Evaluation of groundwater resource and estimation of its potential in Pathri Rao watershed, district Haridwar (Uttarakhand)

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The present study attempts to delineate aquifers in the piedmont zone of Himalayan foothill region in Pathri Rao watershed, district Haridwar, Uttarakhand, India by using integrated hydrogeologic and geophysical techniques. The geophysical techniques included vertical resistivity soundings, two-dimensional resistivity image profiling and electromagnetic surveys. Nuclear isotope studies have been carried out to estimate groundwater recharge and its relative age. An assessment of groundwater availability and stage of groundwater development has also been made from the available and generated field data. On the basis of the study, it was found that the rate of recharge into the aquifers is of the order of 19% and the stage of groundwater development in the watershed is 164% indicating critical over-exploitation of groundwater. Based on the findings, possibilities of artificial recharge of groundwater have been looked into in the study area for augmentation of groundwater resources by proposing a few check dams at the suitable sites in the upstream areas of the watershed.

Keywords: Aquifer delineation, groundwater assessment, isotope studies, watershed resistivity imaging.

Introduction

GROUNDWATER forms one of the important sources of water supplies in many areas, as it is believed to be safe and free from pathogenic bacteria and from suspended matter. The pace of groundwater withdrawal in many fertile regions is increasing phenomenally due to the fast pace of population growth accompanied by agricultural and industrial development. Large databases need to be developed for relating the aquifer geometry vis-á-vis availability of groundwater resources especially in the hilly regions of Himalayas. The present study attempts to delineate aquifers in the piedmont zone of Himalayan foothill region in Pathri Rao watershed, district Haridwar, Uttarakhand by using integrated hydrogeologic and geophysical techniques. Nuclear isotope studies have been carried out to estimate groundwater recharge and its age. An assessment of groundwater availability and stage of groundwater development has also been made from the available field data.

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Previous work

Remote sensing and GIS techniques have been increasing in use to generate groundwater potential maps[1,2]. The satellite remote sensing data along with collateral information and limited field checks have been used to establish base line data for groundwater prospective zones[3–7]. A critical review of the assessment of the groundwater recharge was given by Lerner *et al.*[8] and Scanlon *et al.*[9] in which the recharge estimation was made by considering rainfall infiltration and seepage from irrigation fields. The Groundwater Estimation Committee[10] of the Government of India suggested comprehensive norms and methodology for estimation of groundwater potential in the soft and hard rock areas. This approach is currently in common use by the government agencies. Israil *et al.*[11,12] gave applications of resistivity surveys, GIS analysis and isotope studies for hydrogeologic zoning and for evaluation of groundwater resource of the Ratmau–Pathri Rao watersheds of district Haridwar. Subsequently, Israil *et al.*[13] described the use of geophysical methods for direct delineation of aquifer configuration in the Pathri Rao watershed.

Study area

The study area is located between lat. 29°55′–30°3′N and long. 77°59′–78°6′E and covers an area of about 52 sq. km in the Pathri Rao watershed (Figure 1). The area is comprised of two hydrogeomorphic units, viz. Siwaliks and the Upper Piedmont zone, also referred to as ‘Bhabhar’ in the Himalayan foothills region, Uttarakhand. A third unit, viz. Lower Piedmont (Terai) zone falls further south of the Upper Ganga Canal. A notable flood plain has also been demarcated in the central part towards the eastern fringe of the watershed (Figure 2).

Geologically, the study area is comprised of sediments derived from Tertiary deposits of the Siwaliks. The

Siwaliks are exposed towards the northern extreme of the Pathri Rao watershed. The Bhabhar deposits are composed of unconsolidated coarse sand with boulders, fine to medium sand with pebbles, boulders and clay, derived from the Siwalik ranges. The formation exhibits high porosity and permeability, allowing easy infiltration of water with considerable recharge possibilities for the extensive aquifer system. The infiltrating waters move down along the steep gradient towards south and emerge as springs near the junction of Bhabhar with the Terai near the southern boundary of the area. South of this ‘spring line’, the Terai belt is present with effluent seepage at land surface resulting in marshy conditions.

Groundwater conditions

Mufid[13], Shimeles[14] and Kachhwal[15] carried out detailed study of this area using available lithologs of borewells and vertical electrical resistivity sounding data. They found that the depth of aquifers in the area is irregular and varies in a wide range. Admixtures of clay, sand and gravels of varying sizes are present in tube wells, though their properties vary from one place to another. The aquifers are composed of sand with pebbles and boulders generally fining upwards. Clay beds are also present with variable thickness but with limited aerial extent; however, at places, thick clays are present in some parts. Though all types of aquifers, i.e. unconfined, confined, semi-confined and perched aquifers are present, generally unconfirmed or confirmed two aquifers are commonly met with.

The fluctuation of groundwater table has been monitored in the study area in six existing well hydrographs. The locations of these wells are shown in Figure 1. However, these wells are located mostly in central and southern parts. It may be mentioned that the northeastern hilly terrain is an inaccessible and protected forest; therefore, no direct hydrogeological observations in this zone have been possible. The depth of water table was monitored during pre-monsoon (pre-rainy season) and post-monsoon (post-rainy season) period for 2004 and 2005 which are given in Table 1.

From overall water table data of the watershed, it is observed that the depth of water table is minimum (8.7 m bgl) near Qutubpur (W-4) located near the southwestern boundary of the Bhabhar zone and the deepest water table (32 : 79 m in June 2005) being recorded in the northern part of Bhabhar zone at Hetampur (W-10). The reason for occurrence of generally deep water table (9–32 m bgl) in the Bhabhar zone seems to be the high permeability of assorted and unconsolidated deposits in the vadose zone and due to the general absence of confining clay layers at shallow depths. Figure 3 shows a generalized groundwater potential map of the watershed based on selected seven geohydrological parameters[11].

Geoelectrical studies

With the purpose of aquifer delineation in the study area, an integrated approach comprising of vertical electrical soundings (VES), resistivity image profiling (EIP) and time domain electromagnetic (TEM) surveys was planned. Two-dimensional (2D) resistivity tomography carried out through EIPs helped in defining the horizontal and vertical geometry of the aquifer system[16]. A total of 11 VES, two TEM profiles and nine EIP profiles were recorded as shown in Figures 1 and 2. VES data were recorded using the Schlumberger configuration with maximum

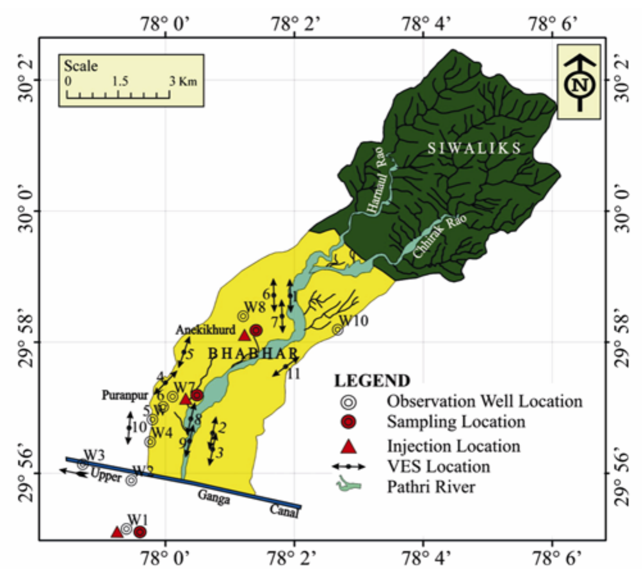

Figure 1. Location map of the project area.

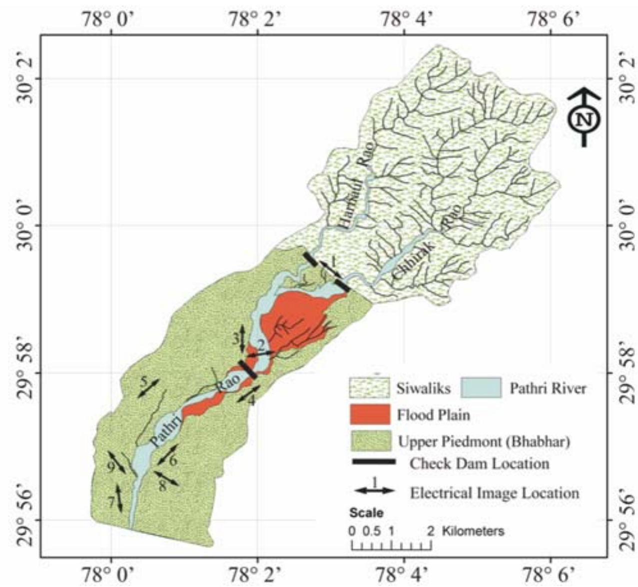

Figure 2. Hydrogeomorphological map of Pathri Rao watershed.

Table 1. Water table fluctuation data of observation wells

Well no.	Location	Depth of water table for pre-monsoon 2004 (m bgl)	Depth of water table for post-monsoon 2004 (m bgl)	Seasonal water table fluctuation (rise) (m), in 2004	Depth of water table in pre-monsoon 2005 (m bgl)	Decline during dry season (m)
W-4	Qutubpur	9.35	8.68	0.67	9.88	1.20
W-5	Garh Mirpur-1	12.50	11.40	1.10	12.30	0.90
W-6	Garh Mirpur-2	15.63	14.14	1.49	Dry	–
W-7	Puranpur	16.36	15.95	0.41	16.75	0.80
W-8	Aneki Kalan	16.40	15.63	0.77	16.33	0.70
W-10	Hetampur	30.53	28.50	2.03	32.79	4.29
				Average = 1.078 m		Average = 1.578 m

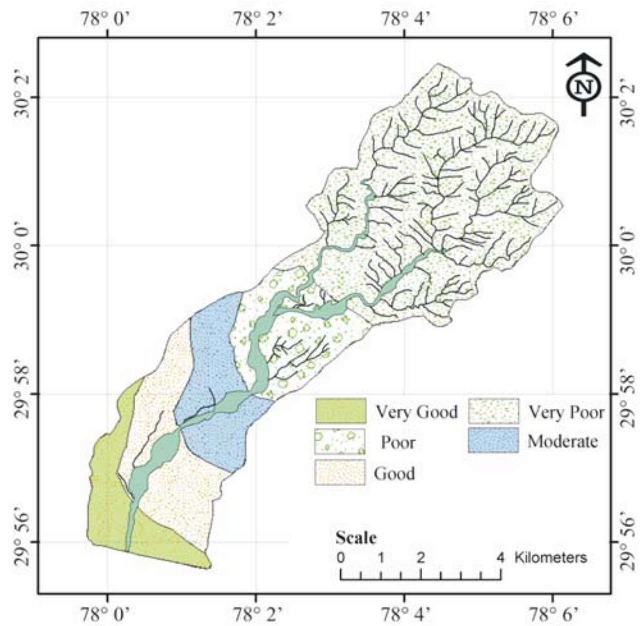

Figure 3. Groundwater potential map of Pathri Rao watershed.

electrode spacing of 900 m. As the northern zone of the area is restricted and inaccessible, the survey was carried out only in the southern part. The least squares method was used to invert apparent resistivity data in terms of resistivity and thickness of the subsurface layer. The interpreted 1D model consists of 3–5 layers with varying resistivity and thicknesses. The root mean square (rms) error obtained between the observed and modelled apparent resistivity lies below 6% in all the datasets. For geological interpretation, resistivity values were calibrated with known lithology from the available borehole data[16]. The results of the TEM survey carried out at two locations have been found to be in general agreement with the findings of the resistivity investigations[16]. The interpreted results of the sounding data in terms of true resistivity and layer thickness indicated that the resitivity of the top layers varies in a wide range up to 695 ohm-m[17]. The resistivity generally decreases at deeper levels (35–73 ohm-m), indicating presence of saturated zone at depths varying from 8 to 38 m below ground level. It may be noted, however, that most of these aquifers being of confined nature, the water level in the wells tapping such aquifers may rise much above the aquifer zone.

With the objective of mapping the detailed lateral and vertical variation of resistivity in the area, nine EIPs were recorded to cover the entire accessible region. These profiles were arranged serially from north to south. The location and orientation of these profiles are shown in Figure 2. Data were recorded using an IRIS resistivity meter in a sequence generated using the Schlumberger–Wenner configuration with 895 quadripoles (datapoints) in each sequence. Subsequently, 2D inversion was performed for each EIP dataset using RES2DINV code with smooth constrained least square method to delineate resistivity depth image along the profile line. Figure 4 shows the 2D model representing the resistivity-depth section along the nine EIP lines. The absolute rms error between the observed apparent resistivity data and the modelled data is less than 1.5. In the northern part of the study area unconsolidated coarse materials and boulders transported from the Siwalik hills are characterized by high resistivity for near surface unsaturated layers. At a depth of about 30 m, the resistivity is low (50 ohm-m), indicating saturated sand below the river channel (Harnaul Rao). Thus, the profiles oriented in different directions show the configuration of the aquifer zone and its elevation along the profile line. The aquifer zones are normally dipping southward, indicating local groundwater flow direction from north to south in the area. The direction of groundwater flow delineated from electrical images is consistent with the local hydrogeological setting. The middle part of the study area is a typical example of two aquifers separated by a thick, impermeable clay layer (EIP-5). Similar hydrogeological conditions are also revealed on the eastern side of the Pathri Rao River[16].

The geophysical studies indicate high resistivity of unsaturated, unconsolidated and porous coarse material of the Bhabhar Formation. Finer subsurface material in saturated condition towards the southern part is indicated by low resistivity. Two aquifers separated by a clay formation are inferred in the middle part of the area. The clay layer is discontinuous in some areas, indicating interconnection between the two aquifers.

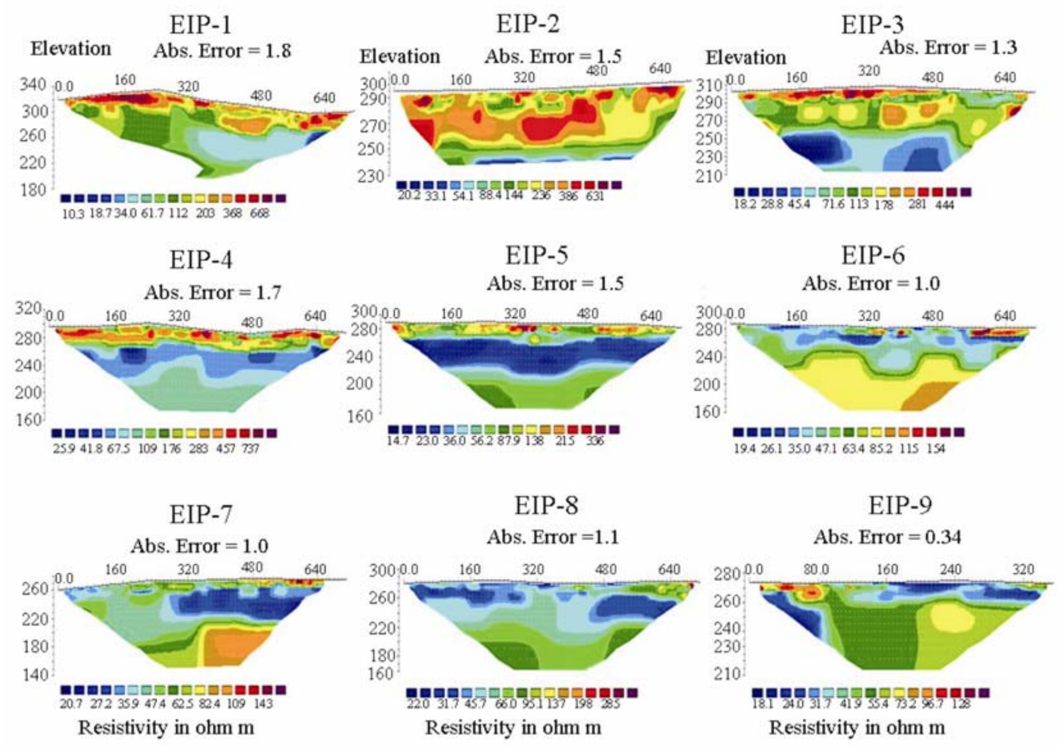

Figure 4. Interpreted 2D resistivity imaging sections.

Isotope studies

Three isotopic techniques, viz. tritium tagging technique, environmental tritium dating technique and stable isotope of oxygen (^{18}O) analysis have been used to estimate vertical recharge due to precipitation, age of groundwater and possible recharge zones in the study area.

Tritium tagging technique

Tritium tagging studies have been carried out at three sites (Figure 1) selected as representative of the area on the basis of soil type and regional topography. The groundwater recharge has been estimated by monitoring the vertical movement of injected tritium. The position of the injected tracer is indicated by a peak (maximum) in tritium activity versus depth plot. The radioactive tritium obtained from Bhabha Atomic Research Center (BARC), India with specific activity of 40 micro curie/cc were injected in five holes placed in a circular geometry at each site. The soil samples were collected at the time of injecting the tritium (pre-monsoon) and after four months in post-monsoon during December 2004. Volumetric moisture content of each soil sample was estimated in the laboratory. A liquid scintillation counter (LSC) has been used to measure the tritium activity of soil moisture extracted from each soil sample. The count rates were corrected for background counts to get net tritium counts per minute. The counting rates so obtained were plotted with depth for each site and the shift in tritium peak was estimated by using the depth of injection and centre of gravity of peak position. The shift in tritium peak and volumetric moisture content in pre-monsoon and post-monsoon season is shown in Figure 5. The amount of recharge during the time interval of tritium injection (pre-monsoon) and sampling (post-monsoon) could be estimated by multiplying the tritium peak shift and average volumetric moisture content in the tritium peak shift region[18,19] and is given in Table 2.

Environmental tritium dating technique

Tritium is a short-lived isotope of hydrogen with a half life of 12.32 years. Currently, natural concentration in atmosphere is about 10–12 Tritium Unit (TU). Dating of groundwater by decay of tritium is based on the assumption that the tritium input into a groundwater is known and that the residual tritium measured in the groundwater is the result of decay alone. The decay equation can be written as:

$$C_t = C_i \exp(-\lambda t), \quad (1)$$

here C_i is the initial tritium concentration (expressed in TU), C_t the residual activity remaining after decay over a time t, λ the decay constant ($= 0.693/t_{1/2}$) and $t_{1/2}$ the

Table 2. Tritium concentration and corresponding tentative age, electrical conductivity and $\delta^{18}O$ values at different sites

Sample no.	Sampling site/ type of aquifer	Tritium value (TU)	Relative age (years)	Electrical conductivity (μS)	$\delta^{18}O$ values (‰)	Recharge rate (%)
WS-5	Aneki khurd/Shallow	7.37	5	450	–6.9	19.00
WS-6	Aneki khurd/Intermediate	1.28	40	3000	–6.7	–
WS-4	Puranpur/shallow	4.60	14	800	–	8.94
WS-3	Bahadurpur/intermediate	6.38	8	350	–	29.01
WS-1 (neighbouring Terai area)	Bahuri/intermediate	9.01	2	650	–6.6	17.82

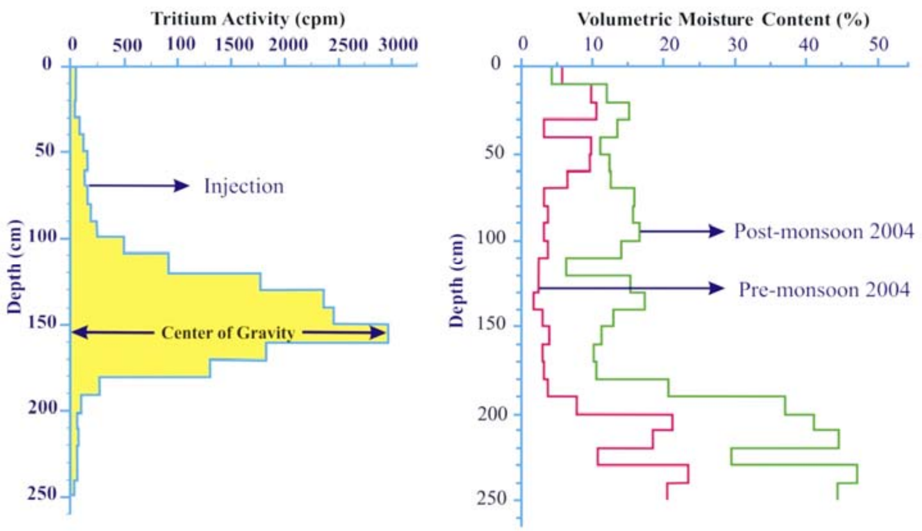

Figure 5. Movement of tritium peak and soil moisture at Aneki khurd site (TIS-4).

half life of tritium (12.32 years). The tritium values (in TU) were used to calculate uncorrected age of groundwater samples using exponential decay equation as given in eq. (1). The maximum tritium activity of 9.01 was recorded at a nearby site (Bhauri) towards south in the Terai at some deeper depth; therefore, the present day atmospheric activity, i.e. 10 TU was assumed as an initial activity of tritium in precipitation. The relative age of groundwater at different sampling points is given in Table 2.

Stable isotope ^{18}O analysis

In regions where direct and rapid infiltration of rain occurs, the composition of the groundwater will have the same isotope character as that of precipitation. The samples which were used for tritium dating were also used to find out their $\delta^{18}O$ values. Out of these, one sample is of shallow aquifer and other two are of deeper aquifer. These samples were analysed through the IsoPrime Dual Inlet Isotope Ratio Mass Spectrometer (GV) installed at Nuclear Hydrology Laboratory, National Institute of Hydrology, Roorkee. Table 2 shows the estimated values of tritium in TU and per mil of $\delta^{18}O$ from groundwater samples collected from the study area.

Source of groundwater recharge

The results obtained suggest the possible recharge zones for shallow and deeper aquifers at different sites. The water sample, with high tritium concentration (or smaller age) is recharged recently from nearby area, whereas the water that has low tritium concentration (or old age) is recharged from a location far away from the sampling location. Figure 6 provides a pictorial representation of the flow regime in the study area deduced from the present analysis.

The tritium activity at the Aneki khurd site in shallow aquifer recorded as 7.37 ± 0.33 TU (age ≈ 5 years) indicates the slow rate of recharge to the aquifer. However, as the site is located near Pathri Rao River, some recharge is expected from the riverbed as well. It has little depleted values of $\delta^{18}O$ (–6.9‰) than the local precipitation (–6.6‰). The lower tritium value, i.e. 1.28 ± 0.27 TU (age ≈ 40 years) at the deeper well (deep aquifer) at the Aneki khurd site clearly indicates that the second aquifer at this site is not connected with the shallow aquifer. This is also supported by the electrical conductivity (EC) value of groundwater (3000 μS) observed in the deeper aquifer. It appears that recharge zone for this aquifer is located far

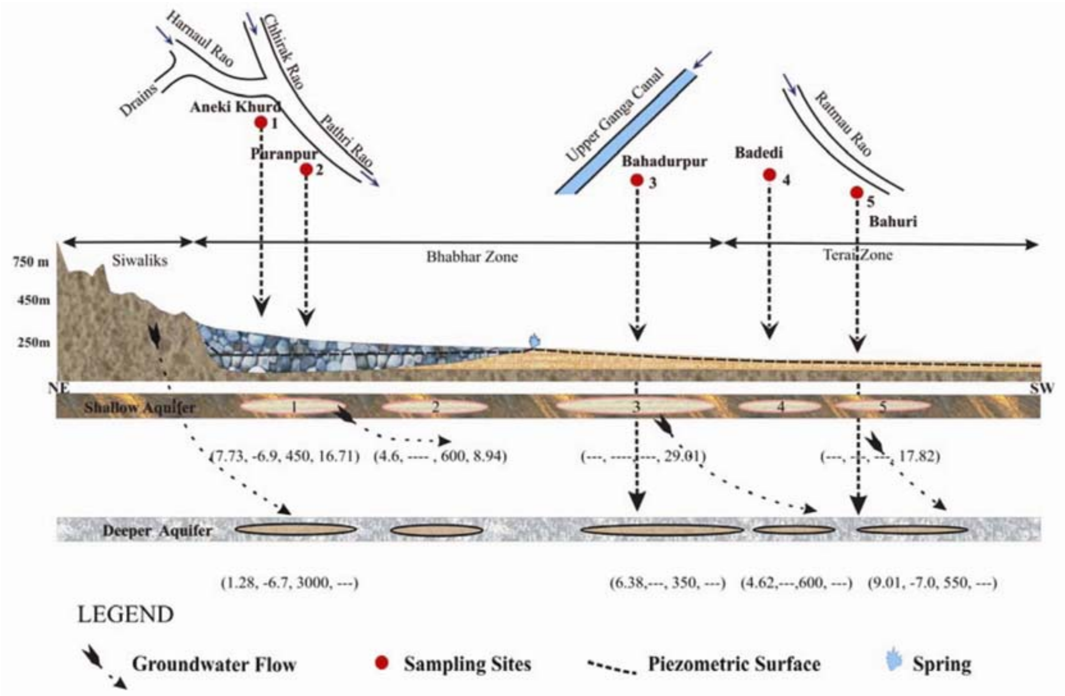

Figure 6. Schematic section representing groundwater flow direction, recharge sources and aquifer interconnections.

Table 3. Rainfall data in monsoon and non-monsoon seasons for 2002–05

Sl no.	Year	Monsoon (mm) (A)	Non-monsoon (mm) (B)	Total (A + B)
3.1	2002–03	681.0	369.0	1050
3.2	2003–04	702.0	219.0	929
3.3	2004–05	741.6	242.4	984
3.4	Average	708.2	276.8	985

away (18–20 km) but not at a higher altitude, as the $\delta^{18}O$ value is –6.7‰.

At Puranpur village, tritium value is measured only for shallow aquifer. The observed tritium value is 4.6 TU (~14 years) and estimated vertical recharge by tritium tagging technique is 8.94%. In this area shallow aquifer has high clay content (21.2%) too. So this aquifer is not getting rapid vertical recharge of water and it is also possible that this is getting good recharge from the water which is recharging the shallow aquifer at Aneki khurd village and is flowing down towards Puranpur village because of altitude difference. During the movement from Aneki khurd to Puranpur in shallow aquifer, some local salinity may be added and its electrical conductivity is modified from 450 to 800 μS.

On the other hand at the Bahadurpur site, measured environmental tritium value in intermediate aquifer is 6.38 TU (~8 years) and estimated vertical recharge rate in shallow aquifer by tritium tagging technique is very high (29.01%). The water, which is recharging the shallow aquifer, is also connected with deeper aquifer and the vertical flow rate of 260 cm/year is estimated from tritium tagging technique. The water from shallow aquifer will take around nine years to join deeper aquifer while the tritium value indicates the age of around eight years.

Groundwater resource estimation

The groundwater resource estimation of the project area has been carried out for the year 2004–05. The project area has an areal extent of about 5153 ha, out of which 2460.5 ha is hilly area and the remaining 2692.50 ha is almost plain area with slopes lesser than 6%[15]. It does not contain any poor groundwater quality area. The area can be categorized according to CGWB[10] as non-command area, because the area does not have any command of canal systems. Here, the return flow from Upper Ganga Canal falling outside the southern periphery of the project area has been ignored.

The depth to water table data for six observation wells given in Table 1 shows that the average yearly water table decline comes to 1.578 m during the dry season in 2004–05. The rainfall data for three years, from monsoon season, 2002–03 to non-monsoon, 2004–05, are collected from Block Development Office, Bahadarabad. The data is given in Table 3 for monsoon and non-monsoon periods. This data has been used for calculating normal rainfall of the study area. Specific yield has been calculated using groundwater balance equation for dry season. Gross groundwater draft (D_G) during non-monsoon season (2004) is 866.52 ha m and gross recharge during non-monsoon season from groundwater irrigation and all other sources is

Table 4. Computations of groundwater recharge assessment in the project area

Sl no.	Parameter	Value/description	
4.1	State	Uttarakhand	
4.2	District	Haridwar	
4.3	Area/Tehsil	Pathri Rao/Roorkee	
4.4	Year of assessment	2004–05	
4.5	Predominant type of terrain	Alluvial	
4.6	Geographical area (in square kilometers)	51.53	
4.7	Geographical area (in hectares)	5153.00	
4.8	Type of groundwater estimation unit	Watershed	
4.9	Monsoon season	June to November	
4.10	Non-monsoon season	December to May	
4.11	Groundwater assessment unit		
4.12	Name of the groundwater estimation unit	Pathri Rao	
4.13	(a) Total area of the groundwater unit (ha)	5153.00	
	(b) Hilly area (ha) [slope > 20%]	2460.50	
4.14	Groundwater recharge area (ha) = Sl No. [4.13(a)–4.13(b)]	2692.50	
4.15	Poor groundwater quality area	0.00	
4.16	Command area (ha)	0.00	
4.17	Non-command area (ha)	2692.50	
4.18	Gross groundwater draft in non-command area in ha m	Monsoon (A)	Non-monsoon (B)
4.19	Irrigation uses (data from IRI, Roorkee)		
4.20	State tube-wells (17 wells)	64.26	192.44
4.21	Pvt tube-wells (160 wells)	88.00	264.00
4.22	Pump sets (500)	175.00	525.00
4.23	Total groundwater draft for all uses	327.26	981.44
4.24	Domestic water supply requirement (ha m)	48.31	114.92
4.25	Gross groundwater draft (ha m) DG	278.95	866.52
4.26	Annual gross groundwater draft (ha m)	1145.47	
4.27	Recharge from 'other sources' in non-command area*		
4.28	Recharge from groundwater irrigation (ha m)	69.74	216.63
4.29	Total recharge in a year from groundwater irrigation return flow (ha m) Rgw: Sl No. [4.28(A) + 4.28(B)]	286.37	

*Recharge from Upper Ganga Canal is taken as zero as the canal forms the southern boundary of the watershed.

216.63 ha m (Table 4). The data about the number of different types of existing wells in the area and their unit groundwater drafts for irrigation tubewells and domestic water supply are available from Irrigation Research Institute, Roorkee (Table 4). Using these values, specific yield (S_y) is calculated as 15.3% (or 0.153) using the approach of CGWB[10] as given in Table 5.

The rainfall recharge in the study area during monsoon season of 2004 is estimated by water table fluctuation (WTF) method (Table 5). Normalized rainfall recharge during monsoon season in the non-command area from this approach is assessed as 624.66 ha m. By comparing the results of the RF infiltration and WTF methods, the percentage difference (PD) between them is calculated as 40%. As recommended by CGWB (1997) methodology, if PD is greater than +20%, then normal rainfall recharge during monsoon season is taken as 1.2 times that estimated by RF infiltration method. So normalized rainfall recharge for monsoon season in the study area is assessed as equal to 434.76 ha m (Table 6).

Likewise, the total recharge for groundwater aquifer in the study area during non-monsoon season is assessed as equal to 358.23 ha m. According to groundwater balance equation the storage increases in the monsoon season = total recharge – gross discharge (groundwater draft) = 225.55 h am. On the other hand, the storage increases in the non-monsoon season = total recharge – gross discharge = –508.29 ha m. This shows the negligible storage during monsoon season while a severe overdraft of groundwater takes place during non-monsoon season. Annual recharge to the groundwater unit includes total recharge during monsoon and non-monsoon seasons. Then the annual recharge of groundwater for a normal rainfall year in the project area is assessed as 862.73 ha m.

Thus, the stage of groundwater development is found to be 164% (Table 6). It shows a critical overexploitation of groundwater which is recharged annually with only a slight increase in storage during rainy season. Therefore, further groundwater development in the area is not recommended.

Table 5. Specific yield and recharge assessment in the non-command study area by water table fluctuation (WTF) method and rainfall infiltration method

Sl no.	Description	Value
5.1	Average water level decline (m) in non-command area in meters during non-monsoon season (from Table 1)	1.58
5.2	Specific yield from groundwater balance equation for non-monsoon season in % (S_y) = Sl no. [4.25(B) – 4.28(B)]/Sl no. (5.1 × 4.17)	15.30
5.3	Average water table rise in m in monsoon season (from Table 1)	1.08
5.4	Change in groundwater storage during monsoon ($S = h \times S_y \times A$) in ha m in non-command area = Sl no. [(4.17 × 5.3 × 5.2)]/100	444.91
5.5	Rainfall recharge by WTF method in non-command area during monsoon season in ha m in 2004 = Sl no. [5.4 + 4.25(A) – 4.28(A]	654.12
5.6	Normalized rainfall recharge for monsoon season in non-command area in ha m (by WTF method) = Sl no. [5.5 × 3.4(A)/3.3(A)]	624.66
5.7	Percentage of normal non-monsoon RF to normal annual RF = Sl. No. [3.4(B)/3.4(A + B)]	28.10
5.8	Rainfall recharge factor (%) (from isotope studies)	19.00
5.9	Rainfall (recharge) factor as a fraction	0.19
5.10	NORMAL rainfall recharge in non-command area by rainfall infiltration factor method (ha m) in monsoon season = [Sl no. 4.17 × 0.19 × Sl no. 3.4(A)/1000]	362.30
5.11	Normal rainfall recharge in non-command area by rainfall infiltration factor method (ha m) in non-monsoon season = [Sl no. 4.17 × 0.19 × Sl no. 3.4(B)/1000]	141.60

Table 6. Computations of stage of groundwater development

Sl no.	Description	Value
6.1	Percentage difference (PD) between rainfall recharge estimated for monsoon season by WTF method and rainfall infiltration method for non-command area	40.1% (i.e. >20%)
6.2	Normalized rainfall recharge for non-command area in monsoon season [factor 1.2 × Sl no. 5.10]	434.76 ha m
6.3	Total recharge during monsoon (for normalized rainfall) R_{rf} (normal) sl no. [6.2 + 4.28(A)]	504.5 ha m
6.4	Normal recharge from all sources in non-monsoon season (normal non-monsoon rainfall recharge + return flow from groundwater irrigation in non monsoon) sl no. [5.11 + 4.28(B)]	358.23 ha m
6.5	Net yearly recharge from all sources	862.73 ha m
6.6	Net groundwater draft during the year	1145.47 ha m (being more than sl no. 6.5)
6.7	Drinking water requirement for the watershed for whole year sl no. [4.24(A) + 4.24(B)]	163.23 ha m
6.8	Utilizable water for irrigation [sl no. 6.5–6.7]	699.50 ha m
6.9	Level of groundwater development [sl no. 6.6/6.8]	163.75%
6.10	Stage of groundwater development	Overexploited

Possibilities of artificial groundwater recharge

The analysis of the groundwater assessment data has indicated clearly that in the Pathri Rao watershed, over-exploitation of groundwater is being carried out resulting in the steady decline of the water table in the observation wells both before and after the monsoon during the last few years (Table 1). Such a groundwater scenario in the watershed calls for urgent measures for groundwater replenishment through artificial recharge in the project area. It has been revealed from the investigation and interpretation of the geophysical resistivity and electromagnetic data in the project area that assorted admixture of gravels and sands comprise the Bhabhar belt in the unsaturated zone above the aquifers without significant presence of clay horizons at shallow depth. As such, a method of artificial recharge which enables direct infiltration of the rain water without causing significant run-off may be a successful method for replenishment of the groundwater in the area. In such a geomorphic terrain, construction of 'check dam' seems to be the most suitable means for storing and re-charging groundwater. The construction of check dams is often considered suitable across 2nd or 3rd order streams having gentle slope and is thus feasible in the Bhabhar type of alluvial formation.

Before construction of a check dam, it is necessary to choose suitable sites for the purpose. CGWB[20] has suggested important criteria for selection of sites for construction of check dam(s).

In accordance with their approach, the following locations seem to be suitable for construction of check dams. (i) One check dam each on Harnaul Rao and Chirak Rao upstream of their confluence where the width of these tributaries is narrow (Figure 2) in the vicinity of resistivity image profile number EIP-1. (ii) One check dam on the main Pathri River (east of Aneki Kalan village), in the

Table 7. User departments and information needs

Users (Govt departments/ NGOs)	Information needs	Scheme for which information is needed
Pey Jal Nigam	Identify source areas for construction of new tubewells and hand pumps	Construction of tubewells and hand pumps
Jal Sansthan	Identify source areas for construction of new tubewells and hand pumps	Construction of tubewells and hand pumps
Minor Irrigation	Identification of sites for drilling of irrigation tube wells and details thereof	Details of drilling of irrigation tube wells
Watershed Management Directorate	Identification of watershed and hydrogeomorphic parameters	(i) Watershed management (ii) Construction of artificial recharge structures
CGWB	Sites for artificial recharge	To carry out artificial recharge at identified sites

vicinity of profiling site EIP-2 where the width of the river is narrow (Figure 2).

It is also recommended that suitable monitoring may be carried out after construction of the above water conservation structures so as to carry out studies for the worthiness of the executed artificial recharge schemes.

Conclusions and recommendations

The results of the present study can be utilized by relevant user agencies in Uttarakhand (Table 7) for watershed management, artificial recharge and identification of sites for construction of tubewells and hand pumps for irrigation, drinking and for providing relevant details of drilling. However, it needs to be noted that as the basin is already in the 'overexploited' category, any groundwater development is to be carried out in the area only after getting viable results from the artificial recharge/rainwater harvesting schemes.

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