Determination of specific yield using a water balance approach – case study of Torla Odha watershed in the Deccan Trap province, Maharastra State, India

Dipankar Saha · A. K. Agrawal

Abstract Specific yield is an essential parameter for any groundwater management plan. Volumetric analysis in the domain of groundwater budgeting for the non-monsoon months has been undertaken for a typical watershed of the Deccan basalt province. The Torla Odha watershed covers an area of over 22 km^2 on a third-order tributary of the westerly flowing Bhima River. The watershed receives a normal annual rainfall of 643 mm. The entire water demand is supplied by dug wells, which penetrate a shallow aquifer. The specific yield was estimated by comparing the monthly net volume of water removed from the aquifer, with the volume of aquifer de-saturated, based on monthly water level data. The estimated specific yield ranges from 0.0019 in May to 0.0173 in November with an average value of 0.0093. A correlation of the groundwater levels with the detailed geology suggests that the higher specific yield value (0.017) corresponds to dewatering of the weathered zone within the shallow aquifer. The specific yield of the massive basalt immediately below the weathered zone varies from 0.0089 to 0.0103. The underlying vesicular basalt, which is dissected by sheet joints, has a relatively higher specific yield (0.0121). The massive basalt, which forms the base of the shallow aquifer system, has a lower specific yield from 0.0019 to 0.0022.

Résumé Le débit spécifique est un paramètre essentiel pour tout plan de gestion des eaux souterraines. Les analyses volumétriques, dans le cadre des bilans hydriques des eaux en dehors des mois de mousson, ont été entreprises pour un bassin-versant typique de la province basaltique du Deccan. Le bassin-versant du Torla Odha couvre une superficie de 22 km^2, et alimente l'affluent du troisième ordre de la rivière Bhima, qui coule vers l'Ouest. La pluviométrie annuelle atteint 643 mm. Toute la demande en eau es assurée par des puits foncés pénétrant dans l'aquifère phréatique.

Le débit spécifique a été estimé en comparant le volume net mensuel d'eau captée dans l'aquifère, avec le volume de l'aquifère dé-saturé, basé sur les données des niveaux piézométriques mensuels. Le débit spécifique estimé s'étend entre 0,0019 en Mai et 0.173 en Novembre; la moyenne se situe à 0,0093. Une corrélation entre les niveaux des eaux souterraines et la géologie, suggère que les débits spécifiques les plus importants (0,017) correspondent aux zones altérées de l'aquifère phréatique. Le débit spécifique du massif basaltique, immédiatement sous la zone altérée, varie entre 0,0089 et 0,0103. Le basalte vésiculaire, situé juste en dessous et traversé par des diaclases parallèles, possède un débit spécifique sensiblement plus élevé (0,0121). Le basalte massif, qui forme la base de l'aquifère phréatique, possède un débit spécifique moins important, compris entre 0,0019 et 0,0022.

Resumen El rendimiento específico es un parámetro esencial para cualquier plan de manejo de aguas subterráneas. Se ha llevado a cabo el análisis volumétrico, en el entorno de balance de aguas subterráneas, para los meses sin monzón de una cuenca típica de la provincia de basaltos Deccan. La cuenca Rorla Odha cubre un área de 22 km^2 en un tributario de tercer orden del Río Bhima que fluye al oeste. La cuenca capta una lluvia anual normal de 643 mm. La totalidad de la demanda de agua es abastecida por pozos manuales que penetran un acuífero somero. Se estimó el rendimiento específico al comparar el volumen neto mensual de agua removido del acuífero con el volumen de agua de-saturado estimado a partir de datos de niveles de agua mensuales. Los valores estimados de rendimiento específico varían de 0.0019 en mayo a 0.0173 en noviembre con un valor promedio de 0.0093. La correlación de niveles de agua subterránea con la geología de detalle sugieren que el valor más alto (0.017) de rendimiento específico corresponden con el desaguado de la zona de intemperismo dentro del acuífero somero. El rendimiento específico del basalto masivo que se encuentra inmediatamente debajo de la zona de intemperismo varía de 0.0089 a 0.0103. El basalto vesicular subyacente, el cual está disectado por fracturas laminares, tiene un rendimiento específico relativamente más alto (0.0121). El basalto masivo, que forma la base del

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sistema de acuífero somero, tiene un rendimiento específico más bajo el cual varía de 0.0019 a 0.0022.

Palabras clave: basalto Deccan · India · Rendimiento específico · Recarga de agua subterránea · Balance hídrico.

Keywords Deccan basalt · India · Specific yield · Groundwater recharge · Water budget

Introduction

Continental flood basalts are widespread in various parts of the world. Spatially, the Deccan basalt (Deccan Trap) province is the fourth largest in the world in areal extent covering about 0.5×10^6 km^2 in the western part of the Indian subcontinent. The age of outpouring of this basalt was estimated to be 60–65 Ma (Duncan and Pyle 1988) with a maximum thickness of 1,500 m (Kalia 1978).

The Deccan Trap basalt shows a high degree of heterogeneity by virtue of its weathering, jointing and fracturing properties. Accordingly, the occurrence and movement of groundwater is largely controlled by the factors similar to those of other hard rocks (Singhal and Gupta 1999). An additional factor, which has a bearing on the storage and movement of groundwater, is the vesicular part that occupies roughly about one-fourth to one-third of the total thickness of individual flows. The vesicular part of a flow provides primary porosity and its transmissive capacity increases considerably as it is often affected by sheet jointing. The Deccan basalt is an important hydrogeological unit in the western part of India, as it provides more than 80% of the rural drinking water needs and a substantial share of irrigation for winter crops. In the Torla Odha watershed of Maharastra (Fig. 1), the shallow unconfined aquifer is comprised of fractured massive basalt of Flow 1 (the flow exposed at the ground surface) and the vesicular portions of Flow 2 (Fig. 2). A red tuffaceous layer (also known as red bole), about 0.5–0.8 m thick, occurs between these two flows. The two flows form a shallow aquifer that is extensively exploited by large-diameter dug wells, and dug-cum-bored wells for both drinking water supply and for irrigation. In the Deccan Trap basalts, deeper aquifers may be present and groundwater can occur under semi-confined condition. The vertical fractures are believed to provide a conduit for recharge to the deeper aquifers (Deolankar 1980).

High demand for groundwater in trap basalts in different parts of the world has led to extensive work on its aquifer parameters. The porosity of dense massive basalt and vesicular basalt typically ranges from 0.1–1% and from 5–11% respectively (UNESCO 1975; Sharp 1993; Singhal and Gupta 1999). A decreasing trend in porosity and hydraulic conductivity is reported with increasing age of the trap basalts from different parts of the world (Walton and Stewart 1961; Adyalkar and Mani 1974; Rogbeer 1984; Niedzielski 1993; Jalaudin and Razack 1993). In Deccan Trap basalts, transmissivity (T) ranges from 10 to 700 m^2/day and the storativity ranges from 10^{-3} to 10^{-1} (Versey and Singh 1982; Kittu and Mehta 1990). The specific

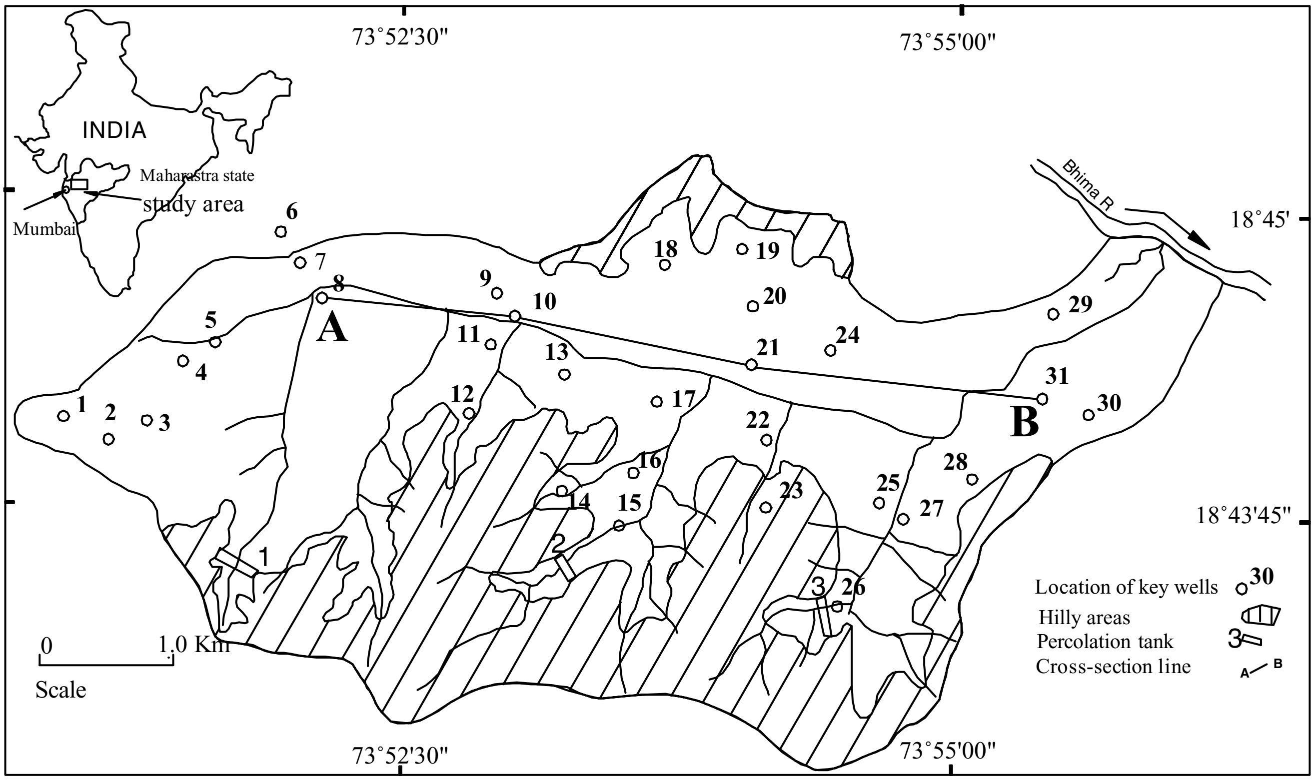

Fig. 1 Location of the Torla Odha watershed. The key wells shown are the open dug wells in which water levels are measured

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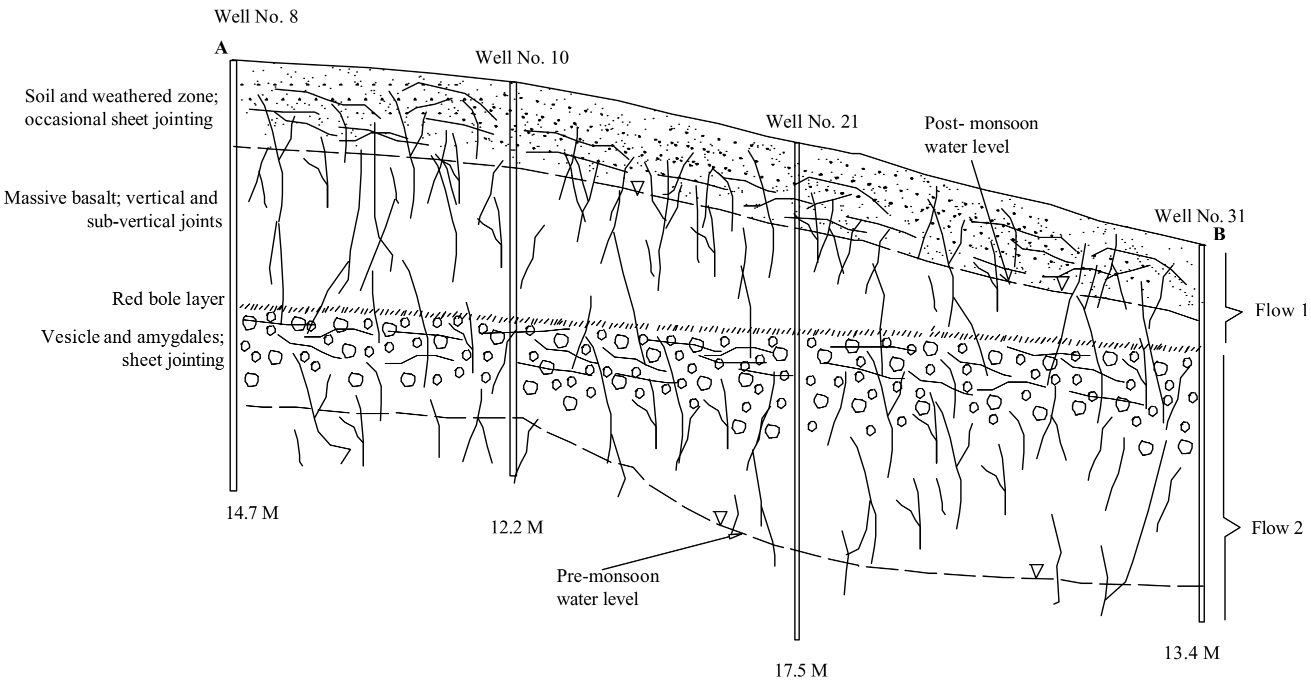


Fig. 2 Geological section along A–B (Fig. 1), showing Flow 1 and Flow 2, which are exploited to meet domestic and irrigation water demand

yield for Deccan basalt typically varies from 0.01 to 0.015 (Angadi 1986; Sahoo 1989; Naik and Awasthi 2003).

The present study emphasizes the importance of specific yield in assessing available groundwater resources. The specific yield is defined as the volume of water that an unconfined aquifer releases from storage per unit surface area of the aquifer per unit decline in the water level (Meinzer 1923; dos Santos and Youngs 1969). In this study, specific yield is estimated using a water balance approach for the Torla Odha watershed where the entire domestic and irrigation water demand is met by groundwater. The water resources assessment was based on pumping test analyses of selected open wells, monitoring of groundwater levels, and analysis of data on crops grown and groundwater abstraction.

The Torla Odha watershed, covering 22.05 km^2, is drained by a third-order tributary of Bhima River. The watershed is located in Rajgurunagar block of Pune district to the east of Chakan town on the Pune-Nasik road (Fig. 1). The area is inhabited by 7,550 persons. Thirty-one percent of the area of the watershed is classified as having steep slopes (>20%) with only limited groundwater potential and 64.8% of the area is under cultivation. The remaining area is in residential use.

The southwestern monsoon, which commences in the middle of June and continues until October, is the main source of groundwater recharge. The mean annual rainfall in the area for 20 years is 643 mm. More than 80% of the total rainfall occurs from July to September. The number of rainy days in a year is about 45 (Government of Maharastra 2000).

The watershed is elliptical in shape being elongated in the east–west direction (Fig. 1). The northern and southern boundaries of the watershed are flanked by flat-topped uplands which are 30–40 m above the flat-bottomed valley. The regional slope of the area is towards the east-southeast. Three percolation tanks are present in the watershed.

The entire drainage system in the watershed is ephemeral. All the first and second-order streams become dry within 15 days of withdrawal of the monsoon. The trunk stream (Torla Odha) continues to flow for some time although the spring line in the trunk channel shifts continuously downstream until the entire course dries up by the second week of January.

Hydrogeology

The abstraction of groundwater in the main valley of the watershed, where slopes are gentle, is limited to the top two basalt flows. The central part of the valley is underlain by massive basalt of the top flow (Flow 1) beneath a thin veneer of soil which is underlain by decomposed (weathered) basalt. The thickness of this soil plus weathered basalt varies from 3 to 5 m. The contact between Flow 1 and Flow 2 is observed to vary between 7.5 and 14.65 m below ground level (bgl) depending upon the altitude of the area. Two sets of joints strike ENE–WSW and E–W and dip sub-vertically to vertically as observed in the vertical walls of dug wells. A layer of vesicular basalt, 3.5–5.6 m thick, occurs below the base of Flow 1. This vesicular basalt forms the top of Flow 2, in the central part of the watershed (Fig. 2). The bored well data in the area reveals that the thickness of the second flow ranges from 24 to 27 m. The thickness of individual flows in the Deccan Trap basalt in Pune district and in the adjoining Satara district is reported to range between 9.0 and 88.0 m (Karmakar 1974; Kulkarni

1975; Gupte et al. 1978; Phadtare et al. 1979). Most dug wells in the Torla Odha watershed tap the entire thickness of vesicular basalt of Flow 2 and terminate in the massive basalt of the same flow. However, some dug wells, which are used to irrigate a small area, are of limited depth and terminate within the vesicular zone of the second flow only. The vesicular basalt is highly dissected by sheet jointing. In some unlined sections of dug wells (nos. 7, 21 and 23), vertical fractures are discernible with apertures up to 1 mm in width within massive basalt. These fractures appear to act as conduits between the near surfaces weathered zone and the vesicular zone of Flow 2. In some unlined well sections, the vesicular basalt is so intensely sheet jointed and friable that a 2-to-3-m-wide cavity has been created along the wall of the well by washing out the red bole and the underlying fractured vesicular basalt. The cavity penetrates horizontally as deep as 0.90–1.20 m into the formation from the periphery of the well. The thickness of the weathered zone generally increases towards the central part of the watershed. Groundwater within the shallow aquifer occurs under unconfined conditions.

Monthly water levels have been measured from October 1993 to September 1994 in 31 dug wells distributed evenly in the area (Table 1). Only those dug wells that penetrate the vesicular zone of the 2nd flow and a considerable thickness of the underlying massive basalt were selected for water level monitoring.

The water levels were measured in the morning, before the commencement of pumping. Total depth of the wells ranged between 8.45 and 21.3 m bgl and diameters ranged from 5.7 to 9.8 m. The pre-monsoon (May) water level ranged from 7.2 to 18.5 m bgl with an average of 12.4 m. During the post-monsoon (November) period, the range was 2.7 to 8.9 m bgl with an average of 5.2 m. The shallowest water level was observed in the month of September when the average was 4.0 m bgl (Table 1). The large fluctuation of water level is indicative of the low porosity of the rocks (Bidaux and Drouge 1993). The maps of depth to water level for the months of May and October are presented in Figs. 3 and 4. The elevation of the water table, showing the direction of the flow is presented in the Figs. 5 and 6.

Four pumping tests were conducted on open dug wells by using the pumps installed in the well. During the test, more than two-thirds of the existing water column was de-watered (Athavale et al. 1983). The recovery of the

Table 1 Depth to water levels in key observation wells located in the Torla Odha watershed (m bgl)

Well no.	Oct	Nov	Dec	Jan	Feb	March	April	May	July	Aug	Sept
1	3.10	4.58	7.85	8.30	9.52	10.58	12.29	13.90	14.80	12.32	3.50
2	2.82	4.50	10.06	10.57	12.00	12.45	12.93	12.83	13.20	11.80	2.59
3	1.00	3.00	7.66	12.90	12.39	13.51	14.81	15.38	12.20	9.30	0.00
4	0.90	2.95	7.29	12.52	12.90	12.67	12.70	12.73	12.70	11.12	0.00
5	0.36	2.67	6.48	10.59	13.90	14.50	14.66	14.68	13.20	12.31	0.00
6	4.87	6.00	8.43	8.82	9.30	9.75	10.79	11.23	11.06	9.20	7.80
7	6.93	8.30	12.80	14.01	15.95	16.12	16.80	17.65	15.60	14.90	9.10
8	0.76	3.08	5.55	7.05	8.12	9.45	11.00	11.02	12.15	8.00	0.00
9	4.93	5.30	8.16	9.23	9.36	9.18	9.17	9.13	5.61	4.31	8.18
10	2.42	3.10	4.97	6.70	7.80	9.88	9.89	9.91	8.80	7.13	0.00
11	3.83	5.00	6.34	8.65	9.50	8.66	11.71	11.62	9.40	8.12	3.10
12	5.71	7.60	11.43	12.92	13.20	14.10	14.20	14.17	11.40	8.79	5.20
13	4.48	5.80	7.40	8.79	8.00	10.04	10.20	10.00	Dry	6.00	4.90
14	5.40	7.20	9.40	10.70	Dry	Dry	Dry	Dry	8.99	6.70	2.00
15	3.62	3.57	4.79	10.72	16.70	17.76	17.99	18.50	Dry	17.20	2.31
16	3.40	4.88	5.95	8.50	11.53	13.90	15.00	16.30	4.58	4.15	1.60
17	5.57	6.64	8.41	9.77	12.62	13.45	14.32	15.01	13.11	13.40	5.51
18	3.74	5.52	6.05	6.82	6.89	6.92	7.11	7.65	13.30	11.12	3.92
19	5.58	5.72	6.21	6.69	7.50	7.70	8.56	8.62	5.61	4.23	4.13
20	2.73	3.29	4.97	5.13	5.36	5.21	5.60	5.70	5.36	4.24	2.40
21	5.26	5.47	7.78	10.87	12.09	14.51	14.92	15.47	14.07	11.02	3.84
22	6.10	7.52	7.94	10.30	11.50	11.34	11.70	11.80	11.60	4.90	9.00
23	4.50	8.60	11.41	13.85	14.90	13.69	13.90	14.50	13.73	11.32	4.21
24	3.84	5.59	6.92	9.98	11.70	11.84	12.20	12.32	12.20	10.10	3.90
25	3.46	4.83	4.51	6.75	7.33	6.91	7.10	7.21	7.80	7.40	4.40
26	3.20	3.35	3.78	8.60	10.00	12.02	12.62	13.82	14.26	12.21	2.90
27	1.87	3.80	4.31	8.20	8.50	12.28	12.77	13.90	13.63	11.80	2.30
28	8.15	8.93	9.61	9.68	11.20	13.37	14.39	14.26	13.81	13.93	13.60
29	3.42	4.66	6.68	8.89	9.44	9.81	10.22	10.82	10.84	9.23	3.86
30	2.49	2.90	3.38	4.90	5.71	9.91	8.80	9.58	9.23	7.24	3.97
31	5.59	6.66	6.00	6.98	9.06	9.89	11.73	11.58	12.13	10.40	6.27

Fig. 3 Map showing the water level below ground level (May). The contour value is in m bgl. Contour interval is 1 m

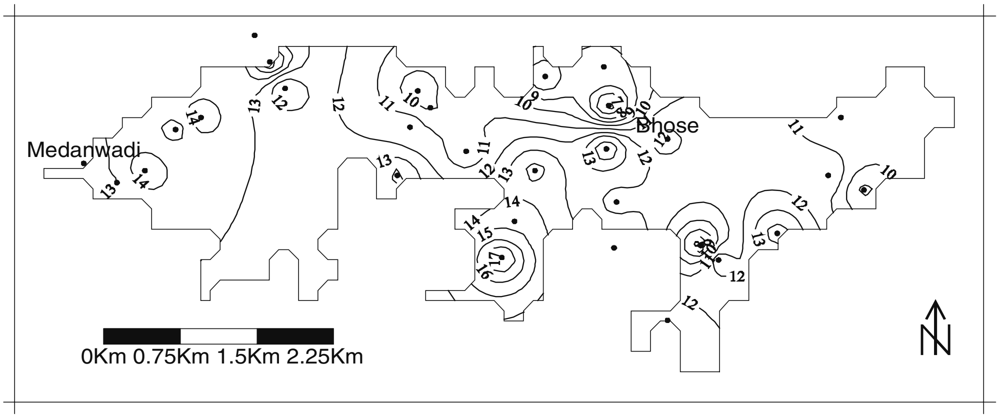


Fig. 4 Map showing the water level below ground level (October). The contour values are in m bgl. Contour interval is 1 m

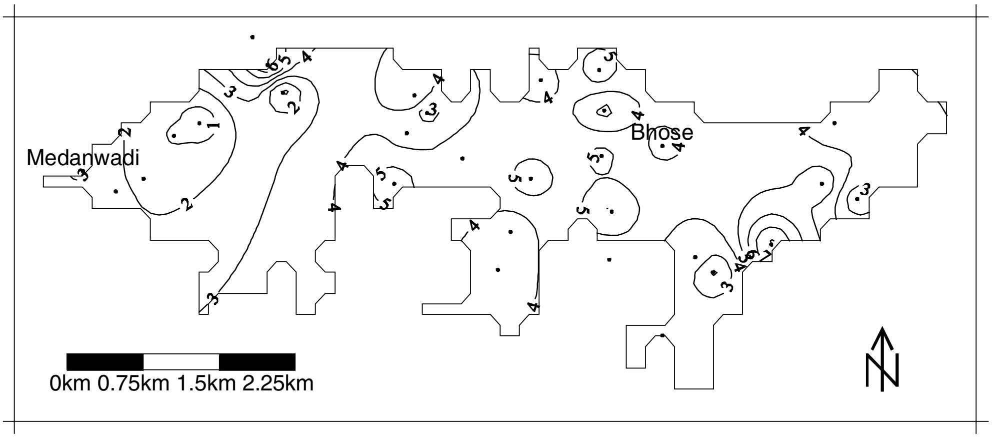
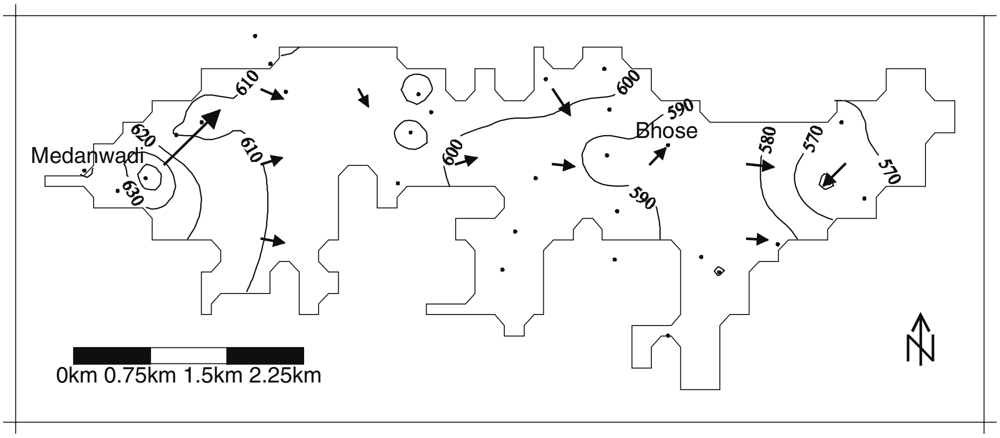


Fig. 5 The water table contour map (May). The contour values are in m above mean sea level. The contour interval is 10 m. *Arrows* indicate direction of ground water flow



water levels was used to determine the specific capacity (Slichter 1906). The unit area specific capacity (specific capacity/ cross sectional area of well) ranges from 0.11 to 1.73 lpm/m/m^2 (litres per min per meter per m^2). The values of the specific capacity are similar to those observed in other parts of the Deccan Trap and are indicative of a moderate potential yield from the shallow aquifer (Saha 1998). The 'hard rock permeability' as proposed by Kumarswamy (1973), provides an idea of the permeability of the hard rock aquifer. This parameter is worked out by analysis of pumping test data. It ranges from 0.4 to 1.4 m/day (Table 2).

Specific yield

There are various methods for determining specific yield. The water budget method (Walton 1970) is a comprehensive approach for its determination. The water budget relation proposed by Healy and Cook (2002) is used in this study to estimate the net volume of water that leaves the aquifer.

$$V_{\text{out}} = \text{WP} - S_{\text{pt}} - \text{RE} + \text{ET} + E_{\text{sr}}$$

where

V_{out} = Net volume of water discharged from aquifer

Table 2 Results of pumping tests in selected open dug wells in Torla Odha watershed

Location	Well no.	Total depth (m bgl)	Diameter (m)	Static water level (m bgl)	Specific capacity (lpm/m)	Unit area specific capacity (lpm/m/m^2)	Hard rock well permeability (m/day)
Rase	13	10.9	4.9	4.48	49.0	1.73	1.4
Medenkarbari-I	2	13.5	7.4	0.9	22.0	0.44	0.82
Bhose	25	10.12	8.65	3.49	4.0	0.11	0.4
Medenkarbari-II	7	17.82	5.4	6.93	37.0	0.69	0.73

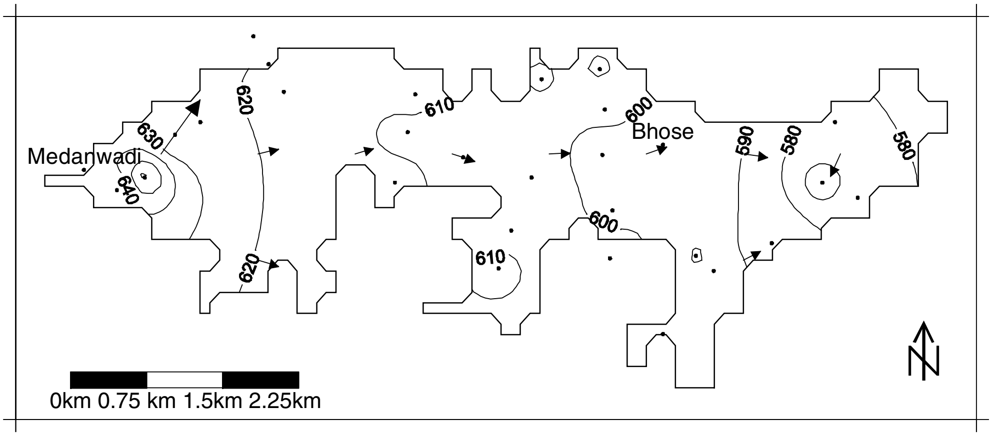


Fig. 6 The water table contour map (October). The contour values are in m above mean sea level. The contour interval is 10 m. *Arrows* indicate direction of groundwater flow

WP = Groundwater pumped for domestic and irrigation purposes
S_{pt} = Seepage from percolation tank
RE = Return seepage from irrigation
ET = Evapotranspiration
E_{sr} = Effluent seepage from the aquifer to the river

Finally, specific yield was determined by the following equation

$$\text{Specific yield} = \text{Net volume of water removed from the aquifer} / \text{Volume of rock de} - \text{saturated}$$

Using the above equation, the specific yields were determined for the seven non-monsoon months viz., November to May (Table 3).

Volume of water pumped from the aquifer

Dug wells are the common groundwater abstraction structures both for drinking and irrigation purposes. About 25 hand pumps in bored wells are operational in the area (depth 10–25 m bgl) and used only for drinking. A detailed plot-by-plot field survey reveals that 224 open dug wells are regularly used for irrigation (Table 4). The dug wells are fitted with high-capacity centrifugal pumps either of 5 or 3 HP (British Horse Power; 550 ft-pound per second) capacity. Pumps of 5 HP capacity are fitted in 107 wells (Table 4). Most of the pumps (90%) are electrically operated. The pumps and motors are fitted on a platform attached to the wall of the well. Two or three platforms are constructed at different depths so that the pumps can be kept close to the water level in different seasons.

Two factors that control the draft for irrigation in the area are crop-type and crop-stage. The area is devoted predominantly to a single crop (October to March) when onions are cultivated in more than 90% of the total sown area. After harvesting the onions in mid-March, the summer crop is sown in a limited area, consisting of vegetables and *bajri* (millet). The summer crops are grown in less than 5% of the winter cropped area. A field survey was conducted, between the 1st and 15th of December, on the pattern of abstraction from irrigation wells. The area was divided into 12 segments (Fig. 7) depending on the uniformity in the pattern of well use and availability of groundwater from the wells (Table 3). The number of pumping hours in a day ranged from 2.5–6.5 h/day for 3 HP pumps and 3–9 h/day for 5 HP pumps. The pumping rate was measured by a bucket and indicates that for a 3 HP pump, the rate varies between 8 to 12 m^3/h and for a 5 HP pump, 12–17.5 m^3/h. The variation of discharge is primarily due to three factors viz. (i) depth to water level from the point where the pump is fitted (ii) condition of the pump and (iii) frictional loss in the delivery pipes. The average discharge has been calculated to be 15.5 m^3/h for the 5 HP pumps and 11.2 m^3/h for the 3 HP pumps.

The irrigation requirement is at its peak in November, December and January. Based on the survey results, the average pumping during this period is 125 h/month. In February and March the pumping is reduced to 90 h/month, and it is further reduced to 50 h/month for April and 30 h/month in May. From June to mid-September, the draft from the aquifer for irrigation is negligible.

The number of pumping hours for the dug wells in different months for irrigation has been collected from the owners by visiting about 40% of the wells in each segment (Table 4). The discharge has been measured in each segment from three wells each fitted with 5 HP and 3 HP pumps. The pumping rate measured for the wells appears to have an error of ±20%.

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Table 3 Summary of data used to calculate specific yield for different months in the Torl Odha watershed

Item	November	December	January	February	March	April	May
Volume of aquifer desaturated (m^3/month)	2.31×10^7	3.45×10^7	3.65×10^7	1.57×10^7	1.36×10^7	1.21×10^7	0.985×10^7
No. of wells in operation for irrigation							
(a) 5 HP pumps	107	107	107	107	64	21	21
(b) 3 HP pumps	117	117	117	117	70	24	24
Average hours of pumping (hr/month/well)	125	125	125	90	90	50	30
Volume of water pumped out (m^3/month)							
(a) Irrigation	371,648	371,648	371,648	267,586	160,070	29,757	17,854
(b) Domestic	7,335	7,335	7,335	7,335	7,335	9,420	9,420
Effluent seepage to the stream (m^3/month)	77,760	44,264	14,560	Nil	Nil	Nil	Nil
Return seepage from irrigation (m^3/month)	55,747	55,747	55,747	40,138	24,011	4,464	2,678
Seepage from percolation tank (m^3/month)	15,288	13,398	11,886	10,500	9,240	8,022	7,056
Evapotranspiration (m^3/month)	15,060	Nil	Nil	Nil	Nil	Nil	Nil
Net volume of water de-saturated from aquifer (m^3/month)	400,767	354,101	325,909	224,283	134,155	26,691	17,540
Specific Yield (%)	0.0173	0.0103	0.0089	0.0143	0.0099	0.0022	0.0019

Table 4 Data on the number of dug-well pumps, pump capacities and average discharges in different sectors of the Torla Odha watershed

Sector no. (ref Fig. 7)	Total no. of wells	Number of wells fitted with 5 HP pumps	Number of wells fitted with 3 HP pumps	Average discharge of wells (m^3/h)	
				5 HP pump	3 HP pump
1	5	3	2	12	8
2	20	8	12	16	12
3	19	8	11	14	10
4	14	5	9	16	12
5	25	12	13	16	12
6	29	9	20	16	12
7	34	18	16	17.5	12
8	9	4	5	14	10
9	37	23	14	17.5	12
10	12	7	5	17.5	12
11	12	4	8	16	12
12	8	6	2	14	10

The water abstracted for domestic use is estimated based on the likely demand. It was not possible to survey all dug wells or hand pumps used by the domestic sector and no census is available. The human population of the watershed is 7,550 while that of the cattle is around 800. The entire human and livestock consumption is from groundwater. For April and May, the months experiencing the highest consumption, the per capita consumption for humans is considered as 40 l/day and for cattle as 15 l/day. For the remaining months, the per capita consumption is considered as 30 l/day and 15 l/day respectively for humans and cattle. The monthly total groundwater draft for domestic and irrigation purposes is approximately 0.38 million m^3/month for November, December and January, which reduces to 0.03 million m^3 in the month of May (Table 3).

Effluent seepage to the Torla Odha nala (stream)

All the first and second-order streams in the watershed become dry within 15 days of the end of the monsoon period. The trunk stream continues to flow until about mid-January. The volume of effluent seepage from the groundwater system of the watershed to the *nala* (stream) is estimated using Darcy's equation (Todd 1995).

$$Q = T * i * L$$

where T = Transmissivity (m^2/day), i = Hydraulic gradient of water table, L = Length of the flowing section along the contour (m).

During the month of November groundwater contributes 77,760 m^3 to the Torla Odha stream. This volume reduces to 14,560 m^3 in January and for 4 months February–May, there is no ground water contribution to streamflow.

Return seepage from irrigation

During the non-monsoon period, i.e. between October and May, onions are the main crop. They are grown between October and March although the period of maximum crop-water demand for onions is during the months October to January. During the summer, only 5% of the area is under cultivation. The return seepage from irrigation is considered as 15% of the total volume of water applied (CGWB 1997),

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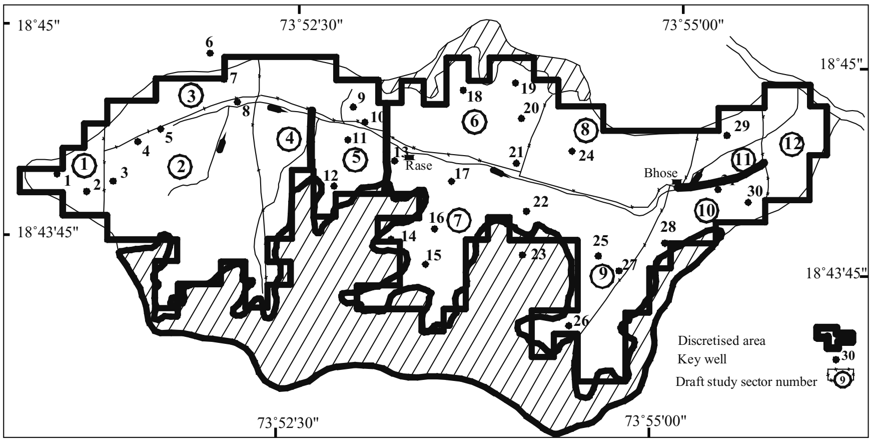

Fig. 7 Study area showing part of the watershed divided into 12 sectors for the groundwater draft survey. The white areas indicate the part of the watershed considered for Figs. 3–6

which is equivalent to 55,747 m^3/month for November, December and January. This volume is considerably reduced from February and is a minimum during May (2,678 m^3).

Evapotranspiration

Evapotranspiration (ET) is the total loss of groundwater due to evaporation and/or transpiration. The ET rapidly decreases as the water table declines and becomes almost negligible when the water table is below 3.5 m bgl (White 1932). The average position of the water table (Table 1) for the study area remains deeper than 3.5 m bgl for the period in which specific yields were determined. However, in the month of November the water table was observed to be less than 3.5 m bgl in seven wells. This area of the shallow water table covers 3.56 km^2 area of the watershed. The evaporation data (US Class I Pan) for Pune station (20 km from the study area) is 141 mm for the month of November (average of 10 years, IMD 1980). The actual ET is estimated to be 3.0% of the monthly pan evaporation (White 1932) for an average water level of 3 m bgl. The total ET for November is estimated as 15,060 m^3.

Infiltration from percolation tanks

At their full capacity the areas under impoundment for the three percolation tanks viz. Tank 1, Tank 2, and Tank 3 are 0.13 km^2, 0.127 km^2 and 0.142 km^2 respectively. Monthly field observations indicate that the tanks remain at full capacity in August, September and October. The surface area of stored water reduces by 10% in November and from December onwards until June it decreases continuously at a rate of 15% per month. Recharge from a percolation tank is assumed to be 1.4 mm/day based on the studies on infiltration from water harvesting structures (CGWB 1997). The infiltration from the three tanks is about 17,000 m^3/month in October when the tank is at full capacity but by June, the total infiltration from the tanks is less than 7,000 m^3/month (Table 5).

Table 5 Monthly contribution to the groundwater from three percolation tanks located in Torla Odha watershed (m^3/month)

Month	Seepage from percolation tank		
	Tank no. 1	Tank no. 2	Tank no. 3
October	5,670	5,334	5,964
November	5,124	4,788	5,376
December	4,494	4,200	4,704
January	3,948	3,780	4,158
February	3,486	3,360	3,654
March	3,066	2,940	3,234
April	2,688	2,520	2,814
May	2,352	2,226	2,478
June	2,100	1,974	2,184

Volume of aquifer de-saturated

The depth to water level maps was used to determine the volume of aquifer de-saturated in the time interval between water level measurements. In a scenario of progressively declining water table, the levels between the two successive months were used and the volume of the slice between the two water table surfaces was determined by using Surfer 7.0 (1999) program. The change in volume was measured by three methods viz. Trapezoidal rule, Simpson rule and Simpson 3/8 rule (Surfer 7.0 1999) and finally the average of these three methods was selected (Table 3). The volume of aquifer de-saturated was highest during December and January (34.5 and 36.5 million m^3 respectively, Table 3). After January, there is a rapid decrease in the volume of aquifer de-saturated and it reaches a minimum in May (9.85 million m^3).

Results and discussion

The Torla Odha watershed is a typical flat-bottomed watershed in the Deccan Trap province surrounded by an upland water divide. The entire water demand in the watershed for domestic and irrigation is supplied from the shallow aquifer, which is restricted to the upper 30–40 m of the subsurface. Infiltration from rainfall is the main source of recharge to the aquifer. The groundwater levels are deepest during the early June (average 12.38 m bgl) and begin to rise during July. During July and August, the water levels rise at a constant rate. This rise accelerates in September, and almost 65% of the annual water level rise occurs

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within this month. The non-monsoon rainfall accounts for only 6% of the total annual rainfall and makes no contribution to the groundwater recharge (CGWB 1997; Naik and Awasthi 2003).

Table 3 presents a summary of the data used to estimate specific yield, which was calculated for 7 months (November–May) outside the monsoon period. The valley part of the watershed is devoid of any dense woodland or deep-rooted phreatophytes. During the non-monsoon months, the water table remains below 3.5 m bgl, except for the month of November when the water levels in 7 of the 31 monitoring wells are within 3.5 m of the ground surface. The ET is considered negligible when the water table remains below 3.5 m bgl (Naik and Awasthi 2003; CGWB 1997). For the month of November, the ET is estimated for the area in which the water level was within 3.5 m of the ground surface as 15,060 m^3.

The average specific yield in the watershed estimated for the period November–May is 0.0093. This value, although low, compares well with previous estimates for basaltic terrain (CGWB 1984; Sahoo 1989; Naik and Awasthi 2003). The maximum specific yield was determined for November (0.0173) when the main contributing aquifer is the weathered zone. It is recognized that weathering can increase the porosity of fractured hard rocks (de Marsily 1986). The specific yield of the shallow aquifer steadily declines during December and January (Table 3). The contributing layers to groundwater outflow during these months are the massive basalts of Flow 1, immediately below the weathered zone. In February and March, the estimated specific yield increases (0.0143 and 0.0099 respectively) and a comparison of groundwater level data with the geological sections suggests that the vesicular basalt of Flow 2 contributes much of the groundwater flow (Fig. 2). For the months of April and May the specific yield values are considerably lower (0.0019 and 0.0022 respectively). During these 2 months, the average water level remains more than 12.0 m bgl. Only 45 wells are operational during these months with limited pumping hours. In 14 wells, the water level falls below the vesicular basalt of Flow 2 and the contributing layer is massive basalt of Flow 2 (Fig. 2). The low specific yield estimated for that portion of the shallow aquifer which was dewatered during the months of April and May is consistent with the low porosity of the massive basalts of Flow 2 which have fewer fractures and joints. The massive basalt forms the base of the shallow aquifer. The correlation of variation in the specific yield with the depth to water levels for the Torla Odha catchment is illustrated in Fig. 8, which confirms that most groundwater is stored in the upper part of the aquifer. Once water levels decline below a depth of 11 m, a major part of the aquifer storage has been depleted. This has important implications for those responsible for managing water resources in this aquifer.

The largest component of outflow from the aquifer is groundwater abstraction for both domestic and irrigation use. However, the volume of water pumped is difficult to estimate and is subject to significant error, possibly ±20%. The impact of this error in estimating groundwater pumpage, on specific yield determinations is presented in Table 6. It suggests that the average specific yield is likely to be between 0.0072 and 0.0105.

Conclusions

The specific yield of the shallow aquifer in the Torla Odha watershed, which is comprised of the Deccan Trap basalts flows, has been determined using a water budget approach. The specific yield determined for non-monsoon months (for 7 months, November–June) indicates considerable variation with depth to the water table. The maximum specific yield was 0.0173 during November, when the water table is shallow, and the minimum is 0.009 during May, when the water table is deepest. The variations result from differences in the hydrogeological properties of the different layers that make up the shallow aquifer (e.g. weathered zone, vesicular basalt, and massive basalts).

The highest specific yield is observed when the contributing layer is the soil and the weathered zone at the top of the aquifer. This value is closely followed by the specific yield of the vesicular basalt. Massive basalts underlying the vesicular zone of Flow 2 have the lowest specific yield value, indicating the compact nature of this sub-unit. This sub-unit appears to form the base of the shallow aquifer in

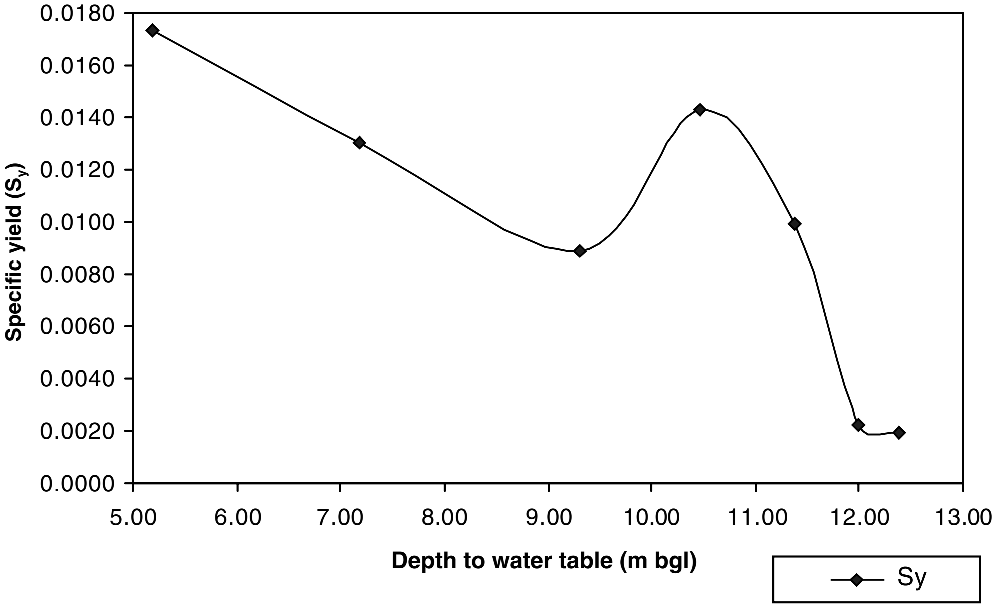
Table 6 **a** Specific yield computed under different scenarios of pumping. **b** Difference between specific yield determined (cf. Table 3) and computed values under different scenarios of pumping. **c** Percentage difference between specific yield (cf. Table 3) and computed values under different scenarios of pumping

Scenario	November	December	January	February	March	April	May	mean
a Specific yield								
I	0.0190	0.0117	0.0103	0.0166	0.0115	0.0025	0.0020	0.0105
II	0.0137	0.0082	0.0070	0.0110	0.0076	0.0017	0.0014	0.0072
b Difference in specific yield								
I	0.0017	0.0014	0.0014	0.0023	0.0016	0.0003	0.0001	0.0013
II	0.0036	0.0021	0.0019	0.0033	0.0023	0.0005	0.0005	0.0020
c Difference in specific yield in %								
I	10	14	16	16	16	14	5	14
II	21	20	21	23	23	23	26	22

Scenario I: 20% increase in discharge (for irrigation) from mean discharge values considered for specific yield calculation in this study

Scenario II: 20% decrease in discharge (for irrigation) from mean discharge values considered for specific yield calculation in this study

Fig. 8 Plot of specific yield vs. average monthly depth to water table. The lower specific yield is related to massive basalts of Flow nos. 1 and 2



this catchment. The weathered zone is an important part of the shallow aquifer, but groundwater from this layer also contributes base flow to the streams in addition to the abstraction from the wells. The vesicular zone nearest to the surface also yields a significant part of the water in the shallow aquifer but contributes little to streamflow. This vesicular basalt is heavily exploited by dug wells in the in the Torla Odha watershed. It would appear that currently most of the water in the shallow aquifer is exploited. Further, the net rate of abstraction does not appear to be sustainable or achievable unless groundwater infiltration can be enhanced by diverting surface runoff to recharge structures.

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