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Reuse of treated sewage in Delhi city: Microbial evaluation of STPs and reuse options

Priyanka Jamwal[a], Atul K. Mittal[b,*]

[a] Department of Civil Engineering, Indian Institute of Science Bangalore, 560012, India
[b] Department of Civil Engineering, Indian Institute of Technology, Delhi, New Delhi 110016, India

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ABSTRACT

Microbiological quality of the treated wastewater is an important parameter for its reuse. The data on the Fecal Coliform (FC) and Fecal Streptococcus (FS) at different stages of treatment in the Sewage Treatment Plants (STPs) in Delhi watershed is not available, therefore in the present study microbial profiling of STPs was carried out to assess the effluent quality for present and future reuse options. This study further evaluates the water quality profiles at different stages of treatment for l6 STPs in Delhi city. These STPs are based on conventional Activated Sludge Process (ASP), extended aeration, physical, chemical and biological treatment (BIOFORE), Trickling Filter and Oxidation Pond. The primary effluent quality produced from most of the STPs was suitable for Soil Aquifer Treatment (SAT). Extended Hydraulic Retention Time (HRT) as a result of low inflow to the STPs was responsible for high turbidity, COD and BOD_5 removal. Conventional ASP based STPs achieved 1.66 log FC and 1.06 log FS removal. STPs with extended aeration treatment process produced better quality effluent with maximum 4 log order reduction in FC and FS levels. "Kondli" and "Nilothi" STPs employing ASP, produced better quality secondary effluent as compared to other STPs based on similar treatment process. Oxidation Pond based STPs showed better FC and FS removals, whereas good physiochemical quality was achieved during the first half of the treatment.

Based upon physical, chemical and microbiological removal efficiencies, actual integrated efficiency (IE_a) of each STP was determined to evaluate its suitability for reuse for irrigation purposes. Except "Mehrauli" and "Oxidation Pond", effluents from all other STPs require tertiary treatment for further reuse. Possible reuse options, depending upon the geographical location, proximity of facilities of potential users based on the beneficial uses, and sub-soil types, etc. for the Delhi city have been investigated, which include artificial groundwater recharge, aquaculture, horticulture and industrial uses such as floor washing, boiler feed, and cooling towers, etc.

1. Introduction

Delhi, capital city of India is about 1485 km^2 in area, out of this approximately 63% is urbanized. River Yamuna serves about 75% of the total population of the watershed. Problem of water shortage in Delhi has been exacerbated as a result of high natural population growth, urbanization, industrialization and migration. Consequently, Delhi is facing a future of very limited water resources. About 30% of the total water demand in Delhi watershed is met by groundwater sources. Consequently, due to overexploitation, the groundwater level in Delhi city has declined to 10–20 m below ground level and the deepest water level is about 40 m below ground level in south Delhi region.

Wastewater reuse has recently been looked up as a potential option to cope up with the increasing water stress. Reclaimed water is suitable for many applications, such as irrigation, toilet flushing, cleaning, industrial reuse and environmental enhancement (El-Gohary et al., 1998; Scott et al., 2003; Jimenez et al., 2001; Jimenez and Chavez, 2002; Chang et al., 2007; Chiou et al., 2007). Because of its stable quantity, reclaimed water from domestic Sewage Treatment Plants (STPs) could be a reliable alternative water resource.

Delhi city has 17 STPs located in the outskirts and along the banks of river Yamuna. City generates 2.98×10^6 cubic meter sewage per day (m^3/d). The actual treatment capacity of STPs of Delhi watershed is 1.44×10^6 m^3/d, thus around 50% of the total wastewater generated gets treated that can be reused. STPs are usually designed to efficiently remove organic matter (suspended and dissolved) and nutrients, but seldom have they been planned specifically to remove pathogenic microorganisms from wastewater. Thus, reuse of treated wastewater from such STPs needs careful evaluation.

* Corresponding author. Tel.: +91 11 26591239; fax: +91 11 26581117.
E-mail address: akmittal@civil.iitd.ac.in (A.K. Mittal).

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The removal efficiency of pathogenic and indicator microorganisms in conventional STPs vary according to the characteristics of influent sewage, type of treatment process, Hydraulic Retention Time (HRT), biological flora present in treatment plants, pH, temperature and the efficiency in removing suspended solids (Jimenez et al., 2001; Koivunen, 2003; Chuang et al., 2005; Zhang and Farahbakhsh, 2007). Though conventional STPs have been reported to reduce the numbers of enteric microbes but as reductions in treatment processes vary extensively depending on the above listed factors, effluents still contain high Fecal Coliforms (FC) levels (Mara, 2001; Abdel-Shafy et al., 2004; Foppen and Schijven, 2005).

The reuse options depend on the quality of effluent produced after the treatment of the sewage (Megdal, 2006; Chiou et al., 2007). At present the data regarding organic load, i.e., BOD_5 and COD removal is available for the STPs in Delhi. The absence of microbial data for these STPs restricts the wastewater reuse options. Besides, the level of tertiary treatment shall also depend on the FC and FS levels in the secondary effluent.

Improper planning of wastewater reuse may expose large number of people including workers, and farmers to pathogenic microorganisms thus posing a high risk to public health (Friedler et al., 2006; Zaidi, 2006). Keeping in view the interest of public health, National River Conservation Directorate (NRCD, 2005) in India has reviewed the wastewater standards with special reference to the levels of microbial load.

In the present study, microbial quality of wastewater for all 17 STPs at different stages of treatment has been studied. A number of different biological treatment processes are employed at STPs. Effluent quality has been related with the type of treatment process. Reuse options are evaluated with respect to the local conditions and applicability of specific reuse options in conformity with the local geographical, hydrological, and accessibility issues. Evaluation of STPs employing different technologies is carried out with special reference to FC and Fecal Streptococcus (FS) removal at different stages of treatment. The study focuses on the wastewater reuse options for STPs taking public health into consideration.

2. Methodology

In this study all 17 STPs located in Delhi were sampled (Table 1). Water quality was analyzed at the influent, after primary treatment and after secondary treatment.

2.1. Sampling

The sampling campaigns for all STPs were carried out for a period of 12 months, i.e., from November 2005 to November 2006. Samples were collected at after every treatment step from all STPs. During the evaluation period, each STP was sampled four times. Samples were collected at every stage of the treatment (Figs. 1–6). The influent samples were collected from the sump constructed to hold the water after pumping the sewage from open drains or sewerage system. In all, 234 samples were collected and analyzed.

2.2. Physiochemical and bacteriological analysis

Samples were preserved at 4 °C during transportation to laboratory. They were immediately analyzed for FC, FS, Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD_5), pH and turbidity. All the analyses were carried out as per the Standard Methods (APHA, 1998).

FC and FS were enumerated using Most Probable Number method (MPN). For the enumeration of FC and FS, samples were suitably diluted using sterile de-ionized water before inoculation in appropriate medium. Enumeration of FC was carried out by direct inoculation technique using A1 broth (Difco) as per Standard Methods. FS were recovered on Azide dextrose broth (HiMedia) at an incubation temperature of 35 ± 0.5 °C for 48 h. All positive tubes were subjected to the confirmation test by using Pfizer selective enterococcus Agar (HiMedia).

2.3. Treatment process description

All the STPs investigated consisted of either single stage treatment (secondary) or two stage treatment (primary and secondary). Different types of primary and secondary treatment processes were employed in these STPs (Table 1).

2.3.1. Primary treatment processes

Figs. 1–6 present the process flow diagram of different STPs in Delhi city. In conventional ASP, the Primary Settling Tank (PST) is employed to remove the suspended particles. The designed HRT for PST was 2.5 h. The PST for all STPs employing ASP was of circular cross-section (Figs. 1–2). In Trickling Filter process recirculation ratio was 1:1, so as to dilute the effluent after Primary Settling Tank and thereby improving the total treatment efficiency (Fig. 3).

Table 1
Wastewater treatment plant characteristics.

Sewage Treatment Plant	Technology	Design flow (MLD)	Hydraulic retention time (h)				Utilization (%)
			PST/physical treatment	Biological reactor/chemical treatment	SST/biological treatment	Total HRT	
Kondli (KND)	ASP	204	7.33	17.33	7.33	32.00	30.00
Yamuna Vihar (YV)	ASP	91	7.33	17.33	7.33	32.00	30.00
Rithala I (RIT I)	ASP	182	3.83	9.04	3.83	16.70	57.50
Coronation pillar (CP I)	ASP	136	4.40	10.40	4.40	19.20	50.00
Okhla (OKH)	ASP	636	2.93	6.93	2.93	12.80	75.00
Nilothi (NIL)	ASP	182	17.60	41.60	17.60	76.80	12.50
Keshopur (KSH)	ASP	327	4.40	10.40	4.40	19.20	50.00
Papankallan (PPK)	ASP	91	4.89	11.56	4.89	21.33	45.00
Vasant Kunj I (VKI)	Extended aeration	14	–	30.00	3.30	33.30	66.67
Mehrauli (MEH)	Extended aeration	23	–	58.82	6.47	65.29	24.00
Nazafgarh (NAZ)	Extended aeration	23	–	83.33	9.17	92.50	24.00
Coronation pillar CP (TF)	Trickling Filter	45	3.75	5.00	3.75	12.50	40.00
Rithala II (RIT II)	High rate aeration	182	3.20	2.26	3.20	8.66	66.25
Oxidation Pond Timarpur (OP)	Oxidation Pond	27	–	433.90	33.33		
Delhi gate[a] (DG)	Biofore	10	2.50	4.00	2.50	9.00	100.00
Sen nursing[a] home (SNH)	Biofore	10	2.50	4.00	2.50	9.00	100.00

[a] Physical, chemical and biological treatment (BIOFORE).

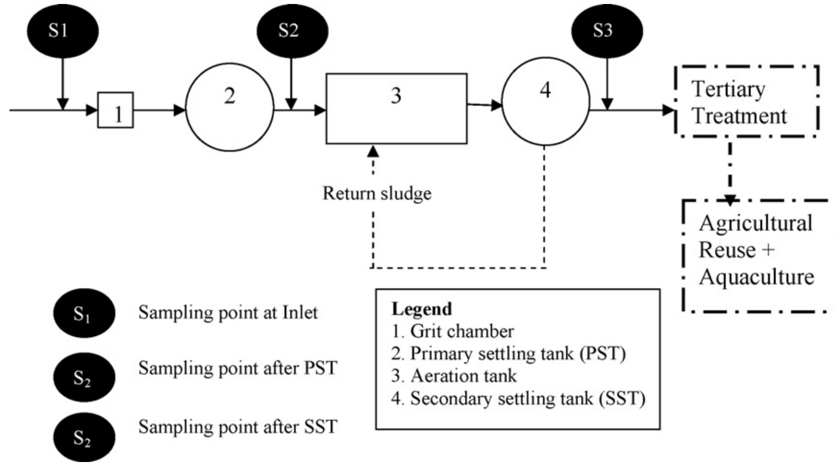

Fig. 1. Sampling points at different locations in Activated Sludge Process.

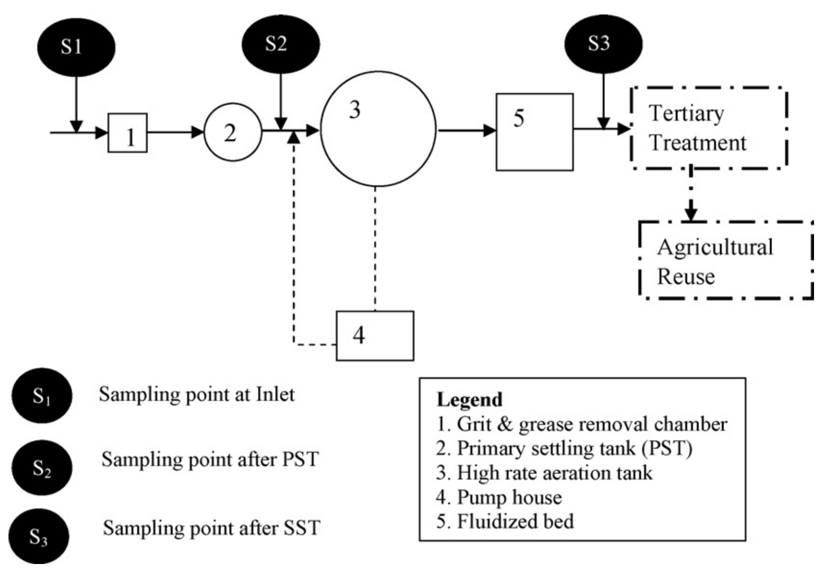

Fig. 2. Sampling points at different locations for high rate aeration process.

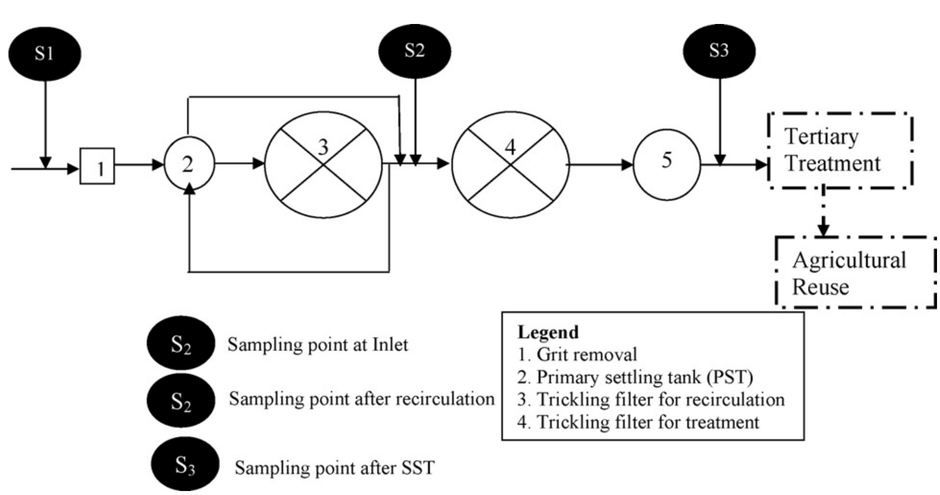

Fig. 3. Sampling points at different locations in Trickling Filter process.

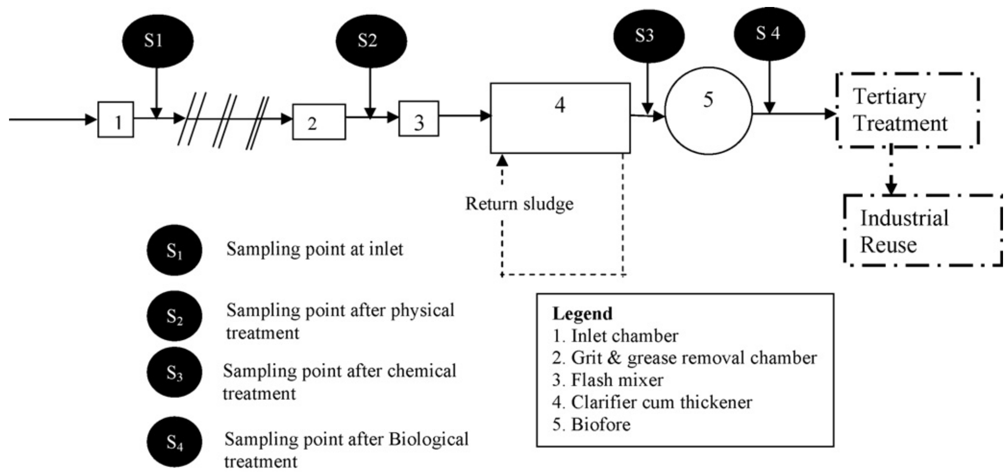

Fig. 4. Sampling points at different locations in BIOFORE.

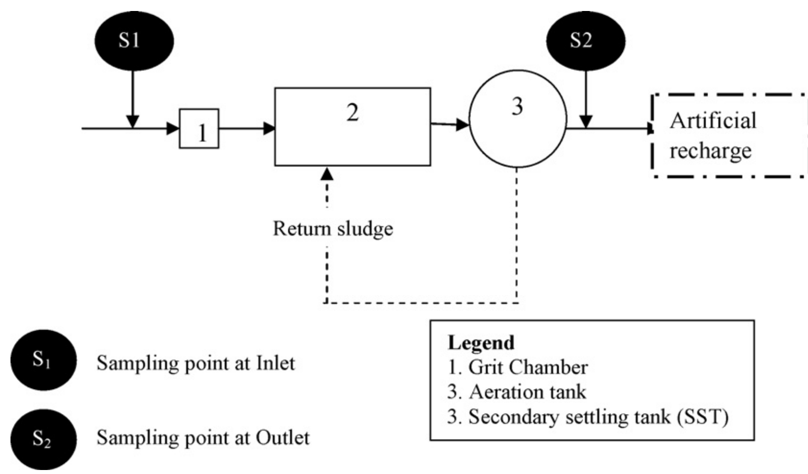

Fig. 5. Sampling points at different locations in extended aeration process.

In STPs employing physical, chemical and biological process (BIOFORE), the primary treatment consists of removal of suspended particles by screening. This process involves passage of influent through a series of screens having 30, 20 and 15 mm pore sizes (Fig. 4).

As STPs based on extended aeration process and Oxidation Pond, employ single stage treatment the influent and effluent samples of these STPs were analyzed (Fig. 5). The Oxidation Pond STP, which consists of series of four ponds, middle sample was also analyzed (Fig. 6).

2.3.2. *Secondary treatment*

In ASP, the primary effluent is treated for dissolved organic matter. To evaluate the efficiency of secondary process, samples were collected after secondary clarifier. Because of low incoming sewage, the HRT of biological reactor in case of all STPs employing ASP was more than design HRT (5.5 h) (Table 1). “Rithala II” STP was based on the high rate aeration process followed by upflow fluidized bed for removal of dissolved organic matter and coliforms (Fig. 2). In case of Trickling Filter the samples were collected after the secondary clarifier as shown in Fig. 3.

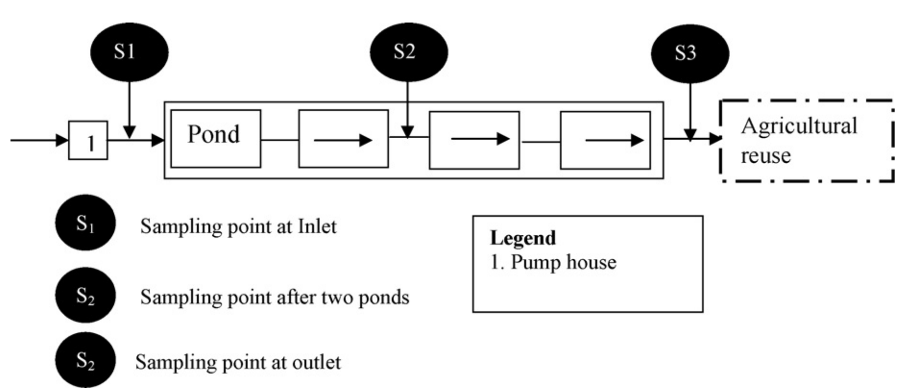

Fig. 6. Sampling points at different locations in Oxidation Pond.

For STPs based on BIOFORE technology, the secondary treatment consists of two steps, i.e., chemical and biological treatment. After physical treatment wastewater is pumped to a rapid mix coagulation tank where a high dose of coagulant is added followed by a slow mix flocculation tank where high molecular weight polymer electrolyte is added. After coagulation and flocculation, effluent flows to the tube settlers and then finally flows to fluidized bed for bacteriological removal. To evaluate the effect of chemical and biological treatment for these STPs, samples were collected after tube settlers and fluidized bed reactor as shown in Fig. 4.

For STPs based on extended aeration process, samples were collected after secondary clarifier as shown in Fig. 5. Oxidation Pond consists of series of similar ponds through which sewage flows in horizontal direction. To evaluate the removal efficiency, samples were collected when half and full treatment process was over as shown in Fig. 6.

3. Results and discussion

3.1. Raw sewage characteristics

Table 2 lists the influent sewage characteristics of the STPs. COD varied from 202 mg/l at "Nazafgarh", to 714 mg/l at "Vasant Kunj", while BOD_5 varied from 160 mg/l at "Nazafgarh", to 380 mg/l at "Papankallan" and turbidity varied from 50 NTU at "Coronation Pillar" to 646 NTU at "Vasant Kunj". FC and FS levels were observed to be maximum at "Kondli" (7.90 log order) and at "Vasant Kunj I" (7.48 log order), respectively. Minimum FC and FS levels were found at "Oxidation Pond" (5.54 log order) and at "Coronation Pillar" (4.17 log order).

Low COD and BOD_5 values observed at "Nazafgarh" STP which was due to irregular power supply, as a result of which the influent samples collected from the sump were of better quality as compared to influent samples from other STPs. "Delhi Gate" STP receives wastewater through open drain from industrial areas, contributing to high COD value.

"Vasant Kunj" STP receives domestic sewage from residential areas therefore has high turbidity, COD and FC levels, similar to that of raw domestic sewage, whereas "Coronation Pillar" received industrial and septic, dark colored sewage contributing to low turbidity. "Kondli" and "Yamuna Vihar" STPs are located in the Trans-Yamuna area. It gets sewage from resettlement colonies and slums through open drains. Both resettlement colonies and slums are not served by sewerage system and as a result around 3 million people defecate in open drains everyday (YAP, 2006) contributing to high levels of FC.

Low FC and FS levels and FC/FS ratio less than 1.2 at "Delhi Gate", "Oxidation Pond" and "Coronation Pillar" further support the fact that these STPs receive large quantities of industrial as well as septic sewage from open storm drains that effects the survival of indicator organisms.

3.2. Primary treatment

Figs. 7–12 present physiochemical and biological quality of wastewater at different stages of treatment in Delhi city. In case of STPs based on ASP, maximum turbidity removal (70%) was observed at "Kondli". Increase in turbidity was observed in primary effluent from "Coronation Pillar". "Coronation Pillar" STP was fed by septic and stale sewage from open drain collecting domestic as well as industrial areas, thereby causing increase in the turbidity due to prolonged stagnation. Minimum turbidity removal of 5% was observed at "Yamuna Vihar" STP.

The COD removal efficiencies in primary treatment ranged from 26 to 73% at "Yamuna Vihar" and "Coronation Pillar", respectively.

Table 2
Physiochemical and biological investigation of raw wastewater, primary effluent and secondary effluent in wastewater treatment plants, Delhi.

	Turbidity (NTU)			COD (mg/l)			BOD (mg/l)			TKN (mg/l)			FC (log MPN/100 ml)			FS (log MPN/100 ml)		
	Raw	PST	SST	Raw	PST	SST	Raw	PST	SST	Raw	PST	SST	Raw	PST	SST	Raw	PST	SST
KON	425.98	125.34	5.98	551	128.00	24.00	140.00	60.00	9.00	64.96	23.80	3.64	7.87	6.21	4.20	6.62	5.70	3.89
YV	237.62	255.99	39.82	261.33	192.00	64.00	220.00	102.00	10.00	–	–	–	7.02	6.58	5.09	5.96	5.96	4.71
RIT I	308.17	130.95	50.75	464.00	229.33	112.00	329.33	145.00	72.00	53.52	43.36	37.24	6.54	5.37	5.37	6.89	6.76	5.39
RIT II	308.17	232.28	226.12	464.00	213.33	141.33	329.33	106.33	90.00	53.52	33.69	33.62	6.54	5.99	5.64	6.89	5.84	5.53
CP I	50.77	110.36	8.343	208.00	56.00	8.00	264.00	48.00	18.00	46.2	29.12	6.72	6.00	5.55	4.84	4.17	3.00	2.60
OKH	281.63	227.04	2.98	356.84	205.31	25.39	220.00	45.00	37.50	51.52	48.44	19.04	6.91	6.03	5.27	6.44	5.69	4.49
NIL	446.71	224.43	33.46	357.33	181.33	40.00	215.00	53.75	17.20	35.84	31.36	7.84	7.16	6.97	4.20	6.30	5.96	4.24
KHSP	336.35	220.15	60.56	512.00	298.67	170.66	340.00	60.00	50.00	73.36	43.68	37.80	7.27	6.74	5.19	6.89	6.40	5.94
PPK	397.23	210.88	11.94	424.00	165.33	48.00	380.00	94.00	40.00	51.89	33.60	17.55	6.60	6.23	5.41	6.64	6.38	5.24
CP(TF)	50.77	61.72	91.03	320.44	112.00	48.00	264.00	108.00	40.00	46.20	25.48	20.44	6.00	5.51	4.52	4.17	3.00	2.65
OP	252.145	105.15	5.38	312.00	40.00	21.33	183.45	26.63	6.46	41.81	19.97	5.70	5.54	4.99	2.08	5.93	3.97	1.86
DC[a]	276.42	347.42	23.18, 4.68	666.67	688.88	100.00, 21.33	350.00	370.00	24.00, 2.00	64.21	64.96	23.12, 19.18	7.02	6.19	5.67, 4.95	7.21	7.07	5.73, 4.70
SNH[a]	303.47	279.92	25.57, 7.39	592.00	512.00	128.00, 53.33	317.50	195.45	73.40, 17.4	59.78	58.10	26.04, 20.81	7.01	6.19	5.72, 4.49	6.99	6.70	5.97, 4.19
VKI	646.03	–	3.43	714.66	–	24	205.33	–	16.00	59.84	–	18.85	7.31	–	4.602	7.48	–	4.11
MEH	311.00	–	3.80	432.00	–	32.00	402.00	–	4.80	92.96	–	4.29	7.11	–	3.02	6.25	–	2.92
NAZ	136.80	–	31.38	202.67	–	72.00	160.00	–	26.00	52.83	–	25.39	6.50	–	3.88	5.30	–	3.42

[a] Physical, chemical and biological treatment (BIOFORE).

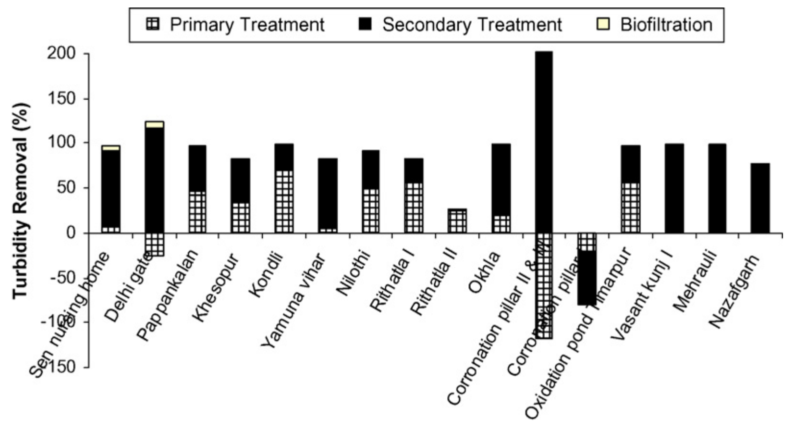

Fig. 7. Turbidity removal efficiency at different stages treatment process.

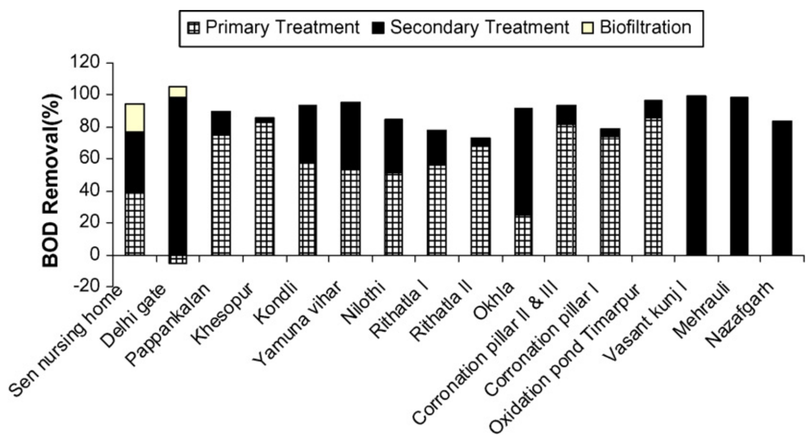

Fig. 8. BOD_5 removal efficiency at different stages treatment process.

Low COD removal at "Yamuna Vihar" STP indicated presence high colloidal and dissolved matter (organic and inorganic) in influent sewage. "Yamuna Vihar" STP serves the Trans-Yamuna area comprising of slums and resettlement colonies with no sanitation system. The per capita water supply is for these areas are 50 liters per capita per day (lpcd); thereby the sewage generated is rich in organic matter. The organic matter gets enough time to decompose as it reaches the STP through open drains, thereby contributing to low turbidity and COD removal after primary treatment.

Highest BOD_5 removal efficiency of 82% was observed at "Keshopur" STP. At "Nilothi" the average HRT was highest of all other STPs employing ASP which stimulated development of anaerobic conditions in PST thereby converting particulate to dissolved organic matter and is responsible for lowest BOD_5 removal efficiency (52%). Maximum and minimum TKN removal efficiencies achieved during sedimentation process were 63% and 5% at "Kondli" and "Okhla" STPs, respectively.

FC removal observed by primary sedimentation process ranged from 0.19 to 1.66 log orders at "Nilothi" and "Kondli" STP, respectively, whereas minimum and maximum FS removal of 0.01 and 1.05 log orders was observed at "Yamuna Vihar" and "Rithala II" STP. Zhang and Farahbakhsh (2007) recently observed less than 1 log order removal in FC and coliphage level by primary sedimentation process. Average 2 and 4 log order removal was observed in

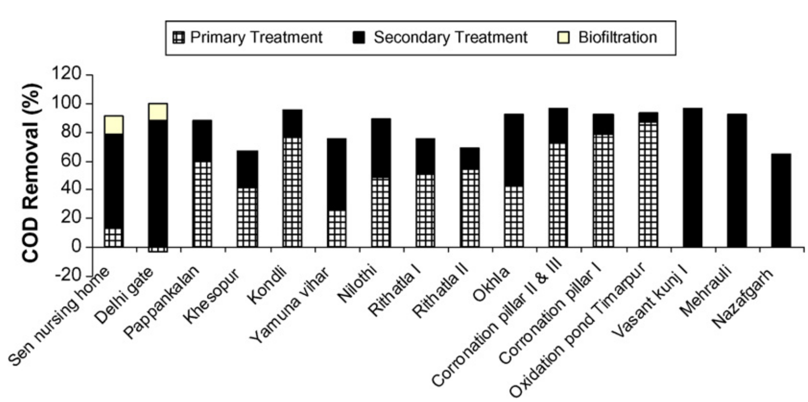

Fig. 9. COD removal efficiency at different stages treatment process.

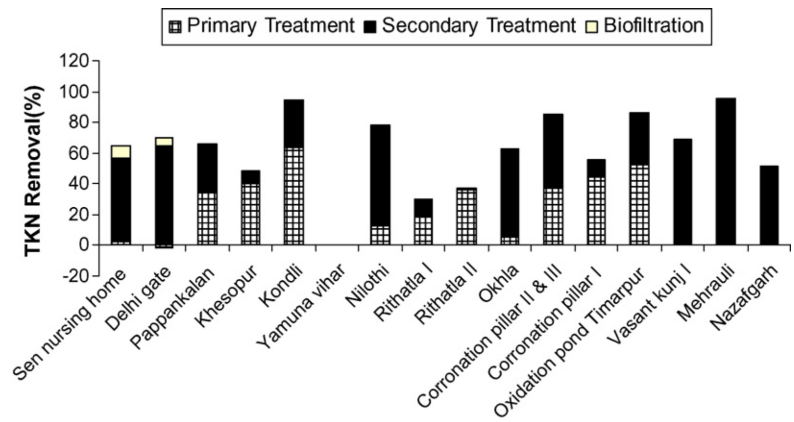

Fig. 10. TKN removal efficiency at different stages treatment process.

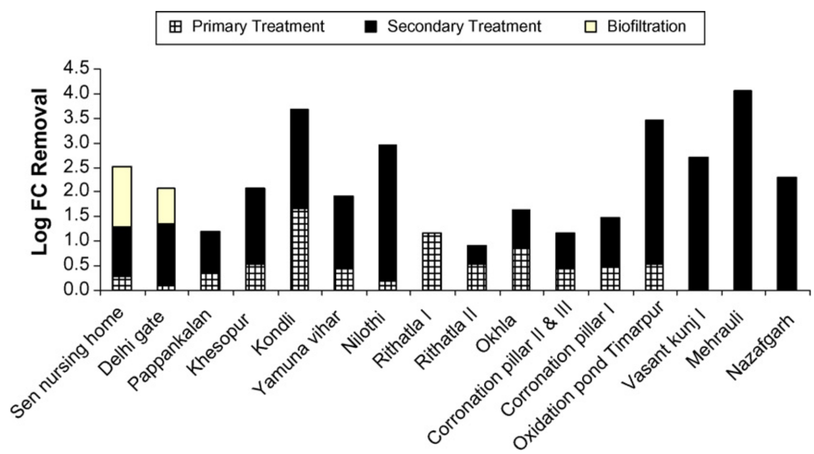

Fig. 11. Log FC removal at different stages treatment process.

FC and FS level by primary sedimentation process (El-Gohary et al., 1998). The FC and FS removal in STPs may be attributed to the operating parameters such as HRT, influent sewage characteristics and re-growth capabilities depending on the environmental factors.

The primary effluent characteristics of wastewater are presented in Table 2. Nema et al. (2003) reported 90% reduction in COD, BOD_5 and TSS concentration by Soil Aquifer Treatment (SAT) of primary settled sewage. The average input concentrations of BOD_5, COD and TSS reported were 93, 230 and 110 mg/l, respectively. Removal of bacteria was found 4–5 order of magnitude with initial TC, FC and FS counts in wastewater were 2×10^7, 3×10^6 and 2.8×10^6 MPN/100 ml, respectively. Depending on the above influent characteristics for Soil Aquifer Treatment proposed by Nema et al. (2003), except for “Keshopur”, “Nilothi”, “Rithala I”, “Rithala II” and “Yamuna Vihar” STPs, primary effluent produced from other STPs can be used for soil aquifer recharge depending on the soil characteristics of the proposed area.

“Delhi Gate” and “Sen Nursing home” STPs employ physical and chemical treatment as a primary treatment process. Average COD, BOD_5 and TKN removals from these STPs were more than 80, 85, and 60%, respectively. FC and FS levels were above log 5.5 (Table 2). The effluent after physical and chemical treatment from these STPs

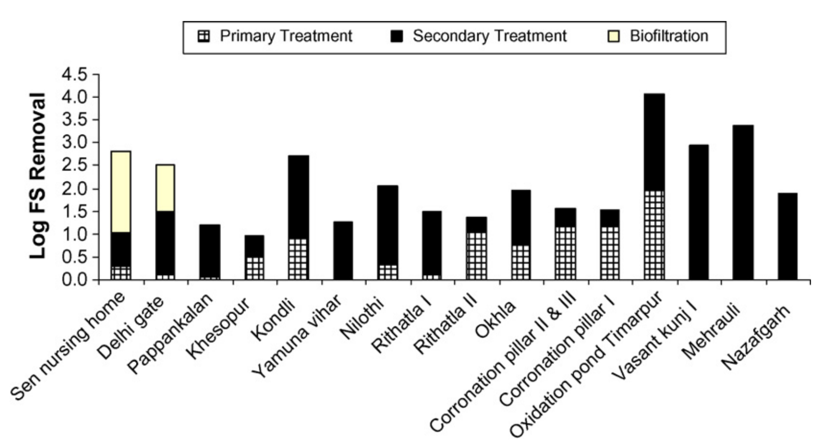

Fig. 12. Log FS removal at different stages treatment process.

is not fit for any direct wastewater reuse option. However, indirect reuse option like SAT could eliminate the use of secondary treatment. Otherwise, secondary treatment is warranted for any direct reuse option.

"Coronation Pillar II" STP is based on attached growth process. The physiochemical and microbiological quality of diluted effluent after recirculation from PST is presented in Table 2. More than 50% reduction was observed in BOD_5, COD and TKN concentration (Figs. 8–10). Slight increase in turbidity was observed after PST which could be attributed to dilution from first stage Trickling Filter. The diluted effluent after PST has low concentration of COD, BOD_5 and TKN, but not much reduction has been observed in FC and FS (0.48 and 1.17 log order) indicating that single stage Trickling Filter is not effective in improving the biological quality of primary effluent (Table 2).

In the "Oxidation Pond" based STP, high improvement in the physico-chemical quality of the wastewater observed during first half of the Oxidation Pond treatment process (Figs. 7–10). Low FC and FS removal, i.e., 0.54 and 1.96 log order, respectively, were observed during the initial treatment process indicating that ambient environmental factors support the growth of indicator organisms (Figs. 11–12).

3.3. Secondary effluent characteristics

Secondary treatment is employed for the removal colloidal and dissolved organic matter present in primary effluent. Removal efficiencies depend on the type treatment technologies employed and on the climatic conditions of the area (Hendricks, 1972; Gerba and McLeod, 1976). The secondary effluent characteristics of all STPs in Delhi watershed are presented in Table 2.

From Fig. 7 it is clear that the turbidity removal by secondary treatment ranged from 80% at "Okhla" to 26% at Rithala II. Maximum removal of COD (50%), BOD_5 (67%) and TKN (57%) were observed at "Okhla". "Okhla" STP received fresh domestic sewage through well maintained sewerage system without any mixing of the industrial wastewater; thereby a high degree of biodegradation in the aeration tank of the biological process occurred there.

Minimum COD removal (18%) was observed at "Kondli" STP whereas lowest BOD (24%) and TKN (8%) removal was achieved at "Keshopur" STP. Except "Okhla" all other STPs were based on ASP and received mixed sewage from open storm drains thereby affecting the removal efficiency of biological reactors.

FC and FS removal was 2.0 and 1.8 log order, respectively, at "Nilothi" STP. Extended HRT of 76 h was responsible for observed greater removal efficiency. Predation by higher organisms and environmental factors such as sunlight, temperature, etc. also contributes to removal efficiency (Fujioka et al., 1981). No reduction in FC level by secondary treatment was observed at "Rithala I" indicating possible re-suspension of sediments and re-growth of FC within the biological reactor and secondary clarifier. High turbidity (50 NTU) of secondary effluent also indicates poor settling characteristics of sludge which leads to re-suspension of particles.

Performance of STPs in Delhi to remove FC and FS were in accordance with other published works, i.e., FC and FS removals by 1.66 and 1.06 logs order (Aulicino et al., 1996), and 2.0 log order for FC (Scott et al., 2003).

STPs based on extended aeration process, i.e., "Vasant Kunj I", "Mehrauli" and "Nazafgarh" showed better performance with COD and BOD_5 removals more than 98 and 92%, respectively, except for "Nazafgarh" STP. COD and BOD_5 removal at the "Nazafgarh" STP were 65 and 84%, which could be attributed to the frequent power failure at the "Nazafgarh" STP. Microbial quality of the effluent from these STPs was the best, with 4.07 and 3.37 log order removal of FC and FS, respectively, at "Mehrauli" STP. Low F/M ratio in extended aeration imparts good settling characteristics to flocs thereby responsible for better removal efficiencies.

The newly installed STPs, i.e., "Delhi Gate" and "Sen Nursing home" were based on new BIOFORE (physical, chemical and biological) treatment technology (Fig. 4). The final microbial quality of effluents from these plants was inferior to the microbial quality of effluent from the extended aeration based plants (Table 2). It is a clear case for elimination of chemical step in context of the microbial quality of the final effluent. However, the efficiency of BOD_5 removal has improved by the chemical step. It has been reported in the literature that the addition of chemical coagulants improves the efficiency of treatment process (Jimenez et al., 2001; Jimenez, 2007; Zhang and Farahbakhsh, 2007). Microbial quality is an important issue for the direct reuse of the wastewater, which is not addressed by this technology.

"Coronation Pillar II" STP which employs the attached growth treatment process was expected to provide better turbidity removal as compared to ASP based STPs. However, the final effluent has high turbidity compared to the ASP based STPs. This STP received industrial sewage, presence of various compounds and their oxidation during treatment process may impart color and turbidity to final effluent.

"Oxidation Pond" based STP showed best removals for all parameters, i.e., turbidity, COD, BOD_5, FC and FS. FC and FS were less than 3 log order. Jimenez (2007) has also reported Oxidation Pond to be more efficient to remove microorganisms. Effluent from this STP can be reused for horticulture safely. Indirect reuse employing SAT would make good quality water available which could be used for air conditioning, toilet flushing, and gardening, etc.

3.4. Determination of integrated efficiencies of STPs evaluated

From the above results, it is clear that STPs exhibited different physical, chemical and microbiological efficiencies depending upon the characteristics of influent, HRT, percentage of capacity utilization, etc. Therefore the need is to define one common parameter that could determine the overall efficiency of STP in terms of physical, biochemical and microbiological removal efficiencies. This parameter will also help in making decisions for efficient reuse of effluent.

Colmenarejo et al. (2006) determined general efficiency indicator to compare overall performances of the different plants. General efficiency was an average of total suspended solids, COD, BOD_5 and ammonia removal efficiencies. In cases, where wastewater is used for irrigation purposes, microbiological quality of reclaimed water is important along with the physical and chemical qualities, since presence of microbes directly effects the health of the farmers and the people consuming raw vegetables, etc.

So, actual and standard integrated efficiency (IE) for STPs were determined taking into consideration turbidity, BOD_5 and FC removal. Calculations of actual and standard integrated efficiencies for each STP were based on influent sewage characteristics

$$IE_a = \frac{1}{3}[E_{TUR} + E_{BOD_5} + E_{FC}] \quad (1)$$

where IE_a is the actual integrated efficiency in (%), E_{TUR} is average efficiency of turbidity removal (%), E_{BOD_5} is average efficiency of BOD_5 removal (%), E_{FC} is average efficiency of FC removal (%). Thus, in order to evaluate integrated efficiency physical, chemical and biological removal efficiencies of STPs were determined.

For standard integrated efficiency (IE_s) physical, chemical and microbiological removal efficiencies were evaluated assuming that all STPs produced effluent quality meeting wastewater reuse criteria. Whereas in case of actual integrated efficiency (IE_a) actual removal efficiencies of STPs were considered.

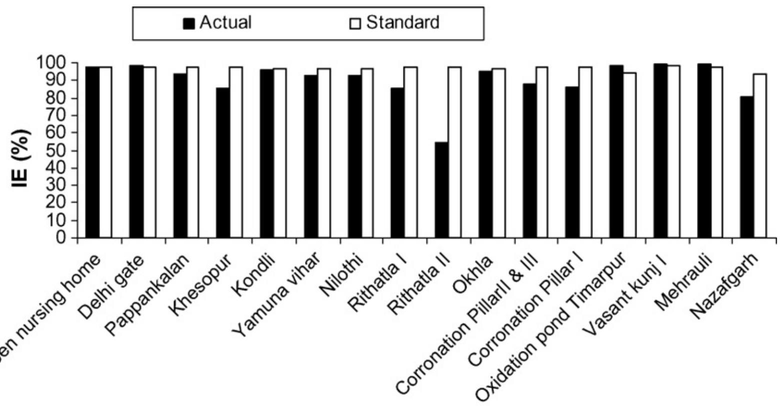

Fig. 13. Standard and actual integrated efficiency of all STPs evaluated. *Wastewaters reuse criteria: turbidity—2 NTU (Andreadakis et al., 2003); BOD_5—30 mg/l and FC 1000MPN/100 ml (NRCD, 2005).

The IE_a greater than 98% was observed for "Vasant Kunj I", "Oxidation Pond" and "Mehrauli" (Fig. 13). Effluents from these STPs are comparatively safer for agricultural use than from other STPs.

For STPs with extended aeration process IE_a was in the range 96–99% except in the case of "Nazafgarh", where irregular power supply was the main reason for poor performance. For STPs based on ASP, IE_a varied from 85–97%, "Kondli" having highest IE_a of 97%. IE_a value greater than 97% was also obtained for "Sen Nursing home" and "Delhi Gate" STP based on BIOFORE treatment process.

3.5. Wastewaters reuse option in Delhi city

3.5.1. Existing reuse

Table 3 presents the final disposal points of secondary effluent from STPs in Delhi watershed. Presently in Delhi, 46,100 and 5000 ha of land is available for agriculture and floriculture, respectively. Secondary effluents from "Keshopur" and "Okhla" STP are used for floriculture, horticulture and irrigation (restricted and unrestricted) and effluent from "Coronation Pillar" STP is discharged into irrigation channel for further use. Treated wastewater from "Sen Nursing Home" and "Delhi Gate" STPs, are used by Delhi Vidhyut Board (DVB) for cooling towers in thermal power plant and is finally discharged into river Yamuna. Vaidya et al. (2003) reported increased Risk of Hepatitis E in sewage workers from India suggesting that strict adherence to good working practices must take top priority for protection of these workers from sewage pathogens. World Health Organization (WHO) recommended standards for microbiological quality of treated wastewater when used for restricted and unrestricted irrigation, to be 10^5 FC/100 ml and 10^3 FC/100 ml, respectively. When wastewater effluent is to be used for aquaculture the FC level should not exceed 10^3MPN/100 ml. Thus, based on these guidelines and research outcomes, the secondary effluent from all STPs except "Oxidation Pond" and "Mehrauli" STP shall pose risk to public health. So, direct reuse is not possible before improving the quality of the effluent.

Table 3
Disposal of effluent from existing STPs.

STP	Final disposal point	Treatment required + potential reuse options
Delhi Gate	Thermal Power Plant/Horticulture	Tertiary treatment + industrial reuse
Sen Nursing Home	Thermal Power Plant/Horticulture	Tertiary treatment + industrial reuse
Okhla I–V	Irrigation and Floriculture	Tertiary treatment + agriculture and Industrial reuse
Keshopur	Nazafgarh Drain, Irrigation and Floriculture	Tertiary treatment + agricultural reuse
Rithala I	Supplementary Drain	Tertiary treatment + agricultural reuse
Rithala II	Supplementary Drain	Tertiary treatment + agricultural reuse
Coronation Pillar	Irrigation Channel	Tertiary treatment + agricultural reuse
Oxidation Pond	Nazafgarh Drain	No tertiary treatment required + agricultural and industrial reuse
Yamuna Vihar	Shahdara Trunk Drain No. 1	Tertiary treatment + aquaculture
Kondli	Shahdara Drain	Tertiary treatment + aquaculture
Nazafgarh	Nazafgarh Drain	Tertiary treatment + agricultural reuse
Papankallan	Nazafgarh Drain	Artificial groundwater recharge
Vasant Kunj	Local Drain	Artificial groundwater recharge
Mehrauli	Local Drain	Artificial groundwater recharge
Nilothi	Nazafgarh Drain	Tertiary treatment + agricultural reuse

From the present study, it is evident that the potential usage of the treated effluent in Delhi city is for irrigation, horticulture and recreation (water bodies—uncontrolled public access). Thus to mitigate public health risk, it is mandatory to employ tertiary treatment unit employing disinfection, if reclaimed water is to be used for unrestricted irrigation, aquaculture, recreation and for artificial recharge.

3.5.2. Reuse potential

At present, about 33% of the total wastewater produced (1.50×10^6 m^3/d) is used for irrigation purposes, either directly from open storm drains or treated effluent from STPs. Only 1% of secondary effluent is being utilized for industrial purposes. About 66% of the total reclaimed water produced finds its way to open storm drains, therefore the entire effort of treatment is wasted. Figs. 1–6 presents the potential reuse options for the STPs in Delhi city.

Out of total 17 STPs in Delhi, 6 STPs are located on the outskirt of city, where large swathes of fallow land is available. Some of the STPs like "Nazafgarh", "Papankallan", "Keshopur" and "Nilothi" STPs are located along the Nazafgarh drain (Fig. 14). The land use of the area surrounding these STPs is predominantly based on agriculture. All these STPs except "Keshopur" STP discharge their effluents in Nazafgarh drain. Local framers lift water from the Nazafgarh. Water quality of this drain is inferior since this drain also receives untreated sewage, industrial wastewaters and partially treated sewage. The treated sewage from the above 6 STPs can be directly supplied to the farmers. It would reduce the public health risk which may otherwise arise from the direct exposure of far workers to poor quality water and ingestion of microbes result-

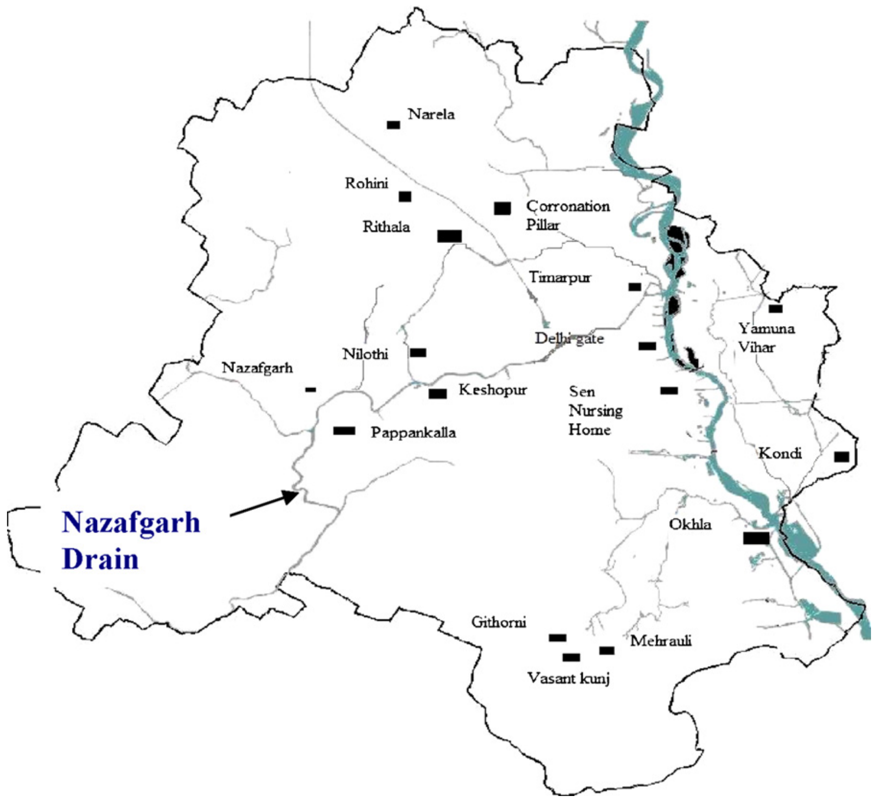

Fig. 14. Location of wastewater treatment plants in Delhi watershed.

ing from the consumption vegetable, etc. grown using the water from the drain.

"Vasant Kunj" and "Mehrauli" STPs are located in the Vasant Vihar ridge forest area. Central Groundwater Authority (CGWA, 2004) stated that this area is a "Water Recharge Area" for the underlying aquifers in the vicinity. This report also stated that the fractured, weathered rocks allow 85% percolation of rainwater. Artificial recharge structures are constructed in this area by CGWA, but due to non-availability of sufficient runoff they are not utilized efficiently. Treated secondary effluent from "Mehrauli" and "Vasant Kunj" STP is available throughout the year, thus instead of discharging effluent to open drain, the secondary effluent could be used for the artificial recharge. The expected recharge from these recharge structures is $0.4 \times 10^6\,m^3/d$.

"Yamuna Vihar" and "Kondli" STPs are located in Trans-Yamuna area (Fig. 14). This area is characterized by large slum clusters like Yamuna Pushta slums where raw wastewater is commonly used for aquaculture, serving as a source of income as well as food for personal consumption (IWMI, 2004). Steps need be taken by government to supply secondary effluent from "Yamuna Vihar" and "Kondli" STP to these aquaculture facilities so as to protect health of workers as well as consumers.

Presently effluent from the "Rithala" STPs is discharged into the Supplementary drain. However, it can be used for irrigation or horticulture within the catchment. Treated wastewater can be supplied in bulk quantities to the users at their centralized storage tank(s) on continuous basis. Other facilities required for application of treated wastewater on horticulture land, such as pumping, distribution, piping, etc. can be arranged by the respective users.

Effluent from the "Okhla" STP is partially utilized for irrigation and horticulture purposes. "Okhla" STP is located within the Okhla industrial area; therefore the reclaimed water can be supplied to industries for cooling, washing and other purposes. The total water demand of industrial area is $26 \times 10^3\,m^3/d$, which could be easily met by reclaimed wastewater after treatment (DSIIDC, 2007). For wastewater reuse in industries, turbidity has been identified as an important criterion. Effluent with turbidity range from 1 to 30 NTU can be used in boilers, cooling towers, etc. (Chiou et al., 2007). The guidelines for industrial reuse of wastewater effluent do not exist in India; therefore these should be introduced and implemented for sustainable reuse of wastewater.

4. Conclusions

This study clearly identifies the performance of various types of treatment processes to remove physiochemical and biological contaminants. Treatment technology has a bearing on the quality of the final effluent from the STPs. Extended aeration, and Oxidation Pond based STPs produce better quality effluent.

STPs employing both chemical and biological process do not produce better effluent as compared to the quality of water from the Oxidation Pond based STPs. There is high potential of direct and indirect reuse of the treated sewage.

Effluents from some of the STPs like "Okhla", "Keshopur", "Yamuna Vihar" and "Kondli" after primary treatment could be reused using SAT. Whereas secondary effluent produced from most of STPs require tertiary treatment for unrestricted irrigation, aquaculture and artificial groundwater recharge.

Effluent from "Oxidation Pond" based STP could be directly used for unrestricted irrigation. "Sen Nursing home" and "Delhi Gate" STPs are located near thermal power plants. After tertiary treatment, effluents from these STPs are well suited for the make-up water in the cooling towers.

Total quantity of sewage being treated is $1.16 \times 10^6\,m^3/d$. At present, 40% of it is being reused. Additional measures would result in making $0.696 \times 10^6\,m^3/d$ of water available for reuse. Location of STPs in context of the land use pattern to their proximity makes reuses like agriculture, industrial and SAT viable options in Delhi's watershed. The tertiary treatment of secondary effluent coupled with the proper conveyance of effluent to proposed reuse may ease out the water problem in Delhi city to large extend.

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