates a decline of 58% in Greater Bangalore which can be attributed to intense urbanisation processes. This is evident from a 466% increase in built-up area from 1973 to 2007 (Ramachandra and Kumar, 2008). The undulating topography, featured by a series of valleys radiating from a ridge, forms three major watersheds, namely the Hebbal Valley, Vrishabhavathi Valley and the Koramangala and Challaghatta Valleys. These form important drainage courses for the interconnected lake system which carries storm water beyond the city limits. Bangalore, being a part of peninsular India, had the tradition of storing this water in these man-made waterbodies which were used in dry periods. Today, untreated sewage is also let into these storm water streams which progressively converge into these waterbodies. Varthur Lake is one such lake at the end of a chain of lakes.

Varthur Lake, situated in the south of Bangalore, was built to store water for drinking and irrigation purposes (Government of Karnataka, 1990). Today, large-scale developmental activities in recent times due to unplanned urbanisation in the lake catchment has resulted in reduced catchment yield and higher evaporation losses. Inefficient primary feeder channels feeding the lake have also contributed to water shortage. However, this shortage has been supplemented by an increased quantum of sewage inflow. Due to the sustained influx of fresh sewage over a decade, nutrients in the lake are now well over safe limits. Varthur Lake has been receiving about 40% of the city sewage for over 50 years resulting in eutrophication. There are substantial algal blooms, Dissolved Oxygen (DO) depletion and malodour generation, and an extensive growth of water hyacinth that covers about 70–80% of the lake in the dry season. Sewage brings in large quantities of C, N and P which are trapped within the system. A similar situation prevails in many other cities such as Bhopal (Shahpur Lake), Jabalpur (Sardar Lake), the Sihora, Gosalpur, Kundam and Seoni towns of Madhya Pradesh (Ghosh et al., 2008), Udaipur, Rajasthan (Chaudhury and Meena, 2007), Hussain Sagar (Hyderabad), Nainital Lake (Region Special Area Development Authority, 2002) and Kandy Lake in Sri Lanka (Silva, 2003). Such instances have been recurring despite the fact that a certain part of the sewage undergoes at least primary treatment in most cities of India. Thus, any solution to this problem can go a long way in restoring thousands of such waterbodies in India.

The extent of N (nitrogen) flowing through the Belandur–Varthur lake system is large (16.4 t/d; Chanakya and Sharatchandra, 2008) and is about 20–40 mg/l. The various forms of nitrogen influent in sewage are organic N (protein N), urea, ammonia, nitrites and nitrates through processes like nitrification, denitrification and ammonification. Autotrophic nitrification consists of two consecutive aerobic reactions, the conversion of ammonia to nitrite by *nitrosomonas* and then from nitrite to nitrate by *nitrobacter* (Hooper et al., 1997; Koops and Pommerening-Röser, 2001). Nitrite-Oxidising Bacteria

(NOB) use CO_2 and bicarbonate for cell synthesis and ammonium or nitrite as the energy source (Hooper et al., 1997). Ammonia-Oxidising Bacteria (AOB) belongs to β -Proteobacteria which includes two genera, *nitrospira* and *nitrosomonas* (Stephen et al., 1996; Purkhold et al., 2000; Purkhold et al., 2003). Complete nitrification stoichiometry requires 4.6 kg oxygen per kg NH_4^+ (ammonia N). Dissolved oxygen concentrations of 1 mg l^{-1} are sufficient for the oxidation of ammonium (Hammer and Hammer, 2001). However, at DO concentrations lower than approximately 2.5 mg l^{-1} , nitrite oxidation is inhibited, leading to its accumulation (Paredes et al., 2007). In such conditions, the oxygen transfer rate may be as important as the actual O_2 concentration. Plants provide an oxygenated zone around the roots which enhances nitrification (Zhu and Sikora, 1994; Johnson et al., 1999; Munch et al., 2005). In less-aerated systems, however, the transfer rate varies according to the plant species and other environmental and operational factors (Faulwetter et al., 2009).

Higher concentrations of nitrates and phosphates primarily contribute to the eutrophication of urban waterbodies. Higher values of $\text{NO}_3 \text{ N}$ were observed during the post-monsoon season (Srivastava et al., 2007; Bharali et al., 2008; Dhanalakshmi et al., 2008; Edokpayi and Aneke, 2008). There is, however, scant mention about the various forms of nitrogen being observed and analysed in all these studies. In most of these studies, the N forms have not been partitioned into protein, urea, ammonia, nitrate, nitrite and nitrate denitrified into di-nitrogen. The conversion rates from one form to another as well as their uptake/release by various biological agents and their quantification are often not carried out. Higher P values were recorded in July (Heron, 1961) and pre-monsoon (Bharali et al., 2008; Kapil and Bhattacharya, 2009). Moderate to high values of Biochemical Oxygen Demand (BOD) were reported in the pre-monsoon (Solanki et al., 2007; Dhanalakshmi et al., 2008; Raveen et al., 2008).

In all the cases above, it is not clear what extent of the input water (influent into the lake) is sewage and therefore the contribution of sewage to the C, N and P loads have seldom been estimated. Earlier estimates indicate that Varthur Lake receives about 500 MLD of sewage (Chanakya et al., 2006). This also serves as a water source for crop irrigation to downstream farmers. There were indications that the sewage passing through such a lake system was being partially treated. In this study, we examined the nature and extent of changes in water quality (treatment levels) during various seasons. It is of interest to determine whether such a lake could be converted to a sustainable and passive sewage treatment system adaptable to other locations, considering that water and energy are fast becoming scarce in the developing world.

2 Materials and methods

2.1 Study area and its characteristics

Varthur Lake ($12^\circ 57' 24.98''$ to $12^\circ 56' 31.24''$ N, $77^\circ 43' 03.02''$ to $77^\circ 44' 51.1''$ E) is the second largest fresh waterbody in Bangalore built by the Ganga kings over a thousand years ago (Figure 1) for domestic and agricultural uses. It covers a water-spread area of 220 ha (mean depth 1.1 m, Figure 2). It is part of a series of connected and cascading waterbodies. The Varthur Lake catchment has seen large-scale land use changes after 2000, consequent to the rapid urbanisation process in the region. Now the lake receives

inadequately treated sewage of about 500 MLD. The average annual rainfall of Bangalore is 859 mm and temperatures vary from 14°C (December to January) to 33°C (maximum during March to May). There are two rainy periods, i.e. from June to September (south-west monsoon) and November to December (north-east monsoon). During the rainy periods, fresh water also enters the lake as runoff. Water samples were collected regularly on a monthly basis from five predetermined sampling points to represent inlets, outlets and midpoints (Figure 1).

These locations were confirmed by using a hand-held GPS (Garmin 48), which was mapped on to the earlier spatial map (of 2002). From a hand-held GPS survey carried out as part of the study, it was confirmed that the shape and water-spread area have not changed drastically (Figure 2). The lake had a varying extent of floating macrophytes during different seasons. The presence of water hyacinth impeded the use of boats for sampling water quality all over the lake in all seasons. Only a sample closer to shore could be reliably sampled at specific times of day during the year-long study as the wind-induced drift of floating macrophytes on the lake made time-specific sampling of all the points unfeasible. Figure 3 illustrates the spatial extent of macrophytes in March as compared to December. A False Colour Composite (FCC) was generated using geo-referenced LANDSAT data (of 30 m spatial resolution) for December, and IRS LISS III data (of 23 m) for March. The lake had less of a macrophyte cover during November–December due to the north-east monsoon runoff with human interventions (pushing macrophytes downstream). Macrophytes cover about 70–80% of the water-spread area during summer, as is evident from the March FCC.

Figure 1 Varthur Lake, Greater Bangalore, India with sampling locations (see online version for colours)

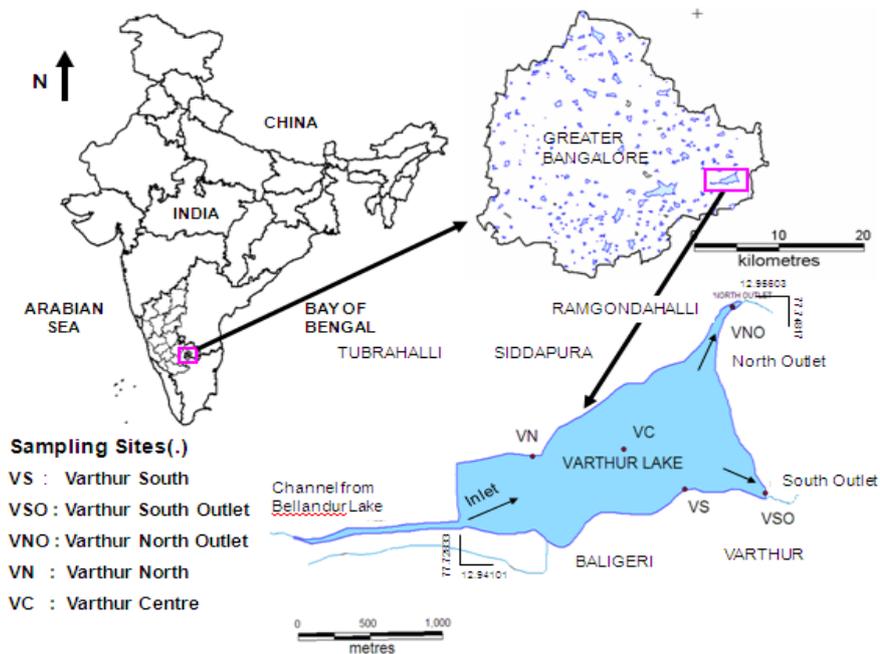
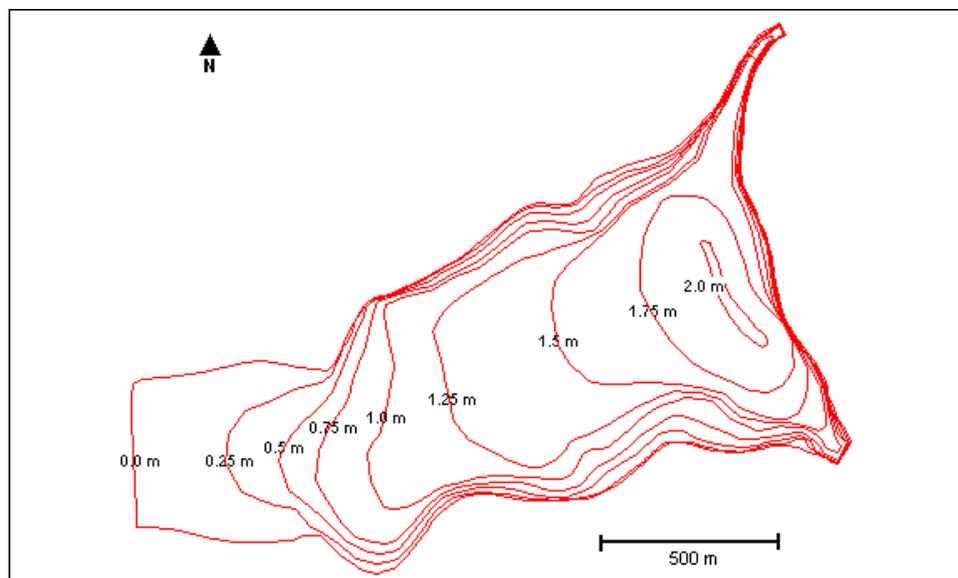
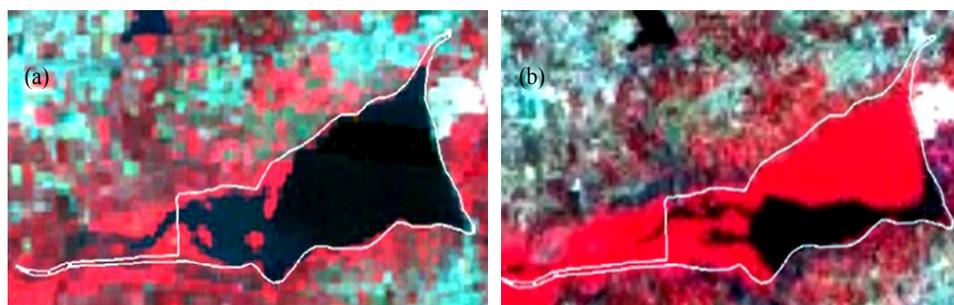


Figure 2 Depth profile of Varthur Lake (see online version for colours)**Figure 3** (a) FCC of LANDSAT (30 m) and (b) IRS LISS III (23 m) (see online version for colours)

2.2 Water sampling and analysis

Water samples were collected in the last week of every month during July 2008–June 2009 from five sampling sites (Figure 1) to examine the influent and the effluent water quality. Care was exercised to ensure that the sampling bottles were free of any contaminants. These bottles were treated with 10% HNO₃ and subsequently washed with distilled water. Grab sampling was followed at all points. On-site measurements include estimation of pH (pH probe), water and ambient temperature (lab thermometer), Total Dissolved Solids (TDS) (TDS probe), conductivity (conductivity probe), dissolved oxygen (iodometry) and transparency (Secchi disc). The samples were then carried to the lab and were analysed for various parameters according to Standard Methods (APHA AWWA WEF, 1998). Water samples were analysed for total alkalinity (titrimetry), total hardness, Ca, Mg (complexometric titration), Na, K (flame photometer), chlorides (argentometric

method), nitrates (phenol disulphonic acid method), phosphates (stannous chloride method), chemical oxygen demand (dichromate oxidation with open reflux) and BOD (5-d BOD).

3 Results and discussion

The volume of water held is computed to be 2.42×10^9 l at an average water depth of 1.1 m with a water-spread area of 220 ha. The sewage received by this lake is about 5.00×10^8 l/d (500 MLD). Based on these data, the retention time would be 4.84 d. However, as the flow is not uniform and the presence of macrophytes impedes uniform flow, the actual residence time would be lower than the estimated 4.84 d. From an open pan evaporation value of 10 mm in summer and 5 mm in the rainy season, the daily evaporation loss for open surface water is estimated to be 2.2×10^7 l/d in summer and half of that for the rainy months. This, in turn, works out to 4.4% of influent for the summer. It is, therefore, envisaged that any changes in the composition of the wastewater between the inlet and the outlet are not likely to be affected by evaporation losses to any significant extent.

The inlet area is quite narrow and shallow (0.5–0.75 m deep, Figure 2) and has a surface flow rate ranging between 0.16 (Siddapur, VN) and 0.38 m/sec (inlet). This zone is generally covered with floating as well as rooted macrophytes round the year (Figure 3 – a and b). As a result, water flow occurs in a narrow and open channel. Algal species found in water are listed in Table 1 (genus level), while Table 2 lists macrophytes. Algae are dominated by *Microcystis* sp. which is indicative of a stressed lake followed by *Chlorella* sp. and *Nitzschia* sp. It has been observed that the primary coloniser of this zone is the water hyacinth. When the plant density becomes high, these detach themselves from the main body of floating water hyacinth and form small floating islands which later become infected by disease and pests. Significant water hyacinth mortality leads to succession by other species such as *Alternanthera* sp., local grasses, etc. growing on the floating debris of the decaying water hyacinth. Some water hyacinth, however, still grows between these otherwise luxuriant growths of floating terrestrial weeds, especially during the summer months. A large part of this *Alternanthera* sp. and grass biomass is also harvested manually and used as green fodder. However, the biomass growth rates far outstrip the harvest rates. As a result, during the months of April and May, nearly 70–80% of the water-spread area is covered by these macrophytes. This completely changes the way the lake functions in purifying the wastewater of the lake, which is discussed in detail later.

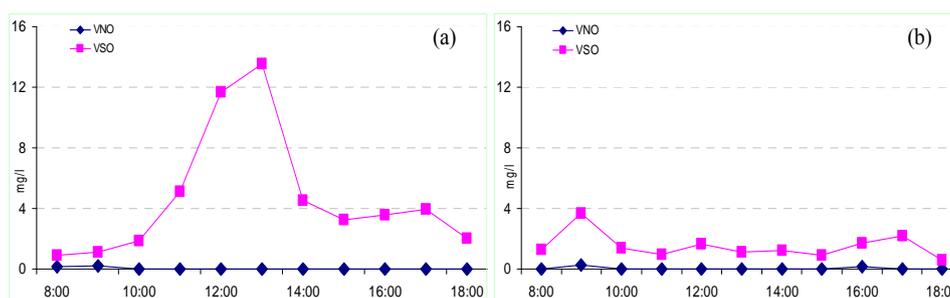
The diurnal (January and April 2009) changes of DO levels in water given in Figure 4 seems to be influenced by the macrophytes covering the lake. Figure 4(a) shows DO measured at the south outlet when it is free of macrophytes cover, while Figure 4(b) shows lower DO values when the lake is infested with macrophytes. Higher levels of nutrients during the summer (due to lack of dilution in the absence of rain and higher evaporation) have resulted in the profuse growth and dense spread of macrophytes hindering the light penetration and hence algal photosynthesis. Reduction of algal population coupled with poor photosynthesis has lowered DO in April month. Also, persistent stagnation of water due to blockage of north outlet has resulted in the consistent lower DO values at north outlet throughout the year.

Table 1 Algae communities (identified up to genus level) in Varthur Lake

<i>Algal family</i>			
<i>Chlorophyceae</i>	<i>Cyanophyceae</i>	<i>Bacillariophyceae</i>	<i>Euglenophyceae</i>
<i>Chlamydomonas sp.</i>	<i>Cylindrospermopsis sp.</i>	<i>Gomphonema sp.</i>	<i>Phacus sp.</i>
<i>Chlorogonium sp.</i>	<i>Arthrospira sp.</i>	<i>Cymbella sp.</i>	<i>Euglena sp.</i>
<i>Scenedesmus sp.</i>	<i>Microcystis sp.</i>	<i>Navicula sp.</i>	<i>Trachelomonas sp.</i>
<i>Ankistrodermus sp.</i>	<i>Oscillatoria sp.</i>	<i>Pinnularia sp.</i>	<i>Lepocinclis sp.</i>
<i>Chlorella sp.</i>	<i>Anabaena sp.</i>	<i>Nitzschia sp.</i>	
	<i>Merismopedia sp.</i>	<i>Synedra sp.</i>	
	<i>Lyngbya sp.</i>	<i>Fragillaria sp.</i>	
		<i>Cocconeis sp.</i>	
		<i>Melosira sp.</i>	

Table 2 Macrophytes in Varthur Lake (includes riparian vegetation)

<i>Plant species</i>	<i>Common Name</i>
<i>Typha augustifolia</i>	Cat tail
<i>Colocasia esculanta</i>	Taro
<i>Cyperus haspans</i>	Dwarf papyrus sedge
<i>Alternanthera phylaxioides</i>	Alligator weed
<i>Eichhornia crassipes</i>	Water hyacinth
<i>Lemna gibba</i>	Duckweed
<i>Lemna minor</i>	Lesser duckweed
<i>Pistia stratiotes</i>	Water lettuce

Figure 4 Diurnal changes of DO levels during January and April 2009 at (a) south outlets and (b) north outlets (VNO represents Varthur North Outlet and VSO represents Varthur South Outlet) (see online version for colours)

The inlet region is predominantly anaerobic throughout the year as the channel connecting Varthur Lake from the Belandur lake receives raw sewage from the immediate vicinity (~100 MLD) apart from partially treated sewage (~400 MLD) from Belandur Lake. The samples at these locations are characterised by organic sludge under anaerobic

conditions which is evident from dark grey colour, higher turbidity, lower DO (zero mg/l) and negative Oxidation Reduction Potential (ORP), i.e. from -220 to -180 mV. These conditions have aided the spread of macrophyte mats, which has reduced the flow of water. However, there are few distinguishable zones of rapid flow of incoming wastewater in the inlet channel. Spatial analysis of macrophytes spread in the lake using remote sensing data (Figure 3 – a and b) highlights that the anaerobic zone occupies a third of the distance from the inlet (water hyacinth cover is about 74 ha) during the rainy and winter months (July to January) and extend two-thirds of the water-spread area (148 ha) during February to June. During rainy season, the runoff and high-velocity wind (17 kmph, westerly wind) play a major role in the spread and dispersal of floating macrophytes across the water-spread area apart from transporting to downstream regions. In the absence of floating macrophytes, the water rapidly turns green to indicate the presence of microalgae and their role in treating water evident from higher DO and lower BOD during these months. However, at northern outlet, compaction of macrophytes happens due to wind and blockage.

Water quality monitoring was carried out covering all seasons to understand the variations in water quality across space due to seasons. The analysis was carried out as discussed in the methods section. Figure 5 depicts monthly variations at inlet and outlets, while Figure 6 portrays water quality across all sampling locations. Parameters such as DO, BOD, PO_4 and hardness exhibit seasonal variations across the lake. Figure 7 further highlights the extent of variations across space and time through whisker plots. Parameter-wise variations are discussed next.

The ambient air temperature was found to be in the range of 15°C (winter) to 35°C (summer) at the time of sampling (Figure 7a). Water temperature influences the rate of various biochemical reactions, and enhances BOD removal rates. The water temperature showed the variation of 18°C (winter) to 32°C (summer) (Figure 7b).

TDS comprise mobile charged ions, including minerals, salts or metals dissolved in water. TDS value (Figure 7c) ranged from 528 (December) to 994 mg/l (April) and are in agreement with earlier studies (Ramachandra et al., 2006). Higher values of TDS are due to the reduced flow rates, an influx of concentrated sewage and an enhanced water retention period. Electrical conductivity is an indirect measurement of the salt concentration. It varies (Figure 7c) from 751 (December) to 1420 $\mu\text{S/cm}$ (April). EC is positively correlated with TDS ($r = 0.93$, $p < 0.05$) as reported earlier (Kataria et al., 1995; Bharali et al., 2008).

Transparency indicates the extent of turbidity and also measures the light penetration through the water. It ranged from 24 (summer) to 28 cm (monsoon). Reduced transparency during summer is due to increase of suspended particles on account of organic debris's decomposition with higher water temperature and reduced flow.

pH is largely governed by carbon dioxide, carbonates and bicarbonate equilibrium (Chapman, 1996). pH ranged from 6.82 (August–October) to 8.2 (July), which coincides with increased cations found in the water ($r = 0.8791$, Mg; $r = 0.8823$, Na; $r = 0.8817$, K; at $p < 0.05$) (Figure 7d). A sudden decrease in pH (during June–September) comparable to other studies (Bindiya et al., 2008; Raveen et al., 2008) may be attributed to the dilution on account of the inflow of the runoff. Slightly alkaline conditions are favourable for the growth of primary producers (Bellum, 1956) and a low pH is a consequence of macrophytes cover (Parinet et al., 2004).

Total alkalinity ranged from 240 (October) to 460 mg/l (May), as shown in Figure 6. Higher values during summer are due to reduced microalgal photosynthetic activities resulting in higher respiration (and higher total CO₂) and anaerobic decomposition by bacteria on account of profuse spread of macrophytes (Figure 3b). Total alkalinity is higher at inlet (Figure 5f) due to high concentration of carbon-based mineral molecules suspended in the solution at the inlet region and prevailing anoxic conditions. This is comparable to earlier similar studies (Sinada and Abdel Karim, 1984; Hujare, 2008) but higher (Ramachandra et al., 2006).

Figure 5 Comparison of inlet and outlet characteristics (VN – Inlet and VSO – Outlet) (see online version for colours)

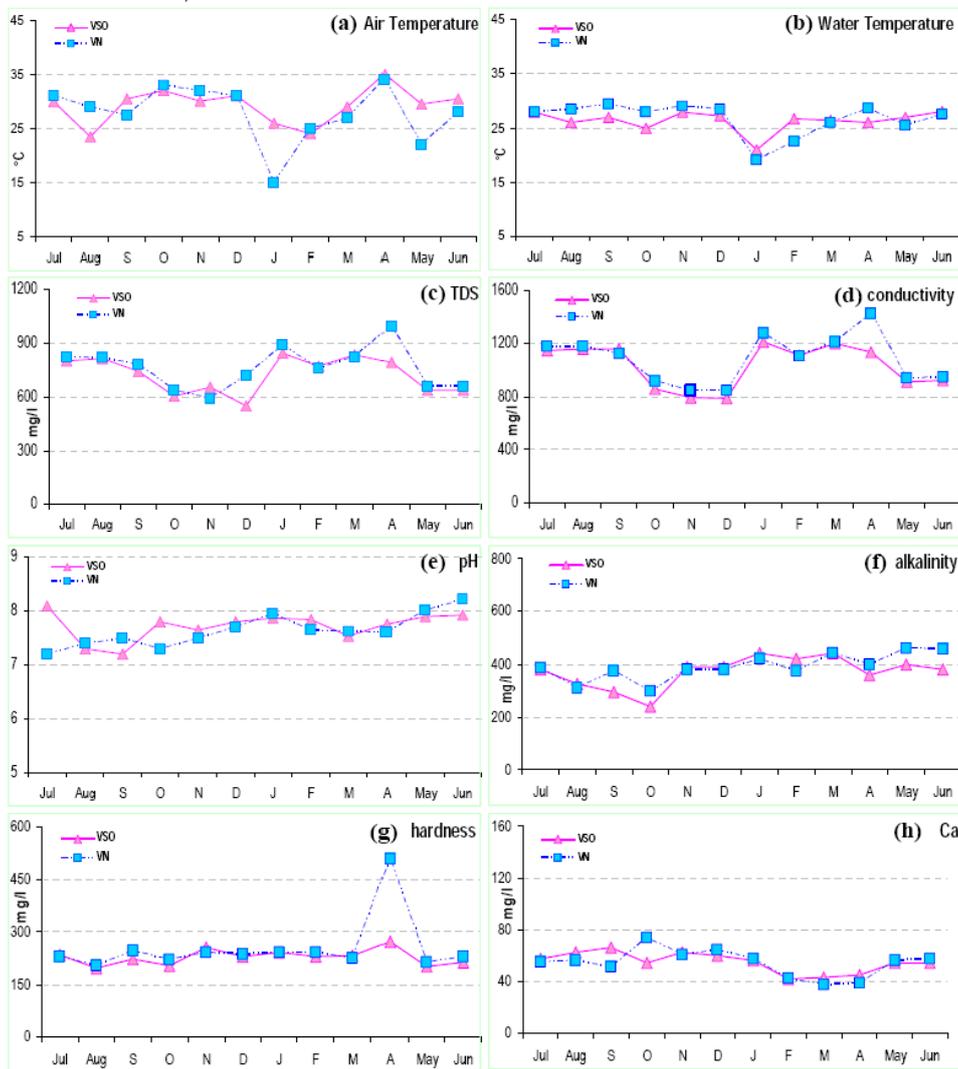
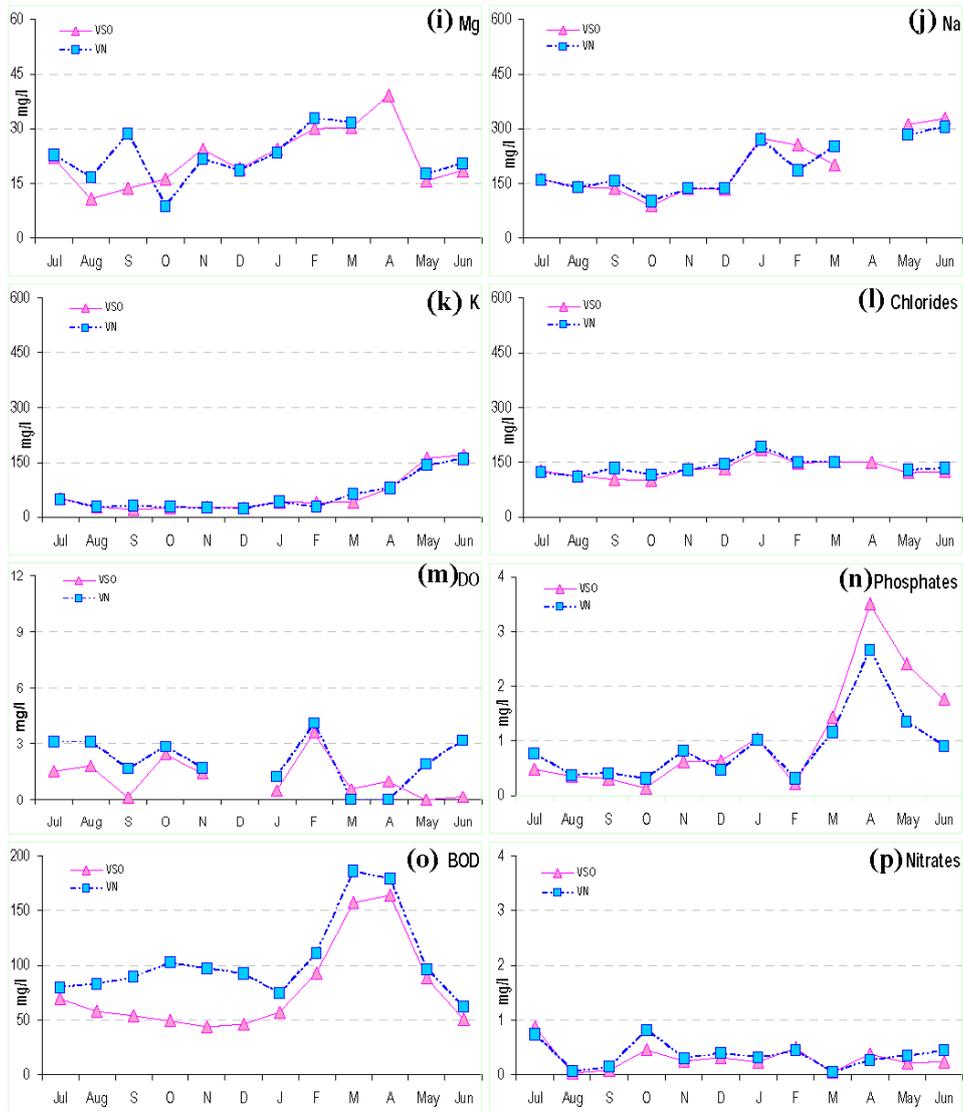
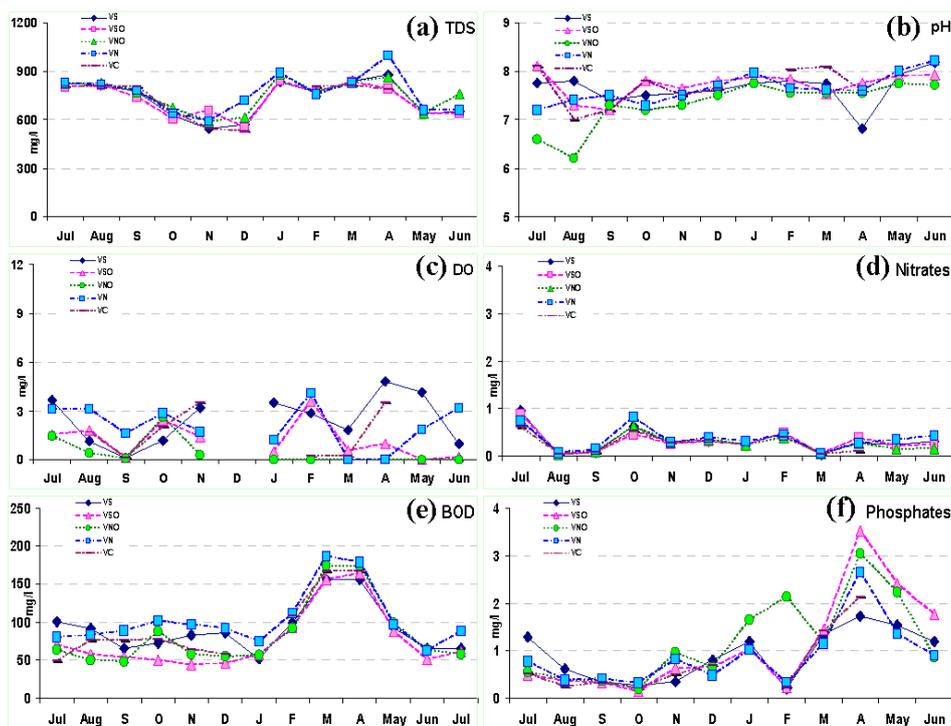


Figure 5 Comparison of inlet and outlet characteristics (VN – Inlet and VSO – Outlet) (see online version for colours) (continued)



The total hardness (Figure 7f) ranged from 192 (October) to 288 mg/l (April). Relatively lower value during monsoon is due to dilution (similar with other parameters), while higher value in summer can be attributed to a decreased flow rate and stagnation due to the blockage of one of the outlets, apart from the profuse macrophyte cover. There is no significant difference ($p = 0.307 > 0.05$) between the inlet and the outlet values (Figure 5g).

Figure 6 Overall variation of water quality at different sites in different seasons (see online version for colours)

Calcium varies (Figure 7g) between 37.6 (March) and 73.75 mg/l (October) without marked differences between inlet and outlets (Figure 5h). Magnesium ranged (Figure 7h) from 8.7 (October) to 40.5 mg/l (February). Higher value of 40.5 mg/l (February; Figure 7g) can be attributed to higher dependency of groundwater during non-monsoon seasons in the catchment. Sodium (Figure 7i) ranged from 90 (October) to 810 mg/l (April). Higher values during summer are due to higher evaporation and consequent concentrations in summer apart from higher dependency on groundwater. This higher value (of Mg, Na, K, etc.) has also contributed to higher TS. However, this is much higher in comparison to earlier studies (Ramachandra et al., 2006). Potassium is one of the essential nutrients for plant growth and it ranged (Figure 7j) from 11 (September) to 210 mg/l (April). There is no considerable difference between inlet and outlet K concentrations ($p = 0.9 > 0.05$) (Figure 5k) due to anoxic conditions (at inlet) and dense macrophyte cover (at outlet).

Chlorides vary from 100 (October) to 195 mg/l (January) (Figure 7k). These values are in conformity with earlier studies in the range of 120 mg/l for sewage-fed aquatic systems (Toshiniwal et al., 2006; Garg, 2007).

Dissolved oxygen decides the prevailing conditions of the water. Higher DO in the middle and south outlet regions (Figure 6c) is indicative of better algal photosynthetic activities and oxidative decomposition of dissolved organic matter. Low DO at inlet and at

north outlet has been discussed earlier (macrophytes bloom hindering algal photosynthesis). Dissolved oxygen ranged from 0 (post-monsoon) to 4.83 mg/l (pre-monsoon) (Figure 7m). Hypoxic conditions prevailed at inlet, due to raw sewage inflow and stagnant conditions at north outlet (due to the blockage). Hypoxic and anoxic conditions can be correlated with a higher demand for oxygen for bacterial decomposition, which results in higher decomposition rates of organic matter and, consequently, creates an anaerobic environment.

Figure 7 Whisker plots showing the extent of variations across space and time (see online version for colours)

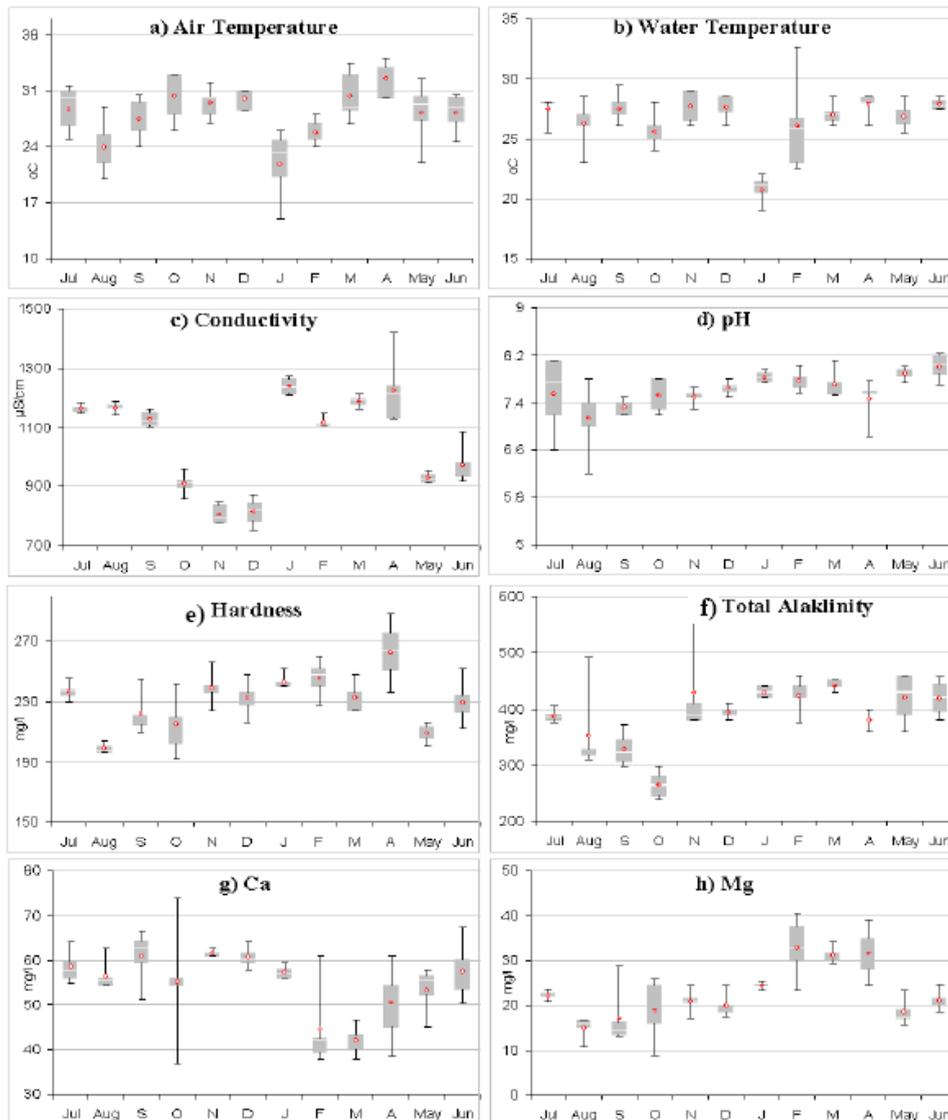
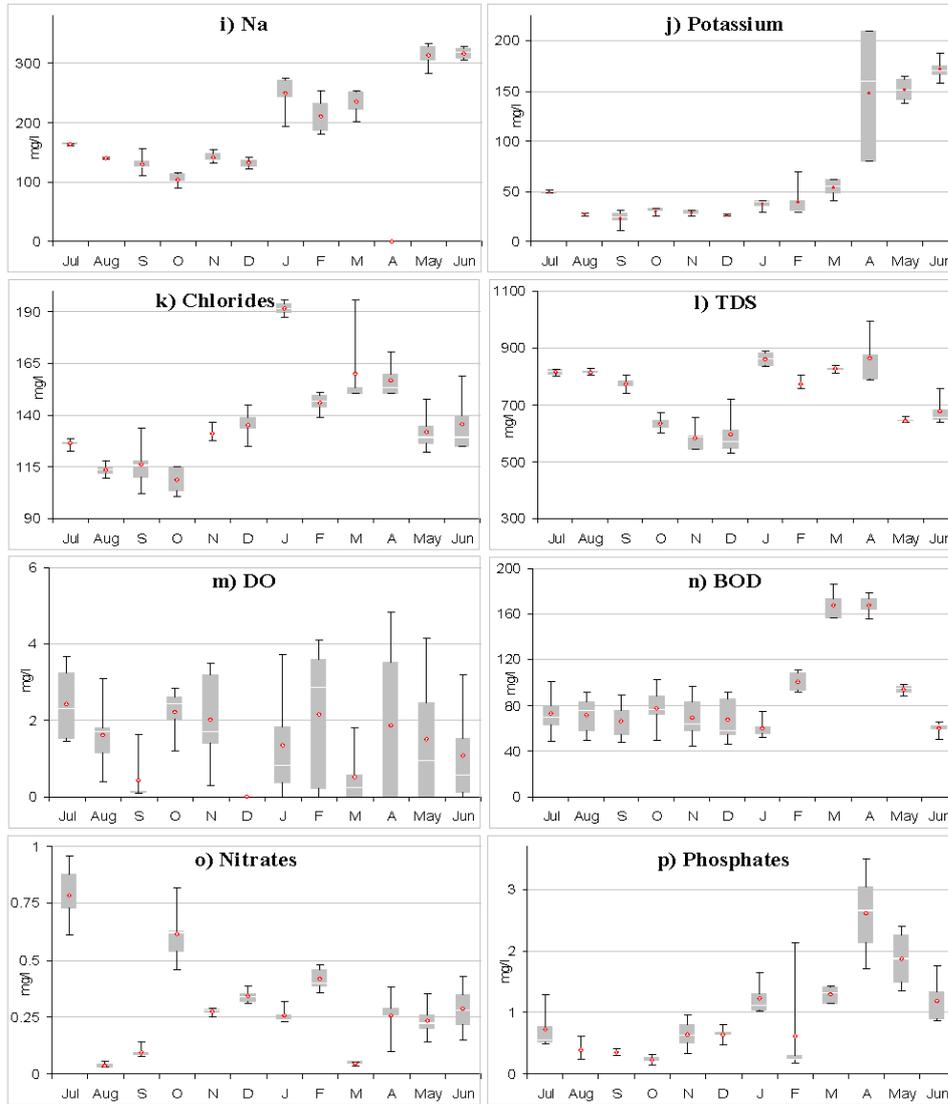


Figure 7 Whisker plots showing the extent of variations across space and time (see online version for colours) (continued)



BOD is indicative of the quantum of biodegradable organic matter in a lake. BOD values ranged from 44 (November) to 186 mg/l (March) (Figure 7m). A considerable reduction in BOD up to 50% (from 100 to 50 mg/l) was observed between the inlet and the outlets (Figure 5o) during August–January. However, the extensive coverage of macrophytes during February–May lowered the organic decomposition, and hence the BOD removal. BOD at the inlet was found to be higher in comparison to the outlet BOD throughout the study period (figure 5o), which shows a gradual reduction of BOD with space and residence time of 5 d. Similar results were reported – 96 mg/l (July–September) in

three fresh waterbodies at Chennai (Raveen et al., 2008), 49.0 mg/l in Coimbatore, Tamil Nadu (Dhanalakshmi et al., 2008), 13.8–96.8 mg/l in two freshwater lakes of Bodan, Andhra Pradesh (Solanki et al., 2007).

Quantum and distribution of the nutrients (such as N and P) are decisive factors for biota in an aquatic ecosystem. Nitrogen, generally found as nitrate, is essential to all algal and aerobic microflora and goes predominantly into the proteins, etc. The extent of N (generally as NO_3^-) is also used as an indicator of the trophic state of the waterbodies. Higher concentrations of nitrate primarily contribute to the eutrophication of waterbodies. Nitrate values (Figure 7p) ranged from 0.03 (March) to 0.96 mg/l (July). There were no considerable differences between the inlet and the outlet nitrate concentrations (Figure 5p). The overall nitrate levels were below 1 mg/l (mostly due to uptake by macrophytes or by algae/bacteria) and did not vary temporally or spatially in any significant manner comparable to Kapil and Bhattacharya (2009), Ramachandra et al. (2006) and Kumara and Belagali (2008). However, higher values of NO_3^- N were reported due to agriculture runoff (Bharali et al., 2008), from 7.9 mg/l (Srivastava et al., 2007; Edokpayi and Aneke, 2008) to 62.85 mg/l, due to enrichment through domestic sewage (Dhanalakshmi et al., 2008). Lower concentration of nitrates during monsoon is due to dilution apart from algal and bacterial uptake (Sharma et al., 1981).

Ammoniacal N (4–21 mg/l during April) substantiates hypoxic and anoxic conditions prevailing in the lake which is very toxic to biotic components. This is in agreement with the study of Belandur Lake, Bangalore (Chanakya et al., 2006). Varthur Lake behaves like a highly anoxic system mostly at the initial reaches, which makes ammonia the predominant N form with low nitrification and ultimately results in very low nitrate values. Anoxic conditions do not favour NH_4^+ to be nitrified to a large extent. On the other hand, low DO (0 mg/l) and negative redox (–220 to –180 mV) conditions favour denitrification. Similar values were reported for urban lakes in Hosurs (16.25–30 mg/l) (Karibasappa et al., 2009), Varthur Lake (>3 mg/l during October) (Ramachandra et al., 2006) and at the inlets and outlets of Bellandur Lake (31 mg/l during November) (Chanakya et al., 2006).

Phosphorus, an essential part of the biological system, is present mostly in the form of inorganic phosphates, which is taken up by the biota (Martin, 1987) and also constitutes a limiting factor to eutrophication (Vollenweider et al., 1980). Phosphate values ranged from 0.14 (October) to 3.51 mg/l (April) (Figure 7q). Appreciable differences were found in the inlet and outlet P concentrations (Figure 5n) during the summer months. Higher values during dry seasons may be attributed to lower algal activities (due to macrophyte cover) and to resuspension of sediment phosphorus leading to release of mineral phosphate accumulated in sediments (Ryding and Rast, 1994). Lower levels of phosphate are reported in lakes with higher phytoplanktonic biomass (Parinet et al., 2004).

Lower P concentrations during the monsoon could be attributed to dilution (due to runoff) and enhanced algal activities in the absence of macrophyte cover. Higher P values in July may be due to runoff. Higher values of phosphates were observed during the pre-monsoon (Bharali et al., 2008; Kapil and Bhattacharya, 2009), implicating evaporation losses coupled with the release of P from sediments (Hujare, 2008) and decayed plankton (phyto and zoo) wastes (Heron, 1961). Higher values were reported in Madivala Lake (Ramachandra et al., 2001) and urban lakes in Hosur (0.2–3 mg/l; Karibasappa et al., 2009).

BOD decreased from the inlet to the outlet (Figure 5o) in the monsoon and post-monsoon period (six months) highlighting the decline of organic content. This coincides with the low macrophyte coverage and availability of large oxic zone (evident from DO at midday as well as in the evening). Also, aerobic decomposition coupled with functioning of algal photosynthetic activities enhanced DO levels while lowering BOD. On the other hand, BOD reduction is very poor with dense macrophyte cover (late winter and summer months), with higher anaerobic conditions. This illustrates that lake would function as an anaerobic (upper reaches)–aerobic (lower reaches) lagoon system while bringing the desirable utility of sewage treatment to an appreciable level. Attempts, therefore, need to be made to increase the efficacy of conversion as well as water purification, leading finally to a sustainable technology that is applicable to a large part of India and the developing world.

It may be estimated that at about 100 g TS of waste/capita/d entering the sewage system the loading rate may be estimated to be 0.125 g TS/l/d and about 0.2 g BOD/l/d at the inlet, which is close to the functional limit for typical lagoons. On the other hand, when one considers the maximum potential of the anaerobic–aerobic systems, higher loading rates and higher conversion rates are possible. There is, thus, a need to further examine the potential for higher quality of water at the outlet to enable the recycling and reuse of water in the future. In order to make this more sustainable, the extent of the harvest and the reuse of plant nutrients for the system need to be examined. The macrophytes and the algae together with wetland vegetation have an important role in regulating the amount of nutrients. The contribution of macrophytes and phytoplankton in removing nutrients in these sewage-enriched systems varies with the nature of the effluent and the age of the wetland, in addition to other environmental factors like sunlight.

4 Conclusion

The water quality of sewage-fed Varthur Lake, Bangalore, India has been measured at five different locations. A BOD removal of 70% (filterable) was achieved when the lake functioned as an anaerobic–aerobic lagoon for 6 months at an estimated residence time of 5 d. During this period, the biota of the lake, especially primary producers (phytoplankton, algae), treated the water to nearly standard water quality levels. The growth and spread of macrophytes (water hyacinth) renders the lake anaerobic and reduces its capacity to treat the water. Keeping an open surface and permitting microalgal growth provides a high level of water treatment, and it may be used in a larger number of small towns to enable local reuse of water.

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