Application of QUAL2E for the river Yamuna: to assess the impact of pointloads and to recommend measures to improve water quality of the river

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Abstract

In this study, QUAL 2E is applied to determine the impact of discharge from various pointloads on the water quality of the river Yamuna during its course through the National Capital Territory (NCT) of Delhi, India, for low flow season. The findings of the study indicate that river is getting a load of 296.1 tonnes/day that several times higher than the assimilative capacity of the river. Of all the point sources, waste load contributed through Najafgarh drain impacted the river severely. Model results were interfaced with Geographical Information System (GIS) for clear display of model outcomes to demarcate polluted zones. To achieve river water quality, specified by regulatory authorities, a scenario was analysed which recommends to maintain a flow rate of more than 10 m^3 per second in the river, substantial load curtailment from various drains along with the adequate treatment to the drains.

Keywords: Water Quality Modelling, River Yamuna, BOD, DO, QUAL 2E, GIS.

1. Introductions

Yamuna is a major tributary to river Ganga and in recent years, it has specially been focused for water quality conservation initiatives due to its grossly polluted status. The Ministry of Environment and Forest, to rejuvenate the river launched the Yamuna Action Plan in 1993. This project was implemented under Ganga Action Plan (1985) on realizing the contribution of river Yamuna to the total load of river Ganga. Delhi is the foremost pollution load contributor with 26 identified industrial areas adding their load to the river Yamuna.

The river has been getting a large amount of partially treated and untreated wastewater during its course through National Capital Territory (NCT) of Delhi, especially between Wazirabad and Okhla. The BOD load from the NCT has increased from 117 tonnes/day in 1982, 211 tonnes/day in 1998 (CPCB, 1999-2000) to 231.2 tonnes/day in 2003 (CPCB, 2003). Delhi generates about 3296 million litres per day (MLD) of wastewater but currently existing sewage treatment facilities can treat only about 1800 MLD[1].

The effective management of this polluted segment of the river is of prime importance. On understanding implications of water pollution on human and aquatic health, the judiciary has also directed central and state authorities to take initiatives to river water quality. In this regard computer aided models have gained wide acceptance as a potential tools to predict and manage the water quality.

This paper describes the application of QUAL2E to the stretch of Yamuna between Wazirabad and Okhla to evaluate its water quality in terms of Dissolved Oxygen (DO) and Biological Oxygen Demand (BOD). The DO and BOD concentrations are predicted to assess the impact of various point loads on the river, for the low flow conditions. Further, the present analysis involves comprehensive application of QUAL 2E to determine assimilative capacity of the river and also to visualise the effect of the different remedial measures in

[1] Yamuna Action Plan site, under National River Conservation Directorate, Ministry of Environment and Forest, New Delhi, http://yap.nic.in/delhi-balance.asp

improving the river's water quality. The outputs generated by QUAL 2E have been interfaced with the GIS as a means to identify pollution zones along the river stretch under study.

2. Site description

The river Yamuna originates from the Yamunotri glacier near the Banderpunch peaks (38^o 59' N, 78^o 27' E) of the lower Himalayas at an elevation of 6320 m above mean sea level, in the state of Uttaranchal of northern India (CPCB, 1999-2000). In addition to Delhi, it traverses parts of the states of Himachal Pradesh, Haryana, Uttar Pradesh, Uttaranchal, Rajasthan and Madhya Pradesh.

The river enters Delhi 1.5 kilometres (km) above village Palla and leaves Delhi at Jaitpur, downstream of the Okhla Bridge (Figure 1). This study covers a 25 km stretch starting 2 km upstream of Wazirabad and extending to the Okhla barrage. Waste streams from 14 drains join the river at different points along this stretch. In the first 5 km the major drains flowing into the river are Najafgarh, Magazine Road, Sweeper Colony and Khyber Pass (Figure 1); of these, the Najafgarh drain is the largest contributor. The Meltcalf House, Qudusia Bagh, Mori Gate and Tonga Stand drains add their discharges along the next 5 km. Other significant drains are the Civil Military, Power House, Sen Nursing Home, No. 14, Barapulla and Maharani Bagh along the remaining 15 km stretch. The river also gets direct load from the wastewater treatment plant located at Okhla and from a diversion called Hindon Cut. The Hindon Cut is the second largest contributor of waste after the Najafgarh drain. Withdrawals of water from the river takes place at two points Wazirabad Waterworks and Agra canal. Drinking water is supplied to the cities of Delhi and Agra, respectively, from these withdrawals.

3. Model description

QUAL-2E is a popular computer model for evaluating stream water quality (Abbasi et al., 1999; Chaudhury et al., 1998; Drolc and Koncan, 1996, 1999; Ghosh, 1996; Ghosh and Mcbean, 1998; Himesh et al., 2000; Kazmi, 2000; McAvoy et al., 2003; NEERI, 1996; Ning et al., 2001, Paliwal, 2001; Paliwal et al., 2006; Yang et al., 2000). The enhanced version, QUAL IIE or QUAL-2E has evolved from QUAL-I and QUAL-II (Brown and Barnwell, 1987). Since then, the model has undergone several upgradations. The Environmental Protection Agency's (EPA) Centre for Exposure Assessment Modelling (CEAM) in Athens, Georgia maintains the model.

QUAL-2E simulates up to 15 water quality constituents in a system. The model divides the stream into a network of 'headwater', 'reaches' and 'junctions'. The most functional subdivision is the reach, for which input data is provided as physical, chemical and biological parameters and coefficients. Each reach is further divided into a number of computational elements. For these elements, hydrological balance is maintained through flow; heat balance through temperature and material balance is kept through concentration. Both advective and dispersion mode of transport are considered in mass balance. This mass balance can be written as:

$$V \frac{\partial c}{\partial t} = \frac{\partial \left(A_c E \frac{\partial c}{\partial x} \right)}{\partial x} dx - \frac{\partial \left(A_c U \right)}{\partial x} dx + V \frac{dc}{dt} + s$$

Where, V = volume

c = concentration of constituent

A_c = element cross-sectional area

E = longitudinal dispersion coefficient

x = distance (in the direction of flow from point load)

U = average velocity

s = external sources (positive) or sink (negative) of the constituent

4. Model calibration

For the study QUAL 2E was calibrated for the month of March to May representing a low flow period. The model was operated as a one-dimensional steady state and completely mixed system. The 25 km long stretch from upstream of Wazirabad to Okhla was divided into 5 reaches with further segmentation of 0.25 km each.

Input Variables

Model required input variables as hydraulic constants to simulate the transport of pollutants, reactions rate constants to simulate kinetics of decay of pollutants and flow rates and concentration of sources and sinks to simulate flow/load balance.

4.1 Hydraulic constants

Manning's coefficient was taken as 0.05 for this natural stream channel with weeds, pools and windings (Chapra, 1997). The power equations, written below, were used to calculate coefficient and exponent of depth and velocity utilizing depth, width, velocity and flow rate for different reaches (CPCB, 1982-83; Ghosh, 1996, Chapra, 1997) (Table 1).

$U = a\,Q^{b}$; $H = c\,Q^{d}$; $B = e\,Q^{f}$

U = average cross-sectional velocity

B = average cross-sectional width

D = average cross-sectional depth

Q = flow rate

a, c, e = coefficients for flow on velocity, width and depth respectively

b, d, f = exponents for flow on velocity, width and depth respectively.

4.2 Reaction rate constants

The BOD decay constant had the highest value of 0.95/day for reach one; otherwise, its value fluctuated between 0.2/day and 0.4/day for other reaches. The settling rate and Sediment Oxygen Demand (SOD) were assumed to be zero for the entire course of the river. CPCB

(1982 – 83) reported that only 25 % of the total BOD reaching Yamuna was settleable for the considered stretch and a part of this settled material decomposes anaerobically because the river generally has low DO levels (CPCB, 1982 - 83 and Kazmi, 2000). Moreover, methane bubbles rising to the surface during anaerobic process cause resuspension of the settled material (CPCB, 1982 – 83). Thus the settling process removes only a small part of the total BOD without disturbing the DO profile of the river. Whatever BOD was removed through settling was assumed to get balanced by the loads contributed by non-quantified non-point sources such as bathing, washing, cattle wading and religious offerings of flowers, sweets and milk (CPCB, 1999 – 2000).

The O'Connor and Dobbins (1958) steam reaeration equation were used for this slow moving stream with depth less than 1 m (PDER, 1981). The high turbidity in the stretch diminishes the penetration of light to deeper layers, preventing the growth of phytoplankton (Kazmi, 2000). Therefore, photosynthetic oxygenation was taken as zero.

4.4 Flow and Pollution loads

The low-flow conditions of the non-monsoon period prevail for most of the year except monsoon months of July to September and are critical from the viewpoint of water pollution (CPCB, 1999-2000). Thus, in this study, average river flow in the dry season (March to May) was considered for simulation. Pollution load details of headwater as well as point sources and withdrawals are given in Table 2. The surface water recharge through ground water was reported to be poor for Delhi[2]. Therefore, the incremental flow to the river in the model was considered zero.

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[2] Total ground water available in National capital territory was reported as 291.54 million m^3/year, which was 9.24 m^3/s. Out of which 142 million m^3/year is extracted for drinking purposes and 118 million m^3/year for irrigation (CGWB, 1995).

5. Model outputs

To analyse the accuracy of the simulated results, errors in simulations were estimated as the difference between model outputs and observed data at four locations. The highest relative error, for BOD, was 16 % at the Okhla Bridge monitoring site while it was within 8% at all other locations (Figure 2). Differences between the observed and predicted values of DO were insignificant and showed a good fit at all the study locations.

Najafgarh drain was found to be the chief source of pollution in reach 1; it discharged 171.7 tonnes/day of loading, which is 58% of the total load (Table 2). Collective load of all the drains in reach 2 and 3 was negligible as compared to the other reaches. Hindon Cut and Okhla Barrage falling in the last reach contributed 19% and 7.4 % of the total load respectively additionally affected the water quality.

Out of the 25 km segment of the Yamuna under the current study, the highest DO level of 7.89 mg/l was observed at headwater (Figure 3a). More than 12 km of the river was found to be septic after assimilating loading from Najafgarh drain (i.e., DO = 0 mg/l). Absence of any photosynthetic activity kept the DO at zero most of the time. However, replenishment of DO content was observed at about 15 km downstream from the headwater. But due to the huge pollution load from Okhla Barrage, the DO content dropped down again to 0.44 mg/l. The BOD concentration of the stream at the headwater was 5.84 mg/l. Subsequent loading from Najafgarh drain resulted in an increase in BOD level to 64.79 mg/l. At all the places downstream of Najafgarh drain, the lowest BOD level was found to be 36.44 mg/l (Figure 3b). At the most downstream, diversion of flow to Agra canal and pollutant loading from Okhla barrage resulted in an increase in the BOD levels. The water quality of the river was found to correspond to class E (Table 3) suggesting that the water could not be used for purposes of drinking, fisheries, bathing, and swimming (Figure 3c) (CPCB, 1980-81).

A comparison of DO and BOD levels just upstream and downstream of the sources was made to analyse the impact of various pointloads on the river water quality (Table 4). It was evident that Najafgarh drain had deleterious effect on both water quality parameters. BOD levels increased several folds from 5.42 mg/l to 63.38 mg/l whereas DO decreased to zero from 6.81 mg/l in the river. Impact of pollution load added through other drains is not much in comparison to Najafgarh drain. Only small rise in BOD was observed as and when any drain joined the river.

7. Assimilative capacity of the river

The calibrated model was employed to figure out the assimilative capacity of stretch (NEERI, 1996). BOD and DO of 3mg/l and 6 mg/l were set as desired levels in accordance with the class C. During these simulations all waste flows were set as zero and the load was supposed to be coming to the study stretch from an imaginary upstream source. To calculate the maximum load river can assimilate without any change in the present conditions, model was executed several times with different loading rate to achieve the BOD of 3 mg/l at most downstream point. Assimilative capacity of the river was estimated to be about 9 tonnes/day[3], in contrast to the load of 296.1 tonnes/day, which was about thirty three times higher.

8. Suggestions for water quality management of river Yamuna

The model was further applied to determine strategies that would help in bringing down the water quality of the river to an acceptable limit. The simulations were made to explore how the water quality would change with change in loads as well as environmental modifications i.e., flow augmentation to the river. The scenario helped to visualise the effectiveness of approaches intended to prevent pollution before their actual implementation.

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[3] Calculated as: (33 mg/l of BOD from source – 6mg/l BOD from headwater) X (3.89 m^3/s or 3.89 X 10^3 l /s) of flow X (3600 s) X (24hrs) = 9.07 tonnes/day

The scenario was generated in order to achieve water quality of the river corresponding to class C, i.e., achieving DO more than 4 mg/l and BOD less than 4 mg/l every where in the river. Table 5 provides a summary of the simulations made for the scenario.

The BOD and DO levels of all the point sources were set at 30 mg/l and 4 mg/l. These are in lieu of the permissible levels for discharging wastewater to surface water from any point outlet[4], and which may be achieved by providing proper wastewater treatment to all the drains. In addition, headwater quality was restricted to a BOD level of 4 mg/l[5]. Thereafter, a source was assumed to add 7 m^3/s of fresh water upstream of Najafgarh drain. This implied that water of about 10 m^3/sec would flow through the river, even after the withdrawal for Wazirabad water-works, as per the directives of the Supreme Court of India[6]. It was noteworthy that till this exercise, desired DO levels were attained but the targeted BOD levels (less than 4 mg/l) could not be achieved. Further simulation was carried out by curtailing flow of some of the major drains in order to achieve BOD levels below 4 mg/l at all locations.

Above generated scenario suggested that achieving the water quality of the river corresponding to the class C is a major challenge. But in order to maintain desired water quality in this stretch the following approaches would be helpful.

- All the drains should be given adequate treatment: Waste water discharge from all the drains should be treated to achieve the BOD and DO levels of 30 mg/l and 4 mg/l.
- Flow curtailment from drains: Discharge rate of some of the drains is very high which may be curtailed from entering into the river to maintain its quality. It was also

[4] As specified in Water (Prevention and Control of Pollution) Act, 1974.

[5] As specified by Central Pollution Control Board, to maintain river water quality as Class C.

[6] Recently, on the 14th May '99, the Supreme Court of India had ordered that a minimum flow of 10 cumics (353 cusecs) must be allowed to flow throughout the river Yamuna. For this case, Commander Sureshwar D. Sinha, a resident of Delhi and Chairman of a Delhi-based NGO, Paani Morcha, submitted original writ. This case is listed as Cmdr. Sureshwar Sinha vs Union of India and Others No. 537 of 1992.

suggested long back that curtailed flow of drains might be diverted to Agra Canal through covered pipelines where further treatment could also be provided (NEERI, 1996).

- Flow augmentation to the river: Flow of this river is very lean thus dilution of waste stream is not possible and flow after Najafgarh drain is contributed by waste discharges from drains only. Thus, a flow of 10 m^3/s in the river should be maintained.
- Other measures: These are the measures to aid to the measures mentioned above: (i) Artificial aeration is also deemed necessary as DO levels in the river are less then 1mg/l through out the stretch, which presents constraint for biological degradation of organic load: (ii) Common Effluent Treatment Plants (CETP) are indispensable, especially for all small-scale industries, which cannot afford to treat their effluents; (iii) Sewage treatment facilities should be expanded in the city to abstain untreated domestic waste to the river; (iv) Adopt rain water harvesting, which may increase natural recharge capacity of the river to provide sufficient flow.

9. Conclusion

The QUAL 2E model was calibrated, for the dry season BOD and DO profiles of the stretch of river Yamuna under study. The findings of the study indicated that Najafgarh drain was the principle source of pollution. Because of very high organic loads, the river water could no longer be used for day-to-day life activities and low DO is very crucial for aquatic life. The river is receiving an organic load of about 300 tonnes a day, which is far exceeding the assimilative capacity.

Recovery of this polluted river is a challenge. This study suggests that drains should not be allowed to discharge wastewater without adequate treatment. Keeping river water quality within limits to achieve Class C status requires sustained water flow in the river along with substantial load cut from incoming drains. Both the options are hard-hitting and the economic feasibility needs to be analysed. To achieve the standards, CETP for all small-scale industries and provision of artificial aeration in the septic zones of the river, is also deemed necessary.

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Table 1

Ranges of discharge coefficients and exponents

Input variable	**Value (range)**
Coefficient on flow for velocity	0.032 – 0.08
Exponent on flow for velocity	0.300 – 0.425
Coefficient on flow for depth	0. 126 – 0.33
Exponent on flow for depth	0.245 – 0.475

Table 2

Characteristics of various pollution loads and withdrawals

S. No.	Discharge / Withdrawal	Flow (m^3/s)	D O (mg/l)	BOD (mg/l)	Load (tonnes/day)
1	Head water	15.0	8.10	6.00	__
2	Wazirabad waterworks**	-11.1	__	__	__
3	Najafgarh drain**	26.5	0.0	75.00	171.720
4	Magazine Road drain	0.04	0.0	308.18	1.1982
5	Sweeper Colony drain	0.04	0.0	139.25	0.4813
6	Khyber Pass drain	0.04	0.0	42.60	0.1546
7	Metcalf House drain	0.08	0.0	112.83	0.7506
8	Qudusia + Mori Gate drain	0.20	0.0	156.30	2.7144
9	Tonga Stand drain	0.05	0.0	184.30	0.7962
10	Civil Military drain	0.5	0.0	114.00	4.8923
11	Power House drain	0.41	0.0	163.00	5.7276
12	Sen Nursing Home drain	0.31	0.0	168.33	4.4606
13	Drain No. 14	0.83	0.0	133.35	9.5282
14	Barapulla drain	1.23	0.0	63.00	6.6951
15	Hindon Cut**	14.48	0.1	45.00	56.2944
16	Maharani Bagh drain	0.39	0.0	258.85	8.8117
17	Agra Canal**	-45.83	1.2	20.00	–
18	Okhla Barrage**	3.62	0.0	70.00	21.8938
Total					296.119

Negative sign signifies withdrawal

Source: CPCB, 2000, CPCB 1999-2000; ** NEERI, 1996

Table 3

The surface water quality classification given by Central Pollution Control Board, India

Characteristic	**Class**				
	A	**B**	**C**	**D**	**E**
DO (mg/l)	> 6	> 5	> 4	> 4	< 4
BOD (mg/l)	< 2	< 3	< 4	< 6	> 6

A: Drinking water sources without conventional treatment but after disinfection
B: Bathing, Swimming and Recreation
C: Drinking water source after conventional treatment
D: Propagation of wild life, fisheries etc.
E: Irrigation, industrial cooling and controlled waste disposal.

Source: (CPCB, 1980-81)

Table 4

Impact of the various point loadings on the water quality of river Yamuna

S.No.	Point discharge	DO (mg/l)		BOD (mg/l)	
		U/S of source	D/S of source	U/S of source	D/S of source
1	Najafgarh drain	6.81	0.29	5.42	63.38
2	Magazine Road drain	0.00	0.00	59.34	57.13
3	Sweeper Colony drain	0.00	0.00	55.89	53.59
4	Khyber Pass drain	0.00	0.00	52.43	50.66
5	Metcalf House drain	0.00	0.00	50.66	49.91
6	Qudusia + Mori Gate drain	0.0	0.00	49.91	49.13
7	Tonga Stand drain	0.00	0.00	46.12	44.90
8	Civil Military drain	0.00	0.00	37.39	38.09
9	Power House drain	0.00	0.00	37.65	38.73
10	Sen Nursing Home drain	0.00	0.33	36.86	37.62
11	Drain No. 14	0.52	0.89	37.46	39.38
12	Barapulla drain	2.48	2.57	36.91	37.43
13	Hindon Cut	2.60	1.69	36.44	37.43
14	Maharani Bagh drain	1.53	1.35	38.18	39.46
15	Okhla Barrage	0.59	0.44	37.77	38.61

Table 5

Scenarios presented for the water quality improvement of river Yamuna

S. No.	Discharge/ Withdrawal	Scenario specifications		
		DO (mg/l)	**BOD (mg/l)**	**Flow (m^3/s)**
1	Head water	8.10	4.0	15.0
2	Fresh water Intake	4.0		7.00
3	Wazirabad water works	-	-	-11.1
4	Najafgarh drain	4.0	30	0.8
5	Magazine Road drain	4.0	30	0.04
6	Sweeper Colony drain	4.0	30	0.04
7	Khyber Pass drain	4.0	30	0.04
8	Metcalf House drain	4.0	30	0.08
9	Qudusia + Mori Gate Drain	4.0	30	0.20
10	Tonga Stand drain	4.0	30	0.05
11	Civil Military drain	4.0	30	0.45
12	Power House drain	4.0	30	0.32
13	Sen Nursing Home drain	4.0	30	0.17
14	Drain No. 14	4.0	30	0.06
15	Barapulla drain	4.0	30	0.22
16	Hindon Cut	4.0	30	Nil
17	Maharani Bagh drain	4.0	30	0.21
18	Agra Canal	-	-	-
19	Okhla Barrage	4.0	30	0.22
	Total load (tonnes/day)			12.7892

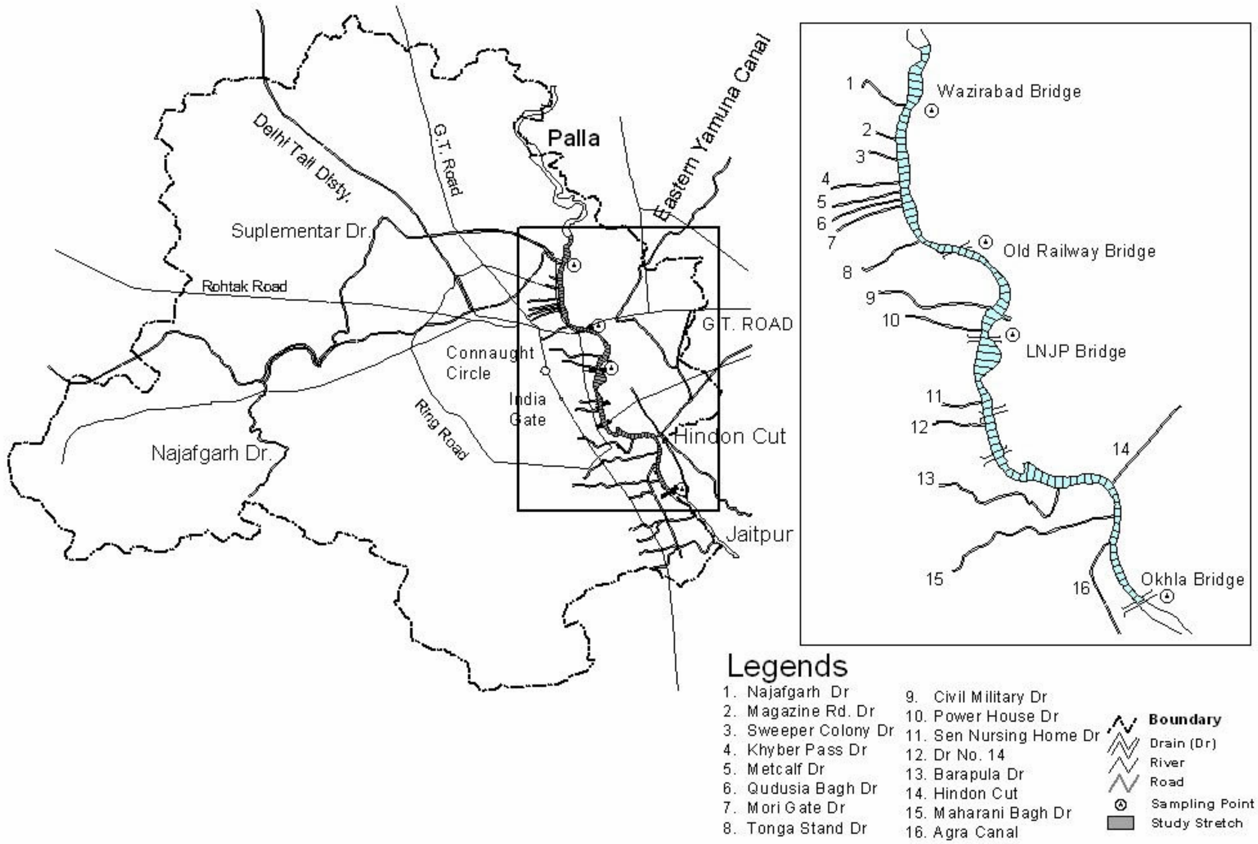

Figure 1. Description of the study area

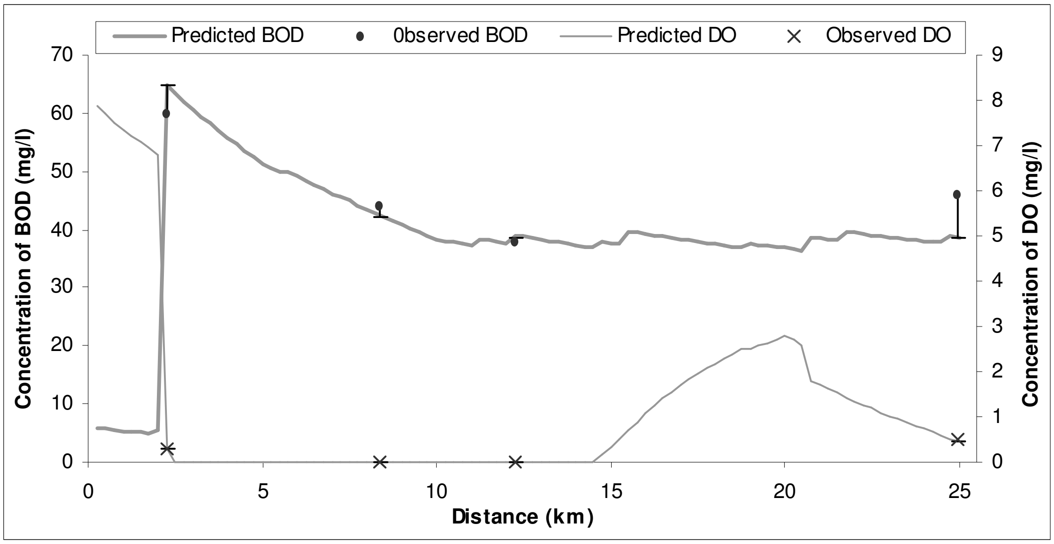

Figure 2. Validation of QUAL2E results- comparison of observed and predicted DO and BOD values

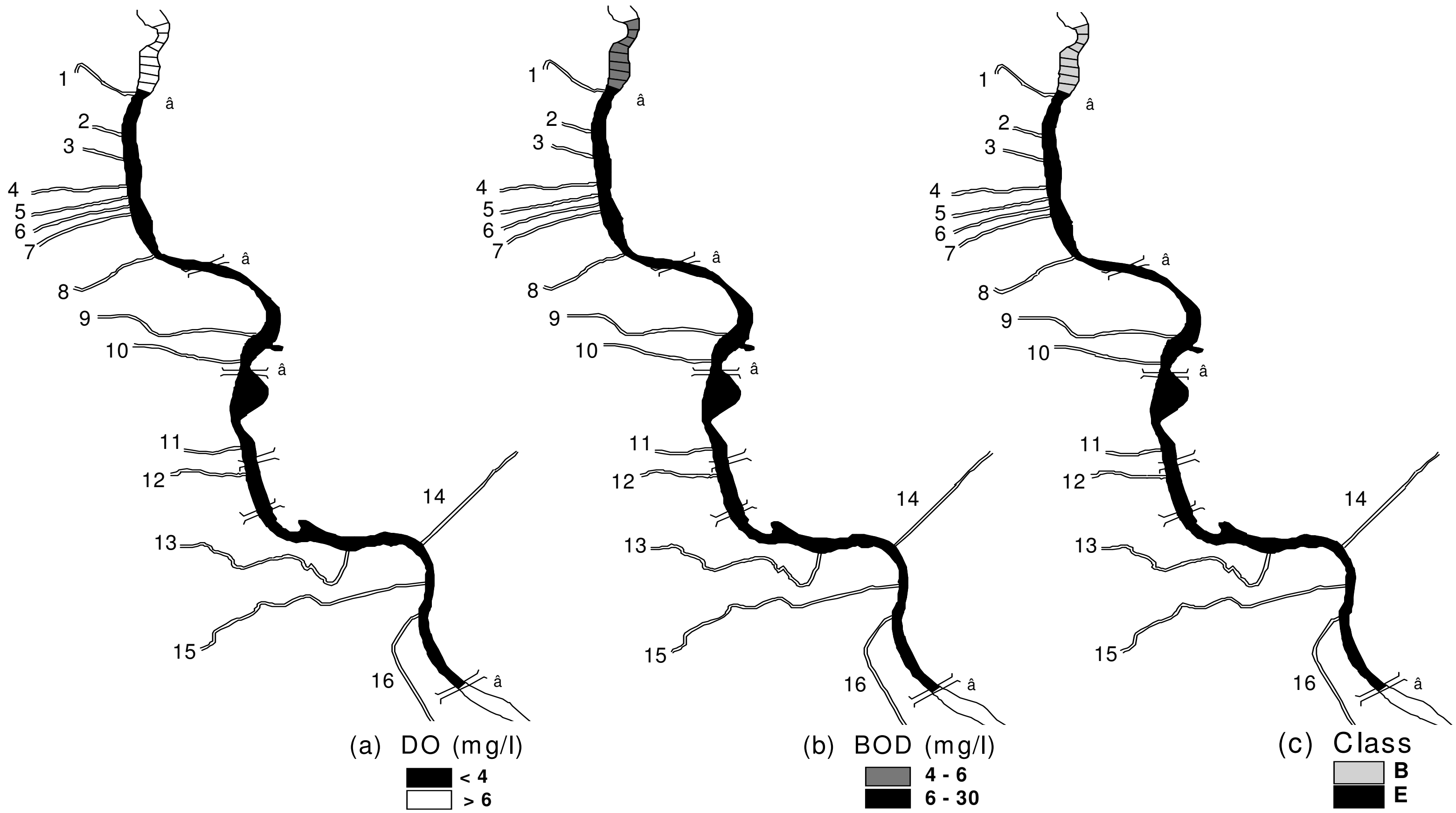

Figure 3. Business as usual Scenario: pollution profile of the river Yamuna