Contribution of sewage treatment to pollution abatement of urban streams

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In this study, we assessed the efficiency and effectiveness of the Vrishabhavathy Valley Treatment plant (VVTP) in Bengaluru city, which is the oldest STP in the city. Since VVTP treats both raw sewage and polluted river water, with the latter constituting 80% of the influent, we sampled water quality at locations upstream and downstream of the plant to evaluate overall efficacy as well.

We found that VVTP is able to reduce biochemical oxygen demand (BOD_5) by only 47%. This low efficiency can be attributed to the high and variable levels of chemical oxygen demand, consistent with episodic industrial discharges. Moreover, the mean values of pH, dissolved oxygen, total suspended solids, BOD_5, nitrates, faecal coliforms and faecal streptococcus did not change significantly between upstream and downstream locations.

Treating river water using an STP is clearly not an efficacious way of improving river water quality. Thus, before setting up new STPs, sewerage boards need to invest in building the underground drainage network to bring raw sewage to existing STPs.

Keywords: Biochemical oxygen demand, particulate re-suspension, wastewater treatment, urban stream, water quality.

As human societies urbanize, the volume and concentration of sewage increases rapidly. Modern cities typically use wastewater treatment technologies in combination with underground sewerage networks to reduce the damage to the environment and risk to public health that raw sewage may cause. Sewage treatment plants (STPs) use a combination of physical, chemical and biological processes to reduce the organic load in wastewater. The treated wastewater is then either discharged to a surface water body (lake or stream) or is reused for non-potable purposes. In India, as per standards set by the Central Pollution Control Board[1], effluent from STPs should have organic matter less than or equal to 30 mg/l if discharged to a surface water body and faecal coliform (FC) levels less than or equal to 1000 MPN/100 ml if used for irrigation purposes. In developing countries such as India that are experiencing rapid urbanization and consequently high levels of sewage generation, there is an urgent need to monitor and improve the sewage treatment infrastructure.

There is substantial literature on the performance of STPs[2–7]. Much of this literature tends to focus on the internal functioning and technological choices: do the plants use resources efficiently, which technologies work better than others, and so on. Limited attention has been paid to the effectiveness of STPs in controlling pollution of streams[8–10]. Furthermore, the literature focuses on technologies rather than looking at an array of factors influencing effectiveness of these systems. We present here a case study of an STP in Bengaluru that examines efficiency of an STP and its effectiveness in improving stream water quality.

Site description

The population of Bengaluru city has grown from 4.2 million in 2001 to 8.4 million in 2011 (as per data from the Census of India). This rapid growth has overstressed the existing infrastructure of water supply and wastewater collection and treatment. While expanding water demand has been met through a combination of major increases in water imported from the Cauvery River and groundwater pumping, the wastewater treatment system has lagged far behind. Thus, while imported water increased from 453 million liters per day (MLD) to 1360 MLD from 1991 to 2013, in the same period, STP capacity increased only from 420 MLD (primary treatment level) to 720 MLD (secondary treatment level)[11,12].

Assuming that another 500–700 MLD is sourced from groundwater pumping[13], and 80% of the total water supplied for domestic non-consumptive use returns as sewage, about 1600 MLD of sewage is generated by Bengaluru each day[14]. Figure 1 shows the present scenario of sewage treatment in Bengaluru. Out of the total sewage generated, only an estimated 30% is treated[15]. A very small fraction of the treated sewage (0.4%) is reused; the rest is discharged into streams and lakes[16]. Urban streams that were once seasonal now carry wastewater (treated as well as untreated) from residential as well as industrial areas and flow throughout the year. The

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dissolved oxygen (DO) levels in such streams are very low and cannot support any kind of aquatic life[17].

We investigated the effect of sewage treatment on urban stream water quality using a case study of the Vrishabhavathy Valley Treatment Plant (VVTP). This is one of the oldest sewage treatment plants in Bengaluru and is located on the bank of one branch of the Vrishabhavathy stream, a stream that originates in Bengaluru and flows southwards to join the Arkavathy River, which eventually joins the Cauvery River. This study estimates the efficiency of VVTP, then assesses its effectiveness in improving stream water quality, and seeks to understand the factors constraining the effectiveness of sewage treatment. This study is part of a larger research project examining the sources and impacts of urban water pollution.

Vrishabhavathy stream originates from the northwest part of Bengaluru and is a second order tributary of Cauvery River. The Vrishabhavathy catchment upstream of VVTP is about 78 sq. km. A part of the catchment lies in the urban area of Bengaluru (Figure 2).

VVTP is located on the bank of Vrishabhavathy stream at a point 14 km from its origin. The designed capacity of VVTP is 180 MLD. It employs primary, secondary and tertiary water treatment technologies. The STP is designed to treat 180 MLD sewage to secondary levels out of which 60 MLD of secondary treated water is diverted to a tertiary treatment unit for further treatment. Due to the lack of an underground drainage (UGD) network in the VVTP catchment, VVTP receives only 20% of its daily inflow via the sewerage network (26 MLD); 80% is taken in via gravity flow directly from the Vrishabhavathy stream (104 MLD) (Figure 3). During the study period, due to some technical issues at VVTP, only 15 MLD of secondary treated water was treated to tertiary levels; vendors such as Aravind Mills were reusing 3 MLD and the remaining 127 MLD of treated effluent was discharged into Vrishabhavathy stream.

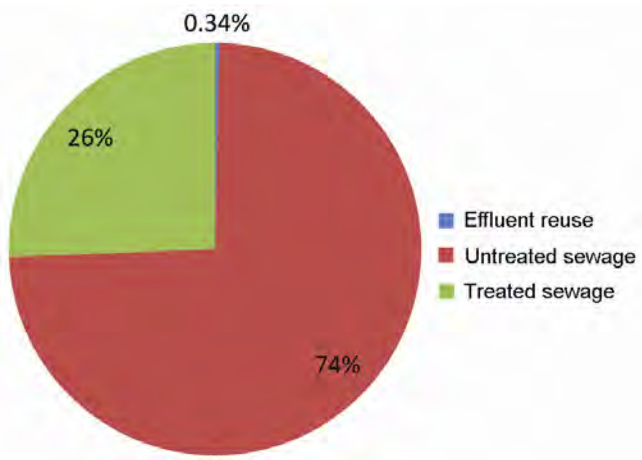

Figure 1. Wastewater scenario of Bengaluru city[15,16].

Framework and research design

We analyse the functioning of STPs at two scales. At the plant-scale, we define STP efficiency in the usual manner, viz. the percentage reduction in pollution parameters between the influent and effluent from the STP[18]. To estimate efficiency, we sampled and analysed water quality at the inlet and exit of VVTP; points VVTP-1 and VVTP-2 in Figure 4. Based on the organic matter removal efficiency, we estimated organic load capture and cross-checked this with sludge production at VVTP.

In addition, we also examined the effectiveness of the STP at the stream-scale, as its ability to improve water quality by reducing the organic load in the stream. To estimate effectiveness of sewage treatment, we collected water quality at points in the stream represented upstream (u/s) by VRH-5 and downstream (d/s) by VRH-6. We estimated the mass balance of biodegradable organic load in the stream.

We first estimated the total organic load in the stream with and without the presence of STP followed by an estimation of organic load capture by VVTP. In this estimation, while the volume of influent from the UGD system, the volume of water diverted from the stream into VVTP and the volume of treated effluent released back into the stream by VVTP were known (information provided by the plant operators), the total flow in the stream was unknown. We therefore measured the total flow in the stream using a simple float method. It was assumed that there was no significant stream flow addition (other than the VVTP outflow) to the stream between points VRH-5 and VRH-6, which were only 1.5 km apart.

Methodology

Sample collection

VVTP water samples were collected every week for three months, i.e. from August to October 2013. Water samples were collected in 1 litre polypropylene bottles, stored in an icebox at 4°C, and were transported to the ATREE Water and Soil Laboratory. The samples were analysed for physical, chemical and biological parameters following *APHA* (*American Public Health Association*) *Standards Handbook*[19].

STP efficiency estimation

The total suspended solids (TSS), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), nitrate, FC and faecal streptococcus (FS) removal efficiency of VVTP was estimated using the equation

$$\text{Efficiency (\%)} = (\text{IC} - \text{EC})*100/\text{IC}, \quad (1)$$

where IC is the influent concentration (mg/l) at VVTP-1; EC is the effluent concentration (mg/l) at VVTP-2.

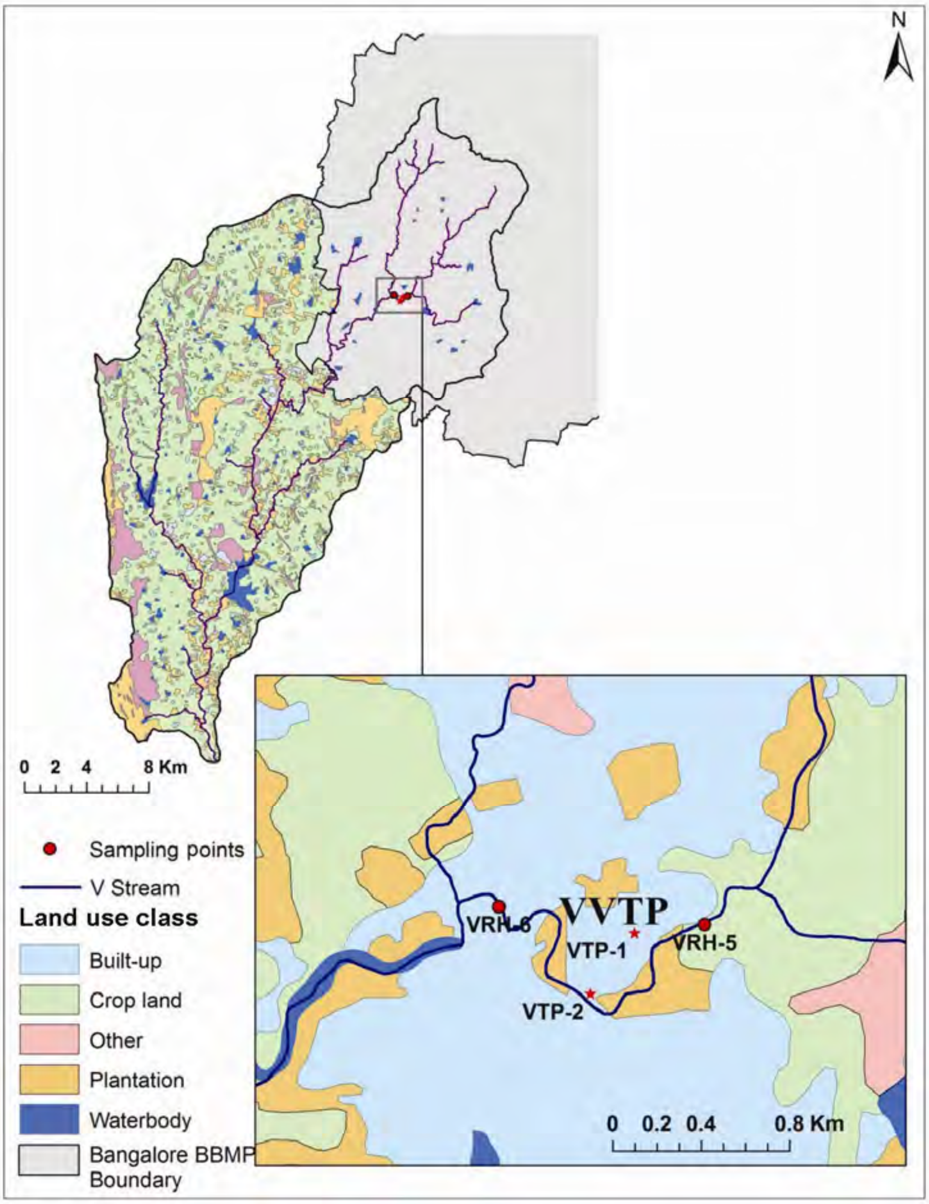

Figure 2. Vrishabhavathy watershed and location of sampling sites in Vrishabhavathy stream and VVTP.

Figure 3. Diversion of wastewater from Vrishabhavathy stream to VVTP.

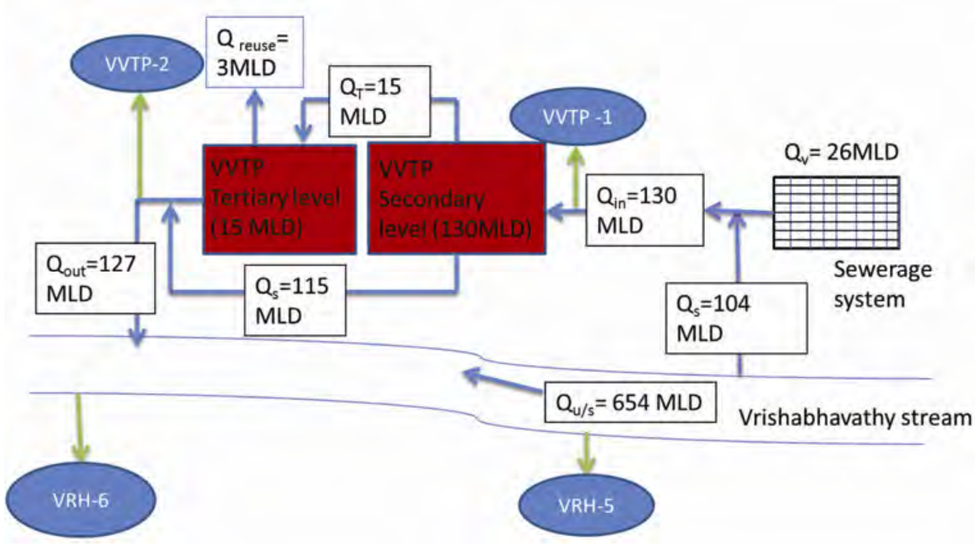

Figure 4. Schematic diagram of the study site indicating routing of water and sampling points.

Flow measurement

Next, we measured the total flow in the stream. The flow measurements could only be done during April 2013, because that was a low-flow period. Possible errors that might be introduced due to extrapolating this flow estimate to the other periods when water quality was measured are discussed here.

The float method was used to determine the flow at VRH-5 sampling site, after the STP has taken in some of the water from the Vrishabhavathy stream. Since the only additional flow between VRH-5 and VRH-6 was effluent discharge from VVTP, the flow at VRH-6 was calculated as the sum of flow at VRH-5 and effluent flow from VVTP. Cross-section profiling was undertaken once at the sampling site and flow velocity was measured in April 2013. The velocity measurement was carried out thrice and the average flow velocity was recorded. WinXSPRO software[20] was used to create a cross-sectional profile and calculate its area. Finally, the flow was calculated as the product of cross-sectional area and velocity. Samples for water quality analysis were collected from the stream during dry weather; the flow was assumed constant during this period because there were no major rain events.

Mass balance of organic load in stream

The main objective of this mass balance exercise was to explain the contribution of VVTP in altering stream water quality downstream of VVTP. Although, we only had a single measurement of water flow, we were able to collect multiple samples for water quality analyses over time. To estimate the average BOD_5 levels at the VRH-6 site, a simple mass balance model was used. Equation (2) presents the mass balance equation used to estimate pollutant concentration at VRH-6. The various parameters presented in eq. (2) are indicated in Figure 4 of the study area.

The average pollutant level was estimated using the mass balance equation and compared with the observed pollutant levels at VRH-6 site. Equation (2) presents the simple mass balance model used to estimate pollutant levels at VRH-6. $C_{d/s}$ and $Q_{d/s}$ are respectively, the concentration and flow at VRH-6.

$$C_{d/s} = \frac{C_{u/s}Q_{u/s} + C_{out}Q_{out}}{Q_{u/s} + Q_{out}}, \qquad (2)$$

where $C_{d/s}$ is the pollutant level in mg/l at VRH-6; C_{out} the pollutant level in mg/l at VVTP-2; $C_{u/s}$ the pollutant level in mg/l at VRH-5; $Q_{u/s}$ the Vrishabhavathy stream flow in MLD at VRH-5; Q_{out} the effluent flow in MLD at VVTP-2; $Q_{d/s}$ is the Vrishabhavathy stream flow in MLD at VRH-6 = $Q_{u/s}$ + Q_{out}.

The pollutant concentration and flow data were assumed to follow a normal distribution. Input values for concentration variables were based on the observed water quality at VRH-5. Estimate of effluent discharge (Q_{out}) were based on the interactions with VVTP staff. For modelling purposes, both $Q_{u/s}$ and Q_{out} were assumed constant over the period for which BOD_5 levels were measured and estimated.

Organic load capture estimation

We assessed the contribution of VVTP in reducing the organic load of Vrishabhavathy stream by estimating the organic load in stream under two scenarios, viz. in the presence and absence of VVTP. The difference between the organic load for the two scenarios provided the estimate for organic load capture by VVTP. To validate our estimates, we then compared organic load capture estimates with the sludge production data from VVTP. Organic load estimation at VRH-6 is calculated using the equation

$$BOD_5 \text{ load (kg/day)} = C_{u/s}Q_{u/s} + C_{out}Q_{out}. \quad (3)$$

The organic load capture by VVTP is estimated using the equation

$$BOD_5 \text{ load captured by VVTP (kg/day)} = (C_{in} - C_{out}) \times Q_{in}, \quad (4)$$

where $C_{u/s}$ is the BOD_5 level in mg/l at VRH-5; C_{in} the inflow BOD_5 in mg/l at VVTP-1; C_{out} the outflow BOD_5 in mg/l at VVTP-2; $C_{u/s}$ the Vrishabhavathy stream flow in MLD at VRH-5; C_{in} the sewage flow in MLD at VVTP-1; C_{out} is the effluent flow in MLD at VVTP-2.

Results and discussion

Efficiency of VVTP at the plant-scale

Table 1 presents the water quality characteristics of the samples collected from the influent and effluent of the VVTP. The average pH of the influent and effluent samples suggested that water was alkaline in nature. Average conductivities of 1022 and 1030 μS/cm were observed in the influent and effluent water samples respectively, indicating high levels of dissolved inorganic salts. We observed high variability in influent total suspended soilds (TSS) levels, which could be attributed to the variations in the stream TSS. We observed a minor increase in DO levels of the effluent samples, which is the result of oxygen dissolution during biological treatment process.

We observed high levels of nitrates in the inflow water samples of VVTP. This could be the result of nitrification of ammonia-based substances present in the Vrishabhavathy stream. No significant difference was observed in the nitrate level of influent and effluent of VVTP, which could be attributed to the absence of de-nitrification treatment unit at VVTP.

The average COD of the influent into VVTP and at VRH-5 upstream of VVTP were 730 and 635 mg/l respectively. Moreover, standard deviation of the COD at these sites was also high. While about half of the samples showed COD levels consistent with domestic sewage, half of the samples recorded very high COD levels, suggestive of episodic industrial discharges. In contrast, the BOD_5 of the influent into VVTP and in the stream was consistently below the BOD_5 of raw sewage (350 mg/l)[21] at 128 and 116 mg/l respectively. This BOD_5/COD ratio < 0.5 and the relatively low BOD_5 of Vrishabhavathy stream water compared to raw sewage, suggests that the influent into VVTP probably includes a combination of domestic sewage with industrial effluent and that some self-purification occurs in the Vrishabhavathy stream. Both the absolute BOD_5 level and the BOD_5/COD are critical to the proper functioning of the treatment plant because biological treatment is contingent on having a reasonable amount of 'food' for the microorganisms to

Table 1. Physical chemical and biological characteristics of influent and effluent samples from VVTP

Water quality parameter	Statistical parameters	VVTP-1	VVTP-2	Efficiency (%)
pH	Mean	7.5	7.5	NA
	Std. Dev.	0.4	0.1	
Conductivity (μS/cm)	Mean	1022	1030	NA
	Std. Dev.	86	72	
DO (mg/l)	Mean	0.2	0.5	NA
	Std. Dev.	0.1	0.4	
TSS (mg/l)	Mean	510	89	82
	Std. Dev.	140	39	
BOD_5 (mg/l)	Mean	128	67	47
	Std. Dev.	41	15	
COD (mg/l)	Mean	730	166	77
	Std. Dev.	491	66	
Nitrate (mg/l)	Mean	35.0	40.2	–5.2
	Std. Dev.	6.4	14.6	
Log (FC)	Mean	7.8	5.8	2 log order*
	Std. Dev.	0.7	0.4	
Log (FS)	Mean	7.7	7.0	0.7 log order*
	Std. Dev.	0.1	1.3	

*In case of faecal coliforms (FC) and faecal streptococcus (FS) efficiency is measured in terms of log reduction from influent to effluent samples. DO, Dissolved oxygen; TSS, total suspended solids; BOD, biochemical oxygen demand; COD, chemical oxygen demand; Std. Dev., Standard deviation.

Table 2. Physical, chemical and biological characteristics of water samples at VRH-5 and VRH-6 sites

Water quality parameter	Statistical parameters	VRH-5	VRH-6
pH	Mean	7.3	7.3
	Std. Dev.	0.1	0.1
Conductivity (μS/cm)	Mean	923	936
	Std. Dev.	79	55
DO (mg/l)	Mean	0.2	0.2
	Std. Dev.	0.3	0.2
TSS (mg/l)	Mean	475	436
	Std. Dev.	135	128
BOD_5 (mg/l)	Mean	116	113
	Std. Dev.	45	48
COD (mg/l)	Mean	635	422
	Std. Dev.	458	345
Nitrate (mg/l)	Mean	23.9	26.1
	Std. Dev.	5.2	6.5
Log (FC)	Mean	7.4	8.0
	Std. Dev.	0.8	0.5
Log (FS)	Mean	7.5	8.0
	Std. Dev.	0.51	0.5

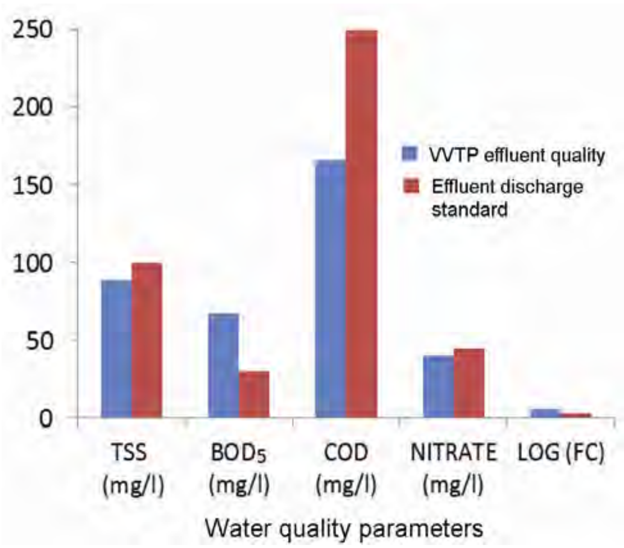

Figure 5. Comparison of VVTP effluent water quality with effluent discharge standards.

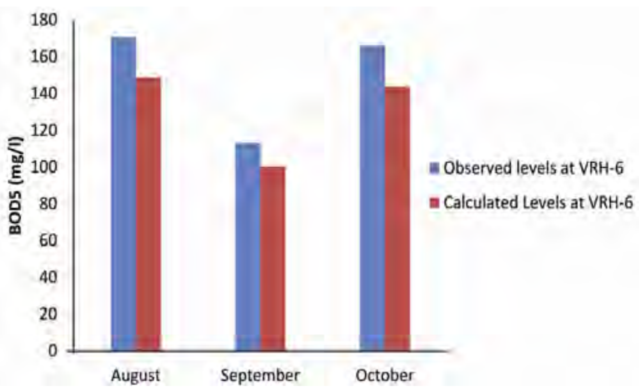

Figure 6. Comparison of observed and calculated BOD_5 levels at VRH-6.

process. This suggests that a biological treatment process is not appropriate given the influent characteristics of VVTP.

We observed that while COD drops on average during the treatment process, BOD_5 does not decrease as much. The average influent and effluent BOD_5/COD ratio at VVTP were 0.2 and 0.5 respectively. We hypothesize that the failure to effectively treat BOD_5 could be indicative of inefficient functioning of the secondary clarifier. The secondary clarifier removes the biomass from treated water by sedimentation. The biomass removal efficiency of secondary clarifiers is a function of biomass quality. The quality of biomass produced in the treatment plants depends on the F/M (food/microorganism ratio). A low F/M ratio promotes the growth of filamentous bacteria, which forms flocs of poor quality. The average BOD_5 observed in influent samples of VVTP is less than the designed BOD_5 levels (350 mg/l) for STPs, this promotes the growth of filamentous bacteria, thereby affecting the treatment process[22]. The biomass formed by filamentous bacteria escapes sedimentation in the secondary clarifier and is likely contributing to the higher BOD_5 in the effluent of the treatment plant.

The effluent FC levels (10^5 MPN/100 ml) from VVTP exceeded the water quality criteria for unrestricted irrigation (10^3 MPN/100 ml). According to STP design manual by the Center for Public Health and Environmental Engineering Organization (CPHEEO), the two stage trickling filters can reduce FC levels in sewage by 4 to 6 log orders. However, the observed reduction in FC and FS levels at VVTP averaged 2 and 0.6 log orders respectively, much lower than the CPHEEO design standard. Theoretically, there are various factors, which affect the survival of FC in sewage treatment plant. Longer retention time, protozoan grazing, competition with the reactor

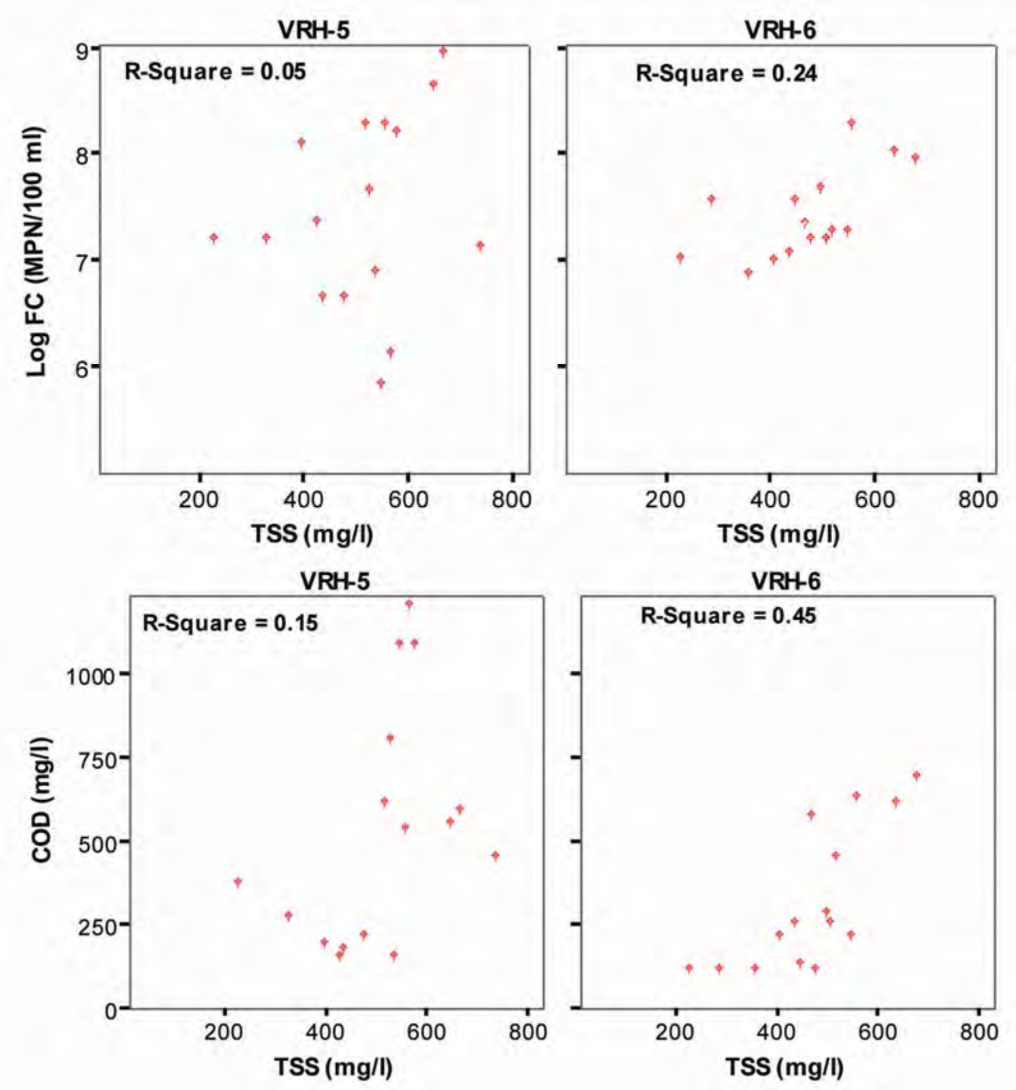

Figure 7. Correlation between TSS versus COD and FC versus TSS levels at VRH-5 and VRH-6.

microflora and sedimentation with flocs favour removal of FC during wastewater treatment. In the case of VVTP, we speculate that poor floc removal by the secondary clarifier has affected the FC removal efficiency.

Figure 5 presents the comparison of effluent water quality with the discharge standards. Except BOD_5 and FC, the other water quality parameters were well within the effluent discharge standards (CPCB).

Effectiveness of VVTP at stream-scale

Stream quality: To evaluate the effectiveness of VVTP on stream water quality, we collected water samples from the stream at the VRH-5 and VRH-6 sites. Table 2 presents the physical, chemical and biological characteristics of the water samples from the Vrishabhavathy stream. We carried out paired-statistical tests (Student *t*-test) to check the difference in means of various physical, chemical and biological parameters at VRH-5 and VRH-6 sampling sites. Interestingly, except for COD, no significant difference was observed in the mean levels of TSS, BOD_5, nitrates, FC and FS levels at VRH-5 and VRH-6 ($P < 0.05$).

To evaluate the impact of VVTP on Vrishabhavathy stream quality, observed and estimated BOD_5 levels at VRH-6 were compared over a three-month period. The estimated BOD_5 levels at VRH-6 were calculated using eq. (2). The flow of 654 MLD, estimated using the float method, was fed into the model and was assumed constant for the sampling period. Figure 6 presents the comparison between the observed and the calculated BOD_5 level at VRH-6. The observed BOD_5 levels at VRH-6 are greater than the estimated levels for all three seasons.

First, the model explains the poor stream quality at VRH-6; the dilution of stream water by treated sewage is too low (dilution factor is 0.2), to see any noticeable improvement in the stream water quality at VRH-6 and the BOD_5 removal efficiency of VVTP itself is very low (47%). Second, the discrepancy between the observed and modelled BOD_5 at VRH-6 site suggests that re-suspension of stream sediments may be reintroducing organic matter into the stream at VRH-6. Effluent discharge from VVTP increases flow velocity in stream, which might have resulted in re-suspension of organic sediments at VRH-6. Figure 7 presents the scatter plot of TSS versus COD and FC versus TSS levels at VRH-5 and VRH-6 sampling sites. COD and FC are positively correlated to TSS at VRH-6, whereas no significant correlation is observed between COD and TSS at VRH-5. This suggests that TSS at upstream site is mainly composed of inorganic particulate matter as compared to downstream where re-suspension might have contributed to organic sediments in stream samples. Thus, we suspect that re-suspension of organic sediments could be one of the reasons for the difference between observed and estimated BOD_5.

Organic load capture: We estimated the organic load in Vrishabhavathy stream at VRH-6 site considering two scenarios, i.e. in the absence and presence of VVTP. The total amount of organic load leaving the catchment at VRH-6 was estimated using eq. (3). We found that in the absence of VVTP, the total organic load leaving the catchment would be 104 tonnes/day. Diversion and treatment of 104 MLD of stream water and 26 MLD of domestic sewage has led to the capture of approximately 7 tonnes/day of organic load (eq. (4)). The estimated biomass production from the organic load capture of 7 tonnes is approximately 1 tonne per day. To check our estimates, we compared biomass production estimated with the sludge production data from VVTP. The actual sludge produced per day at VVTP is reported as 750 kg, which is close to the estimated value. The low level of sludge production suggests that VVTP operates much below its actual operating capacity and there are technical issues that have led to the poor functioning of VVTP. Sludge produced at VVTP is directly sent to the sludge drying beds from where it is either sold to the farmers or used for landfilling.

Conclusion

This study was designed to assess the efficiency of VVTP and its effectiveness in improving the Vrishabhavathy stream water quality. To achieve this, VVTP pollutant removal efficiency was evaluated and the impact of treated effluent on Vrishabhavathy stream water quality was assessed. The question we were trying to answer through this study is why despite discharge of treated effluent from VVTP, there has been very little impact on Vrishabhavathy stream water quality.

Using the combination of empirical water quality testing and mass balance model upstream and downstream of the VVTP in the Vrishabhavathy stream in Bengaluru, we arrived at the following conclusions.

First, most of the wastewater being treated at VVTP consists of water being drawn from the stream, and not from the sewerage network. This is despite the fact that VVTP is one of the oldest treatment plants in Bengaluru, the UGD infrastructure lags behind.

Second, the organic load removal efficiency of VVTP is very low at 47%. The influent to VVTP was very high in COD, with a BOD_5/COD ratio of 0.2. The BOD_5 level in the influent was also much lower than raw sewage (partly because of self-purification in-stream), which the VVTP is not designed for. Moreover, the COD in the influent was highly variable across samples, consistent with sporadic industrial discharges. The presence of industrial effluents may also negatively impact the efficiency of the VVTP plant as 70–80% of the total organic matter in the influent water is non-biodegradable. STPs are typically designed to treat biodegradable domestic sewage. Therefore, to improve the efficiency of VVTP, either taking in stream water needs to be abandoned or treatment technology needs to be changed.

Third, only a small fraction (20%) of the flow in the Vrishabhavathy stream is currently being treated. This suggests that paradoxically, the overall wastewater treatment capacity in Bengaluru city is low, notwithstanding evidence of underutilization of existing wastewater treatment capacity.

Fourth, there was no significant difference in water quality upstream and downstream of VVTP, i.e. no net impact of VVTP on water quality of the Vrishabhavathy stream was observed. Several factors contributed to the poor quality of stream water. (i) Low dilution, as the ratio of treated wastewater to overall stream flow is small. (ii) Low pollutant removal efficiency of VVTP because of low BOD_5/COD ratio at VVTP-1. (iii) Possible re-suspension of particles in stream due to increase in flow velocity downstream of the plant.

Fifth, VVTP captures only 7 tonnes/day of the total 104 tonnes/day of organic load in stream. The amount of organic capture by STP is a function of its BOD_5 removal efficiency, which in case of VVTP is very low (47%). The need of the hour is to maximize organic load capture, which after stabilization could be used for fertilizer application and landfilling.

Finally, DO levels recorded at VRH-5 and VRH-6 were less than 1 mg/l. Vrishabhavathy stream belongs to the category E of the classification suggesting that this stream should only be used for controlled waste disposal and industrial cooling.

The study contributes several interesting insights of relevance to policymakers. Addition of new wastewater treatment capacity without expanding the sewerage network is problematic. The current solution to the lack of sewerage connectivity is to treat the stream water directly, but this approach is also not effective because the high level of non-biodegradable (COD) content and low BOD_5 content in the Vrishabhavathy stream which negatively impacts the pollutant removal efficiency of the VVTP. STPs should focus on local reuse of wastewater to increase organic load capture and expanding the UGD system rather than pollution control by dilution. Policy amendments are required to promote effluent reuse.

A constraint on this study was the absence of continuous monitoring and gauging of Vrishabhavathy stream. We suggest that this should be facilitated in order to track the efficiency of and effluent releases from domestic as well as industrial WWTPs. This exercise would help in identification of pollution sources, which would help in better enforcement of existing pollution laws.

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