Evaluation of effectiveness of artificial recharge measures in parts of Maharashtra using environmental isotopes

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India has good average annual precipitation, but its poor distribution in space and time has led to the scarcity of groundwater in many areas. Artificial recharge to groundwater requires a composite procedure along with detailed morphometric and hydrogeological studies of the area. In Maharashtra State, a programme was initiated to recharge the groundwater by making a cascade of earthen bunds, recharge ponds and using disused open wells. The effectiveness of artificial recharge programmes was evaluated by employing environmental isotopes (^{3}H, ^{18}O and D) in Ozar watershed whereas recharge zones and effectiveness of different recharge sources were evaluated in BM-60 and Bamnod watersheds.

^{18}O and ^{3}H isotopes revealed that the groundwater storage in Ozar watershed remains less and the contribution of canal water was found minimum during July and maximum during October (about 100%). Similarly, the isotopic signatures of groundwater in BM-60 indicate that the precipitation is the main source of recharge to groundwater in the BM-60 watershed and the contribution of other sources is minimal. The higher values of environmental tritium in Bamnod watershed revealed the contribution of artificial recharge that was carried out through Hatnur Canal on casual basis.

Keywords: Artificial recharge, environmental isotopes, origin of groundwater, watershed.

ARTIFICIAL recharge has been defined in many ways, varying with points of view and evolution of applications and methods. It has been defined by Todd as 'the practice of increasing by artificial means the amount of water that enters a groundwater reservoir'. These artificial means include various forms of surface infiltration and direct well injection. Artificial recharge is considered as a tool for water management whereby water is introduced in the aquifers and is stored there. And when demand for water increases, the additional stored water is withdrawn.

The indiscriminate and sometimes excessive use of groundwater has led to questions regarding its sustainability. To what extent can groundwater be exploited without unduly compromising the principle of sustainable development? The sustainability of groundwater utilization must be assessed from an interdisciplinary perspective where hydrology, ecology, geomorphology and climatology play an important role. Depletion of groundwater table at a faster rate in most of the urbanized areas has drawn the attention of water resources managers. This situation has also arisen in areas where surface water bodies such as rivers, canals and natural or artificial lakes/reservoirs do not exist. In order to mitigate the increasing shortage of groundwater, artificial recharge of groundwater by making earthen bunds, through injection wells or roof top rainwater harvesting programmes have been given priority by the concerned organizations and individuals. However, the effectiveness of these programmes has not been assessed at the desired scale as it is difficult to do so using conventional techniques. Isotope techniques have the potential to assess the effectiveness of these programmes using environmental isotopes.

Maharashtra is one of the highly industrially progressive states of India. Owing to the rapid growth in the agro-industrial economy during the last three decades, the demand for water resources, both surface and groundwater, has spirally increased in the state. Similarly, the population growth has put both surface water and groundwater supply systems under great stress. Intensive groundwater development has led to a rather critical situation and manifestation of the problems like declining groundwater levels. This situation has been further aggravated by the hydrogeological setup covering 92% area by hard rocks and uneven distribution of rainfall frequently causing drought situation in the state.

The detailed hydrogeological investigations carried out in three watersheds namely, Bamnod in Jalgaon, Ozar in Nasik and Baramati (BM-60) in Pune by the Groundwater Survey and Development Agency (GSDA), Pune,

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Maharashtra, revealed that the groundwater level is decreasing in wells at least by 1–2 m annually in the Bamnod and other watersheds. The sample survey in the area also revealed that the depth of wells in general increased by 18–30 m when compared to the depths in 1974. This has resulted not only in increasing the depth of wells but also lowering the level of pumping sets. The declining trend of water levels apparently led to the conclusion that unless additional water is added to the present groundwater system, the withdrawal of groundwater at the present rate soon would become unfeasible. Therefore, GSDA, Pune initiated projects on recharging groundwater by artificial means, i.e. adopting well injection technique on experimental basis in Bamnod watershed using disused open dug wells. Hatnur canal water was supplied for this purpose with the assistance of the Bamnod Lift Irrigation Society of farmers. The results of the pilot studies were found encouraging as the unsaturated aquifers tapped in open wells were found to have very good intake capacity. The artificial recharge of groundwater by storing surplus irrigation water in Bandharas (small section by making earthen bunds) was adopted in hard rock areas of central Maharashtra, i.e. in Ozar watershed.

Artificial recharge requires a composite procedure and deep knowledge of the geological structure, more specifically the detailed morphotectonic and hydrogeological study of the area[1,2]. Stable isotopes (D and ^{18}O), tritium and chloride have been used in various semi-arid and arid regions for the study of artificial recharge[3–8]. From various studies, it has been proved that isotope techniques provide more accurate recharge values than conventional methods[9] for aquifer management. Besides the natural recharge estimations, these isotopes can also be used to estimate recharge from artificial structures[10–14]. Artificial recharge methods aim to enhance natural recharge in order to increase the amount of available groundwater. These include surface recharge (e.g. water spreading and recharging through pits and basins[15], and well injection[16–18]). Artificial recharge has also been practised to reduce, balance, or reverse saltwater intrusion by freshwater storage in aquifers[19]. Taking advantage of physical, chemical, and biological processes occurring within the soil, artificial recharge has been successfully applied to potable water production[20], improving groundwater and lake water quality for non-potable reuse[21], and waste water treatment[22–24]. Surface artificial recharge of groundwater requires permeable topsoil (sandy loam, sand and gravel) and an unsaturated zone without extremely low-permeability layers (e.g. clay and silt) that could cause development of perched groundwater and aquifer with sufficient lateral flow through it, to prevent excessive mounding. Vegetation, such as grass or other shallow-rooted plants, increases deep percolation of water through the soil[17]. The thickness of the unsaturated zone is an important factor to achieve a sufficient contact time between soil and water. A thick unsaturated zone also prevents ground water interference with the infiltration process.

Artificial groundwater recharge tests evaluated the effects of the recharge on the groundwater quality at the Gaobeidian Sewage Treatment Plant using treated municipal secondary effluents. The sodium adsorption ratio (SAR) was used to indicate the impact of the artificial groundwater recharge on the soil properties. The results demonstrate that the unsaturated zone of the soil aquifer exhibited favourable elimination of dissolved organic carbon (DOC), ammonia and nitrogen[25]. Bioremediation, phyto-technology and artificial groundwater recharge have proven effective in industrialized countries. They also have great potential for use in the developing world[26]. Artificial recharge of groundwater through geologic formations is of interest in Jordan as it is a proven water resource management technique that increases the efficiency of water use. The research produced designs for an integrated system of seven 2.5 m dykes and one 5 m dam with a total potential recharge volume of 500,000 cubic metres. Once constructed, these multistage reservoirs will conserve part of the water being lost and will provide additional groundwater for future use. The research fills a gap in the lack of standard designs that can be expanded and replicated in other areas in Jordan and elsewhere[27].

Artificial groundwater was produced using sprinkling infiltration through the forest floor. The result of lake water infiltration through the organic horizon and 1 m thick mineral soil layer was a slight increase in the DOC concentrations from 9.4 mg/l in the infiltration water to 13.2 mg/l in percolation water. This indicates that the forest soil represents a potential input of organic matter into infiltration water. However, the DOC concentrations decreased by 27–38% as the infiltration water percolated down through the unsaturated soil layer into the groundwater zone. At a distance of 1450 m from the infiltration area, the mean DOC concentration in the groundwater was below the recommended value for drinking water (2.0 mg/l) in Finland. There was a strong reduction in the concentrations of hydrophilic and hydrophobic acids, but only a slight decrease in hydrophilic neutral organic compounds during the infiltration process. The DOC in the production well consisted of low molecular size fractions. Larger molecular size fractions were removed effectively from the water during the infiltration process[28].

A conceptual reservoir model based on production and transfer functions with spatial discretization was used to simulate flood-wave propagation and infiltration along the Zeroud (Tunisia). After calibration with six flood events, the model produced satisfactory results. Though current data scarcity prevents its validation, the model constitutes a prototype for the evaluation of recharge efficiency and for the prediction of recharge impact on Kairouan aquifers[29].

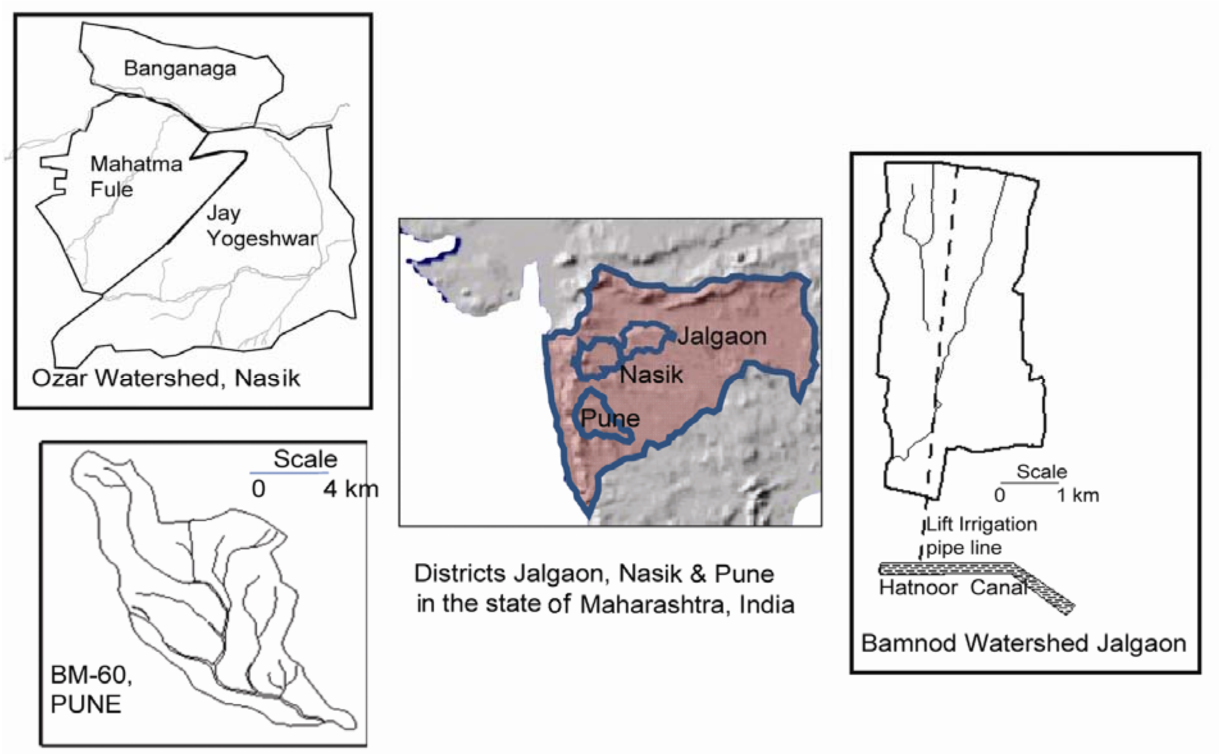

Figure 1. Location of Ozar, BM-60 and Bamnod watersheds in Maharashtra.

In the present study, environmental isotopes like, tritium (^{3}H), deuterium (^{2}H or D) and oxygen-18 (^{18}O) are used to evaluate the effectiveness of artificial recharge measures, particularly in Ozar watershed where the artificial recharge is being practised through earthen channels. The artificial recharge practice in Bamnod watershed was carried out on experimental basis through injection well in 1997, but now it is done only when the need arises. Therefore, the investigations were carried out in Bamnod (Jalgaon) and BM-60 (Pune) watersheds to identify the major recharge source and recharge zones for the existing aquifers.

Study area

The Bamnod area lies between the lat. 21°8′–21°10′N and long. 75°48′–75°50′E. It falls in Yawal taluka of Jalgaon district, Maharashtra. It is located in the extreme south–east corner of the watershed TE-11 (designated and numbered by GSDA) of Tapi basin. The wells pertinent to the recharge study are within the command area of Bamnod Co-operative Lift Irrigation Society, Bamnod. Total area of the village is 1373 ha. The area is famous for banana cultivation. The Ozar area is lying between the lat. 20°04′–20°05′N and long. 76°54′–76°56′E. It comprises parts of Niphad taluka of Nasik district, Maharashtra. It is located in the watershed GV 7 (designated and numbered by GSDA) of Godavari basin. The area is approachable and connected by road and lies on Mumbai–Agra Highway at a distance of 20 km from Nasik. Mahatma Phule Society and Jai Yogeshwar Society operate in the watershed for taking measures required for artificial recharge to aquifers. The BM-60 watershed lies between the lat. 18°15′–18°25′N and long. 74°13′–74°28′E. It covers a part of Purandar taluka and Baramati taluka in Pune district. The watershed BM-60 shows semi-arid climate and falls in the drought-prone areas according to the agroclimatic zonation. The watershed can be broadly classified geographically as moderately dissected plateau having a maximum elevation of 821 m above mean sea level (amsl). River Karha flows west to east in the watershed. The major streams in the watershed exhibit exceptionally straight drainage course and an abrupt change in flow direction, that indicates structural control over the drainage course. The study area indicating all the three watersheds separately is shown in Figure 1.

Hydrogeology

The Ozar watershed comprises weathered, fractured, brownish, amygdeloidal basalt. This is followed by hard compact massive basalt. Hence, only phreatic aquifer is predominating in this area. The maximum thickness of the aquifer is 15 m. This aquifer saturates during monsoon only depending upon the amount of precipitation. As the monsoon recedes, desaturation of the aquifer resumes. The area is drained by river Banganga that flows through the northern part. It flows from west to east and its river-bed is rocky. It is also drained by two drains; one flows from Mahatma Phule Society area whereas other flows through Jai Yogeshwar Society. The elevation between these two through which the river flows ranges from 601 to 588 m. On the left bank of the river, the Banganga Society area exists whereas on the right bank, the Mahatma Phule Society and the Jai Yogeshwar Society areas are located. The river as well as drains are seasonal. The average annual rainfall in Ozar watershed is only 427 mm. Massive basaltic flow units in BM-60 watershed vary in nature from hard massive compact fine-grained basalts to porphyritic basalt, jointed irregularly with two to three sets of joints. The massive basalt is highly weathered on the surface and shows calcareous inclusions along joints. At places a massive trap shows spheroidal weathering on top. There are large numbers of dug wells in BM-60 watershed in depth range between 8.00 and 19.00 m on an average. The pre-monsoon static water level varies from 3.50 to 13.00 m below ground level (bgl). The post-monsoon static water levels range between 1.50 and 5.0 m bgl. The predominant aquifer system consists of weathered basalt jointed basalt and contact zone. Phreatic aquifer occurs up to a depth of 20 m bgl which is underlained by semiconfined aquifer system which ranges up to 40 m depth. The normal annual rainfall is 470 mm, 85% of which occurs during the monsoon season.

Bamnod is the part of Tapi valley that comprises mainly alluvium with clay, silt, sand, gravel and pebbles. The alluvium is broadly divided into younger alluvium occurring up to 80 m below ground level and older alluvium beyond 80 m. The principal water-bearing formation in Bamnod is alluvium where granular zones are encountered at various depths. Groundwater in the area generally occurs under unconfined conditions at shallow depth and under semi-confined to confined conditions at deeper levels. In alluvium, multiaquifer systems are present where each aquifer is separated by confining clayey formation. The thickness of granular zone varies from 4 to 15 m. There are 215 irrigation wells in the project area of which 120 wells are in disused condition due to lowering of groundwater table. The depth of disused wells ranges between 20 and 30 m. The wells in operation are in the depth range between 30 and 50 m. The static water levels range between 27.5 and 48 m bgl. The area receives rainfall from southwest monsoon, which begins from middle of June and lasts up to the end of September. The area receives average annual precipitation of about 768 mm. Good network of pipelines for water conveyance is available in the command area of Bamnod under the Co-operative Lift Irrigation Scheme. An experiment of well injection was carried out for nine days in area during February 1997, where about 12,945 cubic metres of surface water was injected into the sandy aquifers at the rate of 900 LPM. The experiment was considered successful because the water injected continuously for nine days was absorbed by the sandy shallow aquifers.

Methodology

Environmental isotopes such as deuterium, oxygen-18 and tritium are used to understand the contribution of different recharge sources and to identify the recharge zones of aquifers. Groundwater, rainwater, canal and impounded water (in earthen channels) samples were collected for oxygen-18, deuterium and environmental tritium isotopes analyses. The isotope indices for groundwater, precipitation and canal water were determined separately for each watershed. The variation of oxygen-18 values with time and location was studied in each watershed, particularly in Ozar watershed where artificial recharge is being practised by supplying Hatnur Canal water in small channels. The environmental tritium contours were also plotted for Bamnod and BM-60 watersheds to understand the flow direction and recharge areas.

Results and discussion

Ozar watershed, Nasik

The results of δ^{18}O analysis for groundwater, precipitation and canal water samples are given in Table 1. The distribution of δ^{18}O in groundwater and the groundwater flow pattern in the Ozar watershed is shown in Figure 2. The environmental tritium contents in the groundwater samples, measured using Ultra Low Level Liquid Scintillation Counter, were found in the range of 14–16 Tritium Unit (TU). These values are comparable to the Hatnur Canal (~12.6 TU), the water of which is used for artificial recharge through earthen channels, and much different from the rainfall in the area which shows a typical value within the range of 5–6 TU. The Hantur Canal originates from the Tapi River which drained a large area. Therefore, it can have different TU values (high and low) depending upon the sources of water and time period. We have observed high TU values in canal water. The groundwater, being mostly recharged through the canal water, also has TU values comparable to canal water. However, the TU values of canal water might be higher during certain other period during which samples could not be collected, but the higher values of groundwater reflect it. The TU in rainwater could not be observed more than 5 TU in Ozar watershed. Therefore, it is inferred that the groundwater is dominated by recharge from canal water through earthen channels and rainfall recharge component is comparatively less. Moreover, the data reflect that the groundwater is young with negligible aquifer storage.

Table 1. Results of $\delta^{18}O$ for groundwater, precipitation and canal water samples collected from Ozar watershed

		$\delta^{18}O$ (‰)				
Society	Well no.	June 2000	July 2000	August 2000	September 2000	October 2000
Mahatma Phule	M-1	–1.7	–0.8	–1.3	–0.5	0.1
Mahatma Phule	M-11	–0.9	0.0	–0.9	–0.4	–0.5
Banganga	B-1	–1.5	–0.5	0.3	–1.1	1.8
Banganga	B-3	–1.6	–0.8	0.0	–0.4	–0.2
Jai Yogeshwar	J-1	–1.1		–1.1	–1.3	–1.3
Jai Yogeshwar	J-4	–1.0	–0.7	–1.2	–1.2	–0.6
Jai Yogeshwar	J-6	–2.2	–0.3	–1.2		–1.6
Jai Yogeshwar	J-8	–1.2	–1.3	–0.4	–1.2	–1.1
Average of well samples		–1.4	–0.6	–0.7	–0.9	–0.4
Rain		–4.7	–2.7	–4.4	–3.3	–
Earthen channel	Near M1	–0.4	–0.7	0.5	0.3	0.6
Earthen channel	Near B3	–0.3	–1.4	0.6	–0.4	–0.9
Earthen channel	Near J-1	–1.2	–1.0	0.65	0.0	–0.8
Average of channel samples		–0.6	–1.0	0.6	0.0	–0.4

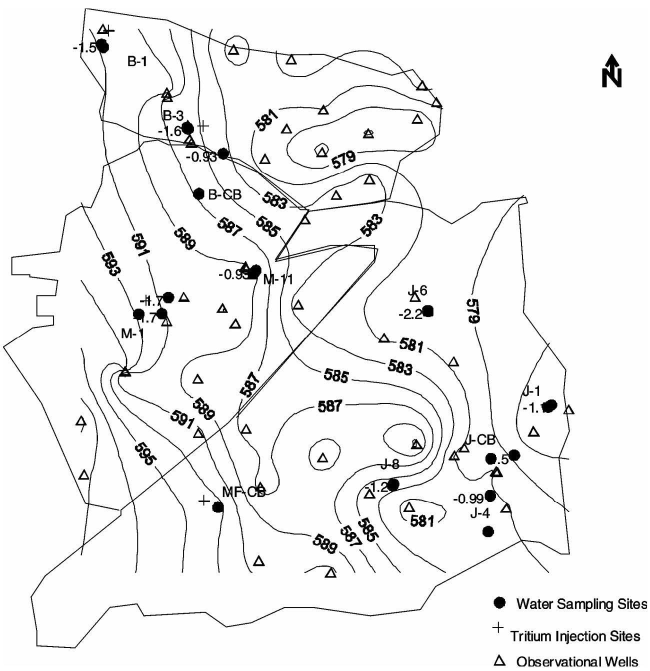

Figure 2. Groundwater level contours (msl values) in the post-monsoon season of 1997 and stable isotope ($\delta^{18}O$) composition (‰) of groundwater in the Ozar watershed, Nasik.

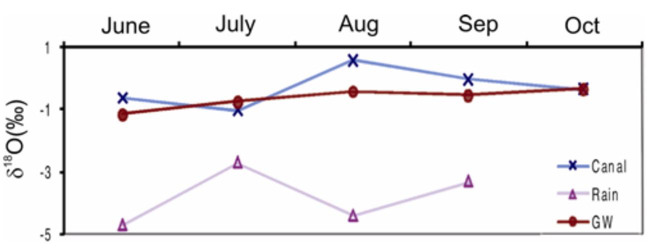

Figure 3. Variation of $\delta^{18}O$ of channel water, groundwater and precipitation with time in Ozar watershed, Nasik.

It is seen from Table 1 that the most depleted and enriched $\delta^{18}O$ values of the groundwater in Ozar watershed are –2.2‰ and 0.0‰ respectively. If we compare the monthly average values of $\delta^{18}O$ (neglecting spatial variations) of groundwater with the surface impoundment, i.e. the earthen channels that carry canal water, it is seen that the groundwater is more depleted in June, than the surface water (Figure 3). This indicates the effect of evaporation on surface water that results in the enrichment of isotopic composition. In July, the isotopic values of both systems get closer probably due to mixing of water from earthen channels that infiltrated during the month of June as enrichment in isotopic composition of groundwater is clearly seen (Figure 3).

The evaporation effect further enriched isotopic contents of small quantity of water stored in channels due to no supply from canal during the month of August, whereas the groundwater also shows a little enriching trend due to delayed contribution from precipitation and channel water.

In September, the input from the canal is provided to the earthen channels and the isotopic contents of channel water comparatively depletes and continue so in the Ozar watershed. However, the $\delta^{18}O$ of groundwater in October is found identical to that of the earthen channel in the Ozar watershed. This fact clearly indicates that major recharge to the groundwater is from the impoundments across the channels locally called as Bandharas. The contribution of rainfall or canal (channel) to groundwater is determined using the following relation based on $\delta^{18}O$ values of end members.

$$m_{ch} = (\delta^{18}O_{gw} - \delta^{18}O_{p})/(\delta^{18}O_{ch} - \delta^{18}O_{p})$$

or

$$m_{p} = (\delta^{18}O_{gw} - \delta^{18}O_{ch})/(\delta^{18}O_{p} - \delta^{18}O_{ch}),$$

where m_p and m_{ch} are the contributions of precipitation and channel water to groundwater respectively; whereas $\delta^{18}O_{gw}$, $\delta^{18}O_p$ and $\delta^{18}O_{ch}$ are the corresponding oxygen-18 values of groundwater, precipitation and channel water (Table 2).

Figure 4 indicates the percentage of contribution of rainfall to groundwater in Ozar watershed. The percentage of artificial recharge to groundwater through earthen channels can be estimated by subtracting percentage of rainfall recharge from 100 as shown in Figure 4. A straight line relation between the amount of rainfall and $\delta^{18}O_p$ values also enables to determine the percentage of contribution of rainfall to groundwater.

BM-60 watershed, Pune

The environmental tritium contents of groundwater ranges from 0.0 to 10 TU. Higher values of environmental tritium in groundwater are found in the Rise village whereas lower values are found near the lower southwestern parts of the study area (near Sherichiwadi and Baburdi). The tritium contours (Figure 5) indicate that the general groundwater flow direction is from northwest to southeast. However, there seems to be a break in the flow near the central portion, i.e. near Borkarwadi. It may be due to some structural control on the flow regime. The main drain that takes a west–east trend from the general north–south flow direction also proves the existence of the structural control in the study area as indicated above. The tritium analysis of rainwater samples show values in the range of 3–5 TU (Table 3). Therefore, the groundwater seems to be generated through infiltration of precipitation at most of the places. However, the higher values found at a few sites in groundwater samples may not be explained by the recharge of rainwater alone. The Karha River that flows through the watershed may be the other possible source of groundwater recharge at some places, but it carries only surface runoff of the precipitation falling in watershed. Therefore, the higher tritium values in groundwater may be due to recharge through precipitation in other seasons for which the samples could not be collected. The results of $\delta^{18}O$ analysis of BM-60 watershed are presented in Table 4.

The geological control is also seen in $\delta^{18}O$ contours near the site Borkarwadi as revealed by environmental tritium contours as shown in Figure 5. The evaporation effect at some sites is clearly seen due to recharge from the storage tanks.

The frequency histogram (Figure 6) shows that the stable isotopic index ($\delta^{18}O$) of the groundwater is about –1.8‰. However, the depleted values of –3.4% to –3.6‰ found in groundwater (comparable to the values observed in precipitation) occurring near the lower parts, i.e. the south-eastern portion of the study area near Baburdi and Sherichiwadi may be the result of quick recharge due to precipitation with negligible effect of evaporation during infiltration. It is clear in the plot of $\delta^{18}O$ vs δD where the depleted values fall on the local meteoric waterline and groundwater line as shown in Figure 7. Therefore, it is clear that precipitation is the only source of recharge in the BM-60 watershed with an increased recharge to groundwater from storage tanks. The $\delta^{18}O$ contours are shown in Figure 8 for February 2001.

Table 2. Recharge percentage due to canal water supplied through channels and rainfall in different months

Recharge in (%) due to	June	August	September	October
Canal or channel (m_{ch})	80	74	73	100
Rainfall (m_p)	20	26	27	0

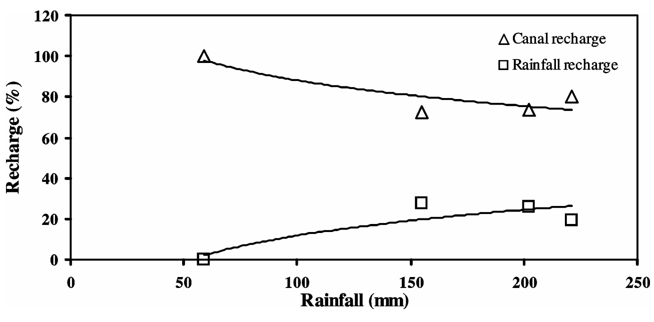

Figure 4. Percentage of recharge to groundwater due to rainfall and canal water in Ozar watershed, Nasik.

Bamnod watershed, Jalgaon

The samples of groundwater, precipitation and canal water collected from Bamnod watershed were analysed for environmental tritium contents. It is seen from the tritium data (Table 5) that the groundwater in Bamnod

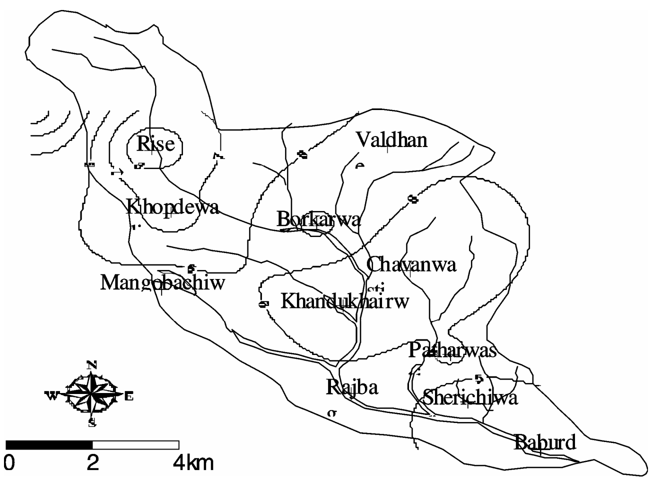

Figure 5. Environmental tritium contours in BM-60 watershed.

Table 3. Tritium data of groundwater and rainwater samples collected from BM-60 watershed (2000–01)

Village/Wadi	Elevation (m amsl)	TU						
		August 2000	October 2000	February 2001	June 2001	July 2001	August 2001	Average
Baburdi	602	4.7		5.9	3.7	3.6		4.5
Sherichiwadi	607	4.1						4.1
Rajbaug	615							
Chandgudewadi	619		5.0					5.0
Patharwasti	620					6.1		6.1
MangobachiWadi	623		6.1	7.0	3.6	6.6	5.6	5.8
Chavanwasti	630	0.0			5.3	15.3		6.9
AmbhiKH	637			4.9				4.9
AmbhiKH	637					5.9		5.9
Borkarwadi	638	3.2			4.7	5.9	5.6	4.9
Rise	656				10.2	9.0	7.0	8.7
Khopdewadi	656			9.3	8.0	7.9	4.1	7.3
BagwastiU/V Chandgu	665	4.2			5.1	5.3	5.8	5.1
Naigaon	680					5.4	7.3	6.4
Rajuri	695	5.8		2.6	1.6	0.5		2.6
Malshiras	714							
Khandukhairewasti	627	6.8		7.2				7.0
Kutwalwadi					6.7	5.4	5.4	5.8
Rain						2.7		2.7
Rain						4.4		4.4
Rain						3.3		3.3

Table 4. Results of $\delta^{18}O$ for groundwater, precipitation samples collected from BM-60 watershed

Village/Wadi	$\delta^{18}O$ (‰)			
	June 2000	August 2000	October 2000	February 2000
Baburdi		–3.1	–3.2	–0.2
Sherichiwadi	–3.6		–3.4	
Rajbaug	–2.0	–0.9	–1.6	–1.7
Chandgude Wadi	–1.1	–3.6		
Pathar Wasti	–1.9		–1.9	–2.6
Mangobachi Wadi	–1.7	–1.7	–2.0	–2.8
Chavan Wasti	–1.6	–1.8	–0.2	–2.5
Ambhi KH	–3.0	–3.7	–1.8	–2.5
Ambhi KH			–2.8	
Borkar Wadi	–1.8	–1.3		–0.9
Rise	–2.1	–0.6	0.5	–2.7
Khopdewadi	–1.7			–0.8
Bagwasti U/V Chandgu	–1.5	–1.4		–1.8
Naigaon	– 2.5	–2.0		–1.4
Rajuri	–3.0	–2.0		–2.0
Malshiras	–0.9	–1.5		–1.6
Khandukhaire Wasti	–2.0	–2.1		–3.0
Kutwal Wadi	–2.2			
Rain	–4.7	–2.7	–4.4	–3.3

watershed exhibits large variation in tritium contents indicating different ages (residence time) of groundwater. The highest value of tritium content is about 15.7 TU (April) found near the well no. OBW8, whereas the lowest value is about 1.29 TU (June) near OBW14. This indicates that the groundwater occurring near well no. OBW8 is new whereas that occurring near the well no. OBW 14 is comparatively older in the watershed. The high TU values observed once in the watershed may be due to the supply of canal water used during the past for artificial recharge through injection wells which might be having high tritium contents as also observed at present (~12.6 TU). The environmental tritium distribution plot (Figure 9) shows that the general groundwater flow direction is from northwest to southeast. Because the tritium input function is not available, a value of 8 TU (June) may be considered as the initial value of environmental tritium for estimating the uncorrected age of the groundwater. Therefore, the age of the water encountered at well no. OBW14 with a tritium value of 1.29 TU is about 32 years. However, this estimated age has to be used with caution as the initial activity has been assumed as 8 TU, which may not be exact. If we adopt the piston flow model with the assumption applicable, then the average groundwater flow velocity may be computed as the ratio of age difference to the distance travelled. Since the distance between the well nos OBW8 and OBW14, is about 2.8 km, the groundwater flow velocity comes about 0.24 m/d or 2.77×10^{-6} m/s.

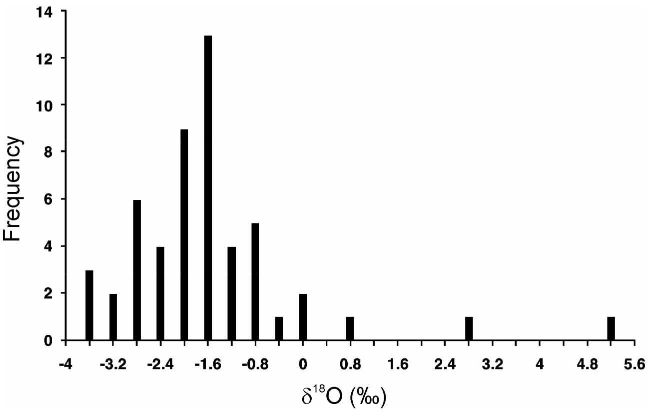

Figure 6. δ^{18}O index of groundwater in Baramati (BM-60) watershed, Pune.

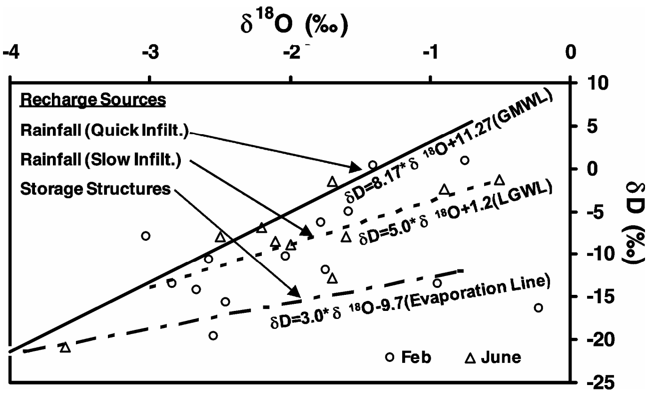

Figure 7. Isotopic characterization of groundwater from BM-60 watershed, Pune.

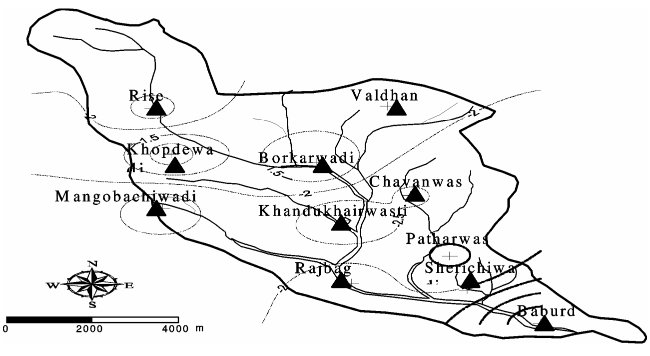

Figure 8. δ^{18}O‰ contours in BM-60 watershed, Pune.

Conclusions

The following conclusions are drawn on the basis of variations observed in environmental isotopic data (tritium, oxygen-18 and deuterium) in the watersheds.

- The average isotopic compositions (δ^{18}O) of channel water, groundwater and rainwater in Ozar watershed are ~ –0.3‰, –0.64‰ and –3.7‰ respectively and the percentage of contribution of artificial recharge to groundwater through channels vary from 10 to 100 with respect to time.
- Enrichment and depletion in the isotopic composition of precipitation is due to the 'amount and seasonal effects' as the secondary evaporation enriches rainwater during the light rains compared to the heavy rain-storms. This further varies with the atmospheric temperature in different seasons.
- Phase lag between the isotopic peaks and troughs amongst the precipitation, groundwater and canal water in Ozar watershed is due to time delay in infiltration process. In addition to the peak shift, the channel water in general is more enriched compared to the rainwater due to its evaporation during long travel and storage at few places in the channels.

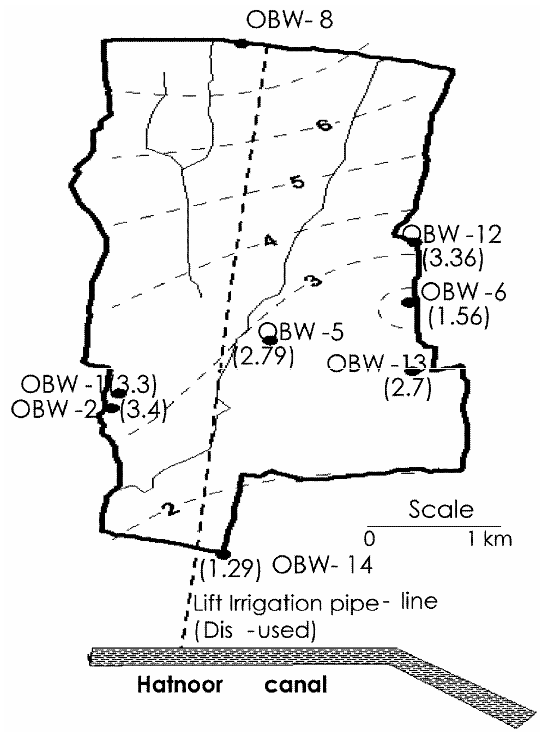

Figure 9. Environmental tritium contours in Bamnod watershed, Jalgaon.

Table 5. Environmental tritium data of groundwater and rainwater samples from Bamnod watershed

				TU				
Gat no.	Well no.	Cultivator	Depth	April 2000	June 2000	July 2000	September 2000	Average
666	OBW2	CJ Talele		8.0	3.3			5.6
1317	OBW5	Zambore	59			2.8	2.8	2.8
1047	OBW8	Bhole	44	15.7				15.7
1390	OBW12		38		1.6			1.6
1399	OBW12	PG Bhirud			3.4			3.4
1470	OBW13	JW Nehete	60	5.8	2.7			4.2
510	OBW14	PWS well	56		1.3		1.29	1.2
	Rainwater	Jalgaon				4.7		4.7
	Canal	Hatnur		12.6			7.3	10.0

- Continuous refreshing of groundwater due to recharge from the channels turns up the average isotopic composition of groundwater in the Ozar watershed similar to the channel water.
- Using the isotopic mass balance approach for the channel water, groundwater and rainwater, the estimated average precipitation input to the groundwater during the monsoon season (June–September) is ~30% while the channel water plays a dominant role in recharging groundwater in Ozar watershed.
- Rainwater is the major source of recharge in Baramati (BM-60) watershed with a good impact of storage structures, constructed in the watershed on groundwater recharge.
- The general groundwater flow direction in the Baramati watershed is from northwest to southeast. However, there seems to be a break in the flow near the central portion, i.e. near Borkarwadi due to some structural control.
- It is seen from the tritium data that the groundwater in Bamnod watershed exhibits large variation in tritium contents (15.7–1.29 TU) and the general groundwater flow direction is from northwest to southeast. Therefore, the recharge area lies in the northwest side of the watershed.
- Precipitation is the main source of groundwater recharge with the influence of canal water that is used for artificial recharge on casual basis. The average groundwater flow velocity in the Bamnod watershed is about 0.24 m/d or 2.77×10^{-6} m/s.

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