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ISOTOPIC INVESTIGATION OF GROUNDWATER RECHARGE MECHANISM IN THAL DOAB

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Isotope techniques were applied in a selected area of Punjab known as Thal Doab for investigating origin, recharge and age/residence time of groundwater. Surface water and groundwater samples were collected from 211 sampling points spread over the entire study area. The sampling points included rivers/canals representing the surface water, hand pumps representing shallow groundwater and tube wells representing deep groundwater. Rain samples were also collected at Chashma. The collected samples were analyzed for environmental isotopes (^2H, ^3H, ^{18}O). Isotopic data of recharge sources indicated that rivers/canals and rainfall have quite different signatures. Data of groundwater clearly demonstrated spatial variation of isotopic composition illustrating recharge from different sources and in varying proportions. Rain appears to be the main source of recharge in upper eastern part of the doab. Rest of the area is mainly recharged by surface water. $\delta^{18}O$ values of shallow and deep groundwater showed similar geographical distribution proving that they are interconnected and have same recharge mechanism. Groundwater has different age/residence time in various zones ranging from fresh to more than 50 years.

Keywords: Isotopes, Groundwater, Recharge, Thal Doab

1. Introduction

Groundwater is an important source of water supply for domestic, industrial and agricultural uses. Fast growth of population, progressive farming to meet the growing food needs and establishment of numerous industries have resulted in rapid increase in water demands. To meet these requirements large amount of groundwater is being exploited through tube wells and hand pumps. On the other hand, urbanization and industrialization has reduced the recharge as significant proportion of the land has become impermeable. As a result of over-exploitation and reduction in recharge, water table is lowering and aquifers are being depleted. This situation is encountered in many highly exploited aquifers in different parts of the country.

Indus Plain is the main source of groundwater in Pakistan. It is underlain by a huge, continuous and well transmissive alluvial aquifer [1, 2]. The spatial variation of groundwater is dependent on the availability of recharge source. Generally, the fresh water occurs near rivers, canals and in irrigated areas. During the last 30 years or so, the increasing population of the country required extensive use of water. After full utilization of surface water resources, the shortages in fresh water supplies were met from underlying Indus Plain aquifer. Indiscriminate and extensive groundwater pumping is causing severe problems of groundwater mining and saline water intrusion. It is, therefore, imperative to make realistic assessment of groundwater potential in Indus Plain for sustainable development and management of this valuable resource not only for present use but also for future uses.

In the present study, isotope techniques were applied in a selected area of Indus Basin known as Thal Doab for investigating groundwater origin, recharge mechanism, interconnection between surface water/ groundwater and age/residence time of groundwater.

2. Study Area

Thal Doab is an interfluvial tract of land bounded by mighty Indus River on west and by the Jhelum River in Upper Thal and Chenab River in Lower Thal in east (Figure 1). The Jhelum and the Chenab rivers join together at Trimmu and continue as eastern boundary of the Thal till its end. The Indus is directly benefiting Thal Doab through surface water supplies as well as

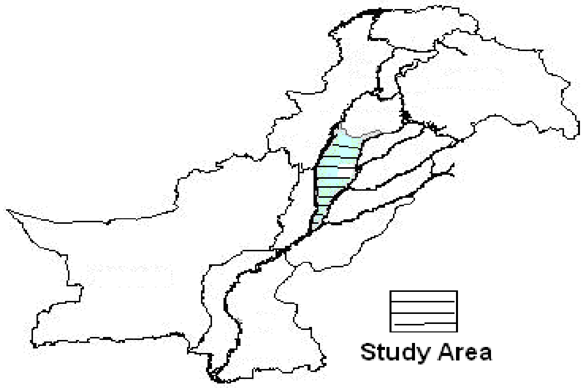

Figure 1. Map of Pakistan showing location of study area.

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through recharge from its bed and flooding on flood plain. The river has been changing its course through the ages. The shifting of the course has been causing the recharge in the study area especially in Lower Thal Doab. Several irrigation canals have also been built for irrigation of agricultural lands in this area. Thal Doab is bounded by Salt Range on its northern boundary

Thal Doab is composed of unconsolidated Quaternary Alluvial and Aeolian deposits. The materials of the alluvial plain are very thick and overlie basement rocks as old as Precambrian [2, 3]. Strata of the Salt Range are composed of highly fractured and folded, fossilferous rocks of Precambrian to Pleistocene age. Piedmont alluvial deposits flank the Salt Range foothills. Surficial Aeolian sand forms an extensive deposit over the alluvium in central Thal Doab. The northeastern portion of the doab around Khushab is generally underlain by thick clay and silt. In the central portion, i.e. around Qaidabad and Bundiyal, the coarse material is much concentrated and with a few exceptions, extends to a depth of 183 m. The 10 to 15 Km wide flood plain belts of the Indus and Chenab rivers are underlain by thick deposits of sand with rare amounts of gravel. Slit and clay occurs in the sand in the form of thin lenses which have limited vertical and lateral extent. The central strip of land between the flood plains is also predominantly underlain by sand. There are occasional intercalated bodies of fine material which are laterally extensive. In the southern part of the doab, between Rohilanwali and Alipur, there is a higher percentage of silt and clay with kanker. Sand is scarce and is in the form of thin lenses. However, near Khairpur Sadaat, the alluvium is predominantly sandy.

3. Methodology

Isotopic techniques have great potential for a broad spectrum of applications in hydrology and provide insights into water's behavior and help build the foundations for rational utilization of this precious resource. In the present study, naturally occurring isotopes (^2H, ^3H and ^{18}O) which are part of the water molecule are used.

^{18}O and ^2H are stable isotopes and their fractionation changes on global basis with the effects like temperature effect (seasonal effect, altitude effect, latitude effect), continental effect, amount effect, etc. As a result various sources of water have different isotopic signatures, which are used to determine the source of recharge of groundwater in a particular regime [4, 5]. Stable isotopes are measured in water samples as isotopic ratios, R ($^2H/^1H$ & $^{18}O/^{16}O$) by mass spectrometry and expressed in terms of per mil (‰) difference with respect to isotopic ratio of the reference standard. This is called the delta (δ) value.

$$\delta\,(‰) = [(R_{sample} / R_{standard}) - 1] \times 1000 \qquad (1)$$

The stable isotopic composition of natural waters is often plotted on δ^2H versus $\delta^{18}O$ diagram. The ^{18}O and ^2H values of natural waters obey a general correlation ($\delta^2H = a\,\delta^{18}O + d$) [6]. This is called the Global Meteoric Water Line (GMWL). For waters which have not been subjected to evaporation the value of 'a' (slope) is 8 and average global value of 'd' for precipitation is 10. When water undergoes evaporation, the lighter isotopic species preferentially leave the surface, so the remaining water becomes enriched, by stages, in heavy isotopic species. Such waters samples will plot off the meteoric water line (along a line having slope much less than 8, usually in the range of 4 to 6).

Tritium (^3H) occurs in the atmosphere as a result of both natural and man-made processes. The man made production has swamped tritium resulting into labeling of water in the hydrological cycle via precipitation. As tritium is radioactive, it decays with half life of 12.32 years which gives the time function (age). By comparison of rain, surface water and groundwater values, tritium is used to identify groundwater age / residence time. The introduction of man-made tritium enables us to find the age of groundwater in term of being recharged prior to or post the bomb test period [7].

4. Sample Collection and Analysis

Two hundred and eleven sampling stations spreading over the entire study area (Mianwali, Khushab, Bhakar, Layyah, Jhang and Muzaffargarh districts) were selected for collection of water samples. Location of sampling stations is shown in Figures 2 and 3. The sampling points included rivers, canals, hand pumps and tube wells. The rivers and canals represent surface water (n = 11) while the hand pumps (n = 132) and tube wells (n = 68) represent shallow and deep groundwater respectively. Important physico-chemical parameters like pH and electrical conductivity (EC) were measured in the field using portable pH and EC meters. To avoid isotope fractionation through evaporation or diffusive loss of water vapour, and/or isotope exchange with the surroundings, appropriate collection methods and sampling bottles were used [8].

For determining the oxygen isotopic composition of water samples, CO_2 equilibration method was used [9, 10]. The standard error of measurement is of the order of ±0.1‰. For hydrogen isotope ratio ($^2H/^1H$) analysis, water samples were first reduced to hydrogen gas using zinc reduction method. The hydrogen produced was measured on mass spectrometer [10]. The standard error of measurement is of the order of ±1‰.

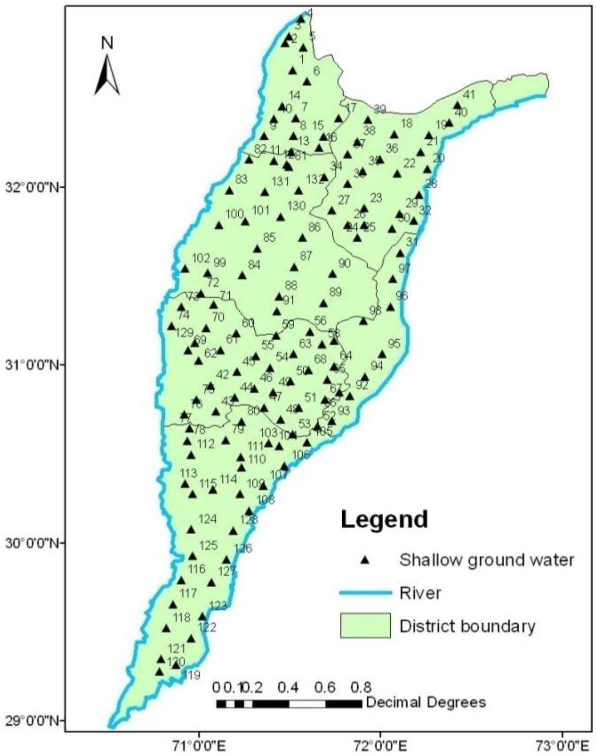

Figure 2. Location of shallow groundwater sampling points.

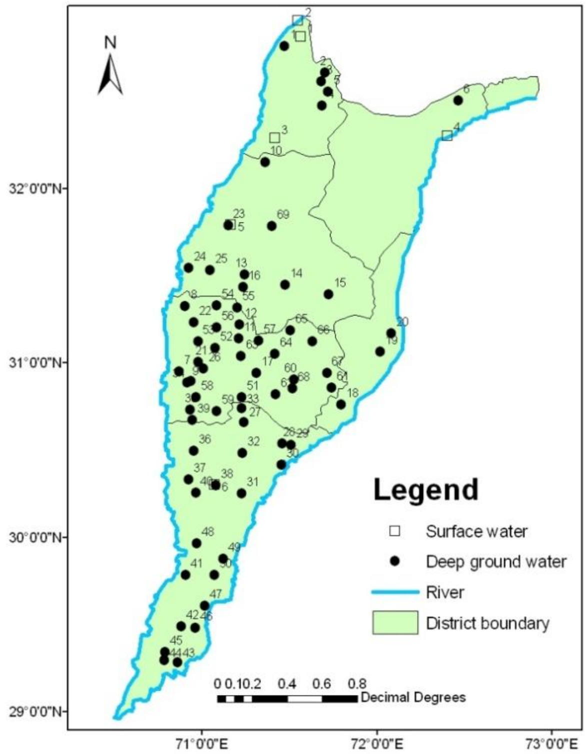

Figure 3. Location of deep groundwater and surface water sampling points.

Tritium (^3H) content of water samples was determined by liquid scintillation counting after electrolytic enrichment. Concentration of tritium is expressed in tritium units (TU). One TU is equivalent to 0.12 Bq/kg of water. The standard error of measurement is of the order of ±1TU [11].

5. Results and Discussion

Isotopic data of groundwater and recharge sources is discussed below.

5.1 Isotopes in Recharge Sources

The possible sources of aquifer recharge in Thal Doab are rain, rivers (Indus, Jhelum, and Chenab) and irrigation canals.

5.1.1. Rain

Rain samples were collected at Chashma. $\delta^{18}O$ values of local rainfall range from -7.2 to +6.8‰ with weighted average of -3.8‰ while δ^2H values range from -45.7 to +29.7‰ with weighted average of -22.3‰. If we consider only those events when rainfall is more than 5mm, weighted averages of $\delta^{18}O$ and δ^2H comes out to be -4.3‰ and -23.6‰ respectively. The data shows that the rainfall isotopic composition is primarily affected by rainfall amount [12]. Regression of the isotopic data gives the Local Meteoric Water Line (LMWL) plotted in Figures 8 and 9 as represented by the following equation:

$$\delta^2H = 7.4\ \delta^{18}O + 6.4\ (r^2 = 0.943)$$

Slope of LMWL is close to that of GMWL (8). This value (7.4) indicates that recharging waters are not subjected to significant evaporation before replenishing the aquifer.

Hussain et al. [13] determined the isotopic index of rainfall at Sargodha (a station located very close to the present study area) during 1984 -`1988. The weighted average values of $\delta^{18}O$ and δ^2H of rainfall over the period of four years were found to be -4.5‰ and -22‰ respectively.

5.2 Surface Water (Rivers/Canals)

Manzoor et al [14] have carried out long term monitoring of the isotopic composition of all major rivers of Pakistan at various stations including different barrages/headworks located in the present study area (Indus River at Chashma & Taunsa, Jhelum River at Rasul, and Chenab River at Trimmu). According to their findings, $\delta^{18}O$ and δ^2H concentrations of Indus River at Chashma vary from -12.1 to -8.0‰ (average = -10.1‰) and -77.8 to -54.7‰ (average = -67.8‰) respectively. These isotopic values at further downstream station, Taunsa Barrage, range from -13.5 to -8.6‰. (average = -11.5‰) and -82.9 to -53.6‰ (average = -73.8‰) respectively. River Chenab at Trimmu Headworks has $\delta^{18}O$ and $\delta^{2}H$ concentrations as -13 to -6.6‰ and -79.6 to -33.8‰ respectively. Average values of these isotopes are -9.1‰ and -57.7‰ respectively. At Rasul Barrage, the river Jhelum has $\delta^{18}O$ ranging from -7.8 to -5.9‰ (average = -6.8‰) and $\delta^{2}H$ ranging from -44.7 to -32.5‰ (average = -38.9‰). Indus and Chenab rivers have more negative values than Jhelum River. These extremely negative values reveal the high content of glacier / snow melt water, which is typical for high altitude rivers.

In this study, samples were collected from Indus River at Kalabagh and from Jhelum River near Khushab. $\delta^{18}O$ and $\delta^{2}H$ contents of Indus River sample are -9.5‰ and -67‰` while those of Jhelum River are -8.3‰ and -54‰, respectively. Samples from major canals were also collected from some stations as shown in Figure 3. Their isotopic (^{18}O, ^{2}H, ^{3}H) composition is similar to the parent river.

The data clearly shows that the isotopic signatures of the rivers and the rain are quite different.

5.3. Isotopes in Groundwater

Isotopic data of groundwater is given in Table 1. The $\delta^{18}O$ compositions of shallow and deep groundwaters range from -12.2 to -2.2‰ (average = -8.4‰) and -11.8 to -4.8‰ (average = -8.7‰) respectively, and the $\delta^{2}H$ compositions range from -87.4 to -17.6‰ (average = 61.4‰) and -84.2 to -34.3‰ (average = -65.6‰) respectively. Interestingly, the average $\delta^{18}O$ and $\delta^{2}H$ compositions of shallow and deep groundwaters are close to each other and to the surface water but entirely different (highly negative) than the weighted average rainfall values (-4.2‰ and -24.6‰).

5.4. Groundwater Recharge Mechanism

Input to the aquifer of the project area may occur as infiltration of rain, infiltration from river system or by sub-surface inflows. Isotopic characteristics of recharge sources and groundwater were employed for determination of groundwater recharge mechanism [5, 15].

5.4.1. Frequency Distribution of $\delta^{18}O$

Histograms of the frequency distribution of $\delta^{18}O$ of shallow and deep groundwater are shown in Figure 4 and 5 respectively. Figure 4 reveals that maximum frequency lies in the classes showing the isotopic index of surface water (-7 to -10‰). Another small population (much smaller than the first one) with modal class at -3‰ (close to the rain index) is also shown. The frequency distribution pattern indicates that most of the shallow groundwater samples have major contribution from the surface water. Number of samples showing rain influence are very few. Frequency distribution of deep groundwater is skewed towards highly negative values representing the isotopic indices of rivers and canals. Maximum frequency occurs close to the composition of the rivers with modal class at -10‰. In this case too, most of the samples reflect the higher fraction derived from the surface waters.

5.4.2. Spatial Variation of $\delta^{18}O$

In general, groundwater in Thal Doab can be divided into three main categories depending upon their isotopic composition viz. Category-1 (enriched isotopic values, $\delta^{18}O$ > -5.5‰), Category-2 (intermediate isotopic values, $\delta^{18}O$ = -7.5 to -5.5‰) and the Category-3 (depleted isotopic values, $\delta^{18}O$ < -7.5‰).

Geographical distribution of these categories in shallow groundwater is depicted in Figure 6. Category-1 waters are found in a narrow zone in the upper eastern part of the doab between Grot, Distt. Khushab and Hyderabad Thal, Distt. Bhakar (Sample # 20, 22, 23, 25, 26, 27, 28, 29, 32, 35, 87, 90 & 132). Their isotopic composition reflects that shallow groundwater in this zone is recharged by the rain and there is no contribution of river water. As we move vertically and laterally away from the rain fed area, isotropic values go on depleting suggesting the decreasing role of rain and increasing role of surface waters in groundwater recharge. Shallow groundwater at sampling points surrounding the rain-fed area show intermediate isotopic values (Category-2 waters) suggesting mixing of varying fractions of rain water and river water. At sampling points immediately below the rain-fed area, shallow groundwater has $\delta^{18}O$ composition in between - 5.5 and - 6.5‰. These values reveal that rain is the dominant source of recharge at these locations and contribution of surface water is very low. In the area shown in light green colour in Figure 9 (Mixed recharge zone), groundwater isotopic composition is relatively depleted (between -6.5 and -7.5‰) reflecting more contribution of surface water as compared to the rain. All the sampling points located along the Indus River right from the start of the doab to the very end show highly negative $\delta^{18}O$ values (< -9‰), which signify that these sites are fed by isotopically depleted surface water. The points located along the Chenab River generally have $\delta^{18}O$ from -9 to -8‰ reflecting the major input from this river.

Table 1. Isotopic data of groundwater.

Sample	Station	$\delta^{18}O$	$\delta^{2}H$	^{3}H	Sample	Station	$\delta^{18}O$	$\delta^{2}H$	^{3}H
Shallow Groundwater									
1	Rokhri	-12.0	-82.6	N.D.	53	Mahmoodwala Khoo	-8.6	-59.2	5.9
2	S. M. Shah Wala	-11.9	-80.1	5.1	54	Shahuwala	-7.5	-48.9	3.4
3	Gunda	-11.0	-75.6	4.4	55	Jamal Chapri	-7.1	-46.0	N.D.
4	Mari Indus	-6.9	-42.3	3.9	56	Kachranwala	-6.3	-41.9	3.8
5	PaiKhel	-12.1	-84.8	4.6	57	Sheruwala	-6.2	-44.6	3.7
6	Suhrabwala	-9.4	-60.3	1.8	58	Karariwala Khoo	-6.7	-46.4	N.D.
7	Chak 4DB	-10.1	-69.7	4.5	59	Chak 303/TDA	-7.3	-48.5	3.9
8	Harnoli	-10.8	-74.1	8.6	60	Fatehpur	-8.8	-60.8	4.8
9	Piplan	-12.2	-80.2	6.5	61	Chak 270/TDA	-8.7	-61.2	N.D.
10	Alluwali	-11.5	-78.3	4.9	62	Head Sumandri	-10.3	-72.8	7.7
11	Chak 15	-11.5	-81.5	3.6	63	Nusratwala	-7.4	-60.9	N.D.
12	Kalurkot	-10.8	-73.6	6.4	64	Rehrewala	-7.5	-59.4	4.8
13	Trangranwala	-10.1	-70.0	N.D.	65	Kherewala-1	-7.9	-56.4	N.D.
14	Kundian	-10.8	-75.6	N.D.	66	Kapuri	-8.5	-58.5	N.D.
15	Chak 29DB	-9.8	-67.6	9.7	67	Kherewala-2	-8.0	-57.2	5.3
16	Bala Sharif	-6.3	-37.9	11.9	68	Mohlanwala	-7.5	-50.3	2.6
17	Shadia	-8.4	-52.3	9.4	69	Basti Shahpur	-10.8	-77.2	N.D.
18	Dera Ganjeeranwala	-11.3	-76.1	8.1	70	Tajabad	-11.0	-80.6	4.8
19	Joharabad	-11.2	-79.0	N.D.	71	Chak 77/TDA	-9.2	-63.2	N.D.
20	Rangpur	-4.7	-29.6	5.1	72	Behl	-9.7	-70.7	5.3
21	Chak 45MB	-7.7	-51.3	11	73	Basti Wado	-10.0	-73.7	N.D.
22	Roda	-4.1	-23.3	6.5	74	Sheenwala Mor	-9.9	-74.6	9.3
23	Nurpur Thal	-3.4	-18.6	1.7	75	Gajanwala	-10.4	-75.7	4.6
24	Nikru	-8.1	-51.8	1.9	76	Ranjewala	-10.3	-74.8	N.D.
25	Katisar	-3.4	-17.6	N.D.	77	Ihsanpur	-11.0	-77.0	5.8
26	Jharkal	-4.4	-26.1	5.6	78	Daira Deen Panah	-9.8	-72.1	6.7
27	Shahwala	-2.8	-22.9	1.9	79	Chak 576/TDA Mor	-9.5	-73.4	9.5
28	Taitri	-3.5	-19.8	N.D.	80	Muhammadwala	-7.4	-51.3	N.D.
29	Sadiqabad	-3.1	-21.3	N.D.	81	Chandni Chowk	-9.1	-70.9	3.3
30	Khatwan	-8.9	-62.2	1.7	82	Kalurkot Adda	-9.5	-72.2	4.1
31	Mari Shah Sakheera	-6.6	-40.0	N.D.	83	Kalurkot	-7.8	-53.4	8.6
32	Saith Shahani	-2.2	-19.8	10.4	84	Sarai Muhajir	-9.6	-70.1	2.8
33	Rangpur Bagor	-7.9	-52.9	0.6	85	Khansar Chowk	-7.7	-58.5	2.6
34	Alikhel	-11.6	-80.2	N.D.	86	Goharwala	-5.9	-44.2	1.3
35	Abdullapur	-3.3	-21.9	1.3	87	Sargiwala	-5.3	-40.2	3.9
36	Mitha Tawana	-7.5	-56.2	0.6	88	Mankera	-6.2	-45.5	2.1
37	Aghi Sargal	-8.3	-55.9	1	89	Hyderabad Thal	-6.3	-51.7	-6.3
38	Maihan Da Dera	-10.6	-73.6	N.D.	90	Obal	-3.3	-24.9	-3.3
39	Dera Bacharanwala	-5.6	-39.2	1.2	91	Shah Alamwala	-6.5	-47.5	-6.5
40	Sandral Chowk	-9.8	-66.2	N.D.	92	Dole	-8.6	-62.0	-8.6
41	Narki	-5.9	-37.1	0.9	93	Ahmadpur Sial Mor	-8.4	-60.6	-8.4
42	Chak 153/TDA	-10.5	-75.5	1.1	94	Sharifabad	-8.1	-56.0	-8.1
43	Pir Jhugi	-8.6	-65.7	N.D.	95	Adda Rodu Sultan	-7.9	-57.9	-7.9
44	Chak 426B/TDA	-10.1	-75.9	3.2	96	Ghaziabad More	-8.2	-52.6	-8.2
45	Chowk Azam	-7.9	-53.7	1.9	97	Kot Shakir	-7.2	-49.9	-7.2
46	Chak 403/TDA	-11.6	-87.4	N.D.	98	Bhereri	-7.1	-51.2	-7.1
47	Chak 469/TDA	-10.3	-69.3	7.4	99	Basti Hussain Khan	-8.2	-62.3	-8.2
48	Adda Chak 408/TDA	-8.3	-59.1	N.D.	100	Darya khan	-9.1	-74.6	-9.1
49	Chak 444/TDA	-9.9	-70.1	N.D.	101	Rakh Digranwali	-10.3	-82.6	-10.3
50	Chobara	-7.4	-47.7	N.D.	102	Bhari Chiragh Shah	-10.8	-83.6	-10.8
51	Khotwala Khoo	-7.4	-50.5	2.1	103	Azizabad	-5.8	-50.2	-5.8
52	Mianwala Nawan Khoo	-8.3	-59.7	N.D.	104	Kharkan Adda	-11.4	-75.5	-11.4

Sample Code	Station	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	^{3}H (TU)	Sample Code	Station	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	^{3}H (TU)
105	Jhal 81	-7.9	-65.1	-7.9	119	Adhiwala	-9.2	-64.7	4.7
106	Sarwani Bangla	-6.4	-48.8	-6.4	120	Sultanpur	-10.2	-75.9	8.2
107	Muhammadwala More	-7.7	-56.5	-7.7	121	Gopang	-10.5	-79.3	5.3
108	Muradabad	-9.3	-65.8	-9.3	122	Chowk Naseerabad	N.D.	N.D.	7.9
109	Chowk Langar Sarai	-8.7	-72.8	-8.7	123	Shehar Sultan	-9.4	-77.2	4.6
110	Chak 599/TDA	-10.1	-70.3	-10.1	124	Karamdad Qureshi	-11.0	-81.1	5.7
111	Chak 593	-10.1	-67.9	2.6	125	Shah Jamal	-8.6	-71.3	3.1
112	Kot Addu	-10.9	-76.7	8.4	126	Khangarh	-8.6	-65.1	4.8
113	Thatti Hamza	-9.6	-72.1	5.3	127	Roheelanwali	-8.1	-63.9	2.8
114	Basti Sanawan	-9.0	-66.3	4.7	128	Muzaffargarh	-8.1	-56.0	4.5
115	Gormani Adda	-9.8	-76.4	4.4	129	Shahpur	-8.6	-73.9	3.7
116	Adda Gohadpur	-10.8	-76.4	14	130	Banuwala	-8.4	-56.0	0
117	Mir Hazar	-9.9	-77.8	6.8	131	Chak 29/RH	-8.0	-67.9	4.3
118	Jatoi	-8.3	-67.7	8.4	132	Raitri	-2.6	-19.9	11.6
Deep Groundwater									
1	S. M. Shah Wala	-11.8	-78.0	2.9	35	Kot Addu	-10.6	-71.8	6.4
2	Baianwala	-5.8	-32.3	8.4	36	Thatti Hamza	-9.6	-77.1	2.9
3	Mastikhel	N.D.	N.D.	5.4	37	Basti Sanawan	-10.1	-74.8	4.6
4	Wan Bachran	-9.4	-67.0	7.6	38	Ihsanpur	-10.5	-70.5	4.7
5	Cheeder	-6.1	-42.9	1.1	39	Gormani Adda	-9.0	-70.6	9
6	Manguwal	-5.6	-35.2	2.4	40	Adda Gohadpur	-9.6	-75.8	15
7	Basti Loharwala	-10.8	-74.2	13.9	41	Jatoi	-10.3	-75.0	3.4
8	Bast Wado	-10.7	-76.4	6.8	42	Dotalian	-10.1	-70.5	8.4
9	Khalilabad	-9.9	-74.5	5.4	43	Sultanpur	-8.8	-71.4	4.2
10	Zimewala	-9.2	-72.9	4.9	44	Gopang	-7.1	-50.2	4.3
11	Chak 230A/TDA	-9.1	-66.0	3.4	45	Chowk Naseerabad	-10.6	-77.9	5.8
12	Sarai Muhajir	-8.8	-63.1	1.8	46	Kot Sultan	-10.9	-78.2	4.7
13	Chakian Stop	-5.1	-40.4	3.5	47	Shah Jamal	-10.8	-81.2	5.8
14	Dera Goraya	-4.8	-39.5	2.6	48	Khangarh	-8.0	-59.0	8.1
15	Basti Lashari	-10.7	-71.1	6.6	49	Roheelanwali	-8.4	-59.7	4.5
16	Rafiqabad	-9.4	-66.9	3.9	50	Hoori Adda	-8.1	-60.2	3.4
17	Adda Pir Abdur Rehamn	-8.0	-55.0	2.4	51	Chak 111/TDA	-7.8	-58.6	2.6
18	Rodu Sultan	-6.8	-50.7	13.5	52	Shahpur	-9.9	-75.9	6.2
19	Attara Hazari	-7.0	-50.4	13.4	53	Chak 90	-10.1	-72.5	6.6
20	Khokha Adda	-9.9	-77.5	11.6	54	Chak 217	-10.0	-75.1	4.7
21	Karor	-10.6	-75.5	12.9	55	Chak 98	-9.9	-74.4	10.6
22	Chak 16/TDA	-10.3	-81.5	10.8	56	Adda Husnainabad	-7.5	-49.5	0.6
23	Bhari Chiragh Shah	-10.9	-74.0	15.4	57	Hafizabad	-11.1	-78.8	0.5
24	Cheena	-10.3	-75.7	9.2	58	Chak 1671/TDA	-10.4	-70.8	2.9
25	Chak 128	-10.7	-74.6	10.6	69	Chobara	-9.7	-70.0	1.4
26	Chak 634/TDA	-5.6	-48.1	3.7	60	Bharoli Adda	-7.8	-54.4	1.4
27	Kharak Adda	-8.2	-56.4	3.4	61	Chak 479/TDA	-8.3	-55.9	4.5
28	Kharak Adda-2	-7.4	-55.3	1.9	62	Chak 318	-8.4	-60.9	1.4
29	Sarwani Bangla	-6.8	-46.0	9	63	Bandral	-7.5	-48.8	0
30	Chowk Langar Sarai	-8.1	-61.2	7.4	64	Fatehpur	-6.4	-44.8	1
31	Chak 593	-8.5	-62.9	3.1	65	Ashtarabad	-6.2	-43.8	0.5
32	Chak 625	-9.4	-65.7	4.4	66	Kherewala	-6.4	-47.0	1
33	Faqeeranwala	-9.5	-70.6	4.8	67	Ganji Khoo	-7.4	-52.1	2
34	Khooni Karlu	-9.5	-70.7	5.2	68	Adda Azeemwala	-7.8	-55.1	0.2

N.D. = Not determined

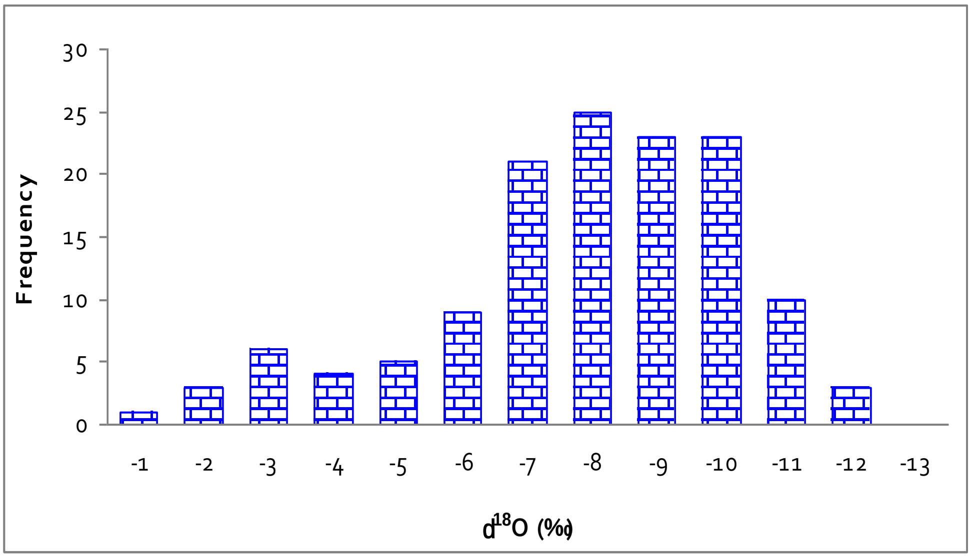

Figure 4. Frequency histogram of $\delta^{18}O$ values of shallow groundwater.

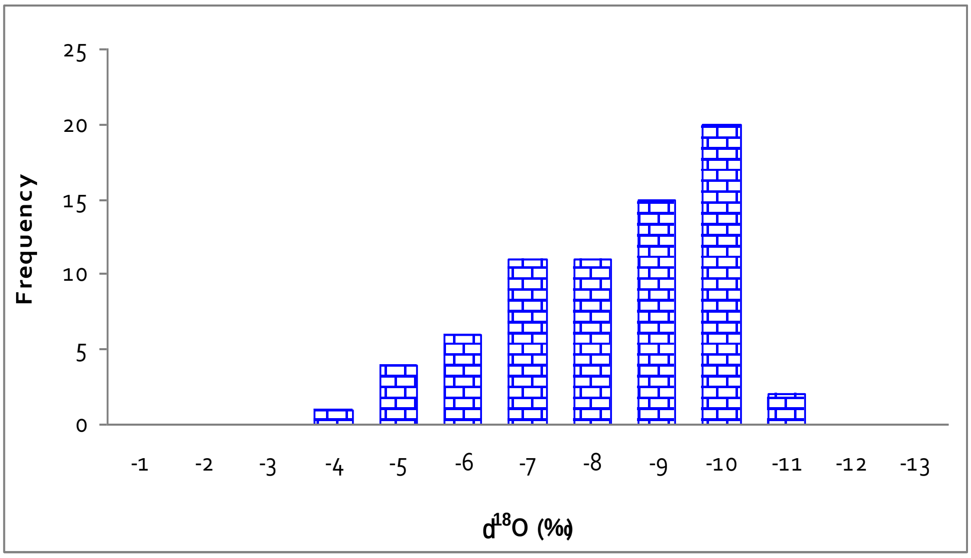

Figure 5. Frequency histogram of $\delta^{18}O$ values of deep groundwater.

Geographical distribution of various categories of deep groundwater is depicted in Figure 7. Unfortunately, deep groundwater samples from the upper part of the study area were not available because the tube wells were either not existing or not in operation during the field sampling period. Two sites near Hyderabad Thal in Distt. Bhakar were sampled (Sample No. 13 & 14) which have $\delta^{18}O$ values -4.8‰ and -5‰ indicating that deep groundwater in this area falls in Category-1 like the shallow groundwater. As in shallow groundwater, the area surrounding the rain-fed locations has intermediate isotopic composition (Category-2) reflecting the mixed recharge from both sources. Three samples (Sample # 64 - 66) taken from the points immediately below the rain recharged locations have $\delta^{18}O$ values (‰) -6.4, -6.2 and -6.4 meaning that rain is the dominant contributor as compared to surface water. Contribution of surface water is more at other locations in mixed recharge zone. All the points located along the Chenab River and Indus River (depleted isotopic values) indicate major contribution from the surface water (Category-3).

$\delta^{18}O$ values in shallow and deep groundwater show similar distribution pattern proving that they are interconnected and influenced by the same recharge mechanism.

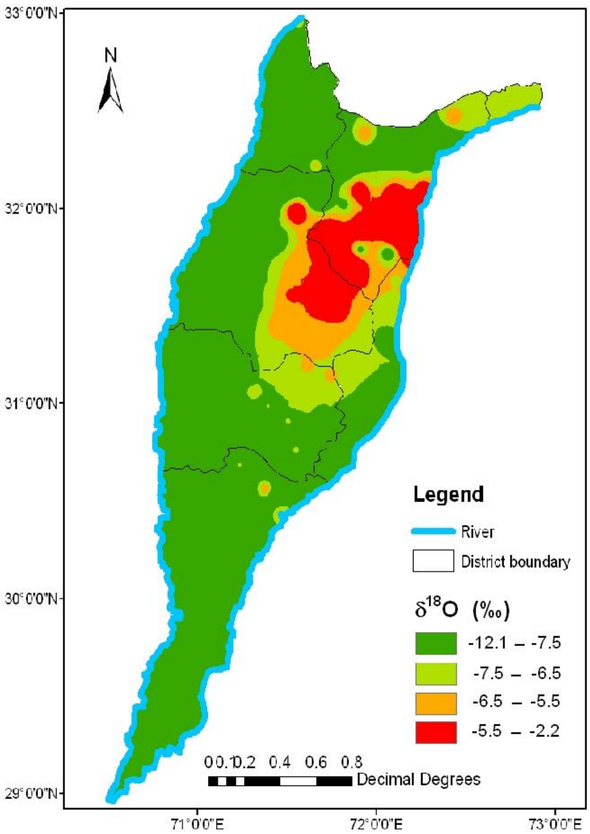

Figure 6. Spatial distribution of $\delta^{18}O$ in shallow groundwater.

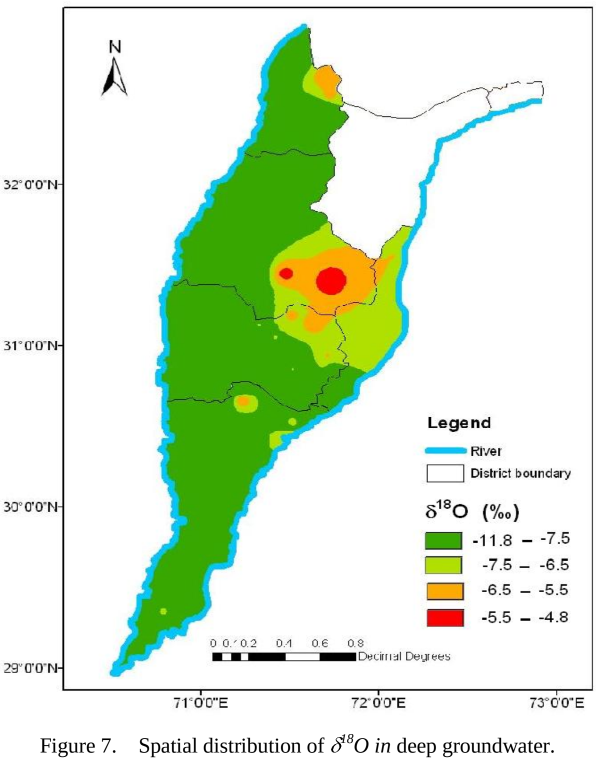

Figure 7. Spatial distribution of $\delta^{18}O$ *in* deep groundwater.

5.3.3. $\delta^{18}O$ and $\delta^{2}H$ Relationship

$\delta^{18}O$ and $\delta^{2}H$ relationship of surface water (river water, RW and canal water, CW) and groundwater samples in comparison with LMWL is plotted in Figure 8 and 9. The δ-plot of shallow groundwater samples shows wide range of isotopic values due to variable isotopic composition of the recharge sources at different times, varying contribution of the recharge sources and some effect of the evaporation on the recharging waters. Most points are scattered around LMWL and are located close to the river points confirming the aquifer replenishment mainly from the rivers. The points falling between the river index and rain index reflect mixing of river and rain recharge. Some samples of this type (mixed recharge) reflect evaporation effect. Samples having enriched values fall close to the rain point suggesting the rain recharge at these stations. Many samples with $\delta^{18}O$ > rain value are distributed below the LMWL showing significant evaporation [4, 5].

$\delta^{18}O$ and $\delta^{2}H$ plot of deep groundwater **(**Figure 10) reveals similar trend as shown by the shallow groundwater. Samples having depleted isotopic values are distributed along the LMWL close to the points representing the rivers and canals. Hence, these locations seem to have major contribution from the surface water. Samples falling in between the river and the rain indices indicate the contribution towards groundwater replenishment from both sources at these locations. Samples having highly enriched isotopic values (rain recharged) generally plot below the LMWL suggesting the significant evaporation of the infiltrating water before recharging the aquifer.

5.4 Groundwater Residence Time

Tritium values of rivers range from 10 to 12 TU which could be considered as the present day tritium content in precipitation in the study area. Tritium values in groundwater range from 0 to 21.2 TU. Tritium activity is found in most of the analyzed samples, which indicates that aquifers are nourished by fresh recharge over most of the doab. In general, groundwater can be divided into following main categories depending upon the tritium values.

a. *0 to 1 TU:* Areas having tritium content in the range of 0 to 1 TU were recharged before atmospheric thermonuclear tests in 1960s releasing a large quantity of tritium into the atmosphere. This is old water having mean residence time (MRT) of more than 50 years [7].

b. *1 to 4 TU:* Tritium content of 1 to 4 TU suggests the mixing of fresh recharge with old water. However, only a small amount of modern water has infiltrated at these locations. The mean residence time of groundwater at these locations is likely to have been longer (40-50 years).

c. *4 to 8 TU:* Groundwater having tritium in the range of 4 to 8 TU is relatively young and contains major fraction of post-1960s water. Areas with groundwater having tritium in this range are related to modern recharge and the groundwater MRT is 20-30 years.

d. *> 8 TU:* Areas where groundwater tritium values are more than 8 TU are associated with recent recharge and groundwater is recent in origin. Mean residence time of such waters is only few years.

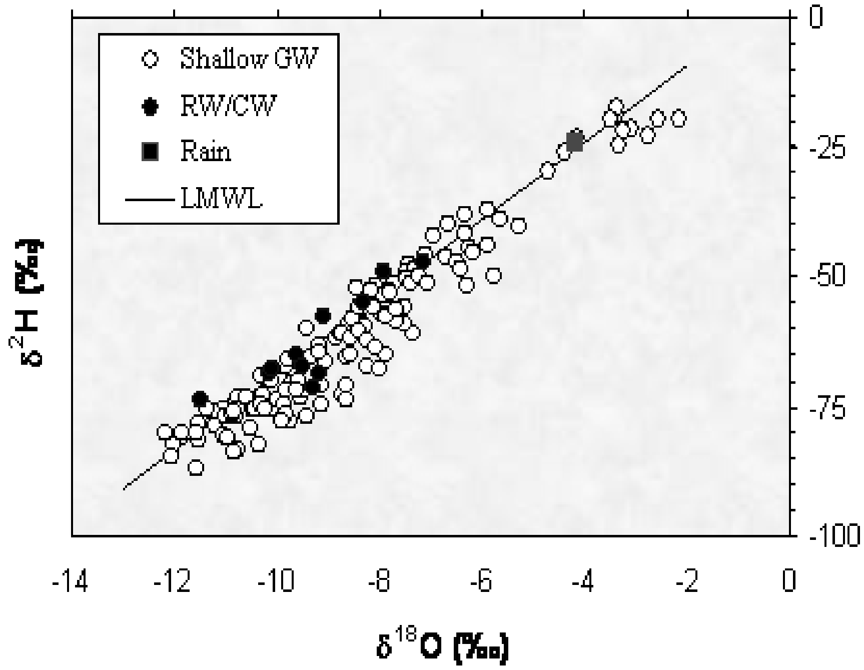

Figure 8. $\delta^{18}O$ vs. $\delta^{2}H$ plot of shallow groundwater.

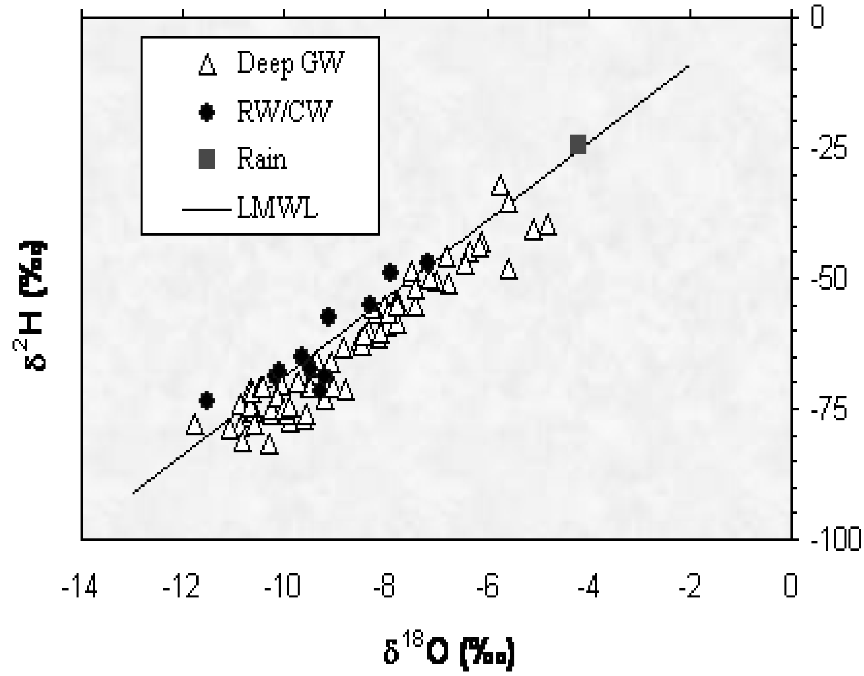

Figure 9. $\delta^{18}O$ vs. $\delta^{2}H$ plot of deep groundwater.

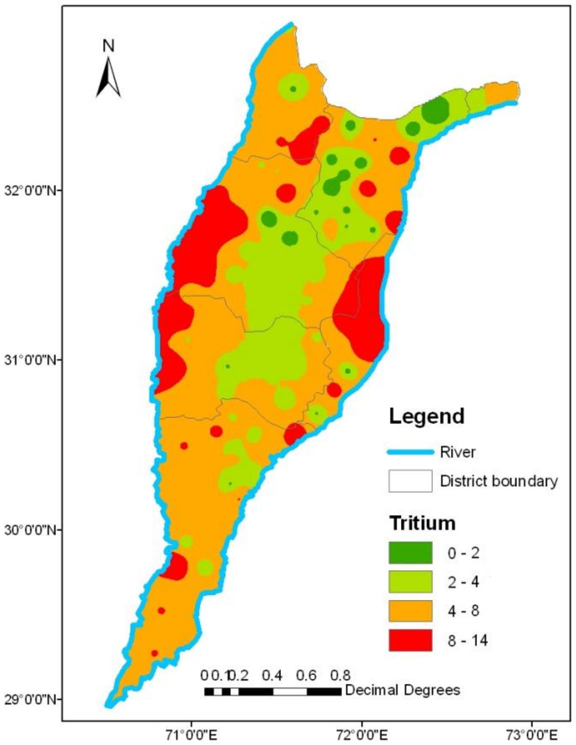

Figure 10. Spatial distribution of tritium (TU) in shallow groundwater.

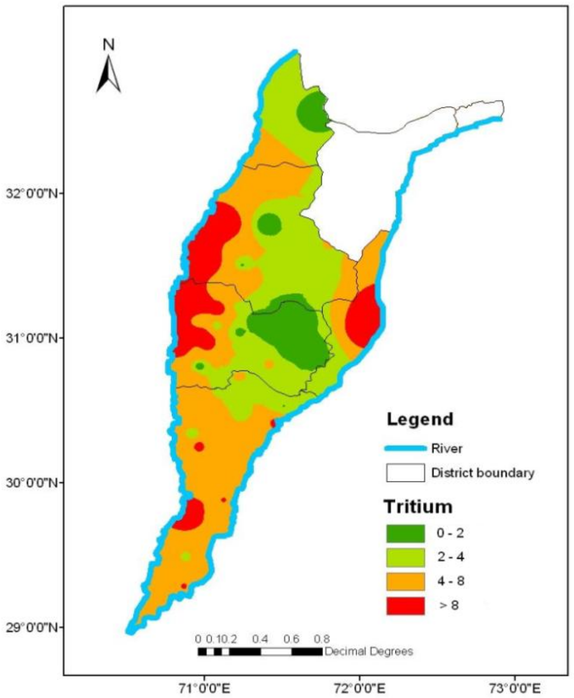

Figure 11. Spatial distribution of tritium (TU) in deep groundwater.

Geographical distribution of above mentioned four categories of water is depicted in Figures 11 and 12. These figures show that sampling locations along the river Indus and in the confluence area generally contain modern to recent groundwater indicating quick recharge. Groundwater in upper middle part of the doab has no or very little tritium. The reason might be the long travel time from a distant area or very slow movement in the unsaturated zone resulting in the loss of tritium activity due to radioactive decay before recharging the aquifer. Hence, groundwater in this zone is old (residence time more than 50 years).

6. Conclusions

Isotopic data clearly demonstrated spatial variations of the isotopic composition of groundwater in Thal Doab aquifers illustrating different recharge sources. By converging all evidences based on environmental isotopes, following conclusions were drawn.

- Shallow groundwater in a small zone in the upper eastern part of the doab between Grot, Distt. Khushab and Hyderabad Thal, Distt. Bhakar is mainly recharged by the rain. Sampling points surrounding the rain fed area show intermediate waters indicating the mixed recharge from rain and surface waters. As we move downwards from the rain-fed area, contribution of rain to groundwater recharge decreases while the rivers/canals contribution increases. At the remaining locations, shallow groundwater is mainly recharged by the rivers either directly or through the canals derived from these rivers.
- Deep groundwater at most of the surveyed locations is recharged by the rivers/canals. As in shallow groundwater, rain influence is limited. Rain appears to be the main source of recharge in upper eastern part of the doab.
- $\delta^{18}O$ values in shallow and deep groundwater show similar geographical distribution pattern proving that they are interconnected and have same recharge mechanism.
- Tritium activity is found in most of the analyzed samples, which indicates that aquifers are nourished by fresh recharge over most of the doab.
- Groundwater (shallow and deep) has different age / residence time at various locations. The river recharged areas generally contain young groundwater indicating relatively quick recharge. Groundwater in Thal Desert is generally old and residence time of groundwater at these locations is more than 50 years.

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