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Optimal Treatment of Domestic Wastewater through Constructed Wetlands

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ABSTRACT Unplanned urbanisation leads to haphazard growth altering the local ecology, hydrology and environment. Sewage generated in urban households is either untreated or partially treated, which is finally let into water bodies through trunk sewers and storm water network. Although sustained inflow of sewage into water bodies has maintained the water levels in the system of interconnected lakes but it has also contributed to the contamination of surface as well as groundwater sources. This study explores the feasibility of bioremediation path to treat wastewater for reuse and mitigate the water crisis in the city. Innovative path of wastewater bioremediation includes integrated wetlands system consisting sewage treatment plant, constructed wetlands (with location specific macrophytes) and algal pond integrated with a lake. Integration of the conventional treatment system with wetlands [consisting of reed bed (with typha etc.) and algal pond] would help in the complete removal of nutrients in the cost effective way.

INTRODUCTION

Wetlands include a wide range of aquatic habitats such as marsh, fen, peat land/open water, flowing water (rivers and streams) or static (lakes and ponds). These ecosystems being the transition zone between land and water are ecologically important in relation to stability and biodiversity of a region and also in terms of energy and material flow. These ecosystems perform a vital function of uptake of nutrients and bioremediation of heavy metals, volatile organics and other xenobiotic compounds and are aptly referred as "Kidneys of the landscape". They also aid in recharge of groundwater aquifers and stabilization of shorelines (Ramachandra and Bharath 2015). These transitional zones or ecotonal region are repository of rich biodiversity and support food chain. Wetlands act as giant sponges, which help in slowing runoff, lower flood heights, reduce shoreline and stream bank erosion. The functional ability of wetlands is dependent on the type of trophic structure and material exchange. The trophic structure includes various trophic levels as producers (algae, etc.), primary consumers (zooplanktons and grazers), secondary consumers (small fish), tertiary (large fish, birds, etc.). Algae being the primary producers synthesize carbohydrates during photosynthesis and give out oxygen along with the production of other essential metabolites. Bulk of the CO_2 gets sequestered into algal biomass in these wetlands systems that aids in combating global warming through reductions of GHG (Greenhouse gases) in the environment. However the stability of every system depends upon the balance between production and consumption of energy and matter at different trophic levels in any system. The functional aspects of wetlands are tied to the tradeoff be-

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tween the ecosystem function and the anthropogenic impact that makes it very sensitive and delicate. Human impacts include altering the catchment (changes in land cover), encroachment, solid waste disposal in lake beds, sustained inflow of untreated sewage from urban localities, etc. (Ramachandra and Bharath 2015; Ramachandra 2001, 2009a, 2009b, 2010; Ramachandra et al. 2003, 2018a).

Bangalore had flourished during 19th and early 20th century owing to a salubrious microclimate and abundance of water in the city of lakes. Globalisation, liberalization, privatization are the agents fuelling urbanization in most parts of India during early 1990's. Consequences of the unplanned urbanisation are enhanced pollution levels, lack of adequate infrastructure and basic amenities. This is evident in Bangalore with severe scarcity of water, frequent flooding, enhanced pollution levels, uncongenial buildings, mismanagement of solid and liquid wastes, etc. Increased and unprecedented population growth has resulted in enormous stress on potable water from a daily consumption point of view and also in regards to increased wastewater generated by the city. Unplanned growth has led to radical land use conversion of forests, surface water bodies, etc. with the irretrievable loss of land resources (Ramachandra et al. 2013a). Land use analyses show 1028 percent growth in built-up area during the last four decades with the decline of vegetation by eighty-eight percent and water bodies by seventy-nine percent (Ramachandra et al. 2017; Ramachandra and Bharath 2016). Analyses of the temporal data reveals an increase in urban built up area of 342.83 percent (during 1973 to 1992), 129.56 percent (during 1992 to 1999), 106.7 percent (1999 to 2002), 114.51 percent (2002 to 2006) and 126.19 percent from 2006 to 2010 (Ramachandra et al. 2009a, 2012a; Bharath et al. 2018).

Rapid urbanisation in recent times has led to the large scale generation of wastewater. Untreated or partially treated wastewaters are fed to surface water that finds its way into ground water sources. The sustained inflow of untreated or partially treated sewage to wetlands leads to the enrichment of nutrients such as nitrogen (N) and phosphorus (P), evident from the algae bloom and profuse growth of macrophytes. This has led to the contamination of existing water resources with pathogens and nutrients resulting in algal bloom due to eutrophic status of surface water.

Cauvery River caters to only fifty-five percent of over 9 million population and balance is met through groundwater. Bangalore city is facing severe water shortages today due to insufficient piped supply coupled with the fast decline of groundwater table. Plummeting groundwater table is due to poor infiltration because of increasing paved surface and also over exploitation. Sustained inflow of untreated sewage to lakes has also contaminated nearby groundwater sources (Department of Mines and Geology 2011; Government of India 2008) affecting the human health. Nitrogen as nitrate-N pollution leads to physiological disorders including blue baby syndrome (methemoglobinemia) and the persistent assimilation of nitrate rich water leads to carcinogenic symptoms (as nitrates get reduced in the body forming nitrosamines, which are carcinogens). Macrophytes grow profusely in these nutrient rich environments and progressively cover the entire surface of the water body hindering the passage of sunlight and diffusion of gases to the underlying water layers. Absence of sunlight affects trophic levels with the reduced algae and photosynthetic O_2 generation depleting the dissolved oxygen concentration and hence affects the local biota. This study explores the feasibility of bioremediation path to treat wastewater for reuse and mitigate the water crisis in the city (Mahapatra et al. 2018; Ramachandra et al. 2018a).

Wetlands are the regional ecological barometers reflecting the health of a region due to the ecosystem services such as regulating the regional micro-climate (Ramachandra and Kumar 2010; Ramachandra and Bharath 2014), recharging groundwater aquifers (Government of India 2008), thereby inûuencing the life of the people adjacent to it. The city landscape (in the current spatial extent of 741 sq.km) had enjoyed 1452 interconnected water bodies in 1800 catering the domestic and irrigation water demand and now there were 193 wetlands (Ramachandra et al. 2017; Ramachandra and Kumar 2008, 2010). Urban water bodies are prone to an increased anthropogenic stress in recent times due to dumping of solid waste, encroachment of wetlands, sustained inflow of domestic sewage and industrial effluents leading to poor water quality with a very frequent algal blooms and rapid macrophyte growth with periodic successions (Mahapatra et al. 2011a, 2011b, 2018; Raj 2013). Influx of partially treated and untreated sewage has resulted in overgrowth, ageing, and subsequent decay of macrophytes creating anoxic conditions and devouring the system from life giving oxygen. This has impacted the food chain and hence the ecological integrity of the system.

Bangalore city is located on two ridges (North-Northeast and South-Southwest) with three watersheds (Hebbal-Nagavara, Koramangala-Bellandur, Vrishabhavathi). Northern and eastern parts of the city are with gentle slopes, while southern and western parts are very rugged undulating terrain of the region has helped in the creation of interconnected water-bodies to meet the domestic and irrigation requirements during the pre-colonial period. These interconnected drainage system is supposed to transfer the storm water from one water-body to another, started receiving sewage with rapid population growth and lack of appropriate sewage treatment systems. Population in Bangalore has increased from 5.6 million (2001) to 9.5 million (2011). Population increase has led to large quantum of sewage influx into wetlands leading to contamination of wetlands and associated groundwater systems.

Collapse of land regulation is evident during the past two decades due to large scale unauthorized occupation of open spaces (wetlands, grasslands, parks) by the influential section of the society in collusion with the bureaucracy. Large scale land conversion of common lands to built-up in recent times further substantiates the nexus (Ramachandra et al. 2017; Ramachandra and Bharath 2016; Ramachandra et al. 2007; Ramachandra and Sudhira 2007). Changes in the land cover have altered the regional hydrology evident from frequent floods, conversion of perennial wetlands to seasonal wetlands and decline of groundwater table. However, authorities have kept some wetlands alive by diversion of sewage, which flows consistently and maintains the water levels in the system of interconnected lakes.

Water Supply in Bangalore

Water is being pumped from Cauvery River ~100 km from the city with an electricity requirement of 75-100 MW. Bangalore is located at higher elevation (900 m above mean sea level) and Cauvery river courses are at 500 m above mean sea level. This exercise suffices the need for approximately fifty-five percent of Bangalore city dwellers, while the rest are dependent on ground water and unauthorized drinking water supplies. Arkavathy River, with two reservoirs at Hesaraghatta (built in 1894) and Tippagondanahalli (built in 1933) insignificantly and irregularly contribute to a small fraction of the demand (30 MLD). The Chamrajasagar reservoir at Thippagondanahalli (or TG Halli reservoir), located at the confluence of the Arkavathy and Kumudavathy rivers, receives inflow mostly from the Kumudavathy but with a low flow rate (Lele et al. 2013; Ramachandra and Solanki 2007; Sawkar 2012). Water demand in Bangalore is roughly about 150 liters per day (lpd) per person and the total water requirement for domestic purposes is about 1, 400 million liters per day (MLD). Water available from Cauvery (Stages I to IV, Phase I) and Arkavathy (Hesarghatta and Tippagondanahalli reservoirs) rivers is about 975 MLD. The loss of water during transportation and distribution is about thirty percent. The surface meets about sixty percent of the city demand while the significant portion is met from groundwater sources (39%) and zone –wise details are indicated in Table 1 and Figure 1. Zone wise water share from Cauvery (compared to groundwater usage) ranges from forty-three percent (south Bangalore), fifty-five percent (west Bangalore), sixty percent (south east Bangalore), sixty-three percent (central Bangalore), seventy percent (north Bangalore) and seventy-seven percent (east Bangalore).

Table 1: Zone-wise piped water and ground water supply

Zone	*Surface water*	*Groundwater*	*Total*
Central	67.1	38.91	106.01
North	210.46	87.08	297.54
West	184.89	149.45	334.34
East	169.19	50.46	219.65
South	133.106	176.00	309.11
Southeast	104.79	67.80	172.59
Total	869.536	569.7	1439.24

Due to the insufficient water from Cauvery River, most of the new city municipal councils and town municipal council (merged with Bangalore city, in the formation of BBMP) are dependent on groundwater sources. A rapid increase in the number of groundwater wells in Bangalore, was observed over the last three decades from 5,000 to around 4.08 lakh. It is esti-

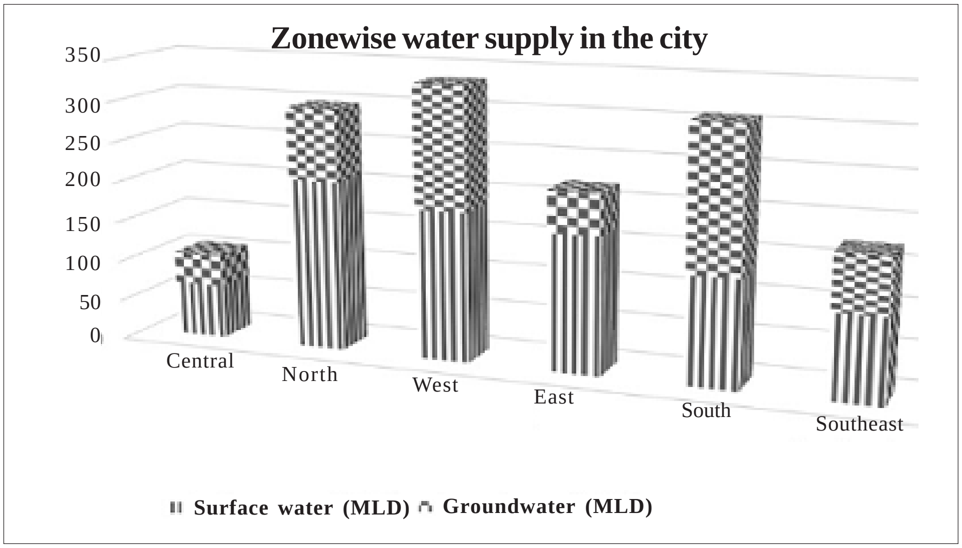

Fig. 1. Water usage in Bangalore (piped water supply and from groundwater sources)
Source: Author

mated that forty percent of population of Bengaluru are dependent on 750 MLD of ground water, which is extracted every day. According to the CGWB (Central Ground Water Board), between 2001 and 2007, the water level in Bengaluru has declined by 7 meters (m) at the rate of about 1m per year. Over exploitation of groundwater coupled with minimal recharge due to changes in land over (increase in paved surface with the loss of vegetation and water-bodies) has led to decline in groundwater table (as high as 500 to 600 m), evident from the prevalence of gray, dark and over-exploited groundwater blocks in the major part of Bangalore.

Communities are dependent on wetlands for food, domestic, agricultural and industrial requirements. The economic benefits from wetlands to the society are in the form of water supply, commercial fisheries, agriculture, energy resource, wildlife resource, recreation, tourism, cultural heritage, biodiversity, etc. (Ramachandra et al. 2011). The myriad ways, in which wetlands are used, along with the numerous anthropocentric activities, have stressed wetlands in diverse ways. This has altered the wetlands quality disrupting its natural functions. Anthropogenic activities include direct physical destruction (drained for agricultural and developmental activities), siltation (soil erosion and removal of vegetative cover) and pollution from both point sources (municipal sewage and industrial effluents) and non-point sources (urban and agricultural runoffs) within the watershed (Ramachandra and Rajinikanth 2003).

Treatment and disposal of wastewater generated in the neighbourhood constitute key environmental challenges faced in urban localities due to burgeoning population in the recent decade. Nutrient laden wastewater generated in municipalities is either untreated or partially treated and is directly fed into the nearby water bodies regularly, resulting in nutrient enrichment resulting in algal blooms. Conventional wastewater treatment options are energy and capital intensive apart from their inability to remove nutrient completely. In this backdrop, algal processes are beneficial and remove nutrients with carbon sequestration and resultant biomass production. Algae grows rapidly and uptake nutrients (C, N and P) available in the wastewater (Ramachandra et al. 2018a, b, 2013a; Mahapatra et al. 2013a) and hence are useful in nutrient remediation. Treatment of sewage and letting into wetlands would help in further treatment (removal of N, P and heavy metals). This also prevents contamination of groundwater resources. Thus wetlands provide a cost effective option to handle sewage generated in the community and also helps in addressing the water crisis in the region.

Microalgae and native macrophytes of the wetlands help in the treatment due to abilities to uptake nutrients and heavy metals. Techniques have been developed for exploiting the algae's fast growth and nutrient removal capacity (Larsdotter 2006; Oswald 1988). The nutrient removal is basically an effect of assimilation of nutrients as the algae grow. Also, nutrient stripping happens due to high pH induced by the algae as in ammonia volatilization, phosphorus precipitation, etc.

Constructed Wetlands with Algal Pond as Wastewater Treatment Systems

Wetlands aid in water purification (nutrient, heavy metal and xenobiotics removal) and flood control through physical, chemical and biological processes (Ramachandra et al. 2018a). When sewage is released into an environment containing macrophytes and algae a series of actions takes place. Through contact with biofilms, plant roots and rhizomes processes like nitrification, ammonification and plant uptake will decrease the nutrient level (nitrate and phosphates) in wastewater (Garcia et al. 2010). Algae based lagoons treat wastewater by natural oxidative processes. Various zones in lagoons function equivalent to cascaded anaerobic lagoon, facultative aerated lagoons followed by maturation ponds (Mahapatra et al. 2011b; Garcia et al. 2001, 2010). Microbes aid in the removal of nutrients and are influenced by wind, sunlight and other factors (Ramachandra et al. 2018a; Mahapatra et al. 2011b, 2013a, b).

Nutrients as Source of Contamination

The conventional wastewater treatment systems (sewage treatment plants - STP) are expensive and require input of external energy sources (for example, electricity, organic carbon) and chemical additives. These treatment systems generate concentrated waste streams necessitating environmentally sound disposal.

There is an urgent need to develop innovative, environmental friendly and cost effective sustainable technologies for treating sewage generated in the community every day. Untreated sewage leads to the neighborhood contamination of land and water resources (groundwater). An easy way to check the sewage contamination is to test the level of nutrients (nitrates and phosphates). Nitrate is a substance that develops from organic waste. Algae convert nitrate into organic compounds (proteins, lipids) through photosynthesis in the presence of sunlight. Algae can exhibit growth rates that are higher than other plants due to their extraordinarily efficient light and nutrient utilization. By taking advantage of rapid availability of nutrient enriched water, high solar intensity and favorable microclimate for algal growth, higher densities of algae can be grown continuously that provides ample biomass and at the same time treat wastewater within a short period of time.

Algal bacterial symbiosis is very effective in these tropical conditions. Algae, the primary producers generate O_2 (during photosynthesis) which aid in the efficient oxidation of organic matter with the help of the chemo-organotrophic bacteria. The type and diversity of the algae grown are potential indicators of treatment process (Morro et al. 2012; Mahapatra et al. 2013a, b; Mahapatra et al. 2014; Ganapati and Amin 1972) and bacterial system disintegrates and degrades the organic matter providing the algae with an enriched supply of CO_2, minerals and nutrients.

Focus of the current research is to assess the efficacy of integrated treatment system of wetlands with algal pond at Jakkur lake. This has been done through water quality assessment (physicochemical analysis) at various stages of the integrated wetland system consisting of sewage treatment plant (10 MLD), wetlands (with macrophytes), algal pond and Jakkur lake. Nitrate and phosphate levels were monitored at various stages of wetlands ecosystem.

Study Area

Jakkur lake (Fig. 2) is situated at 13º 04'N and 77° 36'E, North East of Bangalore. Ten MLD sewage treatment plant is functional in this locality. Partially treated water is let into Jakkur lake through wetlands (consisting of emergent macrophytes and algae). Water samples were collected (Fig. 2) from Inlet (S6), outlets (S1, S2, S3), middle (S4, S5 and S9) and at treatment plant outlet (S6 and S7) totaling nine locations. The treated water from the treatment plant passes through the wetlands to Jakkur lake.

Integrated Wetlands Ecosystem

Integrated wetlands system at Jakkur consists of i) treatment plant (treats sewage partial-

Fig. 2. Integrated wetlands ecosystem: Sewage treatment plant, wetlands (macrophytes and algae pond), Jakkur lake
Source: http://earth.google.com

ly before letting to wetlands), ii) constructed wetlands consisting of macrophytes, iii) algal pond and v) lake (Fig. 2). Jakkur lake is manmade and constructed about 200 years ago to meet the domestic and irrigation water requirement of Jakkur village located about hundred meters south west in the downstream of the lake (Fig. 3). The lake used to be perennial containing water all 12 months due to vegetation cover in its catchment. The lake was a source of livelihood to poor farmers and washer men. Even today during potential fish growth seasons, fish catch is estimated to be as high as 500 kg per day. Twelve to fifteen dhobi (washer men) families are also dependent on the lake for washing cloth daily. In the command area of the lake, agriculture and horticulture (coconut, banana and mango plantations) was practiced and remnants of these plantations could be seen even today in the region. Rapid urbanisation in recent times has led to large scale land use changes leading to an increase in paved surfaces. This has resulted in the decline of infiltration ability of the capacity resulting in lake retaining water for 8-9 months. Lake receives partially treated sewage (of about 6 MLD) daily with the implementation of sewage treatment plant in the upstream of the lake, near the inlet of constructed wetlands. Water flows from the treatment plant (in the north) towards the outlets in the south of the lake. Catchment and command area of the lake was mainly agrarian during pre-ninety's, are now dominated by urban land uses. Around the lake are different kinds of human activities, which include banana plantations, slums, a golf course, and newly built residential buildings.

METHOD

Water quality analysis was carried out to assess physico-chemical and biological properties of water at various stages of the treatment and its suitability for domestic and irrigation purposes. Water samples were collected from nine locations (Fig. 2) twice at 45 days interval. The water samples were collected in clean acid washed one liter polythene bottles. Temperature, TDS, Conductivity and pH were measured

Fig. 3. **Water sampling locations in wetlands system**
Source: earth.google.com

at the site. Water quality parameters were analyzed as per the standard protocol (APHA 2017). Algal samples collected from sampling locations were identified using standard keys (Prescott 1978, 1982) based on their external appearance, colour, morphological characteristics, size, habitat, structure and orientation of chloroplast, cellular structure and pigments etc. Water samples collected were concentrated by centrifuging to 15 ml volume.

RESULTS AND DISCUSSION

Lake water is being used for domestic purposes, irrigation, recreation, etc. Lake is also the source of livelihood as it support fishing and washing activities. Monitoring of water quality would help in maintaining the quality and sustainable management of the ecosystem. Water sampling was done at stations and parameter wise results for sampled locations are listed in Tables 2 (onsite parameters), Table 3 (chemical parameters) and Table 4 (nutrient parameters) respectively and each parameter variability at sampling locations have been discussed next.

Dissolved Oxygen

Dissolved oxygen (DO) is the most essential feature in aquatic system that helps in aquatic respiration as well as detoxification of complex organic and inorganic mater through oxidation. The presence of organic wastes demands high oxygen in the water leading to oxygen depletion with severe impacts on the water ecosystem. The DO of the analyzed water samples varied between 0 to 17.74mg/l. The higher variations of DO especially lower DO values are indicative of high organic matter in the immediate vicinity. The DO was very low at the inlets of wetland and increased immediately after the algal pond. Lower DO values were observed near the macrophytes (invasive exotic weeds as water hyacinth, *Eichhornia crassipes*) infested regions at the outfalls outlets.

Total Dissolved Solids (TDS)

Total dissolved solids present as mineral matter in the form of dissolved cations and anions and to a smaller extent by organics, sourced from decomposing matter. Other sources include runoff from urban areas, road salts used on street, fertilizers and pesticides used on lawns and farms (APHA 2017). TDS affect the water quality in many ways impacting the domestic water usage for cleaning, bathing etc. as well as drinking purposes (Ramachandra et al. 2012b). Surface as well as groundwater with high dissolved solids are of inferior flavor and induce an unfavorable physiological reaction to the dependent population. The TDS values in the samples analyzed, ranged from 612 to 710 mg/l across all locations. It was higher in the inlets and reduced in the middle region of the lake. The TDS was little higher in the outlets than middle due to human activities (like washing, etc.), macrophyte and plankton cover etc.

pH

pH is a numerical expression that indicates the degree to which water is acidic or alkaline, with the lower pH value tends to make water corrosive and higher pH has negative impact on skin and eyes. The pH value ranged from 7.2 to 8.4.

Chlorides

Chlorides are essentially anionic radical that imparts chlorosity to the water. An excess of chlorides leads to the formation of potentially carcinogenic and chloro-organic compounds like chloroform, etc. Chloride values in samples collected from Jakkur lake system ranged from 166-260 mg/l. Chloride values were high at inlets (treated and untreated water) and relatively lower at the outlet of algal pond and the middle portion of Jakkur lake. At outlets, it is higher due to washing activities with the use of bleaching powder that is $CaO (Cl)_2$.

Sodium

Sodium (Na) is one of the essential cations that stimulate various physiological processes and functioning of nervous system, excretory system and membrane transport in animals and humans. Increase of sodium ions has a negative impact on blood circulation, nervous coordination, hence affecting the hygiene and health of the nearby localities. In this study, the concentration of sodium ranged from 256 to 367 mg/l and higher values were observed in samples collected at outlets.

Table 2: Onsite parameters

Site	*GPS*	*DO (mg/l)*		*Water temp (°C)*		*TDS (mg/l)*		*pH*		*EC (µS)*		*Comments*
Period		*1*	*2*	*1*	*2*	*1*	*2*	*1*	*2*	*1*	*2*	
S1	13.07931N, 77.61032E	5.08	7.26	24.3	25	637	636	7.8	8.4	1179	1160	Outlet, People washing clothes
S2	13.08019N,77.61463E	-	3.71	-	24.4	-	631	-	8.2	-	1204	Outlet, after the cover of macrophytes
S3	13.08143N, 77.61428E	16.94	8.06	24	24.2	630	630	8	8.2	1213	1215	Outlet
S4	13.08670N, 77.61265E	16.53	8.06	24	-	629	643	8.1	-	1221	-	Middle
S5	13.08725N, 77.61060E	16.13	9.35	-	25	617	612	7.9	7.8	1134	1256	Middle
S6	13.09266N, 77.60769E	17.74	8.06	-	24.1	648	709	7.4	7.2	1213	1389	Inlet to the lake after algae pond
S7	13.09433N, 77.60767E	2.02	0.00	24.7	22.3	652	692	7.2	7.7	1293	1368	Untreated sewage water entering lake
S8	13.09423N, 77.60767E	5.40	4.60	23	24.9	683	630	7.8	8.2	1327	1244	Treated water from treatment plant
S9	13.08582N, 77.60922E	9.68	7.26	24.3	24.3	631	640	8	7.2	1228	1216	Middle

Table 3: Chemical parameters of water analysis

Sites	*Chloride (mg/l)*		*Total hardness (mg/l)*		*Ca (mg/l)*		*Mg (mg/l)*		*Na (mg/l)*		*K (mg/l)*		*Total alkalinity (mg/l)*	
Period	*1*	*2*	*1*	*2*	*1*	*2*	*1*	*2*	*1*	*2*	*1*	*2*	*1*	*2*
S1	259.86	254.18	212	206	40.88	39.28	26.82	26.33	300.8	331.6	47.6	51.6	260	252
S2	-	249.92	-	204	-	40.08	-	25.36	-	367.6	-	56.4	-	252
S3	249.92	249.92	212	204	42.48	39.28	25.84	25.84	360	359.6	58	57.6	250	248
S4	166.14	190.28	208	200	43.29	40.08	24.38	24.38	343.6	334	52.8	54.4	260	256
S5	180.34	168.98	210	224	44.09	38.48	24.38	21.93	284.8	282.4	54.4	53.2	240	254
S6	251.34	249.92	240	256	59.32	59.93	22.42	22.90	293.6	260.4	53.2	56	290	310
S7	254.18	257.02	252	244	65.73	61.72	21.44	21.93	256.4	266	52.4	55.6	420	444
S8	252.76	254.18	256	254	71.34	67.71	19.00	24.87	268.8	320.8	56	54.8	440	448
S9	230.04	210.16	206	198	44.89	46.49	22.91	19.99	330.4	342.4	55.2	57.6	260	252

Table 4: Nutrient analysis of water

Sites	*COD (mg/l*		*BOD (mg/l*		*Phosphate (mg/l)*		*Nitrate (mg/l)*	
Period	*1*	*2*	*1*	*2*	*1*	*2*	*1*	*2*
S1	28	20	17.14	5.04	0.09	0.15	0.28	0.32
S2	-	20	-	9.58	-	0.2	-	0.34
S3	34	10	19.15	1.01	0.09	0.2	0.26	0.34
S4	30	14	22.18	5.04	0.1	0.25	0.26	0.36
S5	18	20	27.22	1.01	0.1	0.67	0.21	0.33
S6	16	48	25.2	16.13	0.21	1	0.24	0.27
S7	161.3	28	128	6.05	0.72	1.29	0.22	0.22
S8	88	16	46.37	4.54	0.35	0.27	0.36	0.38
S9	18	16	20.16	5.04	0.09	0.18	0.2	0.26

Potassium

Potassium (K) is an essential element for both plant and animal nutrition, and occurs in ground waters as a result of mineral dissolution, decomposing of plant materials and also from agricultural runoff. Potassium ions in the plant root systems helps in the cation exchange capacity to transfer essential cations like Ca and Mg from the soil systems into the vascular systems in the plants in replacement with the potassium ions (APHA 2017). Incidence of higher potassium levels in soil system affects the solute transfer (active and passive) through the vascular conducting elements to the different parts of the plants. The potassium content in the water samples ranges between 47-58 mg/l. The potassium values were high at outlets due to decomposition of plant materials.

Alkalinity

Alkalinity is a measure of the buffering capacity of water contributed by the dynamic equilibrium between carbonic acid, bicarbonates and carbonates in water. Sometimes excess of hydroxyl ions, phosphate, and organic acids in water causes alkalinity. High alkalinity imparts bitter taste. The acceptable limit of alkalinity is 200 mg/l. Alkalinity of the samples was in range 240-444 mg/l. High alkalinity of 448 and 444 mg/l was observed at the inlet of wetlands (or outlet of the treatment plant). These values declined after the water passed through wetlands (in particular the algal pond) and also in the middle of Jakkur lake.

Total Hardness

Hardness is a measure of dissolved minerals that decides the utility of water for domestic purposes. Hardness is mainly due to the presence of carbonates and bicarbonates that is temporary hardness and due to sulphates and chlorides that is permanent hardness. It is caused by variety of dissolved polyvalent metallic ions predominantly calcium and magnesium cation or other cations like barium, iron, manganese, strontium and zinc. In the present study, the total hardness ranged between 198 to 256 mg/l. It was higher in the inlets. High values of hardness are probably due to the regular addition of sewage and detergents.

Calcium

Calcium (Ca) is one amongst the major macro nutrients which are needed for the growth, development and reproduction in case of both plants and animals. The presence of Ca in water is mainly due to its passage through deposits of limestone, dolomite, gypsum and other gypsiferous materials (APHA 1998) along with the Ca (from sewage). It contributes to the total hardness of the water. Ca concentration in all samples analyzed periodically ranged between 39 to 71mg/l. Ca concentration was high in the sewage water (treated and untreated) entering into the lake.

Magnesium

Magnesium (Mg) in one of the most essential macro nutrients that helps as a co-factor in the enzyme systems and in the central metal ions that constitutes the chlorophyll molecule essential for plant photosynthesis. According to WHO guidelines, the maximum admissible limit is 50 mg/l. In this study, the concentration of Magnesium ranged from 19 - 26.82 mg/l.

Nutrients (Nitrates and Phosphates)

Nutrients essentially comprise of various forms of N and P that readily mineralizes (inorganic mineral ions) to enable uptake by microbes and plants. Accumulation of nitrates and inorganic P induces changes in water quality that affects its integrity leading to higher net productivity. Nitrates in excess amounts together with phosphates accelerate aquatic plant growth in surface water causing rapid oxygen depletion or eutrophication in the water. Nitrates at high concentrations (10 mg/l or higher) in surface and groundwater used for human consumption are particularly toxic to young children affecting the oxygen carrying capacity of blood cells (RBC) causing cyanosis (methemoglobinemia). In the present study, nitrate values ranged from 0.2 to 0.38 mg/l and phosphate values ranged between 0.09 to 1.29 mg/l. The nitrate and phosphate values are higher at the wetlands inlets (Fig. 4a) and significantly reduce after the passage through wetlands and algal pond as elucidated in Figure 4b.

BOD and COD

BOD and COD are important parameters that indicate the presence of organic content. Biochemical oxygen demand (BOD) is the amount of oxygen required by bacteria while stabilizing decomposable organic matter under aerobic conditions. It is required to assess the pollution of surface and ground water where contamination occurs due to disposal of domestic and industrial effluents. Chemical oxygen demand (COD) determines the oxygen required for chemical oxidation of most organic matter and oxidizable inorganic substances with the help of strong chemical oxidant. In conjunction with the BOD, COD test is helpful in indicating toxic conditions and the presence of biologically resistant organic substances (Sawyer and McCarty 1978). In this study, the BOD values ranged from 17-128 mg/l. There was reduction of sixty-six percent in BOD after the algal pond and twenty-three percent removal in the water which flows out of the lake. The COD values ranged from 16 to 161 mg/l. The COD reduced by forty-five percent in the algae pond and thirty-two percent in the lake as shown in Figure 4b.

Integrated Wastewater Treatment System – Constructed Wetland with Algal Pond

The treatment of domestic sewage in natural systems such as constructed wetlands and lagoons is being practiced in developing nations. Significant advantages are its construction and operations are simple and economically viable, while supporting local people's livelihood. Lagoon systems are associated with a high growth rate of phytoplankton that are beneficial and are caused by the influence of light and the continuous nutrient inflow. Algal growth contributes towards the treatment of wastewater by transforming dissolved nutrients into particle aggregates (biomass). Algal retention in the lagoon helps in the treatment, which has to be harvested at regular interval to ensure effective treatment. Treatment system consisting of constructed wetlands and algal pond help in the removal of nutrients (Mahapatra et al. 2011a, 2013a, b; Ramachandra et al. 2018a).

Emergent macrophytes (such as Typha) act as a filter in removing suspended matter and avoiding anaerobic conditions by the root zone oxidation and the dissolved nutrients would be taken up by the lagoon algae. This type of treatment helps in augmenting the existing treatment system in complete removal of nutrients and bacteria. The combination of wetlands (with macrophytes assemblages), algal lagoon and a sustained harvesting of algae and macrophytes would provide complete solution to wastewater treatment systems with minimal maintenance. An integrated wastewater treatment system functional at Jakkur Lake since 2009 is explained in Figure 4a. The integration of sewage treatment plant with wetlands (consisting of reed bed and algal pond) has helped in sustained treatment of water for reuse. Integrated wetland system at Jakkur provides an opportunity to assess the efficacy of treatment apart from providing insights for replicating similar systems to address the impending water scarcity in the rapidly urbanising Bangalore.

The treatment plant (1.6 Ha) with an installed capacity of 10 MLD, comprises of an Upflow Anaerobic Sludge Blanket Reactor (UASB) with an extended aeration system for sewage treatment. The treatment effluent then gets into wetlands (settling basin) of spatial extent ~4.63 hecatres consisting of diverse macrophytes such as *Typha* sp., *Cyperus* sp., *Ludwigia* sp., *Alternanthera* sp., *Water hyacinth* sp., etc. in the

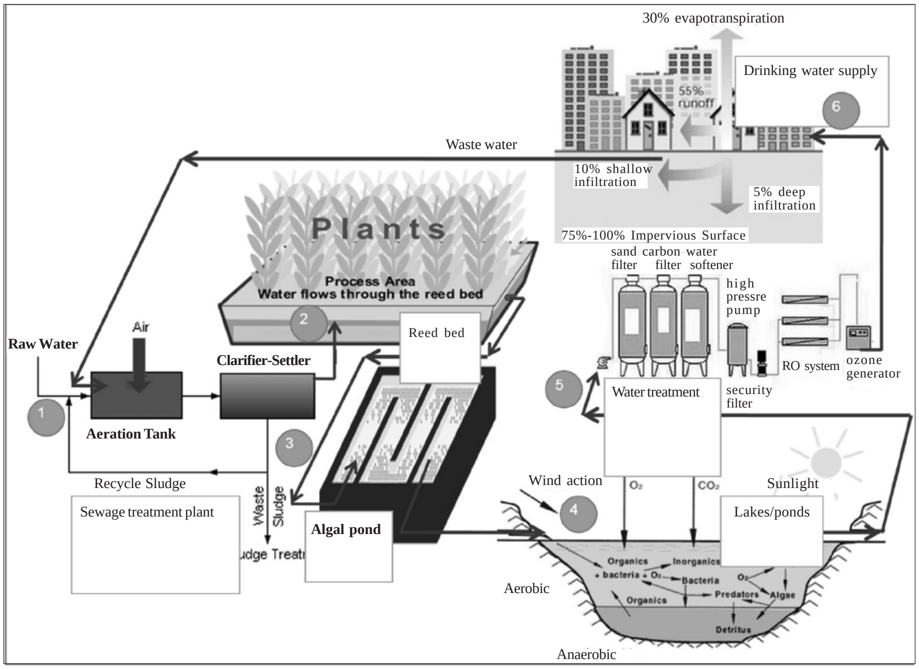

Fig. 4a. Integrated wetlands system for managing water and wastewater
Source: Author

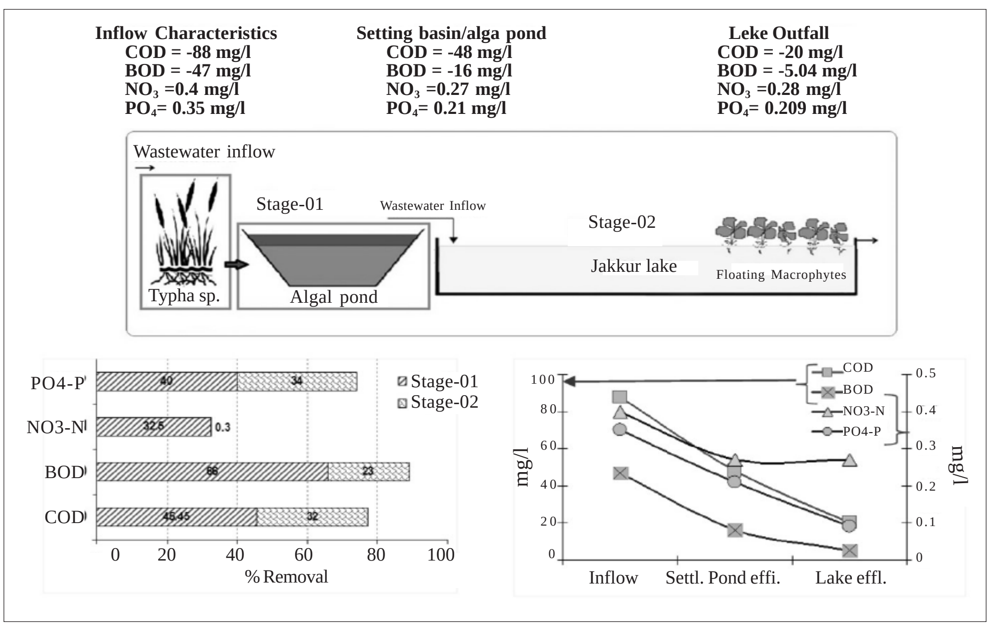

Fig. 4b. Integrated wastewater management system
Source: Author

shallow region (with an area of ~1.8 hectares) followed by deeper algal basin (covering an area of about 2.8 hecatre). This being the significant functional component with macrophytes and algae jointly helps in the nutrient removal and wastewater remediation. The water from the settling basin flow passes through three sluices of which only the middle one is functional (with moderate flow). This water flows into Jakkur lake that spans over 45 hectares. There were notably less occurrence of floating macrophytes, except near the outfalls (~0.5 Ha) due to blockage of the ouflow channels by solid wastes and debris. These macrophytes are being managed by local fishermen. Water in the Jakkur lake is clear with abundant phytoplankton diversity and acceptable densities, which indicates of a healthy trophic status.

The nutrient analysis shows (illustrated in Fig. 4b), that treatment happens due to emergent macrophytes of the wetlands and algae, which removes ~ forty-five percent COD, ~ sixty-six percent BOD, ~ thirty-three percent NO_3-N and ~ forty percent PO_4^{3-}P. Jakkur lake treats the water and acts as the final level of treatment which shown as stage two that removes ~ thirty-two percent COD, ~ twenty-three percent BOD, ~ 0.3 percent NO_3-N and ~ thirty-four percent PO_4^{3-}P. The synergestic mechanism of sewage treatment plants followed by wetlands helps in the complete removal of nutrients to acceptable levels according to CPCB norms.

Jakkur STP (of 10 MLD capacity) treats only 6 MLD of sewage that is drawn from Yelahanka town. Yet, it is observed that sewer channel carrying voluminous wastewater with the treatment plant effluents into wetlands. The major nutrient removal and polishing is done by the constructed wetlands and the lake. This wetland comprise of emergent macrophytes as *Typha angustata*, etc and plays a key role in oxygenation of soil subsystems through root zone oxidation and entrapment of necessary nutrients that otherwise would cause an algal bloom in the lake. The algal species in this manmade wetland region (Fig. 5) primarily comprised of members of chlorophyceae followed by cyanophyceae, euglenophyceae and bacillariophyceae (Fig. 6). The relative abundances are provided in the pie-diagrams (Fig. 6). The detailed list of algal species, their presence and absence have been listed and provided in Table 5.

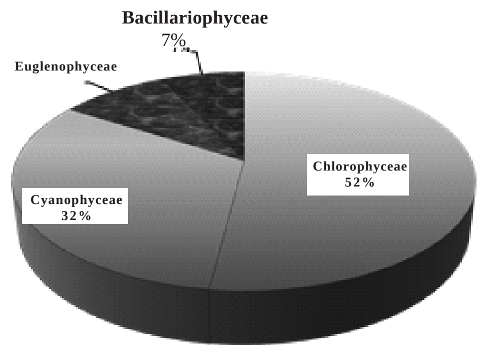

Fig. 5. Composition of algae in man-made wetland system
Source: Author

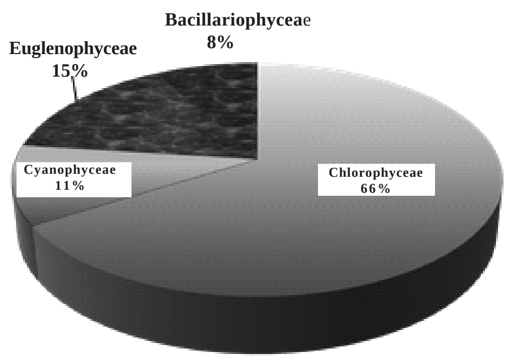

Fig. 6. Composition of algae in Jakkur Lake
Source: Author

Similarly macrophytes play an important role in the effluent stabilisation. The distribution of the macrophytes in the wetland area as well as at the outfalls of the lake is provided in Figure 7. *Typha angustata* species were dominating (54%) in the wetland area followed by *Alternanthera philoxeroides* (28%). However even though the macrophyte population was scarce in the lake, but still amongst them *Eicchornia crassipes* (84%) were dominating (Fig. 8), which were only restricted to the outlet reaches due to fish nets, deployed for fishing in core area.

Land Use (LU) Dynamics in Wetlands Catchment

Land use changes in the wetland catchments are the direct and indirect consequence of human actions to secure essential resources. These changes encompass the greatest environmental concerns of human populations to-

Table 5: Algal species in Jakkur lake system

S. No.	*Algae*	*Site1*	*Site2*	*Site3*	*Site4*	*Site5*	*Site6*	*Site7*	*Site8*	*Site9*
1	*Actinastrum* sp.	+	+	+	+	+	+	+	+	+
2	*Anabaena* sp.	+	+	+	+					
3	*Ankistrodesmus* sp.				+	+			+	+
4	*Aphanocapsa* sp.	+	+	+	+	+			+	+
5	Arthrodesmus sp.		+	+	+	+				+
6	*Asterococcus* sp.	+	+	+	+	+	+	+		+
7	*Chlorella* sp.	+	+	+	+	+	+	+	+	+
8	*Chroococcus* sp.	+		+	+	+		+	+	+
9	*Cladophora* sp.						+			
10	*Closterium* sp.	+	+	+	+	+	+	+	+	+
11	*Coelastrum* sp.		+	+	+	+	+	+	+	
12	*Coelosphaerium* sp.								+	
13	*Coenocystis* sp.								+	
14	*Cosmarium* sp.	+	+	+	+	+		+	+	+
15	*Crucigenia* sp.	+	+	+	+	+	+	+	+	+
16	*Cyclotella* sp.	+	+	+	+	+	+		+	+
17	*Cymbella* sp.			+	+					
18	*Desmodesmus* sp.	+							+	+
19	*Dictyococcus* sp.		+	+	+	+	+	+		+
20	*Dictyosphaerium* sp.		+	+	+	+	+	+	+	+
21	*Eudorina* sp.			+						
22	*Euglena* spp.	+	+	+	+	+	+	+	+	+
23	*Glaucocystis* sp.	+	+		+	+				
24	*Gloeocystis* sp.								+	
25	*Golenkinia* spp.		+			+	+		+	
26	*Gomphonema* sp.							+		
27	*Gonium* spp.	+	+	+	+	+	+	+	+	+
28	*Gyrosigma* sp.					+				
29	*Kirchneriella* sp.	+	+	+	+	+	+	+	+	+
30	*Limnothrix* sp.		+		+	+	+			+
31	*Melosira* sp.	+	+	+	+	+			+	+
32	*Merismopedia* sp.		+	+	+	+	+	+	+	
33	*Micracitinium* sp.		+	+	+	+	+	+	+	+
34	*Microcystis* sp.	+	+	+	+	+			+	
35	*Monoraphidium* sp.	+	+	+	+	+	+	+	+	
36	*Navicula* sp.	+	+		+	+	+	+	+	
37	*Nephrocystis* sp.								+	
38	*Nitzschia* sp.	+	+		+	+		+	+	+
39	*Oocystis* sp.	+		+	+	+	+	+		+
40	*Ophiocytium* sp.								+	
41	*Oscillatoria* sp.	+				+	+	+		
42	*Pandorina* sp.					+	+	+		+
43	*Pediastrum* sp.	+	+	+	+	+	+		+	+
44	*Phacus* spp.	+	+	+	+	+	+	+	+	+
45	*Phormidium* sp.	+	+	+	+	+			+	+
46	*Pinnularia* sp.						+			+
47	*Planktothrix* sp.	+			+			+		
48	*Pseudanabaena* sp.						+			
49	*Quadrigula* sp.	+	+	+	+	+				+
50	*Radiocystis* sp.	+	+	+	+	+		+		+
51	*Scenedesmus* spp.	+	+	+	+	+	+	+	+	+
52	*Schroederia* sp.		+	+	+	+		+		+
53	*Spirulina* sp.		+	+	+	+	+	+	+	
54	*Staurastrum* sp.								+	
55	*Stichococcus* sp.	+	+	+	+	+	+			+
56	*Surirella* sp.					+	+	+		
57	*Synechococcus* sp.								+	
58	*Synedra* sp.		+		+	+	+			
59	*Synura* sp.									+
60	*Tetraedron* spp.							+		
61	*Tetrastrum* sp.			+				+		
62	*Trachelomonas* sp.	+	+	+						
63	*Xanthidium* sp.	+								

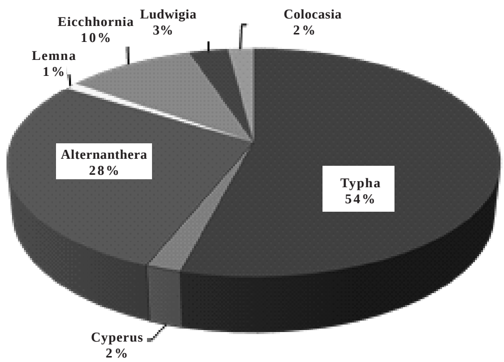

Fig. 7. Composition of macrophytes in man-made wetland system
Source: Author

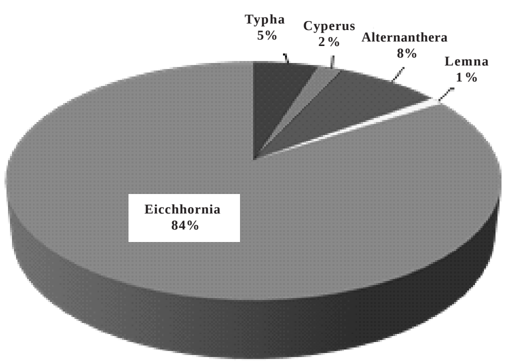

Fig. 8. Composition of macrophytes in Jakkur Lake
Source: Author

day, including loss of biodiversity, pollution of water and soil, and changes in the climate. Monitoring and mitigating the negative consequences of LU changes, while sustaining the production of essential wetlands resources has therefore become a major priority today.

Land use change analyses are done using Landsat MSS (1973), IRS P6 data (2013) and Google Earth (http://earth.google.com). The Landsat data is cost effective, with high spatial resolution and freely downloadable from public domains like GLCF (http://glcfapp. glcf.umd. edu:8080/esdi/index.jsp) and USGS (http://glovis.usgs.gov/). IRS P6 LISS-IV (Indian Remote Sensing Satellite, part of the Indian Space Programme) data was procured from the National Remote Sensing Centre, Hyderabad (http://www.nrsc.gov.in).

Remote sensing data obtained were geo-referenced, rectified and cropped corresponding to the study area. Geo-registration of remote sensing data (Landsat data) has been done using ground control points collected from the field using pre calibrated GPS (Global Positioning System) and also from known points (such as road intersections, etc.) collected from geo-referenced topographic maps published by the Survey of India. In the correction process, numerous GCP's are located in terms of their two image coordinates; on the distorted image and in terms of their ground coordinates typically measured from a map or located in the field, in terms of UTM coordinates as well as latitude and longitude. The Landsat data of 1973 are with a spatial resolution of 57.5 m x 57.5 m (nominal resolution), while IRS P6 are of 5.8 m.

Land use analyses involved (i) generation of False Color Composite (FCC) of remote sensing data (bands–green, red and NIR). This composite image helps in locating heterogeneous patches in the landscape, (ii) selection of training polygons by covering fifteen percent of the study area (polygons are uniformly distributed over the entire study area) (iii) loading these training polygons co-ordinates into pre-calibrated GPS, (vi) collection of the corresponding attribute data (land use types) for these polygons from the ûeld. GPS helped in locating respective training polygons in the ûeld, (iv) supplementing this information with Google Earth and, (v) sixty percent of the training data has been used for classiûcation, while the balance is used for validation or accuracy assessment. The land use analysis was done using supervised classification technique based on Gaussian maximum likelihood algorithm with training data (collected from field using GPS).

Classifier based on Gaussian Maximum Likelihood algorithm has been widely applied as an appropriate and efficient classifier to extract information from remote sensing data. This approach quantitatively evaluates both the variance and covariance of the category spectral response patterns when classifying an unknown pixel of remote sensing data, assuming the distribution of data points to be Gaussian. After evaluating the probability in each category, the pixel is assigned to the most likely class (highest probability value). GRASS GIS (Geographical Resources Analysis Support System, http://ces.iisc.ernet.in/grass) a free and open source software with the robust support for processing both vector and raster data has been used for analyzing RS data. Temporal remote sensing data have been classified through supervised classification techniques by using available multi-temporal “ground truth” information. Earlier time data were classified using the training polygon along with attribute details compiled from the historical published topographic maps, vegetation maps, revenue maps, land records available from local administrative authorities.

Temporal remote sensing data of Landsat (1973) and IRS (2013) were classified into four land use categories (Fig. 9): tree vegetation, built-up, water-bodies and others (agriculture, open area, etc.). The analyses show decline of tree vegetation by fifty percent from 44.06 percent (1973) to 22.38 percent (2013), with an increase in built-up from 1.19 (1973) to 6.56 percent (2013). Details of land use analyses are listed in Table 6.

Integrated Wetlands Ecosystem: Sustainable Model to Mitigate Water Shortages in Bangalore

Performance assessment of an integrated wetland ecosystem at Jakkur provides vital insights towards mitigating water crisis in Bangalore. Functional aspects of the integrated wetlands systems are:

Table 6: Land use changes in Jakkur lake catchment (1973-2013)

	Land use categories (%)			
Years	*Urban*	*Vegetation*	*Water*	*Others*
1973	1.19	44.06	5.63	49.1
2013	6.56	22.38	4.79	65.81
% Change	5.37	-21.68	-0.84	18.71

- Sewage Treatment Plant (STP): The purpose of sewage treatment is to remove contaminants (Carbon and solids) from sewage to produce an environmentally safe water. The treatment based on physical, chemical, and biological processes include three stages – primary, secondary and tertiary. Primary treatment entails holding the sewage temporarily in a settling basin to separate solids and floatables. The settled and floating materials are filtered before discharging the remaining liquid for secondary treatment to remove dissolved and suspended biological matter. STP’s effluents were still nutrient rich requiring further treatment (for nutrient removal) and stabilization for further water utilities in the vicinity.
- Integration with wetlands [consisting of reed (typha etc.) beds and algal pond] would help in the complete removal of nutrients in the cost effective way. A nominal residence time (~5 days) would help in the removal of pathogen apart from nutrients. However, this requires regular maintenance of harvesting macrophytes and algae (from algal ponds). Harvested algae would have energy value, which could be used for biofuel production. The wetland systems helps in the removal of ~ seventy-seven percent COD, ~ ninety percent BOD, ~ thirty-three percent NO_3-N and ~ seventy-five percent PO_4^{3}-P (Fig. 10).

Pilot scale experiment in the laboratory has revealed nutrient removal of algae are eighty-six

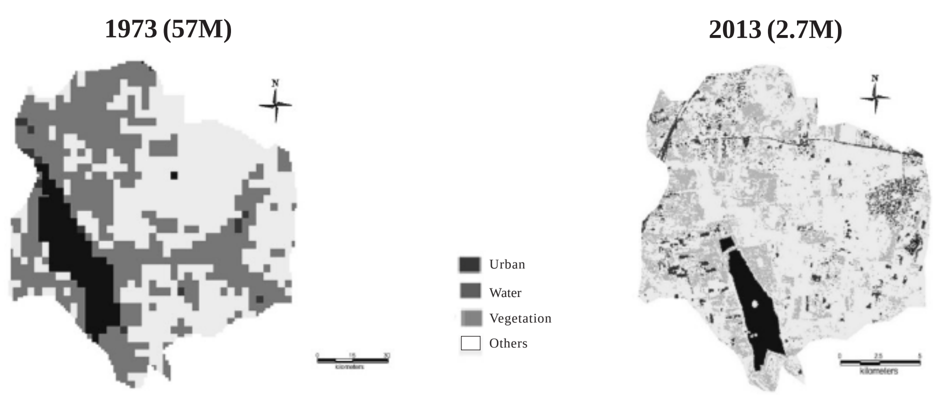

Fig. 9. Land use dynamics in Jakkur lake catchment
Source: Author

percent, ninety percent, eighty-nine percent, seventy percent and seventy-six percent for TOC, TN, Amm.-N, TP and OP respectively (Fig. 11) and lipid content varied from 18-28.5 percent of dry algal biomass. Biomass productivity is of ~122 mg/l/d and lipid productivity of ~32 mg/l/d. Gas chromatography and mass spectrometry (GC-MS) analysis of the fatty acid methyl esters (FAME) showed a higher content of desirable fatty acids (biofuel properties) with major contributions from saturates such as palmitic acid [C16:0; ~40%], stearic acid [C18:0; ~34%] followed by unsaturates as oleic acid [C18:1(9); ~10%] and linoleic acid [C18:2(9,12); ~5%]. The decomposition of algal biomass and reactor residues with calorific exothermic heat content of 123.4 J/g provides the scope for further energy derivation (Mahapatra et al. 2014). Water that comes out of the wetlands is portable with minimal efforts for pathogen removal via solar disinfection.

Earlier experiments have shown the vital role of wetlands in recharging the groundwater resources, evident from the decline of groundwater table to 200-300 m (with the removal of wetlands) from 30 to 50 m. Jakkur lake system is helping in recharging the groundwater sources. There need to be regulation on the exploitation of groundwater in Bangalore. Over exploitation of groundwater through borewells by commercial private agencies would harm the sustainability, depriving the local residents in the vicinity who are dependent on borewells in the absence of piped water supply from the government agency. Measures required to mitigate water crisis in burgeoning Bangalore are:

i. Rainwater harvesting at decentralized levels through wetlands (lakes) is the most efficient and cost effective mechanism to address the water crisis in the region than technically infeasible, ecologically unsound and economically unviable river diversion or inter linking of river schemes being proposed by vested interests in various parts of the country.
ii. Rejuvenation, restoration of existing lakes. This is necessary to decontaminate water bodies due to the unabated inflow of effluents and sewage.
iii. Removal of deposited silt would enhance the storage capacity as well as bioremediation capability of lakes.

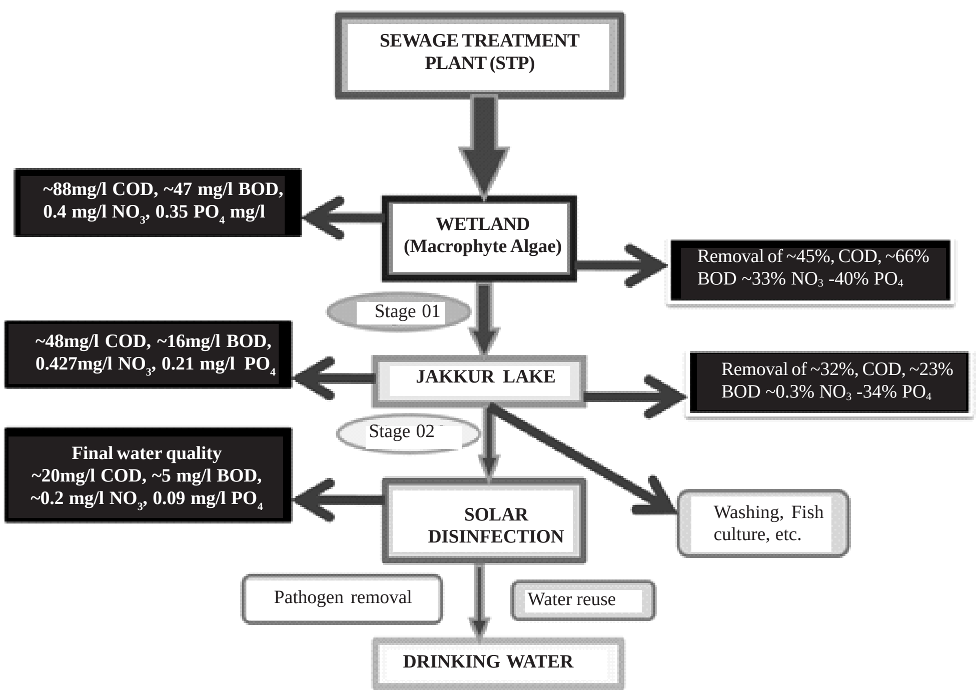

Fig. 10. Level of treatment at various stages of integrated wetlands system
Source: Author

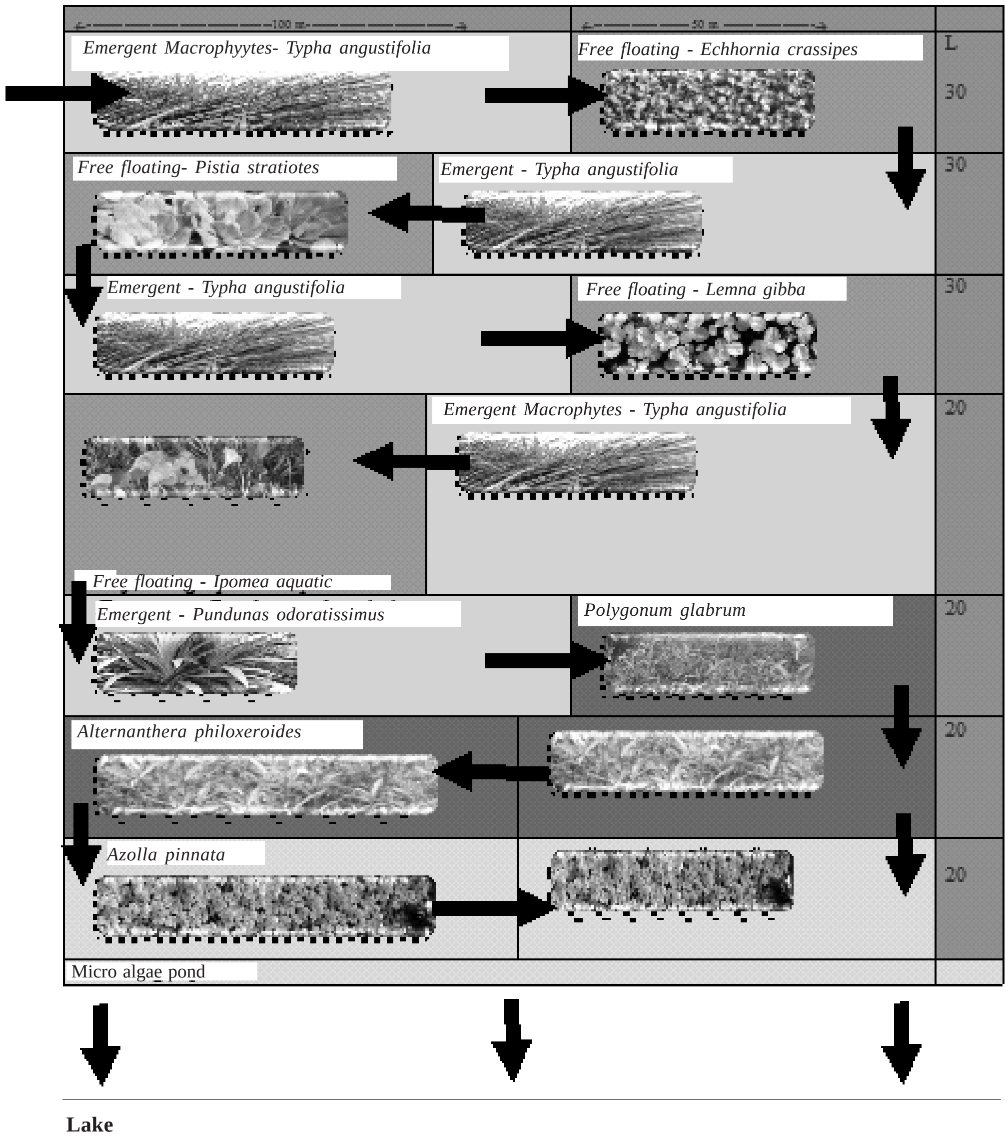

Fig. 11. Conceptual design of wetlands
Source: Author

iv. Integrated wetlands ecosystem (consisting of reed bed (typha, etc.) and algal pond) with lake helps in the treatment of water entering the lake through bioremediation. Replicating Jakkur wetland ecosystem would help in the treatment of water and reuse. This also has an added advantage of maintaining groundwater quality in the vicinity. Studies have shown that groundwater sources in the vicinity of sewage fed lakes are contaminated, evident from the nutrient enrichment, presence of coliform, etc.

v. Sustainable management of integrated wetlands ecosystem includes

vi. Letting only secondary treated sewage to wetlands.

vii. Maintaining atleast thirty-three percent vegetation cover in the lake catchment. This is necessary to ensure sufficient infiltration of rainwater to ensure water in the lake throughout the year.
viii. Ban on number of bore wells (or extraction of groundwater) in the lake catchment and command area.
ix. Restriction on overexploitation of groundwater in the lake catchment to ensure sustained water availability to the local residents.
x. Regular harvesting of macrophytes.
xi. Mechanism to harvest algae at regular interval and manufacture of biofuel and other beneficial biochemical products. These would enhance the employment opportunity in the region.
xii. Provision of appropriate infrastructure for washer men who depend on the lake for livelihood through washing clothes.
xiii. Restriction on the introduction of exotic species of fish by commercial vendors
xiv. Permission to scientific fish culturing through strict regulations (on fish species introduction, type of nets, frequency of harvesting, restrictions during breeding season and locations).

Area Required for Constructed Wetlands

Taking advantage of remediation capability of aquatic plants (emergent macrophytes, free floating macrophytes) and algae, constructed wetlands have been designed and implemented successfully for efficient removal of nutrients (N, P, heavy metals, etc.). Different types of constructed wetlands (sub surface 0.6 m depth, surface: 0.4 m, could be either horizontal or vertical). Area required for constructed wetlands depends on the influent sewage quality and expected treatment (BOD removal, etc.) is given in equation 1 (Vymazal et al. 1998). Estimates show that to treat 1 MLD influent, area required is about 1.7 hectares. Figure 11 gives the proposed design of wetlands to treat 1 MLD.

$$A = Q_d (\ln C_o - \ln C_t) / K_{BOD} \quad \ldots 1$$

Where,

A = area; Q_d= ave flow (m^3/day); C_o and C_t = influent and effluent BOD (mg/L); $K_{BOD} = 0.10$

For example to treat influent (raw sewage: BOD: 60-80) and anticipated effluent (with BOD 10), area required is about 1.7 to 2 hectares.

CONCLUSION

Surface water-bodies (lakes, ponds, tanks, etc.) in Bangalore are subjected to high nutrient loads due to the sustained inflow of untreated or partially treated sewage, altering physico-chemical and biological integrity of water bodies. The treated water from sewage treatment plant in Jakkur still contains nutrients as primary and secondary treatment does not completely remove nutrients. However, passage of STP effluents through wetlands (consisting of emergent macrophytes and algal pond) ensures removal of nutrients to an extent ensuring potability of water. This study investigates the water quality at different stages in the integrated wetland system. Physico-chemical and biological parameters were monitored as water enters the algal pond (wetland) from the STP (sewage treatment plant), outlet of wetlands and at the inlet, middle and outlets of Jakkur lake. The nutrient analysis highlights of nutrient removal by wetlands due to macrophytes and algae, which removes seventy-seven percent COD, ~ ninety percent BOD, ~ thirty-three percent NO_3-N and ~ seventy-five percent PO_4^{3-}P. The first stage comprising of emergent vegetation and algal pond removes ~ forty-five percent COD, ~ sixty-six percent BOD, ~ thirty-three percent NO_3-N and ~ forty percent PO_4^{3-}P. Jakkur lake as a second stage treats the water and acts as the final level of treatment and removes ~ thirty-two percent COD, ~ twenty-three percent BOD, ~ 0.3 percent NO_3-N and ~ thirty-four percent PO_4^{3-}P. The combination of all the stages leads to a complete removal of nutrients to acceptable levels according to CPCB norms. This study provided vital insights towards environmentally sound option of managing wastewater, while addressing water crisis due to unscientific and chaotic urbanisation in Bangalore.

RECOMMENDATIONS

Conservation and sustainable management of ecologically fragile wetlands requires good governance. This entails constitution of single administrative agency with the statutory and financial autonomy to be the custodian of natural resources [ownership, regular maintenance and action against polluters (encroachers as well as those contaminate through untreated sewage and effluents, dumping of solid wastes)]. Effective judicial system for speedy disposal of conflicts related to encroachment. Other suggestions are

1. Stop pollution – only treated sewage shall enter the lake. Sewage treatment through integrated constructed wetlands (similar to Jakkur Model – Secondary Treatment Plant (STP) + Constructed Wetlands + Algae ponds, will remove nutrients, etc.);
2. Implementation of 'polluter pays' principle as per the water act 1974; Zero discharge from industries;
3. No diversion of sewage from upstream to downstream regions and de-centralized treatment and reuse of treated sewage;
4. Remove all blockades at outlets as well as inlets – so that water will not stagnate, which will enhance aeration in the water body;
5. Remove all encroachments without any considerations or political interventions (lake bed, storm water drains, buffer zone);
6. De-siltation of lakes at regular interval to enhance storage capacity and also to remove contaminated sediments; Adopt latest state of the art technology - wet dredging to remove deposited sediments;
7. Stop dumping of solid waste and construction and demolition wastes in the lake bed, storm water drain;
8. Remove macrophytes (covered on the water surface) regularly;
9. Regular surveillance through vigilant resident groups and network of education institutions;
10. Regular monitoring of treatment plant and lake water quality (physical, chemical and biological) and the availability of information to the public through internet;
11. Install fountains (with music and LED) to enhance surface aeration and recreation value of the ecosystem;
12. No introduction of exotic species of fauna (fish, etc.);
13. Public Participation: Decentralised management of lakes through local lake committees involving all stakeholders - Involve local stakeholders in the regular maintenance and management;
14. Ban on use of phosphates in the manufacture of detergents; will minimise frothing and eutrophication of water bodies;
15. Digitation of land records (especially common lands – lakes, open spaces, parks, etc.) and availability of this geo-referenced data with query based information system to public;
16. Planting native species of macrophytes in the buffer zone (riparian vegetation) as well as in select open spaces of lake catchment area;
17. Restrictions on the diversion of lake for any other purposes;
18. No construction activities in the valley zones and in the buffer zones (75 m) of lakes.

ACKNOWLEDGEMENTS

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