Groundwater quality management: pollution perspectives

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Abstract Water scarcity has been one of the most serious problems in Chennai, India for many years. In particular there has been a decline in both groundwater table level, and groundwater quality over recent years. This paper focuses on the distribution of major and trace elements in ground water of the Chennai basin. It is seen that the concentration of major ions such as Na and Cl are predominantly influenced by anthropogenic activities, whereas natural processes control other major elements. The concentration of trace metals at a few wells along the waterways are high and in general there is a decrease in the relative concentration from summer to monsoon due to local precipitation and seepage which dilutes the concentration of trace metals and aids their migration. This study also highlights the impact on groundwater of urban growth in Chennai.

INTRODUCTION

There is a growing trend towards increasing exploitation of groundwater to meet the needs of a growing population in developing countries both in terms of water availability and its quality. Groundwater quality is mainly controlled by the range and type of human influence as well as by geochemical, physical and biological processes (Table 1) occurring in the ground, and the existing hydro-geological conditions (Vrba & Zaporozec, 1994). Prediction of the effects of human interference requires knowledge of the position of the water table, the hydraulic gradient, the distance of wells from hazardous activities, and the properties of the rocks, such as their adsorption capacity and hydraulic conductivity. Although natural processes (listed in Table 1) may reduce the seriousness of groundwater contamination, many contaminants remain essentially unchanged after entering the groundwater body. Thus, their detrimental effect at a location may persist for years, decades or centuries, because the average residence time of groundwater is measured in years; the comparable residence time of a contaminant in a surface water stream is days. Longer periods are often required for contaminants to be removed from the contaminated aquifers (Zaporozec, 1981; Carter *et al.*, 1987).

An emerging global freshwater crisis in terms of water quality and quantity is already visible in India, involving enormous social, political and environmental costs which are affecting the economy and quality of life (Nigam *et al.*, 1997). In India, nearly 44 million people are affected by water-quality problems either due to pollution such as the prevalence of fluoride, arsenic and iron deposits, or due to the ingress of salt water. In India, the reasons for water scarcity can be placed under five broad categories: (a) imbalance between withdrawal and recharge of groundwater; (b) decay

Table 1 Natural processes controlling human influence on groundwater quality (after Vrba & Zaporozec, 1994).

Geochemical processes	Physical processes	Biochemical processes	Biophysical processes
Acid–base reactions	Advection/convection	Cell synthesis	Filtration of pathogens
Adsorption–desorption	Dispersion	Organic decomposition	Transport of pathogens
Complexation	Evaporation	Transpiration	
Oxidation–reduction	Filtration		
Solution–precipitation	Gas transport		
	Radioactive decay		

of traditional water harvesting structures due to inadequate financial resources; (c) inadequate enforcement of water pollution regulations, inevitably leading to contamination either by industrial pollutants or municipal waste discharges; (d) a lack of foresight and planning; and (e) increasing population.

Scarcity of clean, potable drinking water has emerged in recent years as one of the most serious development issues in Indian metropolitan cities such as Chennai. The critical groundwater contaminants, such as major ions and trace metals, have been analysed over an annual cycle covering seasonal variations. In this paper, an attempt has been made to review the major potential contaminants of groundwater, their natural and man-made sources, and their health and environmental impacts.

STUDY AREA

Chennai city (previously known as Madras), the fourth largest city in India depends heavily on coastal groundwater resources (Fig. 1). Due to the increasing population and rapid industrialization, overexploitation of groundwater resources has been reported for the aquifer of the city and its environs (Ramesh *et al.*, 1995). Total water consumption per person in the city is about 103 l day^{-1}. Together, metro water (mainly stored surface water, supplied to consumers by underground pipelines) and groundwater account for over 98% of the water used by households. Metro water provides 45% of the total water consumed, and the 55% balance is drawn from groundwater. In summer, this proportion changes to 39% and 60% respectively. Not only is there a high degree of reliance of households on groundwater directly, but metro water itself obtains 25% of its supply from groundwater through well fields. Hence the city relies on fulfilling 65–70% of its requirements from groundwater, but heavy reliance has, however, not been accompanied by adequate efforts to maintain the resource base.

METHODOLOGY

Representative groundwater samples were collected from various locations (Fig. 1) covering the major section of the Chennai urban area during the months of April–May 1996 (summer), September–October 1996 (monsoon) and January–February (post-monsoon). New one-litre polyethylene bottles were used for sample collection and

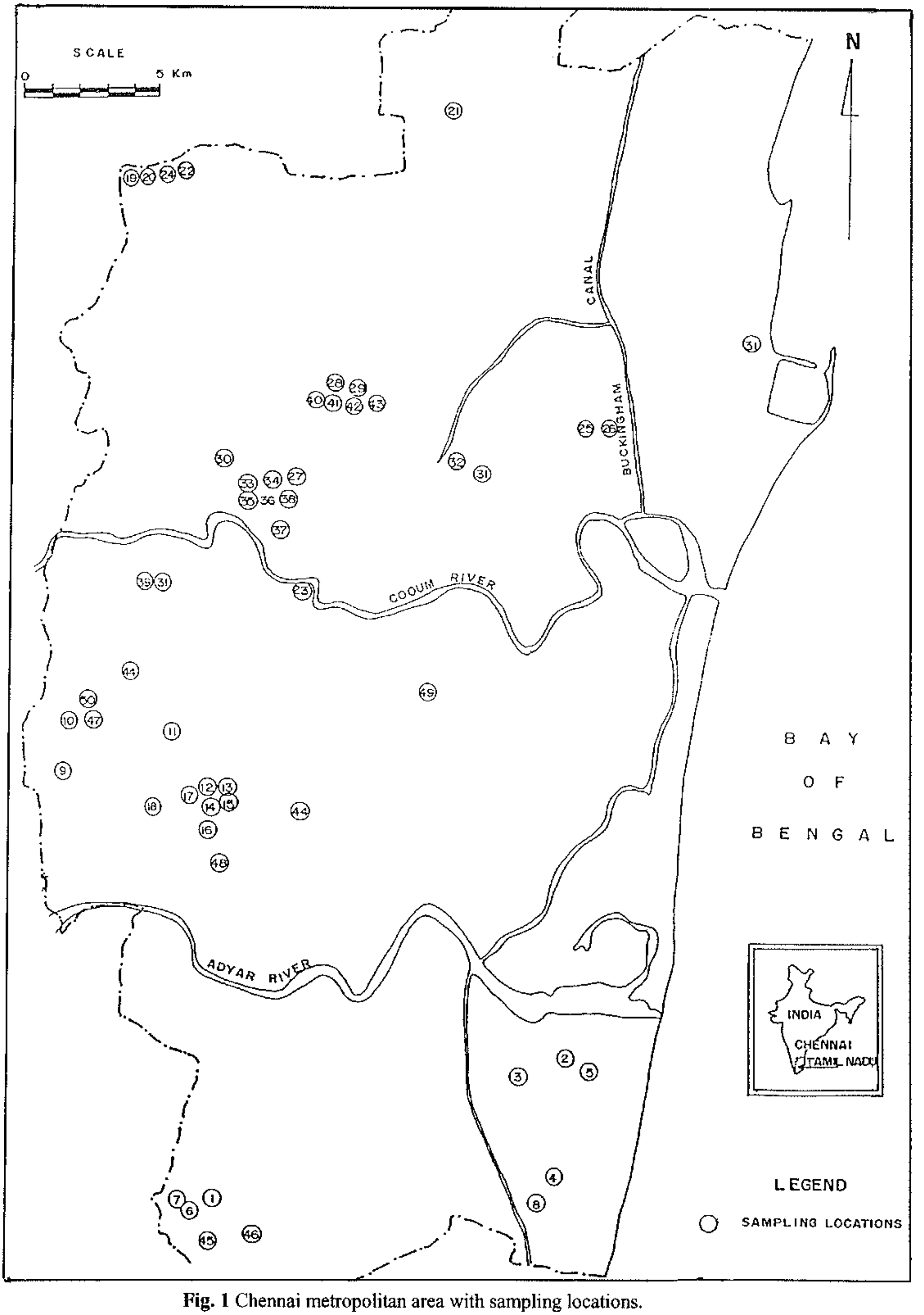

Fig. 1 Chennai metropolitan area with sampling locations.

preservation. Water samples were collected from both open and dug wells. Samples were also collected from wells near the Adyar and Cooum rivers and away from the river terraces (Fig. 1). pH, EC and TDS were analysed *in situ*. The samples were divided into two portions and kept airtight. One part of the sample was acidified with 0.1N HCl, so as to prevent adsorption on to the walls of the container. The other portion was used to determine major ions such as HCO_3, Cl, SO_4, Ca, Mg, Na and K using standard procedures (Ramesh & Anbu, 1996). Trace metals such as Fe, Cr, Cu, Ni and Zn were analysed using the highly sensitive Inductively Coupled Plasma (ICP) method. While performing the analyses, two sets of internal standards were run, one at the beginning and the other in between the analyses, to provide a check on the accuracy and precision of the results. For these elements the detection limits are ~1 ppb.

RESULTS AND DISCUSSION

Major ion chemistry

A few contaminants appear to predominate in groundwater. These include major ions (Na, Cl, K etc.), metals such as Fe, Mn and As (metalloids), nitrates, organic compounds and other substances such as fertilizer and pesticide constituents, bacteria and viruses. The present study is restricted to a discussion of major ions and trace metals. The seasonal variations in major ion and trace element concentration in the groundwater of these regions are presented in Figs 2(a) and 2(b). The results of the average major and trace element concentrations of the groundwater samples of Chennai City collected during three different seasons are presented in Table 2. The study reveals that an average of ~25% Ca, 11% Mg, 38% Na, 43% TDS, 30% Cl and 14% SO_4 exceeded the limit when compared to the water standards established by the Indian Standards Institution in 1983.

When present in large amounts, Na in drinking water can pose a health hazard. Documented research has shown that excessive Na intake is correlated with high blood pressure, with approximately 15–20% of the population at risk of developing hypertension. A majority of the urban communities in India is served by groundwater sources for drinking. Hence, protection of groundwater supplies from Na contamination is needed. Due to many potential pollution sources, it is often difficult to point out the sources of pollutants. The spatial distribution of Cl in 50% of the groundwater samples studied has been found to exceed 1000 ppm during summer, indicating saline water intrusion. A Cl content of 600 ppm has been considered as the highest acceptable salinity level for human consumption (Rosenthal, 1994). The saltwater intrusion can be prevented by carefully selecting the site of the well and its depth, and by limiting the amount of groundwater pumped. While domestic sewage and tannery effluents also contribute to some extent to Cl and Na levels, it is possible that the major sources for the Ca and SO_4 in groundwater are the effluents from the power stations.

The relative concentration of major ions in groundwater of silicate terrain depends largely on the relative abundance of the various rock types and their degree of alteration. In well-drained areas, where the degree of weathering is modest, the

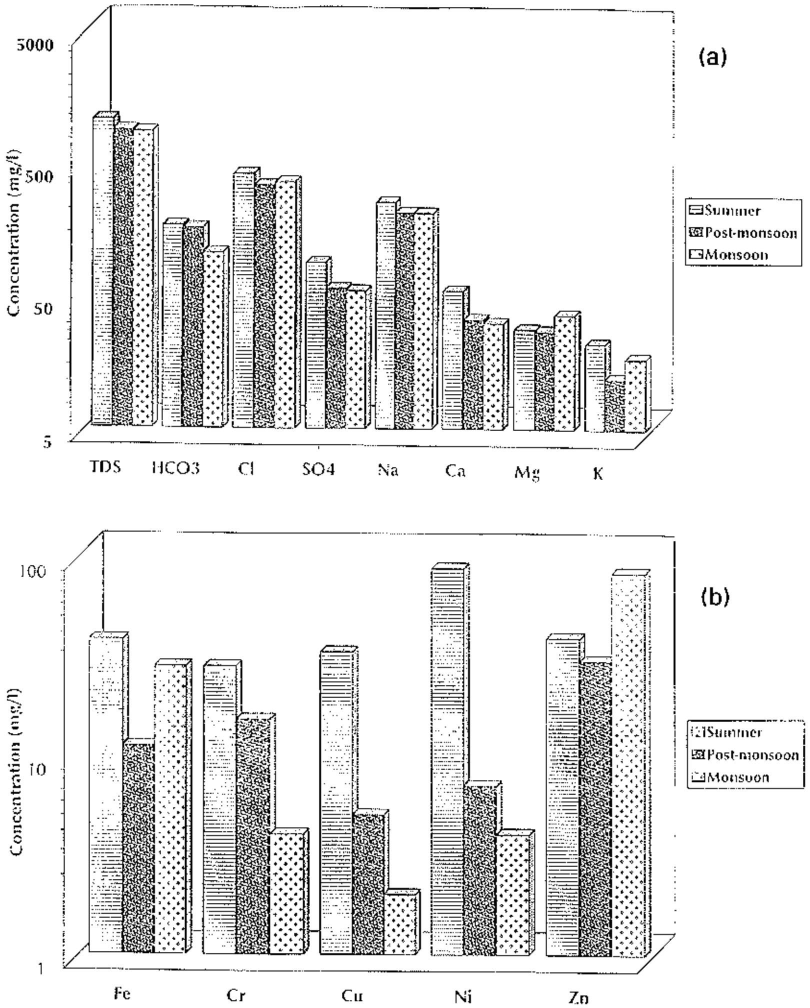

Fig. 2 (a) Seasonal variations of major ions in the Chennai groundwater. (b) Seasonal variations of trace elements in the Chennai groundwater.

abundance of major ions in groundwater depends chiefly on the relative mobilities (Garrels, 1967; Kowda & Somoilova, 1969). The major dominant cations and anions in the ground water of Chennai city are in order: Cl > Na > HCO_3 > SO_4 > Ca > Mg > K respectively. Along the coastline, the major ion concentrations are higher than that of the average groundwater observed in rest of the region. This may be due to continuous withdrawal of groundwater for drinking through bore wells which leads to seawater intrusion into the coastal freshwater zone. The temporal variation in the concentrations of major ions are shown in Fig. 2(a). From Fig. 2(a) it is evident that the concentrations of all the ions in the monsoon season were low and exhibiting an increasing trend towards the post-monsoon and summer seasons. The reason for these changes could be the dissolution of salts and minerals in soils due to over-withdrawal during summer. The examination of the seasonal data of major ion concentration reveals that the Na and Cl are the major cation and anion (Fig. 2(a)) respectively,

Table 2 Average major and trace element concentration in groundwater of Chennai City, India. (Refer to Fig. 1 for sampling locations).

Site no.	pH	EC ($S\ cm^{-1}$)	TDS ($mg\ l^{-1}$)	HCO_3 ($mg\ l^{-1}$)	Cl ($mg\ l^{-1}$)	SO_4 ($mg\ l^{-1}$)	Ca ($mg\ l^{-1}$)	Mg ($mg\ l^{-1}$)	Na ($mg\ l^{-1}$)	K ($mg\ l^{-1}$)	Fe ($g\ l^{-1}$)	Cr ($g\ l^{-1}$)	Cu ($g\ l^{-1}$)	Ni ($g\ l^{-1}$)	Zn ($g\ l^{-1}$)
1	7.0	4226.7	2089	248.0	1057.7	90.0	164.0	99.3	472.7	21.3	17.3	18.0	13.0	20.7	223.0
2	7.0	4910.0	2447	170.7	1252.7	127.0	106.0	63.3	346.3	18.7	23.3	16.3	23.7	23.7	63.0
3	7.0	2506.7	1246	152.3	579.0	59.7	53.7	61.3	279.0	17.3	19.0	15.7	12.3	14.0	43.0
4	7.1	1437.0	724	73.7	502.0	47.3	28.7	33.0	213.3	11.7	20.0	19.3	11.0	16.7	152.0
5	7.0	477.0	240	87.7	74.0	26.3	22.7	10.0	64.3	6.7	14.7	14.7	9.3	11.3	47.3
6	7.1	493.7	246	91.7	77.0	32.3	18.0	13.0	67.7	4.0	14.3	16.3	11.0	16.0	8.3
7	7.1	419.0	209	59.0	73.7	23.0	41.3	18.7	59.0	5.3	17.7	15.0	9.0	21.0	146.0
8	7.0	1763.7	870	130.0	274.7	120.3	56.0	27.3	231.7	16.7	16.7	16.0	8.0	20.3	73.3
9	6.8	1268.3	624	94.0	283.7	39.7	42.3	22.0	161.0	9.7	22.3	19.7	10.3	16.7	26.3
10	7.0	1315.7	651	132.3	254.0	47.7	38.0	26.7	160.0	8.3	18.3	9.3	9.7	18.0	22.0
11	7.0	1680.3	835	223.7	328.0	49.3	32.3	14.7	215.3	7.7	19.3	17.7	16.0	18.0	15.0
12	6.9	3193.0	1519	156.7	702.7	101.7	70.3	24.0	355.3	11.3	23.0	13.3	17.7	42.7	14.3
13	7.0	1494.0	704	154.7	213.0	46.0	37.3	24.0	188.0	33.3	21.0	14.3	22.0	48.3	32.3
14	7.1	508.3	256	83.3	71.0	28.7	22.7	49.0	71.7	10.0	25.0	18.3	27.0	31.0	307.3
15	7.1	654.0	327	113.7	97.3	26.3	27.0	22.0	89.0	11.0	12.7	14.0	6.3	25.0	98.3
16	7.1	961.0	467	105.7	124.0	38.3	36.7	16.3	128.0	26.3	17.3	20.7	12.3	34.0	4.7
17	7.1	1324.7	673	140.3	201.0	43.7	48.3	21.7	179.3	26.0	15.7	18.7	16.3	32.7	19.3
18	7.0	1449.7	723	195.3	195.0	45.7	38.3	30.7	193.0	7.3	15.7	17.3	15.7	25.7	13.3
19	7.2	2261.3	1126	278.7	366.0	83.3	17.3	21.0	250.3	18.0	16.3	12.0	24.3	19.0	17.0
20	7.1	2640.3	1321	138.3	485.0	54.7	33.7	34.3	258.0	39.3	16.0	15.7	18.7	26.3	7.7
21	7.1	3276.7	1232	156.7	602.7	91.7	46.3	40.3	366.0	12.3	16.7	15.3	14.0	39.3	5.3
22	7.2	5333.3	2583	197.0	756.3	255.3	53.3	58.3	525.7	31.3	20.3	18.0	14.0	37.7	5.0
23	7.1	7066.7	3537	217.7	1923.0	215.7	137.3	105.0	886.7	26.7	23.7	17.3	18.7	51.7	5.3
24	7.2	4173.3	2063	311.3	1509.7	189.7	86.7	87.7	808.0	21.7	23.3	19.7	15.3	49.0	6.0
25	7.2	1272.3	639	144.3	216.0	45.7	59.7	32.3	231.7	26.7	14.7	12.0	13.3	31.7	4.3
26	7.1	1297.7	648	150.3	224.7	38.3	59.0	35.3	146.7	5.3	15.3	14.3	17.0	34.7	9.7
27	7.4	1694.3	920	175.0	372.3	78.7	60.7	53.3	212.0	15.3	13.7	16.7	10.3	38.3	5.7
28	7.1	553.3	276	118.0	76.7	23.3	14.0	9.3	68.3	5.0	13.3	5.0	4.7	22.0	194.3
29	7.4	740.7	369	131.0	103.3	23.7	18.7	8.3	108.3	5.3	15.0	16.0	11.7	30.3	6.3
30	7.5	431.0	217	71.3	59.0	18.0	15.0	8.0	59.7	6.3	29.7	20.0	13.7	33.3	13.3
31	7.5	647.0	322	120.0	118.3	35.7	15.0	7.3	62.3	6.3	16.7	13.3	9.7	32.3	30.3
32	7.4	1590.3	795	163.0	277.7	38.7	41.0	36.7	187.7	24.7	16.0	19.0	12.0	42.0	50.3
33	7.4	1934.3	964	170.7	340.0	43.0	23.3	32.0	179.0	39.0	14.3	13.7	10.7	35.0	26.7
34	7.5	1072.0	537	128.0	165.3	36.0	20.0	21.7	95.0	6.7	17.0	17.0	11.3	43.7	178.0
35	7.5	1016.0	492	187.3	162.7	45.3	24.0	20.3	146.3	47.0	12.7	13.0	9.3	38.3	9.7
36	7.7	1046.3	519	71.3	215.7	16.0	22.0	30.3	70.3	4.7	19.0	10.3	8.7	35.3	58.0
37	7.5	1413.7	708	87.3	283.7	46.0	25.0	16.3	132.0	16.3	97.7	13.0	11.7	42.0	18.0
39	7.7	384.3	192	51.0	62.0	15.0	15.3	3.7	60.3	6.3	105.0	17.0	12.0	36.3	157.0
40	7.3	4233.3	2107	193.3	685.3	364.3	12.7	65.0	536.7	43.3	17.7	15.0	11.3	46.3	4.3
41	7.5	3013.7	1505	109.7	756.7	53.0	16.0	28.0	356.7	15.3	18.0	14.7	12.3	42.7	11.3
42	7.5	1990.7	991	197.3	295.3	63.7	30.7	20.7	259.0	25.3	17.0	15.7	14.3	37.7	32.7
43	7.1	1865.7	929	211.3	313.3	50.7	48.7	17.0	191.3	27.0	15.7	12.0	12.3	36.7	4.7
44	7.1	1820.0	907	102.0	334.0	41.0	34.7	35.0	239.3	21.0	36.3	11.0	9.7	35.7	6.3
45	7.3	1195.0	598	122.0	100.3	36.0	30.0	7.0	118.3	28.0	17.3	16.0	14.0	47.3	5.3
46	7.4	1192.7	591	148.3	136.0	36.0	16.0	7.7	134.7	12.3	35.7	15.0	13.7	39.3	39.0
47	7.2	2620.3	1313	134.3	431.3	52.7	18.0	20.3	291.0	18.3	12.7	14.3	10.3	34.7	5.0
48	7.3	1263.0	628	107.7	168.3	44.0	14.0	6.7	134.0	8.0	24.0	13.7	12.7	40.0	5.7
49	7.2	1531.7	767	191.0	191.7	53.7	20.0	14.3	200.0	13.3	16.7	20.0	12.3	44.0	64.0
50	7.3	1689.0	839	115.7	165.3	37.3	18.0	14.0	268.0	9.7	186.0	13.3	13.7	36.3	182.0

irrespective of the season mainly because of seawater intrusion. Figure 2(a) also shows minor variations in Ca, Mg and K concentration due to their low mobility in the groundwater system. The electrical conductivity (EC) shows strong positive correlation (>0.78) with TDS, Cl, SO_4, Ca, Mg and Na during both monsoon and post monsoon seasons and with TDS, Cl and Na during summer due to their geogenic nature. The major elements show very poor correlation with trace metals irrespective of the season and hence it can be concluded that the elements accumulate independently of each other.

Trace elements

The average concentrations of some of the trace elements of environmental concern such as Fe, Cr, Cu, Ni and Zn in the ground water of Chennai city are shown in Table 2. The mean seasonal variation in trace element concentration is shown in Fig. 2(b) which shows an overall decrease in the relative concentration of trace elements from summer to the monsoon period, due to local precipitation and seepage which not only dilutes the concentration of the trace metals, but also aids in their migration. The aquifers of the Chennai basin are generally shallow and are recharged by precipitation and flow through riverbeds and from surface water bodies. Unplanned industrialization and indiscriminate disposal of untreated effluents into the adjoining rivers has probably resulted in anomalous distribution of these elements of environmental concern.

Iron in the groundwater is mostly in the form of inorganic complexes derived from laterite and other types of soils. High amounts of iron may be found under naturally acidic or reducing conditions. Three natural conditions that have been found to produce high levels of iron in groundwater are: (a) aquifers located over crystalline bedrock, (b) swamps, and (c) organic material interbedded with alluvial sediments located near areas of groundwater discharge. Iron is also present in the environment due to man's activities. Industrial wastes and mine drainage waters are two common anthropogenic sources. Excess Fe would be mostly accumulated and discharged through the industrial effluents. The WHO standard (1984) for Fe in drinking water is 500 ppb. Fe levels in the area studied in Chennai, fall well below this limit during all the three seasons (Fig. 2(b)).

In contrast to most metals, Zn concentrations are higher during the monsoon than in summer (Fig. 2(b)), probably due to the leaching of Zn from the adjoining contaminated river sediments through seepage. Anomalous Cr concentrations occur along the Adyar River and the coastline, and similar observations have been made by earlier studies (Ramesh *et al.*, 1995). In Chennai, large quantities of effluents are discharged by nearly 90 tanneries in places such as Pallavaram, Chrompet and Pammal, increasing the Cr content in the groundwater. The trace metal pairs Fe-Cr (during summer), Fe-Cu, Cu-Zn (during monsoon) and Fe-Zn (during post-monsoon) show a strong positive correlation (>0.8) indicating that these metals occur together as pollutants mostly derived from industrial effluents, possibly moving together as polymetal complexes.

There are several sources of trace elements in the Chennai urban environment, both natural and man-made: weathering of parent material (rocks), burning of fossil fuels, sewage and industrial effluent discharge, underground disposal of toxic wastes etc. With the exception of the parent material, all are anthropogenic in nature. In the waterways, lakes and aquifers around Chennai, the human impact is many times greater than the natural input of trace elements, as is evident from the results obtained in this study.

Impact of urban growth on groundwater

There is increasing demand for drinking water due to urban growth and a need to explore the various technological options. In India nearly 42 million people live in 12 major cities (Mumbai, Delhi, Calcutta, Chennai, Hyderabad, Ahmedabad, Bangalore, Kanpur, Lucknow, Nagpur, Pune and Jaipur). Together they are provided with more than 8 billion litres a day of potable water or 189 l.p.c.d. (litres per capita per day) on average. Chennai is presently consuming 100 l.p.c.d.. Although it experiences water scarcity at certain times, this amount of water is adequate for other periods. If this amount of water is available and utilized judiciously there should not be any significant impact on health and hygiene. If this norm is available in other urban areas, then the currently available 8 billion litres should be sufficient for 2.5 times more people than are currently living in these cities. Some of the insights highlighted below are based on the Chennai study, but have implications for other cities: (a) prevention of water pollution is not high on the list of political objectives to be achieved; (b) there is a lack of water conservation measures, partly because of an absence of water pricing and full cost recovery and lack of awareness; (c) sufficient water is currently coming into the urban areas but is not necessarily reaching the people due to water losses; (d) water recycling is not widely advocated and practised; and (e) freshwater conservation and environmental protection are not factored into resource strategies; instead the response is to bring more water from afar. Unless actions are taken on the above issues, adequate water supply for cities cannot be ensured with continued ecosystem sustainability.

CONCLUSIONS

India is, and will continue to be in the foreseeable future, heavily dependent on groundwater. This high level of dependence on groundwater has not been accompanied by social, economic, technological and community-based action to ensure the sustainability of this critical resource base. Monitoring of groundwater quality should be undertaken regularly to identify the sources of principal contaminants and other inhibitory compounds that affect the potability of water, and also to identify the wells which are safe for drinking water and protecting them from further contamination.

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