A STUDY OF *EICHHORNIA CRASSIPES* GROWING IN THE OVERBANK AND FLOODPLAIN SOILS OF THE RIVER YAMUNA IN DELHI, INDIA

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(Received 12 August 1997; accepted 30 September 1998)

Abstract. River Yamuna, like most of the major rivers of India, has become increasingly polluted over the years from both point and non-point sources, particularly in the urban sectors such as Delhi. Field studies, conducted in January, 1994 have investigated the impact of wastewater discharges from four major drains (Najafgarh, Power House, Barapula, Kalkaji) on the overbanks, floodplains and *Eichhornia* in River Yamuna in Delhi, with particular reference to elemental contamination. It is concluded that except for Cd and Co, overall mean soil concentrations along the full stretch of the river in Delhi are within the world background levels of uncontaminated soils. However, the wastewater discharges from the drains, with the exception of Barapula drain, generally increase the elemental concentrations of overbank soils downstream of the discharges. *Eichhornia* plants growing along the banks receiving wastewaters from the Najafgarh and Barapula drains are unhealthy and reduced in population which can be attributed to a combination of alkaline pH of the growth medium, metal toxicity and high BOD at the site receiving effluents from the Najafgarh drain, and alkaline pH, metal toxicity and the turbid conditions of water with fly ash particle deposition on the plant surfaces at the site receiving effluents from the Barapula drain. Generally, considering the entire stretch of the river in Delhi, the roots of these plants growing on the overbank soils are found to be accumulators of all elements except Co, Al and Fe, with Co uptake being minimal. There are marked differences in elemental uptake of the water hyacinths growing on the overbanks and floodplains of the river.

Keywords: River Yamuna, *Eichhornia crassipes*, wastewater

1. Introduction

Metals, which are non-degradable, have undesirable effects on the aquatic environment. While many plant species can accumulate heavy metals to concentrations which are not phytotoxic (Lepp, 1981; Adriano, 1986) they may be toxic to consumers higher up in the food chain (Oehme, 1978–79; Merian *et al.*, 1985).

The River Yamuna flows for 48 km through the Indian capital, Delhi, from Palla village in the north to Jaitpur village in the southeast (Dakshini and Soni, 1979). The total area in the Yamuna catchment in Delhi is 1,485 sq km (CBPCWP, 1980–

Environmental Monitoring and Assessment **60:** 25–45, 2000.

81). The river is not only the main source of water supply to the city, but also receives domestic and industrial wastewater discharges from 18 major and minor drains of which Najafgarh, Sen Nursing Home and Power House drains together contribute ∼95% of the total wastewaters being discharged into the river (CPCB, 1993–94).

The rapid increase in population of Delhi (from 2.7 million in 1961 to 10.3 million in 1993) has resulted in increase in the generation of domestic wastewater from 967 million litres per day in 1977 to 1700 million litres in 1993; the capacity of treatment increased from 450 million litres per day in 1977 to 1270 million litres in 1993 (CPCB, 1993–94). Delhi has 20 large, 25 medium and approximately 93,000 small scale industries. Large and medium scale industries constitute less than 0.05% of the total industries located in Delhi but contribute ∼ 50% of the total 300 million litres of industrial wastewater generated everyday (CPCB, 1993–94). The large and medium scale industries have some facilities for effluent treatment but the small scale industries do not have any such setup (CPCB, 1993–94). Hence vast quantities of domestic and industrial wastes generated are released directly into the river without treatment. This results in sharp increases of heavy metal concentrations in river water, sediments and overbank soils (Dakshini and Soni, 1979; Ajmal *et al.*, 1985a; Farago *et al.*, 1989).

Eichhornia crassipes, the water hyacinth, is a common aquatic plant in many tropical countries which has the ability to take up and accumulate elements from water and has been successfully used as an indicator of heavy metal pollution (Ajmal *et al.*, 1985b; Pfeiffer *et al.*, 1986). Many studies have reported that it is possible to use it for removing toxic and heavy metals from aqueous solution/contaminated waters (Wolverton and McDonald, 1975; Haider *et al*, 1984; Low *et al*., 1994; Schneider *et al*., 1995). *Eichhornia* plants are endemic in the River Yamuna although its population and health varies in certain stretches of the river.

The present study examines the impact of wastewater discharges, in terms of elemental contamination, from four major drains on the soils (overbanks and floodplains) and vegetation (water hyacinth) of River Yamuna.

2. Materials and methods

2.1. Sample sites and sampling strategies (see Figure 1)

Sampling was carried out in January, 1994 when temperatures in Delhi ranged between 20–22°C and there was access to the floodplains which may become flooded during the monsoons (June-July). *Eichhornia crassipes*, generally described as free floating, was found to be mainly rooted in the mud along the margins of the river; a few free floating plants were present as well. To study the effects of wastewater discharges from drains on the river, four drains, viz. Najafgarh, Power House,

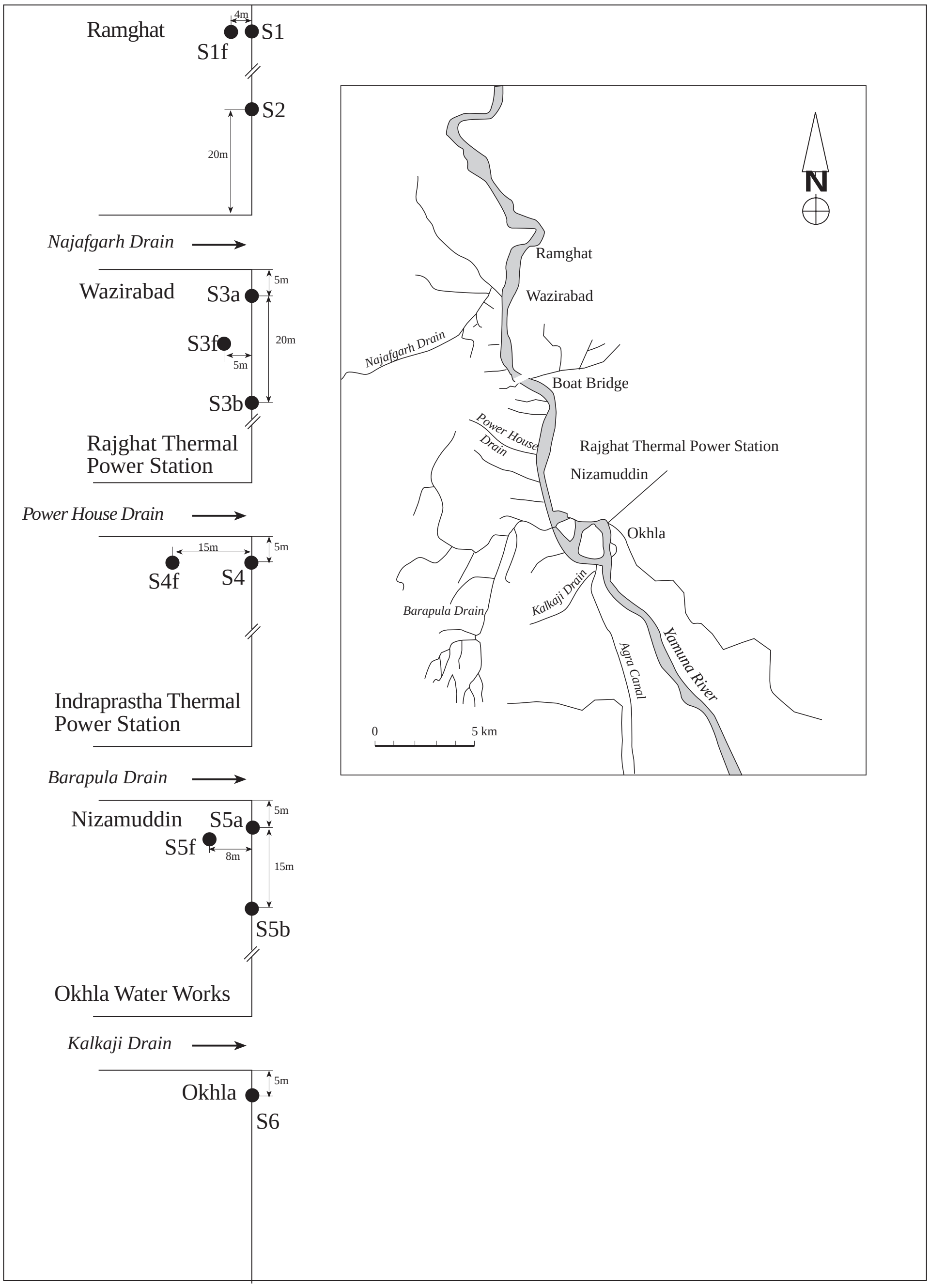


Figure 1. Map of River Yamuna in Delhi showing sampling sites, drains and a schematic of sampling points (Adapted from CBPCWP, 1979).

Barapula and Kalkaji drain (Figure 1) were investigated. Samples were collected from the overbanks and floodplains of the river from upstream to downstream. To obtain composite samples from each overbank site, six sub-samples of soils and six similar sized *Eichhornia crassipes* plants rooted in these soils were collected from a 3–4 m river length and bulked. *Eichhornia* plants were collected in clean polythene bags, rinsed with river water and transported to the laboratory. Six sub-samples of soils (0–5 cm) from a 1 m triangular area from the floodplains were also collected from each of the sites and bulked. Details of the main inputs from the drains and sample collection at each site are given in Table I.

2.2. Treatment of Samples

Soil samples were air dried in Kraft bags (made of wet strength brown paper), ground with a pestle and mortar and finally dried at 50 °C for 4 h. Replicate samples (0.25 g, sieved and ground in a tema mill to grain size of 100 μm) were digested by nitric and perchloric acids (Thompson and Wood, 1982) and analysed for a range of elements by Inductively Coupled Plasma Emission Spectroscopy (ICP-AES).

Plant samples were carefully washed several times with deionized water in the laboratory, divided into tops and roots, transferred to Kraft bags, air dried and then oven dried at 50 °C for 6 h. Replicate samples (2 g, ground in a herbage mill to a fine powder) were digested by nitric and perchloric acids (Thompson and Wood, 1982) and analysed for a range of elements by ICP-AES as above.

Quality control of results was carried out using sample replicates, blanks and house and certified reference materials. Certified reference materials for soils and plants used were NRCCRM and Peach leaves, respectively.

Measurements of pH were made using a standard soil:water ratio of 1:2.5 (w:w) and measuring pH using a glass electrode (Sakata, 1987).

The loss on ignition (LOI) of soils to determine their organic matter content was determined using the method BS 1377:Part 3:1990 (BSI, 1990) using 5 g of soil heated at 440 °C for four hours.

3. Results and discussion

3.1. Soils

The pH and loss on ignition (LOI) values of soils from the overbanks and floodplains of River Yamuna are shown in Table II.

3.1.1. *pH* (see Table II)

The pH values for the overbank soils investigated in the present study have increased slightly from a range of 6.8–7.6 (mean 7.07) in an earlier study on these sites in 1987 (Farago *et al*., 1989) to a range of 7.45–8.73 (mean 7.88) in the present study (Table II). pH of floodplain soils range from 7.44–8.25 (Table II). pH of soil

TABLE I

Main inputs from drains and sample collection from study sites (see Figure 1)

Site	Input from Drains	Description of waste and river waters	Sample Collection Points
S1 Ramghat	no drain discharges	river waters appear clean and free from debris	Overbank soil and *Eichhornia* (S1); Floodplain soil (S1f)
S2 Wazirabad	no drain discharges – upstream of wastewater discharges	river waters appear clean but some floating debris	Overbank soil and *Eichhornia* (S2) (No floodplain samples as inaccessible)
S3 Wazirabad	wastewater discharges from **Najafgargh drain** carrying effluents from electroplating works and other small-scale industries	wastewaters dark and turbid with strong disagreeable odour; river waters with some floating cattle carcasses, grey at S3a clearer at S3b	Overbank soil and *Eichhornia* (S3a, S3b) – (unhealthy plants); Floodplain soil (S3f) (Flood-plains contain sand dredged out of the river to facilitate water flow, hence floodplains on a sharp slope)
S4 Rajghat Thermal Power Station	wastewater discharges from **Power House drain** carrying domestic and industrial waste	wastewaters dark; river waters appear clearer as the river widens downstream	Overbank soil and *Eichhornia* (S4); Floodplain soil and *Eich-hornia* (S4f) (Floodplains – *Eich-hornia* cultivation, these plants ∼ 1m tall as compared to ∼ 20 cm tall at overbanks indicating dif-ference in biotypes)
S5 Niza-muddin	wastewater discharges from **Barapula drain** and from fly ash settling basins of coal-fired Indraprastha Power Station	wastewaters turbid and grey; river wa-ters appear clearer further downstream	Overbank soil and *Eichhornia* (S5a, S5b); Floodplain soil (S5f) (*Eichhornia* vegetation scanty, stunted, unhealthy and covered in fly ash particles)
S6 Okhla	wastewater discharges from **Kalkaji drain** carrying domestic and industrial wastes	wastewaters and river waters appear clear	Overbank soil and *Eichhornia* (S6) (No floodplain samples taken as river bed sand transported by carriers leading to disturbance of floodplain soils)

rather than water is used in this discussion as the plants studied were rooted in mud and hence were growing in a soil medium rather than in a water medium.

As can be seen from Table II pH of both the overbank and floodplain soils are above 7. Field studies for the present work showed that the population of water hyacinth at sites S3 and S5 were significantly reduced as compared with the earlier study conducted in 1987 by Farago *et al.* (1989). The pH at sites S3

TABLE II

Means of pH and Loss on ignition (LOI) values of soils from the overbanks (OB) and floodplains (FP) of River Yamuna (see Figure 1)

	Site S1	Site S2	Site S3	Site S4	Site S5	Site S6
pH (OB)	7.65	8.73	8.06	7.86	7.45	7.55
(FP)	7.47	na	8.25	7.44	7.87	na
LOI%(OB)	4.92	1.18	3.00	4.11	3.83	4.79
(FP)	6.40	na	1.12	10.96	5.97	na

na: not available (samples not collected from site)
Site S3: mean of sites S3a and S3b
Site S5: mean of sites S5a and S5b

and S5 have increased from 6.8 and 7.35 in 1987 (Farago *et al.*, 1989) to 8.06 and 7.45 in the present study, respectively. Although a rise in pH can be considered as a contributory factor for the reduction in plant growth, mainly at site S3, it cannot be attributed as a significant factor because the water hyacinth has been shown to be a very versatile plant which can grow in varying pH conditions. Chadwick and Obeid (1966) have reported that *Eichhornia crassipes* has a maximum growth rate in freshwater at pH around 7.0; Balsooriya *et al.* (1984) have reported that the optimum pH range for the growth of water hyacinth is 6.0-7.0 and in alkaline waters (pH 7.3–7.9) where pollution occurs, growth is restricted; the water hyacinth can survive in pH ranges of 4.4–9.9 (O'Keeffe *et al.*, 1984; Hardy and Raber, 1985) and even up to 10.02 (Akcin *et al.*, 1993) but deficiencies in a number of nutrients may occur at high pH values because although the water hyacinth can adapt itself to the conditions in its growth medium and can neutralize an acidic solution, it does not have the capacity to neutralize a highly basic solution. Thus it can be suggested that in the present study alkaline pH of the growth medium can be partly responsible for the reduction in the population and growth of *Eichhornia crassipes* at site S3.

3.1.2. *LOI* (see Table II)

Loss on ignition values (Table II) indicate that the carbon content of floodplain soils are always higher than the overbank soils except at site S3 where the floodplains receive sand dredged out of the river to facilitate water flow of the river. Generally, the higher carbon content of floodplain soils can be attributed to the floodplain soils receiving human wastes as was evident from field studies, and due to cultivation of vegetation at sites S4 (*Eichhornia crassipes*) and S5 (*Brassica juncea*).

TABLE III

Means of concentrations of elements in the overbank soils of River Yamuna (Means of replicate analysis of samples from composite soil samples) (see Figure 1). Values in mg kg^{-1} dry weight unless otherwise stated

Element	S1	S2	S3a	S3b	S4	S5a	S5b	S6
Cd	0.95	0.7	1.27	0.6	1.30	0.75	0.70	1.63
Co	69	73	86	81	21	37	76	56
Cr	73	49	95	43	87	43	54	95
Cu	21	6.39	47	10.8	33	31	29	39
Mn	399	388	651	306	614	142	224	563
Ni	24	11.8	48	15.7	33	35	30	38
Pb	30	9.90	32	11.8	31	16.2	12.6	30
Zn	78	31	100	39	96	33	33	108
Al%	3.70	2.06	2.49	2.00	5.08	3.92	3.18	5.06
Fe%	2.77	1.75	2.60	1.60	3.62	1.63	2.05	3.57

3.2. Impact of Drains on Elemental Concentrations of River Overbank and Floodplain Soils (see Figure 1, Tables III and IV)

Elemental concentrations in River Yamuna overbank and floodplain soils for the different study sites are given in Tables 3 and 4, respectively. The impact of each of the four drains on the elemental content of soils in the overbanks and floodplains are investigated. Statistical analysis of data using Student's t-test shows that the differences in soil elemental concentrations at the points of wastewater discharges are not statistically significant, as is exemplified below. However, certain trends can be observed which are discussed.

3.2.1. *Effect of Najafgarh drain: (sites S3a, S3b, S3f)*

Concentrations of all elements (except Al and Fe) in the overbank soils increase at site S3a as compared to sites S1 and S2, (Table III). Although this increase is not statistically significant (Student's t-test comparing soil elemental concentrations in sites S2 and S3a give t-value = –0.66 with a 2-tailed significance value of 0.521 at 95% level of significance), it shows that there is an input of toxic metals from the wastewater discharges from this drain which is not surprising as these waters carry, in many cases, untreated effluents from electroplating works. However, the river shows a capacity to dilute down the effects as the concentrations of all elements downstream at S3b (20 m from S3a) get lower although, once again, this reduction is not statistically significant (t-value = 0.80, a 2-tailed significance value of 0.436 at 95% level of significance).

TABLE IV

Means of concentrations of elements in the floodplain soils of River Yamuna (Means of replicate analysis of samples from composite soil samples) (see Figure 1). Values in mg kg^{-1} dry weight unless otherwise stated

Element	S1f	S3f	S4f	S5f
Cd	1.15	0.65	1.75	0.95
Co	33	47	24	48
Cr	85	49	108	71
Cu	26	8.50	52	30
Mn	660	382	552	343
Ni	28	14.60	46	31
Pb	31	12.30	48	19.80
Zn	85	40	142	47
Al%	4.68	2.41	7.31	4.54
Fe%	3.27	1.91	4.45	2.58

Co, Cu, Mn, Ni and Pb concentrations are highest at site S3a as compared to all the other sites indicating that Najafgarh drain is responsible for a major input of these contaminants into the river. These results further emphasize the findings of CPCB (1993–94) which report that Najafgarh drain contributes about 80% of the total wastewater discharges into the River Yamuna from the Delhi sector.

Elemental concentrations in overbank soils at site S3a are higher than the floodplain soils at site S3f, (the difference is not statistically significant, t-value = 0.65, a 2-tailed significance value of 0.528 at 95% level of significance). Moreover, elemental concentrations (with the exception of Co) in the overbanks at site S3b and floodplains at site S3f are quite similar. These results lead to suggest that the input from Najafgarh drain does not have any marked effect on the floodplain soils in terms of metal contamination.

3.2.2. *Effect of Power House drain (sites S4, S4f)*

Moving downstream from site S3b, concentrations of all elements except Co increase at site S4 (Table III) although the increase is not statistically significant (t-value = –0.72, a 2-tailed significance value of 0.481 at 95% level of significance).

Power House drain contributes about 7% of the total wastewaters discharged by the drains in the Delhi sector (CPCB, 1993–94). Therefore, overbank soil Cd concentrations of 1.3 mg kg^{-1}, indicating some anthropogenic input (Kabata-Pendias and Pendias, 1984), and highest overbank soil concentrations of Al and Fe at this site compared to all other sites, may be attributed to the input from wastewater discharges at this site.

Although all elemental concentrations (with the exception of Mn) in the floodplain soils at site S4f are higher than the overbank soils at site S4, which leads to suggest that elements may be deposited from the river, this increase is not statistically significant (t-value = –0.07, a 2-tailed significance value of 0.942 at 95% level of significance).

3.2.3. *Effects of Barapula drain and leachates from ash settling ponds: (sites S5a, S5b, S5f)*

Although the leachates from the ash disposal ponds would be expected to add to the elemental load of the river overbank soils (as field studies showed the wastewaters to be turbid containing fly ash particles), concentrations of all elements in the overbank soils at site S5a (with the exception of Co and Ni) decrease as compared to the soils from site S4 (Table III). However, this decrease is not statistically significant, t-value = 1.00, a 2-tailed significance value of 0.349 at 95% level of significance. Calculations on data from Table III show that at site S5b, 15 m downstream of site S5a, concentrations of Co and Mn in the overbank soils increase by 105 and 58%, respectively. As to whether the fly ash particles are leaching out these elements and their overall effects on the soils and vegetation downstream of site S5b can be explained by sampling further downstream of site S5b and this is recommended for future studies. Somewhat higher concentrations of Cd, Cr, Mn, Zn, Al and Fe in the floodplain soils (S5f) as compared to the overbank soils at both S5a and S5b may be attributed to their leaching from fly ash particles being deposited on the floodplains.

3.2.4. *Effect of Kalkaji drain: (site S6)*

Except for Co, concentrations of all elements in the overbank soils at site S6 are higher than at site S5b (Table III) suggesting an input of these elements into the river system from both domestic and industrial effluents through the Kalkaji drain. However, these increases are not statistically significant, t-value = -0.86, a 2-tailed significance value of 0.409. It is noteworthy that very high Zn concentrations (1215 mg kg^{-1}) were reported for the overbank soils at this site in an earlier study conducted (Farago *et al.*, 1989), but the present study shows that Zn values have fallen down considerably (108 mg kg^{-1}), the present Zn values being comparable to Zn values for Indian soils reported to range between 40-131 mg kg^{-1} in Indore and 33-90 mg kg^{-1} in Rajasthan (Ure and Berrow, 1982) and mean total Zn contents of surface soils from various countries reported to range between 17-125 mg kg^{-1} (Kabata-Pendias and Pendias, 1984). However, the highest Cd and Zn concentrations at this site compared to all other sites investigated (Table III) indicates that there is an input for these elements from the wastewater discharges at this site.

3.2.5. *Overall effects of the drains on the overbank and floodplain soils*

Overall elemental ranges and mean concentrations in soil samples from the overbanks and floodplains of River Yamuna for all the sites investigated are given in Table V. These results show that with the exception of Cd and Co, concentrations of the rest of the elements studied are within levels of uncontaminated soils (Bowen, 1979; Ure and Berrow, 1982, Kabata-Pendias and Pendias, 1984; Berrow and Ure, 1985; Alloway, 1990), and with the HSE (1991) guide for classification of contaminated soils.

Cd levels for all the sites for river overbank soils range between 0.6–1.63 mg kg^{-1} and for the floodplain soils between 0.65-1.75 mg kg^{-1} (Table V). According to Kabata-Pendias and Pendias (1984), the background Cd levels in soils should not exceed 0.5 mg kg^{-1}, and higher values reflect the anthropogenic impact on the Cd status in top soils. Cd values between 1–3 mg kg^{-1} (Alloway, 1990; HSE, 1991) are classified as slight contamination of soils. Holmgren *et al.* (1986) analysed 3305 soil samples from crop-producing areas in 36 states in the United States and found that concentrations of Cd ranged from 0.005 to 2.4 mg kg^{-1}, with mean values of 0.27 mg kg^{-1} . With the mean values of 0.99 for the overbank and 1.13 mg kg^{-1} for the floodplain soils, Cd in the overbank and floodplain soils of River Yamuna can be considered as slightly contaminated which can be attributed to the wastewater discharges from the various drains.

The normal Co content of surface soils usually ranges from 1 to 40 mg kg^{-1} (Kabata-Pendias and Pendias, 1984), with the highest frequency in the range of 3 to 15 mg kg^{-1}; the grand mean Co concentration for world-wide soils being 8.5 mg kg^{-1}. In the Netherlands system (Alloway, 1990) soil Co concentrations of 20 mg kg^{-1} are considered as background, 50 mg kg^{-1} indicate need for further investigation, and 300 mg kg^{-1} indicate a clean-up definitely required. Concentrations of Co in River Yamuna overbank soils range between 21–86 mg kg^{-1} with a mean of 62.4 mg kg^{-1}, and for floodplain soils range between 24–48 mg kg^{-1} with a mean of 38 mg kg^{-1} (Table V) indicating contamination from Co for these soils. The oxide, hydroxide and carbonate of Co are all very insoluble, thus in alkaline conditions the element is immobile resulting in generally greater concentrations of total Co in alkaline than in acid soils (Alloway, 1990). With the alkaline pH of the overbank and floodplain soils (Table II), these soils can render Co immobile and hence these high Co concentrations could be a reflection of the cumulative effect of the input from the wastewaters.

On comparing the elemental concentrations in floodplain soils with overbank soils, it is seen that concentrations of all elements (with the exception of Co) are higher in the floodplain soils than in the overbank soils (Table V) indicating that elements from wastewaters may be deposited in the floodplains from the river. The order of this mean percentage increase is found to be

$$Al > Pb > Fe > Zn > Mn > Cr > Cd > Cu > Ni$$

TABLE V

Overall ranges and means of elemental concentrations in soils from the overbanks (OB) and floodplains (FP) of the entire stretch of River Yamuna in Delhi (OB: n=8; FP: n=4). Values in mg kg^{-1} dry weight unless otherwise stated

Element		Range	Mean	Std. Dev.	Mean % increase
Cd	OB	0.6–1.63	0.99	0.37	14.14
	FP	0.65–1.75	1.13	0.46	
Co	OB	21–86	62.4	22.8	– 39.10
	FP	24–48	38.0	11.6	
Cr	OB	43–95	67.4	22.8	16.17
	FP	49–108	78.3	24.8	
Cu	OB	6.39–47	27.2	13.8	6.99
	FP	8.5–52	29.1	17.9	
Mn	OB	142–651	410	186	18.05
	FP	343–660	484	148	
Ni	OB	11.8–48	29.4	11.9	1.7
	FP	14.6–46	29.9	12.9	
Pb	OB	9.9–32	21.7	9.86	28.11
	FP	12.3–48	27.8	15.52	
Zn	OB	31–108	64.8	33.9	21.14
	FP	40–142	78.5	46.7	
Al%	OB	2.00–5.08	3.44	1.23	37.50
	FP	2.41–7.31	4.73	2.01	
Fe%	OB	1.60–3.62	2.45	0.83	24.49
	FP	1.91–4.45	3.05	1.08	

However, this increase is not statistically significant (t-value = –0.18, a 2-tailed significance value of 0.859 at 95% level of significance). A striking dissimilarity in the trend is the 39.10% reduction in Co concentrations in the floodplain soils as compared to overbank soils (Table V) which is noteworthy.

3.3. Impact of drains on *Eichhornia crassipes* (see Figures 1 and 2, Table VI)

Figure 2 shows the elemental concentrations in the river overbank soils and in the roots and tops of *Eichhornia crassipes* which these soils support; also included is the one floodplain sample for soils supporting *Eichhornia* at site S4f.

TABLE VI

Concentration ratios for root/soil (R/S), tops/soil (T/S) and tops/roots (T/R) in *Eichhornia crassipes* growing in the overbanks (OB) and floodplains (FP) of River Yamuna (see Figure 1)

Element	S1 (OB)	S2 (OB)	S3a (OB)	S3b (OB)	S4 (OB)	S5a (OB)	S5b (OB)	S6 (OB)	Mean (OB)	S4f (FP)
Cd										
R/S	1.67	6.11	2.38	7.38	2.47	7.00	6.26	2.30	4.45	0.83
T/S	1.09	7.51	1.44	3.58	3.81	2.17	2.60	1.29	2.94	0.33
T/R	0.65	1.23	0.61	0.49	1.54	0.31	0.42	0.56	0.73	0.40
Co										
R/S	0.08	0.09	0.04	0.100	0.23	0.17	0.08	0.10	0.11	0.05
T/S	0.004	0.02	0.01	0.01	0.04	0.02	0.02	0.01	0.017	0.01
T/R	0.06	0.18	0.26	0.13	0.16	0.11	0.26	0.09	0.16	0.30
Cr										
R/S	0.22	34.7	4.20	16.61	5.48	9.81	5.11	0.24	9.55	0.09
T/S	0.14	1.34	0.62	0.59	0.52	0.47	0.50	0.07	0.53	0.05
T/R	0.62	0.04	0.15	0.10	0.09	0.05	0.10	0.30	0.18	0.57
Cu										
R/S	1.26	34.9	3.74	23.62	5.52	5.87	4.93	0.74	10.07	0.27
T/S	0.52	3.13	0.61	0.16	0.68	0.59	0.87	0.22	0.85	0.18
T/R	0.42	0.09	0.16	0.09	0.12	0.10	0.18	0.30	0.18	0.64
Mn										
R/S	3.91	1.07	0.29	1.65	0.57	2.47	1.42	1.46	1.61	0.16
T/S	0.86	0.45	0.22	0.92	0.27	1.69	1.17	0.56	0.77	0.18
T/R	0.22	0.42	0.76	0.56	0.48	0.68	0.82	0.39	0.54	1.11
Ni										
R/S	0.34	14.2	3.33	11.91	3.76	3.26	3.16	0.37	5.04	0.06
T/S	0.06	1.52	0.51	0.94	0.62	0.52	0.60	0.07	0.61	0.04
T/R	0.17	0.11	0.15	0.16	0.17	0.16	0.19	0.18	0.16	0.69
Pb										
R/S	0.74	9.79	0.88	3.14	1.23	2.30	2.71	0.32	2.64	0.05
T/S	0.20	0.97	0.21	1.24	0.24	0.37	0.90	0.11	0.53	0.08
T/R	0.27	0.10	0.23	0.39	0.19	0.16	0.33	0.33	0.25	1.45
Zn										
R/S	3.38	19.7	6.34	15.3	5.21	13.2	12.6	1.16	9.61	0.26
T/S	1.08	4.39	1.65	2.90	1.24	2.82	3.42	0.53	2.25	0.24
T/R	0.32	0.22	0.26	0.19	0.24	0.21	0.27	0.45	0.27	0.91
Al										
R/S	0.19	0.73	0.14	0.29	0.10	0.15	0.13	0.11	0.23	0.01
T/S	0.01	0.06	0.02	0.03	0.01	0.01	0.05	0.01	0.0.25	0.07
T/R	0.05	0.08	0.15	0.11	0.14	0.09	0.36	0.09	0.13	0.70
Fe										
R/S	0.32	0.97	0.38	1.32	0.30	0.89	0.65	0.20	0.63	0.02
T/S	0.01	0.09	0.10	0.21	0.04	0.05	0.11	0.02	0.079	0.01
T/R	0.04	0.10	0.27	0.16	0.13	0.06	0.16	0.08	0.13	0.66

Three sets of ratios of concentrations (root/soil (R/S), tops/soil (T/S) and tops/roots (T/R) have been used to investigate the accumulation, indication or exclusion of elements from plants (Farago and Mehra, 1992) with the arbitrary values of means of the ratios of elemental concentrations in plants and soils being taken as:
Accumulator (A) – plant/soil ratio > 1.5;
Concentration Indicator (CI) - plant/soil ratio between 1.5 and 0.5;
Excluder-Concentration Indicator (E-CI) - plant/soil ratio between 0.5 and 0.1;
Excluder (E) - plant/soil ratio < 0.1
Concentration ratios for root/soil (R/S), tops/soil (T/S) and tops/roots (T/R) in *Eichhornia* growing in the overbank soils (at each site and a mean of all sites) and floodplain soils for the present study are given in Table VI.

3.3.1. *Effect of Najafgarh drain (sites S3a, S3b)*

Table VI and Figure 2 show that at sites S3a, *Eichhornia* roots accumulate Cd, Cr, Cu, Ni and Zn, whereas, the tops are accumulators of Zn but also take up Cd to a large extent. At site S3b, the roots accumulate Cd, Cr, Cu, Mn, Ni, Pb and Zn, whereas, the tops accumulate Cd and Zn. Field studies have shown that the population of the water hyacinth at this site is low and the growth of the plants is stunted and unhealthy.

As to whether elemental accumulation by the plants can be regarded as one of the factors for their poor growth at this site is to be treated with caution as the plant is known to accumulate metals to a large extent without showing serious toxicity symptoms (Ajmal *et al*., 1985b; Pfeiffer *et al*., 1986; Schorin *et al*., 1991); also it is seen that the water hyacinths growing at site S2 (which does not receive wastewater discharges) can accumulate comparable elemental concentrations in their plant tissues from lower elemental concentrations in their soils (Figure 2) and yet thrive well. Soil pH at sites S2 and S3 are not too different either (Table II), although the effect of alkalinity of the growth medium at this site cannot be ruled out as alkaline pH combined with pollution can restrict the growth of *Eichhornia* (Balasooriya *et al*., 1984). However, Biochemical Oxygen Demand (BOD) values for wastewaters of Najafgarh drain have been reported to be 62,992 kg d^{-1} which is $\sim$50% of the total BOD load discharged by the major drains into River Yamuna in the Delhi area (CBPCWP, 1982–83). The percentage BOD load has risen to 69% in the recent years (CBCP, 1993–94).

Hence, it can be suggested that the overall pollution load, including alkaline pH, metal toxicity and specially the high BOD introduced by the wastewaters of Najafgarh drain, inhibits the growth and propagation of water hyacinths at this site.

3.3.2. *Effect of Power House drain (sites S4, S4f)*

Table VI and Figure 2 show that at site S4, *Eichhornia* roots accumulate Cd, Cr, Cu, Ni and Zn, whereas, the tops accumulate only Cd but take up Zn to a large extent. Field studies showed low populations of *Eichhornia* at this site.

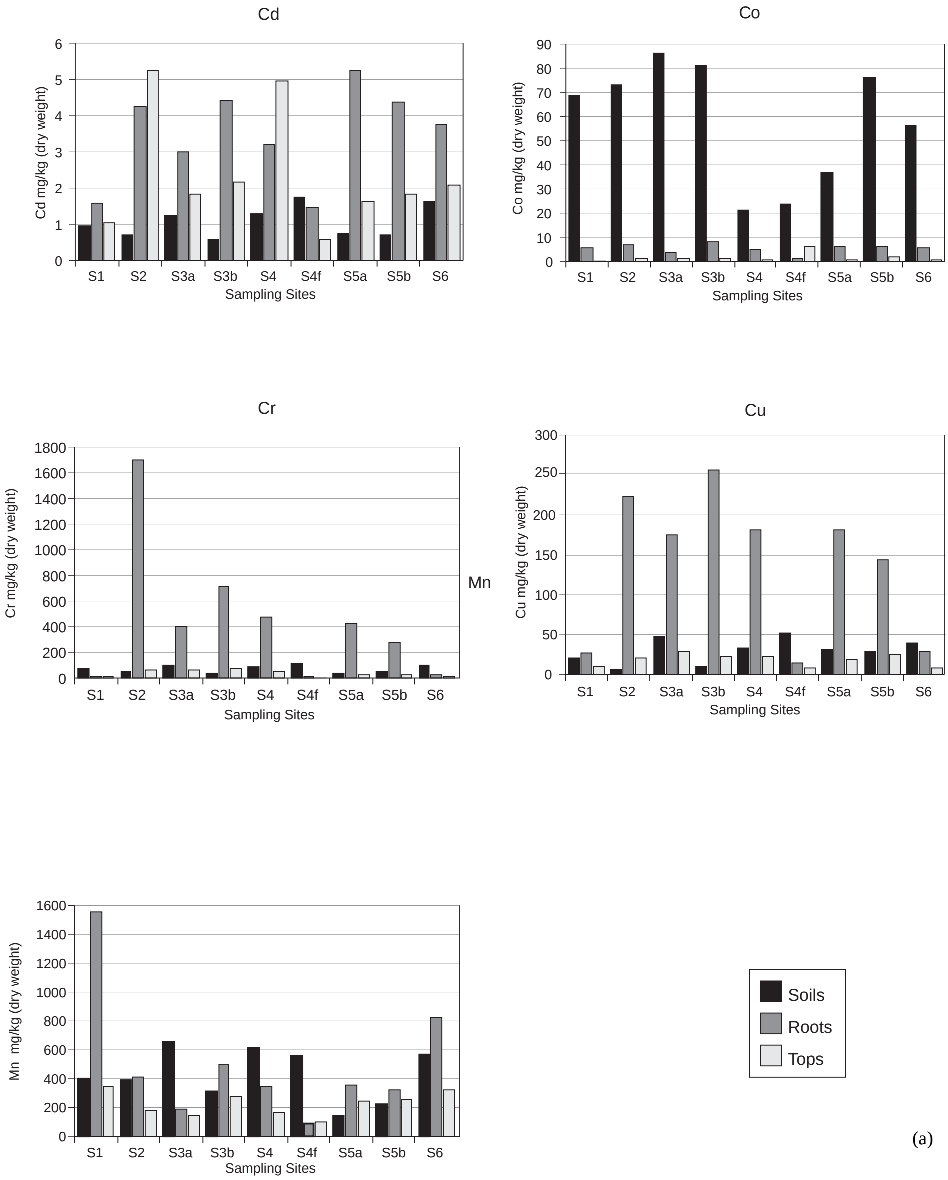
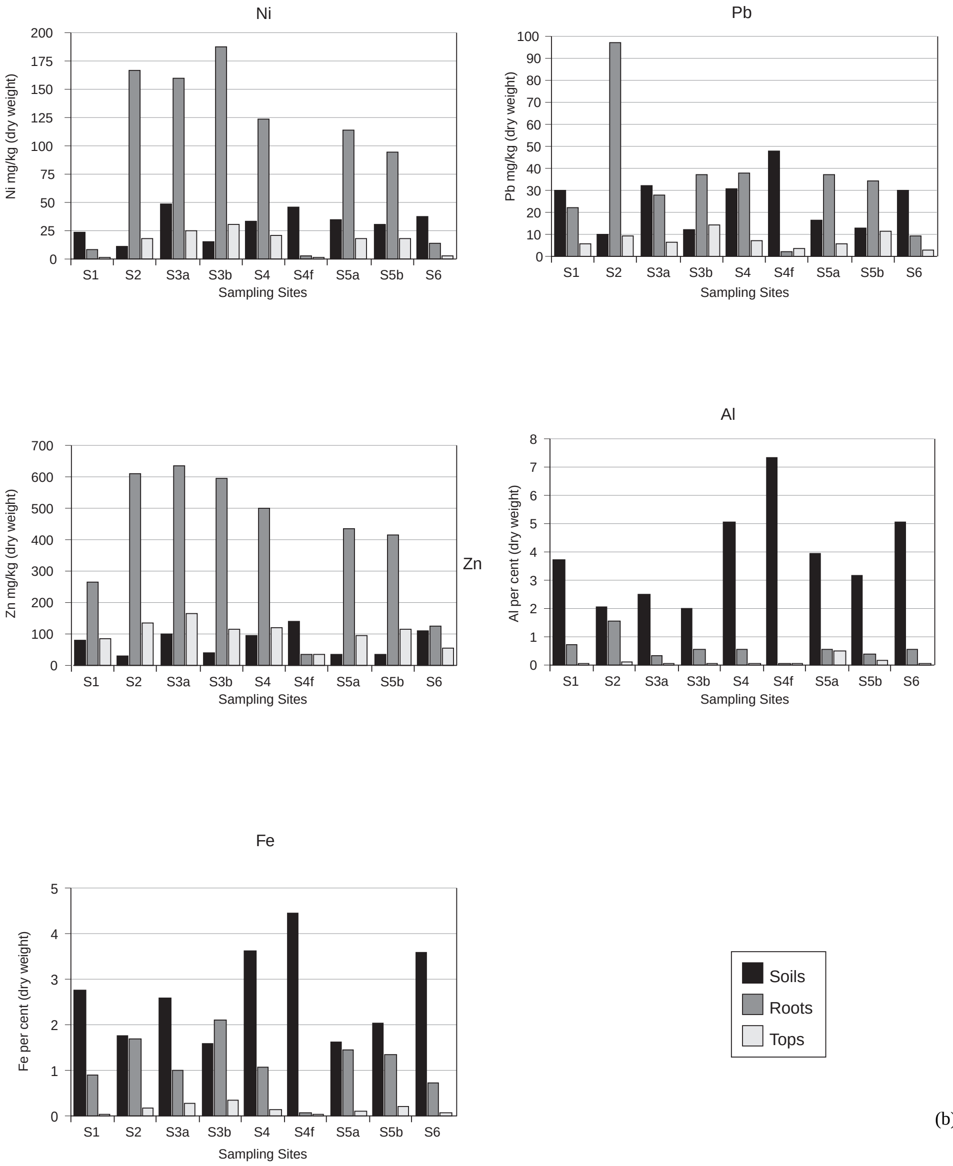

Cd
Cd mg/kg (dry weight)
Co
Co mg/kg (dry weight)
Cr
Cr mg/kg (dry weight)
Cu
Cu mg/kg (dry weight)
Mn
Mn mg/kg (dry weight)
S1 S2 S3a S3b S4 S4f S5a S5b S6
Sampling Sites
Soils
Roots
Tops
(a)

Figure 2a.



(b)

Figure 2a-b. Elemental concentrations in overbank and floodplain soils, and in the roots and tops of *Eichhornia crassipes* (Sampling points – see Figure 1).

An interesting finding at this site is the sharp distinction between the *Eichhornia* growing on the overbanks (site S4) and the floodplains (site S4f) – the roots and tops of *Eichhornia* at site S4f showing much lower elemental uptake than the plants growing in the overbanks at site S4 (Figure 2).

That the roots of *Eichhornia* growing in the overbank soils have shown to have a higher capacity of elemental accumulation than the roots of plants growing in the floodplain soils can be demonstrated by comparing the R/S concentration ratios at sites S4 and S4f which shows that the difference is statistically significant (t-value = 3.14, a 2-tailed significance value of 0.012 at 95% level of significance). Although T/S ratios for plants at S4 and S4f also show a similar uptake pattern, this difference is not statistically significant (t-value = 1.75, a 2-tailed significance value of 0.114 at 95% level of significance). As the elemental concentrations in soils at sites S4 and S4f are not too different (Tables III and IV), lower elemental uptake by *Eichhornia* at the floodplain site may be attributed to the unavailability of the elements in the floodplain soils as compared to the overbank soils.

The difference in metal availability cannot be related to soil pH in this case as both overbank and floodplain soils (S4 and S4f) are in the alkaline range (Table II) where solubility of metals would be low. Table II shows that the organic matter content of soils (related to the LOI values) for the floodplains is higher (10.96%) than the overbanks (4.11%). Moreover, the organic matter content of the floodplain soils (site S4f) is also higher than the normal background organic matter content of surface mineral soils which is usually only about 0.5 to 5% (Bohn *et al*., 1979; Wild, 1993). The humic material in the higher organic floodplain soils may complex with the elements rendering them bio-unavailable and hence lead to lower elemental uptake by the plants in these soils. Moreover, field studies have indicated that the water hyacinths growing in the overbanks and floodplains are of different biotypes.

Hence, differences in soil organic matter content, and more obviously difference in the biotypes of *Eichhornia* can be considered as the possible reasons for the large variation in the elemental uptake patterns of the overbank and floodplain water hyacinths.

3.3.3. *Effects of Barapula drain and leachates from fly ash settling ponds (sites S5a, S5b)*

Field studies at this site have shown unhealthy plants with considerable reduction in population as compared to an earlier study of this site (Farago *et al*., 1989). Table VI and Figure 2 show that apart from Co, Al and Fe, *Eichhornia* roots largely accumulate all elements at both sites S5a and S5b, whereas, the tops accumulate only Cd and Zn, and to a large extent Mn.

Field studies have shown that the leachates from fly ash ponds are turbid, depositing fly ash particles on the water hyacinths thus preventing their normal respiration. Srinivasan (1986) has shown that the effluents from the ash settling basins at this site are alkaline (10.4–11.5) and the bulk river water at this site is above neutral

(7.4–8.3). pH of overbank soils at this site is found to be 7.45 (Table II). Although *Eichhornia* is known to survive in pH ranges of 4.4–9.9 (O'Keeffee *et al*., 1984; Hardy and Raber, 1985) and even up to 10.02 (Akcin *et al*., 1993), deficiencies in a number of nutrients may occur at high pH values leading to their poor growth.

Hence, the combined effects of water turbidity, high pH and metal toxicity may be responsible for the significant reduction and poor health of *Eichhornia* at this site.

3.3.4. *Effect of Kalkaji drain (site S6)*

Table VI and Figure 2 show that at site S6 *Eichhornia* roots accumulate only Cd but take up Mn and Zn to a large extent. The tops of the plants do not accumulate any of the elements studied, although Cd and Zn are taken up to some extent. The water hyacinths at this site are healthy and thriving well as shown by the field studies. pH of overbank soils at this site is alkaline which is similar to the other sites (Table II). As compared to all other sites, the R/S concentration factors for *Eichhornia* at this site (S6) are the lowest for Cu, Pb, Zn and Fe indicating that these metals are not taken up by the plants as readily as they are at most of the other sites although their concentrations in soils are comparable to the other sites (Table III). Thus it seems likely that either these elements are unavailable for plant uptake, or the water hyacinth at this site may be a different biotype which varies in its tolerance to certain elements (Farago and Parsons, 1985) by largely acting as a metal excluder. Hence, the healthy condition of *Eichhornia* at this site may be attributed to both soil factors which may render the elements unavailable, and plant factors where a different biotype may act as a metal excluder.

In general, the following findings on *Eichhornia* growing along the banks of River Yamuna are noteworthy:

Bioaccumulation of elements. Mean R/S values of plants growing in the overbanks for all sites (Table VI) show that *Eichhornia* roots accumulate all elements except Co, Al and Fe. This accumulation of elements is in agreement with several studies which have shown that the water hyacinth is a bioaccumulator of elements (Wolverton, 1975; Wolverton and McDonald, 1975; Gonzalez *et al*., 1989; Jamil, 1990; Schorin *et al.*, 1991; Delgado *et al.*, 1993; Low*et al*., 1994). Moreover, the uptake of all metals by the water hyacinth is stronger in the roots than in the tops of this plant as shown by the mean R/S, T/S and T/R ratios (Table VI) which again agrees with several studies indicating that more uptake and accumulation occurs in the roots than in the tops of the water hyacinth (Wolverton and McDonald, 1978; El-Sharnouby *et al*., 1983; Jana, 1988; Schorin *et al.*, 1991; Ding *et al*., 1994; Fett *et al.*, 1994; Low *et al.*, 1994; Zaranyika *et al*., 1994; Schneider *et al.*, 1995).

Exclusion of Co. From Table VI it can be seen that the uptake of Co by the water hyacinth is different from all the other elements studied. Roots take up Co very sparingly at all sites (mean R/S ratio being 0.11). Also, T/S ratios show that very little Co is taken up by the plant tops (mean T/S ratio being 0.017). Of the Co taken up by the roots some of it is transported from the roots to the tops as is shown by the mean T/R ratio of 0.16. Overall it can be seen that the plant has largely excluded Co. As Co concentrations do not vary much in the soils between the sites (Table III) and the plant is able to take up the other metals to a large extent (Table VI), the inability of the water hyacinth to take up Co can be mainly attributed to the bio-unavailability of the metal to the plant. This unavailability of Co may be related to a number of factors such as:

(i) Co in the soils being present in insoluble and immobile forms. (According to Alloway (1990) the oxide, hydroxide and carbonate of Co are all very insoluble, and in alkaline conditions the element is immobile)

(ii) Co in the soils being rendered unavailable for plant uptake in the presence of moderate amounts of Mn in the soil (McKenzie, 1977)

(iii) Lack of uptake of Co by the plant as a result of biochemical antagonisms between Co and Fe which arise from the similarity of their metallo-organic compounds (Kabata-Pendias and Pendias, 1984).

Difference in uptake patterns in the overbank and floodplain plants. There is a marked difference in the uptake patterns of the water hyacinth plants growing in the overbank soils and in the floodplain soils of the river as shown by the difference in the R/S, T/S and T/R ratios (Table VI). This difference can be attributed to differences in soil organic matter content and plant biotypes. However, it should be noted that floodplain samples of *Eichhornia* were obtained only from one site (site S4f) where they were being cultivated, hence this comparison requires further studies for a conclusive explanation.

Beneficial effects of Eichhornia on River Yamuna. The water hyacinth has been noted to be a potential agent for wastewater treatment due to its ability to absorb minerals, heavy metals and organic substances at a remarkably high rate (Thyagarajan, 1984; Jamil, 1990; Brix, 1993) and Bhargava (1985) has suggested that these plants should be encouraged to grow in the drains before they discharge into the river. As to whether the water hyacinths growing in River Yamuna may be responsible for purifying the river to a considerable extent by (i) reducing BOD which is related to their capability of transporting oxygen from the foliage to the rhizosphere (Jedicke *et al.*, 1989; Reddy *et al.*, 1989), (ii) removing fly ash particles by adhering them to the plant, and (iii) reducing Cd contamination of overbank soils of the river by accumulating it within its tissues, is being further investigated.

From the above discussions it can be concluded that the drains investigated add to the pollution load of River Yamuna and may be responsible for the reduction in its aquatic flora. These findings are in agreement with several other studies carried out on River Yamuna in the Delhi area (CBPCWP, 1980-81; Farago *et al*., 1989; CPCB, 1993-94; CPCB, 1995).

According to the Water Quality Criteria laid down by the Central Board for the Prevention and Control of Water Pollution in India (CBPCWP, 1980-81) the water quality of River Yamuna in Delhi has improved only slightly over several years as shown by a report of the Central Pollution Control Board of India in 1995 (CPCB, 1995). Tighter controls on treatment of wastewaters before discharging into the river have been recommended by the Central Pollution Control Board (CPCB, 1995) with plans to carry out pollution abatement works in all the polluted stretches of rivers in India. Industrial units are being persuaded to adopt clean technologies, and to adopt and operate the treatment plants. Pollution statistics of Delhi (CPCB, 1993-94) show that by 1997, when the schemes under the Yamuna Action Plan would have been implemented, about 98% of the domestic wastewater generated would be treated. Hence the pollution from the various drains discharging domestic and industrial wastewaters into River Yamuna in Delhi may reduce significantly with time.

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