The problem of groundwater pollution: a case study from Madras city, India

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Abstract Groundwater samples collected during monsoon and summer from both open and dug wells in an area of 270 km^2, were analysed for eight ultra trace elements (Cd, Co, Cr, Cu, Mn, Ni, Pb and Zn). The mobility, concentration and geoaccumulation of these metals are important indices to quantify the levels of pollution. Data are presented as elemental contour maps of the Madras basin. The spatial distribution of these elements indicates the pathways of these elements entering the hydrological system during summer and monsoon. Elements such as Mn, Cr and Zn exceed the maximum permissible limits at certain locations. Heavy metals such as Cu, Pb, Cd, Ni, Cr and Mn control the metabolic activity in living organisms. Inter-elemental correlation and factor analyses indicate the gravity of the pollution in the Madras city environment.

INTRODUCTION

Natural waters are increasingly subject to a variety of pollution sources attributed to urbanization, industrialization, the proliferation of chemical, products and even natural sources. Trace elements can be toxic even at low concentration levels. The World Health Organization (WHO) and many national government departments have set standards for trace elements in groundwater, surface water, drinking water etc. However, application of these standards require high analytical precision and accuracy, particularly for trace metals.

In India, the pressure on land has been enormous as can be judged from the fact that in 1961, the total urban population was 78 million and in 1991 this had increased to 217 million representing 25.7% of the total population, as against 18% 30 years ago. Situated on the east coast, Madras is one of the four major cities in India stretching for 19 km along the Coromandel coast and extending inland for about 9 km, covering an area of about 172 km^2. Madras is situated on a fairly low-lying strip of land, its highest point being only 60 m above sea level and is traversed by two east-flowing rivers: the Cooum River and the Adyar River (Fig. 1). The historic Buckingham Canal runs nearly parallel to the coast almost through the entire length of the city. These waterways carry the storm water during the monsoon season. Appasamy & Lundqvist (1993) indicated that these waterways are anoxic with high levels of ammonia, BOD and heavy metals

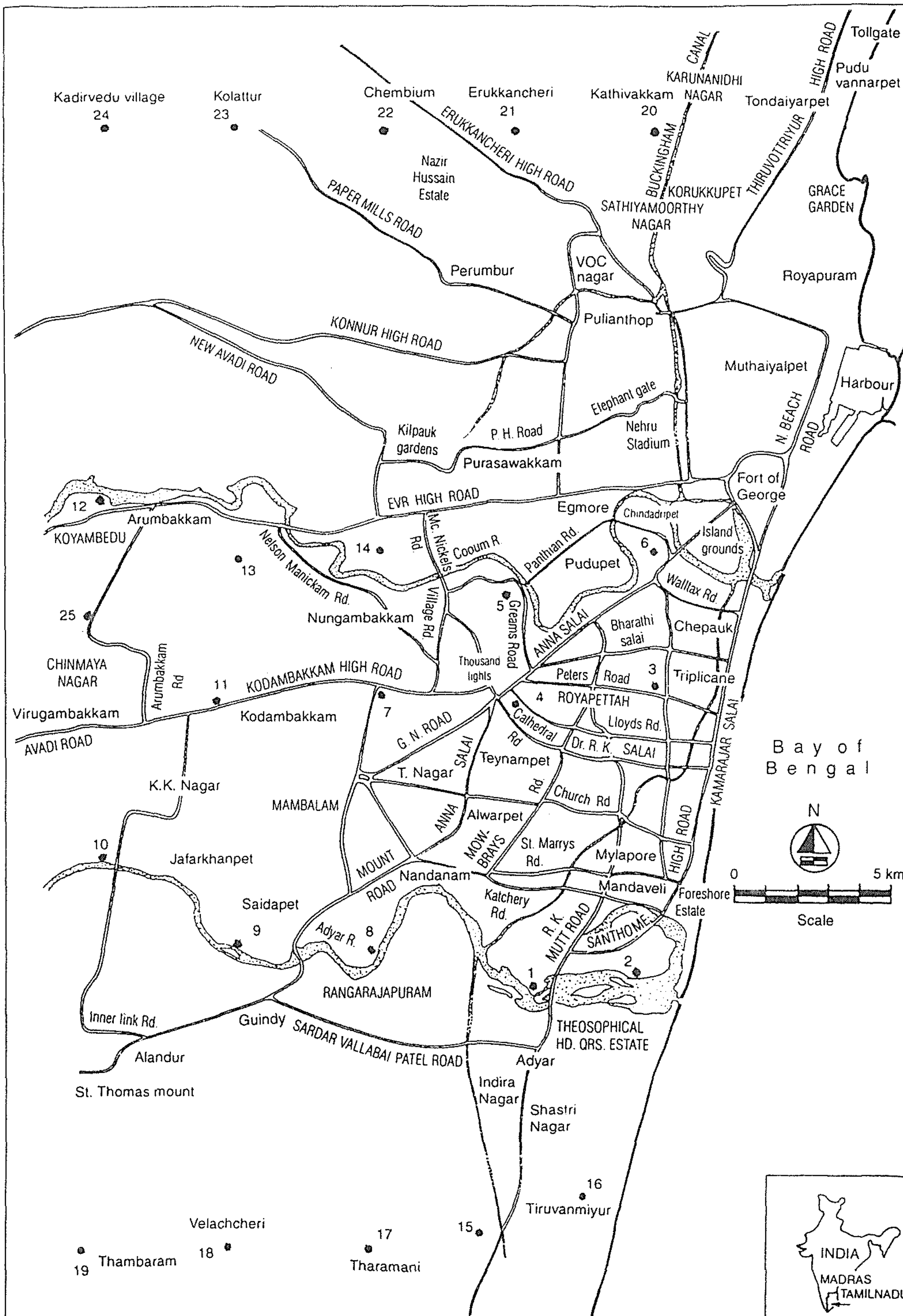

Fig. 1 Sampling locations.

such as Zn, Cu, Cr and Pb. The primary source of water supply for Madras city consists of three interlinked, rain-fed reservoirs (Red Hills, Poondi and Cholavaram), located to the northwest. This source is supplemented with groundwater from aquifers on the northern and southern boundaries of the city.

In coastal areas, the groundwater varies in quality depending on the equilibrium conditions maintained between freshwater and seawater, which in turn is controlled by the quantity of groundwater abstracted. The behaviour of trace elements in groundwater is complex, and is related to the water source (rain, river flow and seawater) and anthropogenic influences – like pollution due to industrial and municipal discharges, and the application of agrochemicals and pesticides (Drever, 1988). Scant attention has been paid to describing the mobility of trace elements in groundwater in urban environments (Ramesh *et al.*, 1994). Tanji & Valoppi (1989) presented an overview of trace element behaviour in agricultural areas and Ramesh *et al.* (1994) describe the concentration ranges of some major and minor elements during summer, and discuss possible mobilization processes, in groundwater of Madras city. This paper reports on the behaviour of trace elements analysed during monsoon and summer, and aims to define migration patterns and the major processes that control the trace element concentration in the groundwater of Madras city.

METHODOLOGY

Representative groundwater samples were collected from various locations (Fig. 1) during summer (May) and monsoon (December) seasons in 1993. New one litre polythene bottles were used for sample collection. The samples were acidified with HNO_3 and stored at 4°C. Trace element concentrations in the water samples were determined by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS, Perkin Elmer Elan 5000). The instrument was calibrated with external standards, and a reference solution provided by the National Institute for Standards and Technology (NIST # 1643 C) was run after every 10 samples to check for drift in the sensitivity of the instrument. For each element, quantification was based on the most abundant isotope of that element free from analytical interferences. Analytical data were processed using inter-elemental correlation matrix, Principal Component Analysis (PCA) and factor analysis.

RESULTS AND DISCUSSION

The seasonal variation in trace element concentration in the groundwater of Madras City is presented in Table 1. This shows an overall decrease in the relative concentration of trace metals (except Mn and Zn) from summer to monsoon, due to heavy local precipitation and seepage which not only dilutes the concentration of the trace elements, but also aids in their migration. In order to show the spatial pattern of those element concentrations in relation to point sources and the local geological and hydrological system, the metals were plotted on the Madras basin map (Figs 2 to 9). These highlight the influences of dilution during the monsoon season. The aquifers of the Madras basin are generally shallow and are recharged by precipitation, flow from river beds and surface water bodies. Elements such as Mn, Zn, Cu, Cd and Ni cover the entire geochemical

Table 1 Seasonal variation in trace element concentration in groundwater of Madras city.

S. No.*	Cd		Co		Cr		Cu		Mn		Ni		Pb		Zn	
	Monsoon	Summer	Monsoon	Summer	Monsoon	Summer	Monsoon	Summer	Monsoon	Summer	Monsoon	Summer	Monsoon	Summer	Monsoon	Summer
1	0.62	1.35	1.81	3.95	2.13	16.14	24.24	29.37	235.77	263.62	26.07	42.12	3.03	3.85	164.88	5443.1
2	2.78	2.50	1.19	2.79	4.64	88.24	152.71	530.13	677.99	315.57	31.15	85.19	6.03	1.55	315.29	350.30
3	0.34	0.90	0.39	1.37	3.03	16.26	12.58	288.29	120.19	19.43	7.09	29.53	3.27	4.90	960.99	169.49
4	1.23	1.66	1.04	1.39	3.21	16.19	23.98	221.24	23.12	18.66	30.64	32.49	1.73	2.87	129.79	373.44
5	1.80	1.66	1.52	2.17	4.77	33.07	47.26	520.55	242.64	18.77	30.62	39.33	2.26	1.42	543.75	534.60
6	2.06	1.54	4.87	4.52	4.17	32.03	29.91	385.75	1151.56	1139.52	84.18	39.39	1.85	13.82	161.75	306.20
7	1.49	0.76	2.45	1.97	8.31	8.73	102.44	125.21	44.85	15.77	33.06	28.06	21.31	4.06	6179.59	81.10
8	0.70	2.49	0.87	27.77	5.85	58.99	25.60	558.93	47.37	10186.71	20.47	75.99	6.85	1.52	843.04	8466.0
9	4.76	1.24	1.79	4.22	8.40	11.18	16.87	39.71	343.36	311.60	24.30	35.68	6.68	24.71	823.68	108.56
10	1.57	1.07	1.10	1.08	7.19	8.61	14.59	33.92	871.75	18.74	22.83	29.31	6.24	9.81	292.85	58.60
11	1.96	1.10	0.59	1.50	13.03	9.43	12.99	36.41	14.99	45.54	11.92	30.99	8.60	11.45	94.91	89.04
12	0.49	1.19	1.59	0.85	7.99	6.40	60.03	24.30	856.31	16.74	16.26	27.54	25.44	7.78	97.78	45.72
13	1.99	1.97	2.25	2.17	8.41	20.32	21.95	144.19	46.39	17.26	36.30	41.14	5.09	3.64	97.53	81.08
14	0.33	1.00	3.09	2.09	4.38	5.08	27.79	32.21	246.08	131.24	50.00	25.79	4.41	14.71	73.81	132.30
15	1.73	1.41	2.75	1.89	12.83	20.26	170.15	153.37	1907.99	283.94	51.03	40.50	5.36	4.99	45.53	271.35
16	0.22	1.64	1.05	1.15	14.08	11.64	26.18	64.16	23.33	71.46	24.01	32.04	10.71	5.93	698.48	127.33
17	0.62	1.08	3.97	3.60	8.15	6.10	16.55	25.33	195.01	153.32	18.79	32.98	5.76	7.14	65.45	177.03
18	1.02	1.42	1.54	2.01	4.97	10.01	14.01	30.23	35.23	46.76	30.10	40.16	4.21	6.97	953.50	1153.4
19	1.21	1.85	1.38	1.76	4.51	9.86	14.25	32.12	20.05	25.05	35.71	45.98	6.91	7.14	219.22	284.42
20	1.43	1.13	1.44	1.84	4.60	7.41	10.55	25.86	135.21	90.81	24.66	35.25	3.96	7.03	1214.67	83.63
21	0.01	1.83	1.61	2.00	3.16	14.37	29.73	51.49	687.60	1194.20	30.28	39.04	3.29	5.68	19.63	217.70
22	0.49	1.38	1.24	1.52	2.79	8.41	14.57	31.02	88.66	56.90	34.85	44.05	3.48	6.07	154.03	58.98
23	0.62	1.56	0.68	1.59	4.17	8.76	61.26	26.66	28.31	21.24	20.06	44.41	8.22	4.66	97.59	298.05
24	0.26	2.17	0.60	1.65	4.42	12.22	6.26	48.02	19.49	40.70	16.75	43.27	3.32	3.48	35.14	166.63
25	1.62	2.02	1.03	1.91	9.99	14.80	24.17	57.20	354.65	1938.26	13.21	45.65	17.83	3.01	130.97	59.70

* Refer to Fig. 1 for sampling locations.

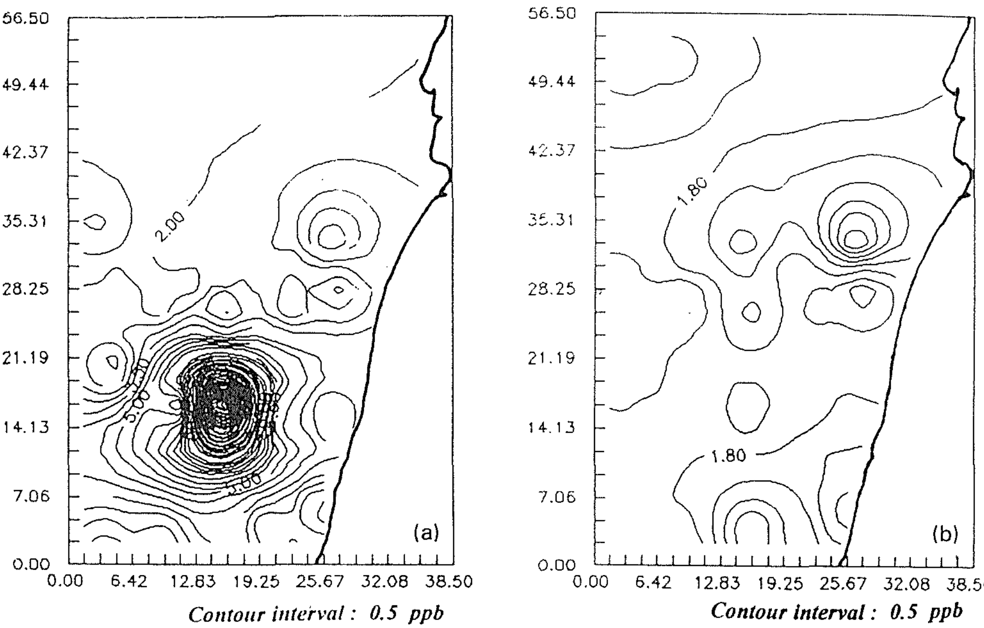

Fig. 2 Concentration contour map of cobalt in the groundwater of Madras city during (a) summer, (b) monsoon.

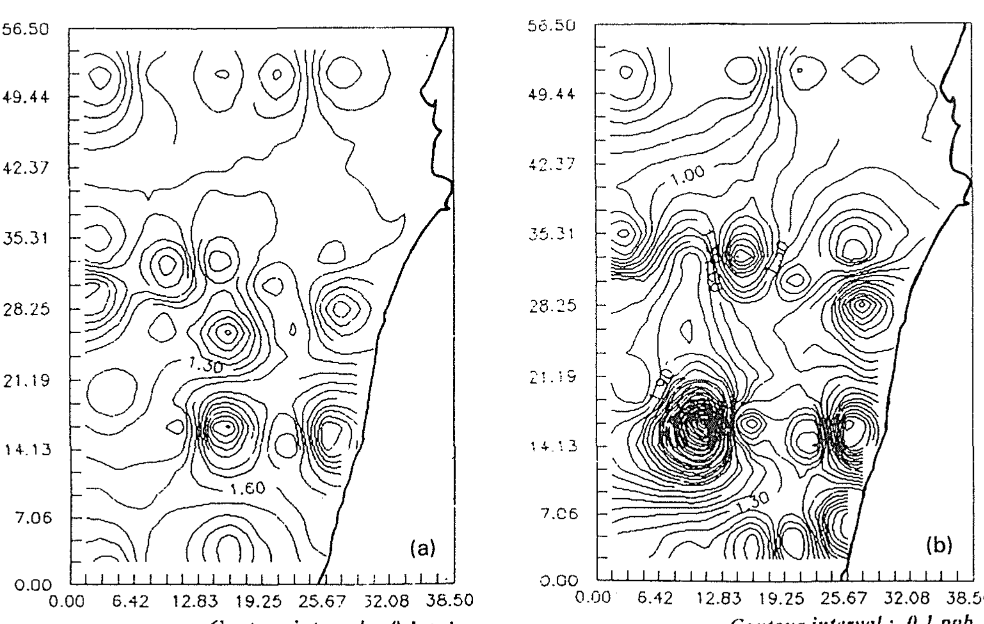

Fig. 3 Concentration contour map of cadmium in the groundwater of Madras city during (a) summer, (b) monsoon.

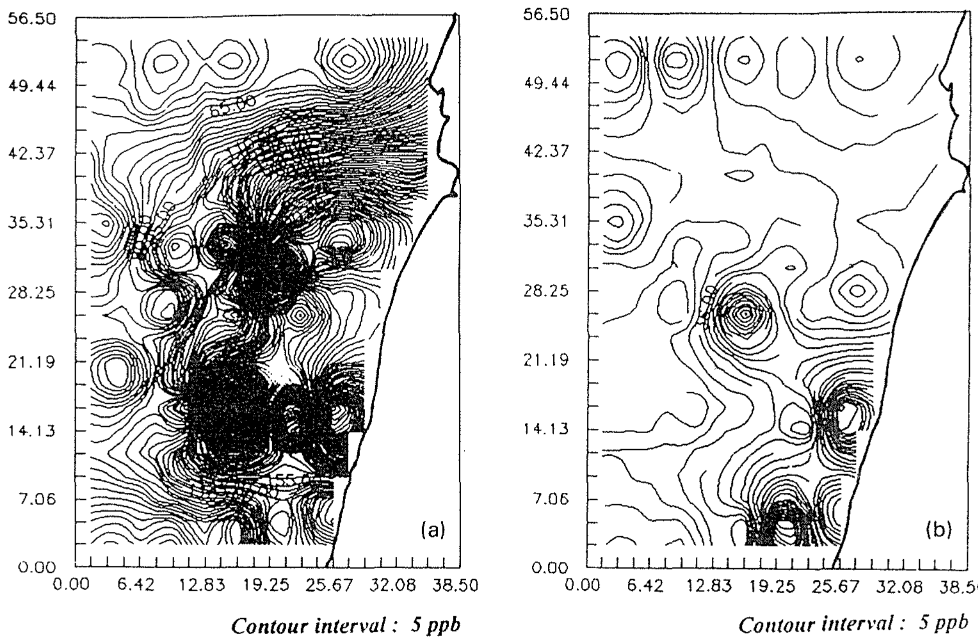

Fig. 4 Concentration contour map of copper in the groundwater of Madras city during (a) summer, (b) monsoon.

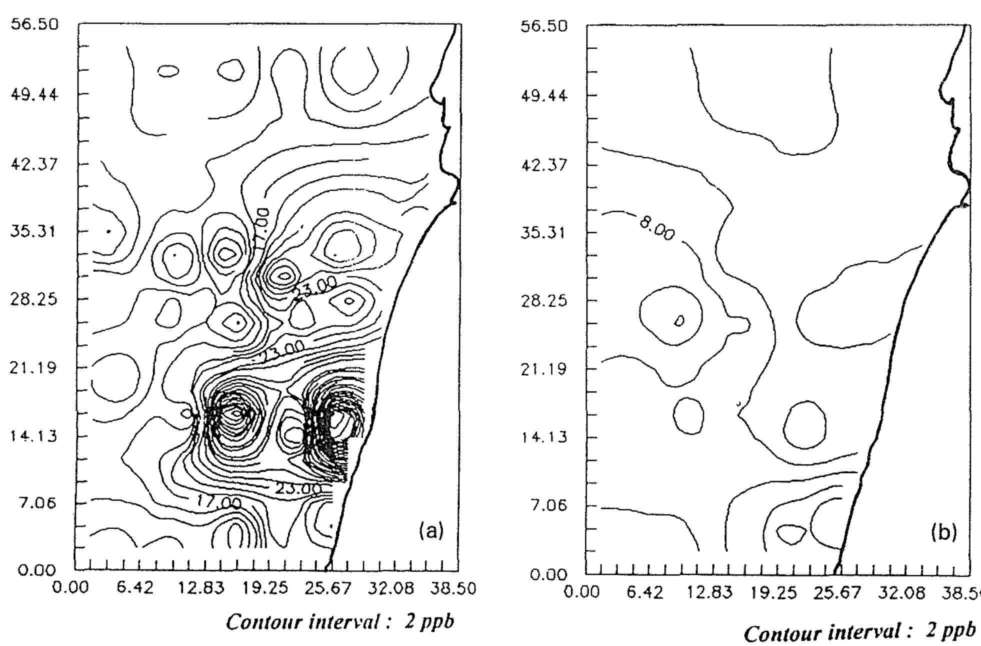

Fig. 5 Concentration contour map of chromium in the groundwater of Madras city during (a) summer, (b) monsoon.

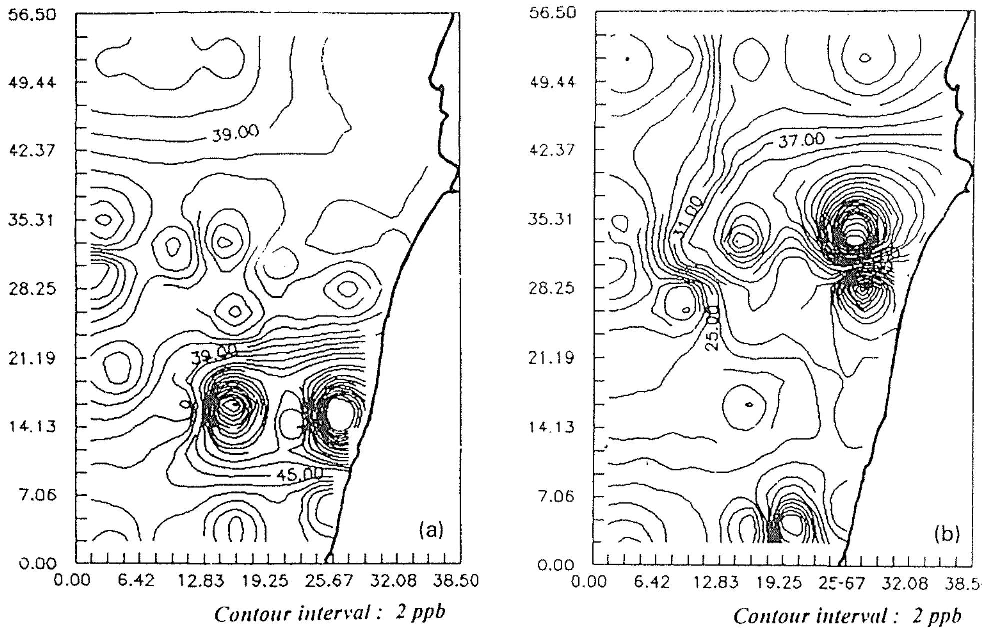

Fig. 6 Concentration contour map of nickel in the groundwater of Madras city during (a) summer, (b) monsoon.

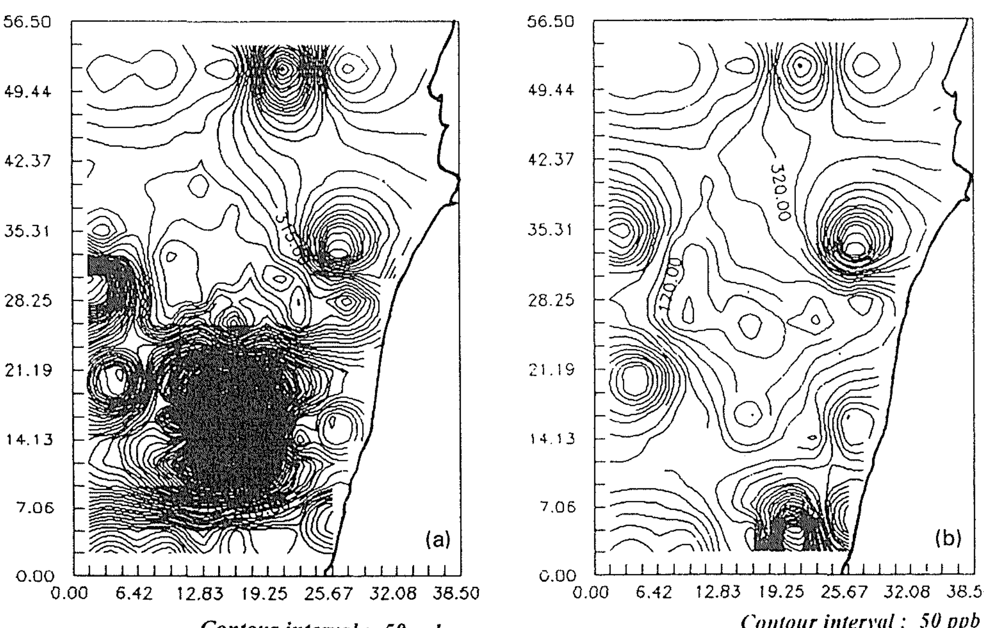

Fig. 7 Concentration contour map of manganese in the groundwater of Madras city during (a) summer, (b) monsoon.

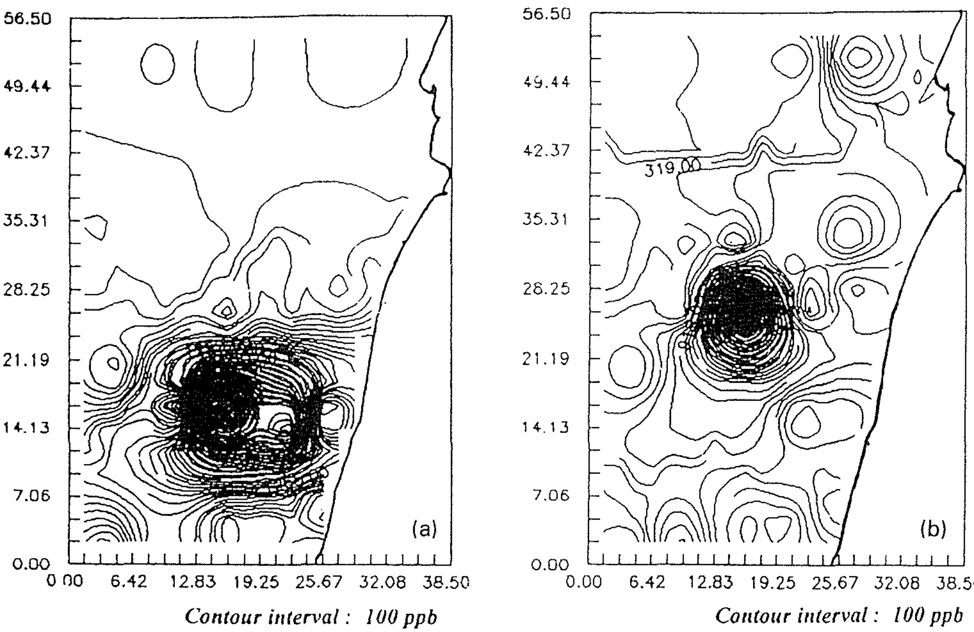

Fig. 8 Concentration contour map of zinc in the groundwater of Madras city during (a) summer, (b) monsoon.

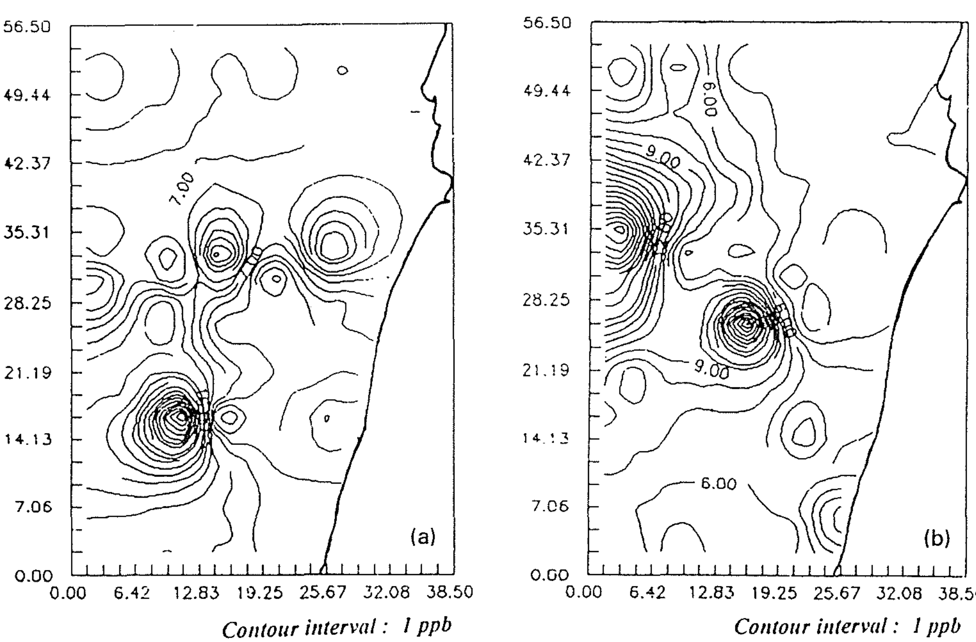

Fig. 9 Concentration contour map of lead in the groundwater of Madras city during (a) summer, (b) monsoon.

map both during summer and monsoon suggesting that the groundwater of the Madras basin is contaminated. In contrast to most metals, Mn and Zn concentrations at most of the locations are higher during monsoon than in summer, probably due to the leaching of these metals from the adjoining contaminated river bed sediments through seepage. Unplanned industrialization and indiscriminate disposal of untreated effluents into the adjoining rivers probably resulted in anomalous distribution of certain elements, such as Mn, Zn, Cu, Cr, Ni. With regard to drinking water standards, Mn values show that more than 50% of the Madras basin is enriched with Mn and at many locations, concentrations exceed the WHO (1984) guideline value of 100 ppb. Rawal (1968) has observed Mn values ranging from 20 ppb to 118 ppb in drinking water collected from different parts of India. Anomalous chromium values occur along the Adyar River and the coastline. In Madras, large quantities of effluents are discharged by 90 tanneries in places such as Pallavaram, Chrompet and Pammal, increasing the Cr content in the groundwaters. Other trace elements were generally below the permissible levels for drinking water.

Statistical analysis

The correlation coefficient matrix for all the trace elements during monsoon and summer are presented in Tables 2(a) and 2(b). During summer, the trace metal pairs such as Ni-Cd, Ni-Cr, Mn-Co, Mn-Zn, Zn-Co, Cu-Cr, Cd-Cr, Ni-Cu show a strong positive correlation indicating that all these metals occur together as pollutants mostly derived from industrial effluents, possibly moving together as polymetal complexes. However, during

Table 2 Inter-elemental correlation matrix for trace elements in groundwater of Madras city.

(a) during monsoon

	Cd	Co	Cr	Cu	Mn	Ni	Pb	Zn
Cd	1.00							
Co	0.14	1.00						
Cr	0.20	0.04	1.00					
Cu	0.22	0.16	0.25	1.00				
Mn	0.27	0.43	0.22	0.60	1.00			
Ni	0.19	0.75	−0.14	0.26	0.49	1.00		
Pb	−0.05	−0.08	0.47	0.25	0.04	−0.30	1.00	
Zn	0.06	0.11	0.11	0.23	−0.22	−0.03	0.44	1.00

(b) during summer

	Cd	Co	Cr	Cu	Mn	Ni	Pb	Zn
Cd	1.00							
Co	0.43	1.00						
Cr	0.68	0.50	1.00					
Cu	0.49	0.53	0.86	1.00				
Mn	0.49	0.97	0.48	0.50	1.00			
Ni	0.82	0.57	0.87	0.62	0.57	1.00		
Pb	−0.46	−0.13	−0.34	−0.35	−0.20	−0.40	1.00	
Zn	0.35	0.86	0.43	0.38	0.81	0.50	−0.26	1.00

the monsoon season all the trace metals show very poor correlation except Ni-Co and Cu-Mn (Table 2(a)) due to dilution.

R-mode factor analysis was used to determine if there were meaningful spatial and temporal differences in the patterns of trace metals present in the groundwater (Joreskog *et al.*, 1976; Legendre & Legendre, 1983). Differences in the patterns of metals reflect variations in the anthropogenic sources or environmental transport of metals. A varimax rotated factor matrix tested on the groundwater of Madras city during summer and monsoon are presented in Table 3(a) and (b). The Eigen values for the first three factors account for nearly 70% of the variance and only these factors have been considered for discussion.

The first factor accounts for 60% and 32% of the variance respectively during summer and monsoon. This factor is characterized by strong positive loads on Cd, Cr, Cu and Ni during summer and Co and Ni during monsoon, indicating that all these metals are of anthropogenic origin. Analysis of the monsoon data set further confirms that the anthropogenically introduced metals such as Cd, Cr, Cu migrate from industrial outlets to groundwater during periods of heavy rain, as indicated by the positive loadings of Cd, Cr, Cu and Mn (Factor 2) during monsoon. Factor 1 can be defined as the level of *pollution* by the toxic metals and complexes.

Factor 2 accounts for 18 and 24% of the variance during summer and monsoon respectively, and shows strong positive loadings on Co, Mn, Zn during summer and Cd,

Table 3 Varimax rotated factor matrix for trace elements in groundwater of Madras city.

(a) during summer

Variable/factor	Factor 1	Factor 2	Factor 3
Cd	0.69	0.23	0.44
Co	0.33	0.93	−0.01
Cr	0.95	0.21	0.12
Cu	0.83	0.26	0.05
Mn	0.32	0.91	0.07
Ni	0.81	0.34	0.29
Pb	−0.21	−0.07	−0.94
Zn	0.16	0.91	0.18
Eigen value	4.81	1.42	0.80
Variance %	60.06	17.75	9.96
Cumulative variance	60.06	77.81	87.77

(b) during monsoon

Variable/factor	Factor 1	Factor 2	Factor 3
Cd	0.12	0.52	−0.08
Co	0.86	0.17	0.10
Cr	−0.30	0.64	0.35
Cu	0.23	0.69	0.27
Mn	0.39	0.79	−0.18
Ni	0.91	0.19	−0.15
Pb	−0.31	0.29	0.76
Zn	0.18	−0.15	0.89
Eigen value	2.52	1.95	1.13
Variance %	31.47	24.31	14.16
Cumulative variance	31.47	55.78	69.94

Cr, Cu and Mn during monsoon. This factor reflects the *migration or mobilization* of toxic metals and pollutants. Factor 3 has high negative loading for Pb during summer suggesting that Pb introduced into the environment is accumulated and then migrates during the monsoon season.

CONCLUSIONS

The quality of groundwater mirrors the quality of surface water. In this study, seasonal variations in trace element concentrations highlights that human perturbation of the surface water leads to deterioration of the groundwater. The concentration of toxic trace metals in the groundwater of Madras city is unequally distributed and highest levels relate to polluted surface waters, particularly during summer. This suggests that the contaminants carried by the Adyar and Cooum rivers drain according to the hydrological gradient of the Madras aquifers. However, local precipitation is shown to dilute concentrations and trace elements are dispersed during the monsoon. Topography, local geological formation, porosity and permeability determine the major pathways for both migration, mobilization and accumulation of trace elements in groundwater.

Groundwater is one of the major sources of potable water in Madras City. Over-abstraction of this limited resource, in addition to erratic waste disposal in surface waters, enhances the contamination of groundwater. It thus becomes obligatory to identify suitable management strategies to balance industrial development without compromising on environment or public health.

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