Assessment of aquifer system using isotope techniques in urban centres Raipur, Calcutta and Jodhpur, India

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Abstract

Three urban centres Raipur, Calcutta and Jodhpur were studied using isotope techniques (^{18}O, ^{2}H, ^{3}H, ^{13}C, and ^{14}C) and chemistry with different objectives. Groundwater in Raipur city is susceptible to contamination near waste disposal sites, landfills and dairy farms. Shallow groundwater is more affected by contamination than deeper zone groundwater. A few shallow zone groundwater samples in Jadavpur area of Calcutta city show arsenic concentration above permissible level. Stable isotope values of these groundwater samples indicate that they are depleted and tritium results show that they have less residence time. Deep groundwater is arsenic free and old. Seepage in the basement and rise of static water level of some parts of Jodhpur city has been observed from March 1998 onwards. Isotopic, hydrogeological and chemical analyses data has indicated that lake water is contributing to seepage water in the basement.

1. IMPACT OF LANDFILLS, DOMESTIC AND INDUSTRIAL WASTE ON THE AQUIFER IN RAIPUR CITY AND CONTRIBUTION OF KARST FEATURE TO THE GROUNDWATER CONTAMINATION.

1.1. INTRODUCTION

Raipur is a major business and educational centre of south–eastern Madhya Pradesh. The city has been rapidly expanding during the last fifteen years as a result of rapid industrialization. Wastes are generated from a wide variety of industrial, commercial, agricultural and domestic activities. These wastes are dumped into pits or low–lying area around Raipur city. The climate is characterised by hot summer and well-distributed rain during monsoon season. Rainy season begins from mid June till the end of September with onset of southwest monsoon. The average annual precipitation is 1250 mm [1].

Groundwater in the study area is susceptible to contamination by landfills; domestic and industrial waste due to karstified nature of geological formation, which is exposed to the surface in Raipur city. Environmental isotopes (^{2}H, ^{3}H, ^{18}O and ^{13}C) as well as chemistry of the water samples has been used to identify few places, which are prone to contamination in Raipur city. Deterioration of groundwater quality is not alarming due to thin shale (impervious layer) cover over the limestone.

1.2. ISOTOPE FIELD STUDY

Isotope techniques are employed to understand the impact of landfills, domestic and industrial waste on the aquifer in Raipur city. Post monsoon samples in 1998 and pre–monsoon samples in 1999 collected from dug wells, tube wells and surface water bodies

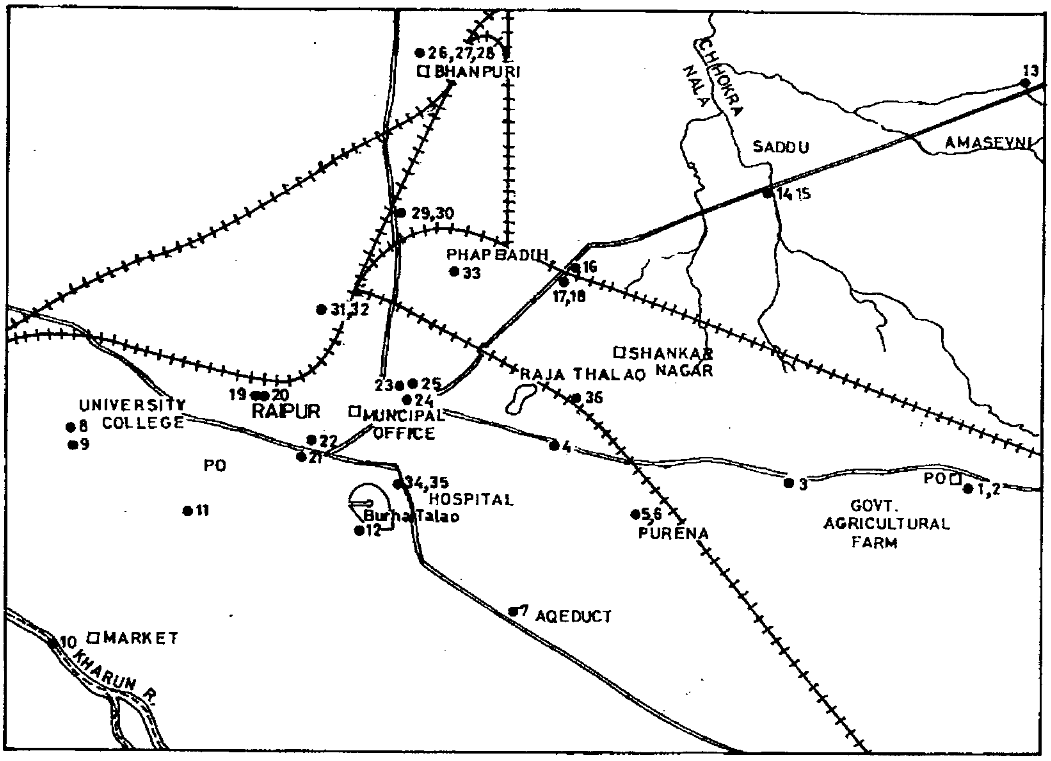


Figure 1 – Location map of Raipur samples

(Figure 1) were analyzed for ^{2}H, ^{18}O, ^{3}H, ^{13}C and chemical species. Rainwater samples were also collected and analyzed for environmental isotopes.

1.3. HYDROGEOLOGY

The Chandi Formation of Raipur Group (of Chhattisgarh Supergroup) is the major geologic unit exposed in Raipur city. Its thickness varies from 103 m to 136 m. The Chandi Formation comprises two members namely Newari limestone and Deodonger shales and sandstone [2]. Limestone exposed at various places in the city is cavernous and jointed. Deodonger member, consist of thinly laminated siliceous shales and sandstone overlies the Newari limestone with a sharp contact.

In general, the elevation varies from 280 m to 300 m with gentle radial slope. The topography of Raipur city is flat with elevated land at a few places with general slope of land towards northwest. The groundwater recharge occurs mainly through canal seepage and direct infiltration of precipitation. Groundwater flows from eastern side having canal network (constant recharging boundary) towards northwest and southwest. The Kharun river in the western side of the city forms the discharging boundary. The joints pattern and caverns mainly govern the flow. The flow from the reservoir and ponds in the city is also towards northwestern and southwestern sides. Wherever the underlying veneer of hard shale pinches out, the inflowing surface water contaminates the surrounding groundwater. The situation at places is aggravated due to excessive exploitation of groundwater causing induced flow of surface water to the groundwater.

1.4. RESULTS AND DISCUSSION

Results of Isotopic analyses of Raipur post monsoon (1998) samples and pre monsoon (1999) samples had been given in table 1 and table 2 respectively. On the plot of $\delta^{18}O$ vs. $\delta^{2}H$ rainwater samples fall on the Meteoric Water Line [3] whereas groundwater (shallow and deep) show slight enrichment in $\delta^{18}O$ and $\delta^{2}H$ compared to the precipitation samples (Figure 2). The pond water samples are more enriched due to evaporation effect [4].

Table 1 – Isotopic analysis of Raipur samples (1998)

S.No	Identifi – –cation	Source and Location	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	^{3}H TU ± 1σ (0.5 TU)	$\delta^{13}C$ (‰)
1	R1–1	Piezometre2, IGKV	–2.36	–11.8	6.62	–14.38
2	R1–2	Piezometre1, IGKV	–1.67	–13.1	4.82	–6.04
3	R1–3	SW/Chokra Nala	–2.02	–16.2	7.78	–8.88
4	R1–4	SW/Telebandh Talab	–0.56	–9.2	10.06	–4.13
5	R1–5	HP, Purena village	–1.75	–14.3	7.26	–12.58
6	R1–6	DW, Purena village	–1.97	–15.8	9.19	–13.5
7	R1–7	HP, Pachpedi naka, opp. Nest Restaurant	–1.79	–14.1	6.09	–12.0
8	R1–8	TW, Mahanadi education society	–2.42	–15.9	6.41	–11.76
9	R1–9	DW, Univ. campus, near banjari temple	–2.02	–15.8	7.44	–9.8
10	R1–10	SW/Kharun River	–2.39	–13.4	8.40	–11.5
11	R1–11	TW, Mukherjee's residence, Sundernagar	–1.87	–14.0	7.76	–13.33
12	R1–12	SW/Burha Talab	+0.68	–3.5	9.65	–7.41
13	R1–13	TW, RGNGTRI, Baronda	–2.68	–18.8	8.84	–12.65
14	R1–14	DW, Saddu village	–1.97	–12.6	7.46	–10.76
15	R1–14A	DW, Saddu village	–2.13	–14.5		
16	R1–15	TW, Saddu village	–1.93	–14.3	2.49	–12.14
17	R1–16	TW, Goel saw mill, Kapa	–2.16	–16.6	6.04	–12.09
18	R1–17	DW, Holy Cross School, Kapa	–2.26	–18.0	7.73	–9.98
19	R1–18	TW, Holy Cross School, Kapa	–1.85	–14.5	5.19	–10.03
20	R1–19	Piez, Bodhankar's house., Samata colony	–3.75	–25.1	9.18	–13.88
21	R1–20	TW, Chadel's house, Samata Colony	–0.93	–11.7	6.80	–11.57
22	R1–21	DW, Ammapara	–1.25	–7.7	6.73	–11.55
23	R1–22	HP, Ammapara, market, near pond (garbage filled)	–1.05	–5.8	0.82	–11.18
24	R1–23	HP, Rajbandh Talab reclaimed	–1.9	–6.9	8.84	–11.98
25	R1–24	HP, opposite Rajbandh Talab reclaimed	–0.7	–12.3	9.32	–11.22
26	R1–25	HP, near Marhimata temple	–1.47	–11.4	8.52	–12.20
27	R1–26	HP, Bhanpuri, Tiwari diary	–1.21	–16.5	6.03	–9.8
28	R1–27	SW/Effluents, Bhanpuri	–3.2	–18.9	7.42	
29	R1–28	HP, Bhanpuri	–3.1	–16.5	7.42	–12.17
30	R1–29	DW, railway colony, opposite Qr. No.296	–0.98	–7.9	6.17	–11.71
31	R1–30	HP, railway colony near chowk	–1.27	–9.7	4.73	–10.38
32	R1–31	DW, Gudhari, Naya mangal bazar	–3.14	–18.5	10.28	–12.17
33	R1–32	HP, Gudhari, Naya mangal bazar	–2.54	–17.2	6.71	
34	R1–33	DW, Shastrinagar	–2.55	–13.5	6.81	–13.28
35	R1–34	DW, Burahapara malaria centre	–2..2	–10.1	7.26	–12.83
36	R1–35	TW, Burahapara malaria centre	–2.81	–17.2	5.86	–10.67
37	R1–36	DW, Shankarnagar	–1.96	–14.7	7.95	–11.72
37	R1–37	RW 27.8.98 to 8.9.98	–6.09	–30.5	15.8	
38	R1–38	RW 9.9.98 to 12.9.98	–12.4	–91.4	12.5	

HP : Hand Pump SW : Surface Water DW : Dug Well TW : Tube Well RW : Rain Water

Table 2 – Isotopic analysis of Raipur samples (1999)

S.No	Identification	Source and Location	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	^{3}H TU ± 1σ (0.5TU)	$\delta^{13}C$ (‰)
1	R2–4	SW/Telebandh Talab	4.75	5.7	10.6	−7.45
2	R2–5	HP, Purena village	−1.95	−16.5	5.7	−15.49
3	R2–6	DW, Purena village	0.54	−10.0	6.8	−12.86
4	R2–8	TW, Mahanadi education society	−2.07	−16.0	00	−11.53
5	R2–9	DW, Univ. campus, near banjari temple	−2.72	−13.5	4.2	−10.2
6	R2–10	SW/Kharun River	+2.2	+9.7	7.1	−10.85
7	R2–11	TW, Mukherjee's residence, Sundernagar	+0.06	−9.3	5.3	−12.4
8	R2–13	TW, RGNGTRI, Baronda	−1.85	−12.2	6.0	−11.53
9	R2–14	DW, Saddu village	−1.23	−0.9	6.1	−11.96
10	R2–15	TW, Saddu village	−2.7	−19.8	4.2	−12.92
11	R2–16	TW, Goel saw mill, Kapa		−27.3	4.1	−12.76
12	R2–17	DW, Holy Cross School, Kapa	−3.13	−13.2		−9.58
13	R2–18	TW, Holy Cross School, Kapa	−3.2	−15.4	3.9	−5.37
14	R2–19	Piez, Bodhankar's house., Samata colony	−2.75	−12.3	5.1	−13.11
15	R2–20	TW, Chadel's house, Samata Colony	−2.68		6.3	−12.37
16	R2–21	DW, Ammapara	−1.65	−15.2	8.2	−13.53
17	R2–22	HP, Ammapara, market, near pond (garbage filled)	−1.89	−12.3	0.6	−16.6
18	R2–24	HP, opposite Rajbandh Talab reclaimed	−1.02	−6.4	9.3	−13.23
19	R2–26	HP, Bhanpuri, Tiwari diary	−2.85	−21.1	6.3	−12.53
20	R2–28	HP, Bhanpuri	−3.07	−21.0	6.3	−12.89
21	R2–29	DW, railway colony, opposite Qr. No.296	−0.8	−8.5	6.1	−12.17
22	R2–30	HP, railway colony near chowk	−1.7	−10.2	4.7	−11.95
23	R2–31	DW, Gudhari, Naya mangal bazar	−1.46	−12.9	6.4	−14.1
24	R2–32	HP, Gudhari, Naya mangal bazar	−1.66	−14.7	6.4	−12.78
25	R2–33	DW, Shastrinagar	−0.94	−3.6	8.1	−12.83
26	R2–34	DW, Burahapara malaria centre	−1.46	−11.7	10.7	−16.27
27	R2–35	TW, Burahapara malaria centre	−1.86	−15.4	7.0	−13.4
28	R2–36	DW, Shankarnagar	−1.83	−17.6	10.2	−10.0
29	R2–39	TW, Surya vihar, Pacchpedi naka	−3.5	−14.9	2.0	
30	R2–40	TW, Surya vihar, Pacchpedi naka	−3.08	−19	3.7	−12.96
31	R2–41	HP, Naharpara, Ahuja,s residence	−1.65	−13.7	9.4	−13.07
32	R2–42	DW, Market	−1.77	−11.7	7.7	−15.66
33	R2–43	TW, Seli Khali village, NH6, Pintu dhaba	−2.06	−15.2	7.7	−11.67
34	R2–44	HP, Sunita park, NH6, near Chokra nala	−1.91	−8.9	8.5	−12.39
35	R2–45	TW old, Ekta farm house	−1.88	−10.3	7.6	−12.17
36	R2–46	TW new, Ekta farm house	−2.44	−19.7	7.0	−12.1
37	R2–47	Bhanpuri, 100 m north of Tiwari diary	−2.47	−13.2	6.0	−12.65
38	R2–48	DW, Bhaelgaon, NH6	−0.4	−4.6	9.5	
39	R2–49	HP, Bhelgaon	−1.79	−19	1.4	−12.1
40	R2–50	DW, near Burha Talab	−1.1	−11.2	8.0	−10.24

HP : Hand Pump SW : Surface Water DW : Dug Well TW : Tube Well RW : Rain Water

Pre monsoon shallow groundwater and surface water show enrichment in $\delta^{18}O$ and $\delta^{2}H$ contents compared to post monsoon samples (Figure 3), which indicates that pond water may be contributing to the shallow aquifer. Tritium content of local rainwater samples varies from 12.5 to 15.8 TU. Tritium content of the groundwater samples varies from 3 to 10 TU except a few places, where it is less than 3 TU (Figure 4 & 5). Higher tritium concentration of the groundwater samples indicate that recharge is taking place in Raipur city. $\delta^{13}C$ contents of

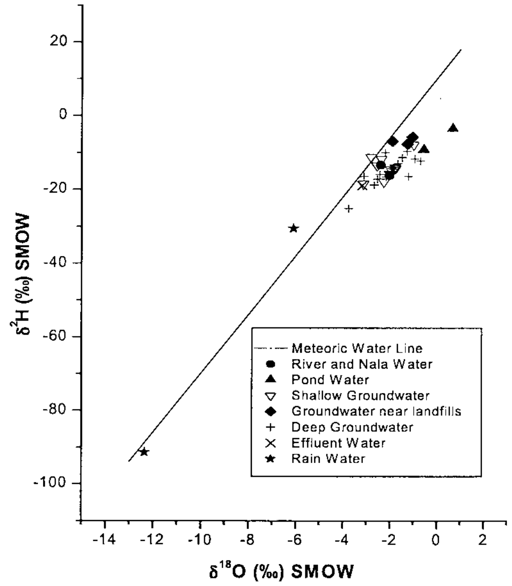


Figure 2 - Post monsoon samples (1998)

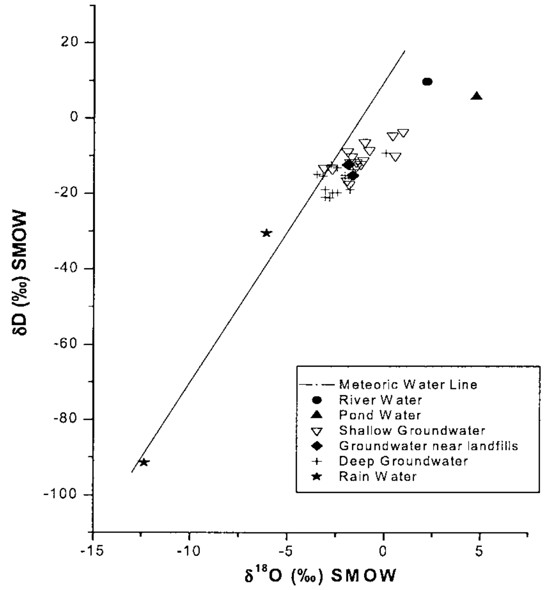


Figure 3 - Pre monsoon samples (1999)

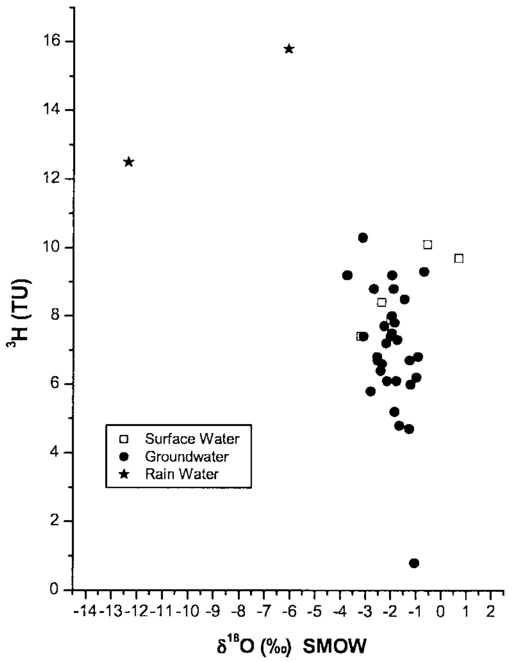


Figure 4 - Post monsoon samples (1998)

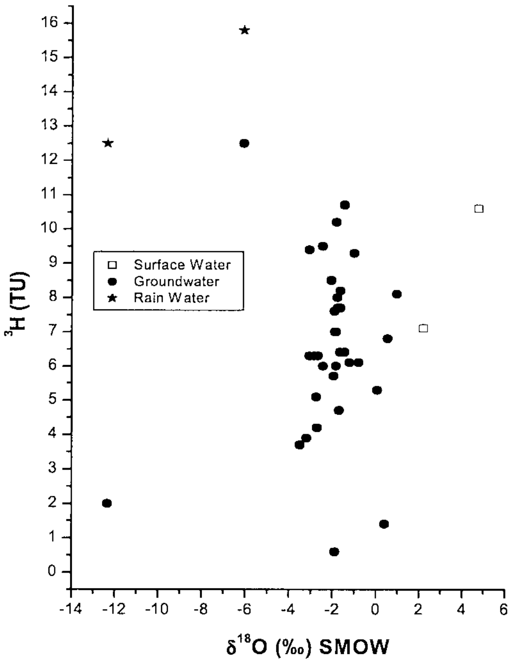


Figure 5 - Pre Monsoon samples (1999)

groundwater (shallow as well as deep) of post monsoon samples (1998) vary from –9.5‰ to –14.5‰ (Figure 6). The groundwater near landfill sites and industrial waste disposal areas shows depleted value of $\delta^{13}C$ compared to most of the groundwater samples and it ranges from –11 to –13‰. The pre monsoon samples (1999) from the same sites (i.e. landfills and waste disposal sites) show further depletion in $\delta^{13}C$ values (Figure 7). The depleted $\delta^{13}C$ values in DIC of groundwater's can be attributed to the production of CH_4 by landfills leachates and subsequent oxidation of methane by aerobic bacteria [5].

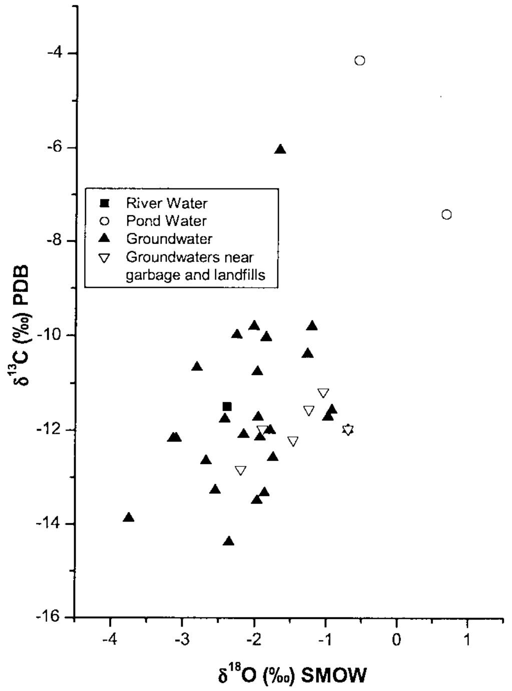


Figure 6 - Post monsoon samples (1998)

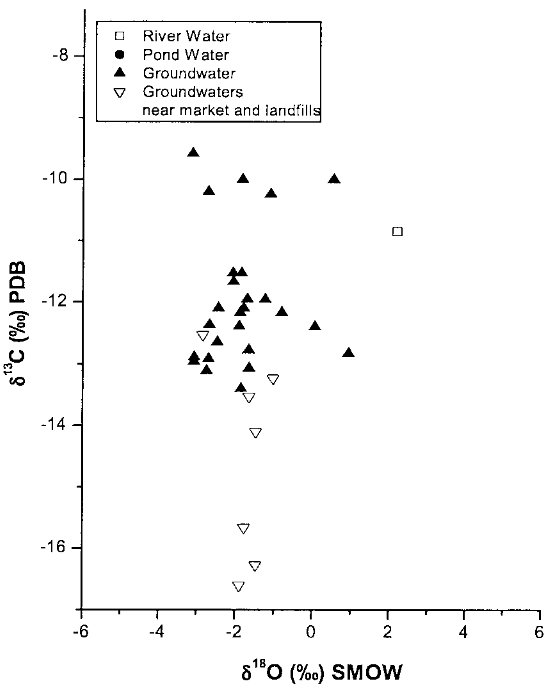
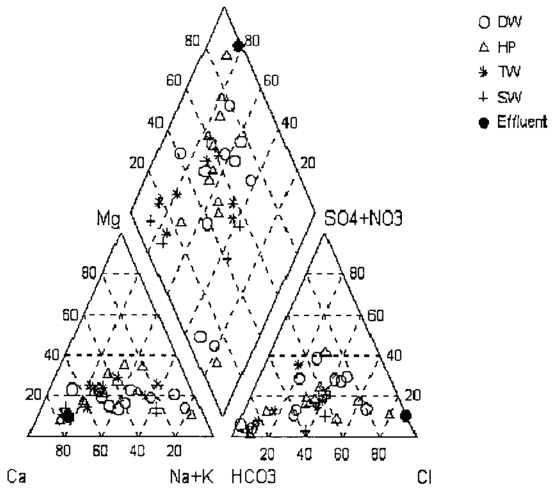


Figure 7 - Pre monsoon samples (1999)

The Piper diagrams (Figure 8 and 9) for major chemical ions of post monsoon (1998) and pre monsoon (1999) samples show that the majority of groundwater samples are characterised by Ca-Mg-HCO_3 and Ca-Mg-SO_4-Cl type.



Post monsoon Raipur samples (1998)

A few samples of Na-HCO_3 type have also been found. Ca-Mg-HCO_3 is more dominant type in the post monsoon water samples whereas Ca-Mg-SO_4-Cl type of water is more dominant in pre monsoon water samples. In general concentration of chemical species is higher in pre monsoon sample (1999) compared to post monsoon sample (1998). Pre and post monsoon tube well and hand pump samples from deep aquifer (~100 m) do not show any significant trend in the concentration of major ions (Figure 10 and 11). Pre monsoon dug well samples from shallow aquifer are more concentrated in chloride sulphate and nitrate ions than post monsoon samples (Figure 12). Pre monsoon climate of Raipur city is very hot. So, increase in the concentration of major ions in pre monsoon (1999) dug well samples (< 25 m) could be due to evaporation processes. Pre monsoon (1999) groundwater samples near landfill and waste disposal sites show increased concentration of chloride sulphate and nitrate than post monsoon (1998) samples (Figure 13). These samples are depleted in ^{13}C also. Nitrate content is high at a few places, which could be attributed to the dairy farms situated in that area.

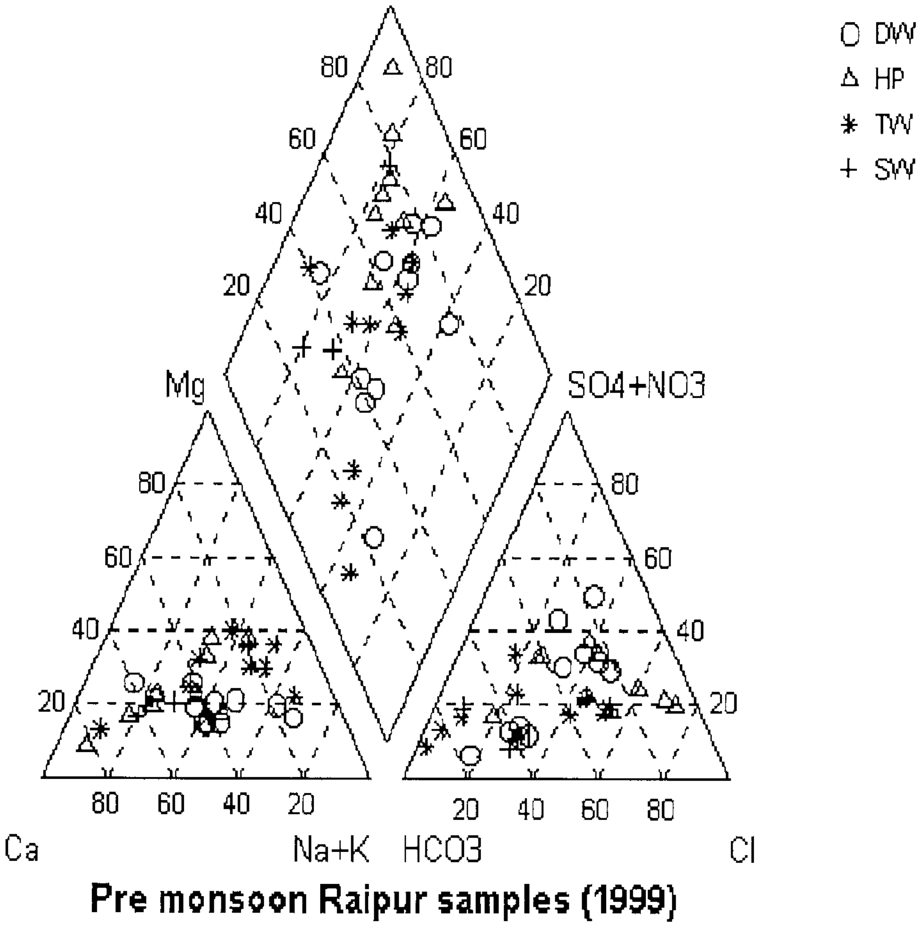


Figure 9

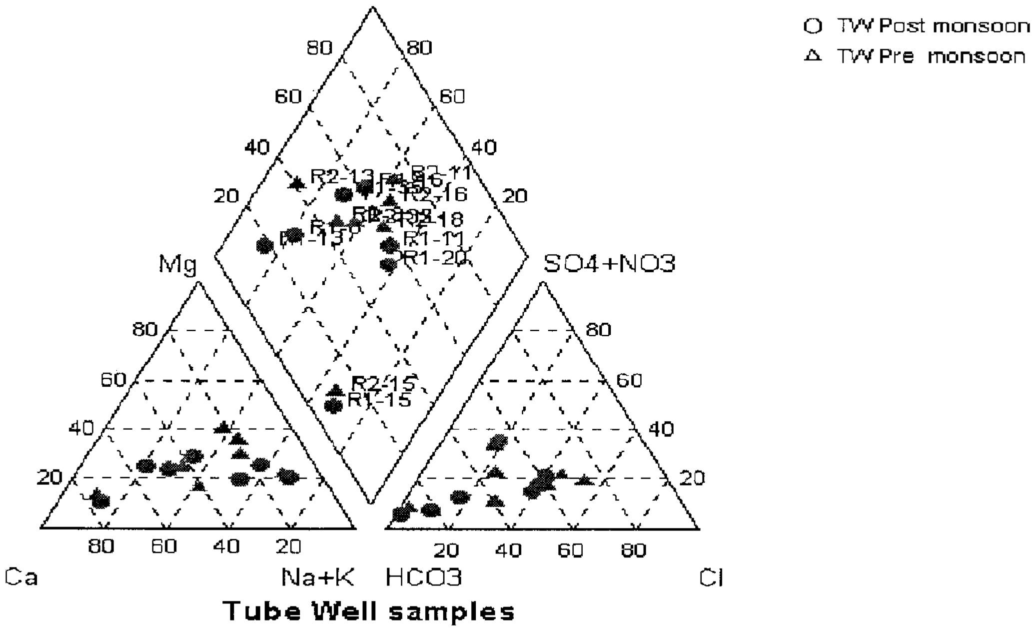


Figure 10

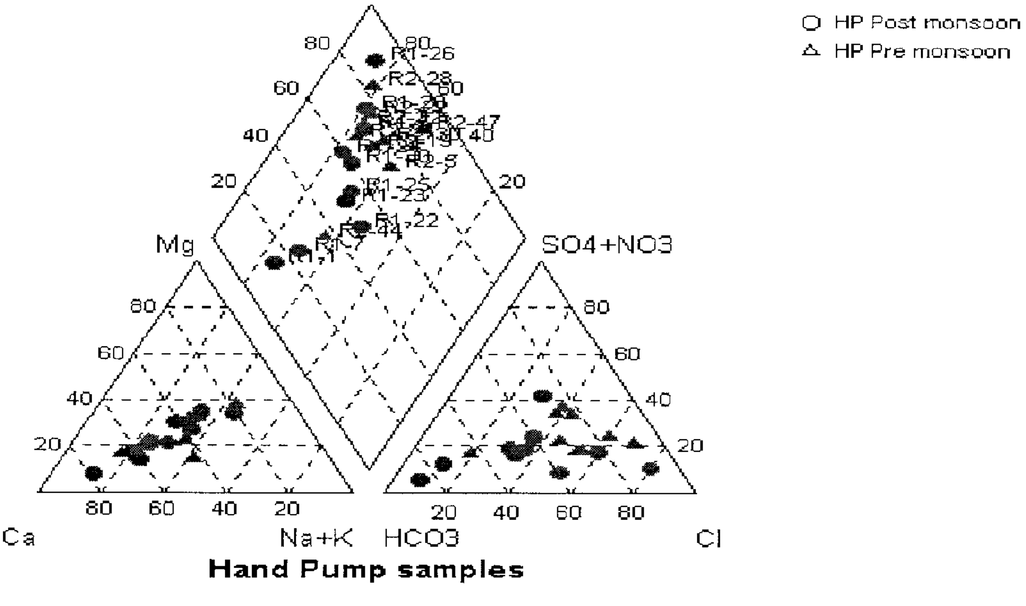
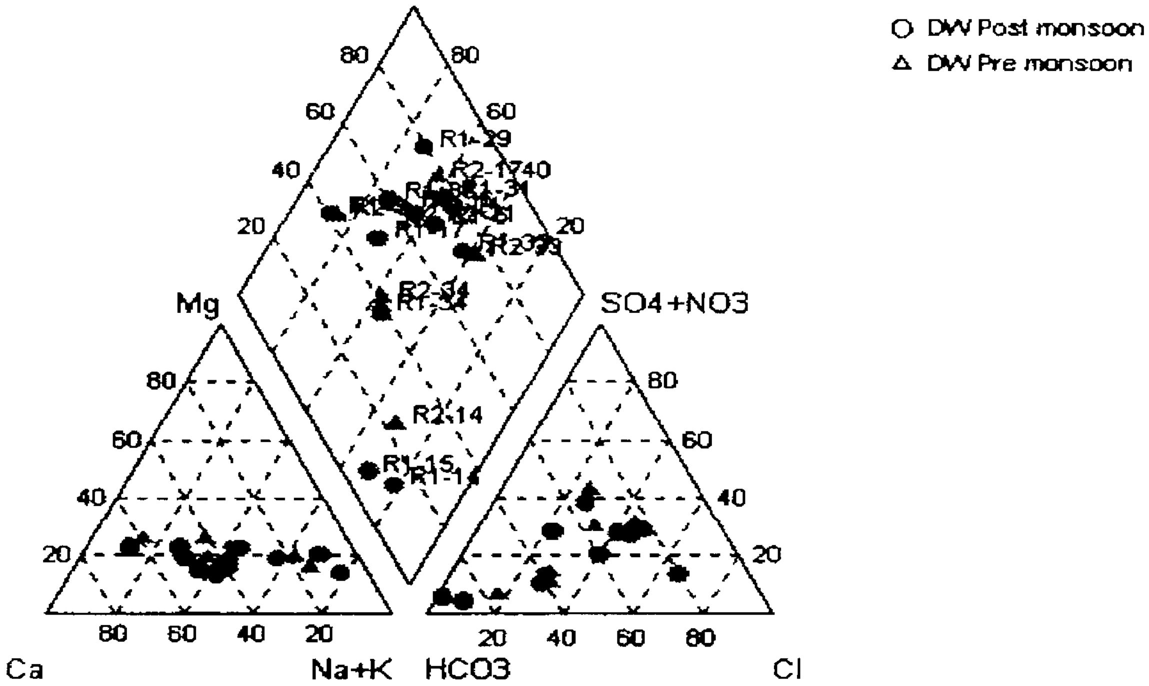
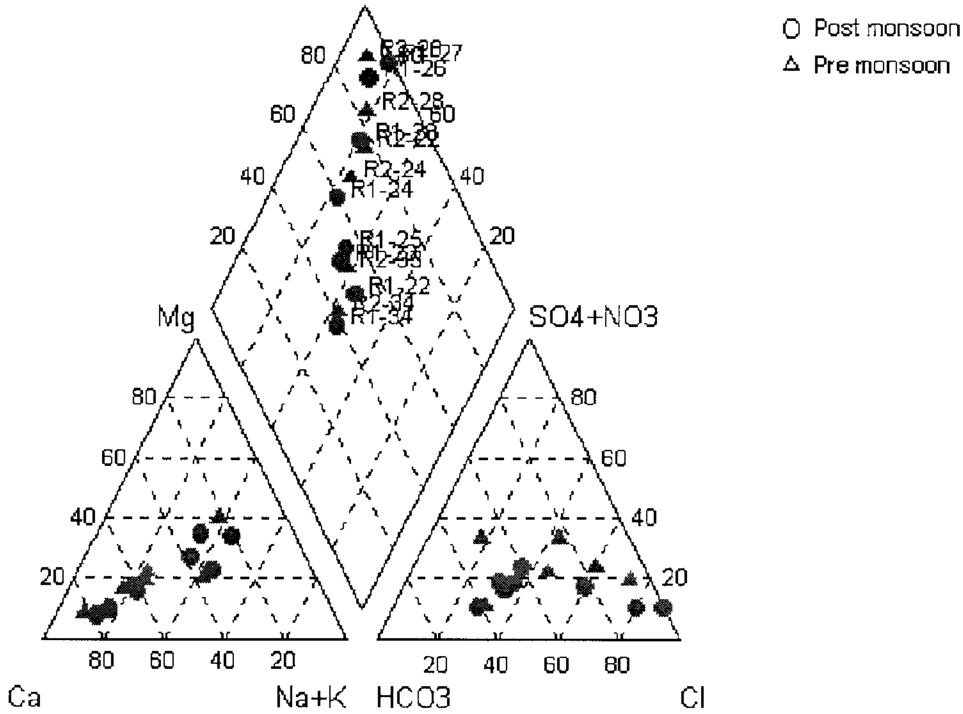


Figure 11



Dug Well samples

Figure 12



Groundwaters near landfills and wast disposal sites

Figure 13

1.5. Conclusion

The isotopic and chemical analysis indicates that

- Groundwater recharge occurs mainly through canal, pond seepage and direct infiltration.
- There is a possibility of groundwater contamination near landfill sites and waste disposal sites.
- Nitrate contents of groundwater are high near dairy farms.
- Shallow aquifers are more affected by contamination than deeper aquifer.
- Pre monsoon samples have higher concentration of major ions than post monsoon samples

2. IMPACT OF OVER EXPLOITATION OF GROUNDWATER ON ARSENIC POLLUTION AND OTHER CONTAMINATION OF GROUNDWATER IN CALCUTTA CITY.

2.1 INTRODUCTION

Calcutta city is one of the biggest cities of the world attained its present status due to steady growth in the last 300 years. The months of June to October are characterised by heavy rainfall. The average rainfall of Calcutta is 1600 mm [6]. Over eighty percent of the total annual rainfall takes place during the monsoon months (June to October). Still, the city is facing with the difficult problems of safe drinking water. The city area is experiencing water crisis for quite some time. With the expansion of urban complexes, industrial development and rise in population growth the total demand for water supply has increased many fold. To meet the demand of water, groundwater has been exploited extensively. The arsenic concentration above the permissible level in the neighbouring district and also some parts of Calcutta has complicated the problem. The indiscriminate exploitation of groundwater has lowered the piezometric surface for fresh water aquifers (>100 m bgl) in the central Calcutta to the tune of about 9 meter over a period of 40 years. The study aims to understand the impact of overexploitation on arsenic pollution and other contamination.

2.2 HYDROGEOLOGY

Calcutta Metropolitan area is located on the lower planes of composite Ganga — Bhagirathi delta. Calcutta Municipal Corporation (CMC) area is underlain by Quaternary sediment consisting of a sequence of alternation of clay, silt clay sand and sand mixed with occasional gravel. Clay horizon ranging generally in thickness from 30 –50 m, occurs at the top of the sedimentary sequence. The clay is underlain by coarse clastics consisting of sands of fine, medium and coarse texture which are occasionally mixed with gravel. These coarse clastics form the aquifer. The principal productive aquifers generally occur within the depth span of 60–180 m. A minor aquifer zone consisting of fine to medium sand has also been found to exists within the depth span of 20–40 m. Groundwater occurs both under unconfined and confined conditions. Groundwater in shallow zone occurs under unconfined condition. The predominance of impervious clay in the near surface strata of Calcutta area and its immediate neighbourhood inhibits the local recharge to deeper aquifers.

2.3 ISOTOPE STUDY

Post-monsoon (1998) and pre monsoon (2000) samples collected from hand pumps and tube wells (Figure 14) were analysed for ^{2}H, ^{18}O, ^{3}H, ^{14}C and major and minor ion chemistry including arsenic. Most of the samples were collected from deep aquifer (more than 100 m). A few shallow aquifer (< 50 m) samples from Jadavpur area of Calcutta city were also collected in 2000 and analyzed for ^{2}H, ^{18}O, ^{3}H, ^{14}C and major as well as minor ion chemistry including arsenic. A few rainwater samples from Calcutta have also been analysed for tritium and stable isotopes. Table 3 and 4 shows results of isotopic analysis for post and pre monsoon samples.

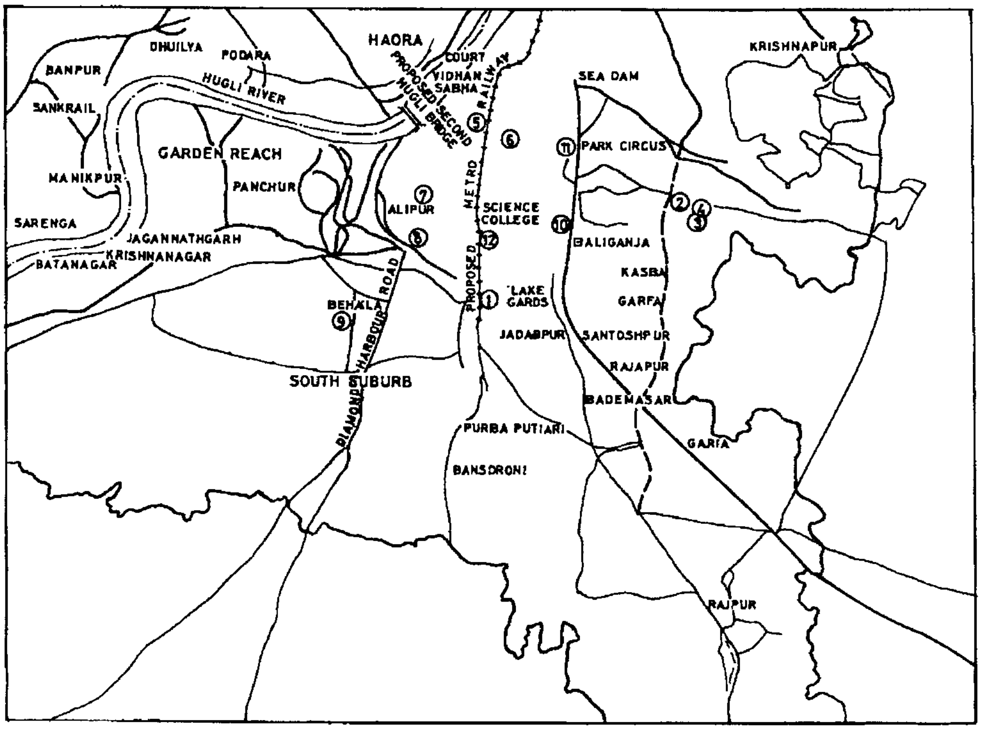


Figure 14 – Location map of Calcutta samples

Table 3 – Isotopic analysis of Calcutta samples (1998)

S.No	Identifi –cation	Source	$\delta^{18}O$ (%o)	$\delta^{2}H$ (%o)	^{3}H TU ± 1σ (0.5 TU)	^{14}C (pMC)
1	C1–1	Hand Pump	–5.20	–34.5	5.5	
2	C1–2	Tube Well	–4.46	–27.4	0.0	
3	C1–3					
4	C1–4	Hand Pump	–4.56	–27.5	1.1	
5	C1–5	Hand Pump	–5.90	–32.9	7.5	
6	C1–6	Hand Pump	–5.40	–37.2	0.6	
7	C1–7	Hand Pump	–5.38	–33.0	0.0	
8	C1–8	Hand Pump	–4.78	–28.1	2.2	
9	C1–9	Hand Pump	–3.79	–20	0.7	20.96±.92
10	C1–10	Hand Pump	–6.82	–51.4	0.8	
11	C1–11	Hand Pump	–5.5	–38	0.5	
12	C1–12	Hand Pump	–4.85	–17.7	0.2	
13		Rain water July 1998	–3.9	–20.4	6.33	
14		Rain water Nov. 1998	–5.5	–30.2	8.05	

Table 4 – Isotopic analysis of Calcutta samples (2000)

S.No	Identifi –cation	Source	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	^{3}H TU ± 1σ (0.5 TU)	^{14}C (pMC)
1	C2–1	Hand pump	–4.8	–28.9	9.26	
2	C2–2	Tube Well	–3.2	–23.8	2.44	22.89±1.6
3	C2–4	Hand pump	–3.68	–24.0	1.45	
4	C2–6	Hand pump	–4.98	–31.3	1.03	
5	C2–7	Hand pump	–4.54	–31.3	1.89	
6	C2–8	Hand pump	–3.54	–26.3	5.25	67.89±2.7
7	C2–9	Hand pump	–3.12	–17.7	1.91	
8	C2–10	Hand pump	–6.46	–51.9	0.62	40.85±2.1
9	C2–13	Hand pump	–3.42	–23.3	1.11	24.20±1.6
10	C2–14	Hand pump	–4.42	–30.9	9.28	72.75±2.8
11	C2–15	Hand pump	–4.84	–29.2	1.94	
12	C2–16	Hand pump	–4.15	–27.5	10.23	
13	C2–17	Hand pump	–3.97	–29.1	9.54	
14	C2–18	Hand pump	–3.90	–24.6	4.76	75.92±2.9
15	C2–19	Hand pump	–1.91	–12.7	6.12	
16	C2–20	Hand pump	–3.32	–22.4	5.42	

2.4. DISCUSSION AND CONCLUSION

Piper diagram (Figure 15) indicates that groundwater is mostly Ca–Mg–HCO_3 type. A few groundwater samples of Na–Cl–SO4 type have also been found. Arsenic concentration in all the samples is below permissible level (.05 mg/L) [7]. A few shallow zone samples in Jadavpur area show arsenic concentration in groundwater above permissible level.

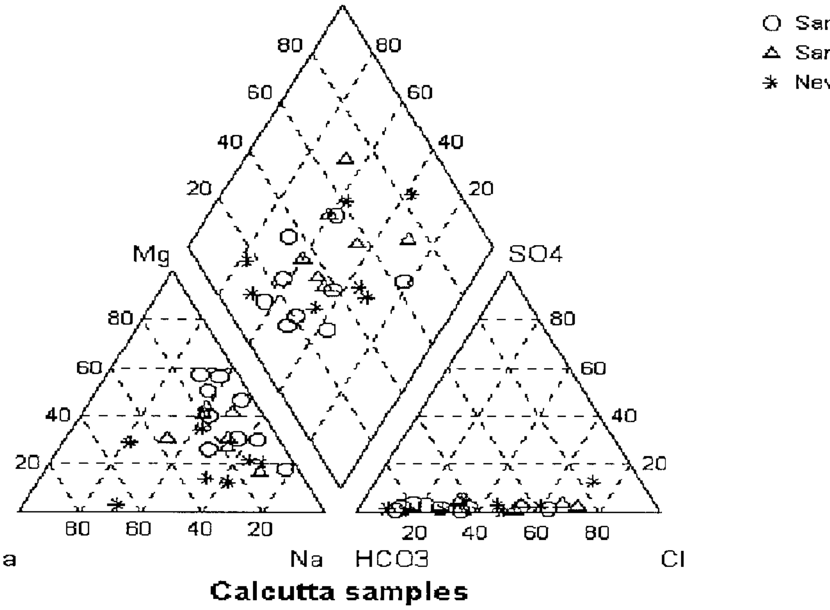


Figure 15

Most of the post and pre monsoon samples fall along the meteoric water line on $\delta^{18}O$ vs. δ^2H plot (Figure 16 & 17). There is no appreciable change in the oxygen–18 and deuterium content of deep groundwater in pre and post monsoon. Some shallow aquifer samples collected only in pre monsoon (2000) also fall along the meteoric water line and are represented by the equation ($\delta^2H = 8.7\delta^{18}O + 10.6$). Tritium content of almost all post monsoon samples (1998) is less 2.5 TU (Figure 18) showing absence of local recharge except two, where it is more than 5 TU. Carbon–14 value of one deep groundwater sample is ~21 pMC. Plot of $\delta^{18}O$ vs. ^3H (Figure 19) for pre monsoon samples (2000) shows that deep groundwater samples have low tritium content and free from arsenic contamination. Arsenic containing shallow groundwater has higher tritium content than arsenic free shallow groundwater and rainwater. Carbon –14 content measured using carbon absorption technique [8] of two arsenic contaminated samples are 72.75 and 75.92 pMC respectively. Carbon–14 content also suggests that groundwater having total arsenic concentration more than permissible level is younger water. Carbon–14 values of deep groundwater ranges from 40 to 20 pMC, which corresponds to uncorrected age of 7500 to 13000 a BP.

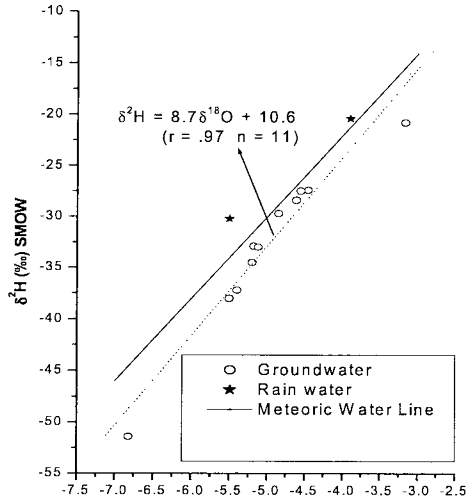


Figure 16 - Post monsoon samples (1998)

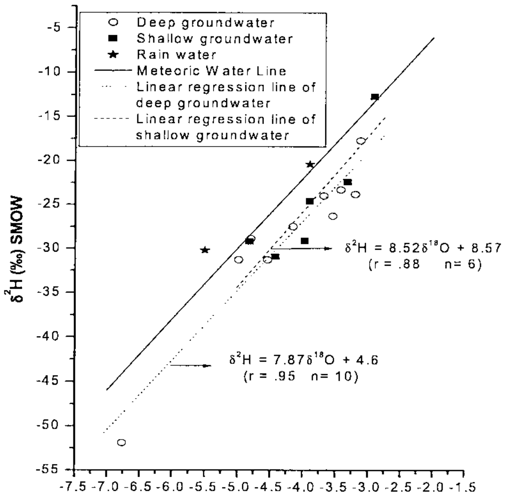


Figure 17 - Pre monsoon samples (2000)

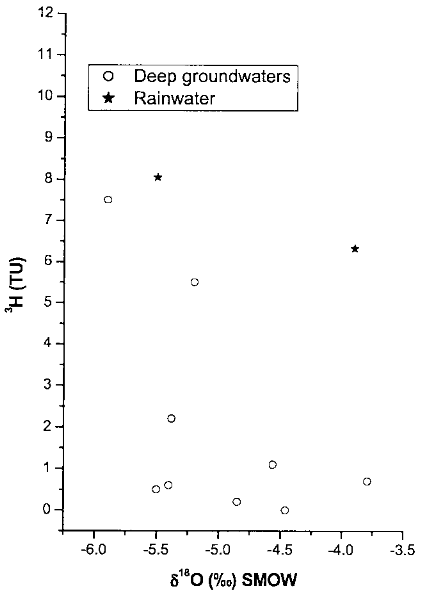


Figure 18 - Post monsoon samples (1998)

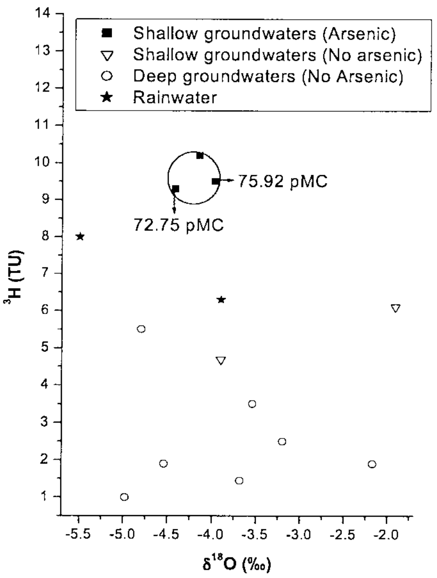


Figure 19 - Pre monsoon samples (2000)

Isotopic and chemical analysis indicates that

- Deep aquifer is arsenic free and contains old water (~7500 to 13000 a BP)
- Shallow aquifer is getting recharged by local precipitation
- Shallow aquifer in Jadavpur area of Calcutta city has arsenic concentration above permissible level (>0.05 mg/L).
- Arsenic contaminated shallow groundwater is younger than arsenic free shallow and deep groundwater.

3. WATER SEEPAGE IN THE BASEMENT IN SOME PARTS OF JODHPUR CITY.

3.1. INTRODUCTION

Jodhpur is a major city of Western Rajasthan. The city was founded about five centuries back. It was primarily designed to arrest rainwater in impounding structures to provide sustained water supply to the populace. The city consists of a number of water impounding structures. Seepage from these structures was exploited through a number of wells and step wells. With the availability of water from lift canal, which is fed to Kailana lake, use of these structures has been suspended since last three years.

Seepage water accumulation in the basement of a number of buildings and rise in the static water level (SWL) in some parts of Jodhpur city (Kunj Bihari Ka Mandir and Sojati Gate areas) has been reported in March 1998. Chemical quality of water accumulated in basement does not completely resemble that of the groundwater in wells in the immediate vicinity. Bacteriological analysis [9] has revealed presence of coliform above permissible limit in all the water samples irrespective of seepage water and groundwater. However, faecal Coliform (E-Coli) is absent in all the samples including basement samples.

3.2. ISOTOPE FIELD STUDY

An isotopic study has been carried out to find out the source of seepage. Water samples from hand pumps, basement, lake, filter houses, baories and ponds were collected in the month of December 1998 for oxygen-18, deuterium, tritium and chemical analysis. Location map (figure 20) shows sampling points.

3.3 HYDROGEOLOGY

Geomorphologically, the city is located on a concealed pediment starting from the foothills and hills encompassing the city along northern and western periphery. Jodhpur city area that includes areas affected by seepage consists of mainly alluvium and rhyolite whereas Kailana lake area, situated about 10 Km on the western side of the city consists of fractured rhyolite. A massive rhyolite ridge is running from northeast to southwest between Kailana lake and city area. Northern and eastern periphery of the Jodhpur city consists of alluvium and sandstone

Figure 21 shows reduced levels of different parts of the city. Reduced level of Kailana lake is 280 m above the mean sea level whereas reduced level of seepage locations is about 250 m above the mean sea level. The affected area is sloping from north to east and southeast. The hills on which the fort is located have higher elevation and the relief is fairly steep. A number of surface water impounding structures was constructed in the immediate foot hills zone and also at suitable location within the city to receive monsoon flows.

In recent years Kailana lake is mainly fed by lift canal. Input from lift canal to Kailana lake is 0.21 million cubic metre per day. Input from lift canal is not a continuos process. The average depth of lake is about 18 metre, which has capacity of about 5 million cubic metre of water. Present consumption from the lake is 0.18 million cubic metre per day while, it was about 0.08 million cubic metre before the feeding by lift canal.

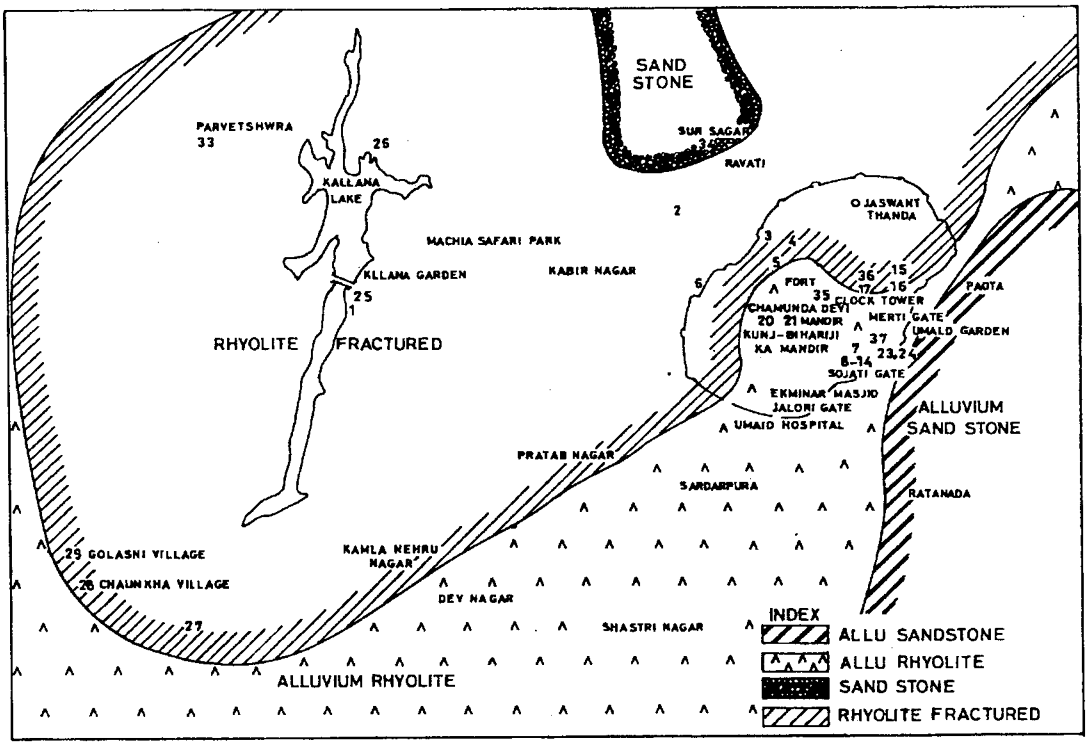


Figure 20 – LOCATION AND GEOLOGICAL MAP OF JODHPUR CITY AND SURROUNDING AREAS

GEOLOGICAL SECTION BHIMBHARAK NATIONAL-STEELS (NAI-SARAK)

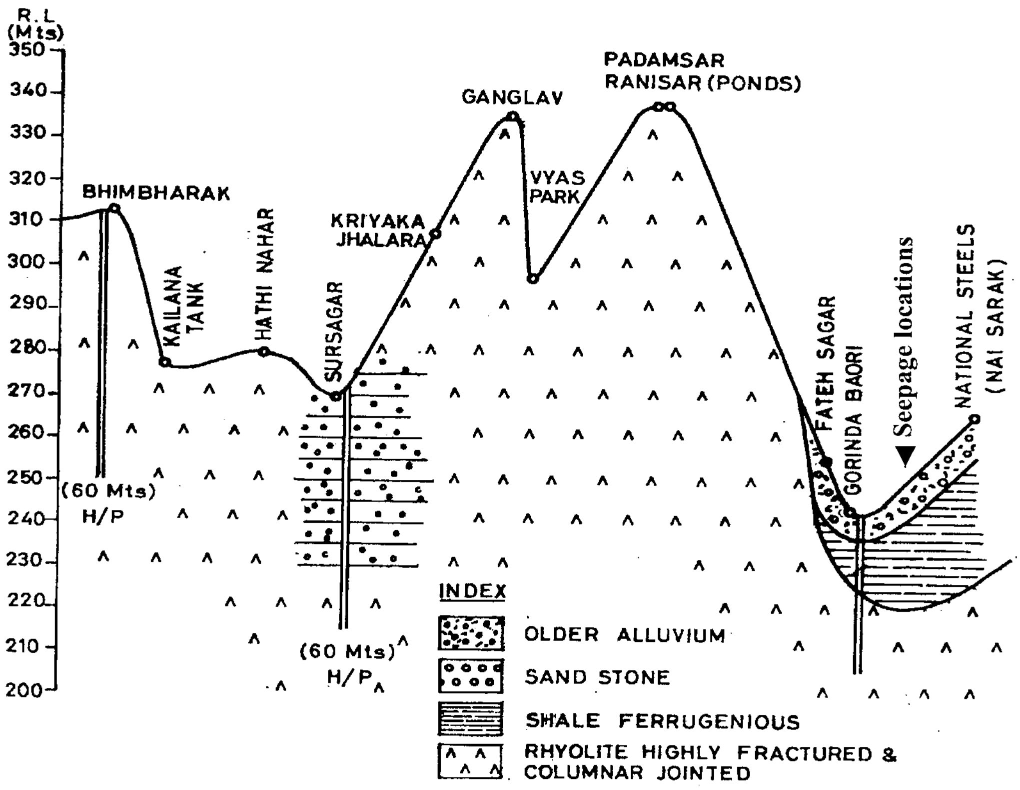


Figure 21 – Reduced level of seepage locations and Kailana lake, etc

3.4. RESULTS AND DISCUSSION

Chemical analysis indicates that electrical conductivity (EC) and major ion chemical contents in seepage water is mostly less than that of nearby hand pumps or dug wells.

Plot of $\delta^{18}O$ vs. $\delta^{2}H$ (Figure 22) shows that the water samples from lake and filter houses (which has been supplied by lake) are depleted in stable isotopes $\delta^{18}O$ and $\delta^{2}H$ compared to other surface water bodies. Basement samples fall between lake water and groundwater, which suggests contribution of lake water to the basement seepage water. Pond water samples are highly enriched in $\delta^{18}O$ and $\delta^{2}H$ showing evaporation effect.

Tritium content of lake water and filter houses water vary from 9 to 12 TU whereas basement samples show tritium content of 6.5 to 10 TU (Figure 23). Tritium content of hand pump samples are in the range of 2.5 to 7 TU. Tritium results also suggest that basement samples are mixture of Lake Water and groundwater.

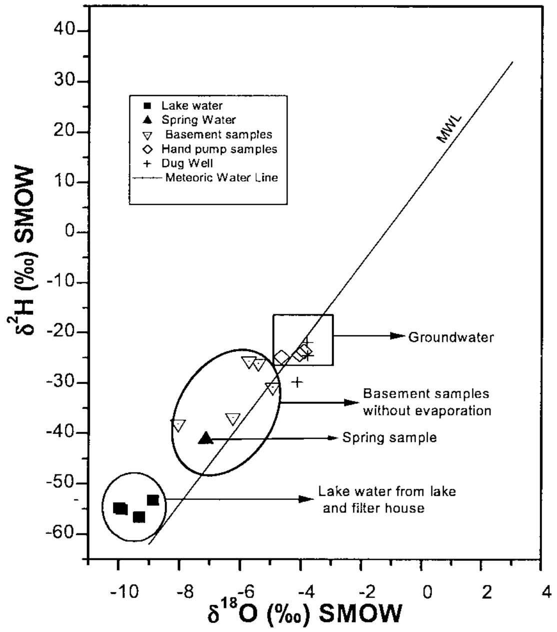


Figure 22 - Stable isotope compositions of Jodhpur waters

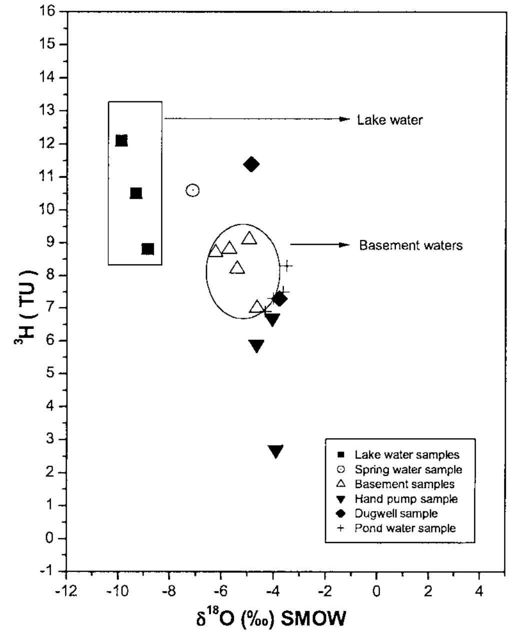


Figure 23

Spring sample from Vyas Park shows depleted value of $\delta^{18}O$ and $\delta^{2}H$ (more depleted than basement samples) and higher tritium content (higher than basement samples) indicating a good component of lake water. Direct seepage from Kailana lake (RL 280 m) to Vyas Park spring (RL 310 m) is not possible due to higher elevation of Vyas Park. Most probably the used water percolating to the subsurface is contributing to the spring.

3.5. CONCLUSION.

On the basis of isotopic, chemical analysis and hydrogeological data it can concluded that the lake water, which is supplied to the city is contributing to the seepage water in the basement.

Absence of E-coli in the entire basement samples rules out the possibility of seepage from sewer lines. The lake water contribution to the seepage could be either due to direct seepage from Kailana lake (due to the fractured nature of Rhyolite) or seepage from pipelines (carrying lake water) and used water percolating to the subsurface. Increased consumption of lake water and discontinuation of groundwater withdrawal have further aggravated the seepage.

ACKNOWLEDGEMENT

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Isotopic evidence for induced river recharge to the Dupi Tila aquifer in the Dhaka urban area, Bangladesh

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Abstract

The population of the greater Dhaka metropolitan area is over 8 million and growing at a rate of six percent per year. Much of the water supply for the area is obtained from the underlying Dupi Tila sand aquifer. Intensive exploitation of the aquifer has led to a progressive decline in water levels beneath the parts of the city. The resulting cone of depression is thought likely to be causing the infiltration of surface water, largely from the polluted Buriganga waterway. The use of oxygen and hydrogen stable isotopes in unravelling the subsurface hydrology of the Dhaka area is hindered by the lack of data regarding 'baseline' conditions. Nevertheless it is clear from the evidence obtained from tubewells across the city that there is leakage from the Buriganga river extending several kilometres beneath parts of the urban area, possibly as far as the centre of the city. Carbon stable isotopes and major ion chemistry confirm this general picture; though appear to indicate that polluted river water has not penetrated quite so far towards the city centre. The Dupi Tila is regarded as a multi-layer aquifer on the basis of its hydrogeology and water quality variations with depth. Since there is little stable isotopic evidence for stratification, future investigations should include sensitive recent age indicators to investigate this, and the rates of groundwater movement in general.

1. INTRODUCTION

1.1 Water Supply

Approximately 95% of the water supply for the Dhaka urban area is derived from groundwater in the underlying Dupi Tila aquifer, with the remainder being obtained from river sources. Currently the water supply utility, Dhaka Water and Sewage Authority (WASA), abstracts 270 Mm^3 per year primarily for domestic water supply, while private boreholes abstract a further 40 Mm^3 per year for domestic and industrial use [1].

The present supply of water is failing to keep up with the demand resulting from a population of 8.5 million with an annual growth of around six percent. The WASA response to this burgeoning demand has been to install increasing numbers of boreholes. Inevitably, intensive abstraction has resulted in declining water levels (up to 0.75 m per year in some areas) which has required either abandonment or deepening of existing wells.

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1.2 The Dupi Tila aquifer

The Dupi Tila aquifer (inset, Fig. 1) consists of a thin zone of fine sands at the top followed by a thick, relatively uniform medium sand sequence, though with enough lower permeability zones to be regarded as a multi-layer aquifer. The aquifer varies in thickness from 100 to 120 m. In its natural state the aquifer is confined by the overlying Madhupur Clay (10-20 m thick), and an underlying clay of indeterminate thickness. The Dupi Tila has no significant surface outcrop, although it is believed to be exposed along part of the bed of the Buriganga River which forms the southern boundary of the city. This, and the adjacent alluvial sediments, would have been the main route for aquifer discharge prior to post-independence development.

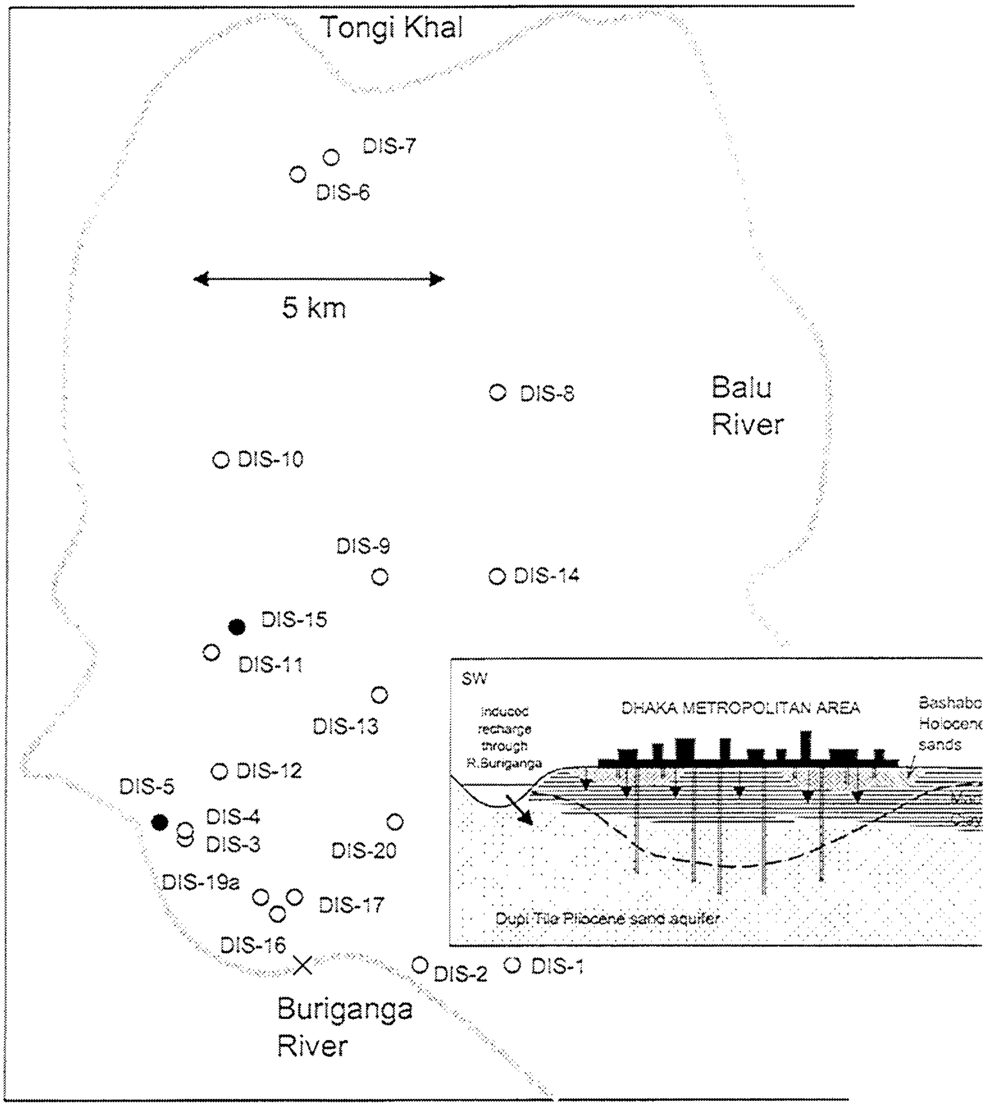

Figure 1. Simplified map of the Dhaka urban area, showing the extent to which the city is surrounded by rivers and other waterways. The city has expanded northwards from its original location on the banks of the Buriganga River; the eastern side of the 'island' is marshy and less developed. Sampling sites are indicated: all are tubewells terminating in the Dupi Tila aquifer except for DIS-5 and DIS-15, which terminate in the upper aquifer, and DIS-18 (marked by a cross) which is surface water. Inset: schematic cross-section across the city indicating the aquifers and the cone of depression resulting from intensive abstraction.

The aquifer could be regarded as 'leaky confined' before large scale abstraction; piezometric heads in the Dupi Tila were somewhat below the level of water in the Madhupur Clay, indicating that the variability in the clays and silts making up the Madhupur Clay permits some vertical recharge to the Dupi Tila. Following intensive abstraction over much of the city, the piezometric level of the aquifer has fallen by about 30 m and the aquifer has become unconfined. The resulting 'cone of depression' is believed to be causing the infiltration of river water to the aquifer.

The quality of the water in the northern part of the city is good. Elsewhere there is some pollution due to industrial activity and also to recharge by polluted river water. In general however the quality is at present adequate, at least in inorganic terms, especially compared to the poor-quality water found in the overlying Madhupur Clay and sands of the Bashabo Formation. A primary concern is how rapidly future water quality may decline owing to induced infiltration from surface water bodies, and leakage from sewers and landfills. This could be compounded by abandoned wells where they are not adequately sealed off.

The purpose of the present investigation has been to combine the use of stable isotope techniques with existing hydrochemical data [2] in order to determine the extent to which they may be able to assist in the understanding of changes in the hydrogeological regime of a major developing city situated on an alluvial aquifer. In this respect Dhaka is typical of many developing cities in the Subcontinent, Southeast Asia and elsewhere.

2. RESULTS

Samples were collected from a range of tubewells across the city, though with a preponderance in the most highly populated southern area (Fig. 1). The majority of tubewells sampled were between 110 and 180 m deep. Two shallower hand-pumped tubewells were also sampled. One sample of river water from the Buriganga River was also collected directly from the intake of the Chadnigat Water Works, which treats river water for subsequent distribution to the water supply system. Field sampling information is presented in Table I.

2.1 O and H stable isotopes

Stable isotope data are given in Table II. A delta-plot for O and H isotopes is shown in Fig. 2. The data fall a little below the World Meteoric Line; the WML may not be ideal for Bangladesh, but no nearby GNIP station exists yet. The nearest station, Shillong in India, is over 1500 m higher in altitude and therefore not very suitable as a comparison. There is a relatively limited spread of the Dhaka data, except for the sample from the Buriganga River, which is enriched apparently by evaporation. Initially it might be considered that the data depict a mixing series between a relatively depleted 'natural' groundwater and an induced leakage of river water. However, consideration of the wider context of isotope hydrology in Bangladesh suggests that this is not the case.

The interpretation of the isotope data depends on determining the average values of $\delta^{18}O$ and $\delta^{2}H$ in recent meteoric recharge across the general region. While there are few data from the immediate vicinity of Dhaka, in the Faridpur thana (county) some 70 km WSW of the city the median values for young groundwaters are -4.2 ‰ $\delta^{18}O$ and -27 ‰ $\delta^{2}H$, based on a total of 59 samples [3].

Although the Dupi Tila aquifer does not exist in this area, fifteen samples were obtained from the aquifer in the more distant Chapai Nawabanj thana some 230 km WNW of Dhaka. The median values were -4.0 ‰ δ^{18}O and -26 ‰ δ^{2}H, i.e. within error of those of the Faridpur thana. It is therefore proposed to use these values as a starting point in the interpretation of the Dhaka data.

Maps of the distribution of δ^{18}O and δ^{2}H within Dhaka are shown in Fig. 3a and 3b. The variations in value are fairly subtle and somewhat irregular, but basically a preponderance of the more depleted samples (δ^{18}O more negative than -5 ‰) is found in the south of the city adjacent to the Buriganga. This suggests that there may be some invasion of water from the Buriganga River, though if so the weighted average isotope value of river water must be very different to the value measured on the sample collected in February 2000 for this study. In fact it could be anticipated that dry-season flow in the river would be somewhat evaporated, while the quantitatively much more important monsoonal flow would be relatively depleted - cf. a study of the Ganges by Navada and Rao [4] - though this remains to be investigated for the Buriganga, which is basically a distributary of the Brahmaputra.

Table I: Field sampling data for the sites sampled during the present survey

Sample No.	**Site name**	**Depth** m	**Temp** °C	**pH**	**EC** µS cm^{-1}	**Diss. O$_2$** %	**Alkalinity*** mg l^{-1}
Shallow tubewells							
DIS-5	Embankment slum	40	27.0	6.10	105	10	228
DIS-15	Argargaon slum	55	26.0	6.50	120	35	98
Deep tubewells							
DIS-1	Jatrabari Chowrasta	152	27.3	6.48	200	12	146
DIS-2	JN University College	179	28.1	5.82	550	35	226
DIS-3	Hazaribagh Pump 4	125	26.8	6.02	510	27	232
DIS-4	Hazaribagh Pump 5	149	28.1	6.14	430	8	179
DIS-6	Uttara 9a						
DIS-7	Uttara 1 (Sector 3)	172	29.4	6.50	190	5	136
DIS-8	Kilkhet Bazar	167	27.9	7.22	150	12	105
DIS-9	Banani No.3	136	28.7	6.03	180	56	92
DIS-10	Mirpur Sector 10	138	26.8	6.50	180	45	77
DIS-11	Pangu Hospital	155	27.5	6.03	200	15	112
DIS-12	Dhanmondi No.8	120	27.1	6.30	440	70	155
DIS-13	Tejgaon No.8	116	27.1	6.02	420	25	95
DIS-14	Shahjadpur (Badda)	175	27.7	6.42	230	15	122
DIS-16	Old Dhaka				620		
DIS-17	Chadnighat Water Works	129	33.8	6.40	810	50	285
DIS-19a	Llalbagh Shastakhan	146			1320		
DIS-20	Curzon Hall campus	120			770		
River water							
DIS-18	River Buriganga (Water Works intake)				640		

* from previous survey [2]

Table II: Stable oxygen, hydrogen and carbon isotopic data for the sampled sites

Sample No.	**Site name**	**$\delta^{18}O$** **‰ VSMOW**	**$\delta^{2}H$** **‰ VSMOW**	**$\delta^{13}C$-DIC** **‰ VPDB**
Shallow tubewells				
DIS-5	Embankment slum	-5.23	-35.8	-14.43
DIS-15	Argargaon slum	-4.89	-31.2	-16.72
Deep tubewells				
DIS-1	Jatrabari Chowrasta	-5.09	-32.1	-18.16
DIS-2	JN University College	-5.53	-36.9	-15.19
DIS-3	Hazaribagh Pump 4	-4.91	-33.7	-15.85
DIS-4	Hazaribagh Pump 5	-4.95	-33.2	-14.88
DIS-6	Uttara 9a	-5.91	-38.3	-15.87
DIS-7	Uttara 1 (Sector 3)	-4.89	-30.4	-16.87
DIS-8	Kilkhet Bazar	-4.71	-29.9	-15.30
DIS-9	Banani No.3	-4.94	-30.7	-18.31
DIS-10	Mirpur Sector 10	-5.24	-31.4	-18.14
DIS-11	Pangu Hospital	-4.64	-30.6	-17.49
DIS-12	Dhanmondi No.8	-4.62	-31.5	-17.00
DIS-13	Tejgaon No.8	-4.79	-30.7	-17.91
DIS-14	Shahjadpur (Badda)	-5.10	-32.4	-18.27
DIS-16	Old Dhaka	-5.17	-34.2	-16.36
DIS-17	Chadnighat Water Works	-5.59	-35.1	-14.60
DIS-19a	Llalbagh Shastakhan	-5.03	-33.9	-14.67
DIS-20	Curzon Hall campus	-5.13	-34.2	-17.46
River water				
DIS-18	River Buriganga (Water Works intake)	-3.83	-25.1	-13.19

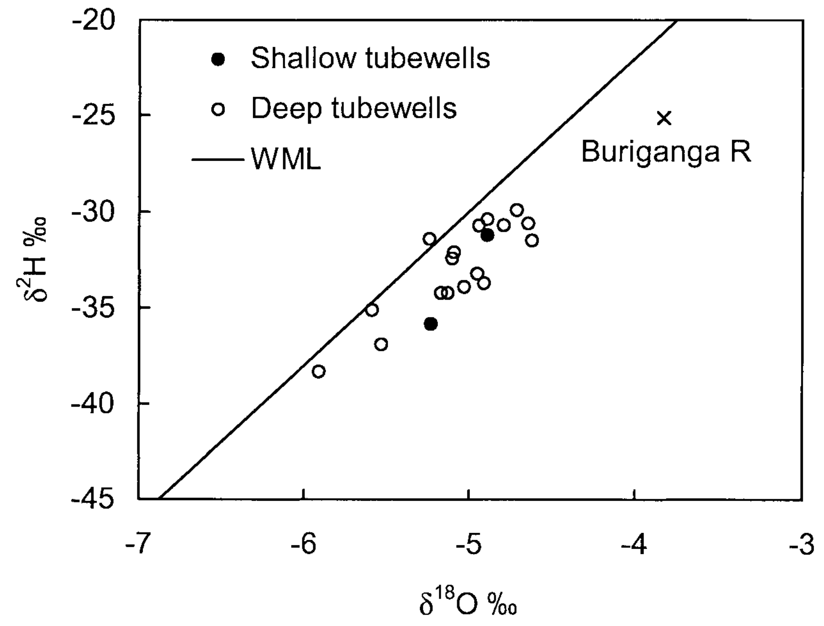

Figure 2. Delta-plot of O and H stable isotope data for the Dhaka sites. All samples from tubewells except for surface water from the Buriganga River (Feb 2000). The World Meteoric Line (WML) is also shown.

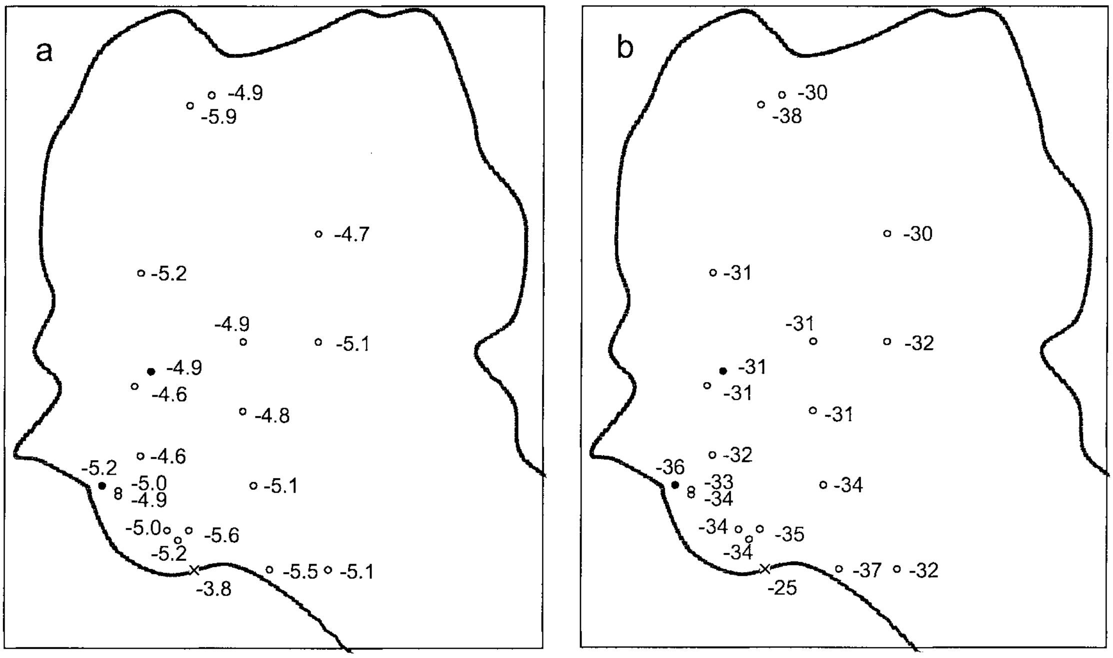

Figure 3. Maps showing the distribution of (a) $\delta^{18}O$ and (b) $\delta^{2}H$ in Dhaka groundwaters. Symbols as in Fig. 2.

If river water is leaking into the Dupi Tila, it might be expected that there would be an approximately linear relationship between isotope value and distance from the nearest region of inflow. The EC distribution [1, 2] suggests that this is in the south west of the city, near the old industrial area. Fig. 4 shows a plot of $\delta^{2}H$ versus simple distance from the nearest major river or khal, showing the proposition to be generally true, though the actual route taken by invading river water may not be the most direct. The sample falling slightly away from the broad trend is the most depleted of all, from a tubewell of unknown depth at Uttara (DIS-6) in the north of the city. Either the water here is derived from the local Tongi Khal waterway, or it is possibly a residual water of early Holocene age; waters as depleted as -50 ‰ $\delta^{2}H$ are known from elsewhere in Bangladesh [3] but their age is not known with certainty. The fact that the other site in Uttara is a deep tubewell with a 'normal' value suggests that a leakage origin is more likely.

For the purposes of the present interpretation it is assumed that the most depleted samples near the Buriganga, from boreholes at the JN University College (DIS-2) and the Chadnigat Water Works (DIS-17) (n.b. this is not treated surface water, but groundwater from a tubewell in the Works compound) can be regarded as the river water end member. Fig. 5 shows that if the 'background' values from Faridpur and Chapai Nawabanj are used, all waters in the Dupi Tila of Dhaka must contain at least 30% river water. In reality it seems questionable that polluted river water could have invaded parts of the aquifer as much as 10 km from the river; chemical evidence tends to suggest that this has not yet happened (see below).

In contrast to the apparent relationship with distance from potential river sources, there is little evidence of any relationship between isotopic values and depth of screen (Fig. 6a). Even when distance is introduced as a supplementary factor, no clear relationship emerges. When plotted against electrical conductivity, however, there is a generally good correlation (Fig. 6b). The only isolated data points are the river water of Feb 2000, already ruled out as being representative of an end member, and from local shallow sources such as the sample from Llalbagh Shastakhan (DIS-19a) which has presumably suffered from pollution.

It appears to make little difference whether samples have been obtained from deep or shallower tubewells. The samples from the two hand-pumped wells (DIS-5, DIS-15) resemble the deep wells in that the site near to the Buriganga embankment has evidence of river leakage while the more 'inland' site in the Agargaon area of the city has a composition closer to background.

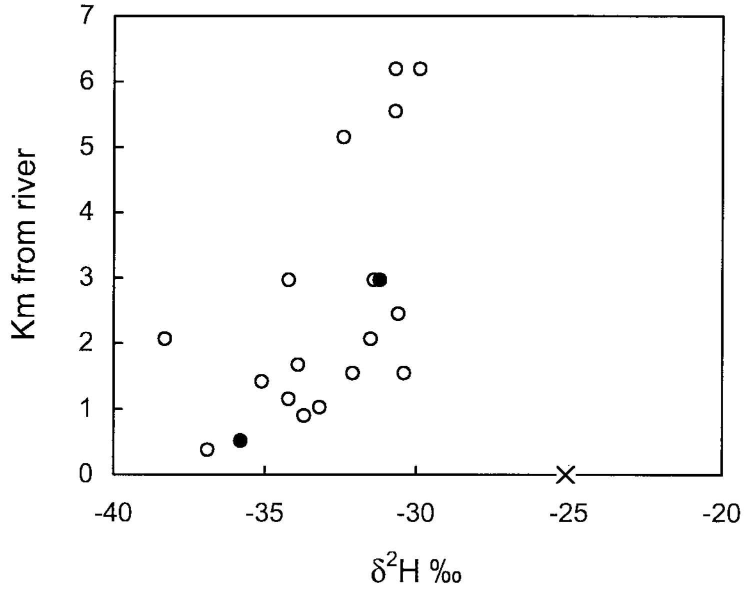

Figure 4. Plot showing the general trend in isotopic enrichment away from river water infiltration areas. Symbols as in Fig. 2.

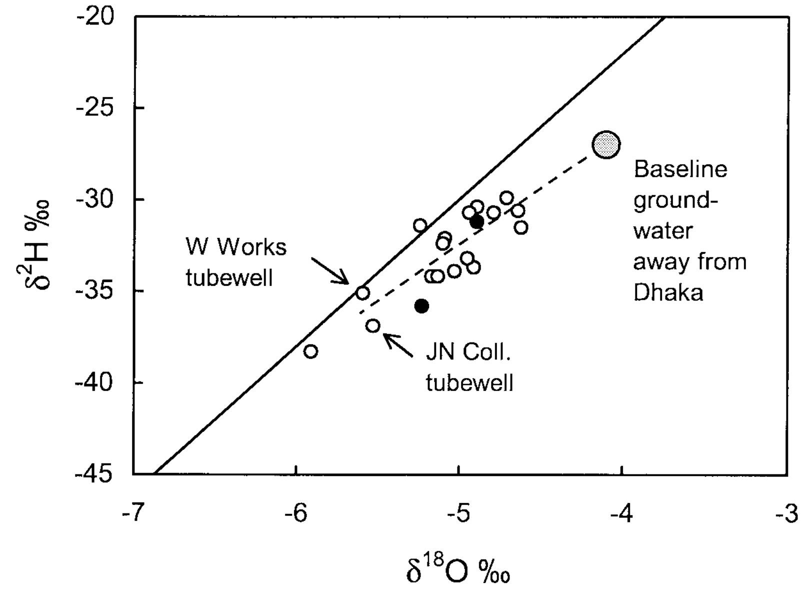

Figure 5. Delta-plot showing the composition of the Dhaka tubewells in relation to the putative 'baseline' composition of the Dupi Tila based on samples collected elsewhere in Bangladesh (see above). Symbols as in Fig. 2. On this basis all the sampled tubewells have at least 30% river water, as represented by the compositions of the Water Works and JN University College tubewells.

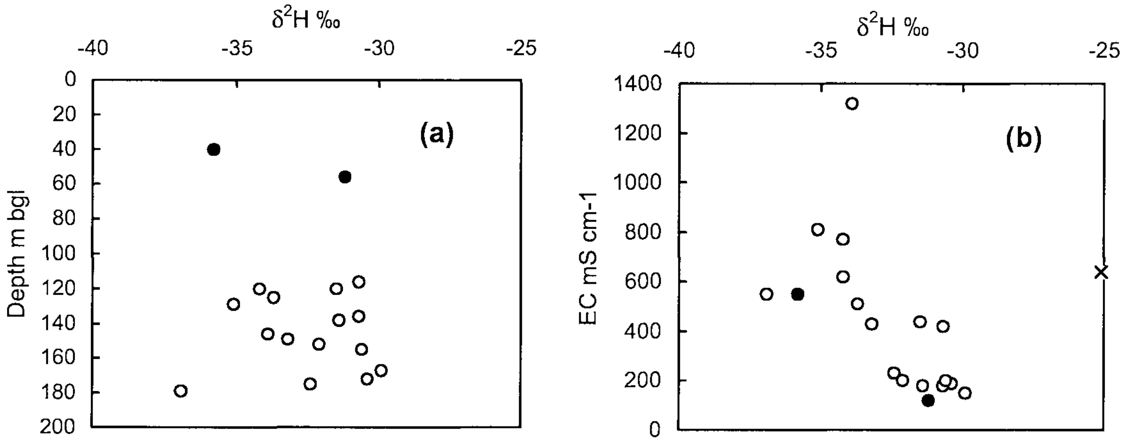

Figure 6. Plots of δ^2H versus (a) depth below surface, and (b) electrical conductivity. Symbols as in Fig. 2.

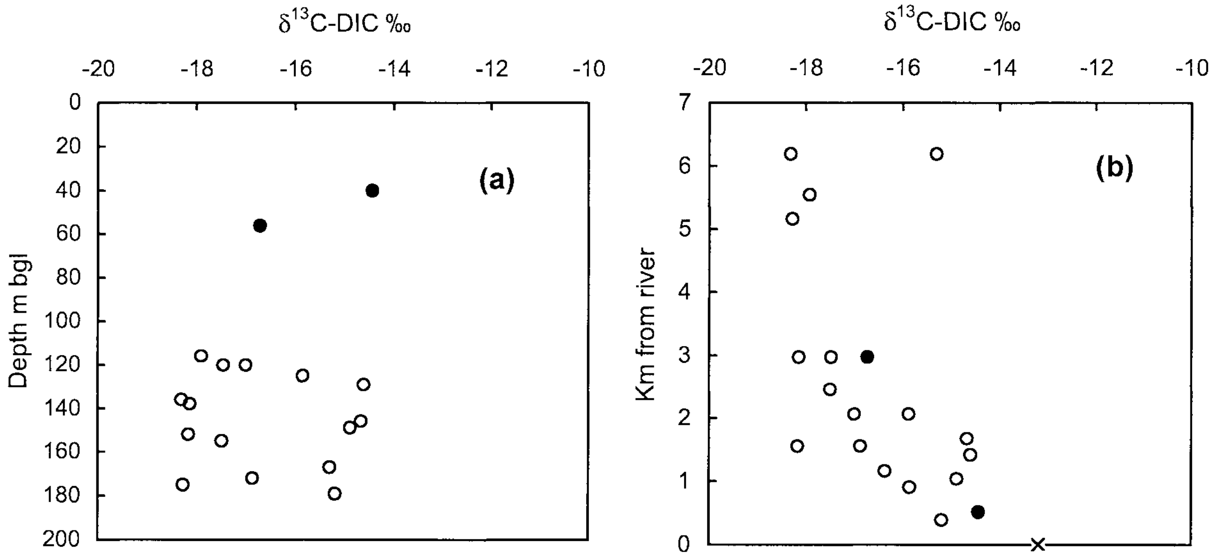

Figure 7. Plots of $\delta^{13}C$-DIC versus (a) depth below surface, and (b) distance from the nearest major river or khal. Symbols as in Fig. 2.

2.2 Carbon stable isotopes

Analyses of $\delta^{13}C$ in dissolved inorganic carbon (DIC) are given in Table II. They range from values more depleted than -18 ‰ in central parts of the city to values more enriched than -15 ‰ towards the Buriganga River. The river water itself has the most enriched composition, presumably due to partial equilibration with atmospheric CO_2. There is a rather better correlation with distance from the nearest river than is shown by O and H stable isotopes, but an equally poor correlation with depth (Fig. 7a and b).

The extent of variation of $\delta^{13}C$ in river water is as yet unknown. If as before it is assumed that the sample from the Chadnighat Water Works tubewell (DIS-17) represents the river water end member, a plot of $\delta^{13}C$ vs alkalinity as HCO_3 (not shown) reveals an apparent mixing series between river and groundwater. Some groundwaters have alkalinities of less than 100 mg l^{-1}; such low values combined with depleted $\delta^{13}C$ values indicate that these waters are relatively younger, i.e. unreacted with aquifer carbonate. They are therefore unlikely to be contaminated by induced river water as the interpretation of the O and H isotope data had originally suggested.

In the Uttara area in the north of the metropolitan area, the two boreholes with different O and H isotopic values also gave somewhat different $\delta^{13}C$ values. The only slightly enriched ^{13}C value for the borehole depleted in ^{18}O and ^{2}H seems likely to indicate that river infiltration is responsible; a water of early Holocene age or older would be likely to have a more evolved, heavier $\delta^{13}C$ value.

2.3 Tritium-helium dating

Two deep tubewells within the southern part of the city (at lat. 23°44.45'N / long. 90°23.86'E, and lat. 23°43.58'N / long. 90°24.03'E) were sampled by a team from the Lamont-Doherty Earth Observatory in order to determine water residence times using the ^{3}H-^{3}He method. The model ages, based on assumptions about tritium levels in rainfall interpolated from IAEA collection stations in neighbouring countries, were 17.7 ± 2 and 18.3 ± 0.8 years respectively (M. Stute, personal communication).

2.4 Hydrochemistry

Major ion data for most of the sites is presented in Table III (from ref. [2]). Some of the wells provide low-TDS waters (e.g. DIS-9, DIS-10 and DIS-13) which seem likely to be original 'baseline' waters. Most of the waters can be characterised as Na-Ca-HCO_3 waters; this seems to be the case even for the apparently original waters, which would indicate that ion exchange is unlikely to be operating on a significant scale.

Consideration of sulphate, nitrate and dissolved oxygen data (Fig. 8) shows that in certain areas (e.g. the Hazaribagh industrial area in the southwest of the city) the redox situation may permit some denitrification and sulphate reduction. Elsewhere the aquifer is not particularly reducing, with decrease in dissolved oxygen percentage broadly associated with *increases* in sulphate and nitrate, suggesting the buildup of urban pollution. The river end-member site (DIS-17) is one of the more oxygenated sites, indicating that the redox status at different sites is locally controlled rather than part of a mixing trend with river water.

Plots of various species versus chloride (assumed to be highly conservative) are shown in Fig. 9. Almost without exception, the data for sodium, calcium, bicarbonate and sulphate support the inference drawn from the stable isotopic data that mixing is taking place between groundwater and infiltrating river water as represented by the sample from the Water Works tubewell (DIS-17). The major exception is the samples from the hand-pumped embankment tubewell near the Hazaribagh industrial area, which has evidently been affected by influx of pollution high in Ca and Cl. As alluded to above, nitrate and dissolved oxygen compositions appear to be much less coupled to the process of river water infiltration, being more linked to local factors.

The sample from Llalbagh Shastakhan (DIS-19a) referred to above in connection with Fig. 6b was not analysed chemically. However, the exceptionally high electrical conductivity (Table I) indicates that local pollution must have affected an area probably already suffering from infiltration by river water.

Table III: Major ion data for the sampled sites. All data from ref [2]

Sample No.	**Site name**	**Na**	**K**	**Ca**	**Mg**	**HCO_3**	**Cl**	**SO_4**	**NO_3**
					mg l^{-1}				
Shallow tubewells									
DIS-5	Embankment slum	48.5	5.9	137.3	37.4	228	255.9	5.9	0.7
DIS-15	Argargaon slum	42.5	15.8	30.5	3.4	98	76.9	14.2	19.8
Deep tubewells									
DIS-1	Jatrabari Chowrasta	23.3	1.5	17.9	6.6	146	5.0	1.6	0.4
DIS-2	JN University College	42.1	5.5	55.0	14.6	226	41.7	17.7	12.7
DIS-3	Hazaribagh Pump 4	39.8	2.5	48.3	18.6	232	55.3	17.7	1.1
DIS-4	Hazaribagh Pump 5	31.3	3.0	45.4	15.8	179	56.5	13.8	2.7
DIS-7	Uttara 1 (Sector 3)	23.3	1.4	19.3	6.8	136	5.1	0.0	0.0
DIS-8	Kilkhet Bazar	19.1	1.6	12.4	4.4	105	2.8	0.1	0.2
DIS-9	Banani No.3	14.1	2.4	16.2	4.9	92	10.1	0.7	13.3
DIS-10	Mirpur Sector 10	17.1	1.8	21.5	8.4	77	30.0	12.4	13.5
DIS-11	Pangu Hospital	17.9	2.1	17.3	6.5	112	12.6	3.1	0.2
DIS-12	Dhanmondi No.8	32.4	2.1	42.9	16.3	155	65.9	12.3	6.9
DIS-13	Tejgaon No.8	25.9	2.9	28.5	9.2	95	37.5	14.0	18.9
DIS-14	Shahjadpur (Badda)	20.1	1.9	18.0	5.4	122	8.1	0.7	0.0
DIS-17	Chadnighat Water Works	80.6	7.0	66.7	21.9	285	109.1	11.0	2.6

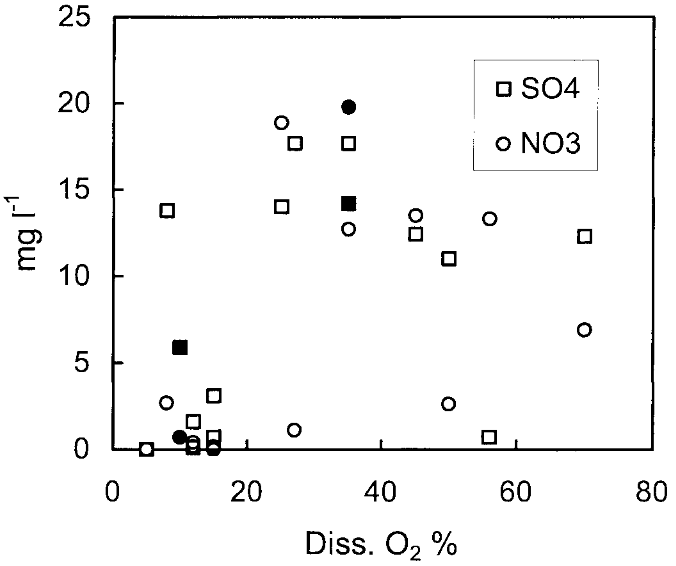

Figure 8. Plot of dissolved oxygen percentage versus sulphate and nitrate concentrations. Black symbols represent samples from the shallow tubewells.

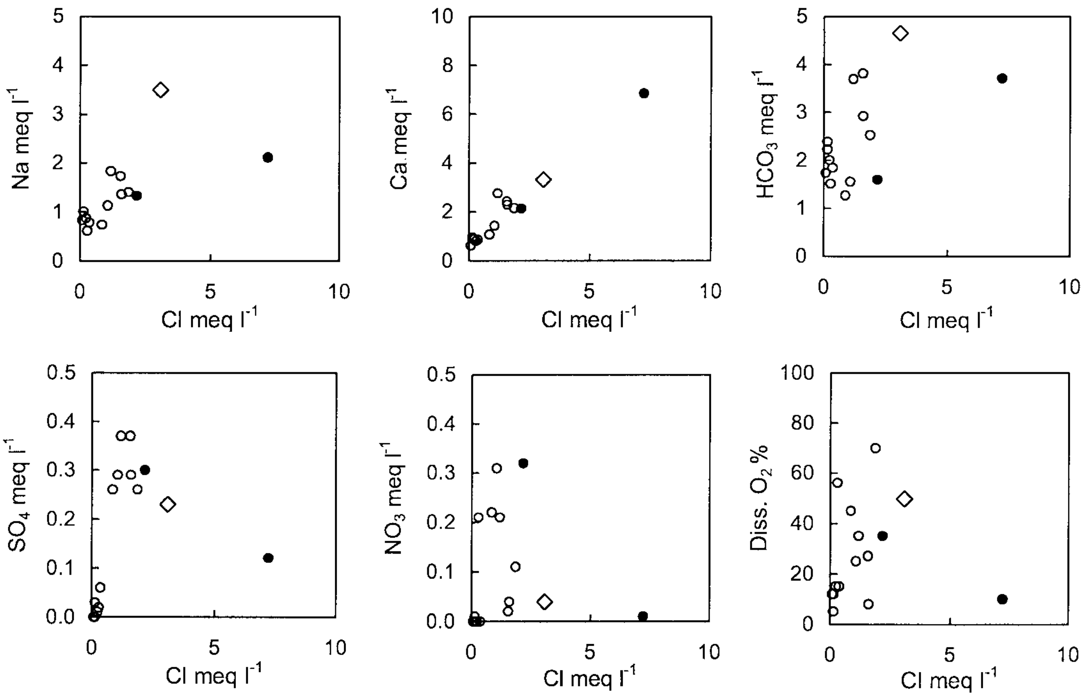

Figure 9. Plots of major chemical species versus chloride for the tubewell samples. Symbols as in Fig. 2, plus diamond showing the composition of the Water Works tubewell, assumed to represent the river water end member.

3. DISCUSSION

On the basis both of the hydrochemical measurements reported here and also hydraulic considerations [1,2] it appears that waters from deep tubewells in the Dupi Tila aquifer close to the centre of the Dhaka metropolitan area may well be the 'baseline' composition with regard to their O and H stable isotopic values. This indicates that contrary to the evidence from the wider region cited earlier, recharge via the Madhupur Clay in this area should be assigned rather more depleted values of approximately -4.5 ‰ $\delta^{18}O$ and -30 ‰ $\delta^{2}H$. However it may be that the Dupi Tila in the Dhaka area, surrounded as it is by rivers which periodically suffer major flood events, has always had a component of river recharge. This would explain why the baseline water appears more isotopically depleted than might be expected.

In view of the large cone of depression in the water table beneath the southern part of Dhaka the occurrence of increasing amounts of river infiltration is predictable, and has been confirmed to a large extent by the distribution of simple measurements such as electrical conductivity and modelling [1,2]. Nevertheless, the isotopic approach is still useful because unlike electrical conductivity or chloride, O and H isotopes are totally conservative within the aquifer. With increasing amounts of local pollution, these isotopes may be the only way in which the extent of river water infiltration in some areas can be monitored and assessed.

The carbon isotope values fit in with the general theme of a mixing relationship with river water; there is no indication (for example) of the decay of organic matter boosting carbon dioxide and bicarbonate concentrations. This confirms that the aquifer material is not high in reactive detrital organic carbon, in contrast to some other aquifers in Bangladesh.

The isotopic investigations have found little evidence of depth-related layering in the Dupi Tila, despite its multi-layer nature, perhaps because of vertical mixing induced by the typically high rates of pumping from tubewells. However this does not preclude the existence of age-related stratification in the undisturbed aquifer.

Particle transport modelling using relatively coarse layering was carried out by Hasan [2] for four regions of the city to give estimates of transport time to (i) the base of the upper aquifer and (ii) the public supply boreholes completed in the Dupi Tila. For the central area of Dhaka, estimates of 35 yrs to the base of the upper aquifer and 45–50 years to the public supply boreholes were obtained. Close to the River Buriganga the estimates were 10 years and 15–20 years respectively for these categories. The two sites dated by the ^{3}H-^{3}He method referred to in 2.3 above are located in between these regions, and therefore the model ages of approximately 17 years are reasonably consistent with the modelling.

4. CONCLUSIONS AND RECOMMENDATIONS

The Dupi Tila aquifer beneath Dhaka is subjected to enormous demands in order to supply potable water to the city's inhabitants. In order to protect this important resource it is essential to have the best possible information on the hydrogeology and hydraulics of the aquifer, so that the optimal management strategy can be followed.

The use of O and H stable techniques confirms beyond reasonable doubt that the large scale leakage of river water into the Dupi Tila is taking place due to intensive exploitation of the aquifer. Although most of this leakage is adjacent to the Buriganga River, it may also be occurring elsewhere on the Dhaka 'island'. Comparison with isotopic data from the wider region suggests that the whole of the aquifer beneath Dhaka may contain an element of river water, but if this is the case the carbon isotopic and hydrochemical data indicate that some infiltration must have occurred prior to modern (i.e. polluted) times.

While river infiltration can be monitored quite effectively simply by measuring electrical conductivity or chloride, there are instances where local pollution has raised the levels of these parameters sufficiently to mask the true hydrology of the situation. The use of stable isotopes is therefore important for future investigations, particularly in those industrial areas which are likely to be suffering the infiltration of river water.

The monitoring of rates of penetration by poorer quality waters can be followed using hydrochemical and stable isotopic tracers, but these can provide little in the way of 'real' age information. However, the initial results of water dating are promising, and it is therefore recommended that age indicators such as tritium (with or without helium-3), sulphur hexafluoride and CFCs (where viable) should be used routinely as part of future investigations. Not only would these provide firmer information on lateral rates of movement, but might help to reveal to what extent the multi-layer nature of the aquifer has resulted in age stratification.

ACKNOWLEDGEMENTS

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Assessment of aquifer system in the city of Lahore, Pakistan using isotopic techniques

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Abstract

Isotopic and geochemical techniques were applied to assess the groundwater replenishment mechanism, pollution levels and pollution sources in the city of Lahore, the second largest city of Pakistan where water supply has been based on the abstraction of groundwater. Isotopic and chemical data indicates that groundwater has major contribution from the river water up to the center of the city while at remaining locations it seems base-flow recharged by rains of distant area or mixed recharge from river and rains. In case of shallow groundwater, different local sources like irrigation canals, sewerage drains, local rain and maybe the leaking main supply lines also contribute. High tritium values of deep groundwater fed by river show its quick movement up to 8-10 Km. Deep groundwater in the adjacent area towards the center of the city, although fed by the river shows residence time of about 45 years. Recharge to shallow aquifer is generally quick as most of the sampling locations have high tritium values. Chemical data shows that groundwater is mainly of sodium bicarbonate and calcium bicarbonate type. The infiltrating river water is of calcium bicarbonate type which changes to sodium bicarbonate type at few kilometers away from the river due to cation exchange and calcite precipitation processes. Water quality was assessed for drinking purpose and it was noted that concentrations of several parameters exceed the norms of good quality drinking water in case of shallow groundwater. This study clearly indicated an increasing trend of groundwater nitrate concentrations. $\delta^{15}N$ values of high nitrate waters reveal the localized pollution from sewerage drains. Bacterial contamination of groundwater especially at locations near the drains also proves the penetration of urban recharge from sewerage drains.

1. INTRODUCTION

Good quality potable water is a fundamental requirement for human health and survival. Fast growth of population, poor town planning and industrialization are causing problems in supplying public services, water being one of the most affected. It is becoming difficult for local authorities dealing with water supply to cope with the increasing demands. Lahore is the second largest city of Pakistan covering an area of about 1000 square kilometers [1]. Its population is increasing at a rapid rate of 3.7 percent per year. In 1901 the population of Lahore was 0.203 million which by 1990 increased to about 4.232 in the Municipal Area (excluding some localities like GOR, Railways, Model Town, colonies in the suburbs etc). At present its population is more than 5.1 million [2]. Water supply of Lahore City has been based on the abstraction of groundwater. Fast growth of population, progressive migration of people to the area and establishment of numerous industries has resulted in rapid increase in water demand. The number of wells and hence, the groundwater abstraction has been increasing in accordance with the growth of population and socio-economic uplift of urban dwellers. On the other hand, urbanization and industrialization has reduced the recharge, as significant proportion of the land has become impermeable. With the increasing number of tubewells, the groundwater, which used to exist at about 4.5 m started declining rapidly. A decline of 15.5 meters in water table during 1960 to 1991 was noticed in Lahore City [3]. At present, the water table in the central area of the city has deepened to 28 m from the surface level [4]. Due to the continued decline in water table, the groundwater is going out of easy reach for exploitation and the cost of pumping is continuously rising.

Quality of surface water and groundwater is under threat due to contamination by pollutants from sewerage systems, municipal solid wastes, unplanned disposal of untreated industrial effluents and agricultural activities. Untreated industrial and domestic effluents are disposed off into watercourses flowing through or in the vicinity of large population centers. The habitants living along the drains get their drinking water supply from shallow pumps installed near the drains. The aquifer surrounding a drain may be recharged and influenced by the sewage drain effluent having all types of pollutants in it. Nitrate is a major groundwater pollutant, which leaches down to aquifer since it is not absorbed by soil matrix due to negative charge. Industries produce huge amounts of wastes containing variety of chemicals and heavy metals. These huge quantities of untreated wastes are thrown into sewerage system, open drains, open fields and water ponds, which may lead to surface as well as groundwater pollution. All these activities are a potential threat for groundwater resources. The existence of saline groundwater [5] in the nearby areas of Raiwind and Kasur in the south of Lahore is a potential threat to the aquifer under the city. There is a danger of deterioration of the aquifer water quality if the saline water finds a path to reach the city area. The flushing out of this saline water, if once entered, would then be nearly impossible. It is therefore, imperative to assess the groundwater replenishment mechanism, pollution levels and pollution sources for sustainable development/exploitation and conservation of these resources not only for present use but also for future uses.

2. HYDROGEOLOGY

Lahore area is underlain by unconsolidated alluvial deposits of quaternary age. The aquifer is composed of unconsolidated alluvial complex formed by the contemporaneous filling of a subsiding trough - a foredeep adjacent to the rising Himalayan ranges. Contemporaneous filling and subsidence have given rise to an extensive sedimentary complex of more than 400 meters thickness. The sediments have been deposited by the present and ancestral tributaries of the Indus River during Pleistocene-Recent periods. In accordance with its mode of deposition by large streams in constantly shifting channels, the alluvial complex is heterogeneous and individual strata have little lateral or vertical continuity. However, in spite of their heterogeneity, the alluvial sediments constitute a large aquifer, which on regional basis behaves as a homogeneous aquifer [6]. The individual lenses of silt and clay do not impede the flow of groundwater, considering long-term pumping.

In the project area, the alluvial complex consists, principally, of grey to greyish brown, fine to medium sand, silt and clay. The chief constituent minerals are quartz, muscovite, biotite and chlorite, in association with a small percentage of heavy minerals. Quartz, being resistant to the abrasive action of water, is the major constituent of sand and determines its coarseness and assortment. Sieve analysis data of a large number of drill cuttings from various parts of the area have shown that the sands, commonly, are fairly to well assorted. The sand grains generally are sub-angular to sub-rounded. Beds of gravel and very coarse sand are uncommon within the Project area. Pebbles of siltstone or mudstone are embedded in silty or clayey sand at many places. Concretions of secondary origin locally known as 'kankar' may be found in association with fine sediments. Clay and silt formations occur as discontinuous layers with limited lateral extent and thickness generally less than 5 meters, however, their thickness may vary between 1 to 20 meters [1].

In spite of heterogenic nature of alluvial complex, groundwater occurs under water table conditions. The aquifer is highly transmissive with co-efficient of permeability ranging from 37.2 to 73.4 m/d (760 to 1,500 Imp.Gpd/ft^2). On the basis of aquifer tests performed in the vicinity of project area, the value of specific yield has been estimated as ranging from 0.1 to 0.25. However, values determined through Nuclear Moisture Probe in various parts of Punjab plain show higher values applicable for long-term pumpage [1].

3. WATER SUPPLY SYSTEM

The source of water supply for Lahore is only groundwater. Groundwater is abstracted through 300 large capacity tubewells installed at various locations in the Lahore Municipal Area. There are four main well centers, three near the Bund Road (Old Ravi Well Center, National Ravi

Park Well Center, Bhogiwal Well Center), and the fourth located at Bund Road to the North of Shalimar Garden. The remaining wells are located throughout the city area, and all wells pump directly to the system, thus eliminating the need for a reservoir. Some more tubewells are being installed to meet maximum day demand. In addition, numerous private owned shallow pumps also exist.

The water obtained from deep boreholes is fortunately of good quality. It does not require primary treatment. However, often secondary treatment i.e. chlorination is provided especially in the rainy season. The water produced through these tubewells is fed into Main Grid with pipes having diameters from 40 to 80 cm. The Main Grid feeds water to distribution system with pipes which have diameters ranging from 7.5 to 30 cm. The distribution system supplies the water to citizens through house connections. Presently no elevated reservoir is in use except the one million-gallon overhead reservoir at Langey Mandi. The reservoirs are used in new developing schemes where water demand is less and reservoir is filled once to meet the day demand [7].

4. CLIMATE

Climate of area is characterized by seasonal changes in temperature and precipitation. The precipitation has a marked seasonal fluctuation. About 70 percent of the average annual rainfall occur in the period from June to September (monsoon). Average annual rainfall for the last 50 years is 615 mm with a long-term average of 575 mm. During summer (June to August), the day temperature is generally more than 40°C, while the maximum temperature during winter (December to February) is generally between 15 and 25°C. The hottest day may reach 50°C while the minimum summer recording may be as low as 21°C. January is the coldest month, when mean minimum temperature is 5°C [1].

5. SAMPLE COLLECTION AND ANALYSES

The study area comprises the city of Lahore and the adjoining areas. Locations of the sampling points are shown in Fig. 1. For sample collection, existing municipal tubewells (deep wells having screen normally from 80 m to 200 m), private shallow pumps up to 50 m depth, the river Ravi, irrigation canals in the city originating from the river Chenab and sewerage drains were selected. In the first sampling carried out in February 1998, 44 samples were collected in which most of the samples were from tubewells. The samples were analyzed for ^{2}H, ^{3}H, ^{18}O, ^{13}C and major chemical ions. Keeping in view the results of first sampling, more sampling points were added for the second sampling which was carried out in July 1998. In this sampling many shallow wells were included and samples were also collected for ^{15}N analysis. Third, fourth, fifth and sixth samplings were carried out in October 1998, February 1999, May 1999 and December 1999/January 2000 by adding new sampling stations and quitting unnecessary ones. Physico-chemical parameters like electrical conductivity (EC), pH and temperature were measured in the field.

The samples were analyzed for ^{2}H, ^{3}H, ^{18}O, ^{13}C, ^{15}N and major chemical ions. Stable isotopes ^{2}H and ^{18}O were measured relative to VSMOW. The $\delta^{18}O$ of water was measured by the CO_2 equilibration method [8]. Water samples were reduced to hydrogen gas by zinc shots for $\delta^{2}H$ measurement [9]. $\delta^{13}C$ was analyzed against PDB by reacting water samples directly with phosphoric acid to convert inorganic carbon into CO_2 and subsequent measurement on mass spectrometer [10]. Tritium concentrations were measured with the help of liquid scintillation spectrometers (Packard) after electrolytic enrichment. For analysis of ^{14}C, inorganic carbon was precipitated as $BaCO_3$ in the field [11] and direct CO_2 absorption method in conjunction with liquid scintillation counting was used [12]. Chemical analyses were performed using standard analytical methods like atomic absorption spectrophotometry, UV-Visible spectrophotometry, Ion selective electrodes etc. [13].

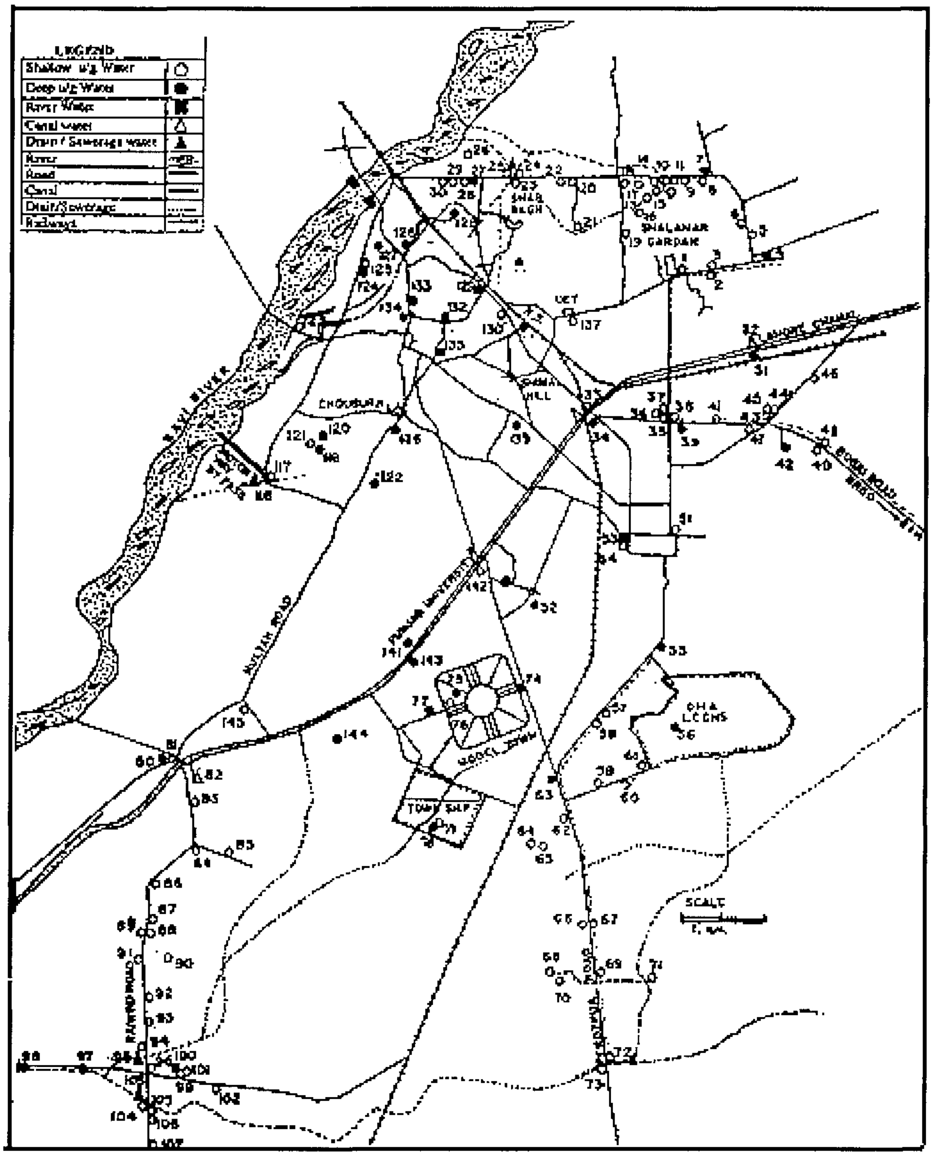

Fig.1. Map showing the study area & sampling locations

6. RESULTS AND DISCUSSION

6.1. Depth to water table

Depth to water table gives basic information required for groundwater studies. During the past 25 years, various studies were carried out to determine the ultimate potential of groundwater and possible decline of water table in response to groundwater withdrawal. In order to update the information on depth to water table, Water and Sanitation Agency (WASA) conducts surveys at selected and representative locations on monthly basis. The water table contour map has been prepared for the year 1998, which is shown in Fig. 2. The map indicates that an irregular shaped depression in water table is being created. The maximum depression is noted in the center of the city at Mozang site. At this locality, the water table was 189 m above mean sea level (a.m.s.l.) in 1989, which was lowered to 185 m a.m.s.l. in 1998. It shows that 4 m decline in water table has occurred within 9 years. The depth to water table maps prepared by National Engineering Services of Pakistan (NESPAK) for various periods indicate that excessive groundwater abstractions have formed a cup-shaped depression in the central part of the city which is gradually expanding towards south [1].

The larger numbers of high capacity wells were introduced after 1973, accelerating the rate of lowering of water table. The average static water level calculated on sub-divisional basis has lowered up to 5.63 meters during the period from 1991 to 1999 [4]. The average decline of water table calculated from the data of all the wells in various subdivisions of Lahore for this period is given in Table 1. The aquifer dynamics is expected to change more rapidly as 42 new tubewells were installed in 1998-99.

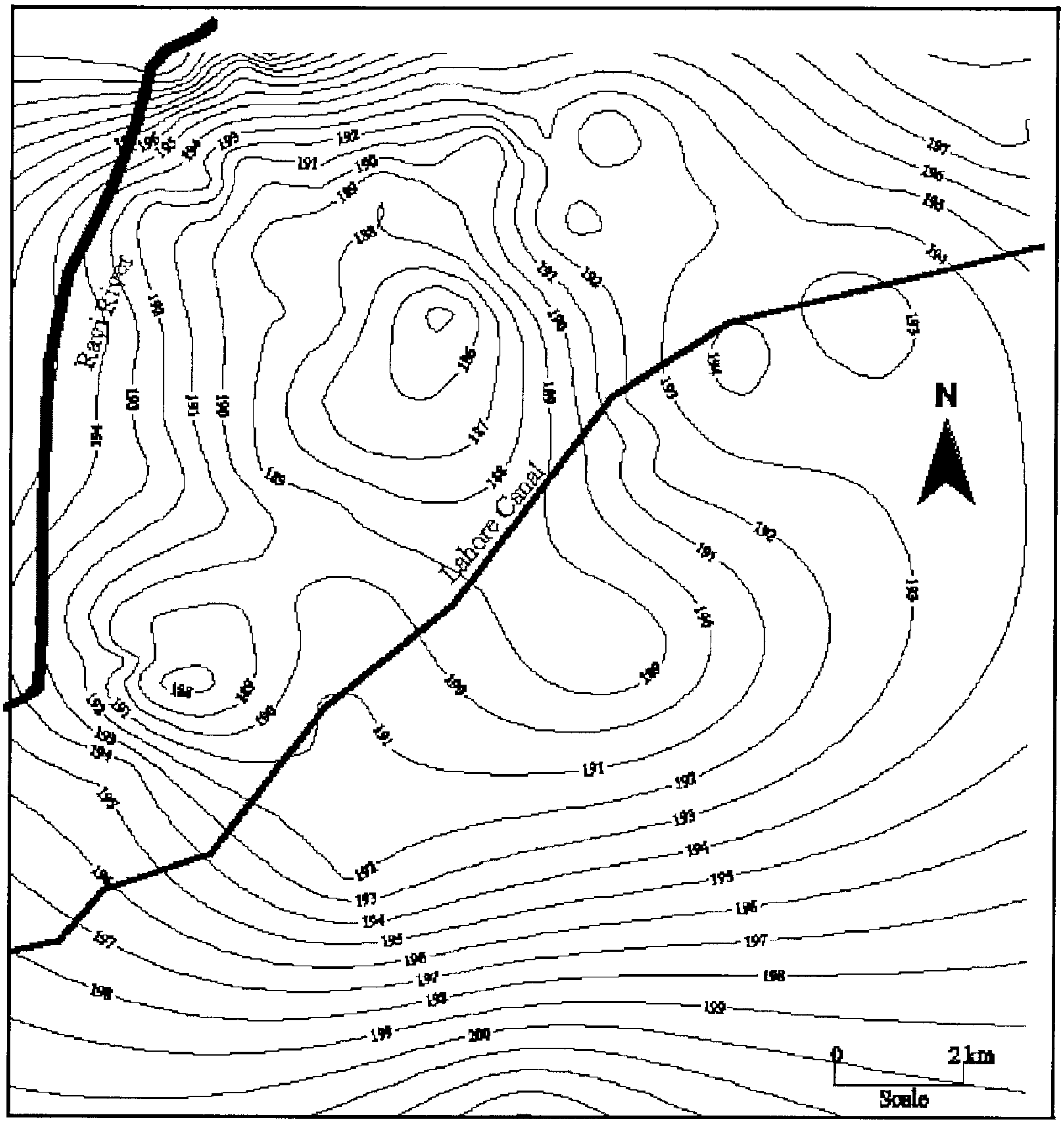

Fig.2. Contours (m) of water level observations in November 1998

TABLE 1. AVERAGE LOWERING OF WATER TABLE IN VARIOUS SUBDIVISIONS OF LAHORE

Sub Division	Reduction in W.T. from 1991 to 1999 (m)	Sub Division	Reduction in W.T. from 1991 to 1999 (m)
Isalmpura	2.43 m	Mughalpura	4.87 m
Samanabad	3.84 m	Mustafabad	3.49 m
Ichra	3.60 m	Allama Iqbal Town	4.21 m
Gulberg	4.98 m	Garden town	1.21 m
Misri Shah	1.40 m	Data Naggar	0.74 m
Baghbanpura	5.63 m	Mozang	3.47 m
City	3.77 m	Shahdara	0.32 m
Ravi road	4.89 m	Anarkali	2.50 m
Shimla Hill	3.82 m	M.E.S. Tubewell	2.98 m

6.2. Hydrochemical evolution

EC of tubewells varies between 294 to 1694 µS/cm while that of shallow wells lies between 279 to 4270 µS/cm. The range of EC for shallow wells is about 2.5 times higher as compared to that of tube wells. Fig. 3 and Fig. 4 show the distributions of EC in shallow and deep wells. EC of shallow wells shows approximately normal distribution while that of deep wells exhibits gamma distribution. It means that chemical quality of shallow and deep groundwater is originating from different sources and by different processes. During the field sampling, it has been observed a number of times that values of a tubewell and a hand pump only 50 meters apart show big difference in the EC values, the hand pump having higher EC.

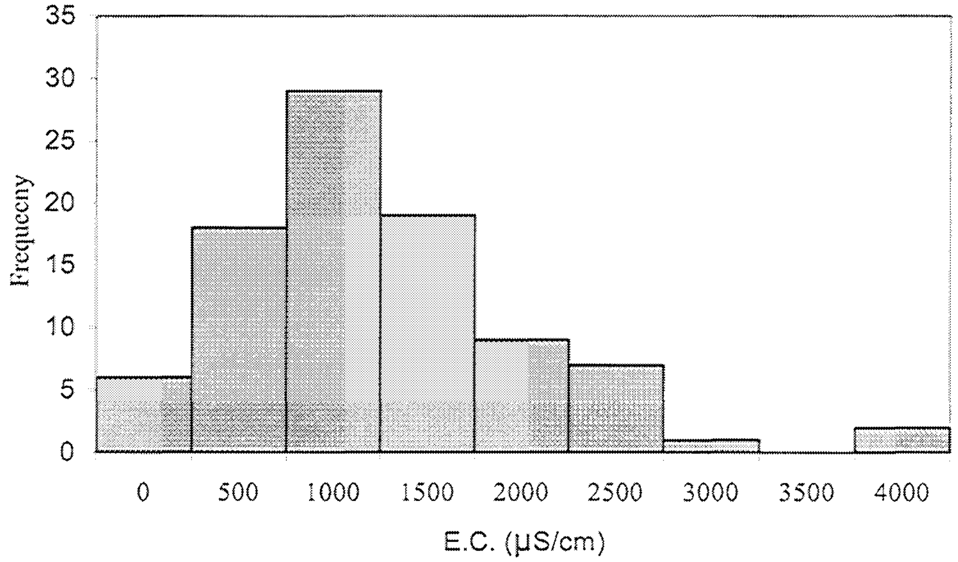

Fig. 3. Frequency histogram of shallow groundwater.

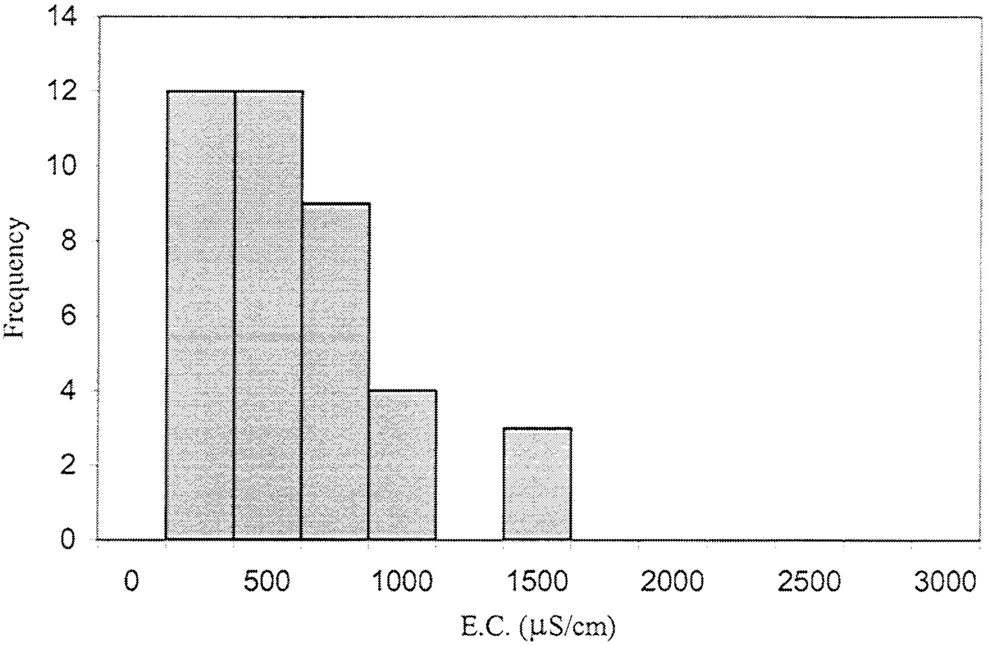

Fig. 4. Frequency histogram of deep groundwater.

The spatial variation of EC in deep groundwater (tubewells) shows approximately a consistent behavior. The EC values of tubewells lying on the riverside are low. The tubewells 129, 132, 135, 136, 122 located in the central part of the city have comparatively higher values. The tubewells (Nos. 31, 139, 52, 77, 144) surrounding the Lahore Canal show slightly higher EC as compared to the tubewells lying towards the River Ravi. The tubewells of the cantonment area also show higher EC values. On the other hand, shallow wells have no spatial trends and are found together in low and high EC values in the whole study area except a few wells located near the River Ravi. Therefore one can get general view that the deep groundwater is getting more mineralized starting from river towards the center of the city and cantonment area. From the EC results, one can also say that there is no efficient interaction between shallow and deep aquifer in the area.

In order to differentiate the chemical type of groundwater, Piper and Durov Trilinear diagrams are known to be used. In the present study, a new diagram called Multi-Rectangular Diagram (MRD) depending upon its geometry [14] has been used. In this scheme, the milli-equivalent per liter (meq/l) percentages of all the cations and anions are calculated separately from each chemical analysis. Then from each chemical analysis, the cation and anion with highest percentage is selected and is plotted on the respective rectangle of the MRD. The measured carbonate and potassium contents in the water samples are not significant, therefore, carbonate has been lumped with bicarbonate and K has been lumped with Na. The identified categories of groundwater with the help of MRD (Fig. 5) are mainly sodium bicarbonate and calcium bicarbonate. Some samples are recognized as other types of groundwater such as magnesium bicarbonate and sodium chloride. Only one sample is of calcium chloride type.

Calcium bicarbonate type of waters are found in the north west of the study area adjacent to river Ravi. In the south east of the study area, sodium bicarbonate water is dominant in both shallow and deep groundwater. Again along the Raiwind Road, groundwater is of sodium bicarbonate type. Groundwater near the river is of calcium bicarbonate type indicating the dominance of river recharge at these locations. Lahore canal does not seem to be recharging the underlying aquifer efficiently as the groundwater near the canal is of sodium bicarbonate type while the canal water is of calcium bicarbonate type.

The water of canals and the river Ravi flowing in the area are of calcium bicarbonate type. One of the processes through which sodium in the groundwater system increases is the exchange process with calcium. Among analyzed cations from the groundwater in the area, an interesting behavior is observed between Ca and Na (meq/l %). Fig. 6 for shallow and Fig. 7 for deep groundwater show a strong inverse correlation between the percentages of Ca and Na. It is general observation that where the fresh surface waters are of calcium bicarbonate type, after getting recharged to the subsurface, these are evolved to sodium bicarbonate type of waters during their movement away from the recharge areas.

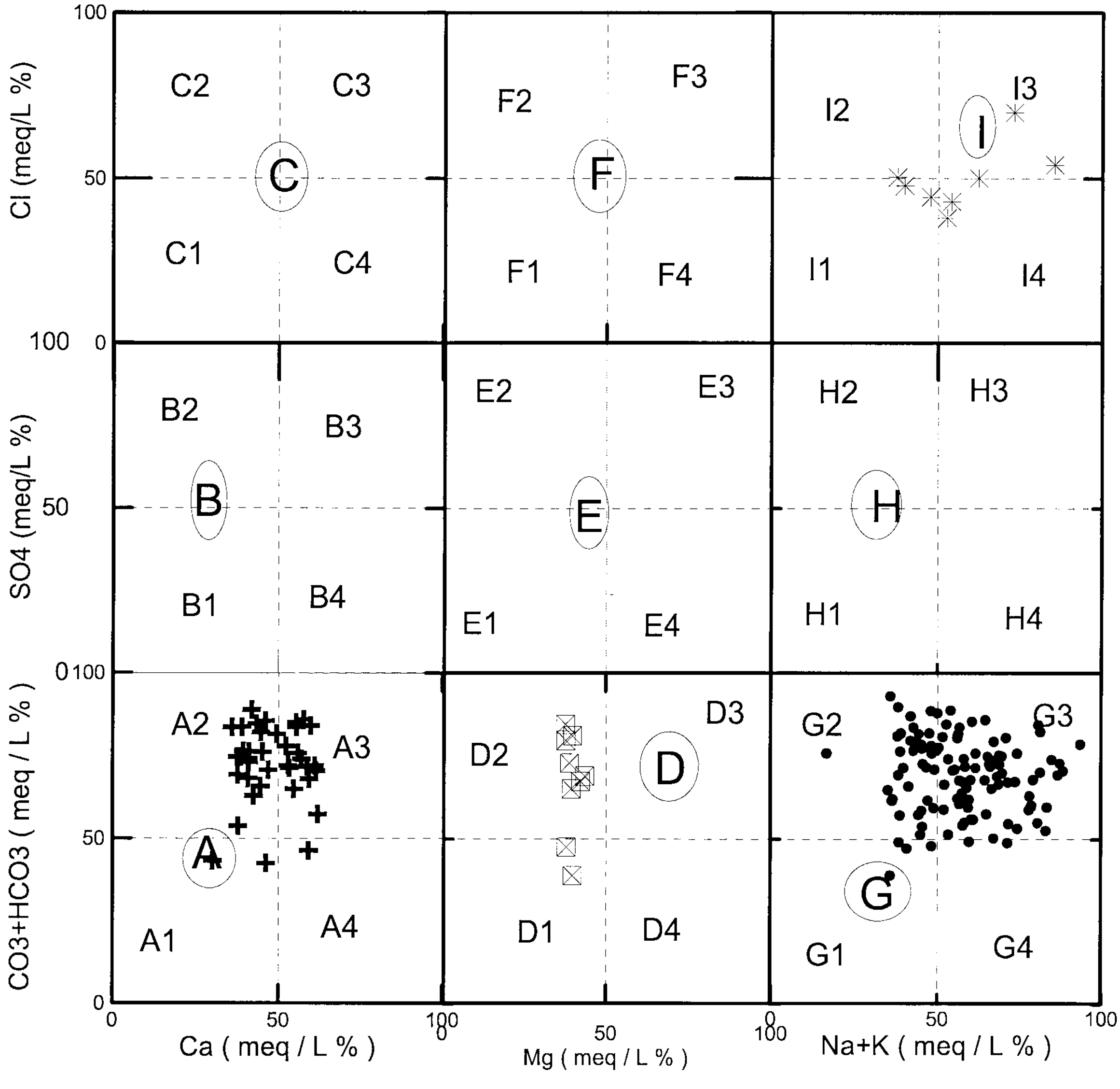

Fig. 5. Classification of chemical analyses by Multi-Rectangular Diagram.

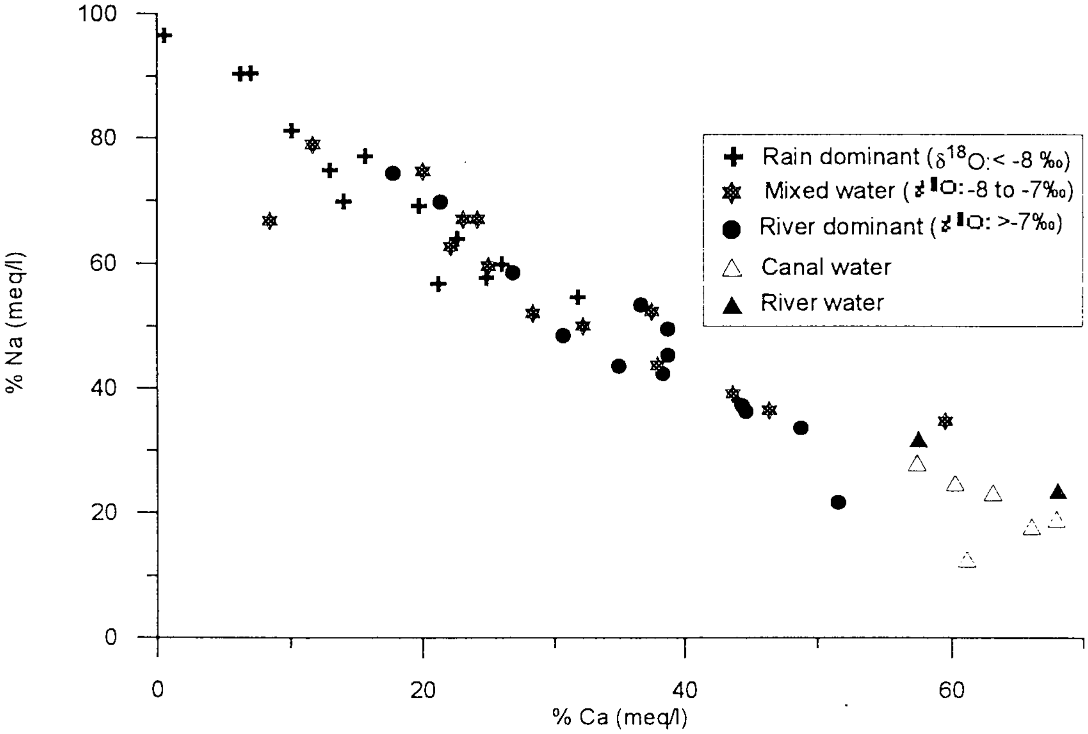

Fig. 6. Relationship between Ca & Na (%meq/l) of deep groundwater

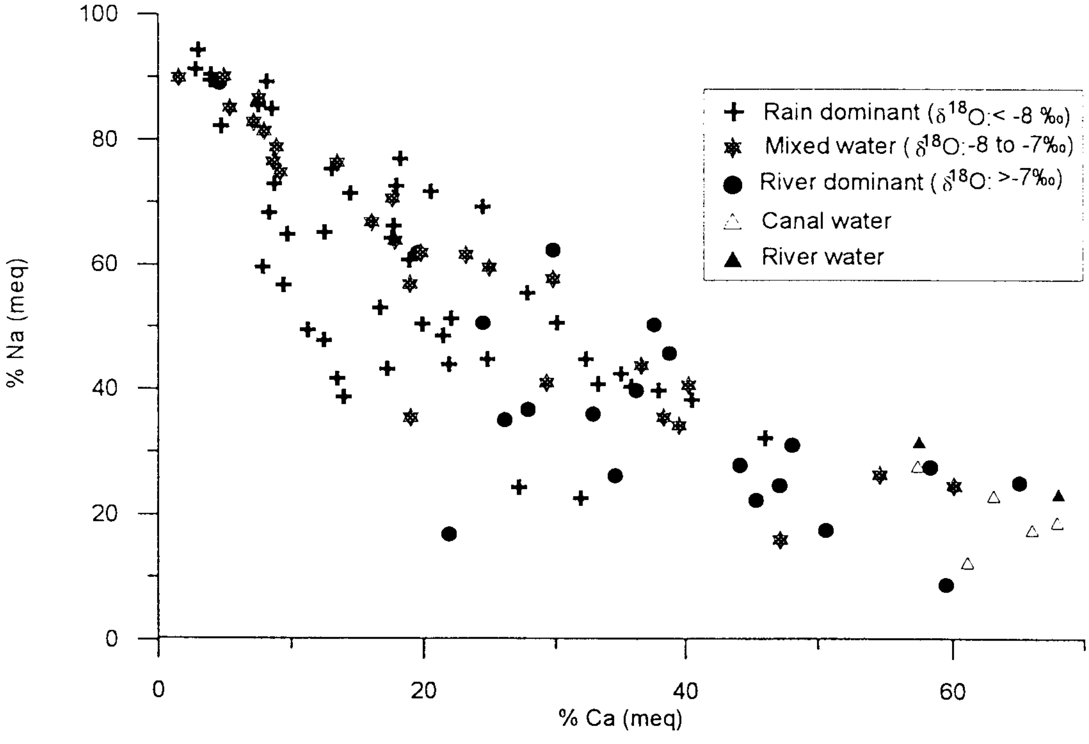

Fig. 7. Relationship between Ca & Na (%meq/l) of shallow groundwater

6.3. Assessment of groundwater quality

Groundwater is the most important source of drinking water supply in Lahore. Its chemical quality is therefore an important factor to be considered as the quality of drinking water significantly affects the human health. High concentrations of several constituents have significant health hazards. Quality of groundwater was evaluated by comparing with WHO drinking water standards [15].

Results of chemical analyses of shallow groundwater samples collected from different locations indicate that EC of shallow groundwater varies from 279 to 4270 µS/cm. Parameters like Na, Mg, K and Ca exhibit ranges of 12 - 944, 3 - 137, 1 - 60 and 3 - 190 mg/l respectively. Carbonate and bicarbonate concentrations vary from 0 to 78 and 134 to 958 mg/l respectively. Chloride and sulfate values in the shallow aquifer lie in the ranges of 9 to 617 mg/l and 11 to 841 mg/l respectively. Selected samples were analyzed for NO_3 and the values of this important parameter were found from 10 to 188 mg/l. In case of deep groundwater, variation of EC is less as compared to that of shallow. EC values of deep groundwater samples encountered at different locations in the study area range from 284 to 1694 µS/cm. Concentrations of Na, Mg, K and Ca vary over the ranges of 5 to 304, 1 to 50, 0.8 to 18.3 and 2 to132 mg/l. Chloride values are in the range of 10 - 165 mg/l while sulfate values vary from 10 to 228 mg/l. Carbonate and bicarbonate show values from 0 to 30 and 127 to 414 mg/l respectively.

Comparison of chemical constituents of groundwater in the study area with WHO Standards shows that concentrations of several parameters are significantly higher than the permissible levels at many locations especially in case of shallow groundwater. Sodium concentration of shallow water at 36 surveyed locations (40 %) is higher than the WHO limit of 200 mg/l. K values of about 25 % and Ca values of 18 % shallow samples are more than permissible limits. Magnesium content of very few samples (only 11 %) exceeds the norms of good quality drinking water. In case of sulfate, shallow water at 31 locations (about 35 %) has concentrations more than the permissible level. Violations of permissible level of chloride are negligible (about 5 % only). Few samples also have very high bicarbonate concentration. NO_3 concentrations of 60 shallow water samples were determined. Out of these, 20 % samples (n = 12) were found to have nitrate more than the WHO limit of 45 mg/l. Fe concentrations of shallow water samples (n = 40) range from 0 to 18.9 mg/l. The WHO limit for this parameter is 0.3 mg/l. Comparison of the observed values with the WHO limit indicates that Fe concentration of 21 samples is above the limit.

Deep groundwater has generally low dissolved chemical load indicating good quality. Only at few locations, concentrations of some parameters are above the permissible levels. Na, which was found to be common contaminant in shallow water, crossed the limit only in 2 samples. Similar is the situation with respect to Mg, K, Ca and SO_4 where observed violations are negligible. Deep groundwater meets the WHO standards for NO_3 and Cl at all the surveyed locations.

Initially, some poorly drained and very heavily populated localities in the city were selected for determination of biological quality of sub-surface water. During this campaign, 17 shallow and 17 deep groundwater samples were analyzed for Total Coliform bacteria. Out of these 34 samples, 91 % samples (n = 31) were found contaminated with Total Coliform bacteria. Is noteworthy that all the shallow groundwater samples appeared contaminated without any exception. Out of these 31 samples tested positive, 36 % samples (n = 11, shallow = 6, deep = 5) had bacterial activity more than the maximum limit. In case of Fecal Coliform, 82 % samples (n = 28) were tested positive. Out of these, 44 % (n = 15) were shallow and 38 % (n = 13) were deep water samples.

6.4. Groundwater pollution

In a previous study conducted by NESPAK [1], chemical quality (EC and TDS) of 88 groundwater samples collected from shallow zone in various parts of the city was monitored. According to the results, TDS of 14 samples (16 %) were less than 500 ppm, 56 samples (63 %) were in the range of 501 to 1000 ppm, 15 samples (17 %) were in the range of 1001 - 1500 ppm and only 3 samples (about 4 %) were more than 1500 ppm. In the present study significant increase in TDS of shallow water was noticed as compared to the above-mentioned study. Data collected during this study reveals that number of samples having low TDS i.e. less than 500 or 501 to 1000 ppm has decreased which are presently 12 % and 40 % respectively while the number of samples in higher ranges i.e. 1001 to 1500 and more than 1500 ppm has increased. Percentage samples falling in these two ranges are now 37 % and 11 %.

Results of nitrate analysis of shallow and deep groundwater indicate that concentrations vary from 10 to 188 and 9 to 41 mg/l respectively. Frequency histogram of nitrate is shown in Fig. 8. The outstanding feature revealed by the data is the increasing trend of nitrate concentrations both in shallow as well as deep groundwater. Nitrates which were generally only a few ppm have increased at almost all the surveyed locations and have even crossed the WHO limit of 45 mg/l in case of shallow groundwater at several locations. Deep groundwater was found to contain less nitrate as compared to shallow ones. High nitrate waters exist as isolated pockets e.g. shallow groundwater sample number 71 has NO_3 as high as 188 mg/l (several times more than WHO limit) whereas other samples taken from the surrounding points do not show any sign of nitrate pollution. Similarly shallow water at station number 64 shows nitrate concentration of 176 mg/l whereas at all the nearby stations nitrate concentrations are low. Results of tritium analysis indicate that high nitrate waters have high tritium values. Presence of nitrate contamination at shallow depths, irregular distribution pattern and high tritium content of contaminated waters suggests that nitrate is derived from presently active surface source. In order to confirm the source of the observed nitrates in groundwater, samples having nitrate more than 45 mg/l were analyzed for $\delta^{15}N$ (NO_3).

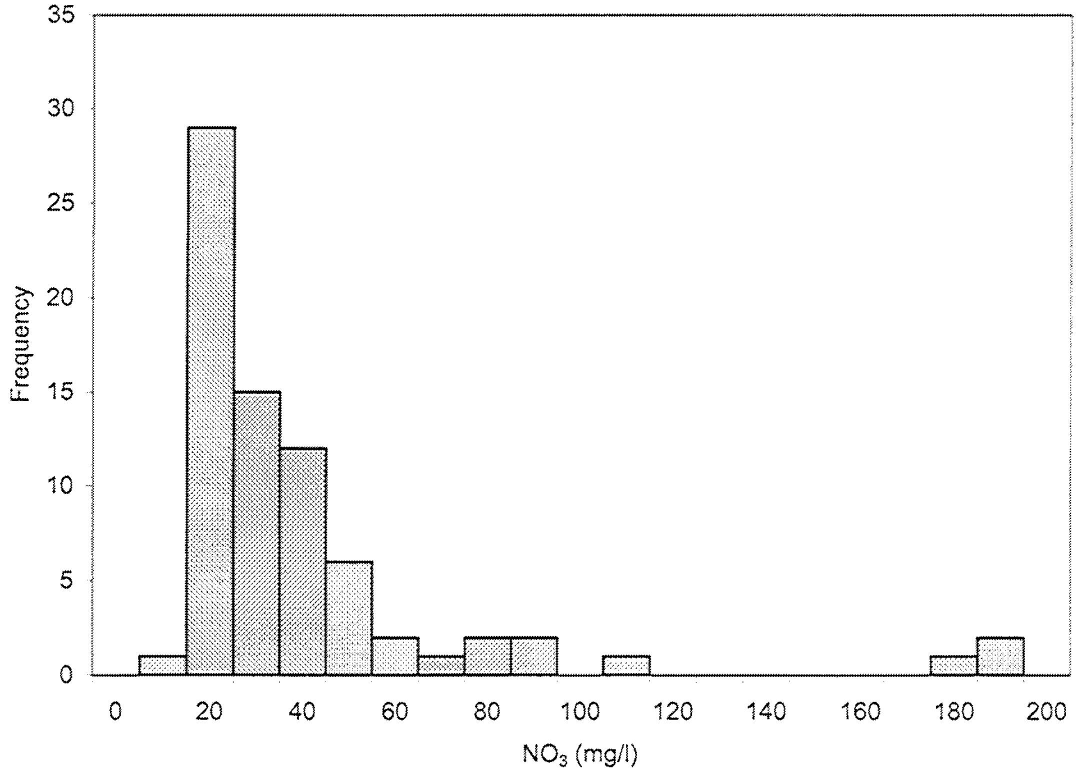

Fig. 8. Frequency Histogram of Groundwater Nitrate Concentrations

All these samples show enriched $\delta^{15}N$ values ranging from +10.3 to +25.1 ‰. $\delta^{15}N$ more enriched than +10 ‰ are consistent with human N-waste converted by nitrification via ammonia to nitrate and enriched by partial volatilization [16, 17]. So the high nitrate with enriched $\delta^{15}N$ represents the localized pollution from sewerage drains.

During the fifth sampling campaign, six points lying near the drain along Ferozepur Road were selected to evaluate the impact of sewerage drain on the groundwater. The samples collected from tube wells (2 Nos.) and handpumps (4 Nos.) located at different locations (Station Nos. 62, 63, 64, 69, 71 and 73) along the drain were collected and analyzed for fecal coliform and total coliform bacteria. Results of these analyses indicate that all these samples have very high bacterial activity (faecal coliform as well as total coliform).

These evidences are a clear indication of penetration of urban recharge into shallow and deep groundwater zones from the sewerage drains.

6.5. Recharge mechanism

The possible sources of recharge of the aquifer are the river Ravi, irrigation canals passing through the area which originate from the river Chenab, and rains. Isotopic data of rivers are already available [18] and their sampling is continued. $\delta^{18}O$ and $\delta^{2}H$ of River Ravi range from -11 to -6 ‰ and -86 to -40‰ with the mean values of -8.9‰ and -61‰ respectively. All the irrigation canals flowing through the study area originate from the River Chenab. Their $\delta^{18}O$ ranges from -13 to -7.9‰ with mean of -10.8‰ and $\delta^{2}H$ ranges from -86.3 to -56.2‰ with average value of -71.8 ‰. Sajjad et al. determined the $\delta^{18}O$ and $\delta^{2}H$ indices (mean values) of river Chenab as -10 and -61‰ with high variability [19]. $\delta^{18}O$ and $\delta^{2}H$ indices for rain of the nearby area i.e. -5.5‰ and -32‰ have been used [19].

6.5.1. Spatial variation of $\delta^{18}O$

As the water supply wells pump the deep groundwater from the depth of 80m to 200m and private hand pumps/shallow motor pumps tap upper groundwater up to 50m, so the data of deep and shallow aquifers are treated separately. Considering the spatial distribution of $\delta^{18}O$ in deep water (Fig. 9), the areas having $\delta^{18}O$ <-8.0‰ show significant contribution of the river. Such areas lie along the river and extend towards the Lahore Branch Canal. The area away from the river having $\delta^{18}O$ > -7 ‰ clearly shows base-flow mainly recharged by the rains. A narrow belt in the center having $\delta^{18}O$ from -8.0 to -7.0‰ indicates mixing of rain and river waters. The original $\delta^{18}O$ and $\delta^{2}H$ indices of the base-flow have been estimated using the sampling points (Nos. 40, 52, 55, 74 and 139) having tritium concentration zero TU. Mean $\delta^{18}O$ and $\delta^{2}H$ values of these stations come out to be -6.4‰ and -41.7‰. The local rain index of $\delta^{18}O$ for the study area is about -5.5 ‰, which is a bit more enriched than that of base-flow mainly recharged at relatively higher altitude. Sajjad et al. (1991) also found the similar values of base-flow in the North-East area of Lahore [19]. Spatial distribution of $\delta^{18}O$ in shallow aquifer (Fig. 10) shows similar trend as in the deep aquifer but the extent of river dominated and rain recharged areas towards the center of the city is relatively less. In this case, large area in the center have mixed type of water. Lateral penetration of the river water in the shallow zone is low. May be, due to high hydraulic gradient towards the center of the cone of depression in the central part of the city, the vertical component of river water flow is dominant. It justifies the less contribution of river water in shallow aquifer than that in deep aquifer in the central part. In the southern part, locations in the cluster having $\delta^{18}O$ from -8.0 to -7.0‰ and enriched than -7.0‰ represent groundwater mainly recharged by rains with varying contribution of local sources like irrigation channels and drains etc. There are few locations in the eastern part which are also away from Lahore canal and have $\delta^{18}O$ values from -8 to -9‰ showing high contribution of canal water. These points being near BRBD Canal, which is flowing away from the study area, show its large contribution in the recharge.

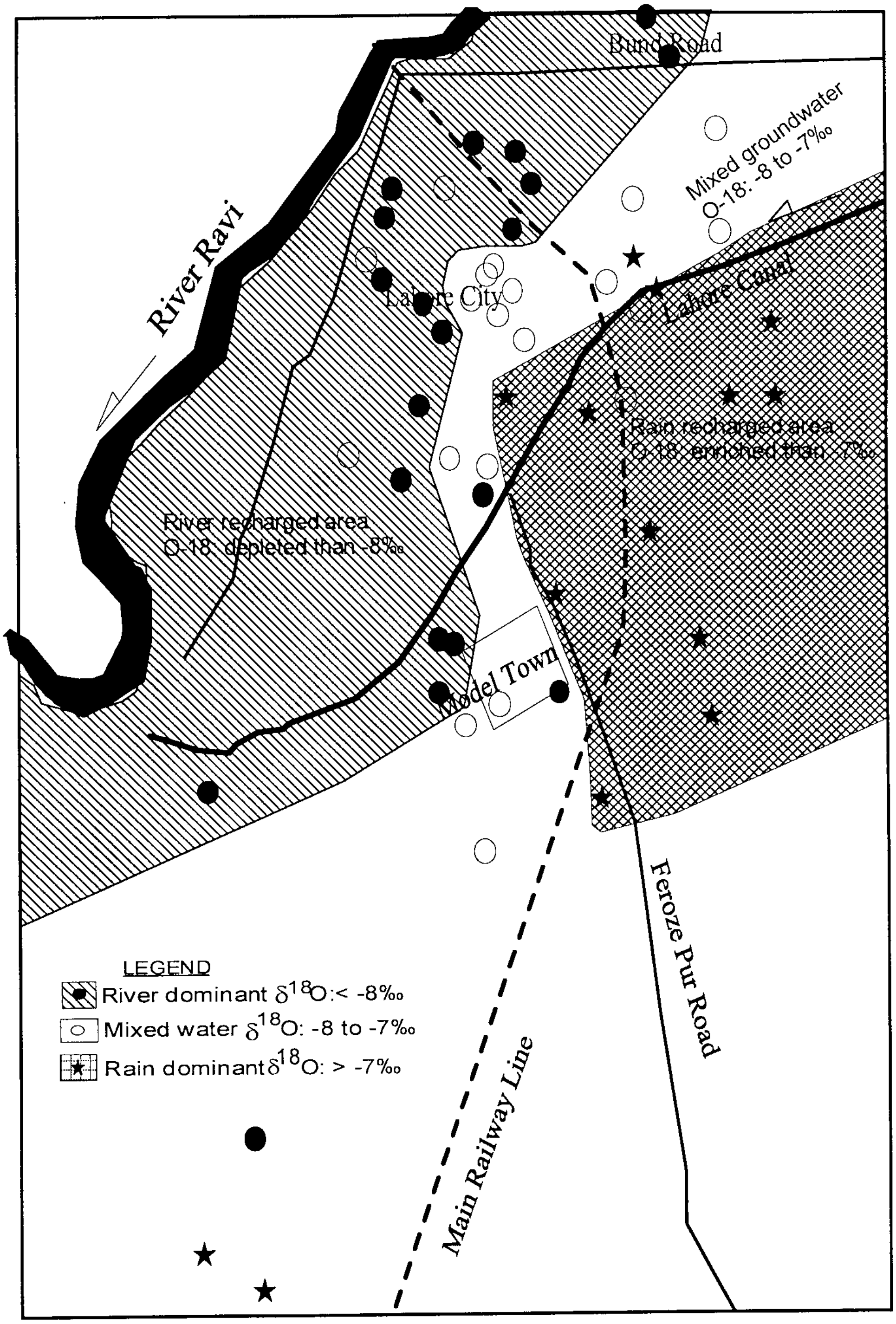

Fig. 9. Spatial variation of $\delta^{18}O$ *of deep groundwater.*

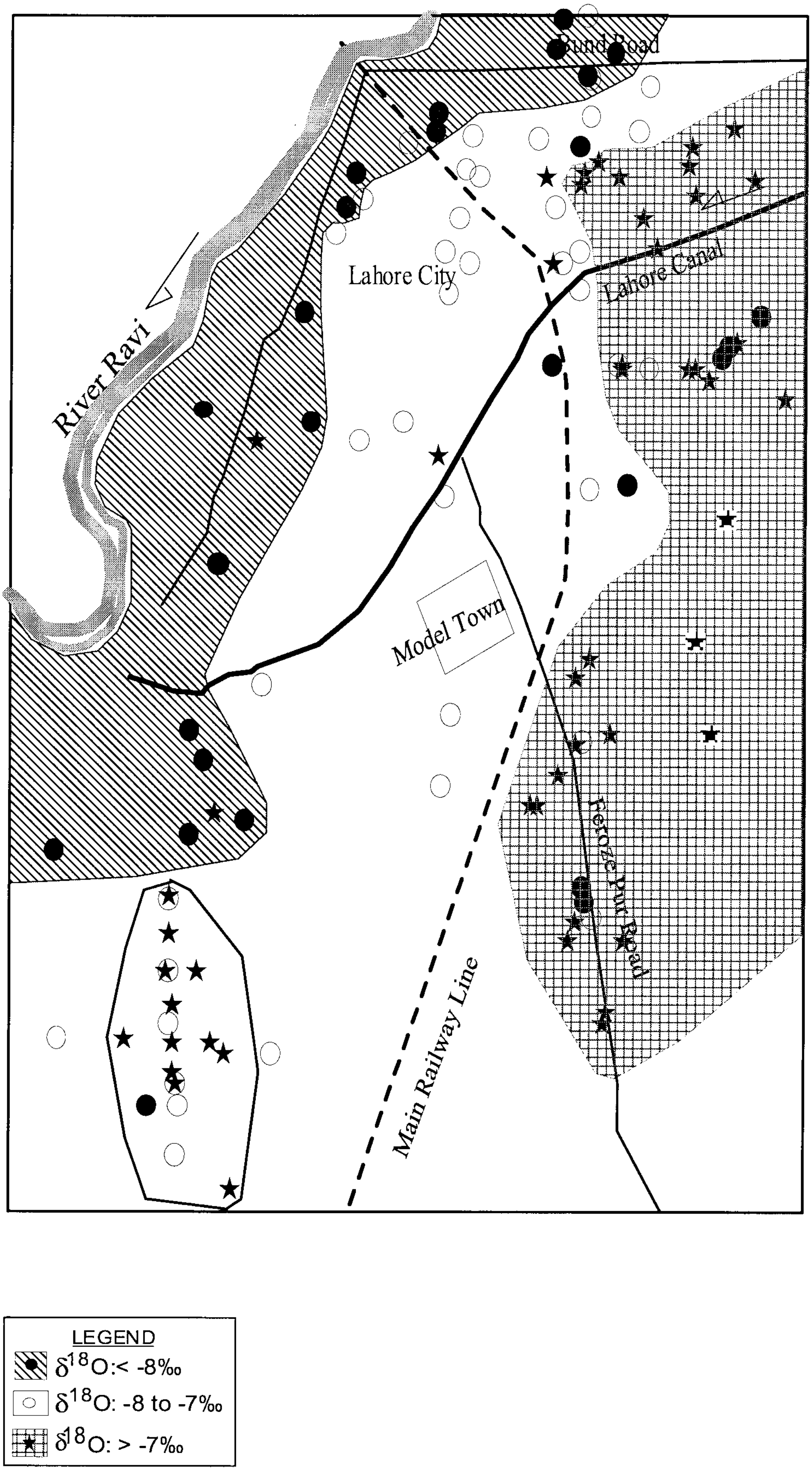

Fig. 10. Spatial variation of $\delta^{18}O$ of shallow groundwater.

6.5.2. Frequency distribution of $\delta^{18}O$

Frequency histogram of $\delta^{18}O$ of deep water (Fig. 11) shows two populations. One population with model class of about -6.5 ‰, which is almost base-flow coming from long distances. The class with higher $\delta^{18}O$ shows little contribution of local rains. The other population is from -9 to -7 ‰ with model class at -7.5 ‰ showing significant contribution of river water. Because of significant difference in $\delta^{18}O$ values of groundwater sources, the following two component mixing equation roughly gives the fraction 'f' of river water.

$$F = \frac{\delta^{18}O_M - \delta^{18}O_{B.F}}{\delta^{18}O_{B.F} - \delta^{18}O_R}$$

Where $\delta^{18}O_M$, $\delta^{18}O_{B.F}$ and $\delta^{18}O_R$ are $\delta^{18}O$ values of mixed groundwater, base-flow and river water respectively. Using the above equation, about half of the sampling locations show 30 to 40% contribution of river water. In Fig. 12, frequency histogram of $\delta^{18}O$ of shallow water, also indicates two populations. One population is with model class at -7.0 ‰, while the second population, which is much smaller than the first one, has modal class at -8.5 ‰. This distribution indicates that the groundwater samples having major contribution from the river are much less in number as compared to those recharged by other sources. The river influenced locations have greater fraction of its water as compared to deep ones. Separation of the second population from the first one means that there is no significant mixing of river water at the locations falling in the second population. Considering the average value of $\delta^{18}O$ of tubewells feeding the Main Supply Grid (i.e. -7.49 ‰) and average $\delta^{18}O$ of drains (i.e. -7.47 ‰), these two sources seem to be one of the possible end components for mixing. Contribution in the recharge by the sewerage drains is also possible as they are mostly unlined. It seems that the shallow groundwater around the drains has high EC, high nitrate and coliform bacteria due to recharge from drainage system. NESPAK also pointed out that 6 to 8 % losses due to leakage from the Main Grid System and losses of 10 % of the total discharge from the sewerage drains contribute to recharge of groundwater [1].

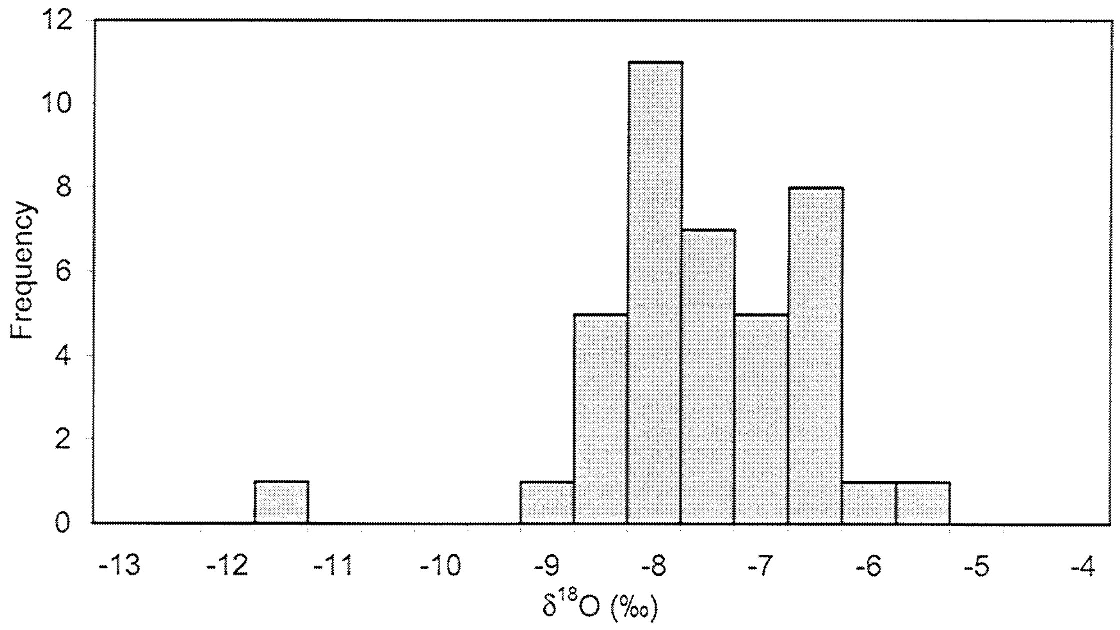

Fig. 11. Frequency histogram of $\delta^{18}O$ of deep groundwater.

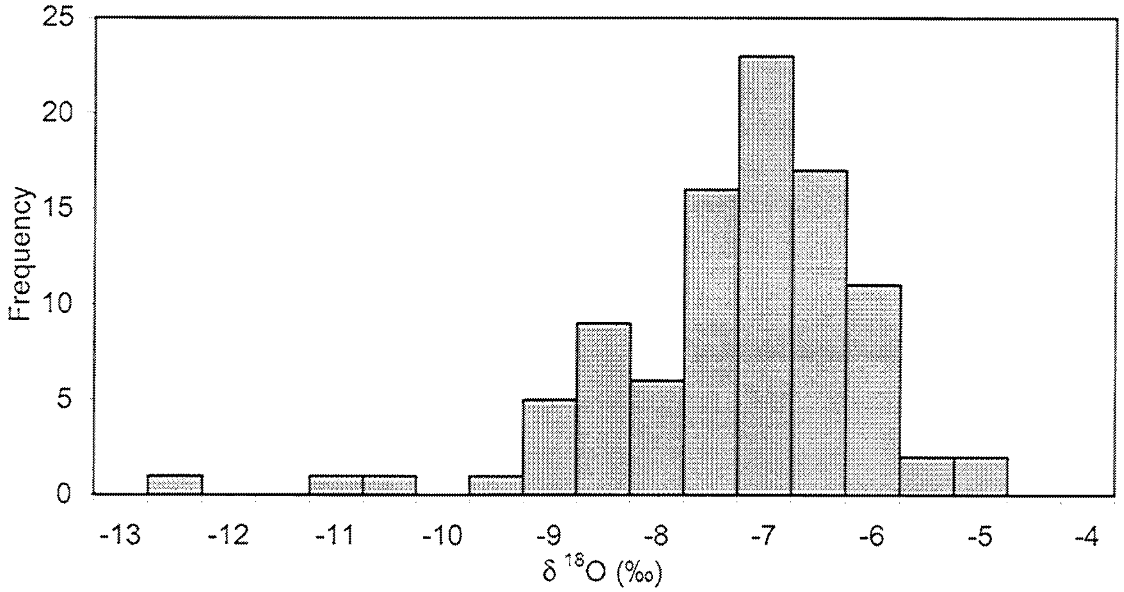

Fig. 12. Frequency histogram of $\delta^{18}O$ of shallow groundwater.

6.5.3. Frequency distribution of $\delta^{13}C$

Frequency histograms of $\delta^{13}C_{DIC}$ for shallow groundwater (Fig. 13) and deep groundwater (Fig. 14) give information about the penetration of urban recharge. $\delta^{13}C$ of sewerage water is from -13 to -11‰, while the distributions of shallow and deep groundwater have $\delta^{13}C$ ranges from -9 to -3‰ and -8 to -3‰ with the modal classes at -7 ‰ and -5‰. Although the ranges do not differ very much but the modal class of the shallow water is depleted by 2‰ than the deep ground water, which brings this population closer to the $\delta^{13}C$ index of sewerage water. Also the distributions of shallow water is negatively skewed towards $\delta^{13}C$ index of sewerage water, whereas skewness of the deep-water distributions is positive showing the dominance of carbonate mineral dissolution. These evidences confirm the contamination of shallow aquifer by the sewerage drains.

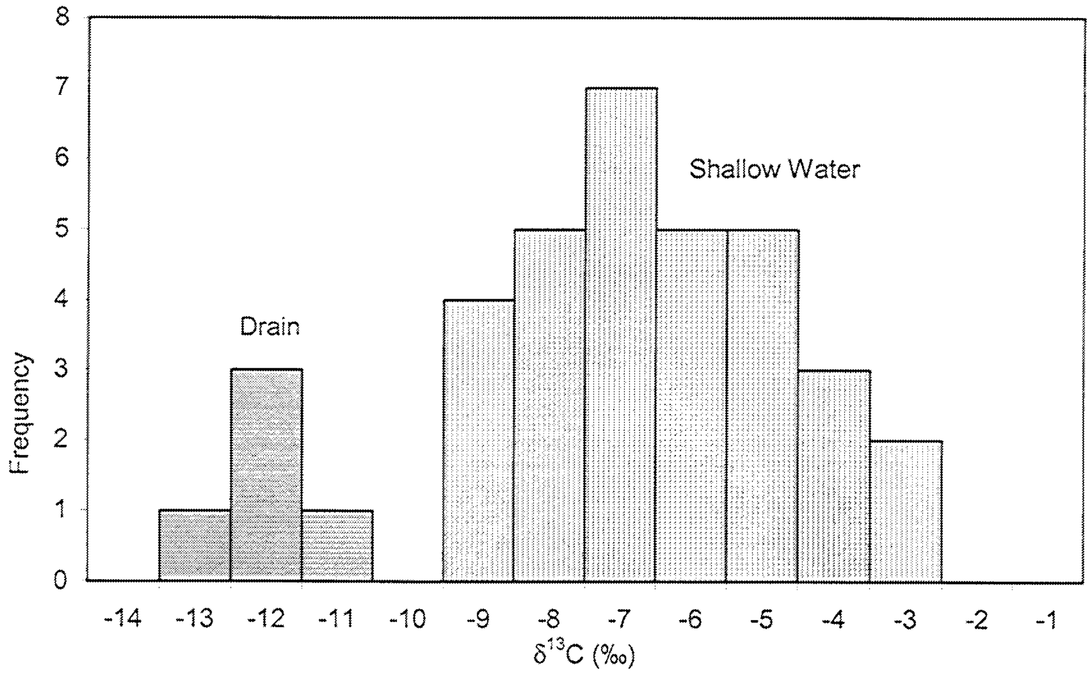

Fig. 13. Histogram of $\delta^{13}C$ of shallow groundwater & drains.

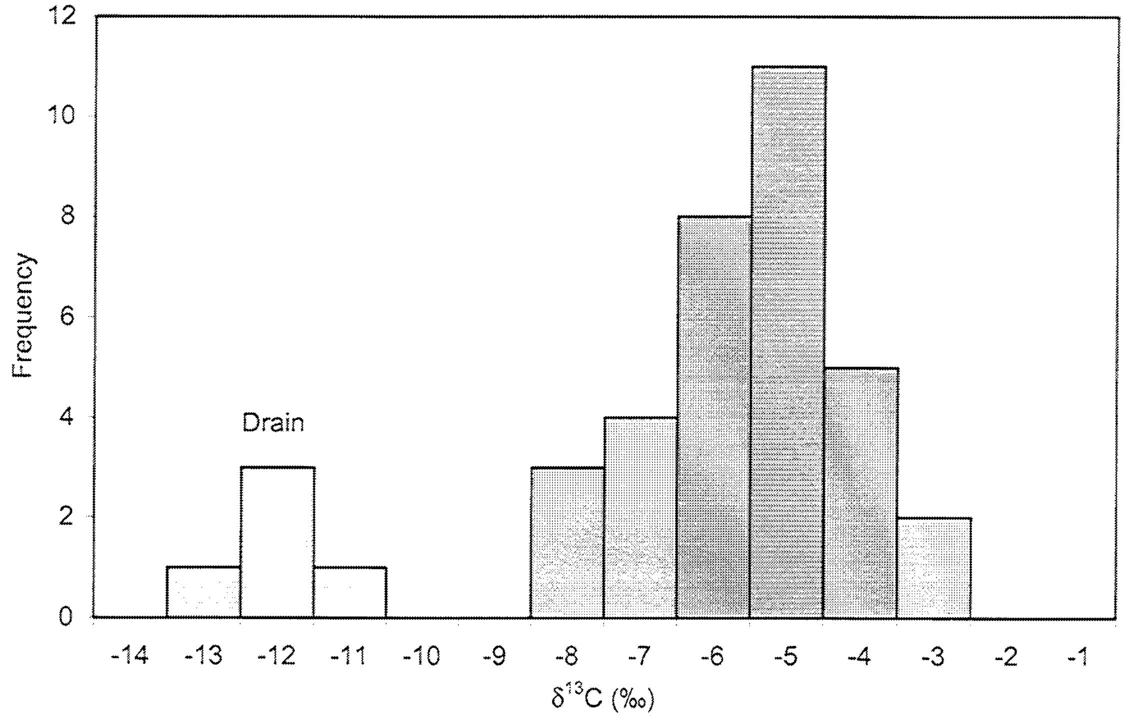

Fig. 14. Histogram of $\delta^{13}C$ of deep groundwater & drains.

Depleted $\delta^{13}C$ values of DIC similar to that of shallow water (i.e. ~-9 to -8 ‰) or even more depleted can also be evolved in both the open systems where the water is in equilibrium with soil CO_2 originating from C_3 type vegetation ($\delta^{13}C = -23.5$ ‰) and having sufficient partial pressure ($\sim 10^{-2.5}$) (Clark et al., 1998). This possibility is ruled out, as there is no or very little vegetation in the city area. Hence the sewerage drains contribute in the recharge.

6.5.4. δ^2H vs. δ^8O

In the first and second samplings, water samples were mostly collected from WASA tubewells tapping deep aquifer (screen: 80m to 200m) along with some private shallow pumps obtaining water from 25 m to 50 m. These shallow pumps do not represent necessarily the phreatic aquifer. Fig. 15 delineates the plot of $\delta^{18}O$ vs. δ^2H for second sampling. All the points are scattered around LMWL between the river index and rain index. It confirms that the aquifer is recharged both by rains and the river. Some of the points being below the LMWL show considerable evaporation effect. In the third and onward samplings a lot of hand pumps, which tap phreatic aquifer were included. All the three plots of δ^8O Vs δ^2H (Fig. 16 to Fig. 18) pertaining to these samplings (No. 3 to 5) show the evaporation in the shallow aquifer. Departure of the points from the LMWL is not much, which does not show extensive evaporation. Such slopes may be obtained due to mixing of evaporated soil water with the infiltrating rain profile [10]. Moreover, the variation in the range of isotopic values reflects the seasonal variation in the input which also indicate that the shallow water has sufficient recharge from local sources. $\delta^{18}O$ of 4th sampling ranges up to -6‰ while that of 5th sampling it goes up to -5‰. It shows that contribution of local rain that might be evaporated, increased in the groundwater sampled in the 5th sampling. This evaporation effect is also confirmed by the plot of $\delta^{18}O$ vs. Cl (Fig. 19). Except a small group and few other points, there is a positive correlation between Cl and $\delta^{18}O$.

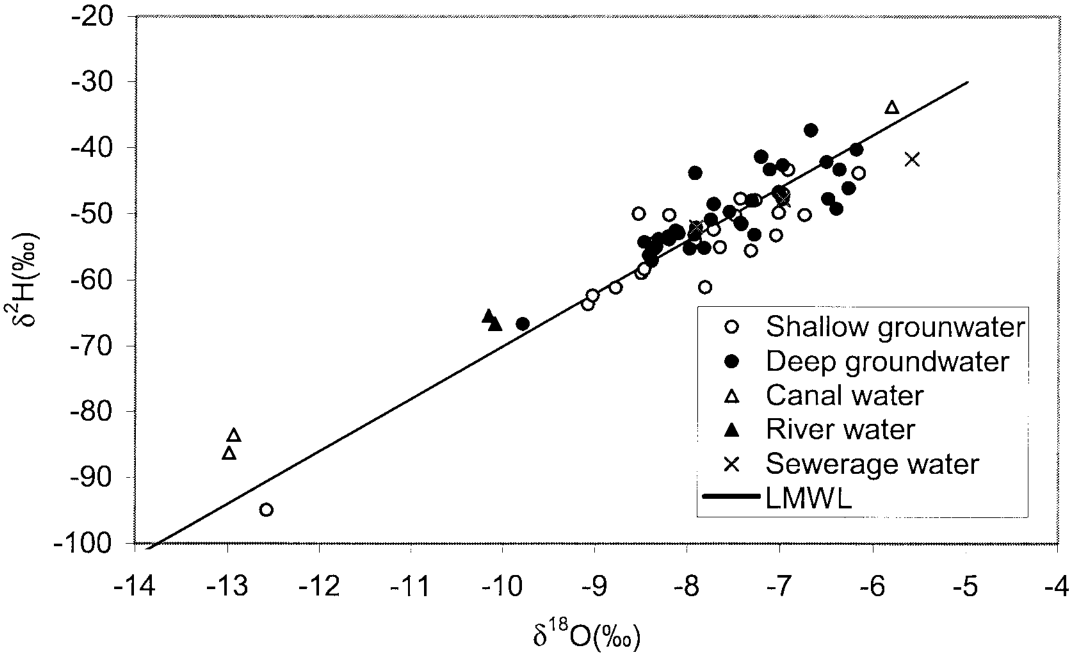

Fig. 15. Plot of $\delta^{18}O$ and ^2H (2nd sampling).

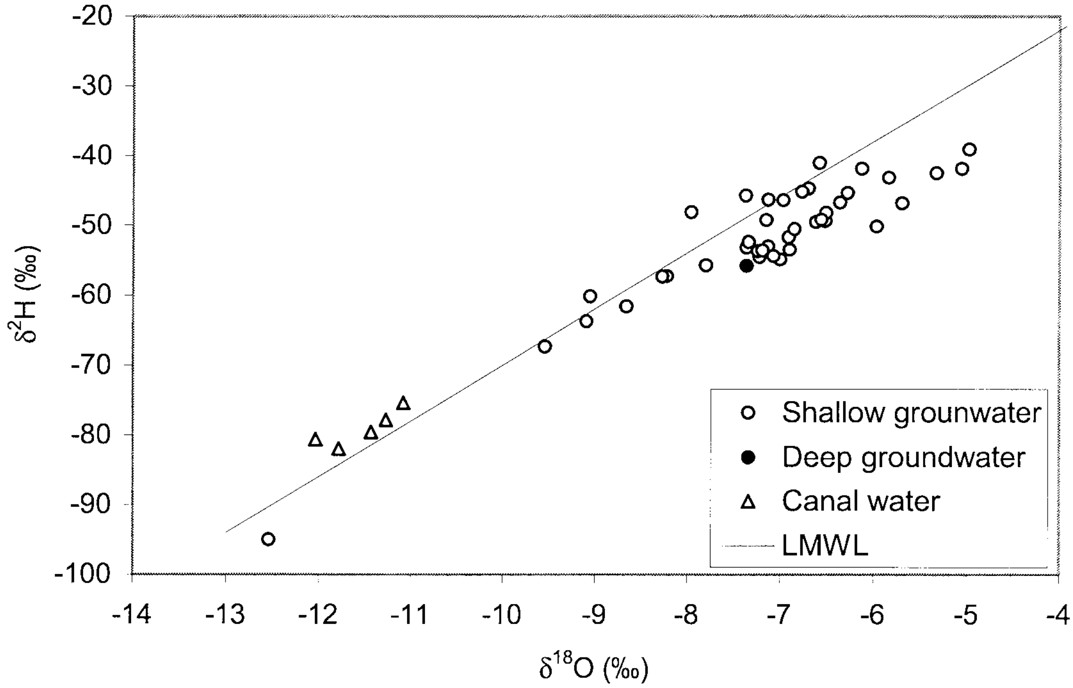

Fig. 16. Plot of $\delta^{18}O$ and ^2H (3rd sampling).

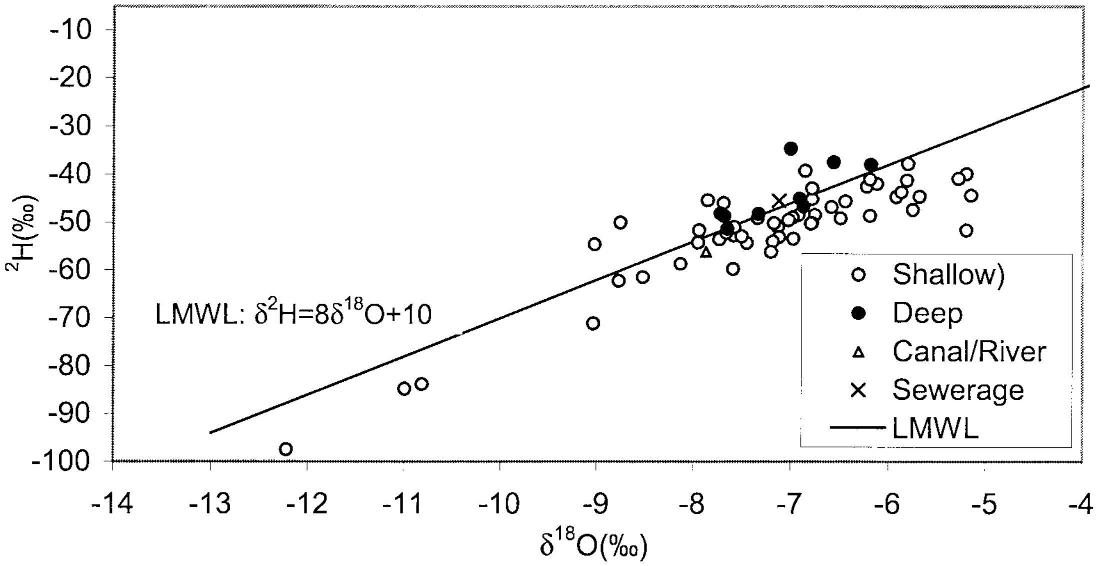

Fig. 17. Plot of $\delta^{18}O$ and ^2H (4th sampling).

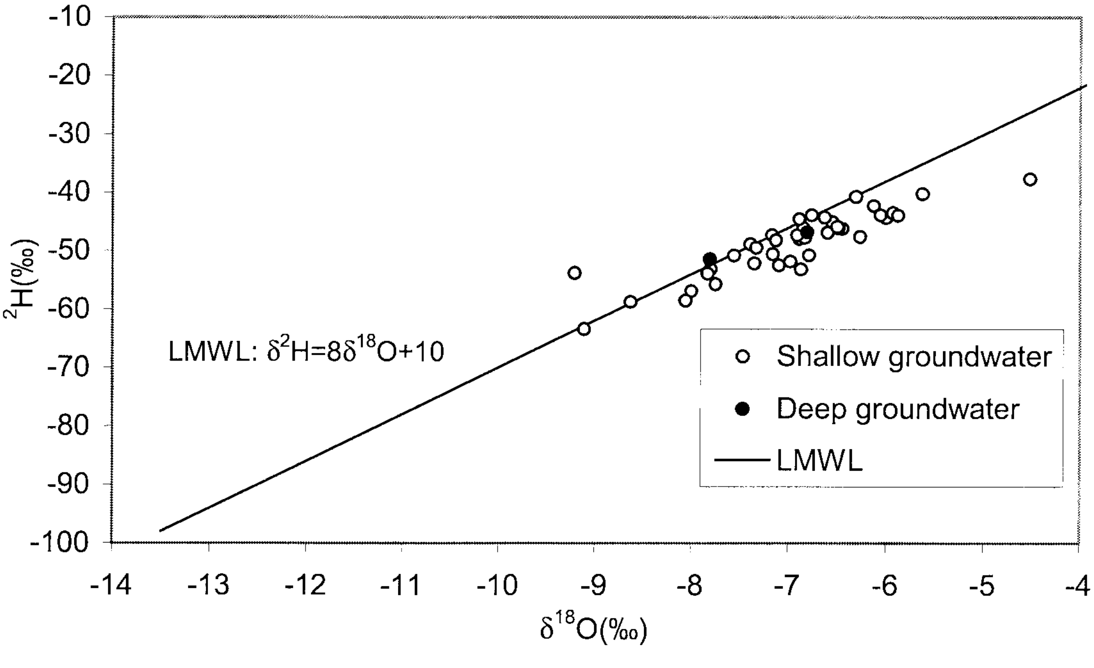

Fig. 18. Plot of $\delta^{18}O$ and ^2H (5th sampling).

6.5.5. Ca – Na relationship

Calcium and sodium are two important chemical ions which provide useful information on groundwater recharge and movement when plotted taking the concentrations of these ions in meq/L percentages out of total cations [14]. Generally, calcium bicarbonate and magnesium bicarbonate type of waters indicates fresh recharge or the recharged water has not moved a long distance from the source area. During the movement of groundwater, the dissolved calcium exchanges with sodium present in the minerals of soil matrix. As a result, sodium gets dominant over other cations when water covers a long distance from the source area which gives rise to an inverse relationship between calcium and sodium. In the present study, Ca/Na relationship has also been used to confirm the recharge area.

Relationships of Ca/Na for deep and shallow groundwater plotted in Fig. 6 and Fig. 7 confirm negative correlation. Three groups of groundwater based on δ^8O have been represented by different symbols. In case of deep water, data points of the river/canals lie at lower end with high Ca and low Na. Groundwater samples with δ^8O depleted than -8‰, indicating major contribution from river system, make a trend which starts from river points and indicates increase of Na with decrease of Ca. This trend confirms the recharge from river system. The groundwaters having δ^8O more enriched than -7‰ (mainly recharged by rainwater), lie in the upper part (high Na and low Ca) and slope of trend becomes slightly high. This type of water evolves after traveling longer distance. It seems the base flow mainly recharged by distant rains. The data pertaining to the middle group (mixed type of water) is scattered showing different contributions of both the sources.

Shallow groundwater (Fig. 7) also shows similar trend to that of deep water but the data points are much more scattered, especially the samples with high δ^8O. It means that shallow groundwater is not recharged in a regular manner like deep groundwater and various local sources are also contributing.

6.6. Groundwater dating

Tritium of groundwater has been used to distinguish old ("pre-bomb waters") and young water (recharged after the start of nuclear bomb tests i.e. after 1953) and to determine the age of young water. Basically the dating models are based on two extreme considerations dealing with the behaviour of groundwater flow [20].

- Each episode of recharge is stratified upon the previous one and the whole flow is moving without any mixing between the respective contributions. This is the so-called piston flow model (PFM).
- Each episode of recharge mixes instantaneously and completely as a continuous and constant flow within the reservoir which discharges an aliquot of the same flow with a tracer concentration corresponding to that of the reservoir. It is called completely mixed reservoir model or exponential model (EM).

It is generally admitted that PFM does not apply to groundwater flow as hydrodynamic dispersion and mixing below the water table tend to attenuate variations in tritium input function. EM also describes the extreme case of mixing. Actual tracer behaviour in hydrological system is between these two extreme cases, so, combination of both the extreme cases have been applied to relate input and output data using Multis Model [21]. The mean input data of tritium in precipitation of Northern Hemisphere has been used for this purpose [22].

During the study period, tritium in local precipitation was about 15 TU. Spatial distribution of tritium in deep groundwater (Fig. 20) shows that most of the sampling stations in the central area have tritium from 0 to 4 TU. For 4 TU in 1997, the best-fitted model (combination of EM and PFM) gives the mean residence time (MRT) of 45 years showing 100% old water. It means that most of the deep groundwater under Lahore was recharged before start of the nuclear bomb testing period (i.e. 1953). Absence of tritium (0 to 1 TU) at many locations indicates even longer residence time. The area near the river Ravi has high tritium values ranging from 5 to 31 TU. The same model determines MRT from 13 to 25 years for the groundwater having tritium values from 15 to 31 with 95 to 83 % contribution of young water. The tritium around 10 TU shows the lowest MRT (3.5 years). The tritium values from 5 to 10 may result due to mixing of fresh water recharged from the river in the base-flow having very low tritium.

Spatial distribution of tritium in shallow groundwater (Fig. 21) does not show any regular pattern. Few locations have low tritium (0 to 3 TU), which shows recharge older than 50 years. One location having tritium 48 TU has MRT 36 years which means that the recharge took place mainly during 1960s when the peak of tritium appeared due to nuclear explosions. Tritium at most of the locations is 10 to 15 TU showing few years residence time.

6.7. Vulnerability of Aquifer to Pollution

As mentioned above the shallow aquifer under all the study area has major contribution of local sources i.e., rains, river, irrigation canals, drains, etc. in different proportions. Only few locations in the central area have tritium from 0 to 2 TU while all the other locations have high tritium. This implies that recharge to shallow aquifer is generally quick. Tritium data suggest that deep aquifer replenishment is quite slow. But this deep aquifer is being highly exploited through several hundred tubewells. As a result of slow replenishment but high exploitation, water table is declining rapidly. In this situation, contribution of shallow aquifer to deep aquifer will keep on increasing. As already discussed, quality of shallow water under the city of Lahore has deteriorated over the years and there are strong evidences that it will deteriorate further in the coming years, the deep aquifer seems to be under threat of pollution. Although, the present municipal water supply derived from deep aquifer is of good quality, but the future prospects are not bright due to vulnerability of aquifer to pollution.

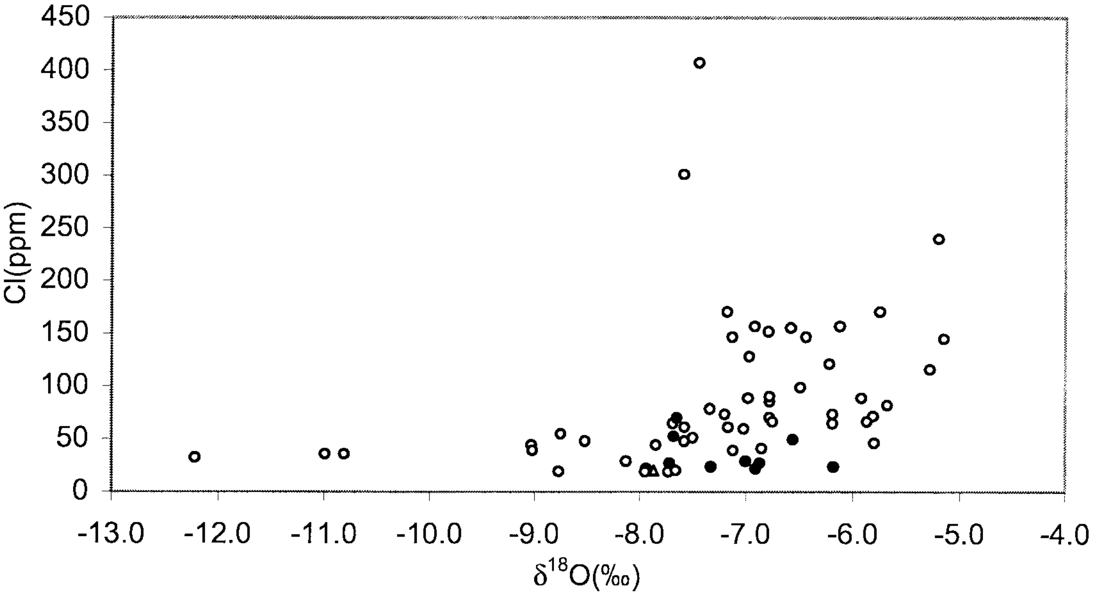

Fig. 19. Relationship of chloride (ppm) to $\delta^{18}O$.

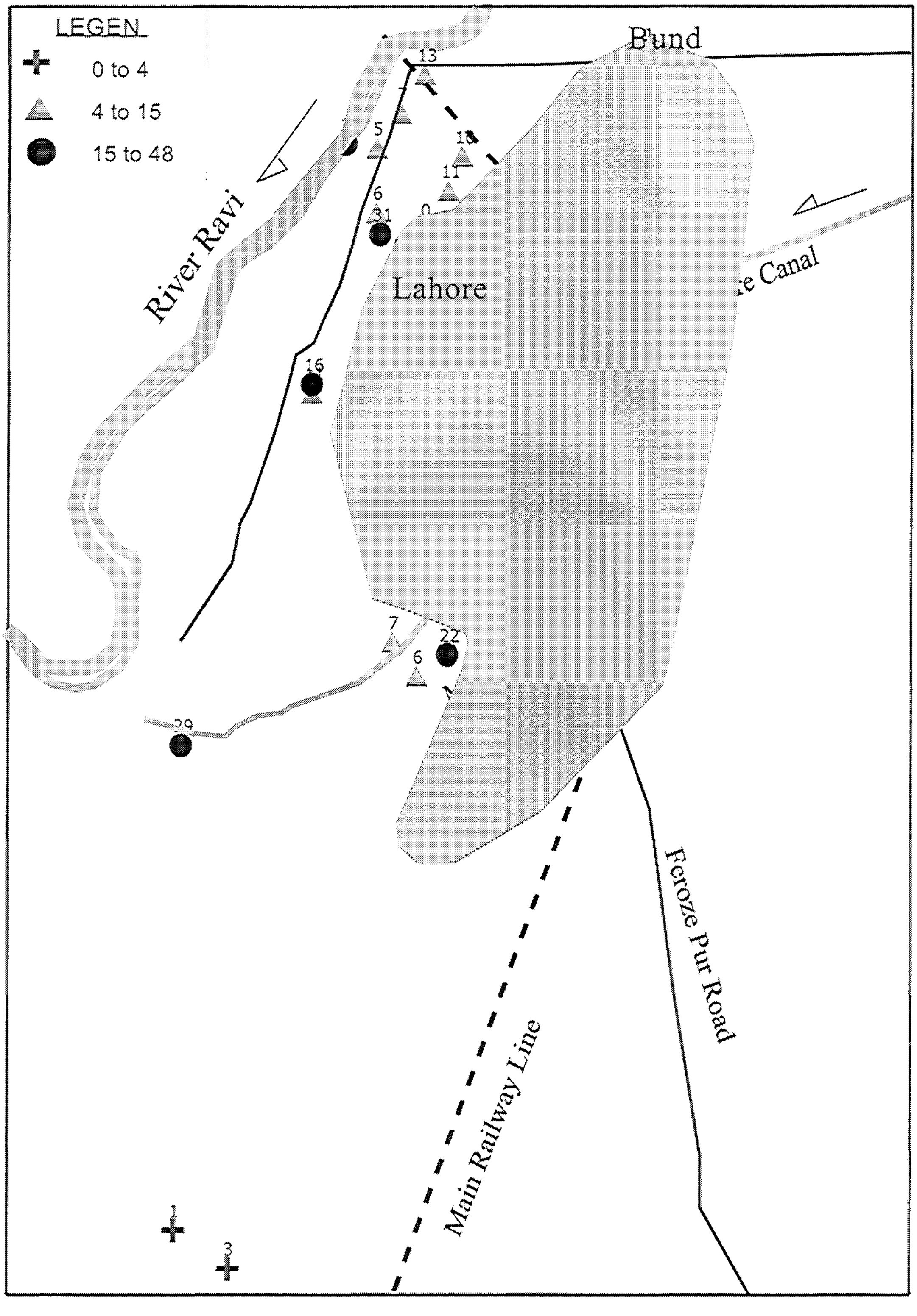

Fig. 20. Spatial variation of Tritium in deep groundwater.

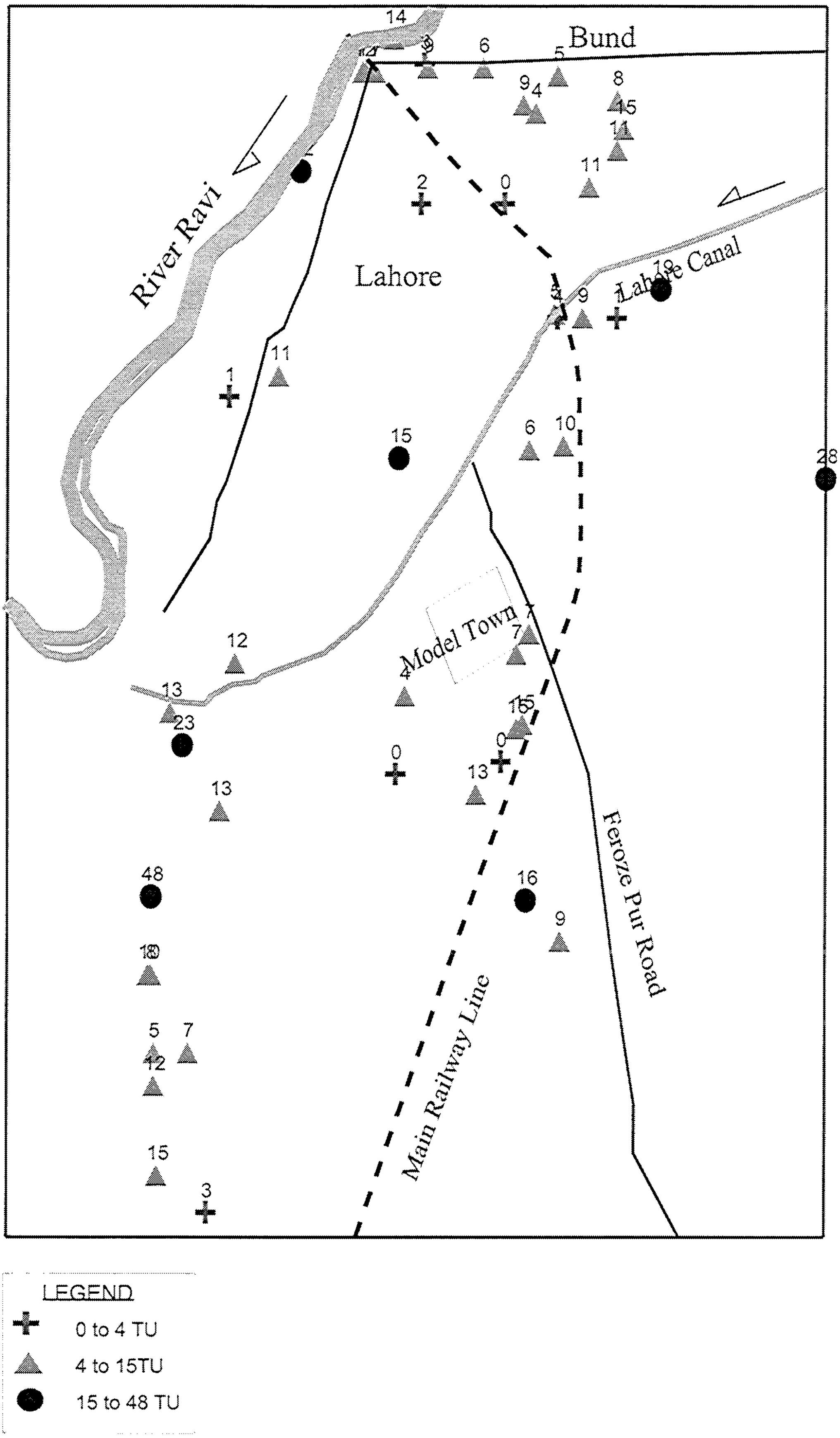

Fig. 21 Spatial variation of tritium in shallow groundwater.

7. CONCLUSIONS

From the data obtained, the following conclusions are drawn.

- Due to heavy abstraction of groundwater, the water table is declining rapidly and a cup-shaped depression has been formed in the central part of the city.
- Stable isotopic data show that the deep groundwater in the area from the river Ravi up to the center of the city has major contribution of river water while at the locations far from the river it seems totally base-flow recharged by rains of distant area in the North-East. Groundwater showing mixed recharge from river and rains is also encountered in the intermediate area.
- The shallow groundwater at the locations near the river is mainly recharged by the river water. River influence is restricted to a smaller area as compared to that in case of deep zone. In the other areas, different local sources like irrigation canals, sewerage drains, local rain and may be the leaking main supply lines seem to be contributing.
- High tritium values of deep groundwater fed by river show its quick movement up to 8-10 Km. Deep groundwater in the adjacent area towards the center of the city, although fed by the river, having tritium concentration 0 to few TU shows residence time of about 45 years. Recharge to shallow aquifer is generally quick as most of the sampling locations have high tritium values except few locations in the central area (0 to 2 TU).
- The identified compositional types of shallow as well as deep groundwater are mainly calcium bicarbonate at sampling points near the river Ravi and sodium bicarbonate going away from the river in rest of the area indicating cation exchange process.
- Deep groundwater has generally low dissolved chemical load indicating good quality. Quality of shallow water is poor at most of the locations except the areas near the river and irrigation canals. Concentrations of different parameters are higher than WHO permissible levels for drinking water at many locations.
- The study has clearly indicated the increasing trend of groundwater nitrate concentrations. NO_3 concentrations have increased at almost all the surveyed locations and have even crossed the WHO limit for drinking water at some places.
- High nitrates accompanied with highly enriched ^{15}N values show that shallow aquifer is being polluted by sewerage effluents.
- Bacterial contamination of groundwater especially at locations near the drains also proves the penetration of urban recharge from sewerage drains.

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