Fate of Nutrients in Human Dominated Ecosystems

A Case Study of Jakkur Lake in Bengaluru

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Jakkur Lake in the city of Bengaluru covers an approximate area of 55 hectares and primarily receives inflows from the Jakkur sewage treatment plant (STP) and an open storm drain. Jakkur STP discharges an average of 10 million litres of treated water daily (MLD) into the lake. The open drain discharges about 0.5 MLD of raw sewage into the lake. In the absence of environmental flows it becomes critical to assess the impact of nutrient flux on the quality of water, and design cost effective treatment solutions to address the issues of lake water quality. As part of this study, we have assessed the impact of these two primary inflows on the overall water quality of Jakkur Lake. The results have shown that nutrient inflows have led to the increase of chlorophyll-a levels, eventually causing hyper-eutrophication of Jakkur lake. We have also used simple mass balance approach to assess the contributions of in-lake activities (sedimentation and reaction) on removal of nutrients from the lake. We have concluded that the phosphorus load has to be reduced by approximately 96% from the current levels to prevent algal blooms within Jakkur Lake.

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1. Introduction

In the past decade Bengaluru has witnessed a tremendous growth in population. The city's population grew from 4.1 million in 2001 to 8.2 million in 2011 [1]. This exponential growth has put enormous pressure on the existing water and wastewater infrastructure of the city. The city generates approximately 1400 million litres (MLD) of sewage per day. According to official data, about 40% of the total sewage is treated [2]. However in the absence of proper utilization of treated water, both treated and

Keywords

Jakkur lake, wastewater, sewage treatment, nutrient flux, mass balance.

Exponential population growth has put enormous pressure on the existing water and wastewater infrastructure of Bengaluru.

untreated wastewater usually finds its way to various surface waterbodies such as lakes and rivers. Sewage across the city gets treated either by centralised (government owned), or by decentralized (privately owned) wastewater treatment systems. The city has 14 centralised wastewater treatment plants and more than two thousand decentralized treatment plants [2]. Centralized wastewater treatment plants treat sewage up to the secondary level, which implies that nutrients such as nitrates and phosphates continue to remain in the treated water. Whereas, in decentralized wastewater treatment plants, the sewage is treated up to the tertiary level, and the treated water is often reused for various non-potable purposes like car washing, flushing, and gardening.

Figure 1 shows the fate of treated and untreated domestic wastewater in the city of Bengaluru. Open storm drains that are designed to carry surface runoff, now carry both treated and untreated/partially treated sewage into the lakes. According to available data, approximately 90% of the lakes in the city are polluted [3]. Data also suggests that about 79% of the city lakes fall into 'category E' of the surface water quality, which implies that lake water is only suitable for irrigation, industrial water cooling, and for controlling waste disposal [4].

The lakes of the city provide environmental amenities and are rarely used for irrigation. Various civil society groups are working together with the government and private organizations to manage lake water quality. In the absence of a clear definition or standards to classify lake water (water quality standards), the goal of such action groups is to achieve visibly clean lake that is home for migratory birds and provides habitat for fish. In spite of all the efforts to achieve a healthy lake, fish kill is a common occurrence

Jakkur Lake is one of the largest lakes in the city of Bengaluru. The lake is roughly 55 hectares in area and has 3 inlets, and 2 outlets.

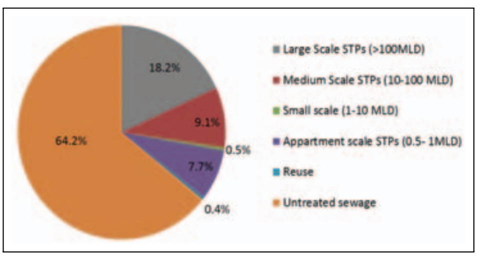


Figure 1. Wastewater treatment scenario in Bengaluru.

in Bengaluru lakes [5, 6]. Jakkur Lake, which once was regarded as the healthiest lake in the city, every year witnesses several fish kill events.

Jakkur Lake is one of the largest lakes in the city of Bengaluru. It is the middle lake in a series of three connected lakes; others being Yelahanka and Rachenahalli. The lake is roughly 55 hectares in area and has 3 inlets, and 2 outlets. The lake receives about 10 MLD of treated water from Jakkur STP. In addition to direct uses, the lake also recharges the local groundwater levels. The secondary treated water from Jakkur STP is allowed to pass through a constructed wetland, before entering into the lake. In addition to the treated water from the STP, the lake also receives 0.5 MLD of raw sewage from an open storm water drain [7]. The untreated sewage also gets partial treatment in the constructed wetland before it enters into the lake. The constructed wetland covers around 5 hectares of the lake area.

Our interest lies in investigating the impact and fate of nutrients (nitrogen and phosphorus) in the lake. Given that the lakes in human dominated ecosystems receive treated/partially treated effluents, it is important to estimate the pollution load assimilation capacity of these urban water bodies. This would allow regulatory agencies/policy makers to devise strategies for the management of nutrient load from various sources such that the lakes meet the recommended water quality criteria.

2. Methodology

To assess the impact of treated and untreated sewage (inflows) on lake water quality, we collected water samples at (a) the outlet of Jakkur STP (*Figure* 2: treated effluents), (b) open drain carrying raw sewage (*Figure* 2: raw sewage), (c) at two locations around the center of the lake (*Figure* 2: center-lake) and a location close to western bank (*Figure* 2: in-lake), and (d) at the two outlets of the lake (*Figure* 2: outlet 1 and outlet 2). Water samples were collected monthly once for a period of one year (May 2015–May 2016).

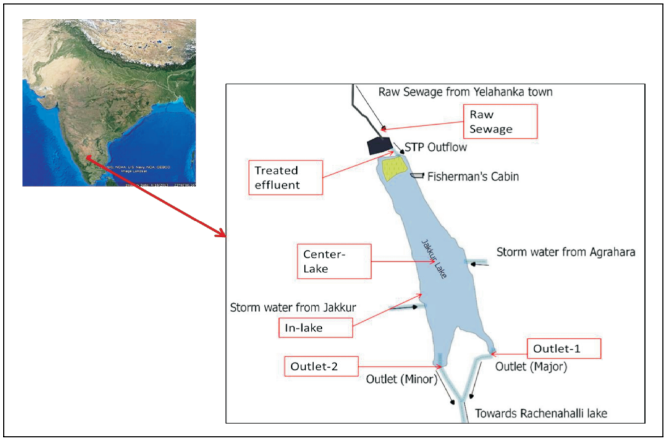


Figure 2. Sampling locations at Jakkur Lake.

Table 1. Methods adopted to assess water quality of Jakkur Lake [8].

Parameters	Method [8]
pH	*in situ*, WTW probe
Conductivity	*in situ*, WTW probe
Dissolved oxygen	*in situ*, Winkler method
Nitrates	Filtration, Calorimetric method
Ammonia-N	Nessler's method
Phosphates	Filtration, Calorimetric method
Chlorophyll-a	Calorimetric method

Table 1 presents the list of the water quality parameters tested and the methods employed to test the respective water quality parameters. Few tests such as pH, conductivity and dissolved oxygen (DO) (partially) were performed *in situ*.

We estimated the nutrient flux by measuring flows (both inflows and outflows) and the lake volume. Stage recorders were installed both at the inlet and the outlet of the lake. Bathymetry[1] was carried out to estimate the lake volume. A weather station was installed to measure rainfall, temperature, solar radiation, and humidity.

[1] The measurement of depth of water in oceans, seas, or lakes.

We adopted the mass balance approach to estimate the nutrient load assimilation capacity of the lake. *Figure* 3 presents the schematic of mass balance approach adopted to understand the fate of nu-

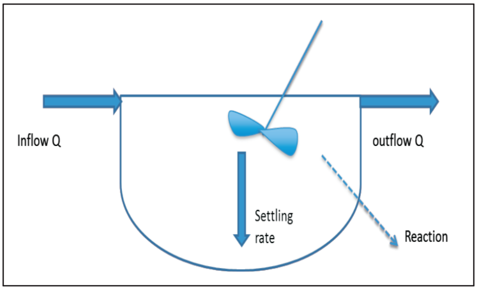


Figure 3. Mass balance approach to assess the fate of nutrients in the lake.

trients in the lake. The average daily total nitrogen (nitrates + ammonia-N) (N), phosphates (P), and BOD loading into the lake were estimated using following equations:

In-flux (kg/day) = Out-flux (kg/day) +
Nutrient load assimilation capacity of lake (kg/day)

$$\text{In-flux (kg/day)} = C_{in} \times F \quad (1)$$

$$\text{Hydraulic retention time in lake (HRT)}^2 = V/F \quad (2)$$

Nutrient load assimilation capacity of lake (kg/day)

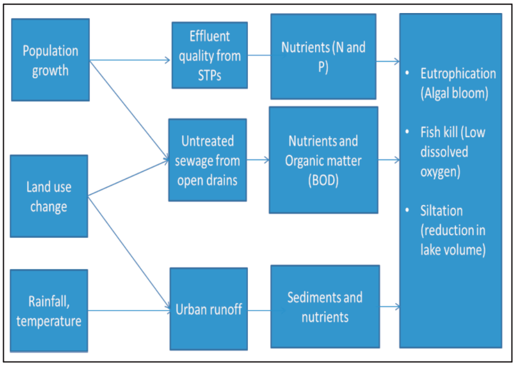
$$= k_d \times C \times V \quad (3)$$

$$\text{Out-flux(kg/day)} = \text{C} \times \text{F} \quad (4)$$

where, C_{in} = nutrient concentration in inflows (mg/l), F = average monthly inflow (million litres /day), C = nutrient concentration in lake (mg/l), V= volume of lake (Million litres), k_d = decay rate (per day).

[2]The hydraulic retention time is a measure of the average length of time that a compound (*e.g.,* water) remains in a storage unit (*e.g.,*lake, pond, ocean).

We estimated the contributions of in-lake activities (sedimentation and reaction/conversion) to nutrient load assimilation capacity of the lake by subtracting inflow fluxes (1) and outflow fluxes (4). We used (3) to estimate the nutrient decay rate (k_d). Finally we used the decay rate from mass balance to estimate the reduction in nutrient load required to meet the nutrient water quality criteria developed by USEPA [9].



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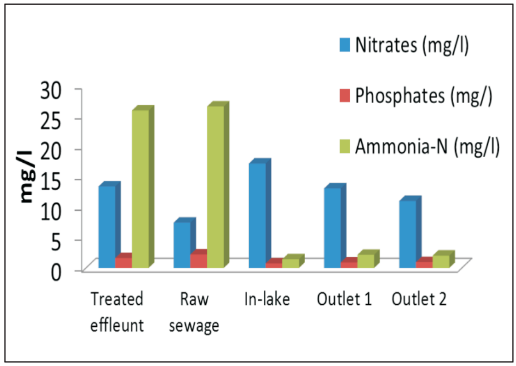

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Figure 4. Framework to assess the impact of nutrient fluxes on lake water quality.

Figure 5. Nutrient levels in samples collected from various locations at Jakkur Lake.

3. Results

We will present the results in two sections. In the first section, we will demonstrate the impact of nutrient flux on the lake water quality, and in the second section we will assess the contributions of in-lake activities (sedimentation and reaction) to the nutrient assimilation capacity of lake. *Figure* 4 presents the framework adopted to assess the impact of nutrient fluxes on lake's health.

3.1 *Impact of Nutrient Inflows on Lake Water Quality*

In this study, we assessed the impact of nutrient inflows on lake health. Lake health is primarily measured with respect to two major parameters, i.e., dissolved oxygen (DO) level and chlorophyll-a (algal concentration). Adequate DO levels are critical for the survival of aquatic life. DO in the lake gets affected by several factors such as algal growth, temperature, salinity, etc. Algal growth in a lake is the direct output of excessive nutrient inputs into the lake. A minimum of 4 mg/l of DO should be maintained in the lake to sustain fish biodiversity.

Figure 5 presents the average nutrient levels in the samples collected for this study. The data shows that as water flows from the inlet towards the outlet of the lake, there is a significant reduction in the levels of phosphorus and ammonia-N, while the average nitrate level remains more or less the same.

The average nitrate levels in the effluents were twice that of the levels present in the raw sewage. Chemoautotrophic bacteria present in the sewage treatment plant convert organic nitrogen and ammonia-N into nitrates. This reaction taking place in the biological reactor causes nitrate levels to increase in the treated water.

We observed higher phosphate levels in raw sewage as compared to that of the treated effluents. Heterotrophic bacteria utilize phosphorus (P) during the sewage treatment process that causes P levels to reduce in the treated water.

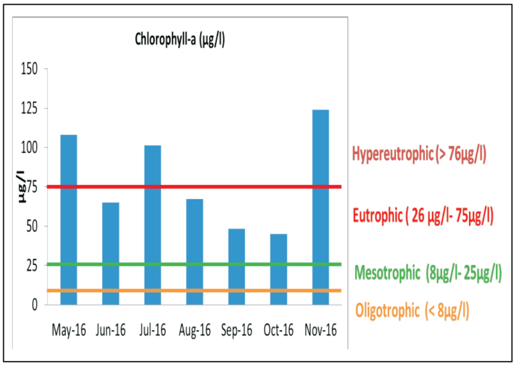
There was no significant reduction in nitrate levels in Jakkur Lake. Significant reduction was observed in ammonia-N and phosphate levels in Jakkur Lake. The lake provides conducive environment for the growth of chemoautotrophic bacteria that convert ammonia into nitrates. The conversion of ammonia and organic nitrogen has led to the increase of nitrate levels. Low in-lake phosphate levels suggests that either phosphates are being utilized for algal growth (reaction term) or are being removed by the sedimentation process.

Figure 6 shows the monthly chlorophyll-a levels observed in Jakkur lake. During the sampling period, the lake was either in the eutrophic state (chlorophyll-a between 25 μg/l – 75 μg/l), or hyper eutrophic state (chlorophyll-a > 75 μg/l) [10]. High nutrient levels had led to algal blooms, which had significantly affected the lake DO levels.

Algal cells are photoautotrophs; they utilize carbon dioxide from the atmosphere, sunlight, and nutrients for their growth (produce more algal cells). Oxygen is the product of algal photosynthesis process. These cells produce oxygen during the daytime, and consume dissolved oxygen from the lake after sunset (respiration). This process causes huge fluctuations in the daily DO levels. *Figure* 7 presents the DO levels in lake.

Studies have reported that both high and low DO levels in the lake can be lethal for fish. Excess DO levels traps air in fish gills, whereas low DO level leads to suffocation.

Early morning DO levels in the lake were below 4 mg/l which is below the minimal levels required for propagation of aquatic life



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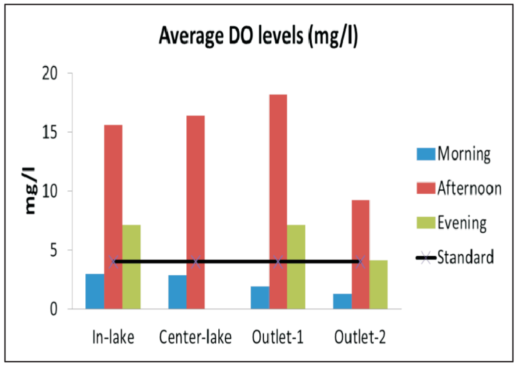

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Figure 6. Monthly chlorophyll-a levels in Jakkur Lake.

Figure 7. Daily dissolved oxygen levels in Jakkur Lake.

like fish [4]. Studies have reported that both high and low DO levels in the lake can be lethal for fish. Excess DO levels traps air in fish gills, whereas low DO level leads to suffocation. Frequent exposure to such conditions for long duration causes stress among fish population, and is one of the major reasons for massive fish kill events.

Given that there is a strong relationship between DO, chlorophyll-a, and nutrients, in order to maintain 4 mg/l of DO it is critical to control the nutrient inflows into the lake. It is important to (a) understand the fate of nutrients in the lake, and (b) apportion nutrient load among various sources so that a minimum of 4 mg/l DO levels can be maintained in the lake. In the next section we apply mass balance approach to understand the fate of nutrients, i.e., nitrogen (nitrates and ammonia-N), and phosphates in the lake environment.

3.2 *Mass Balance of Nutrients*

The volume of Jakkur Lake is approximately 894 million litres. Given that the average inflow into the lake is approximately 10 MLD, the average hydraulic retention time (HRT) is estimated to be around 90 days. For simplicity we have assumed the lake to be a complete reactor (CSTR), operating in steady state condition.

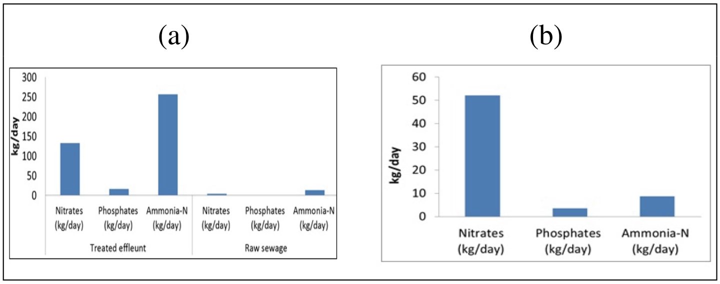

Figure 8. Nutrient fluxes in Jakkur lake **(a)** Inflows **(b)** Outflows

Using (1) and (4), we have estimated the nutrient influxes and outfluxes from the lake. *Figure* 8a presents the nutrient flux inputs from treated effluents and raw sewage in Jakkur Lake. Given that the raw sewage inflows into the lake is very low (0.5 MLD), the nutrient influx from the open drain is significantly lower than that from Jakkur STP.

Figure 8b presents the nutrient flux in the outflows of the lake. The nutrient outflows are less than the inflows indicating the assimilation of nutrients within the lake. The nutrients within the lake are either utilized for the production of algae or are removed by sedimentation process (*Figure* 3).

As explained in the methodology section, we used the mass balance approach to estimate the contributions of sedimentation and reaction terms in assimilation of nutrients. Ammonia-N in the lake converts into nitrates, and therefore we have applied the mass balance to ammonia-N and nitrates together, and have termed it as 'nitrogen mass balance'.

Mass balance of the nutrients shows that a significant amount of nutrient flux gets assimilated in the lake, either by algal growth process or sedimentation process.

Mass balance of the nutrients shows that a significant amount of nutrient flux gets assimilated in the lake, either by algal growth process or sedimentation process, or both. In case of nitrogen, 85% of the influx per day is assimilated, whereas in case of phosphates, 76% of the influx gets assimilated in the lake. Chlorophyll-a data further reinstates the fact that large quantities of nutrient influxes gets assimilated that contributes to the hyper-eutrophic conditions in the lake.

N/P ratio is employed to determine the limiting nutrient for algal growth. To prevent algal growth N/P ratio < 7, and P levels $<$

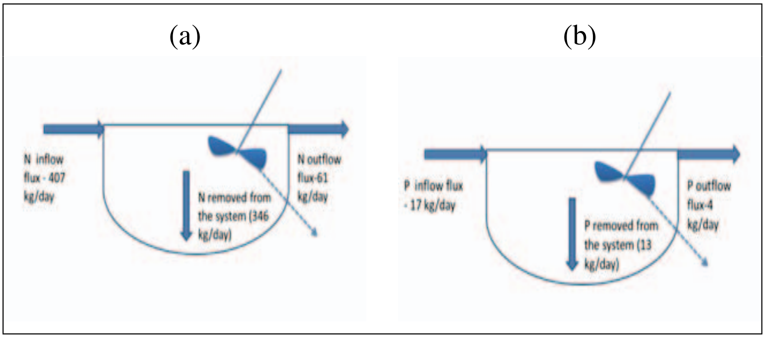

Figure 9. Mass balance of nitrogen and phosphorus in Jakkur Lake.

0.03 mg/l are recommended [9]. Using the outcome from mass balance for P, we determined the P decay rate in Jakkur lake (k_d = 0.016 per day). Using (3) and (4), we calculated the P influx required to maintain 0.03 mg/l of P level in the lake. We estimated that a 96% reduction in P load is required to maintain 0.03 mg/l of P in Jakkur Lake. Though these are approximate assumptions and are based on one dimensional simple mass balance model, but these findings are very important to direct policy decisions on lake water quality management.

4. Conclusions

Water quality management in human dominated ecosystems needs a different approach. Given that the urban lakes and rivers receive treated/partially treated water throughout the year, it becomes important to use modelling tools to apportion nutrient loads among various sources such that the DO level in the lake is maintained above 4 mg/l throughout the year. Using the case study of Jakkur Lake we concluded that:

- The level of treatment given to inflows of Jakkur Lake is not sufficient to meet the water quality criteria.
- High percentage of nutrient assimilation is causing algal blooms that has led to hyper-eutrophication[3] of Jakkur Lake.
- Early morning DO levels in lake is very low (< 4 mg/l), which is one of the major reasons for massive fish kills.
- Nutrient data suggests that algal growth in the lake is controlled by the P influx (N/P > 7).

[3] Excessive richness of nutrients in a lake or other body of water, frequently due to run-off from the land, which causes a dense growth of plant life.

- Mass balance model suggests that 96% reduction in P load is required to maintain 0.03 mg/l of P in Jakkur Lake.

  This study assesses the current condition of Jakkur Lake and using the one dimensional mass balance model suggests the measures required to (reduction in P load) prevent eutrophication in the lakes present in human dominated/modified ecosystems.

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Suggested Reading

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