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Point and non-point microbial source pollution: A case study of Delhi

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A B S T R A C T

The present study identifies major point and non-point sources of microbial pollution during dry and wet weather in Delhi watershed which is the first prerequisite for planning and management of water quality of the river Yamuna. Fecal coliforms (FC) and fecal streptococci (FS) levels were determined from two types of sources – point source (effluent from sewage treatment plants) and non-point source (stormwater runoff during dry and wet weather). FC and FS levels in the river Yamuna were also monitored, which is an ultimate sink for all microbial loads in Delhi watershed.

Effluent from sewage treatment plants (STPs) employing different treatment technologies were evaluated. FC and FS levels greater than the effluent discharge standard (1000 MPN/100 ml) were observed in the effluents from all STPs except "oxidation pond Timarpur". This study also involved field program for characterization of urban runoff from different land-uses. Results indicated that the microbial quality of urban runoff produced during wet weather from different land-uses was similar to that of raw sewage. Sewage overflows along with human and animal sources were responsible for high FC and FS levels in the runoff samples.

Wet weather FC and FS levels in river Yamuna were higher as compared to the dry weather levels suggesting that dilution of the river water during wet weather does not affect its microbiological quality. Thus on the basis of this study it was found that urban runoff also contributes to the microbial quality of the river Yamuna.

1. Introduction

Pollutant sources affecting surface water quality are categorized as point and non-point sources (NPS). The difference in these two types of pollution is that, the impurities from point source enter the water resource at an easily identifiable distinct location though a direct route, e.g., effluent from sewage treatment plants (STPs) whereas in case of non-point source pollution the pollutants enter from unidentified diffused sources and are difficult to control, e.g., stormwater runoff, dry weather runoff from slums, small clusters, etc. Delhi, the capital city of India has significant economic expansion and corresponding high rates of urbanization which have brought rapid changes to this megacity's urban spatial structure. The outcome of this has instigated increase in population, change in landuse pattern (mixed landuse), increase in impervious area and growth of unauthorized settlements in the form of slums, unauthorized colonies, clusters, etc. Increase population due to migration and high birth rate, overstressed the water and sanitation infrastructure. At present nearly 55% of Delhi's 15 million inhabitants are connected to the sewage system and others living in slums and squatter settlements deprive of basic sanitation facilities (YAP, 2008a). The process of urbanization and associated activities increase runoff flows and degrade runoff quality, therefore the wastewater generated from such areas during dry as well as wet weather finds its way directly to river Yamuna.

River Yamuna, which drains an area of approximately 1483 km^2 of Delhi watershed, is the main watercourse through Delhi. It is a source of water supply for downstream population and is also used for various recreational purposes. Various institutional and managerial measures have been taken by the Ministry of Environment and Forests (MoEF) of the Government of India in 12 towns of Haryana, eight towns of Uttar Pradesh, and Delhi under an action plan to improve the water quality of river Yamuna. Under Yamuna action plan (YAP), which is implemented since 1993 by the National River Conservation Directorate (NRCD) of the MoEF, number of sewage treatment plants (STPs) aerobic as well and anaerobic were constructed to treat discharges from point sources, i.e., discharges coming from localities served by proper sewerage system, whereas the non-point sources, i.e., wet and dry weather runoff generated from Delhi city was completely neglected (Sato et al., 2006; YAP, 2008b). In Delhi city, the wastewater generated from slums, unauthorized colonies, clusters, etc. finds its way to the open storm drains which contributes to dry weather runoff. Therefore despite,

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a number of STPs in place, published data on river water quality showed no improvement, particularly in microbiological water quality (YAP, 2005; Karn and Harada, 2001; CPCB, 2005a; Sato et al., 2006). At present, the total coliform (TC) and fecal coliform (FC) levels in river are of the order of 10^7/100 ml (YAP, 2005; CPCB, 2005b). FC are the indicator organisms used to evaluate the biological quality of surface waters for different purposes such as drinking, bathing, swimming, etc. High levels of FC indicate presence of pathogens, thus posing health implication to the downstream population. Therefore to meet the surface water quality standards of 500 MPN/100 ml for bathing (NRCD, 2005) proper design of water management and quality restoration policies is required, which in turn depends upon the understanding of the relative importance of sources degrading the microbiological quality of river.

Past studies in developed countries suggested that effluent discharged from STPs was only responsible for the poor biological quality of river water. At present the point source of pollution has been successfully controlled and managed but developed nations continue facing fecal contamination of surface waters. Urban runoff has been found responsible for closure of 32% beaches at least once during summer season in United States (EPA, 2006). Studies also confirmed that dry and wet weather runoff being directly discharged to surface waters was one of the important factor responsible for the poor quality of surface waters (Wenwei et al., 2003; Taebi and Droste, 2004; Petersen et al., 2005; McLeod et al., 2006). Studies were carried out to determine the affect of different factors contributing to the quality of urban runoff. It was concluded that urbanization and industrialization influenced the chemistry of surface water (Al-Kharabsheh, 1999; Karn and Harada, 2001; Wang, 2001; Marsalek et al., 2002; Kelsey et al., 2004), the temperature of urban streams (LeBlanc et al., 1997), the reduction of urban groundwater supplies (Gupta, 2002) and the physico-chemical and biological quality of surface waters (Goda, 1991; Young and Thackston, 1999; Izonfuo and Bariweni, 2001).

Except very few studies carried out on physico-chemical quality of surface waters no data is available regarding the identification of the pollution sources and their respective contribution to the surface water quality in the growing cities of developing countries like India (Trisal et al., 2008). Data regarding the biological quality of urban runoff produced from the watershed with mixed landuse characteristics is still lacking.

Thus, the objective of this study is to identify different sources of pollution in Delhi city and to study their impacts on the biological water quality of river Yamuna, which would lead to the easy control and application of the mitigating measures to restore water quality.

2. Methodology

To achieve the scope of the study, data were collected both from primary and secondary sources. Primary data include analysis of samples from point sources, non-point sources and river Yamuna. Fig. 1 shows the location of STPs, sampling sites during wet weather within Delhi watershed and sampling location on river Yamuna. Whereas, secondary data consist of data on landuse, population, water supply, wastewater treatment capacity and other factors important for the identification of point and non-point sources.

2.1. Primary data

2.1.1. Site selection for non-point source of pollution

In Delhi, during monsoon season, water logging problem is quite common. During rain events, due to poor stormwater drainage network water gets collected in low lying areas causing temporary flood situation. To overcome water logging problem in low lying areas, Municipal Committee of Delhi (MCD) had installed temporary as well as permanent stormwater pumping stations. Stormwater gets collected in underground sumps and is than pumped into adjacent stormwater drains. Data regarding the population density, catchment area, type of landuse, etc. for such sites was available with MCD. To estimate the pollution load in stormwater from diffuse sources of pollution, six sites prone to water logging were selected on the basis of landuse characteristics (see Table 1).

The institutional areas are characterized by planned development pattern, having full sewerage, and minimum pollution from sources like slums, open defecation, and mixing of sewage with the stormwater. Campus of the Indian Institute of Technology Delhi (IITD), provided such a setting, so two sampling sites (stormwater drains) were selected within the IITD campus. At commercial and slum areas, pumps were installed to manage water logging. The commercial sites exhibited high impervious cover, medium population density and were prone to sewage mixing during high intensity rain events. The slum areas had a high population density (0.3 million persons/km^2) and were located on the outskirts of Delhi city, with poor or no sewerage systems.

Samples were collected in a time series (20 min interval) from storm drains and pumping stations at respective sites. At the time of sampling, the runoff flow rates were also measured. Three rain events from June to September, 2006, were sampled at each site except for Gandhi Vihar where only a single rain event was sampled owing to some technical problems. Water quality samples were stored at 4 °C and transported to the Environmental Engineering Laboratory, IITD for analysis. Samples were analyzed with 8 h from the time of collection.

2.1.1.1. Data analysis. The pollutant concentrations often vary by several orders of magnitude during the storm event, a single index known as event mean concentration (EMC) can be used to characterize runoff constituents. The EMC is a flow weighted average of constituent concentrations. The EMC for a storm event is defined as total pollutant load divided by total runoff volume, as follows:

$$\mathrm{EMC} = \frac{\sum_{i=1}^{N} Q_i C_i \Delta t}{\sum_{i=1}^{N} Q_i \Delta t} \quad (1)$$

where N is the total number of samples taken during storm event, Q_i and C_i are flow rate and pollutant concentration respectively measured at time i, and Δt is the time interval between two measurements. For a specific catchment, the mean of all EMCs, is the site mean concentration (SMC).

2.1.2. Point source of pollution

Delhi watershed is divided into five major zones. Depending upon the population, each zone is served by number of STPs. Total 17 STPs were upgraded and constructed with total treatment capacity of 2.30×10^6 cubic meters per day (m^3/d) (see Table 2). At present only 14 STPs are functional with total treatment capacity of 2.19×10^6 m^3/d. Due to poor sewerage network and unavailability of raw sewage, most of STPs are under utilized having actual treatment capacity of 1.16×10^6 m^3/d. These STPs are fed from the sewerage system and open drains (see Table 3). The details of actual sewage treated and hydraulic retention time (HRT) for all STPs are presented in Table 3. The evaluation of STPs was carried out for a period of 12 months, i.e., from November 2005 to November 2006. Influent sewage samples and effluent samples were collected from all STPs. The influent sewage characteristics varied, depending upon the landuse characteristics and the type of population served.

To determine the contribution of microbial pollution load from the treated wastewater, effluent samples were collected from all the functional sewage treatment plants (STPs). Analysis of microbi-

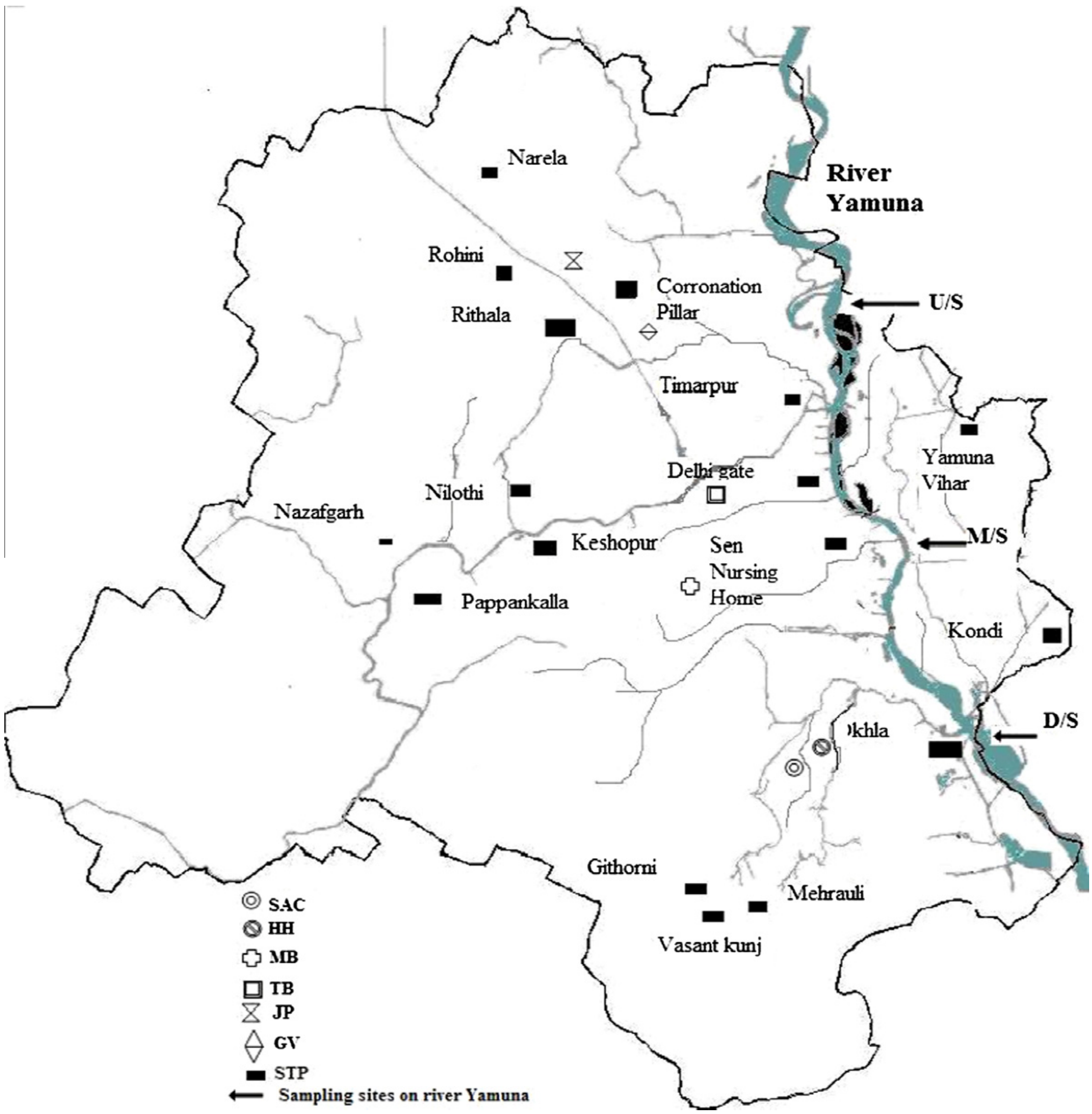

Fig. 1. Location of STPs, stormwater sampling sites and sampling points on the river Yamuna in Delhi city.

Table 1
Landuse characteristic of stormwater sampling sites

Site	Landuse	Area (Hac)	Impervious area (%)	Pervious (%)	Population (person/km^2)
Minto bridge[a] (MB)	Commercial	485937.40	100.00	0.00	93,028
Tilak bridge[a] (TB)	Commercial	765104.10	91.35	8.65	9294
IITD (SAC)	Institutional	173.27	73.70	26.30	5028
Himadri (IITD)	Institutional	204.72	73.70	26.30	5000
Jahangirpur[a] (JP)	Slum	2456250.00	95.74	4.26	300,000
Gandhi Vihar[a] (GV)	Resettlement colony	41614.50	81.23	18.77	9299

[a] Stormwater pumping station.

ological parameters was carried out within 8 h of sample collection. Several sampling campaigns were performed in year 2005 and 2006. During the evaluation period, four influent and effluent samples were analyzed from each plant thus giving total 136 samples.

2.1.3. Sampling of river Yamuna

To determine the effect of wet and dry weather discharges on water quality of river Yamuna, three sampling sites, i.e., upstream Wazirabad (U/S), midstream Nizamuddin (M/S) and downstream Okhla (D/S) were selected (see Fig. 1). Dry weather samples were analyzed from three sites before monsoon season (March–June 2006) and the wet weather samples were analyzed during the monsoon period (July–September 2006).

All water quality samples were collected in sterile bottles, kept at 4 °C and were analyzed for physico-chemical and biological parameters within 12 h. For the enumeration of FC and FS, samples were suitably diluted using sterile deionized water before inocula-

Table 2
Zone-wise distribution of sewage treatment plants

Zone	STPs	Population	Wastewater generated (m^3/d)	Design treatment capacity (m^3/d)
Shahadra	Yamuna Vihar Kondli	2,798,000	0.54×10^6	0.29×10^6
Rithala–Rohini	Narela Rithala Rohini	2,226,333	0.47×10^6	0.48×10^6
Okhla	Vasant Kunj I and II Mehrauli Okhla Sen nursing home Delhi Gate Githorni	3,499,642	0.85×10^6	0.70×10^6
Keshopur	Papankallan Nazafgarh Keshopur Nilothi	2,204,864	0.48×10^6	0.62×10^6
Coronation pillar	Coronation pillars I, II and III Oxidation pond Timarpur	1,029,400	0.20×10^6	0.21×10^6

Table 3
Sewage treatment plant characteristics

Sewage treatment plants	Technology	Source	Design treatment capacity (m^3/d)[a]	Utilization (%)	HRT (h)[b]
Kondli	ASP[c]	Open storm drain	0.201×10^6	30.0	32.0
Yamuna Vihar	ASP	Open storm drain	0.091×10^6	30.0	32.0
Rithala I	ASP	Open storm drain + sewerage system	0.182×10^6	57.5	16.7
Coronation pillars II and III	ASP	Open storm drain	0.136×10^6	50.0	19.2
Okhla	ASP	Sewerage system	0.636×10^6	75.0	12.8
Nilothi	ASP	Open storm drain	0.182×10^6	12.5	76.8
Keshopur	ASP	Open storm drain + sewerage system	0.327×10^6	50.0	19.2
Papankallan	ASP	Open drain	0.091×10^6	45.0	21.3
Vasant Kunj I	Ex. aeration[d]	Sewerage system	0.014×10^6	66.7	36.6
Vasant Kunj II	Ex. aeration	Sewerage system	0.010×10^6	54.5	44.7
Mehrauli	Ex. aeration	Open storm drain	0.023×10^6	34.0	71.8
Nazafgarh	Ex. aeration	Open storm drain	0.023×10^6	24.0	101.7
Delhi Gate	BIOFORE [e]	Open storm drain	0.010×10^6	100.0	8.0
Sen nursing home	BIOFORE	Open storm drain	0.010×10^6	100.0	8.0
Coronation pillar I	Trickling filtration	Open storm drain	0.045×10^6	40.0	8.8
Rithala II	ASP + (high rate aeration process)	Open storm drain + sewerage system	0.182×10^6	66.3	11.4
Oxidation pond Timarpur	Oxidation pond	Open storm drain	0.027×10^6	33.3	433.9

[a] Million liters per day.
[b] Hydraulic retention time.
[c] Activated sludge process.
[d] Extended aeration.
[e] Physical chemical and biological treatment.

tion in appropriate medium. Enumeration of FC was carried out by direct inoculation technique, using A1 broth (Difco) as per standard methods. The inoculated tubes were incubated at 44 ± 0.5 °C for 24 h. Turbid tubes with gas formation were reported positive for FC. FS were recovered on Azide dextrose broth (HiMedia) at an incubation temperature of 35 ± 0.5 °C for 48 h. Turbid tubes were reported positive and were subjected to the confirmation test by using Pfizer selective enterococcus Agar (HiMedia). MPN count for FC and FS was determined using MPN table (APHA, 1998).

3. Results and discussion

3.1. River and urbanization

In 1901, the population density in Delhi was 274 persons/km^2, which increased to 9294 persons/km^2 in 2001; urban population increased from 53% in 1901 and to 93% in 2003 (Economic Survey of Delhi, 2003–2004). The data indicates that in past two decades urbanization occurred at very high rate in Delhi city, thereby increasing the amount of pollutant load in ecosystem. Depending upon the level of planned development, settlements in Delhi can be classified in three broad categories (YAP) as shown in Table 4. The water supply in these colonies varies from 0.05 to 0.27 m^3/d.

The total wastewater generated in Delhi is 80% of the water supplied (3.58×106 m^3/d), which comes out to be 2.87×10^6 m^3/d (CPCB, 2008). Total domestic sewage generated in accordance to the water consumption rate is 1.51×10^6 m^3/d (see Table 4). Only 55% of the population of Delhi is served by the sewerage system. Remaining 45% population uses public or private utilities or defecates in open, thus contributing to diffuse source of pollution (YAP, 2005). So, the estimated collected sewage in Delhi would be 0.83×10^6 m^3/d (considering 55% of 1.51×10^6 m^3/d).

Table 4
Non-point source pollution from different types of settlements in Delhi

Categories	Population (millions)[a]	Consumption rate (m^3/d)[a]	Sewage generated (m^3/d)[b]	Non-point pollution	
				Potential	Duration
Planned colonies	3.3	0.27	0.71×10^6	Low	Wet weather
Regularized, resettlement colonies and urban villages	4.4	0.16	0.55×10^6	Medium	Both dry and wet weather
Rural villages, unauthorized colonies and Juggi Jhopri clusters	6.2	0.05	0.25×10^6	High	Both dry and wet weather

[a] YAP (2005).
[b] Assuming 80% water supply is converted in to the sewage.

Fig. 2 presents the fate of wastewater being generated in Delhi city. The total water supplied is utilized for industrial as well as for domestic purposes. The total wastewater generated is 2.87×10^6 m^3/d, part of which, i.e., $1.17 \times 106\ m^3/d$ represents the unaccounted wastewater being directly discharged to storm drains or river Yamuna. Total industrial sewage ($0.19 \times 10^6\ m^3/d$) is discharged to stormwater drains or directly to river Yamuna (DSIIDC, 2008). The actual treatment capacity of 14 functional STPs in Delhi city is $1.16 \times 10^6\ m^3/d$. However, the coverage of sewerage is only 55% ($0.83 \times 10^6\ m^3/d$) thus remaining $0.33 \times 10^6\ m^3/d$ of mixed sewage is fed from open drains. The mixed sewage fed to STPs affect the overall pollutant removal efficiencies and is responsible for the poor water quality of river Yamuna. The treated and untreated wastewater from industries along with the unaccounted wastewater finds its way to open storm drains. The unaccounted wastewater generated from slums, unauthorized colonies, small scale industries, etc. is diffused in nature and difficult to control thereby act as a non-point source of pollution.

Fig. 3 presents the wastewater management scenario of Delhi city. Industries contributes to 7% of the total wastewater generated out of which 4% is treated and discharged into storm drains. At present in Delhi city due to overstressed water supply system groundwater is illegally exploited to meet the domestic and industrial demands. Thereby about 40% of the total wastewater produced from the small clusters, unauthorized colonies, small scale industries, etc. is not accounted and is directly discharge to the surface water or stormwater drains. Total 40% of the wastewater is treated by the STPs, which are partly fed by domestic sewage (29%) and partly by the mixed sewage being pumped from open drains (12%). Only 17% of the total wastewater generated by the city is reused for gardening, floriculture and horticulture.

Delhi receives an annual average rainfall of 611 mm; surface runoff finds is way directly or indirectly through storm drains into the river Yamuna. Runoff washes away huge quantities of pollutants from the surface thus instantaneously adding up high organic load in to the river, rending its water quality unfit for human use with severe ecological effects. Fig. 4 identifies the point and non-point sources of pollution in Delhi watershed.

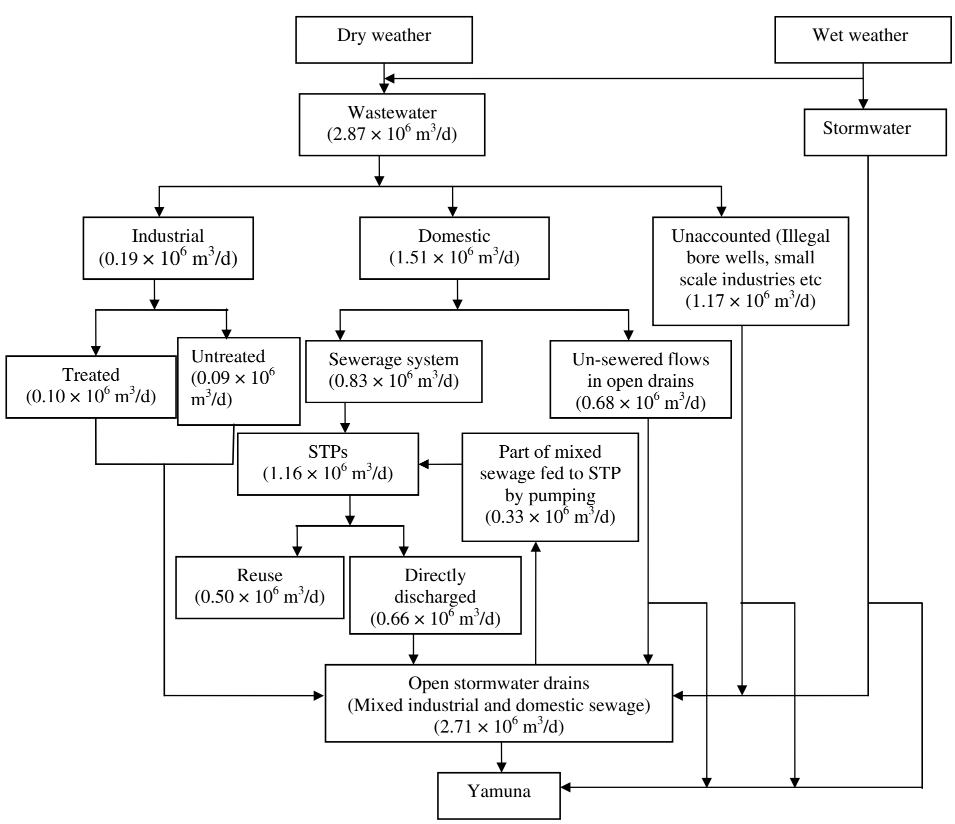

Fig. 2. Fate of wastewater in Delhi city.

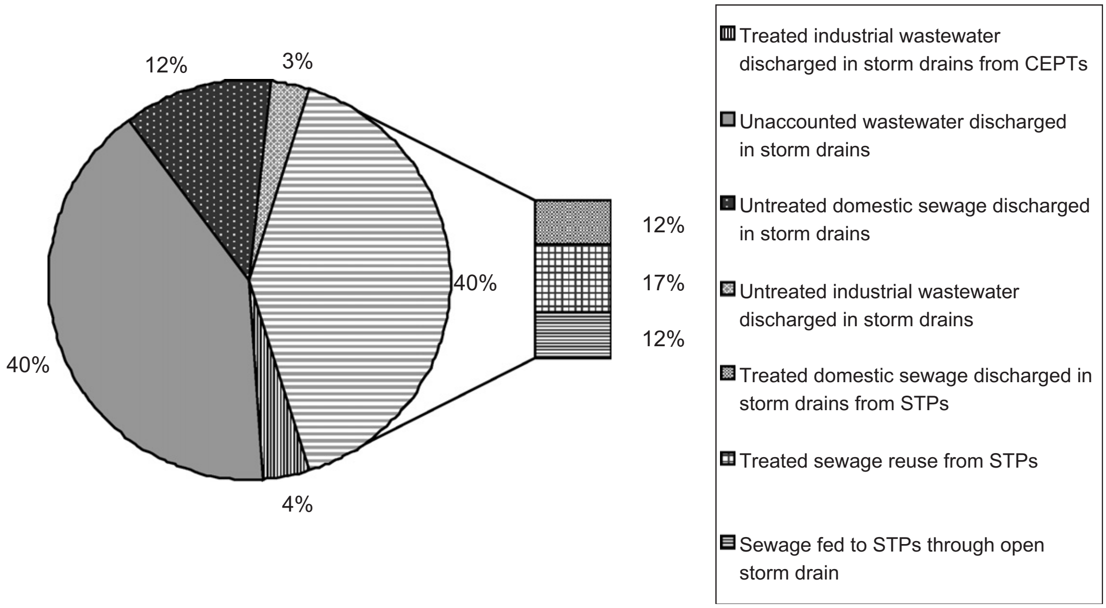

Fig. 3. Wastewater management in Delhi city.

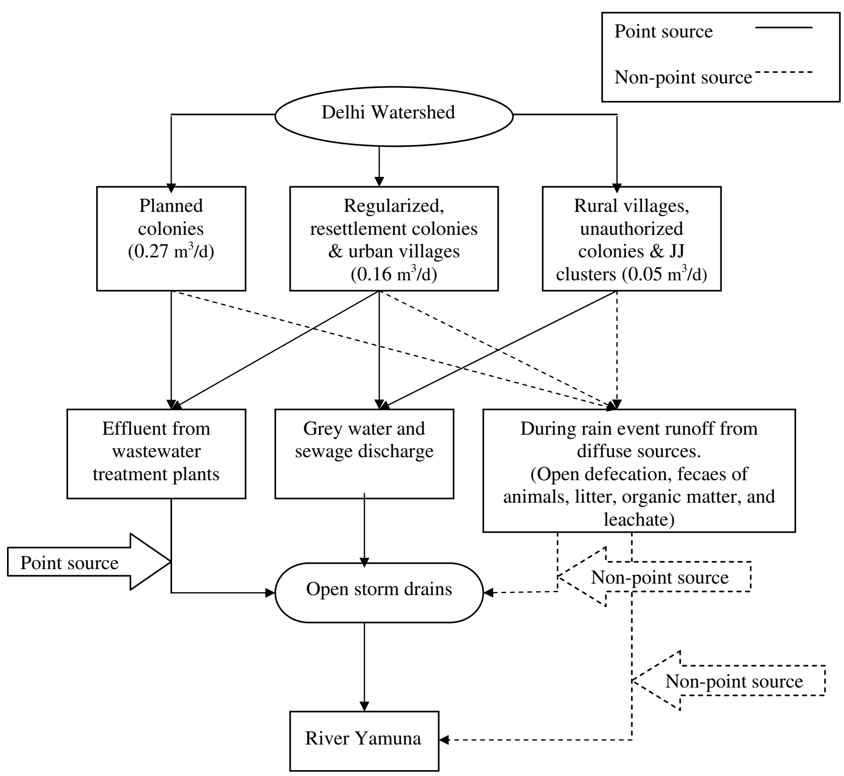

Fig. 4. Point and non-point sources of pollution in Delhi city.

3.2. Microbiological quality of urban runoff

Fig. 5 presents the site mean concentration (SMC) of FC and FS in urban runoff for three rain events. High FC and FS levels were observed at all sampling sites. The microbiological quality of runoff from slums as well as commercial areas was poor as compared to runoff from institutional areas (see Fig. 5). Poor sewerage infrastructure in slums, leads to mixing of sewage with stormwater, thereby responsible for high pollutants levels in runoff from the Jahangirpur and Gandhi Vihar sites. The results indicate that dilution has no effect on physical, chemical and biological quality of dry weather runoff or raw sewage (Mara, 1978). Commercial sites are characterized by high impervious area thus the runoff produced from the selected sites had high total suspended solids (TSS) whereas high organic load was observed in runoff from slum areas where no sewerage network exits (see Table 5). Heavy rain events and poor sewerage systems in commercial areas leads to sewage overflows thus responsible for high FC and Fs levels.

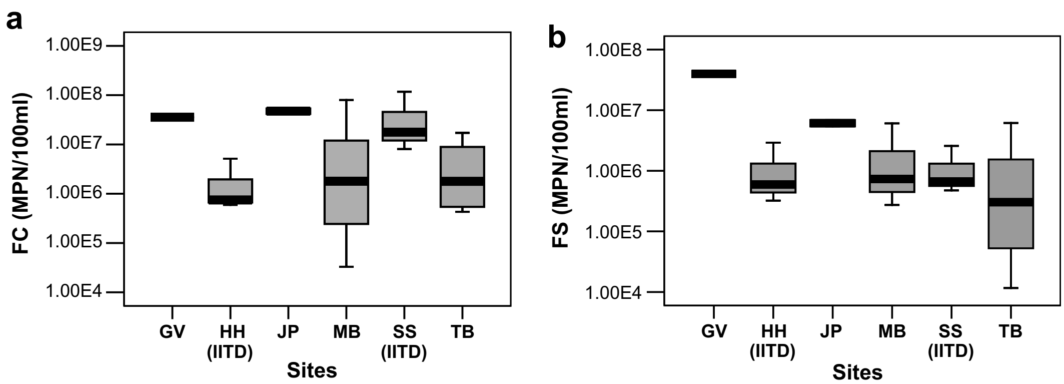

Fig. 5. SMCs of indicator organisms in runoff from different sampling sites (a) FC and (b) FS.

Table 5
Statistical summary of SMCs of water quality characteristics for selected sites

Parameters	Minto bridge (MB)		Tilak bridge (TB)		Himadri (IITD) (HH)		SAC (IITD)		Gandhi Vihar (GV)	Jhangirpur (JP)	
	SMC	Standard deviation	SMC	Standard deviation	SMC	Standard deviation	SMC	Standard deviation	EMC	SMC	Standard deviation
FC (MPN/100 ml)	4.7×10^7	6.0×10^7	2.4×10^7	3.7×10^7	2.1×10^6	2.5×10^6	1.9×10^5	2.3×10^6	3.5×10^7	4.7×10^7	8.4×10^6
FS (MPN/100 ml)	1.2×10^6	1.1×10^6	3.3×10^6	3.2×10^6	1.2×10^6	1.4×10^6	2.1×10^5	1.8×10^5	3.9×10^7	6.1×10^6	1.0×10^6
COD (mg/l)	168.6	88.9	191.6	121.2	114.8	111.1	108.5	75.2	173.5	404.5	38.9
BOD (mg/l)	74.3	18.4	80.0	1.3	50.1	10.3	32.0	26.1	116.2	238.7	135.1
TKN (mg/l)	5.6	4.9	7.2	35.3	8.4	1.8	5.5	1.3	13.3	17.7	1.7
TSSm (mg/l)	631.8	480.6	5296.5	8396.3	397.0	105.3	217.3	189.2	370.9	664.6	60.7
Turbidity (NTU)	297.83	211.82	3028.82	4328.20	293.84	285.32	245.34	34.12	309.26	210.91	30.34

High FC and FS levels were observed in runoff from the institutional sites selected within IIT Delhi campus. These sites are characterized by planned sewerage system; therefore it can be assumed safely that no sewage mixing took place. The campus has large population of peacock and other animals which would have contributed to the biological quality of the runoff from these sites. FC/FS ratio of 1.7 and 0.9 was observed at Himadri (HH) and SAC (IITD), respectively, which further substantiate that animal source was responsible for biological pollution of runoff (Geldreich, 1969; Geldreich and Kenner, 1969). High percentage of pervious and green cover at these sites was responsible for low organic and suspended solid load (see Table 5). In Gandhi Vihar, high FS levels and FC/FS ratio less than one was observed, which could be attributed to the large number of urban animals and livestock populations in the Gandhi Vihar area (Census of India, 2003). The study suggests that landuse has significant impact on the levels of indicator organisms discharged to the surface waters.

3.3. Microbiological quality of effluent from STPs

Fig. 6 presents the geometric mean of FC and FS in the treated effluent from STPs. FC and FS levels in the effluent from STPs employing different treatment technologies ranged from 1.3×10^2 to 3×10^6 MPN/100 ml and 2×10^2 to 2×10^6 MPN/100 ml, respectively. Removal of indicator organism by STPs depends on the type of technology employed and the influent sewage characteristics. Low FC and FS levels were observed in the effluent from STP based on oxidation pond treatment process. High FC and FS levels were observed in the effluents from STPs employing conventional activated sludge process.

FC levels in all STPs except oxidation pond were greater than the effluent discharge standards of 1000 MPN/100 ml set by NRCD. The BOD_5 levels in effluent from all STPs evaluated except seven lie within the effluent discharge standards of 30 mg/l whereas COD levels in effluent from all STPs were lower than the COD discharge standard of 250 mg/l (NRCD, 2005).

From this study it is observed that at present in Delhi city the quality of secondary effluent discharged from STPs is poor. The physico-chemical parameters are partially under control whereas maximum numbers of STPs produce biologically poor quality secondary effluent (see Table 6). The quality of effluent can be controlled by improving the quality of influent sewage, proper operation and maintenance of STPs and employing tertiary treatment process.

3.4. Surface water quality during wet and dry weather

Fig. 7 shows dry and wet weather FC and FS levels at three sampling sites on the river Yamuna. Wet weather FC and FS levels were observed higher at U/S and D/S as compared to the dry weather levels. Table 7 presents FC and FS levels during dry and wet weather at the selected sampling sites. To compare the dry and wet weather FC and FS levels, nonparametric test was used (Kolmagorov–Smirov). Test suggests significant difference between dry and wet FC and FS levels for $p < 0.05$; this analysis demonstrates that during wet weather the FC and FS levels in the river Yamuna are greater than that of dry weather.

Geldreich (1969) reported that the ratio of FC to FS counts in water can be used to distinguish between human and animal origin of fecal contamination. He found this ratio to be 4.0 in case of human sources and less than one in case of animal fecal sources.

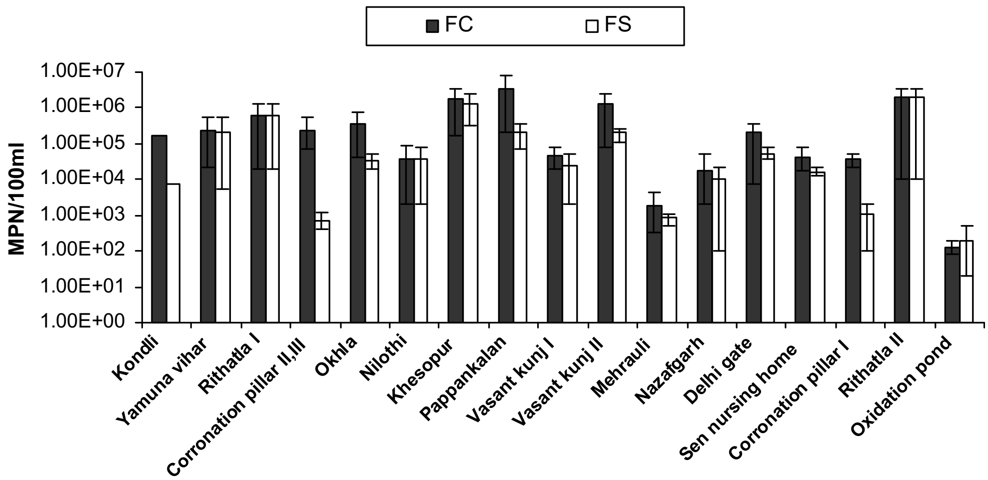

Fig. 6. FC and FS levels per 100 ml in effluent from STPs employing different treatment technologies. Data expressed as geometric mean values ($n = 4$) and vertical bars represent range between minimum and maximum values.

Table 6
Characteristics of effluent from STPs

STPs	pH	Turbidity (NTU)	BOD (mg/l)	COD (mg/l)	TKN (mg/l)	FC log(MPN/100 ml)	FS log(MPN/100 ml)
Kondli	7.1 ± 0.3	6 ± 0.0	9	24 ± 1	3 ± 1	4.2 ± 0.0	3.89 ± .0
Yamuna Vihar	7.4 ± 0.1	39 ± 16	10	64 ± 8		5.10 ± 70	4.7 ± 1.0
Rithala I	7.7 ± 0.2	51 ± 16	72 ± 4	112 ± 24	37 ± 11	5.36 ± 0.94	5.39 ± 0.10
Coronation pillars II and III	6.8 ± 0.0	91 ± 31	40	48 ± 6	20 ± 10	4.52 ± 0.23	2.65 ± 0.91
Okhla	7.5 ± 0.1	5 ± 2	25	25 ± 6	19 ± 1	5.27 ± 0.51	4.50 ± 0.27
Nilothi	7.5 ± 0.2	33 ± 27	32 ± 5	40 ± 8	32 ± 5	4.20 ± 0.82	4.24 ± 0.84
Keshopur	7.4 ± 0.1	60 ± 13	63 ± 18	170 ± 68	37 ± 8	5.19 ± 1.3	5.94 ± 0.61
Papankallan	7.5 ± 0.1	11 ± 0	40 ± 10	48 ± 10	17 ± 3	5.40 ± 0.11	5.24 ± 0.36
Vasant Kunj I	7.5 ± 0.3	3 ± 1	3 ± 1	28 ± 8	18 ± 3	4.6 ± 0.20	4.11 ± 0.72
Vasant Kunj II	7.5 ± 0.2	12 ± 5	3 ± 1	42 ± 24	31 ± 5	5.8 ± 0.78	5.28 ± 0.21
Mehrauli	7.5 ± 0.0	3 ± 1	5 ± 1	32 ± 20	8 ± 2	3.02 ± 0.5	2.92 ± 0.202
Nazafgarh	8.3 ± 0.3	31 ± 2	37 ± 7	72 ± 19	25 ± 7	3.88 ± 0.72	3.41 ± 1.25
Delhi gate	7.2 ± 0.1	4 ± 2	2	21 ± 12	19 ± 4	4.95 ± 0.92	4.71 ± 0.71
Sen nursing home	7.1 ± 0.2	7 ± 2	17	53 ± 9	20 ± 6	4.49 ± 0.36	4.19 ± 0.14
Coronation pillar I	7.2 ± 0.2	14 ± 10	18	40 ± 5	22 ± 8	4.85 ± 0.01	2.61 ± 0.20
Rithala II	7.1 ± 0.1	226 ± 50	90 ± 18	146 ± 20	33 ± 10	5.64 ± 1.42	5.53 ± 0.76
Oxidation pond Timarpur	7.7 ± 0.1	5 ± 1	6 ± 2	21 ± 9	5 ± 2	2.08 ± 0.20	1.86 ± 0.73

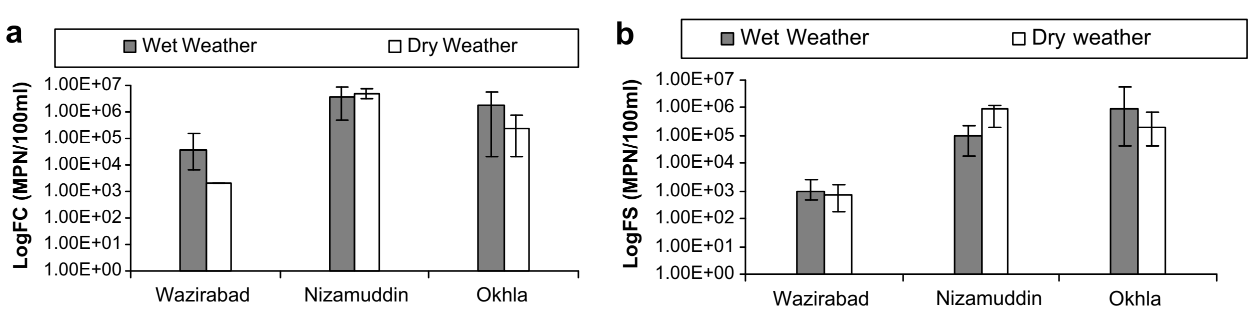

Fig. 7. FC (a) and FS (b) levels per 100 ml in samples from river Yamuna. Data expressed as average values ($n = 8$) and vertical bars represent range between minimum and maximum values.

The reason for this was the different die-off rates of both organisms. However, further studies showed that this ratio is very sensitive and is valid only within 24 h following discharge of the bacteria. In river Yamuna during dry weather FC/FS ratio of 2.7, 5.7 and 1.3 was observed at U/S, M/S and D/S. The ratios are less than four indicating that animal sources being responsible for fecal pollution. But the survival of FC and FS is affected by water temperature, toxic metals, pH, etc. (Geldreich and Kenner, 1969). FS are found to be more resistant to toxic environments as compared to FC. Low pH of 6.8 was observed at M/S and D/S indicating that huge amount of toxic waste enters river Yamuna directly or through storm drains. The prolonged exposure to toxic elements and other environmental factors in storm drains and river water was more lethal to the survival of FC as compared to FS thereby responsible for low FC/FS ratio during dry weather. Wazirabad do not receive runoff from the Delhi city thus the quality of water at U/S is better as compared to the Nizamuddin, where high level of physico-chemical and biological parameters were observed (see Table 7).

Table 7
Average dry and wet weather concentration of FC and FS

Parameters	Wazirabad (U/S)		Nizamuddin (M/S)		Okhla (D/S)	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
Dry weather						
pH	7.6	0.1	6.8	0.2	6.8	0.2
Turbidity	22.3	2.0	127.7	7.3	67.8	29.6
DO	7.8	0.2	0.0	0.0	0.0	0.0
BOD	78.3	2.9	126.7	40.4	105.0	75.3
COD	190.0	17.3	173.3	23.1	160.0	50.6
TKN	–	–	15.1	3.1	10.1	6.2
FC	2.0×10^3	0.0	5×10^6	1.8×10^6	2.5×10^5	2.8×10^5
FS	7.3×10^2	9.2×10^2	8.7×10^5	5.8×10^5	2.0×10^5	2.4×10^5
Wet weather						
pH	7.6	0.6	7.3	0.3	7.4	0.1
Turbidity	41.7	12.6	80.0	27.1	74.3	6.0
DO	5.0	2.7	2.6	1.1	5.3	1.8
BOD	61.7	8.3	50.0	24.1	65.0	66.8
COD	104.0	18.2	296.0	152.4	304.0	72.6
TKN	10.2	0.6	15.5	1.1	24.9	11.3
FC	3.8×10^4	6.0×10^4	4.0×10^6	3.7×10^6	2.0×10^6	1.9×10^6
FS	1.0×10^3	8.0×10^2	1.0×10^5	9.7×10^4	1.0×10^6	9.8×10^5

During wet weather the huge quantities of runoff along with treated, untreated domestic and industrial sewage enters the stormwater drains. Table 7 presents the physical, chemical and biological parameters at three sampling sites during wet weather. Not much difference in the levels of FC and FS was observed during the dry and wet weather. Dilution during wet weather was responsible for low BOD_5 at three sampling locations. FC/FS ratio of 38, 40 and 2 was observed at U/S, M/S and D/S, respectively. The ratio indicated strong impact of human source pollution at U/S and M/S. Before entering Delhi city, runoff received by river Yamuna in upper stretches affected the biological quality of water U/S. As river Yamuna enters Delhi it receives huge quantities of runoff from storm drains thus responsible for high FC/FS ratio at M/S and as the water flows downstream, the increase in contact time with toxic elements and other factors contributed to low FC/FS ratio.

It can be inferred that, even when large quantities of urban runoff from Delhi watershed enters the river Yamuna, no improvement in microbiological quality was observed. It is evident from the study that urban runoff from watershed is highly polluted, which instead of diluting the pollution load, adds to the FC and FS loads in river Yamuna.

4. Conclusions

At the scale of large urbanized Delhi watershed, the input of FC and FS bacteria by non-point source is equally important as point sources of pollution. Unaccounted wastewater from slums, rural villages, small scale industries and Juggi Jhopri clusters was identified important non-point source of pollution during dry and wet weather conditions.

The quality of urban runoff produced during rain events from the sites with different landuse characteristics was very poor. The FC and FS levels range from 6 to 7 log orders. Human and animal sources were found to be responsible for high levels of indicator organisms at slums and institutional sites, respectively. At commercial sites, poor urban runoff quality was observed which could partly be attributed to poor sewerage network.

It is evident that the present installed capacity of the STPs (2.55×10^6 m^3/d) in Delhi is almost sufficient to treat the total sewage generated (2.87×10^6 m^3/d). At present 14 STPs out of 17 are functional with actual treatment capacity of 1.16×10^6 m^3/d. The treated effluent from these STPs is discharged into storm drains where mixing of treated, untreated domestic as well as industrial sewage takes place, thus making the whole treatment process inefficient.

All these factors collectively contribute to the water quality of river Yamuna. The wet weather levels of indicator organisms were higher as compared to dry weather indicating that dilution during rain event has no affect on the microbial quality of river water. Thus, the study concludes that, if surface water quality standards (500 MPN/100 ml) for river Yamuna are to be met, non-point source of pollution needs to be addressed. Point source pollution could be controlled by preventing mixing of influent sewage and employing tertiary treatment process. For unaccounted wastewater from slums and small clusters decentralized wastewater treatment systems should be employed. These systems will prevent mixing of stormwater with sewage which is also an important non-point source of pollution.

Finally implementation of proper landuse, sewer coverage, public awareness and solid waste management practices, in combination with detention basins, wetlands, filter strips and buffer zones to treat polluted runoff, could be an efficient way to improve the water quality of the receiving water body. Combination of structural and non-structural BMPs could be a solution to control the quality of urban runoff produced within the Delhi watershed which will further protect the water quality of river Yamuna.

References

Al-Kharabsheh, A.A., 1999. Influence of urbanization on water quality at Wadi Kufranja Basin (Jordan). Journal of Arid Environments 43, 79–89.
APHA, 1998. American Public Health Association. Standard Methods for the Examination of Waters and Wastewaters, 20th ed. Washington, DC, USA.
Census of India, 2003. Planning Department. <www.indiastat.com/india/showdata> (September, 2006).
CPCB, 2005a. Central Pollution Control Board. <http://www.cpcb.nic.in/annualreport04-05/ar2004-ch7.htm> (April, 2008).
CPCB, 2005b. Central Pollution Control Board. <http://www.cpcb.nic.in/annualreport04-05/ar2004-ch9.htm> (April, 2008).
CPCB, 2008. Central Pollution Control Board. <http://envfor.nic.in/cpcb/newsletter/high99/chap16.html> (April, 2008).
DSIIDC, 2008. Delhi state Industrial and Infrastructure Development Corporation Ltd. <http://www.dsiidc.org/dsidc/cetp.html> (April, 2008).
EPA, 2006. Environmental Protection Agency. National Summary: 2006 Swimming Season Update. <http://www.epa.gov/waterscience/beaches/seasons/2006/national.html> (April, 2008).
Geldreich, E.E., 1969. Water pollution microbiology. Journal of Water Pollution Control Federation 41, 1053–1069.
Geldreich, E.E., Kenner, B.A., 1969. Concepts of fecal streptococci in stream pollution. Journal of Water Pollution Control Federation 41 (Suppl. 8), R336.
Goda, T., 1991. Management and status of Japanese public waters. Water Science and Technology 23, 1–10.

Gupta, R.K., 2002. Water and energy linkages for groundwater exploitation: a case study of Gujarat State, India. International Journal of Water Resources Development 18, 25–45.
Izonfuo, L.W.A., Bariweni, A.P., 2001. The effect of urban runoff water and human activities on some physico-chemical parameters of the epie creek in the Niger delta. Journal of Applied Science and Environmental management 5, 47–55.
Karn, K.S., Harada, H., 2001. Surface water pollution in three urban territories of Nepal, India, and Bangladesh. Environmental Management 28, 483–496.
Kelsey, H., Porter, E.D., Scott, G., Neet, M., White, D., 2004. Using geographic information systems and regression analysis to evaluate relationships between landuse and fecal coliform bacterial pollution. Journal of Experimental Marine Biology and Ecology 298, 97–209.
LeBlanc, R.T., Brown, R.D., Fitz Gibbon, J.E., 1997. Modeling the effects of landuse change on the water temperature in unregulated urban streams. Journal of Environmental Management 49, 445–469.
Mara, D., 1978. Sewage Treatment in Hot Climates. first ed.. John Wiley and Sons Ltd., Great Britain.
Marsalek, J., Diamond, M., Kok, S., Watt, E.W., 2002. Urban Runoff. The National Water Research Institute. <http://www.nwri.ca/threatsfull/ch11-1-e.html>.
McLeod, M.S., Kells, A.J., ASCE, M., Putz, J.G., 2006. Urban runoff quality characterization and load estimation in Saskatoon, Canada. Journal of Environmental Engineering 132, 1470–1481.
NRCD, 2005. Ministry of Environment and Forest Annual Report 2001–2002. <http://envfor.nic.in/report/0102/chap06.html> (April, 2008).
Petersen, M.T., Rifai, S.H., Suarez, P.M., Stein, A.R., 2005. Bacteria loads from point and non-point sources in an urban watershed. Journal of Environmental Engineering 131, 1414–1425.
Sato, N., Okubo, T., Onodera, T., Ohashi, A., Harada, H., 2006. Prospects for a self-sustainable sewage treatment system: a case study on full-scale UASB system in India's Yamuna River Basin. Journal of Environmental Management 80, 198–207.
Taebi, A., Droste, L.R., 2004. Pollution loads in urban runoff and sanitary wastewater. Science of the total Environment 327, 175–184.
Trisal, C., Tabassum, T., Kumar, R., 2008. Water quality of the river Yamuna in the Delhi stretch: key determinants and management issues. CLEAN – Soil, Air, Water 36, 306–314.
Wang, X., 2001. Integrating water-quality management and land-use planning in a watershed context. Journal of Environmental Management 61, 25–36.
Wenwei, R., Zhong, Y., Meligrana, J., Anderson, B., Watt, W.E., Chen, J., Leung, Hok-Lin., 2003. Urbanization, landuse and water quality in Shanghai 1947–1996. Environment International 29, 649–659.
YAP, 2005. Yamuna Action Plan. <http://yap.nic.in> (September, 2006).
YAP, 2008a. Yamuna Action Plan. <http://yap.nic.in/delhi.asp> (April, 2008).
YAP, 2008b. Yamuna Action Plan. <http://yap.nic.in/delhi-stp.asp> (April, 2008).
Young, D.K., Thackston, L.E., 1999. Housing density and bacterial loading in urban streams. Journal of Environmental Engineering, 1177–1180.